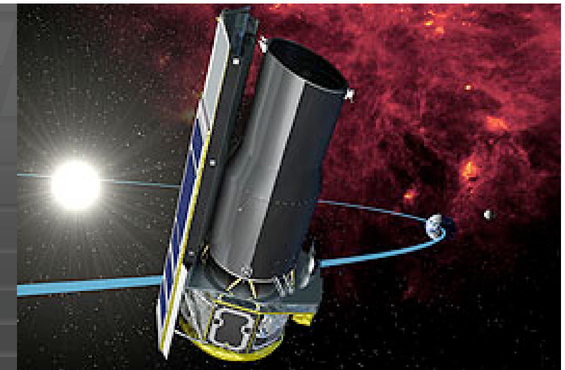


A Large Population of High Redshift Galaxy Clusters in the *IRAC Shallow Cluster Survey (ISCS)*

M. Brodwin (JPL/Caltech)

UC Berkeley Cosmology Seminar

November 5, 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 μm	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)

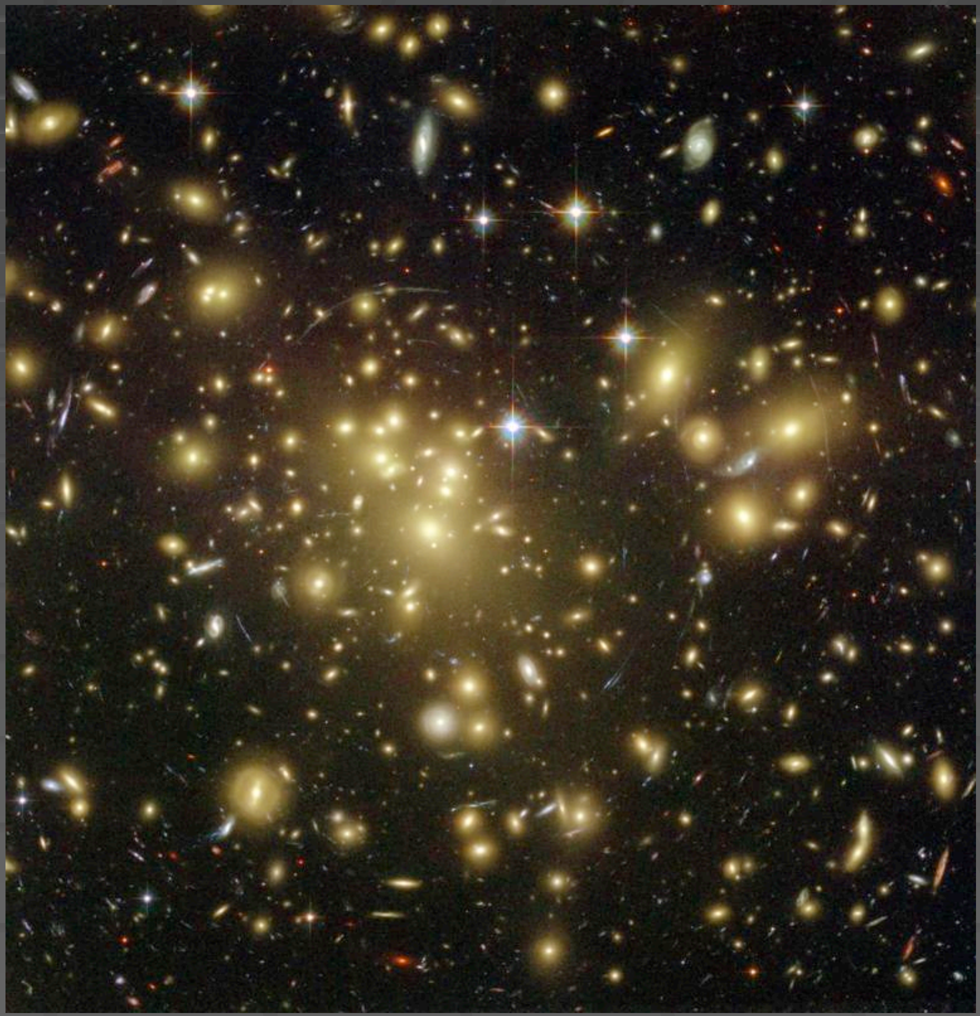
Outline of Talk

- Motivation
- Survey Description
- Methodology & Results
- Implications for Massive Galaxy Formation
- Next Steps & Summary

Motivation: Cluster Surveys

Galaxy Evolution I

- Very efficient for galaxy surveys
- Fundamental plane of elliptical galaxies discovered in cluster surveys
- Study effect of dense environment on galaxy evolution (e.g. T-Σ relation; Butcher-Oemler Effect; etc.)



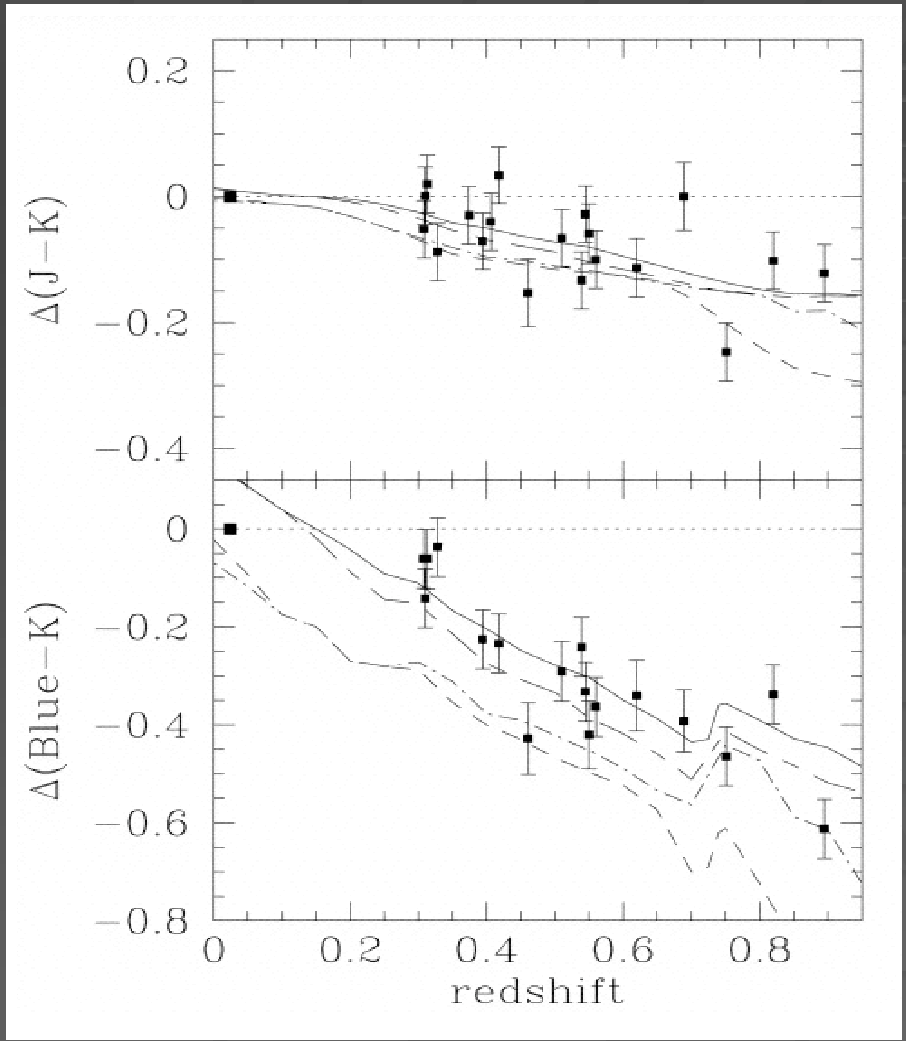
Abell 1689 (ACS; Benitez et al.)

Motivation: Cluster Surveys

Galaxy Evolution I

- Evidence that ellipticals in z<1 clusters form their stars at high-z (z_f~2-5), and evolve passively.

Extend to higher z, closer to the epoch of formation



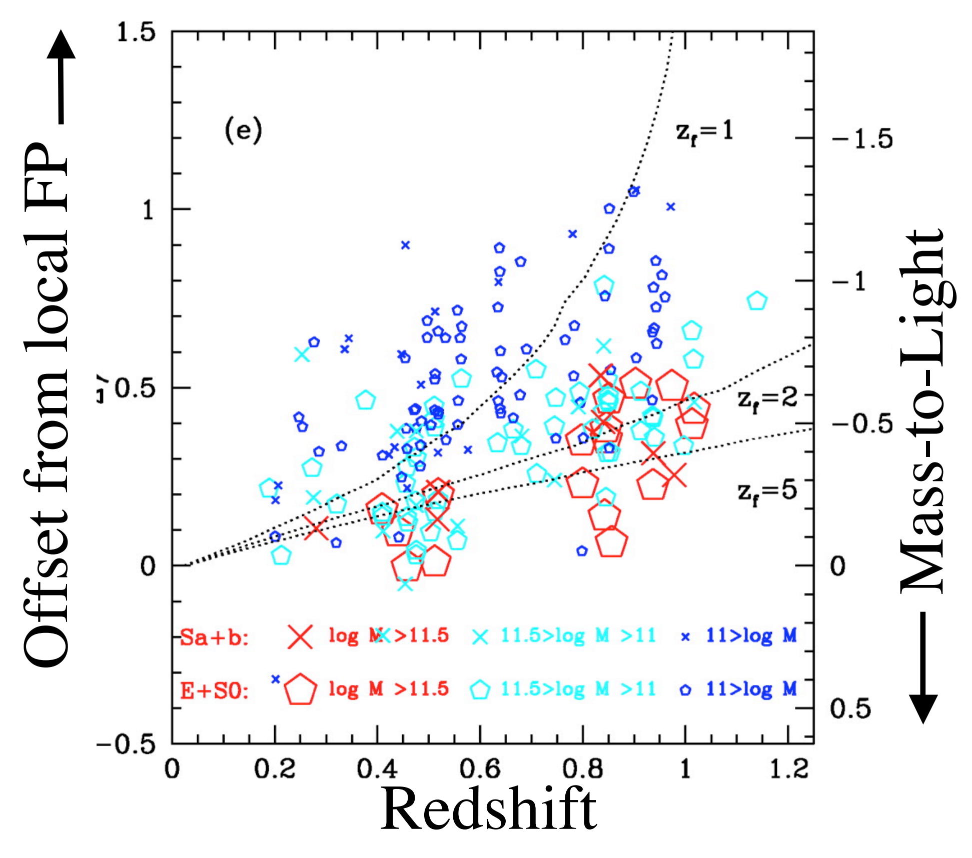
Stanford, Eisenhardt & Dickinson (1998)
see also *De Lucia et al. (2004), van Dokkum & van der Marel (astro-ph/*0609587)

Motivation: Cluster Surveys

Galaxy Evolution II

- Growing evidence for early formation of massive field galaxies
- Anti-Hierarchical?
- Role of “dry merging”?

Need unbiased census of massive galaxies at $1 < z < 2$

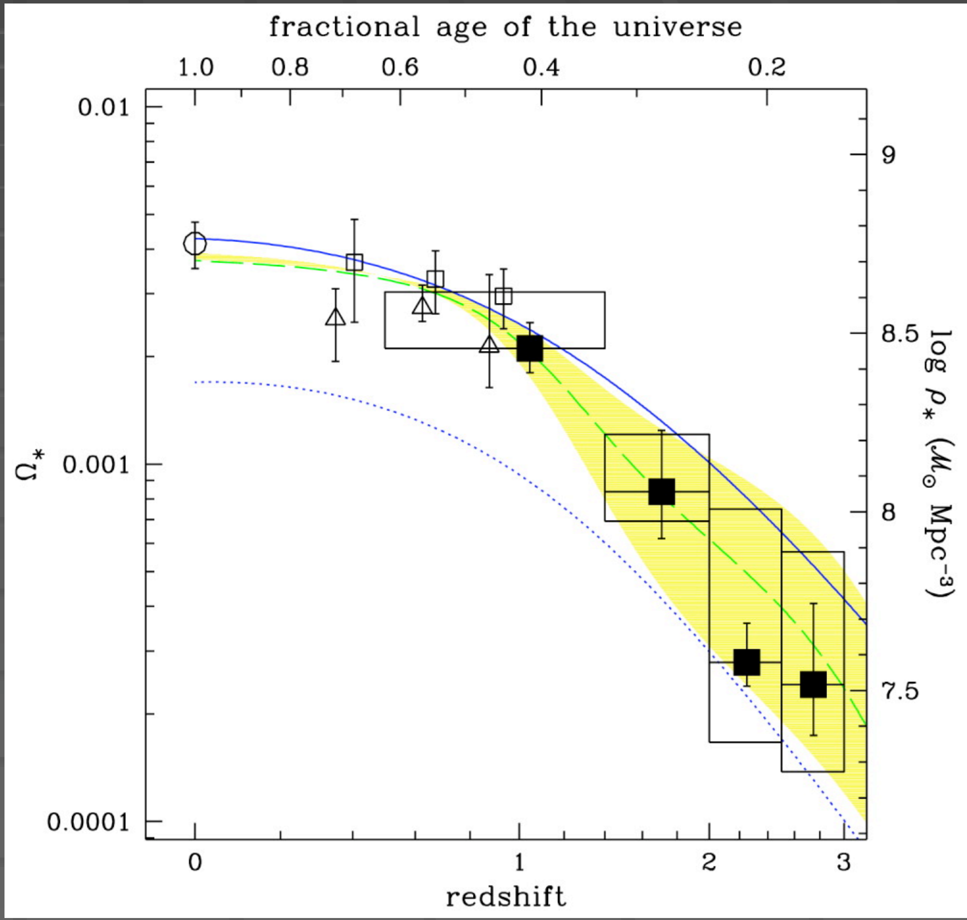


Treu et al. (2005)

Motivation: Cluster Surveys

Galaxy Evolution III

- SFR peaks at 1<z<2
- Most of the stellar mass is created in this redshift regime

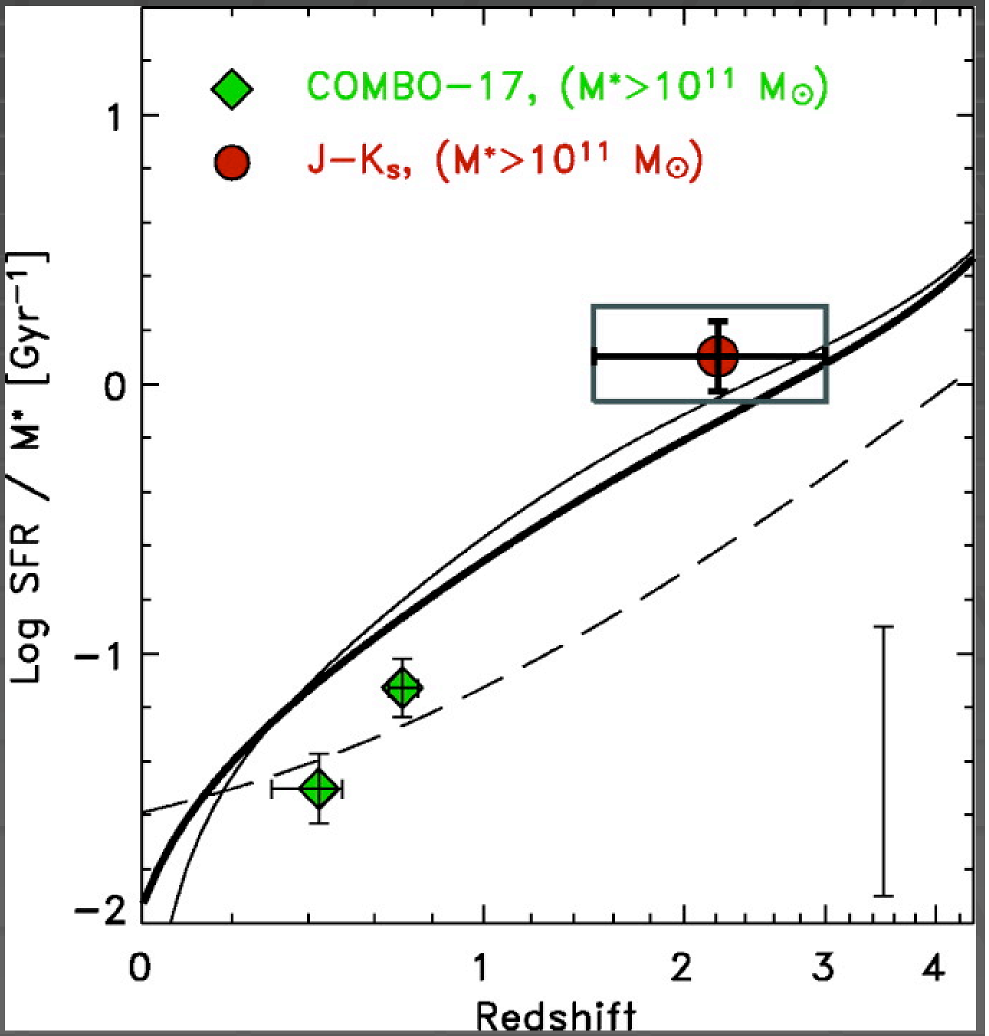


Dickinson et al. (2003)

Motivation: Cluster Surveys

Galaxy Evolution III

- SFR peaks at 1<z<2
- Most of the stellar mass is created in this redshift regime
- Massive galaxies have much higher specific SFR at z=2



Papovich et al. (2006)

Motivation: Cluster Surveys

Galaxy Evolution III

- SFR peaks at $1<z<2$
- Most of the stellar mass is created in this redshift regime
- Massive galaxies have much higher specific SFR at $z=2$

Explore connection between ULIRGS and Galaxy Clusters at $1<z<2$

ULIRGS ($L_{IR} > 10^{12}\ L_{\odot}$) at $1 < z < 3$

- *Massively* starforming (> 100 $M_{\odot}$/yr)
- ~1000x more common than locally
- Highly clustered ($r_0 > 10\ h^{-1}$ Mpc), similar to EROs at these redshifts.

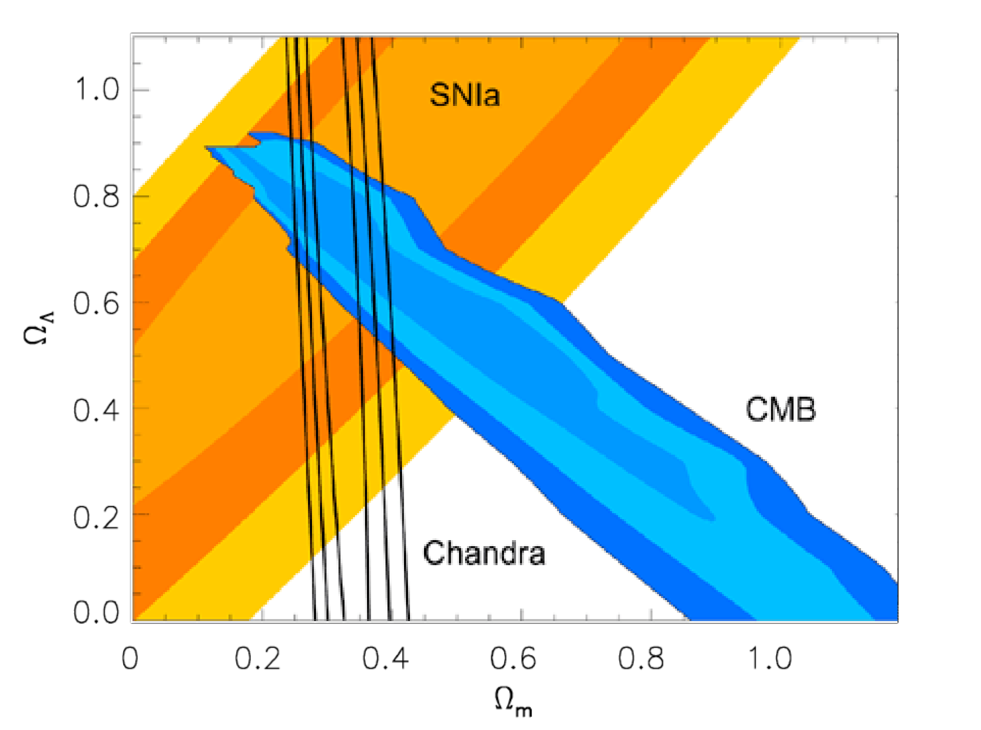
Clusters & Groups at z~0

- Repository for most of the stellar mass in the Universe
- Most clustered structures in the Universe ($r_0 \sim 20\ h^{-1}$ Mpc)

Motivation: Traditional Cluster Surveys

Cosmology I

- "Fair Sample" of Universe, can measure Ω_m directly

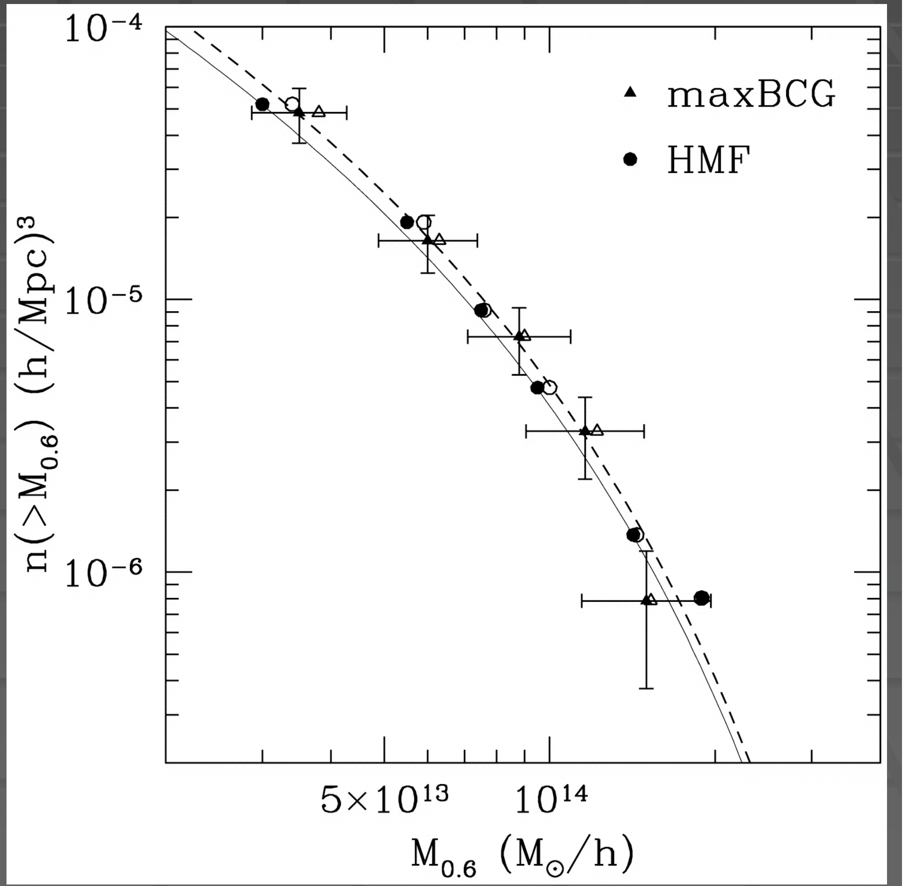


Allen et al. (2002)

Motivation: Traditional Cluster Surveys

Cosmology I

- "Fair Sample" of Universe, can measure Ω_m directly
- Compare dN/dM with Press-Schechter prediction

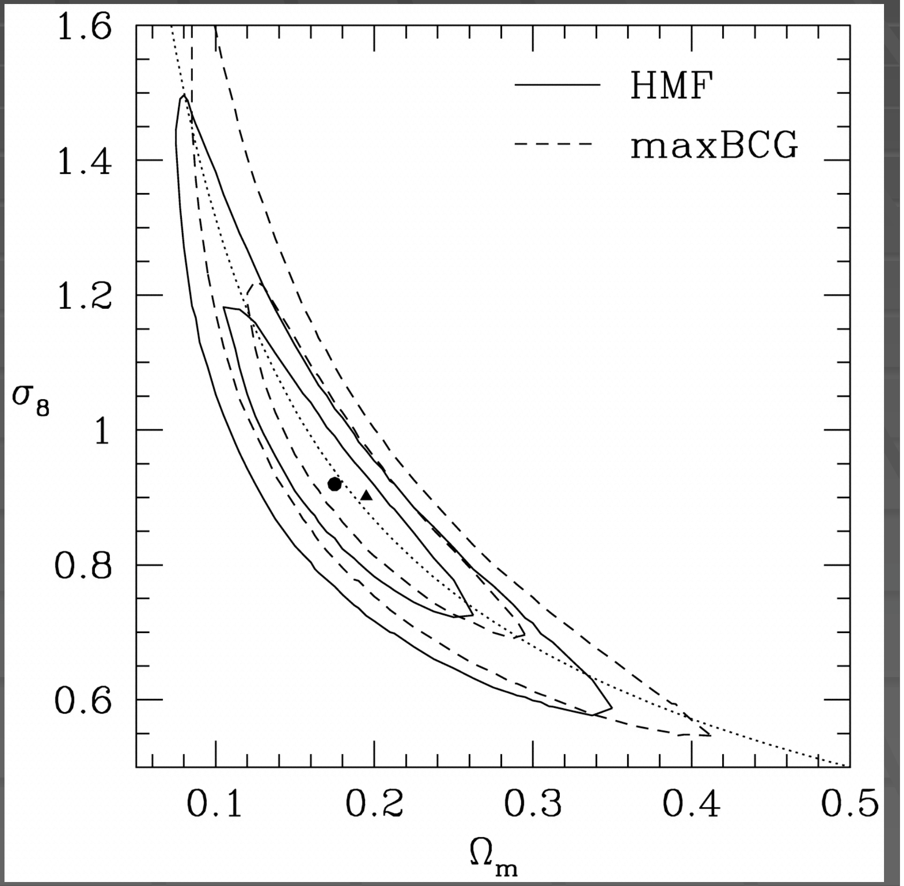


Bahcall et al. (2003)

Motivation: Traditional Cluster Surveys

Cosmology I

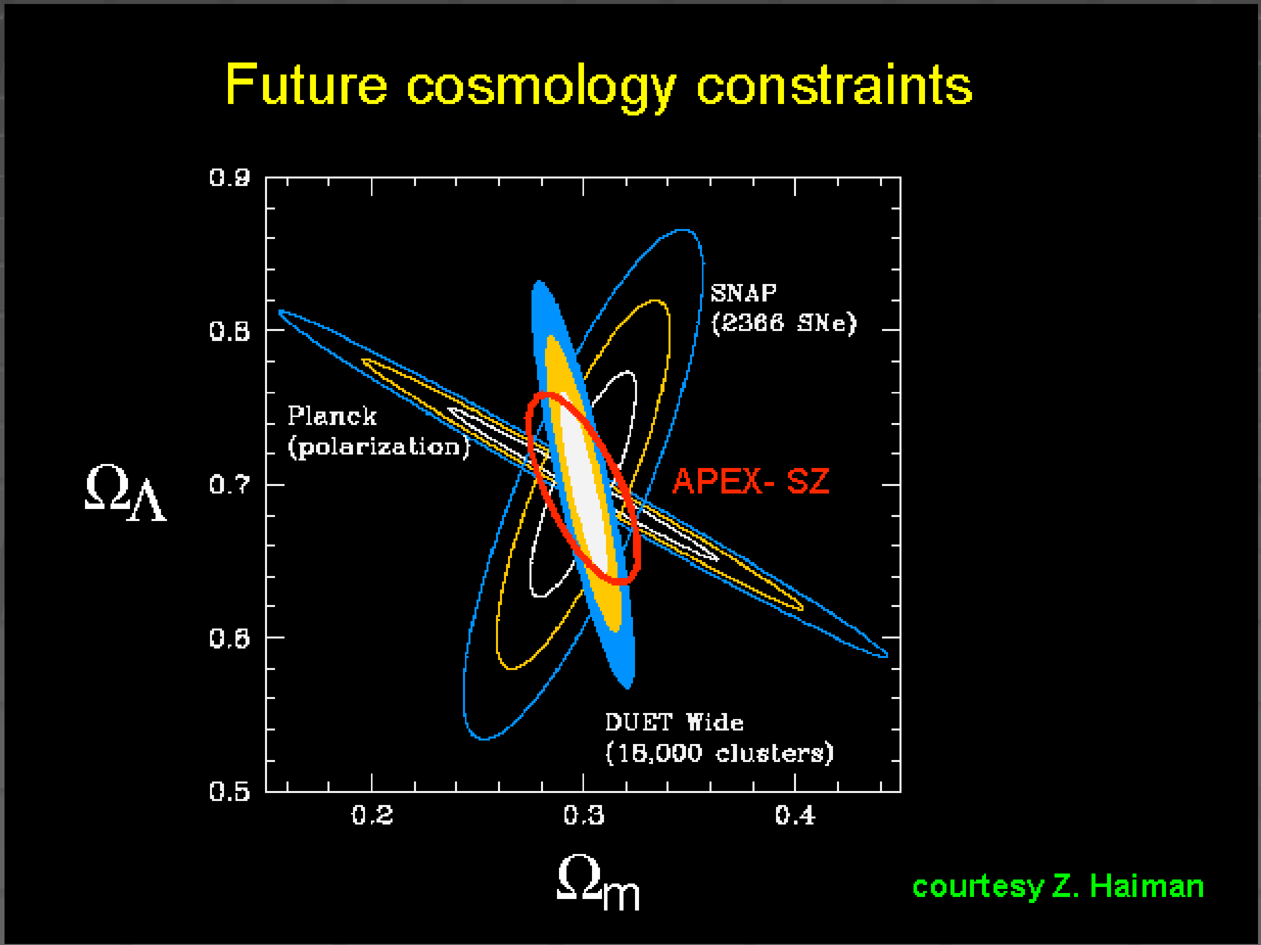
- "Fair Sample" of Universe, can measure Ω_m directly
- Compare dN/dM with Press-Schechter prediction
- Jointly constrain Ω_m and σ_8 by measuring cluster mass function.



Bahcall et al. (2003)

Motivation: Future Surveys

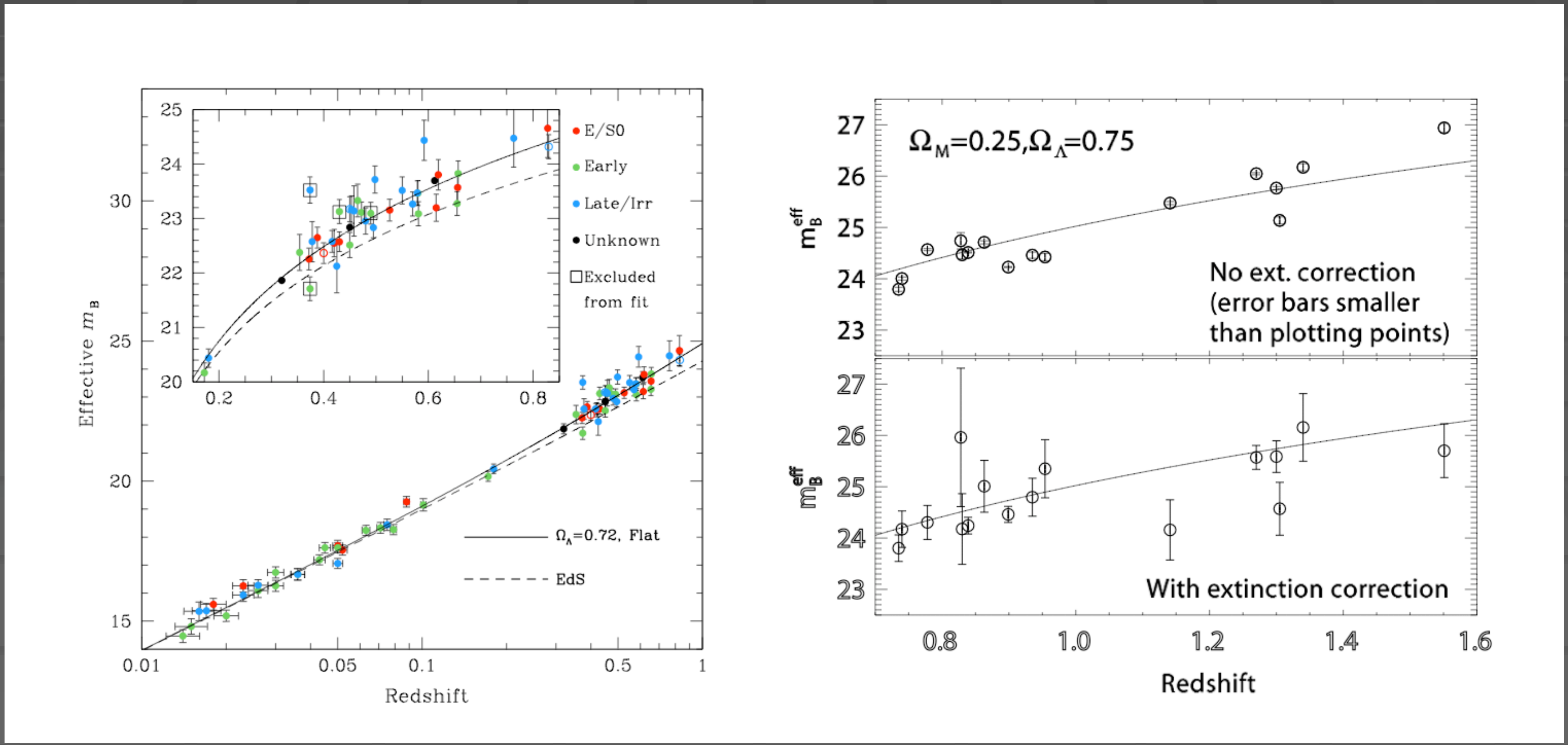
Cosmology II



Frank Bertoldi

Motivation:
Novel Approach Today

Cosmology III

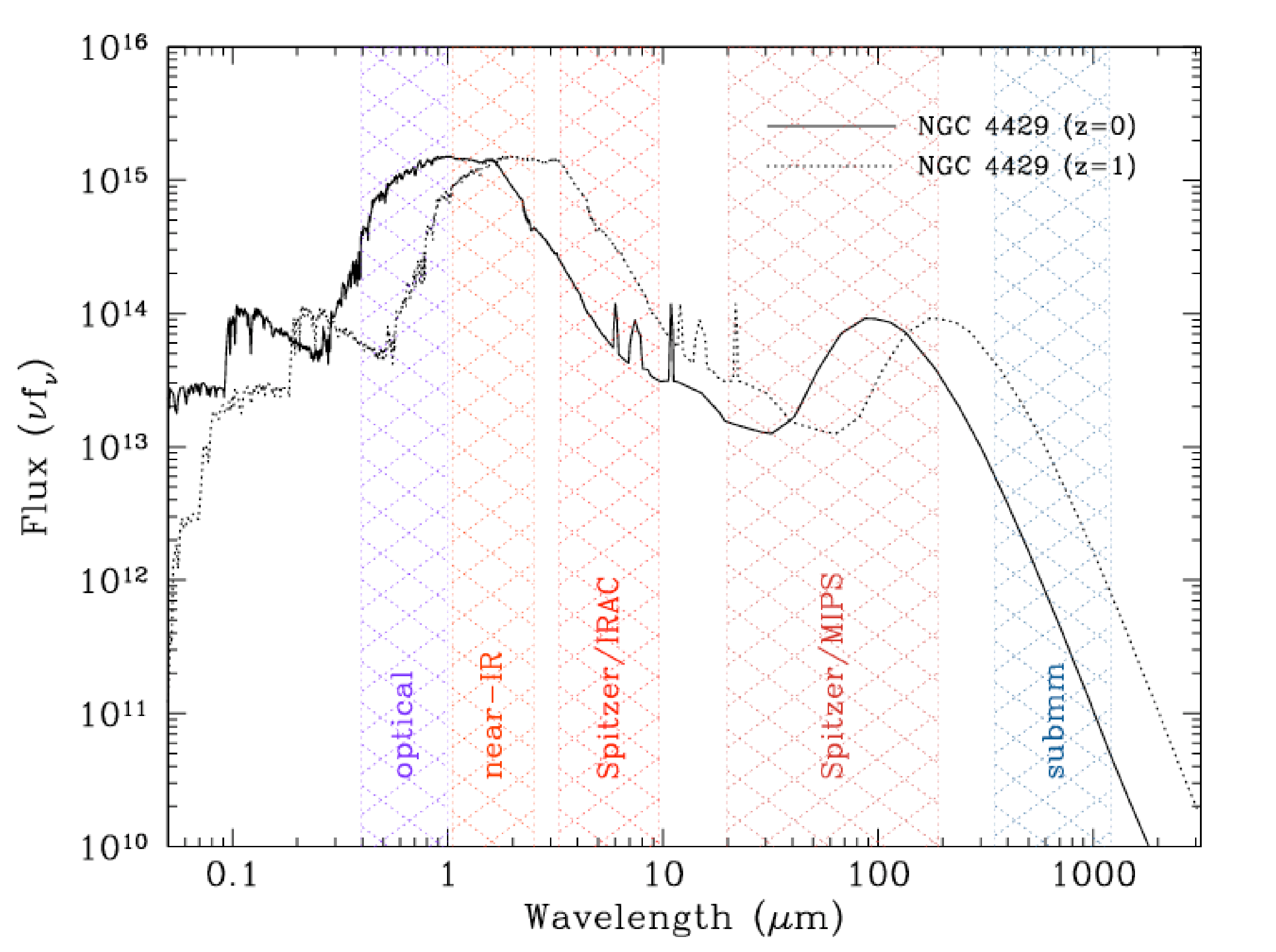


Primary uncertainty in standard SN Ia cosmology is DUST correction.

Cluster Search Algorithms

Method	Z<1	Z>1
X-ray	Efficient	Poor (sensitivity); Biased (shocks, concentration)
Optical (e.g. Red-Sequence)	Efficient	Poor (4000Å break leaves optical window); Biased (against clusters with star formation)
Multi-λ Photo-z	**Efficient**	**Efficient; Unbiased**
	Future	
Sunyaev-Zeldovich	Great Potential; Will *Still* Require Multi-λ follow-up to calibrate	Great Potential; Will *Still* Require Multi-λ follow-up to calibrate

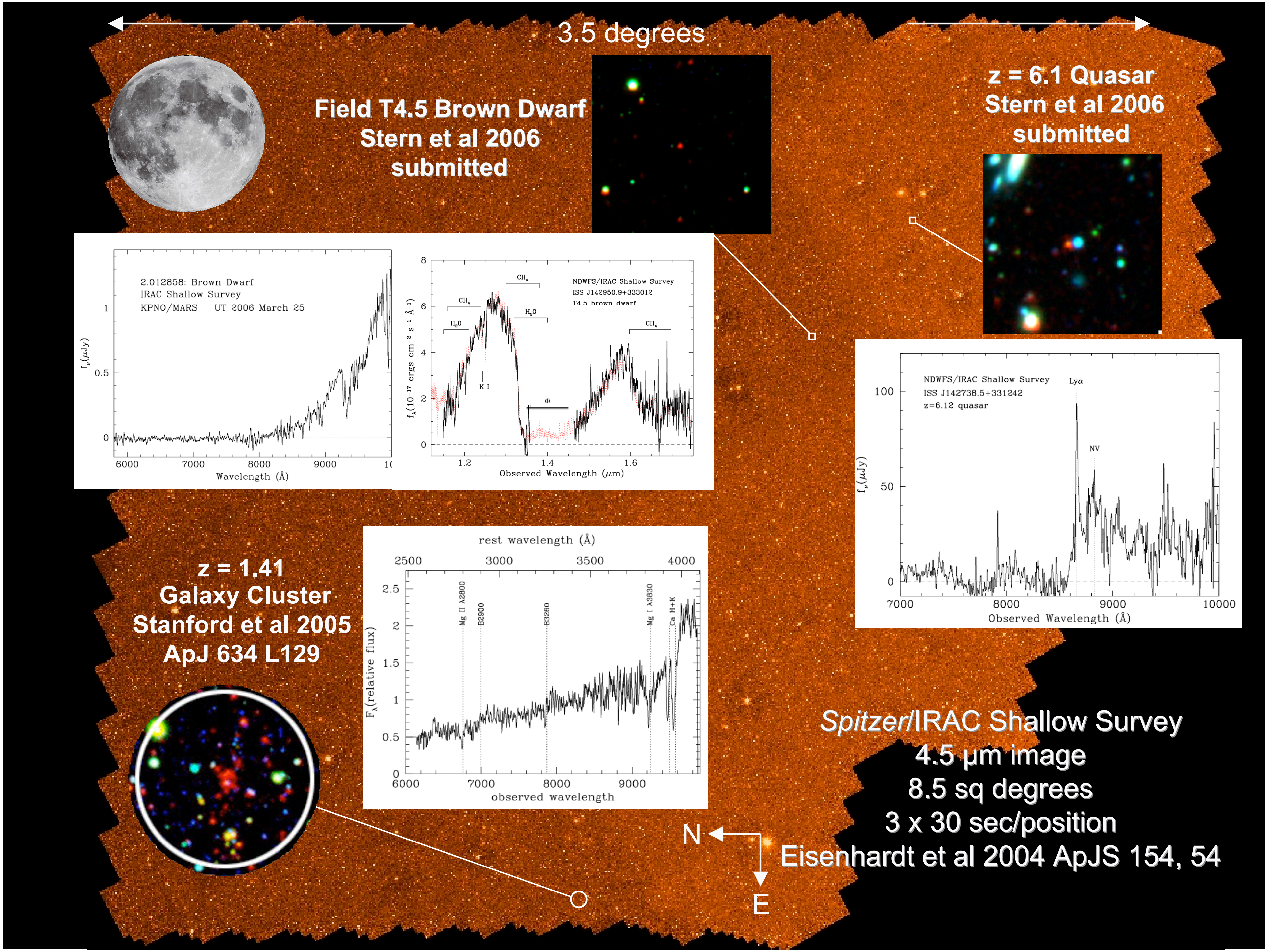
The *Spitzer* Advantage



Spitzer/IRAC Shallow Survey

- 3.6-8.0 μm *Spitzer*/IRAC survey (Eisenhardt, Stern, Brodwin et al. 2004) covering 8.5 deg^2 to a 90-sec depth in the NDWFS Boötes field.

	3.6 μm	**4.5 μm**	**5.8 μm**	**8.0 μm**
Vega Mag 5σ (5”)	18.6	17.8	15.4	14.9
AB Mag 5σ (5”)	21.4	21.1	19.1	19.3
Flux (μJy) 1σ (5”)	2.0	2.7	15.6	13.7

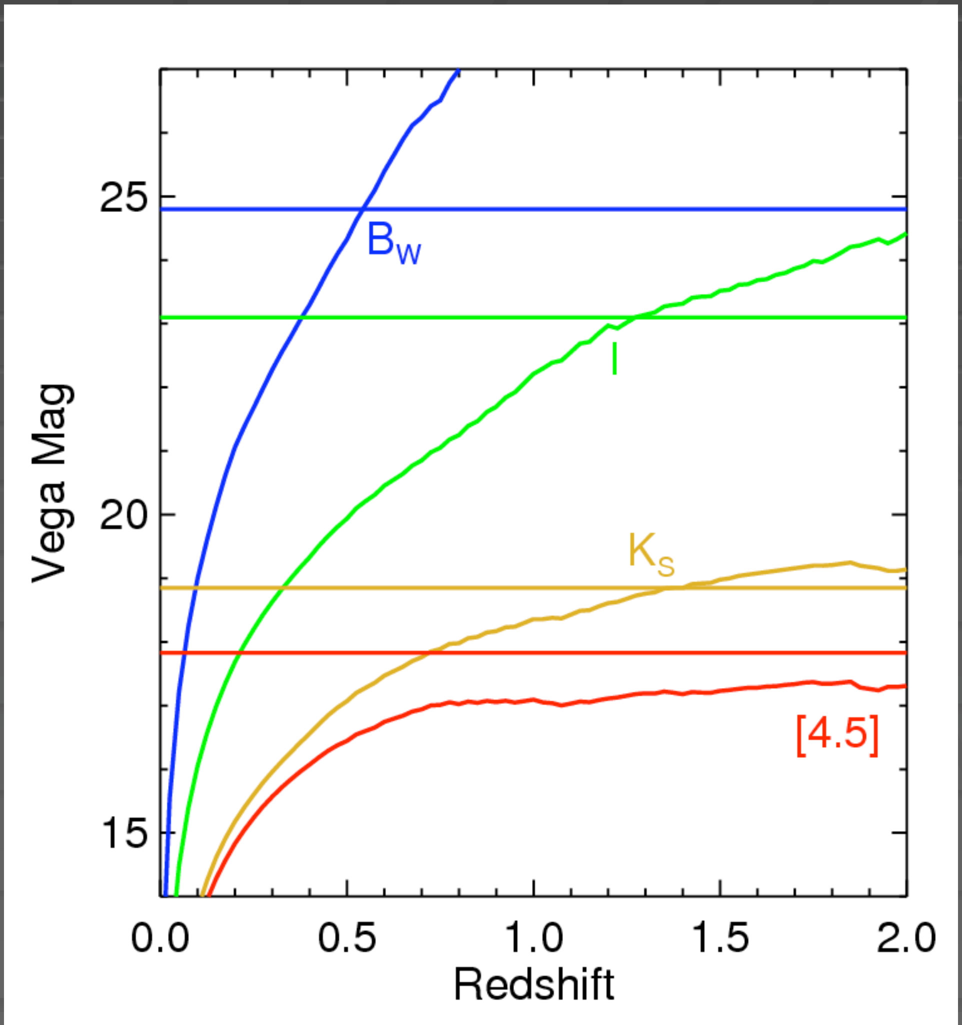


3.5 degrees
Field T4.5 Brown Dwarf
Stern et al 2006
submitted
z = 6.1 Quasar
Stern et al 2006
submitted
2.012858: Brown Dwarf
IRAC Shallow Survey
KPNO/MARS – UT 2006 March 25
Wavelength (Å)
NDWFS/IRAC Shallow Survey
ISS J142950.9+333012
T4.5 brown dwarf
Observed Wavelength (μm)
NDWFS/IRAC Shallow Survey
ISS J142738.5+331242
z=6.12 quasar
Lyα
NV
Observed Wavelength (Å)
z = 1.41
Galaxy Cluster
Stanford et al 2005
ApJ 634 L129
rest wavelength (Å)
Mg II λ2800
B2900
B3260
Mg I λ3830
Ca H+K
observed wavelength
N
E
Spitzer/IRAC Shallow Survey
4.5 μm image
8.5 sq degrees
3 x 30 sec/position
Eisenhardt et al 2004 ApJS 154, 54

Brightness of a Model L* Galaxy

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*.



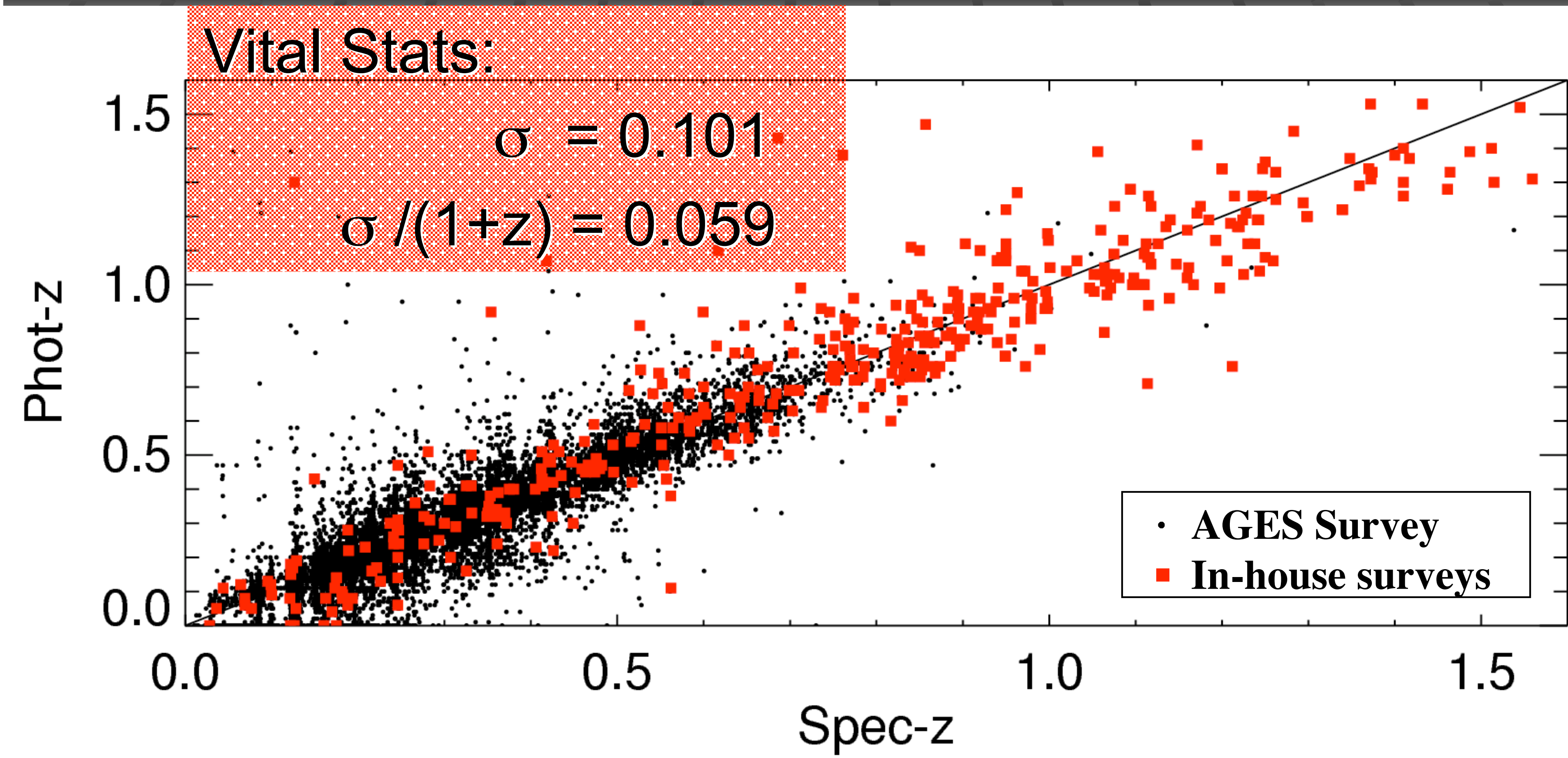
Search Method

- 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 $\{\alpha, \delta, P(z)\}$ catalog, resulting in cluster probability density maps, from which candidates are selected.

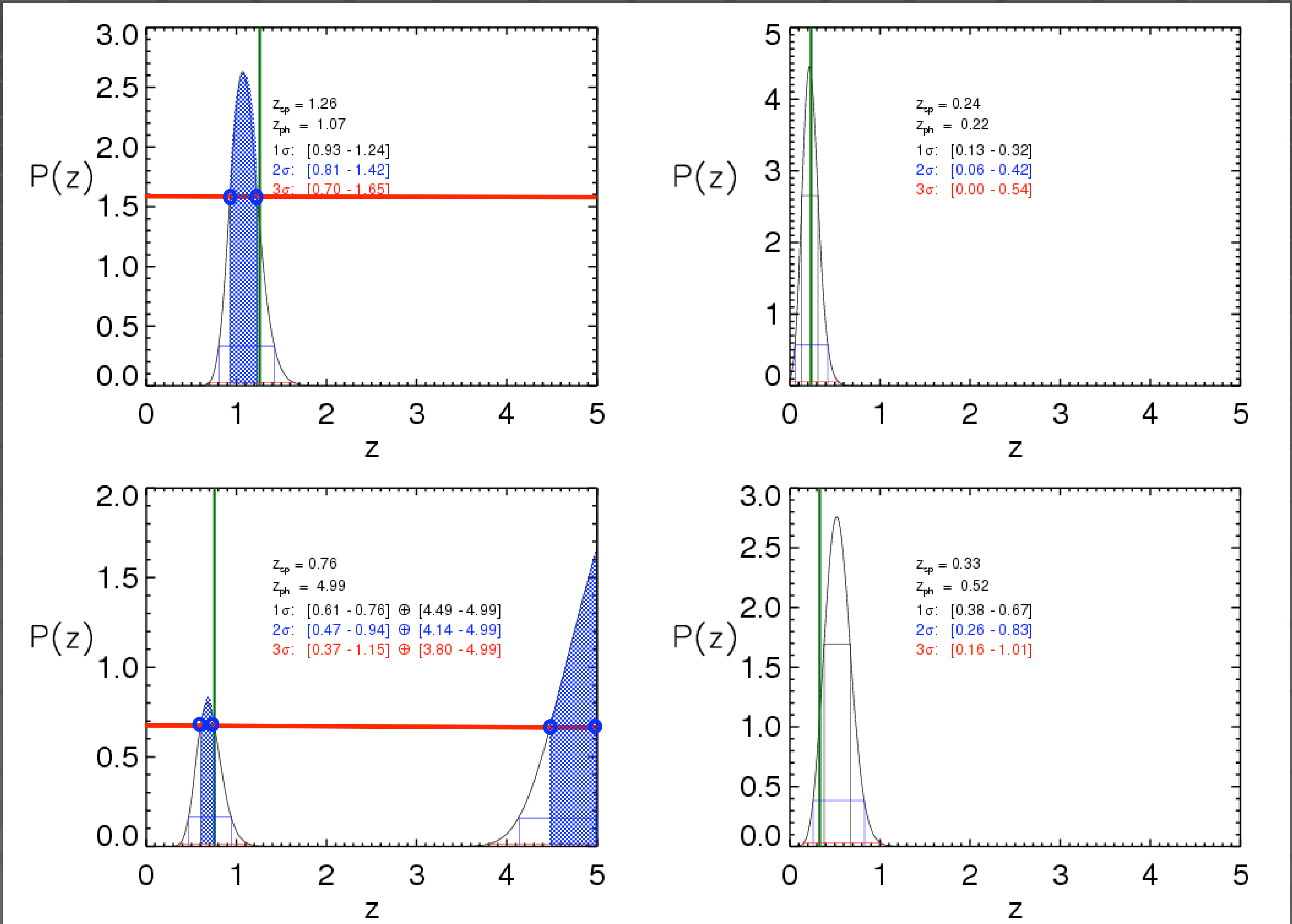
- Method is independent of the tightness, ***or even the presence***, of the cluster red-sequence.

Photometric Redshifts



Brodwin et al. (ApJ, 651, 791)

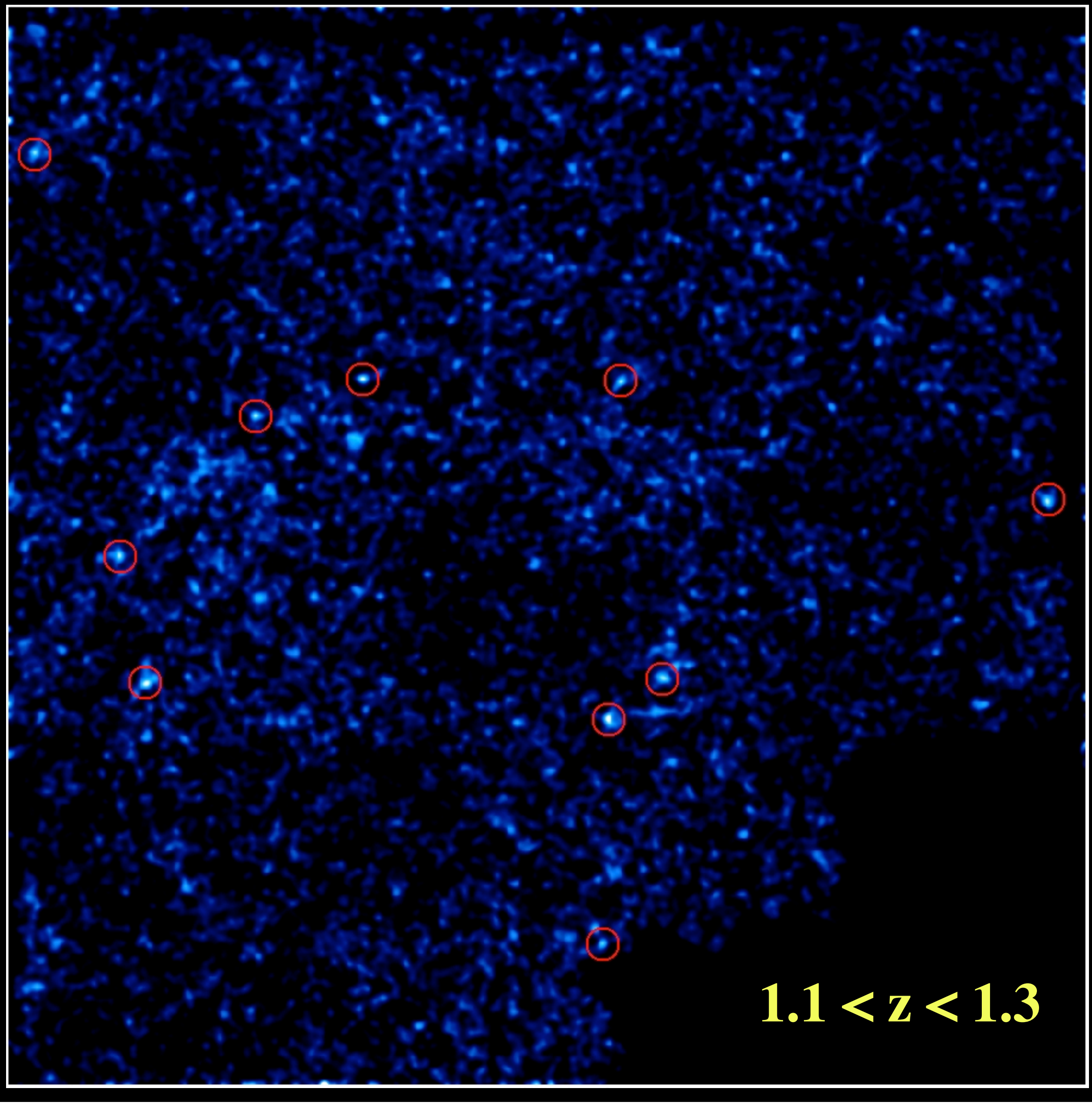
Redshift Probability Functions



Redshift Probability Functions

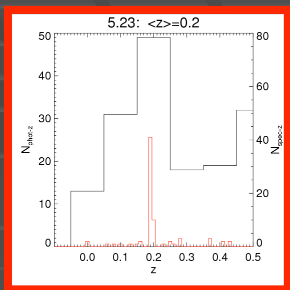
Confidence Interval	Correct Within Confidence Interval	***Observed Fraction***	Gaussian Expectation
$\leq 1\sigma$	9722 / 13043	***74.5%***	68.3%
$\leq 2\sigma$	12335 / 13043	***94.6%***	95.4%
$\leq 3\sigma$	12848 / 13043	***98.5%***	99.7%
$> 3\sigma$	195 / 13043	***1.5%***	0.3%

Cluster Probability Density Map

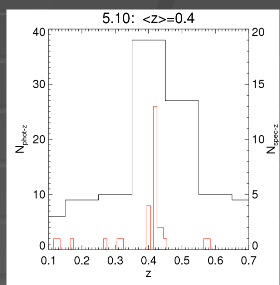


Instant Karma: AGES Clusters

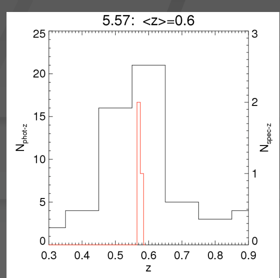
z~0.2

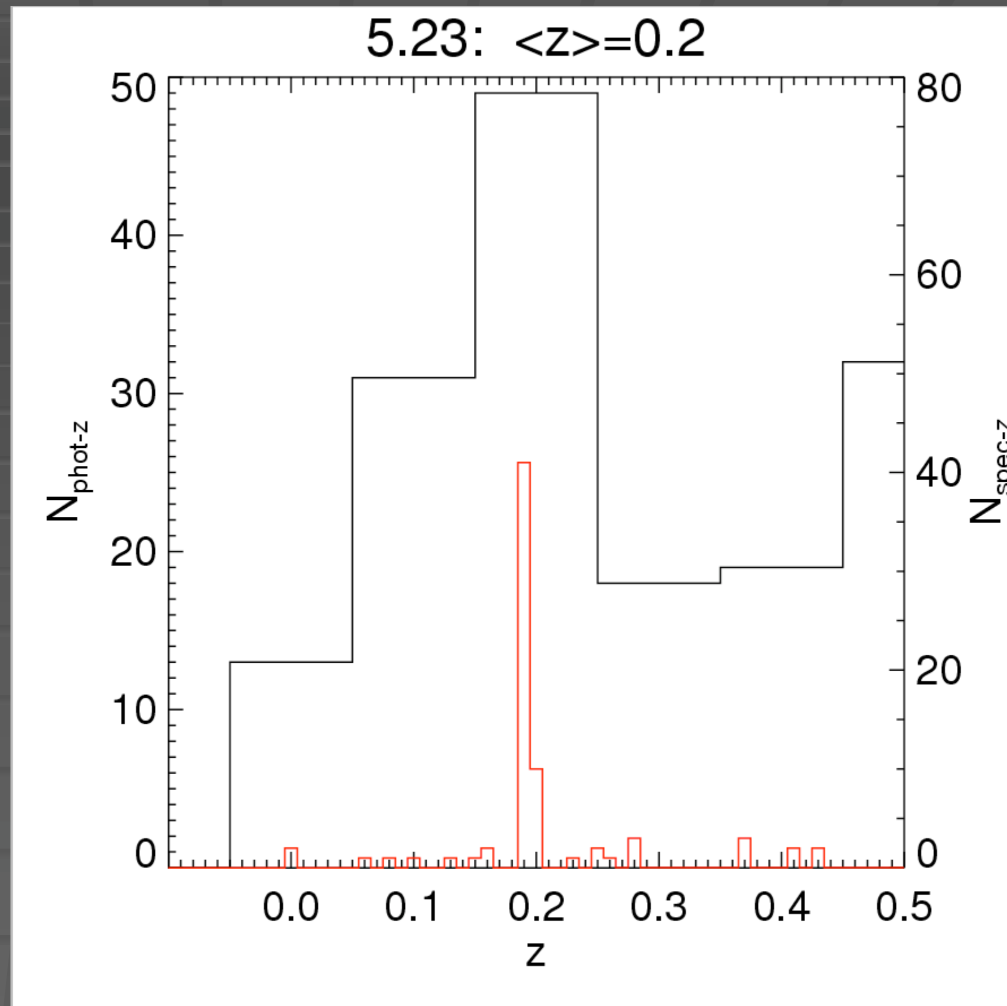


z~0.4



z~0.6



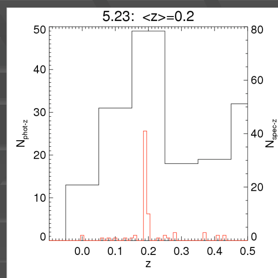


AGES is a complete I<20 spec-z survey, with median <z>~0.3.

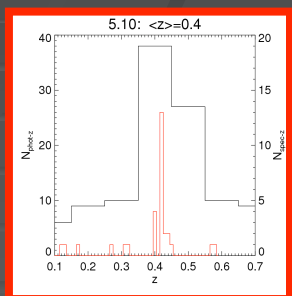
➠Just look up low-z cluster candidates to confirm them!

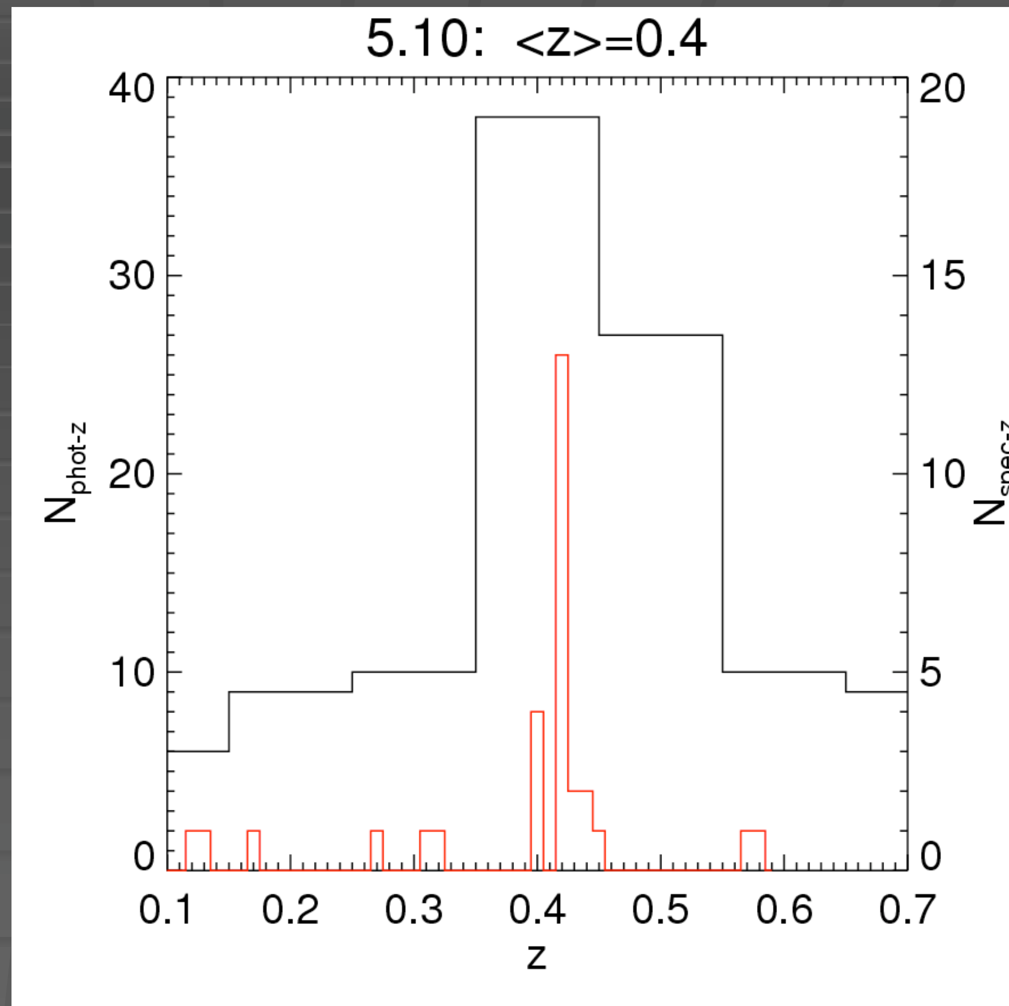
Instant Karma: AGES Clusters

z~0.2

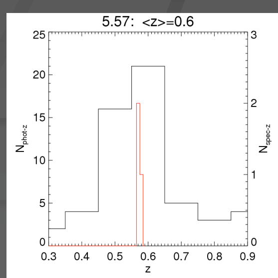


z~0.4





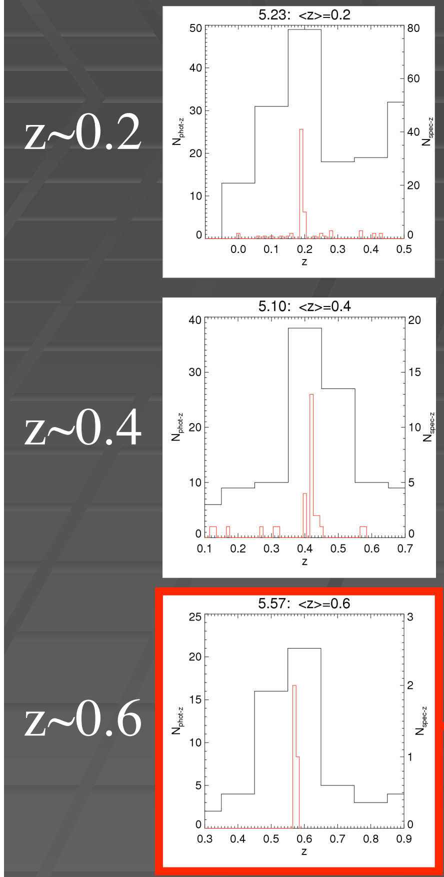
z~0.6

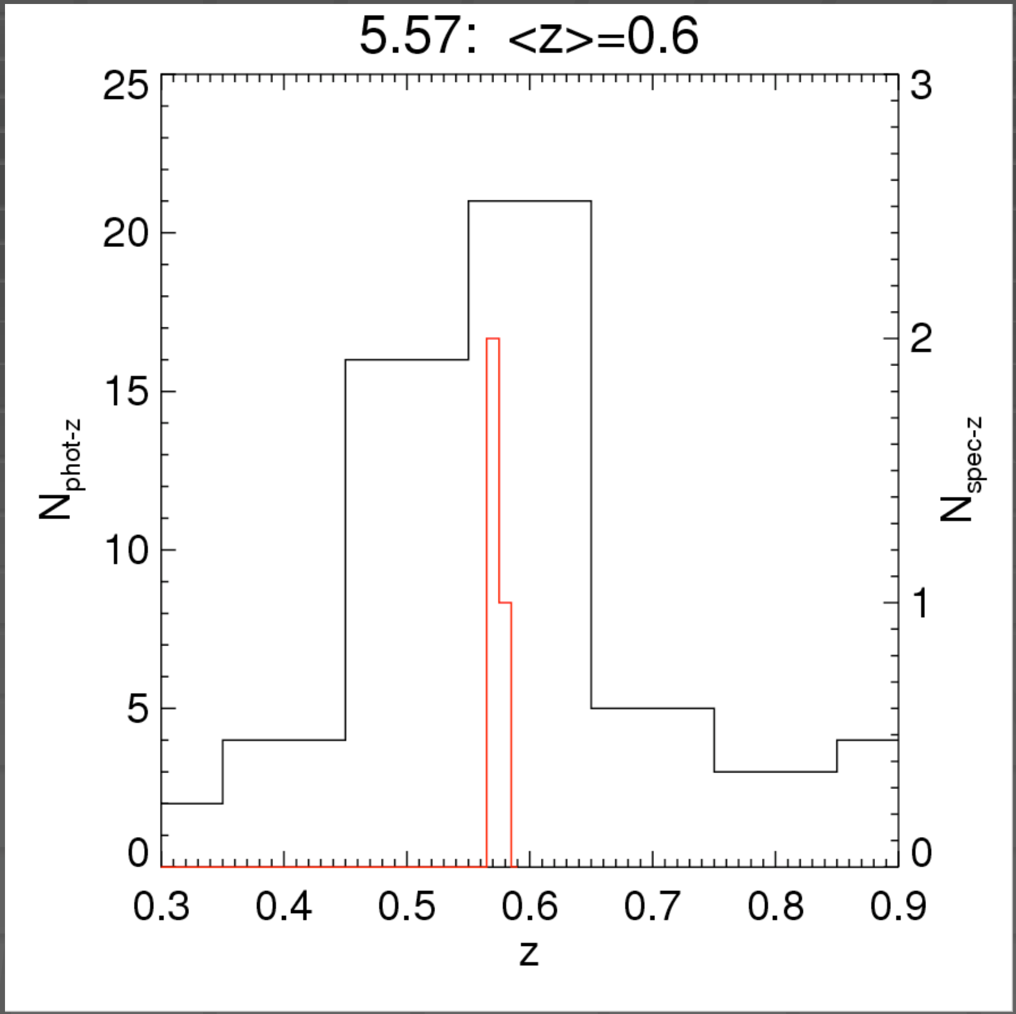


AGES is a complete I<20 spec-z survey, with median <z>~0.3.

➠Just look up low-z cluster candidates to confirm them!

Instant Karma: AGES Clusters





AGES is a complete I<20 spec-z survey, with median <z>~0.3.

➠Just look up low-z cluster candidates to confirm them!

Optical Alone

Brodwin et al. (ApJ, 651, 791)

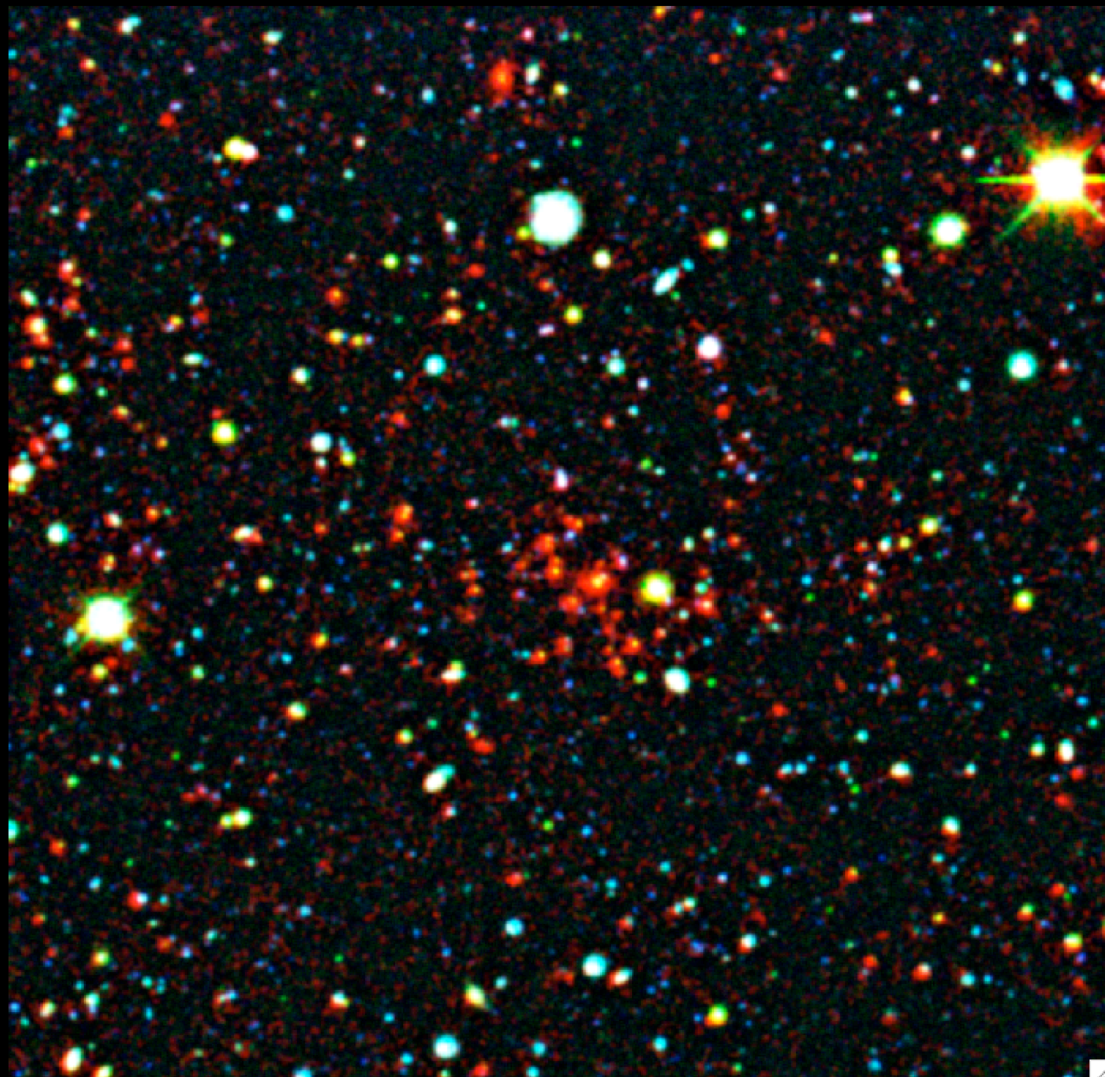
Optical
+
Mid-IR

<z> = 1.24

Optical Alone

Eisenhardt, Brodwin et al. (in prep)

Optical
+
Mid-IR

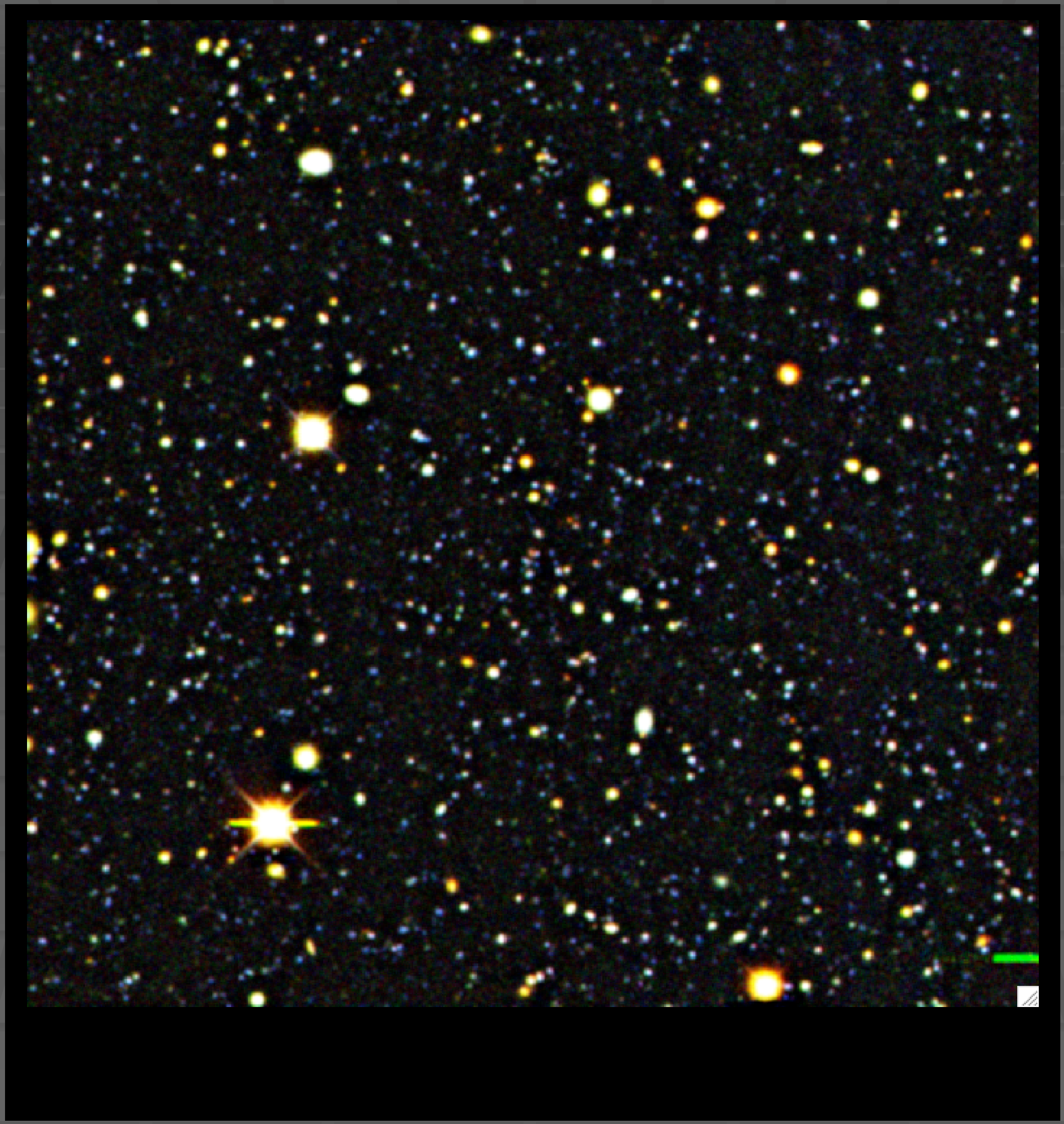


$\langle z \rangle = 1.26$

Optical

+

Mid-IR

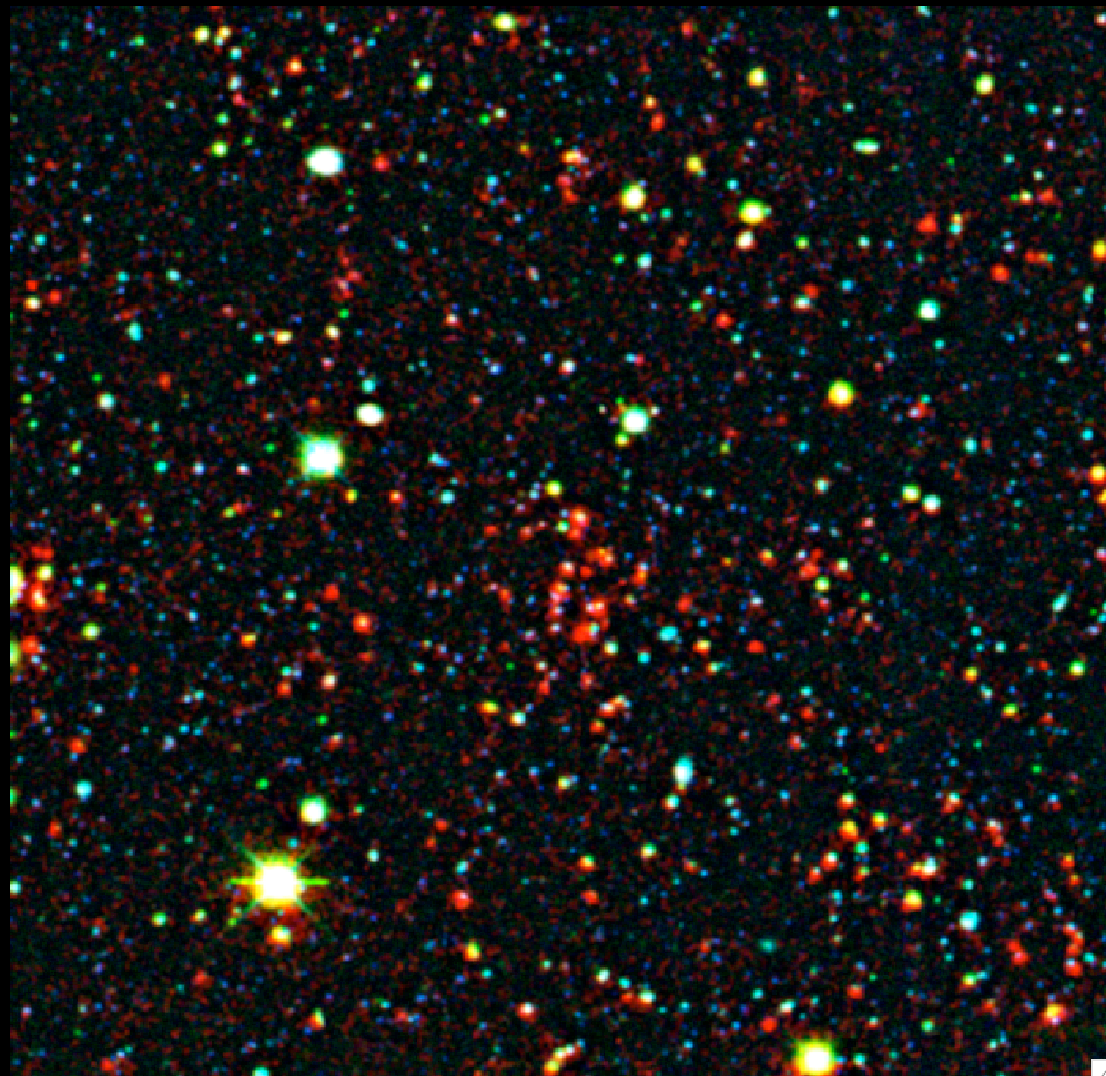


Eisenhardt, Brodwin et al. (in prep)

Optical

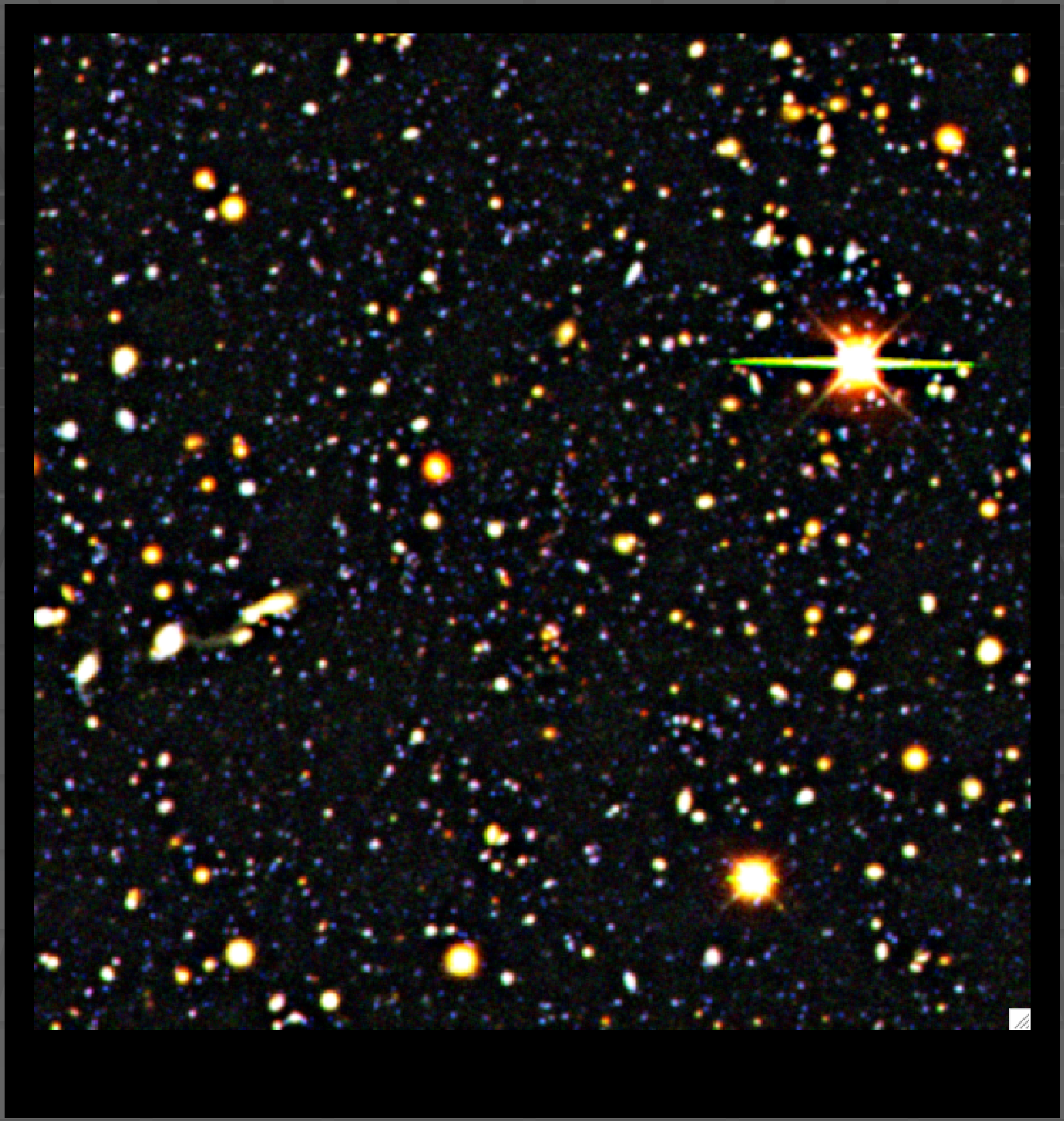
+

Mid-IR



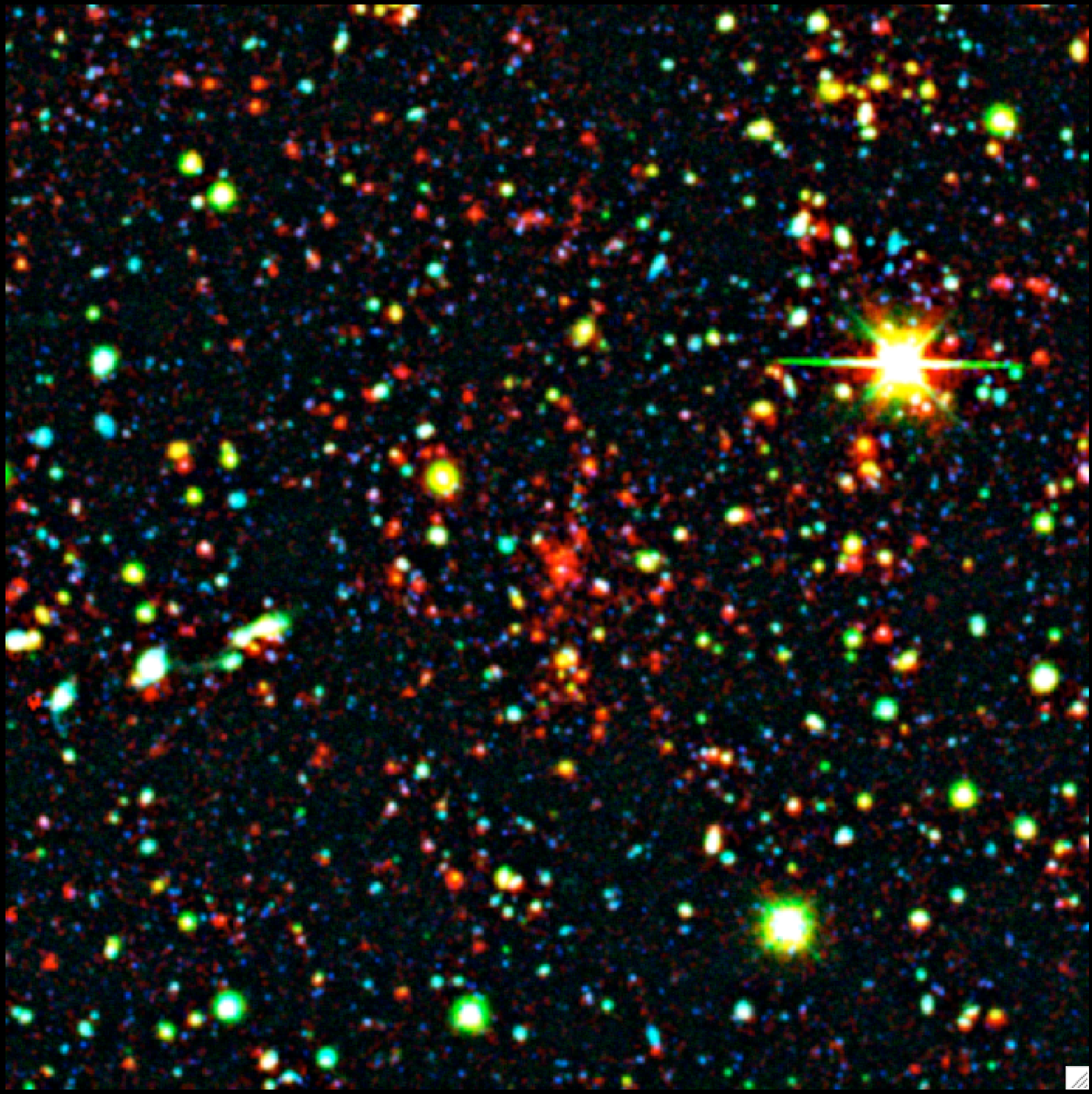
<z> = 1.37

Optical
Alone

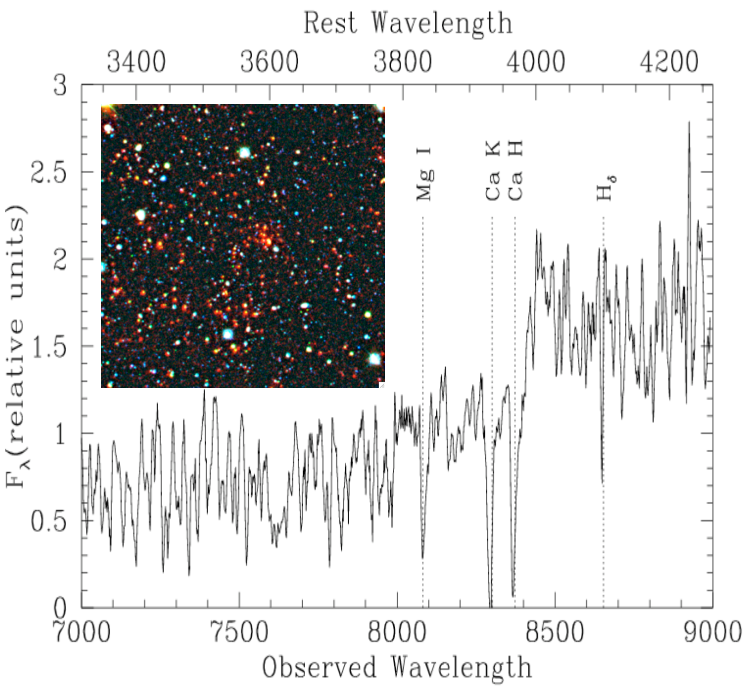


Stanford, Eisenhardt, Brodwin et al. 2005 (ApJ, 634, 129L)

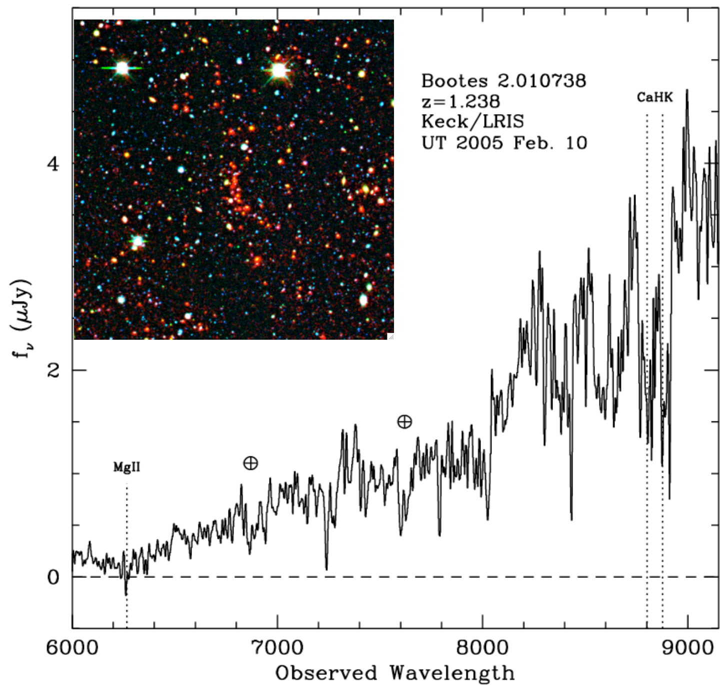
Optical
+
Mid-IR



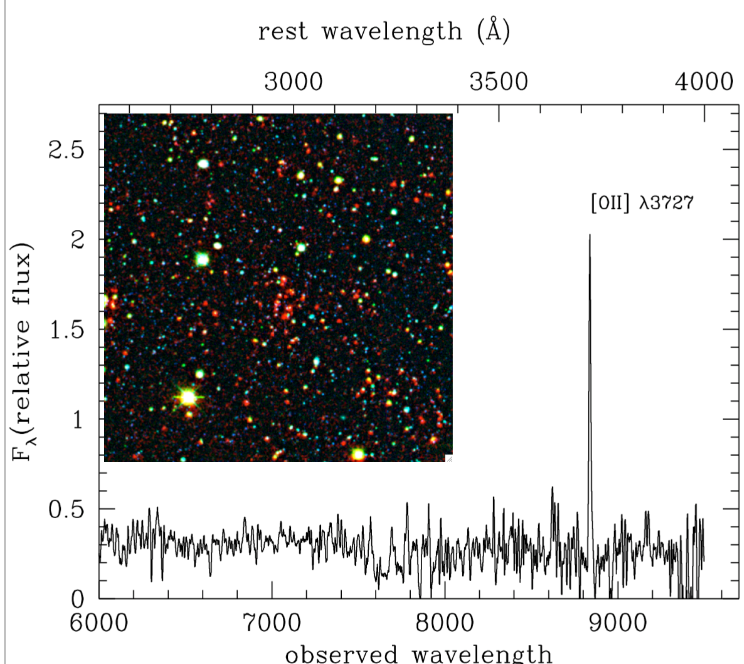
<z> = 1.41



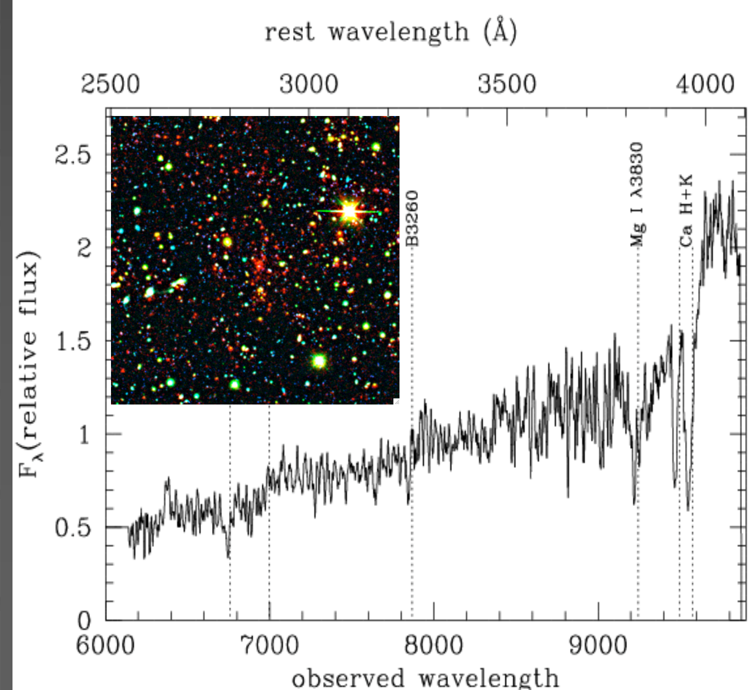
<z>=1.11



<z>=1.24



<z>=1.37



<z>=1.41

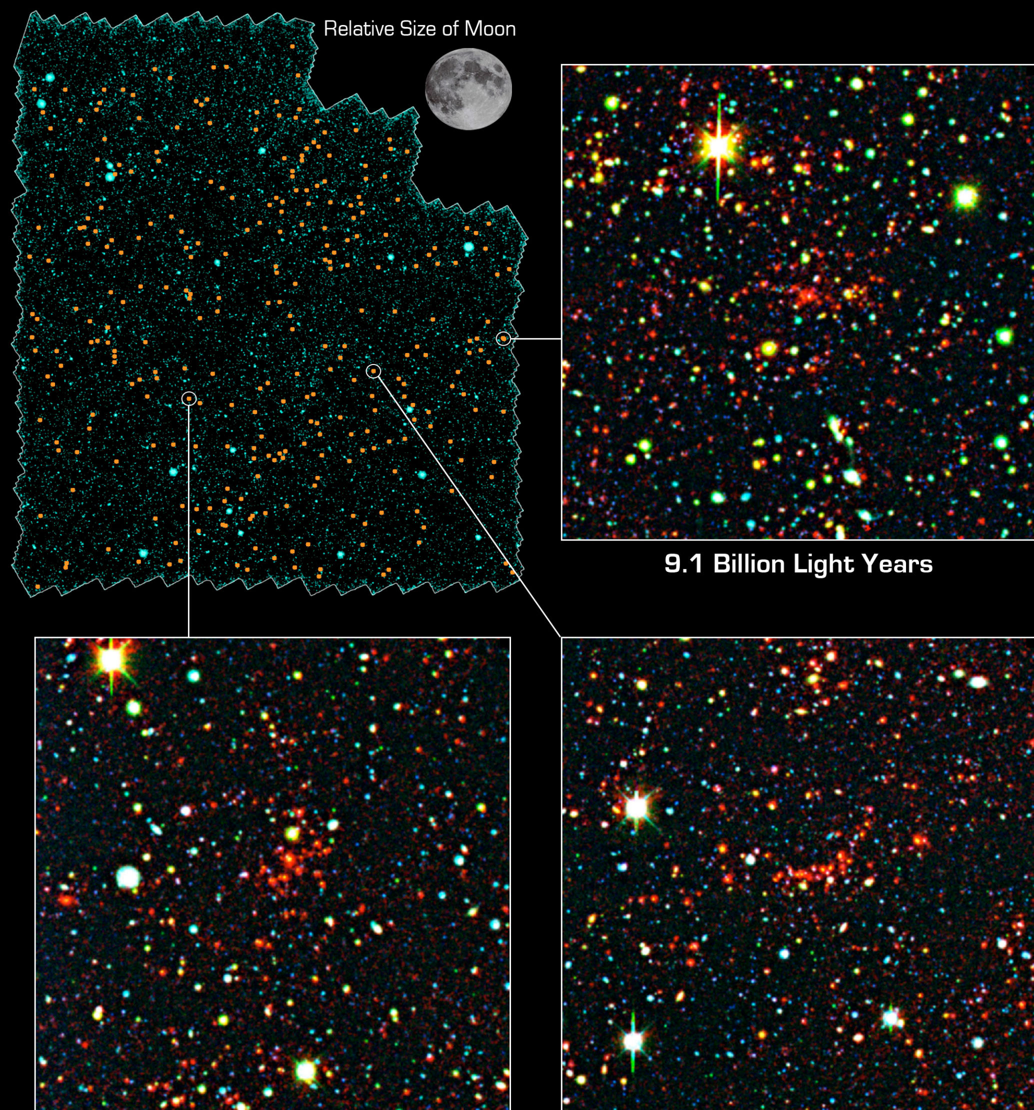
Spectroscopic Confirmation

Keck 2005/2006

- Observed 10 clusters to date
- **8** confirmed with 5+ members within 2000 km/s in the rest-frame (approx $\Delta z \pm 0.015$)
- Cl26 and Cl79: Many objects with faint, red continua, no lines
- Cl90: Evidence of projection. Line-of-sight structure at $z = 1.46$

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	-	-

Subaru 2006 not yet incorporated



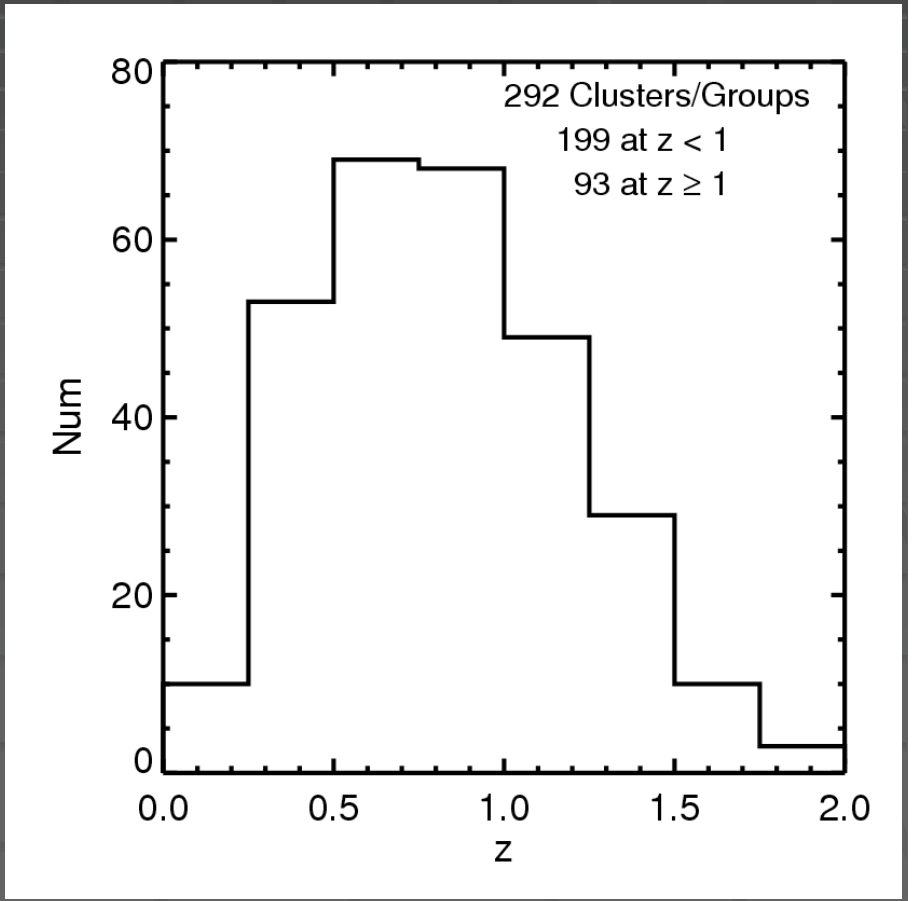
Distant Galaxy Cluster IR Survey **Spitzer Space Telescope • IRAC**

NASA / JPL-Caltech / M. Brodwin (JPL) sig06-015

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

Results

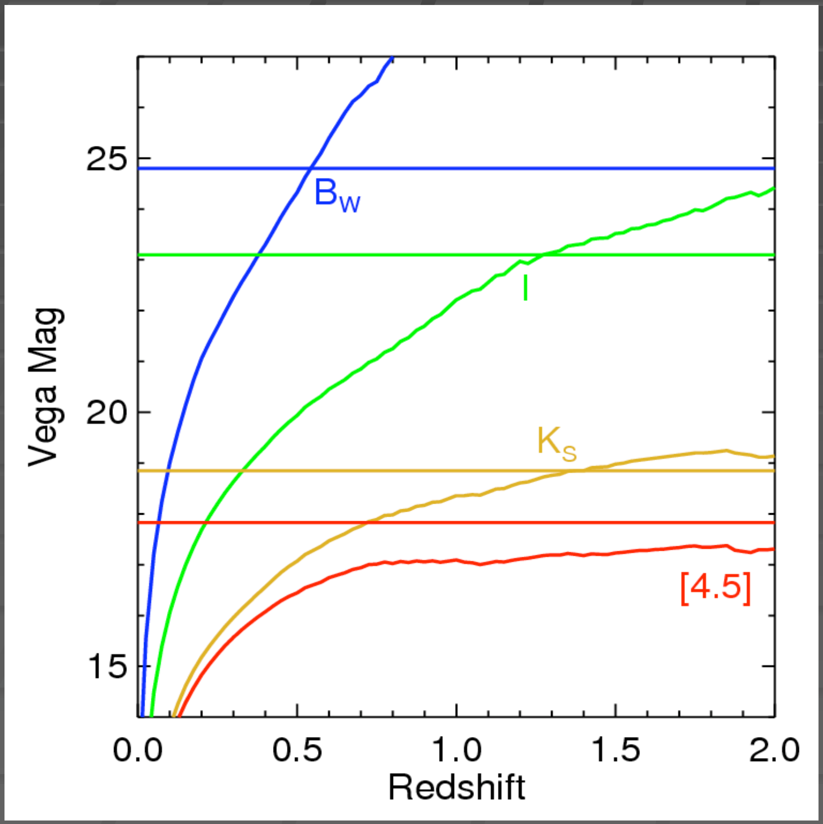
- 292 candidate clusters and groups at $0 < z < 2$ over 8.5 deg^2 in Boötes.
- Of these 93 are at $z>1$, a 6-fold increase over the number of confirmed high-z clusters in the literature.



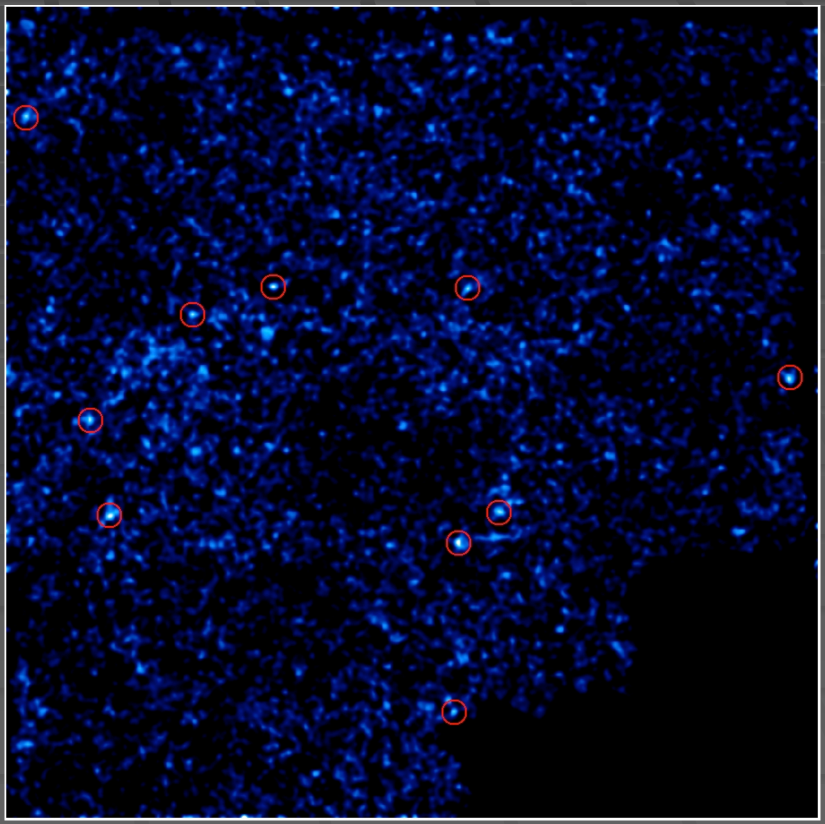
Cluster Masses

- Large follow-up campaign underway:
  - $0 < z < 1.5$:
    - Large spectroscopic campaign (Keck, KPNO, AGES) → Velocity Dispersions
  - $z > 1$:
    - Deeper IR imaging with Spitzer (IRAC+MIPS) and Palomar (JK) → Stellar masses from SED fitting
    - HST → Weak (and strong) lensing masses
    - XMM → X-ray masses

Cluster Masses

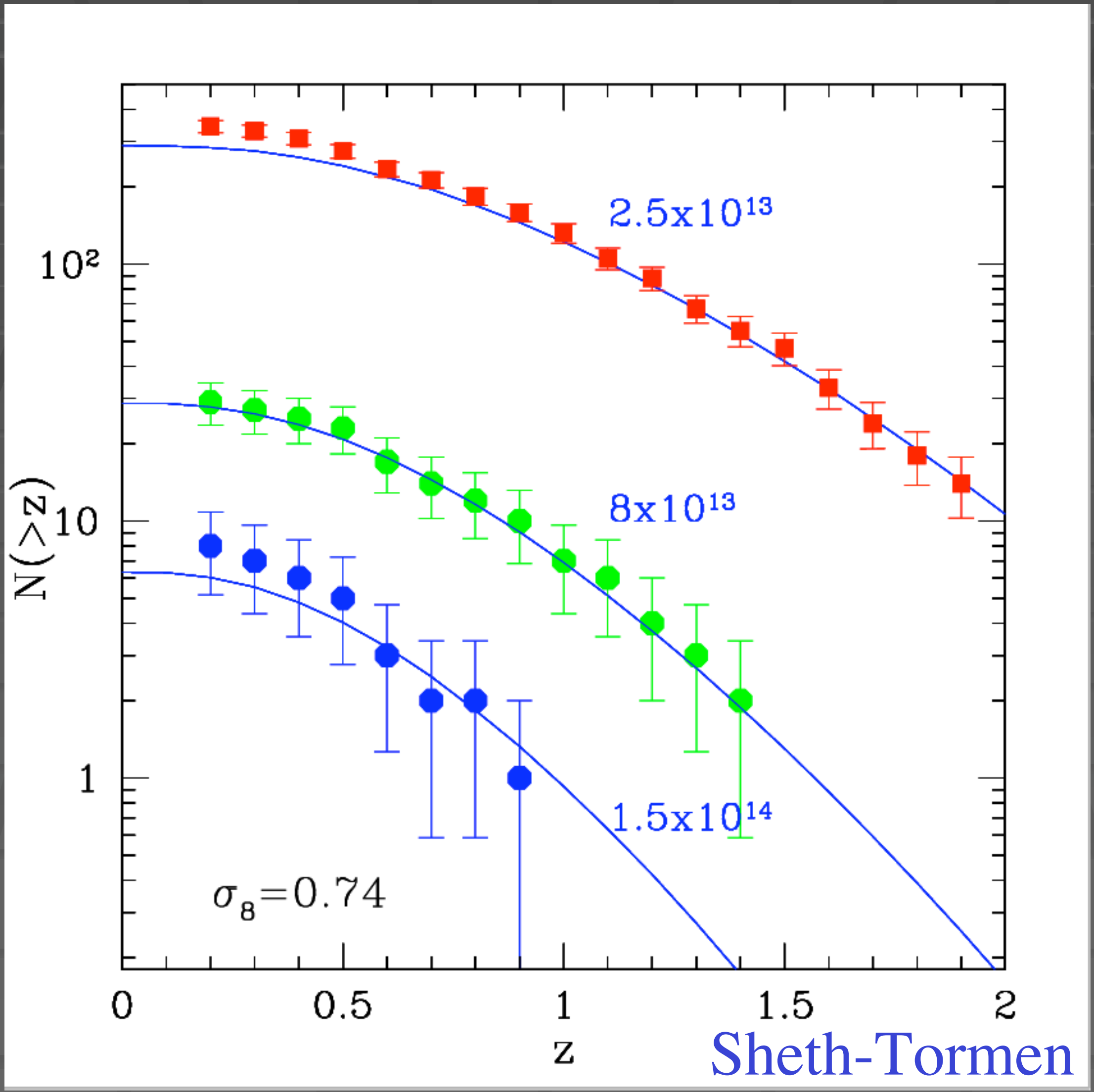


4.5 μm flux ∝ stellar mass at 0.7<z<2



Assume cluster probability density ∝ stellar mass & M/L is constant

Cluster Masses



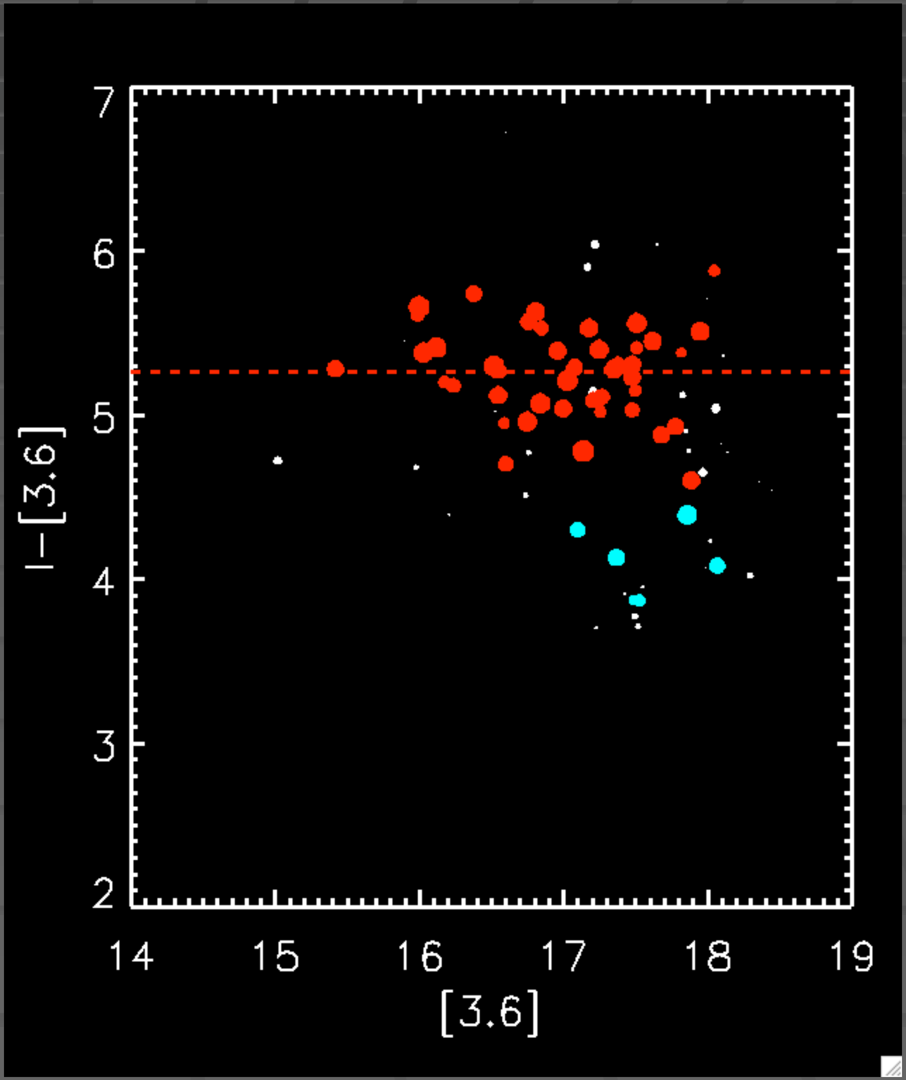
Color Evolution of Galaxy Clusters over $0 < z < 1.5$

Methodology

- Identify objects in I - [3.6] CMD which have integrated redshift probability > 0.3 over the 1σ photo-z error interval at the cluster redshift:

$$\int_{z_{\rm cl}-0.06(1+z_{\rm cl})}^{z_{\rm cl}+0.06(1+z_{\rm cl})} P(z)dz \geq 0.3$$

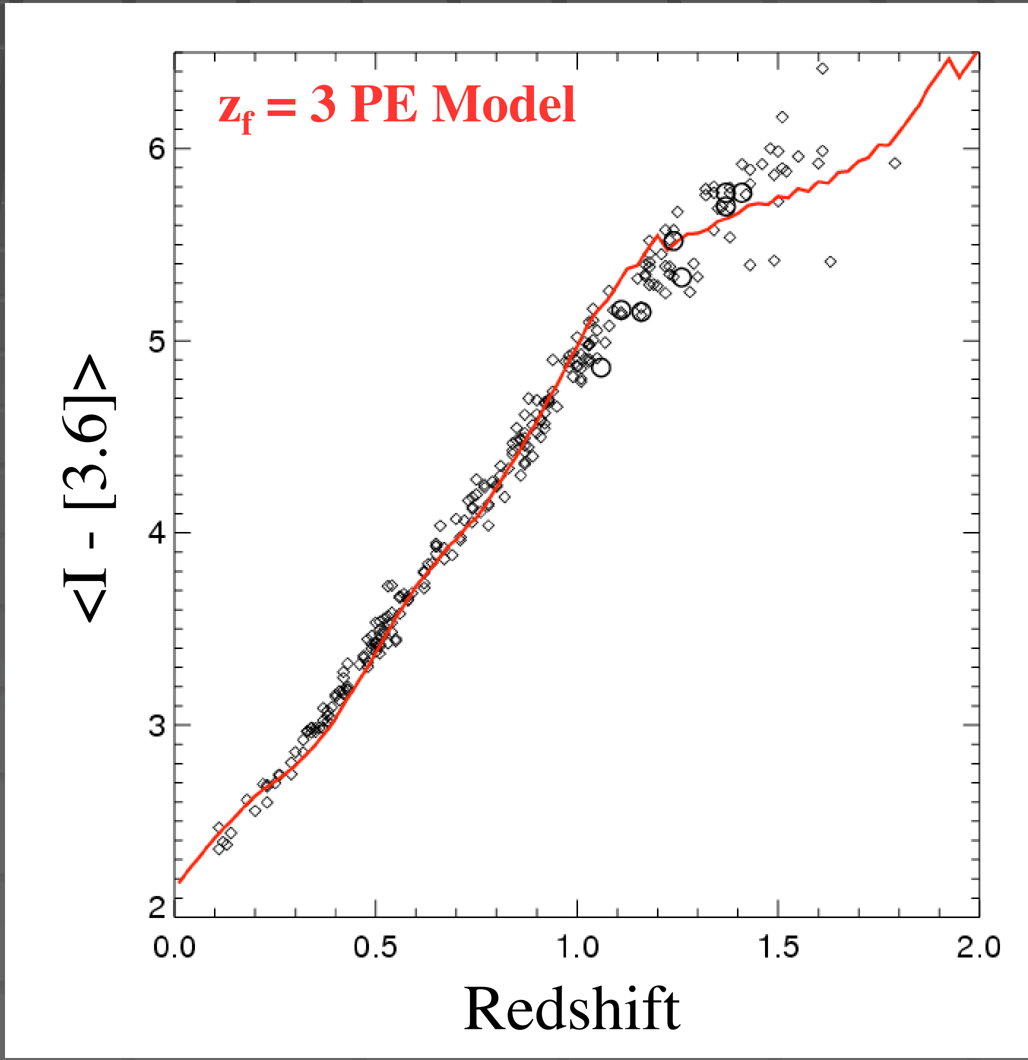
- Apply iterative 3σ clipping
- Adopt simple mean of resulting sample as cluster color at z_{cl}.



Color Evolution of Galaxy Clusters over 0 < z < 1.5

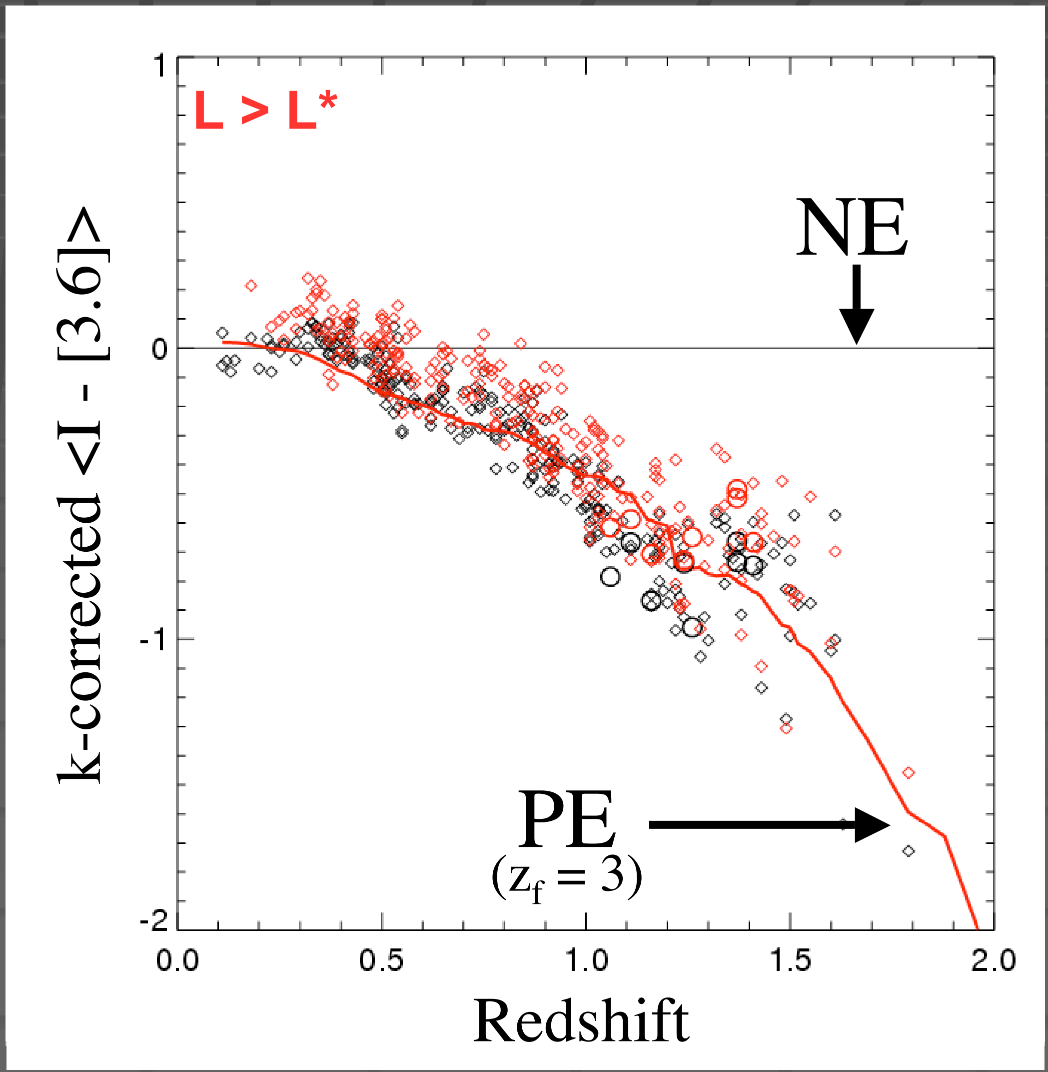
Passive Evolution Model (PE)

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



Relative to No Evolution

- Mean color clearly bluer than NE model, by 0.5 mag at z=1, and 1.0 mag at z=1.5.
- More massive galaxies older than full sample.



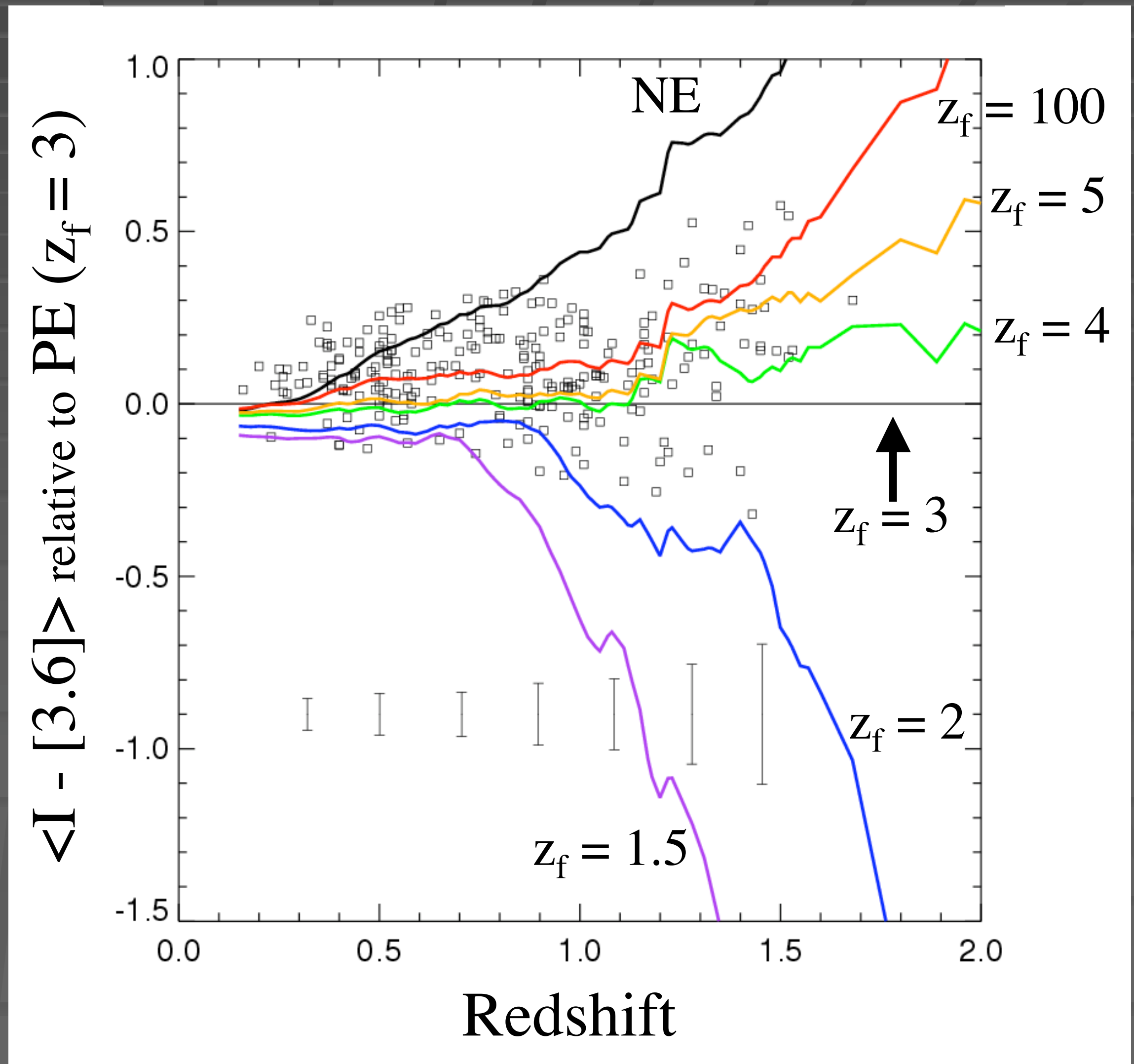
Relative to $z_f = 3$ Model

Points

- All points are brighter than L* at [3.6]

PE Models

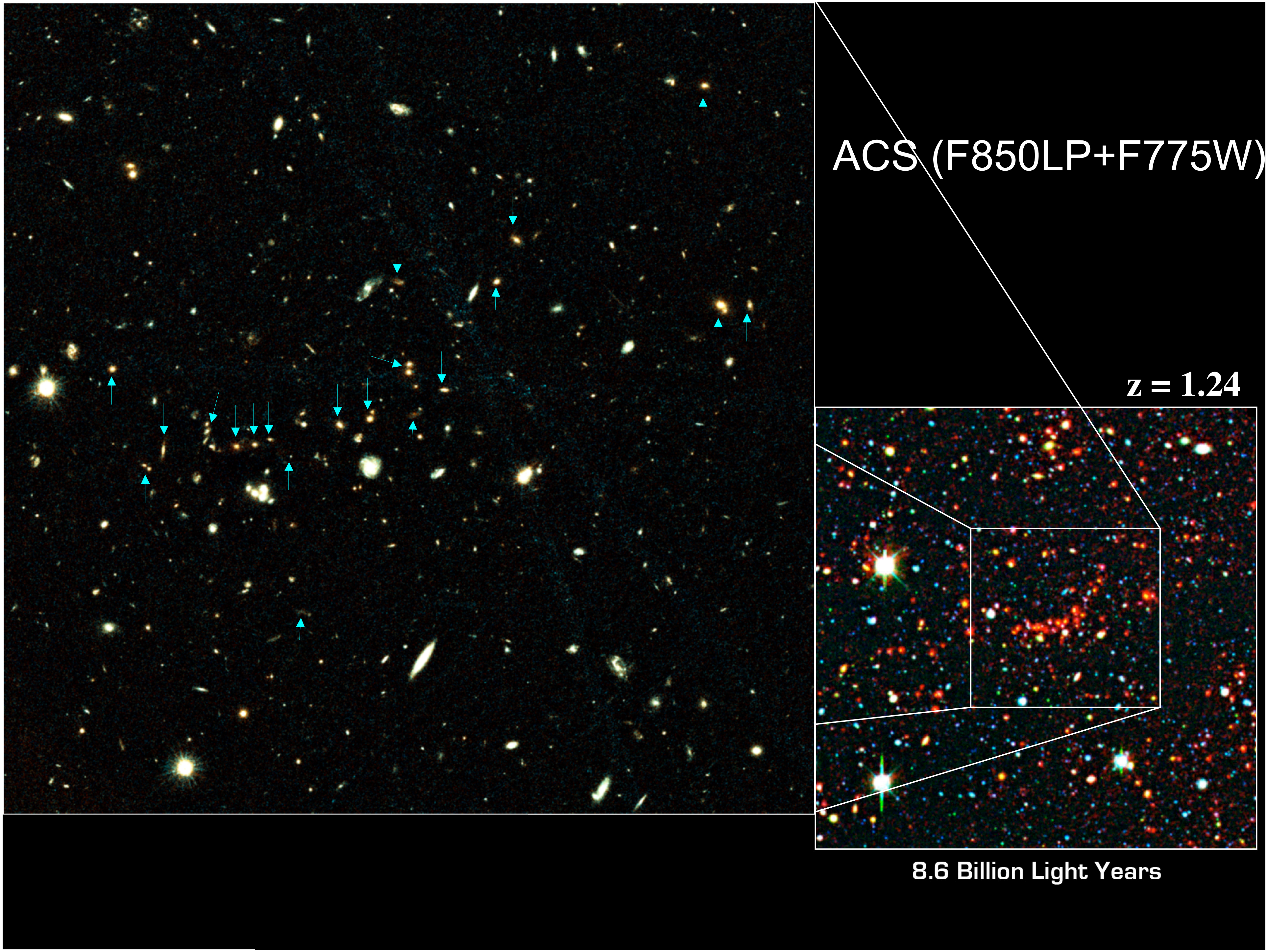
- Bruzual & Charlot
- 0.1 Gyr Burst at $z_f = [1.5, 2, 3, 4, 5, 100]$ followed by simple passive evolution
- H_0=70; Ω_M=0.3; Ω_Λ=0.7



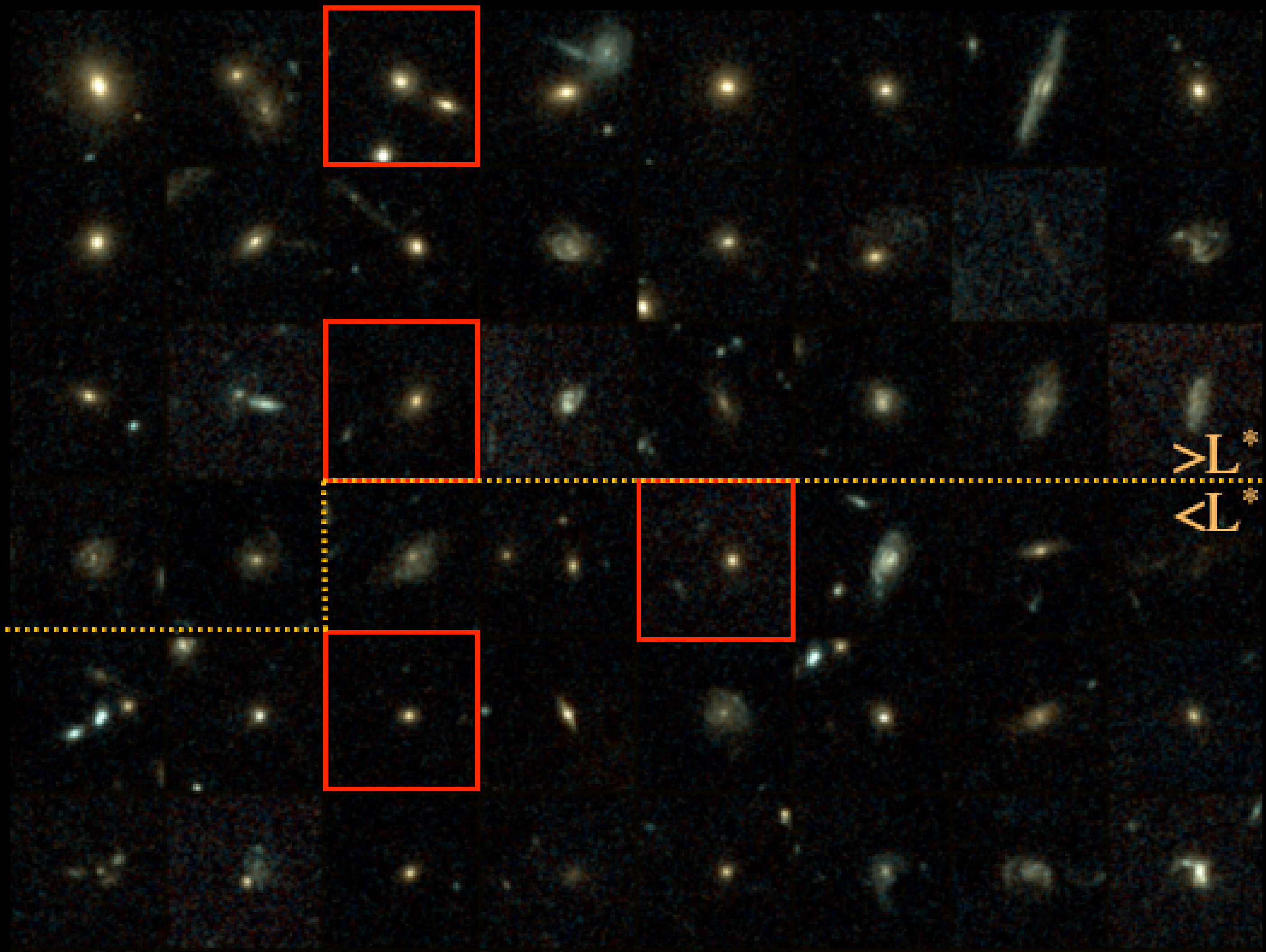
High Resolution Science: Morphologies & Mergers

- Data in Hand
  - Cycle 14 *HST*/ACS data for 8 z>1 clusters from SNe program (PI: Perlmutter).

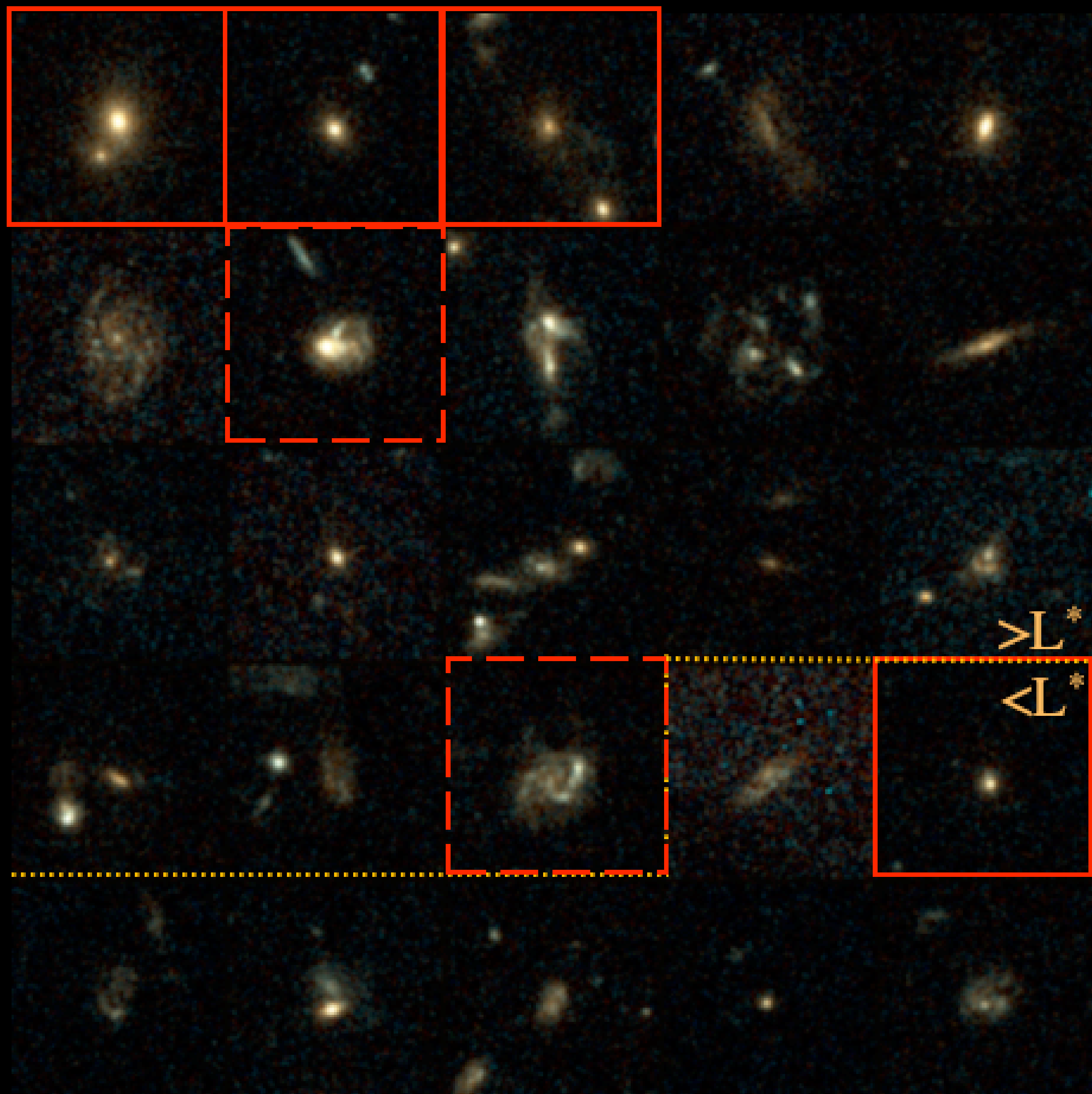
- Allocated Time in Spring 2007
  - GO-3 *Spitzer*/IRAC+MIPS joint with *HST*/ACS in Cycle 15. → Deep IRAC, MIPS, and ACS imaging on 18 z>1 clusters
  - Cycle 15 *HST*/NICMOS on 5 z>1.2 clusters


ACS (F850LP+F775W)
z = 1.24
8.6 Billion Light Years

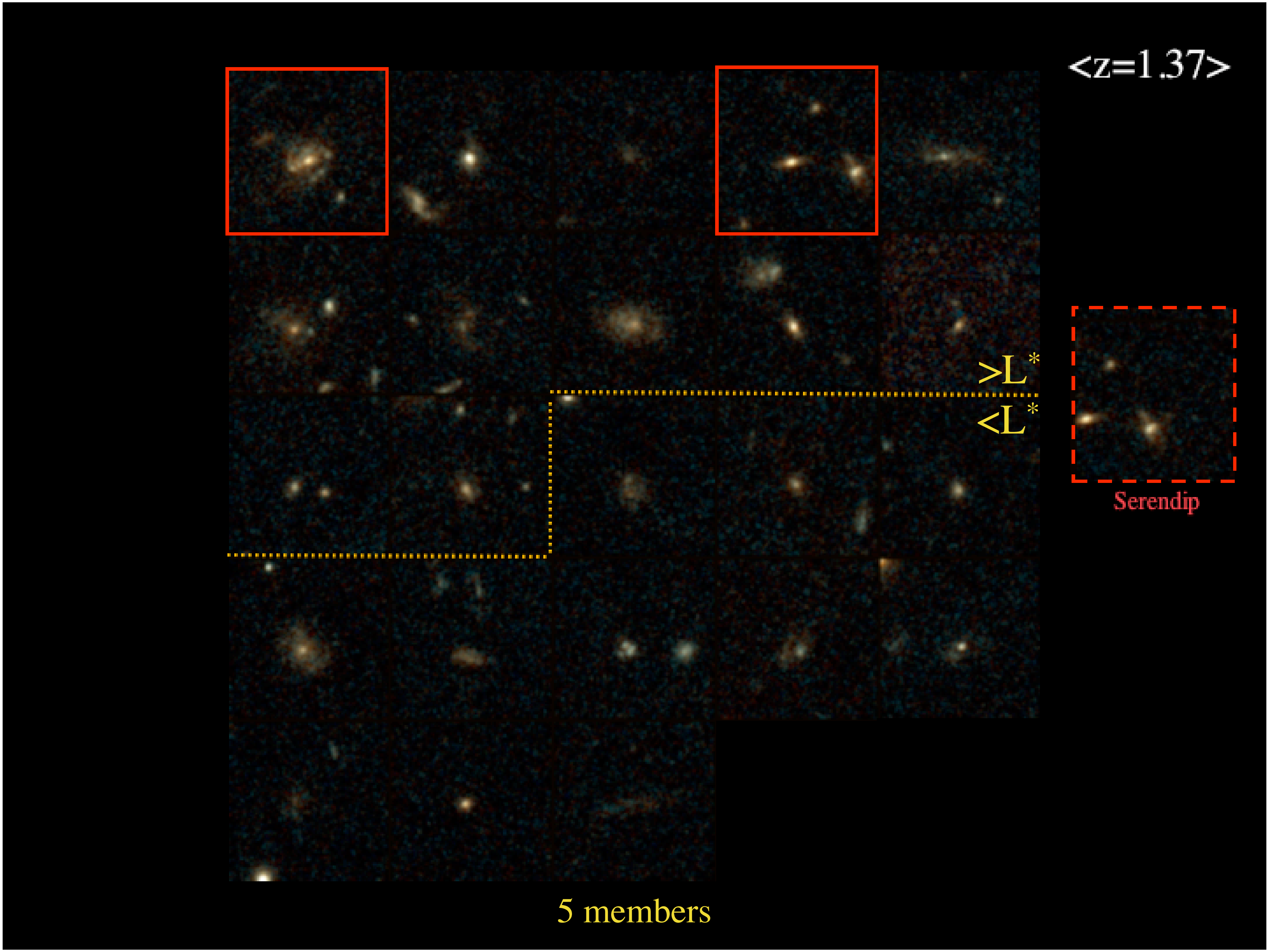
<z=1.11>

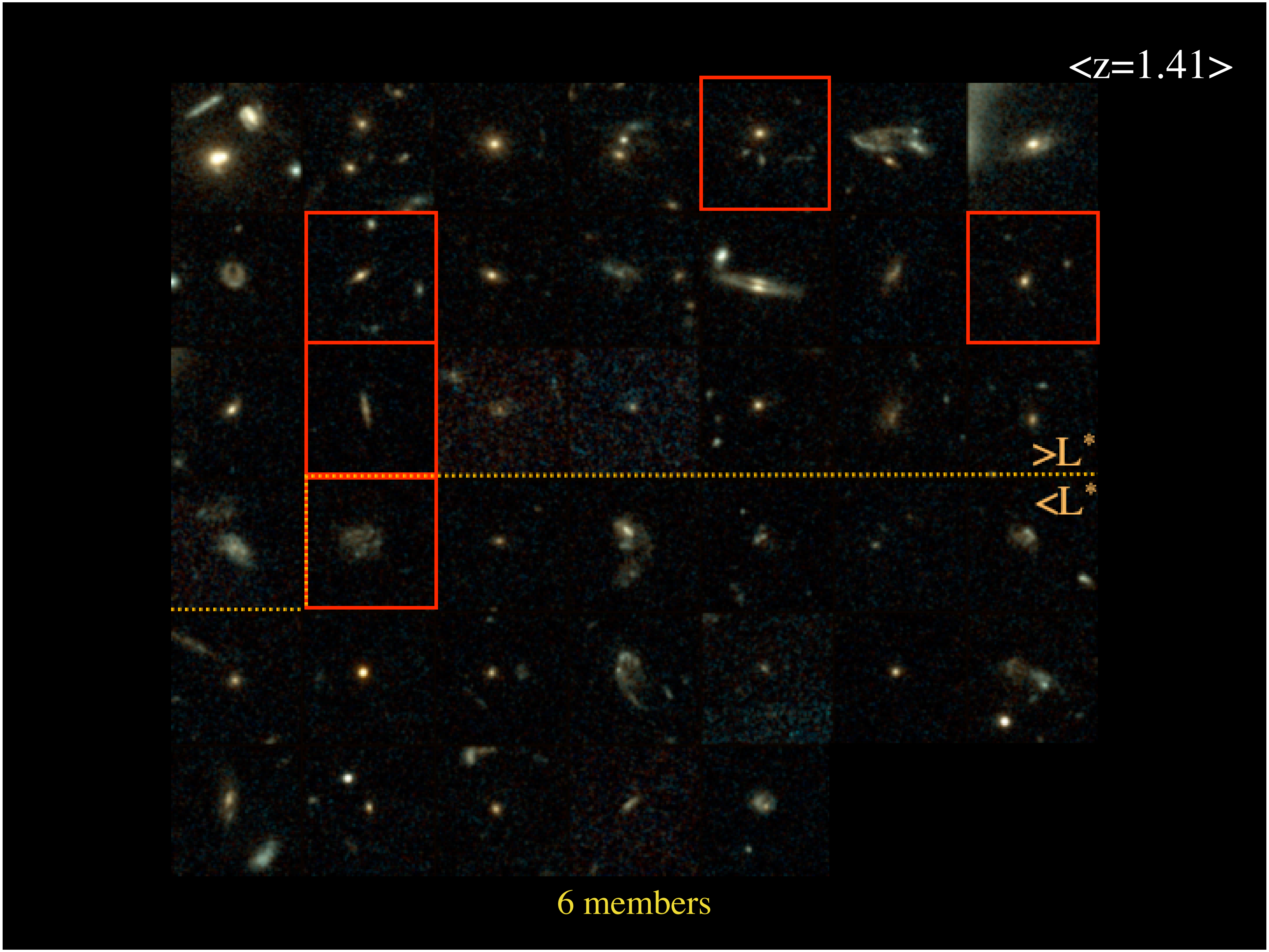


8 members: σ = (920 ± 230) km/s (Elston, Gonzalez et al. 2006)



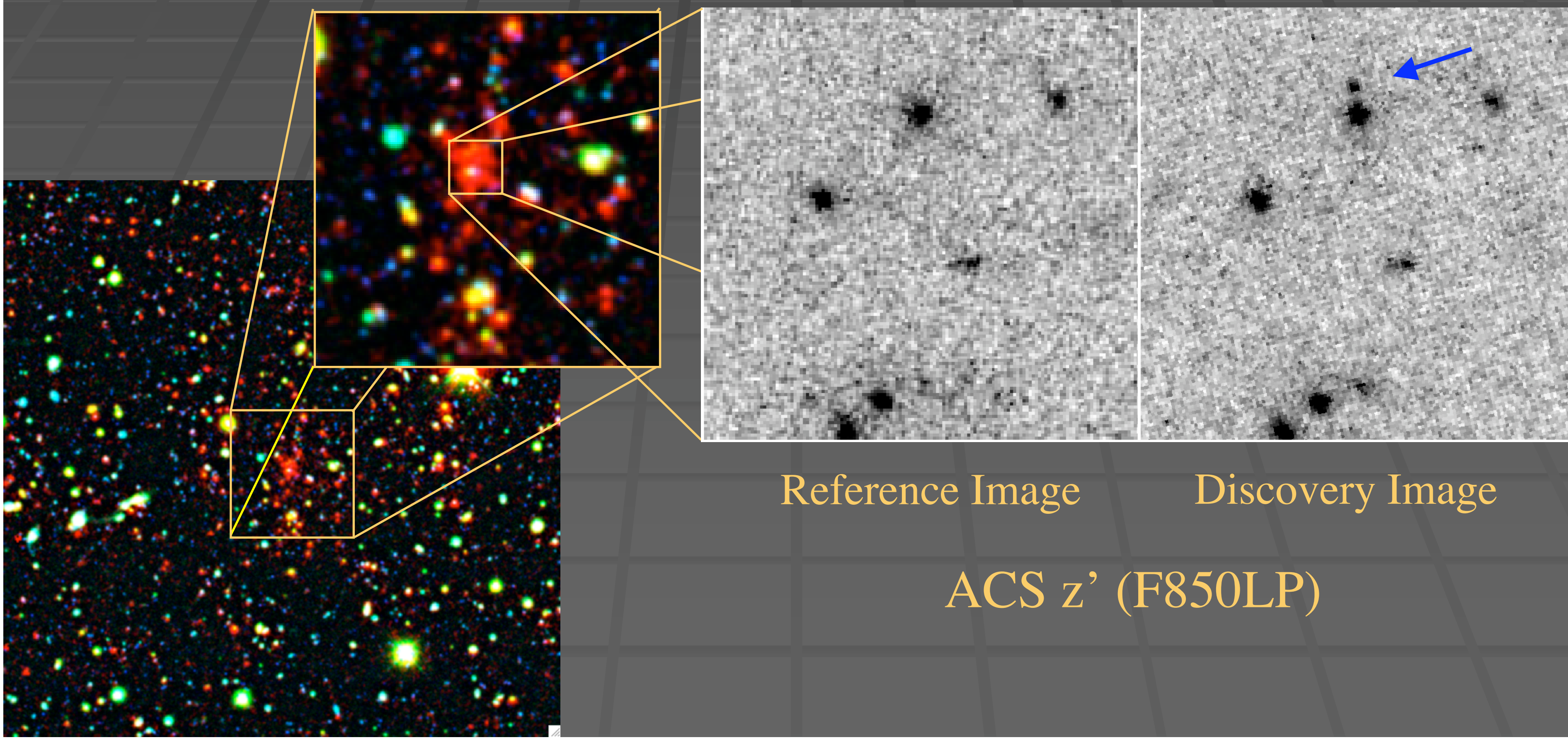
7 members: $\sigma \sim 600$ km/s; preliminary WL mass of ~1-2 x $10^{14}\,M_{\odot}$


<z=1.37>
>L*
<L*
Serendip
5 members


<z=1.41>
>L*
<L*
6 members

Cluster SN Cosmology

- Several good SN candidates in z>1 clusters, including this one in <z> = 1.41 cluster:

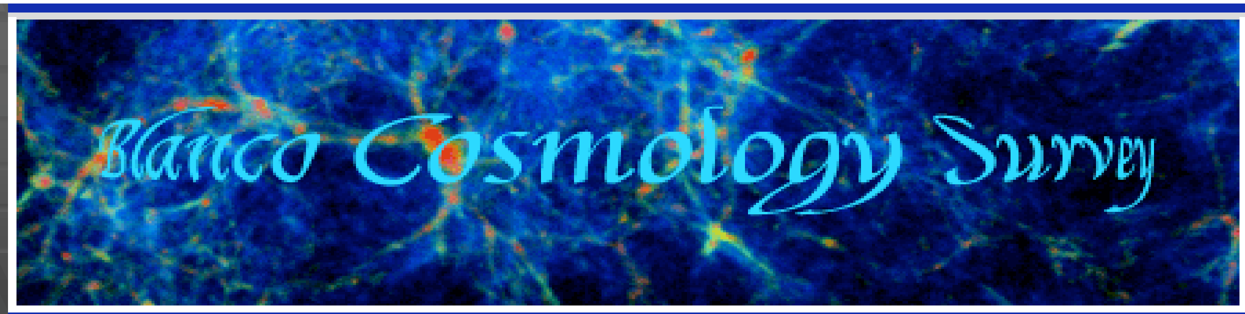


Next Steps

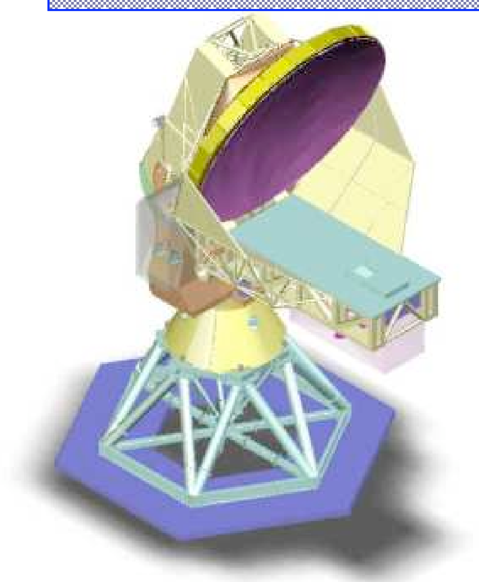
- Forthcoming deeper *Spitzer* and *HST* data will allow us to:
  - Observe the mass assembly history of massive galaxies over 2/3 of the lifetime of the Universe.
  - Measure the evolution of the merger rate and the quantify the dry merger fraction
  - Probe the Cluster/ULIRG connection at the era of peak star formation
  - Measure weak-lensing masses and the mass-richness relation at z>1
  - Constrain the EOS of dark energy from Cluster SNe Ia

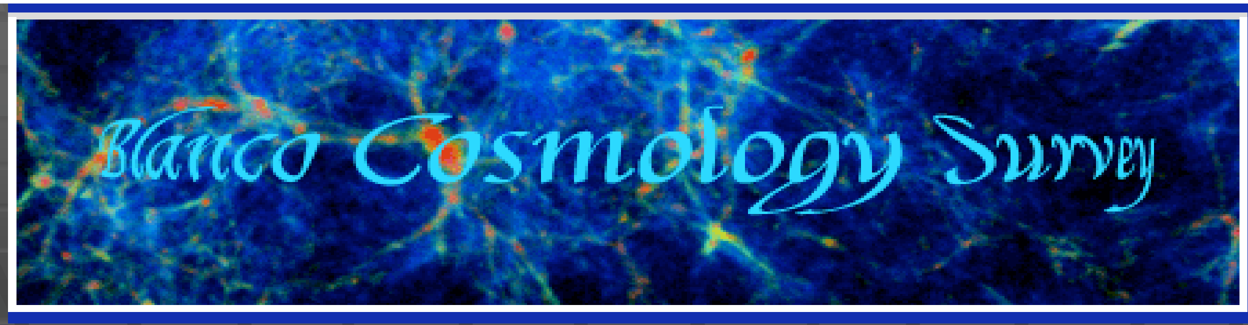
Summary

- Using a probabilistic multi-λ (0.4-5μm) 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 ($z_f > 3$).
- Evidence of a mass-metallicity relation and/or "downsizing" 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.

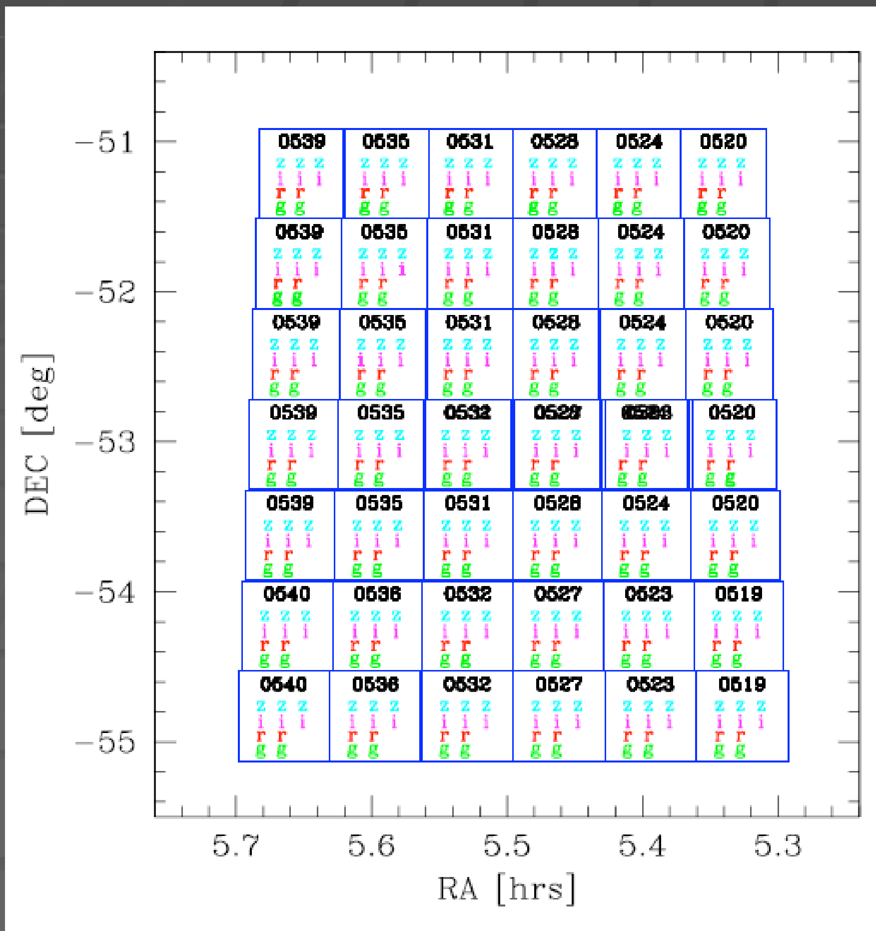


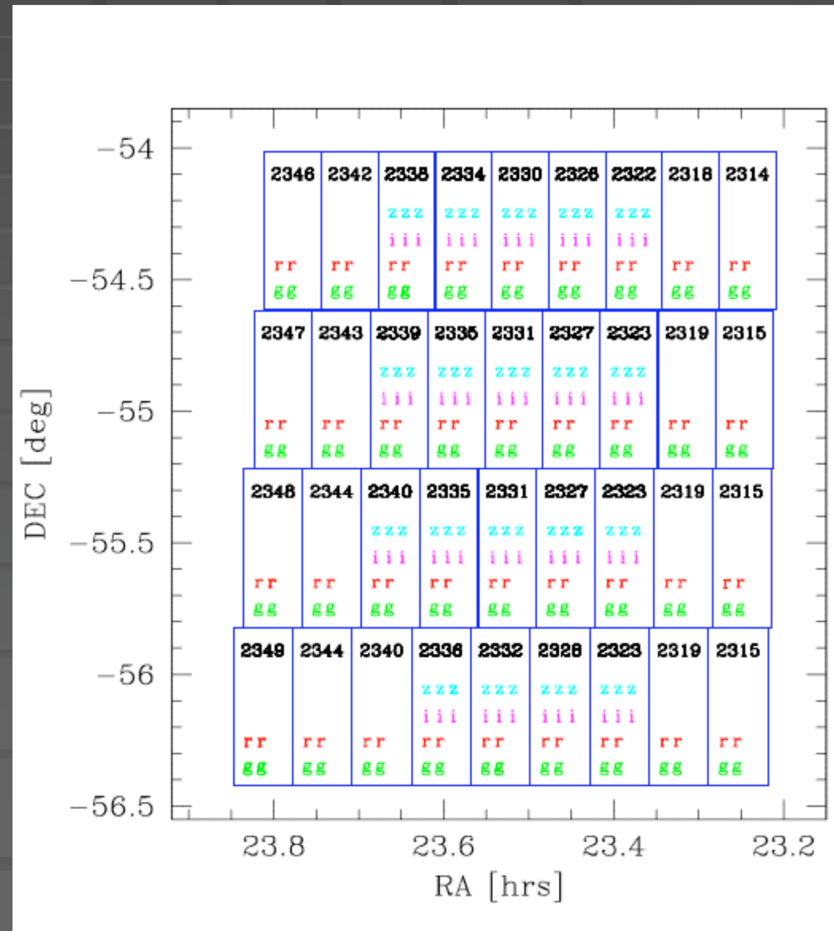
- Deep optical (*griz*) imaging in 2 x 50 deg^2 Southern **APEX, ACT, SPT** fields (PI: Joe Mohr)
- Eventual IRAC and NIR → will find <u>> 3500 clusters and groups to z=2</u>
- Provide **redshifts** and **masses** for all SZ clusters
- Direct measurement of σ_8 from z>1 clusters
- Characterize and calibrate SZ selection function to allow studies of precision cosmology



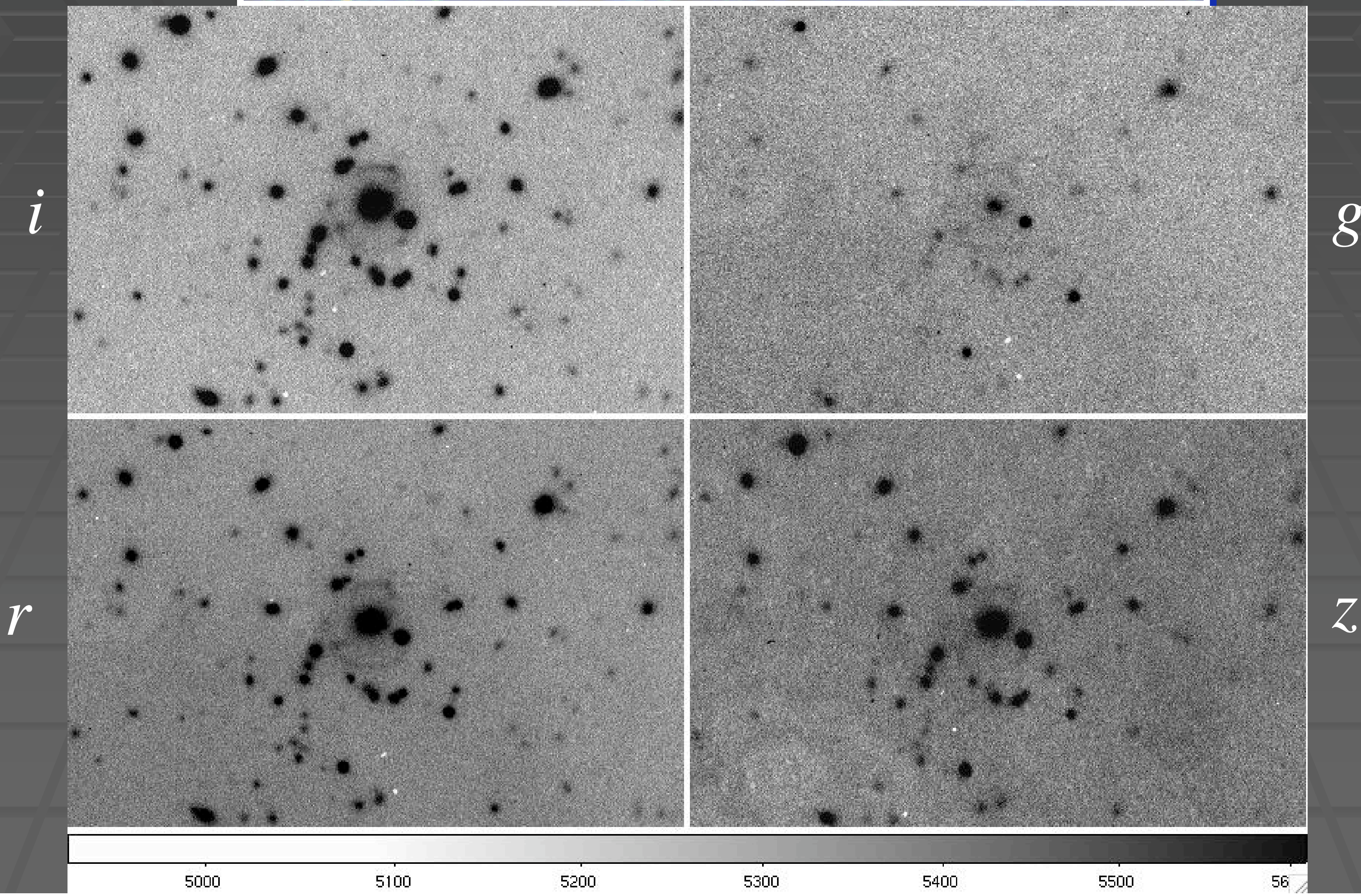


Survey Status





Blanco Cosmology Survey



Thank you!