Spitzer/IRAC Selected Galaxy Clusters at z > 1

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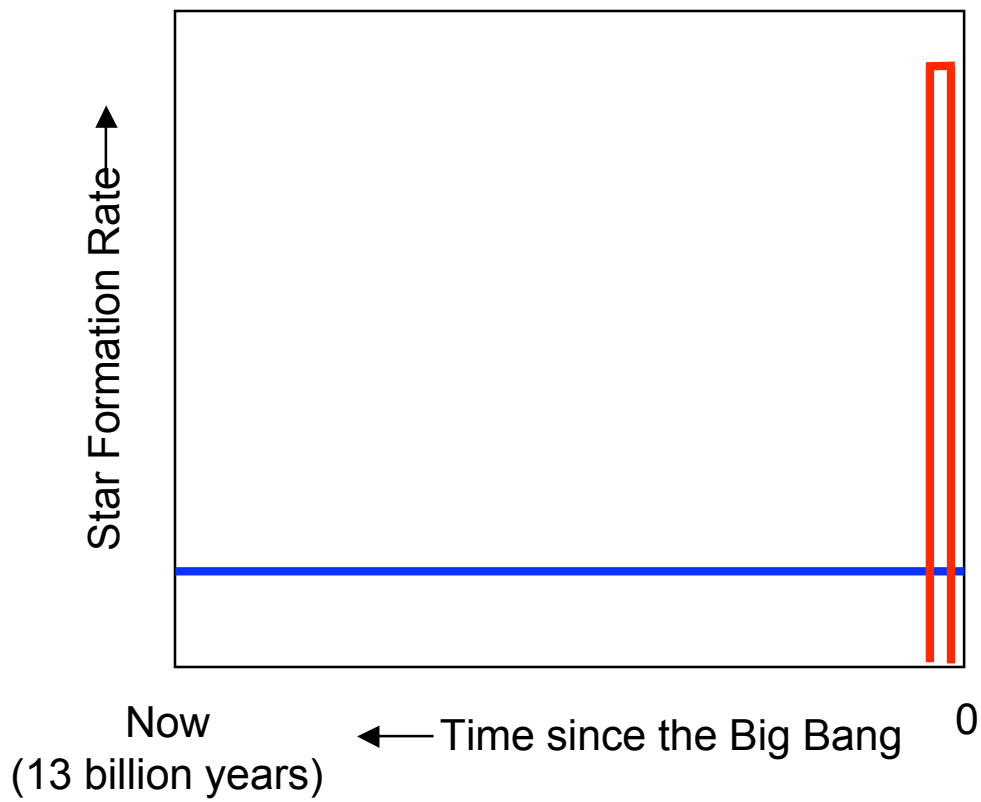
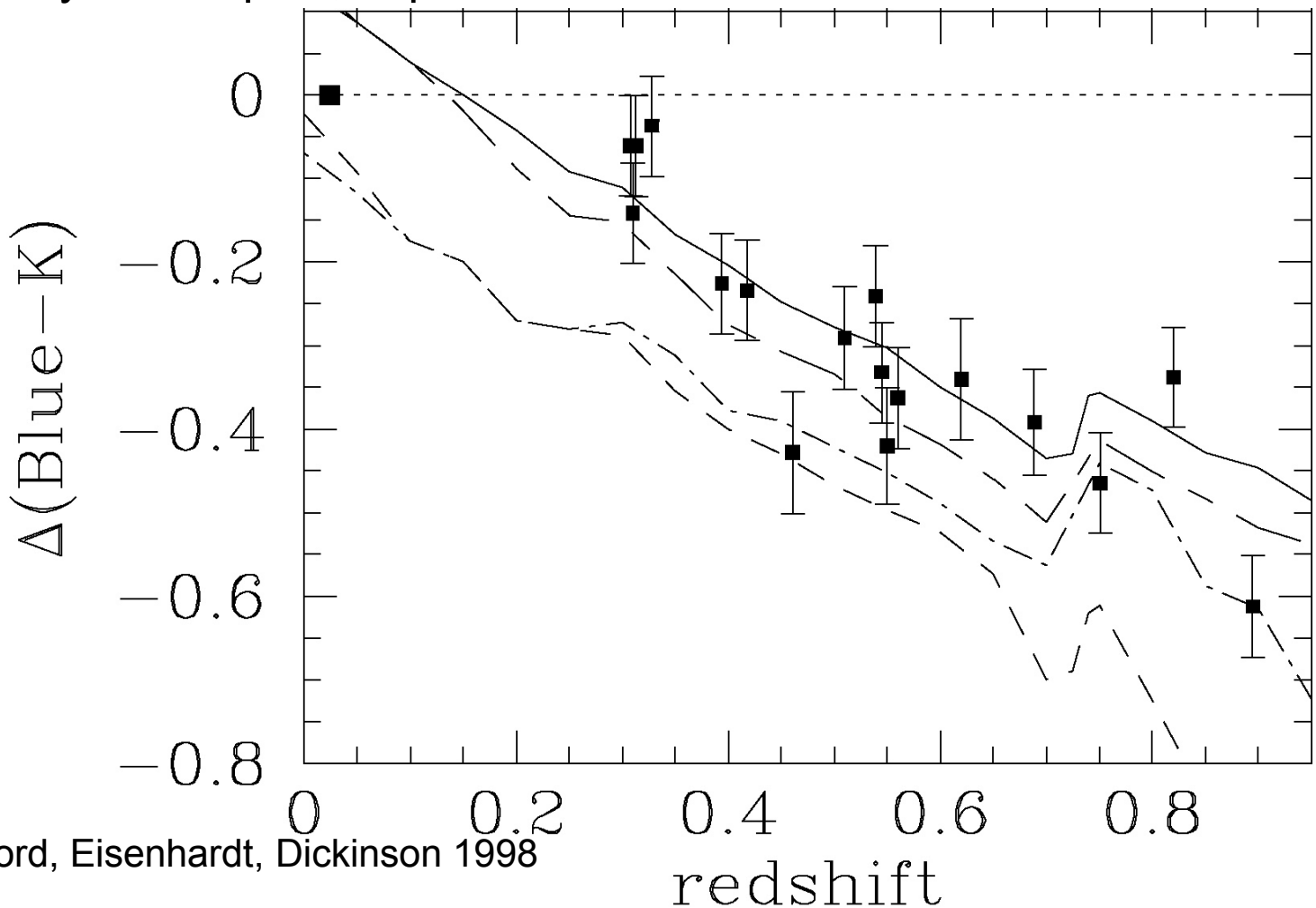
Bimodal Formation?

- Is the star formation history in cluster galaxies more like:
  - a delta function at high redshift, ending early in the history of the universe (red spike), or
  - a continuous process over cosmic time, still going on today (blue plateau) ?



Color-Magnitude Intercept vs Redshift

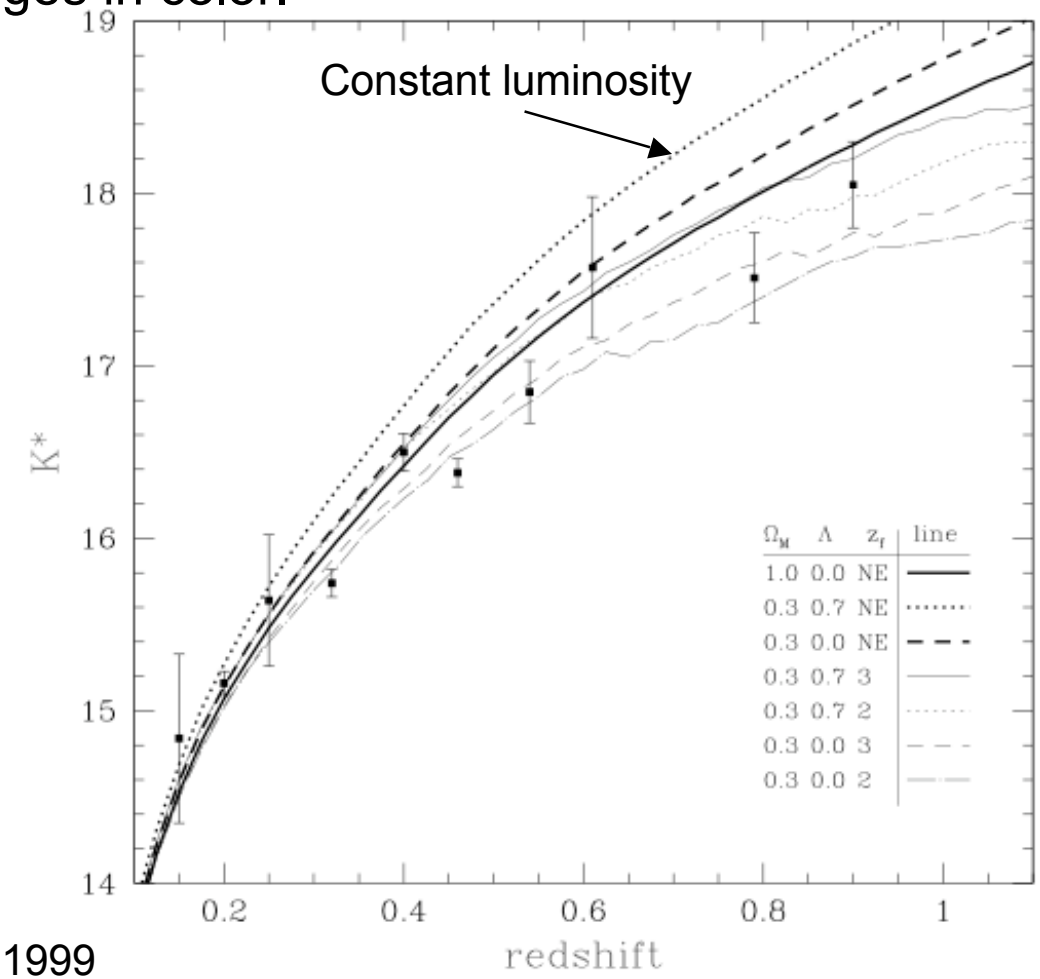
- The scatter, slope and intercept of the color-magnitude relation for cluster galaxies vs. redshift are better matched by a red spike, ie passive evolution with formation at z >~ 3.



Stanford, Eisenhardt, Dickinson 1998

Infrared Luminosity vs Redshift

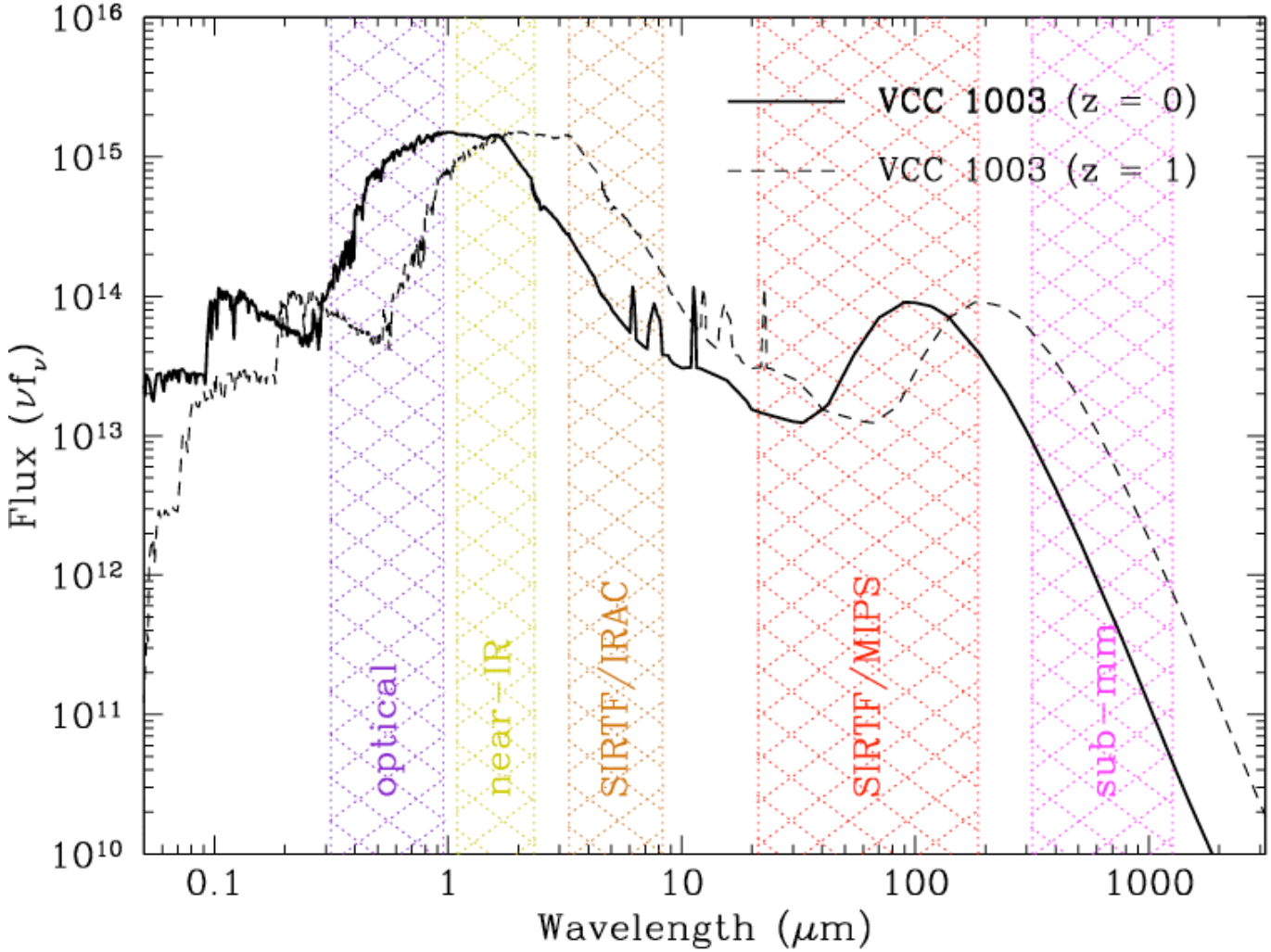
- The characteristic infrared luminosity of cluster galaxies (K*) also increases with redshift, by an amount consistent with the changes in color.



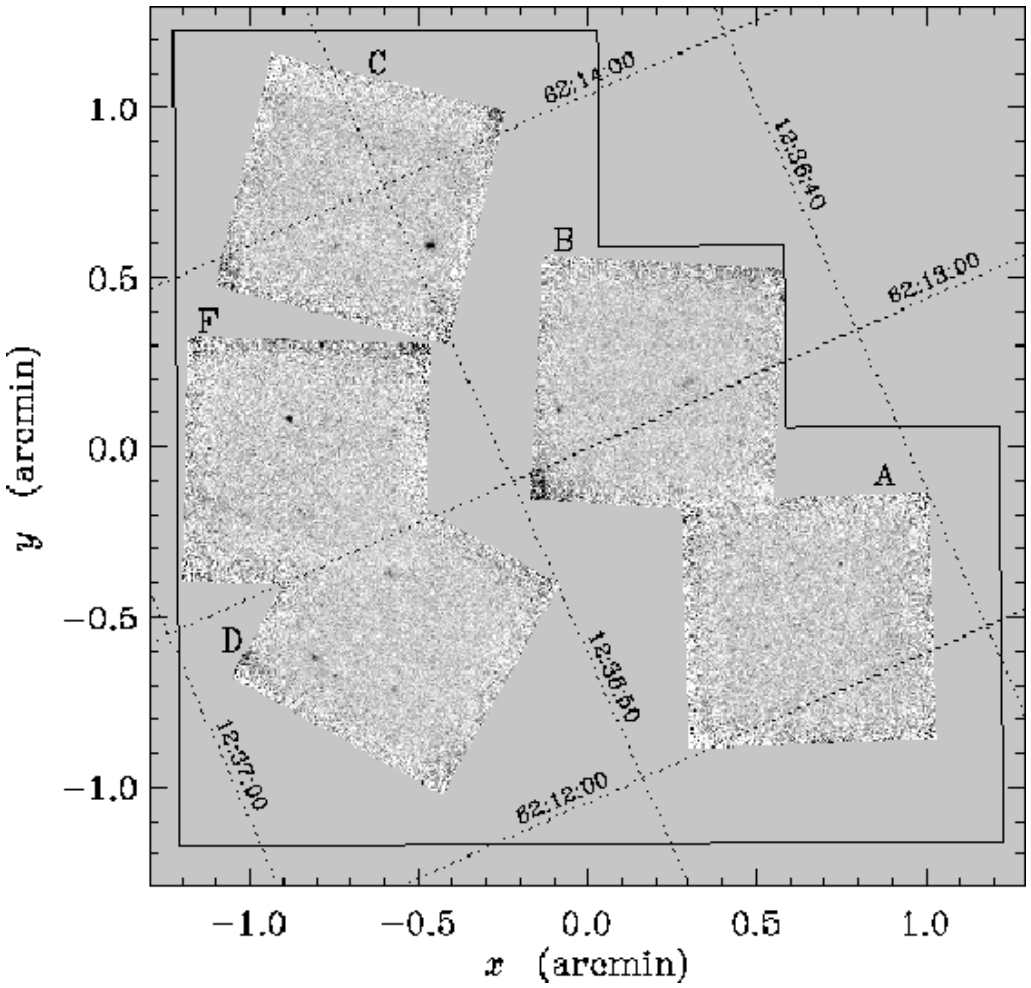
De Propris et al 1999

Mid-IR is a Good Place to Select Distant Galaxies

White, orange, red…IR (McKay)



Ground-based Image of HDF-N at 3.2 microns

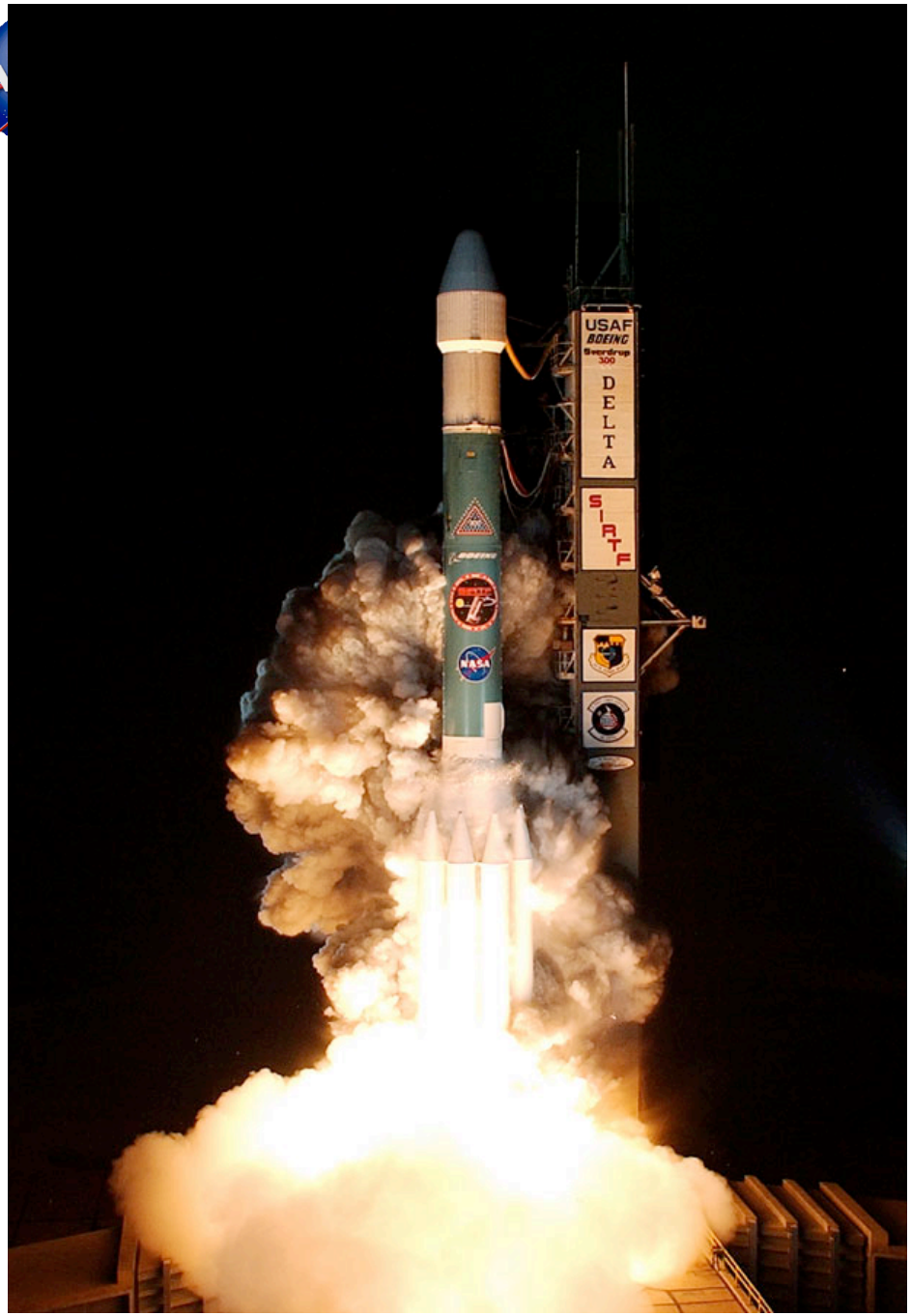


15 hours with Keck

2.5 square arcmin

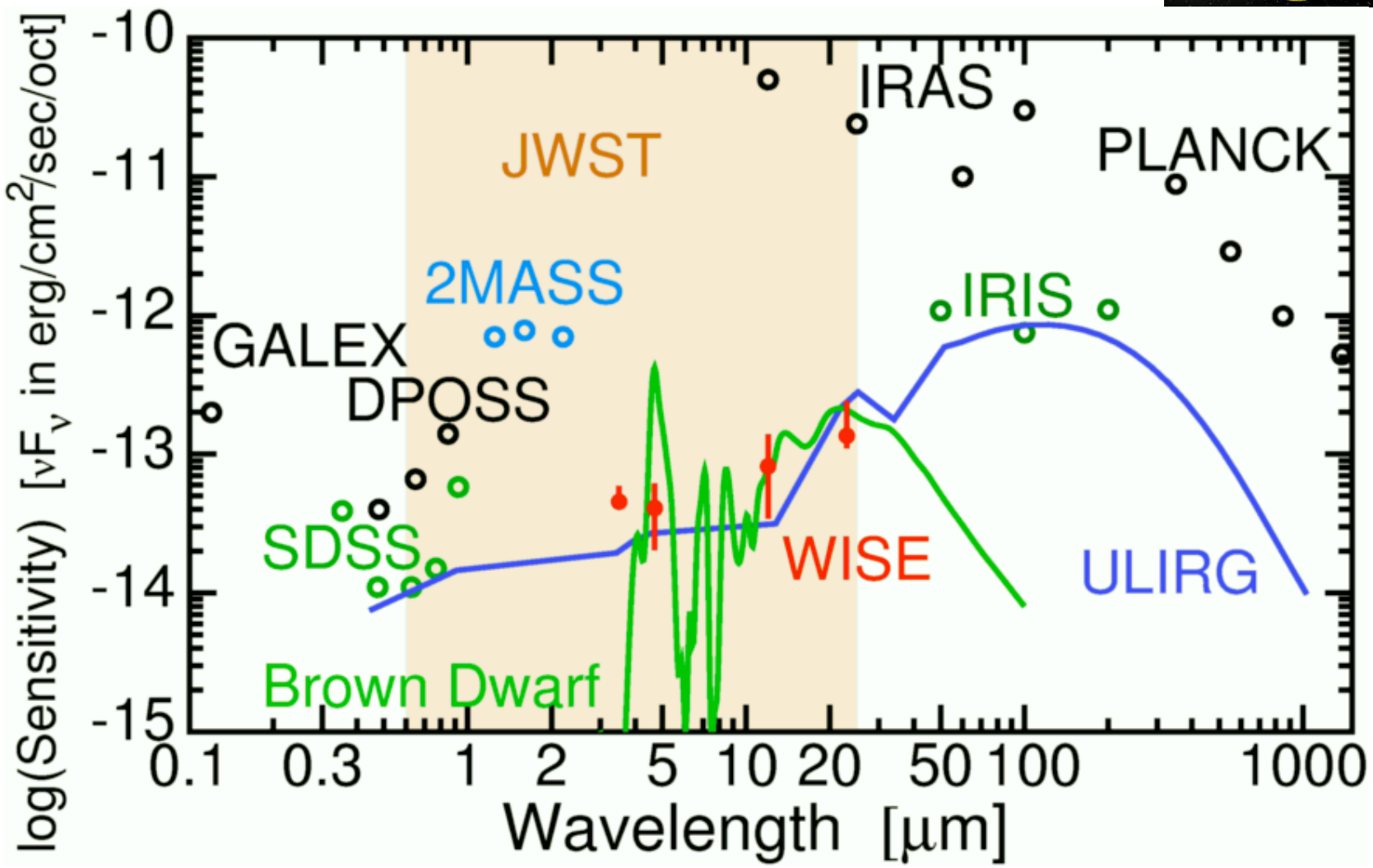
11 sources detected

Hogg et al. (2000)

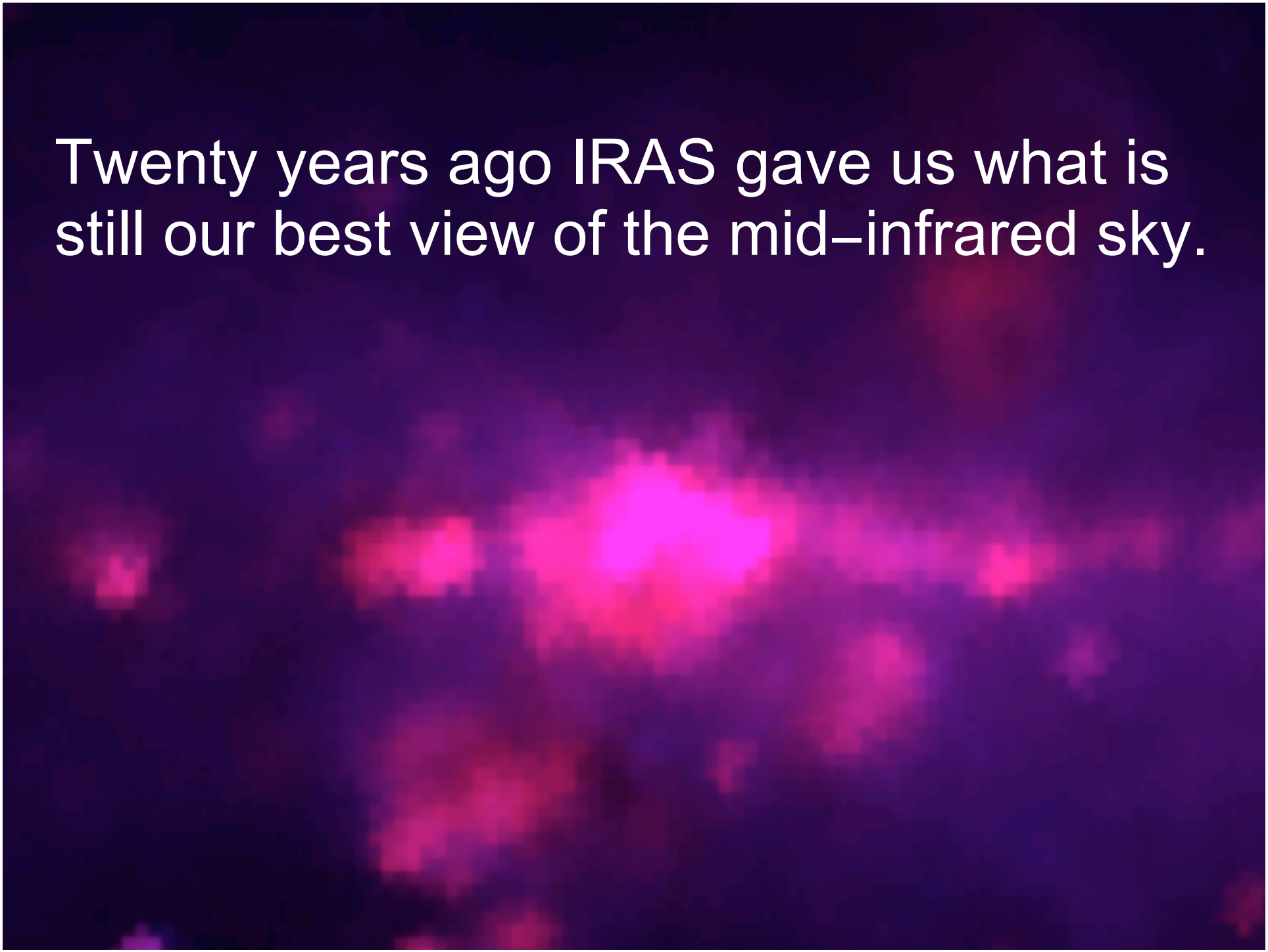


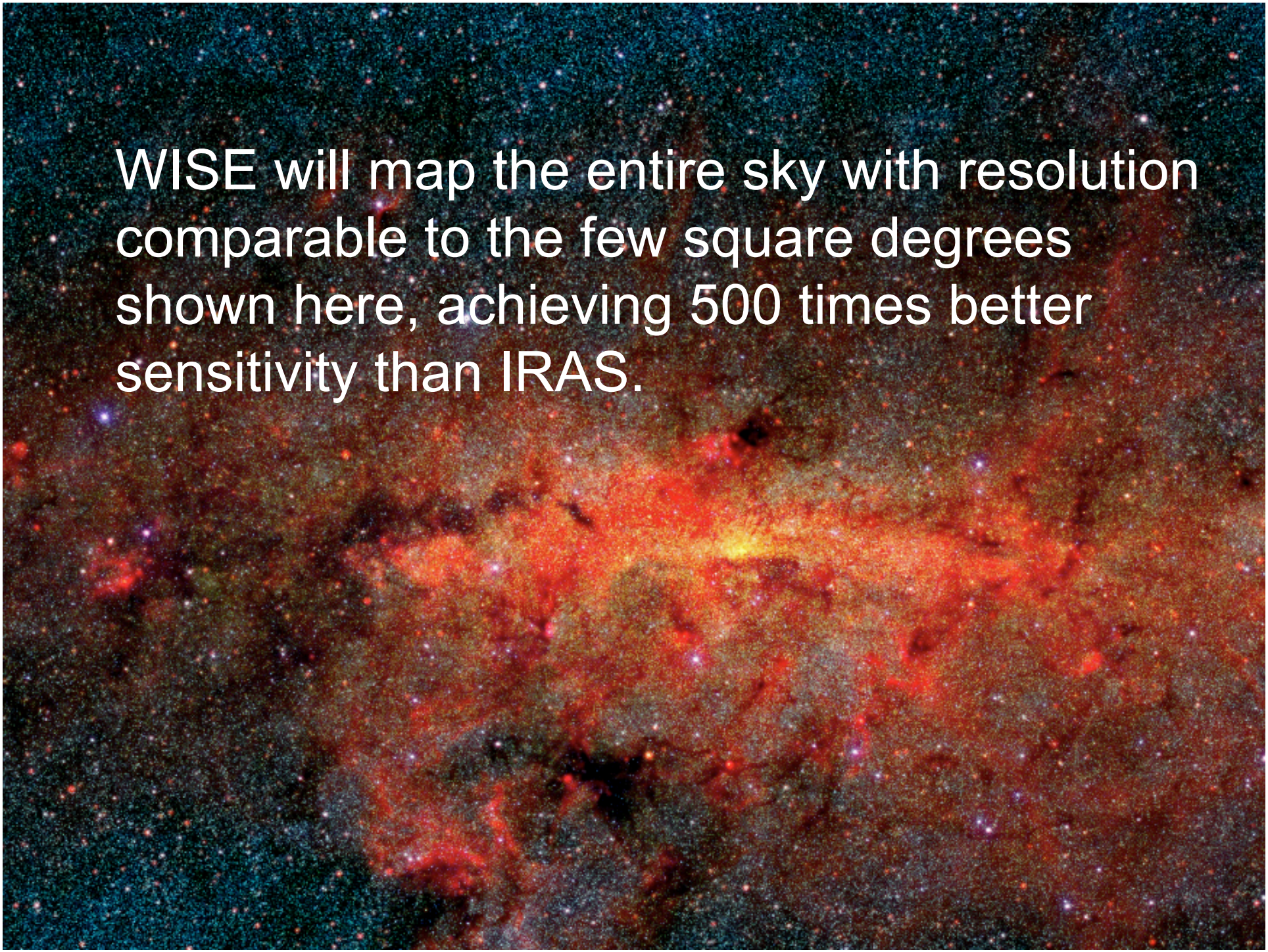
Monday, August 25, 2003
1:35:39 AM EST
Cape Canaveral, Florida

Coming in 2008: WISE
Wide-field Infrared Survey Explorer



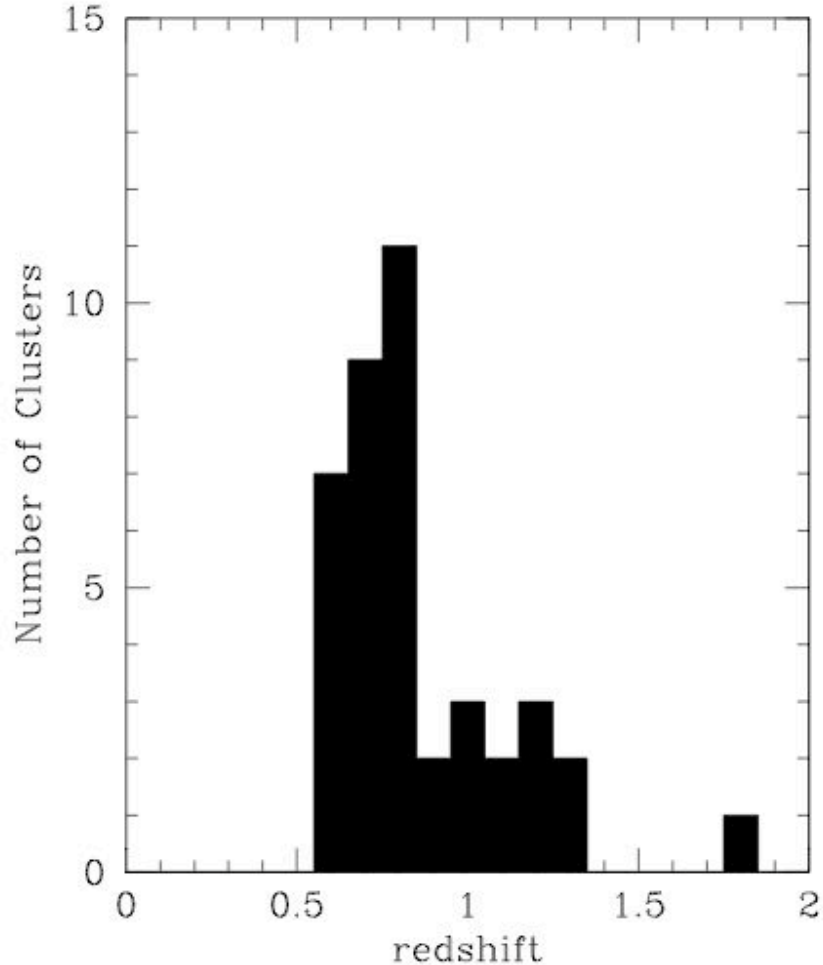
Twenty years ago IRAS gave us what is still our best view of the mid–infrared sky.




WISE will map the entire sky with resolution comparable to the few square degrees shown here, achieving 500 times better sensitivity than IRAS.

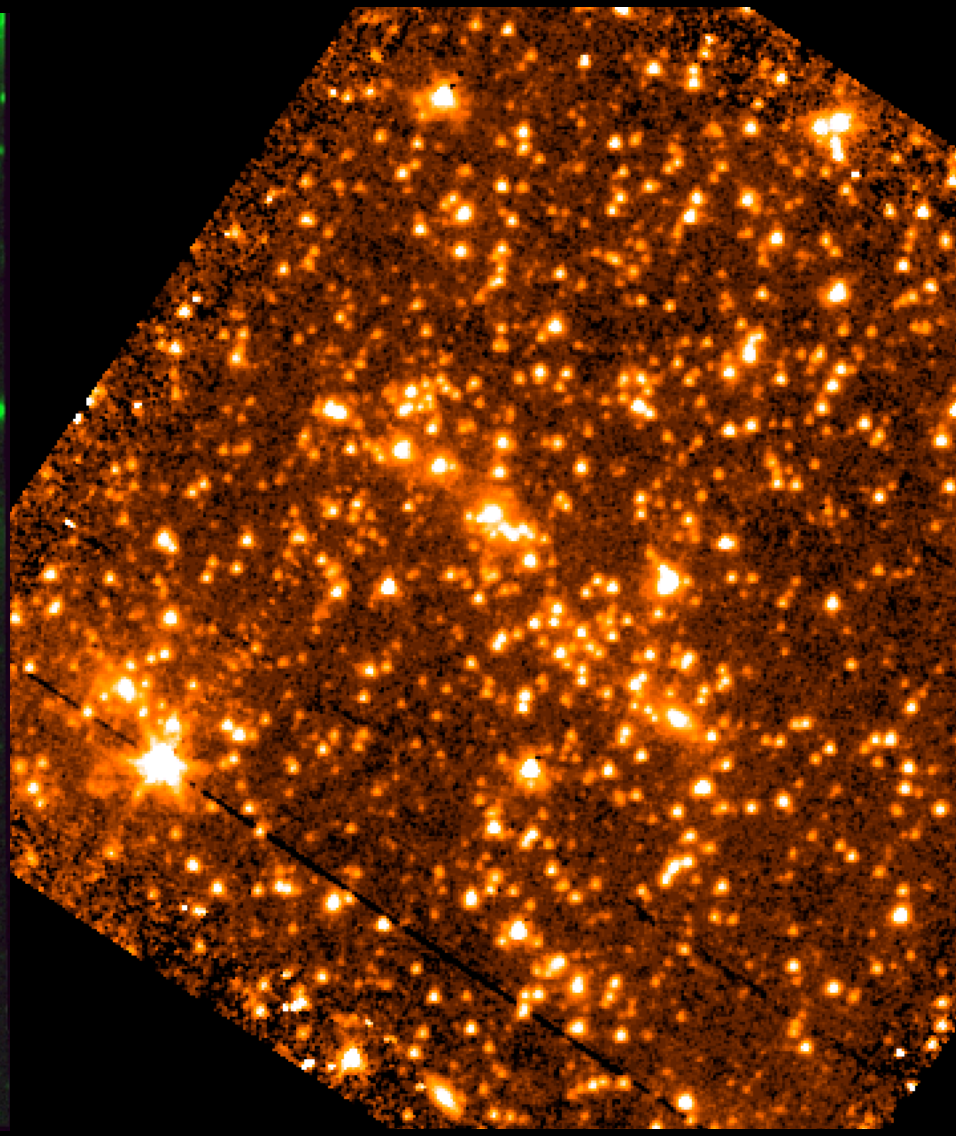
Stellar Masses in Clusters

- Look at rest 1.6 microns for 40 z > 0.6 clusters (mainly RDCS)
- 1000 sec exposures reach ~ L*+4
- It would be nice to have more z > 1 clusters…



Cl 0152-13 at z = 0.83 in vri

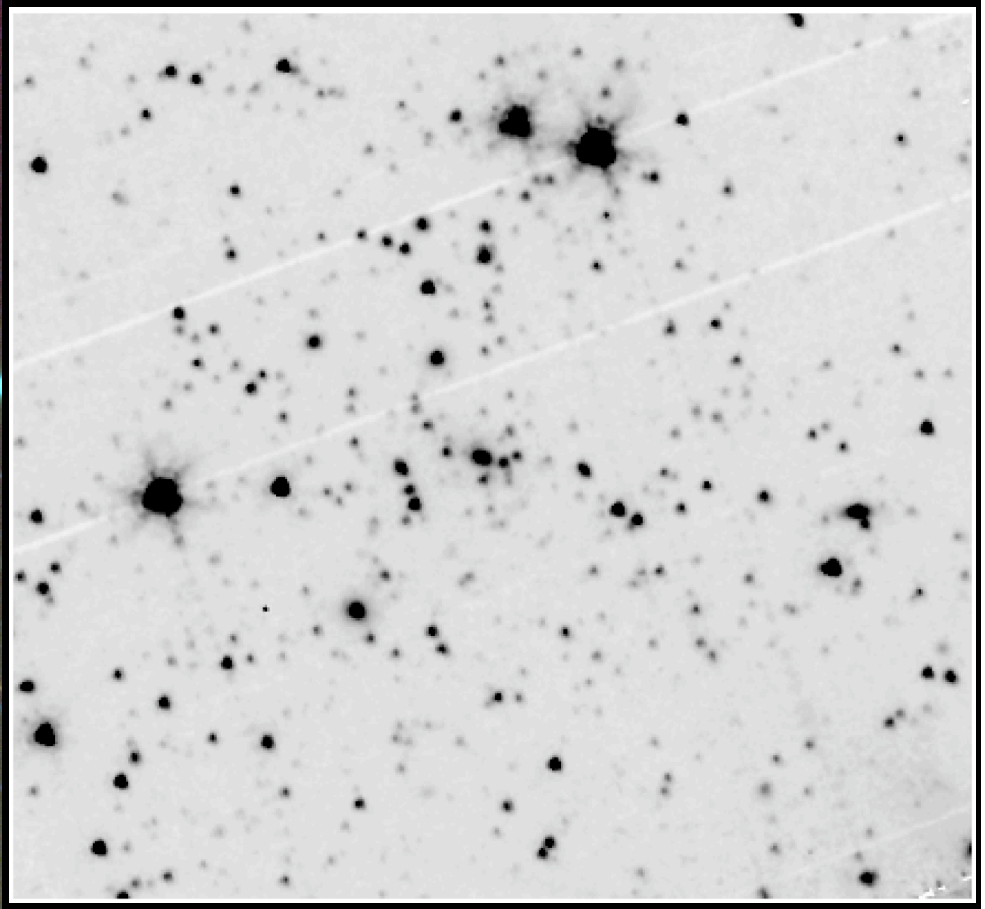
vri image from Piero Rosati, VLT



3.6 micron IRAC image, 5 x 200 sec

RXJ1252-2927 at z = 1.23
(Stanford et al.)

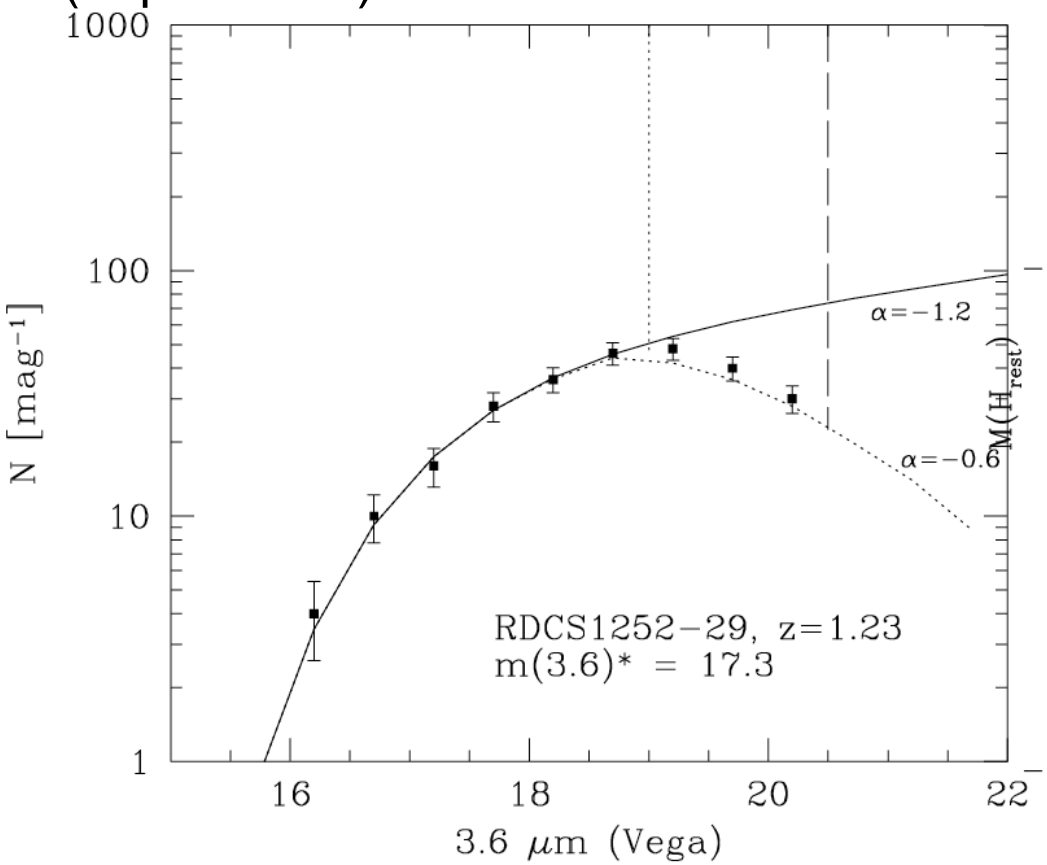
BV+Rz+3.6

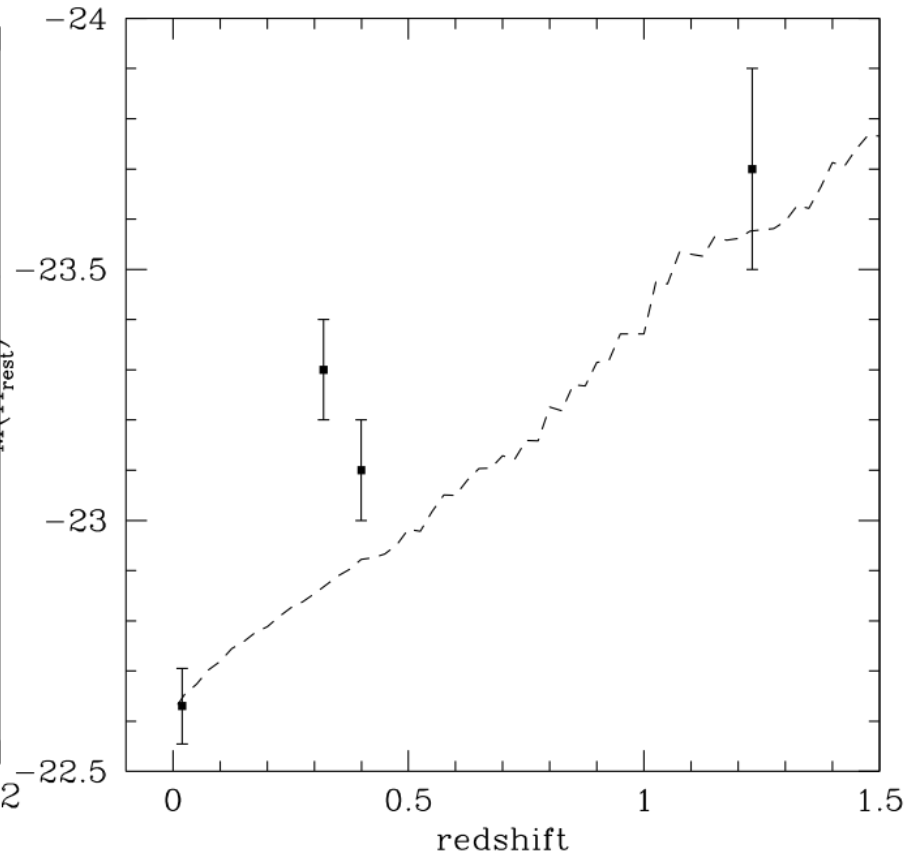


3.6 micron IRAC image, 5 x 200 sec

RXJ1251-2927 Rest 1.6um L* Matches PLE to z=1.23

Faint end slope variations, but bright end still follows simple model (Lopez-Cruz)





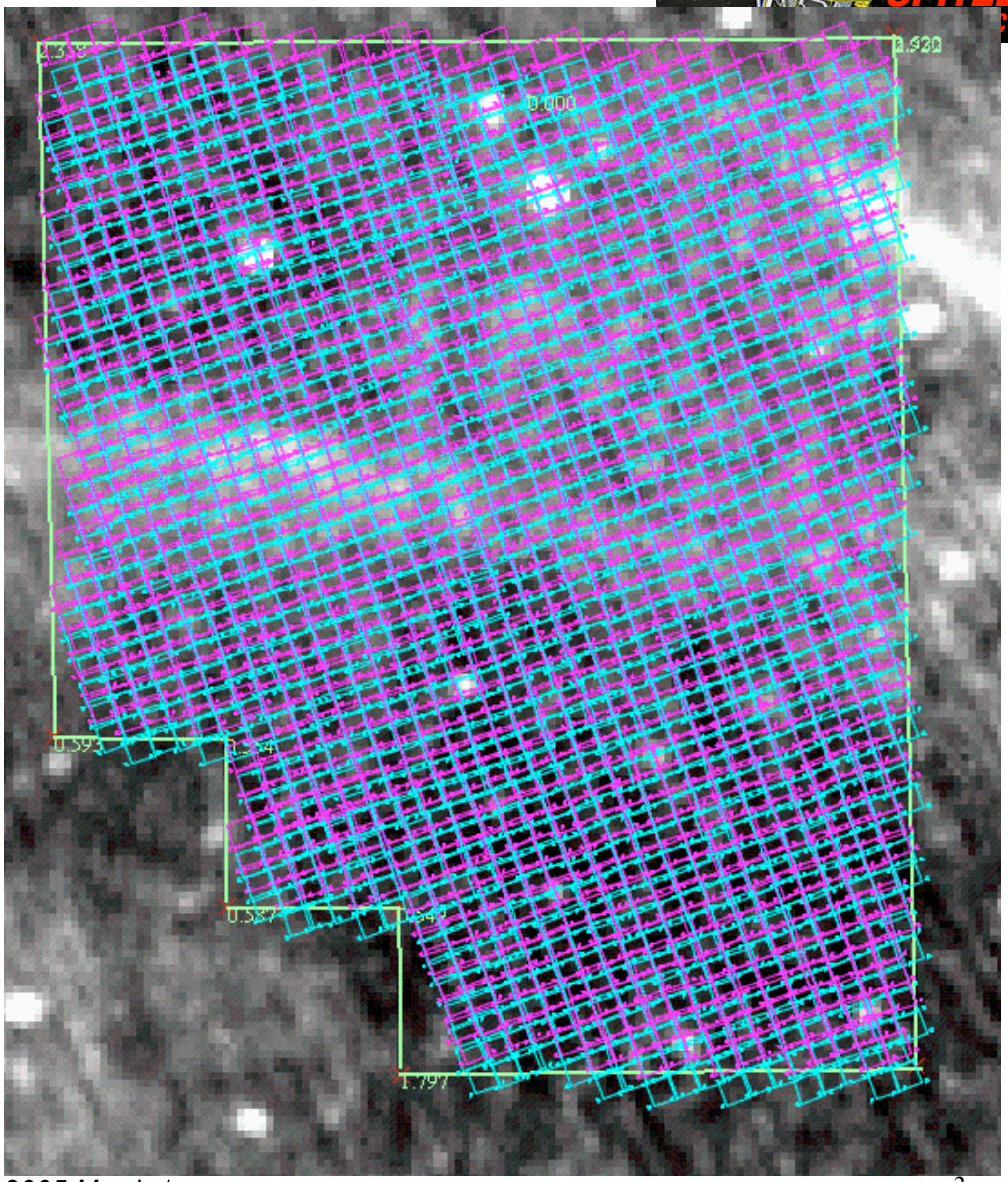
Stanford et al

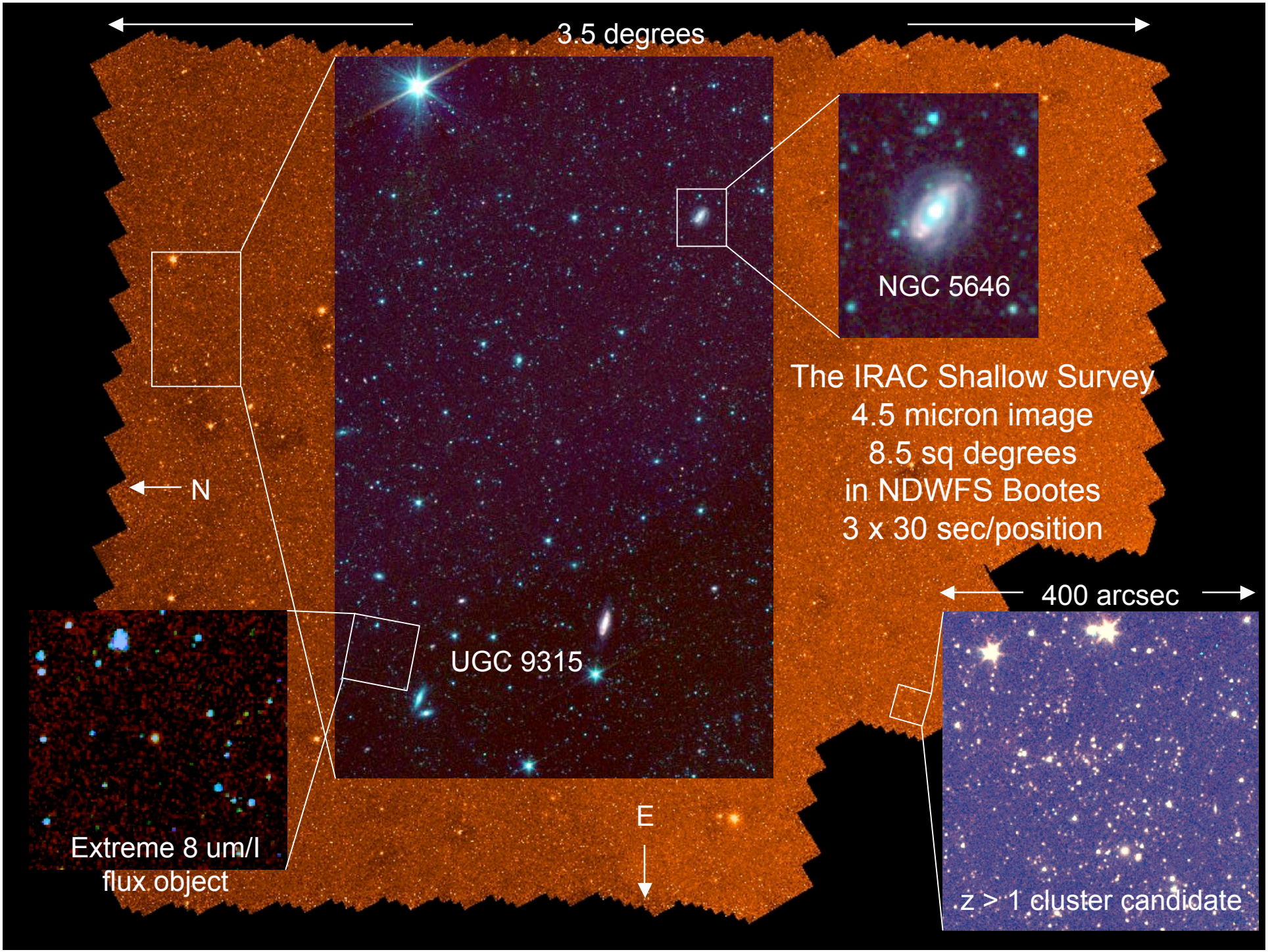
z > 1 Clusters

- Colors and magnitudes of cluster galaxies are consistent with simple passively evolving z_f~3 model out to z ~ 1
- Enables efforts to synchronize stellar evolutionary and cosmological clocks in such simple models, constrain w' (see Simon, Verde, Jimenez astro-ph/0412269, Constraints on the redshift dependence of the dark energy potential)
- Maybe much higher z_f? Egami et al 2005, Kogut et al 2003
- Need to test formation model at z > 1
- But z > 1 clusters are hard to find optically because of foreground clutter

IRAC Shallow Survey Observations

- 30 second frames
  - Approaching background limited at 3.6 um, background limited at longer wavelengths
  - ~ 10 seconds overhead
- 17,076 individual frames
  - 4 at a time in 3.6/5.8 and 4.5/8 micron, so 4,269 pointings
  - 3 repeats per position (on advice of Tombaugh)
- 62 hours Spitzer/IRAC time




3.5 degrees
NGC 5646
The IRAC Shallow Survey
4.5 micron image
8.5 sq degrees
in NDWFS Bootes
3 x 30 sec/position
N
UGC 9315
400 arcsec
E
Extreme 8 um/I
flux object
z > 1 cluster candidate

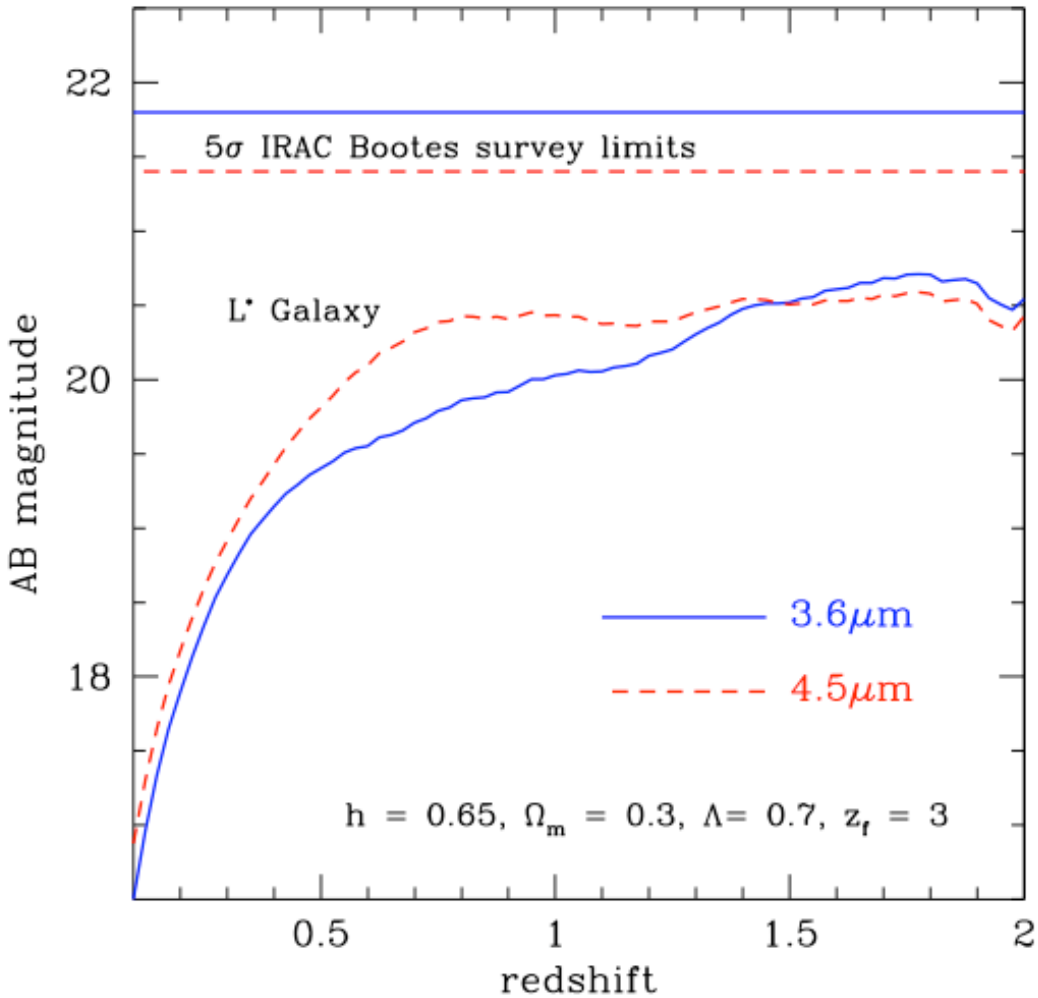
IRAC Shallow Survey

- 3.6-8.0 μm survey covering 8.5 ° in the NDWFS Boötes field.
- B_w, R, I to ~ 26 mag

	3.6 μm	4.5 μm	5.8 μm	8.0 μm
Vega Mag 5σ (3")	19.1	18.3	15.9	15.2
Flux (μJy) 5σ (3")	6.4	8.8	51	50
Number Detected > 5σ (3")	370,000	280,000	38,000	34,000

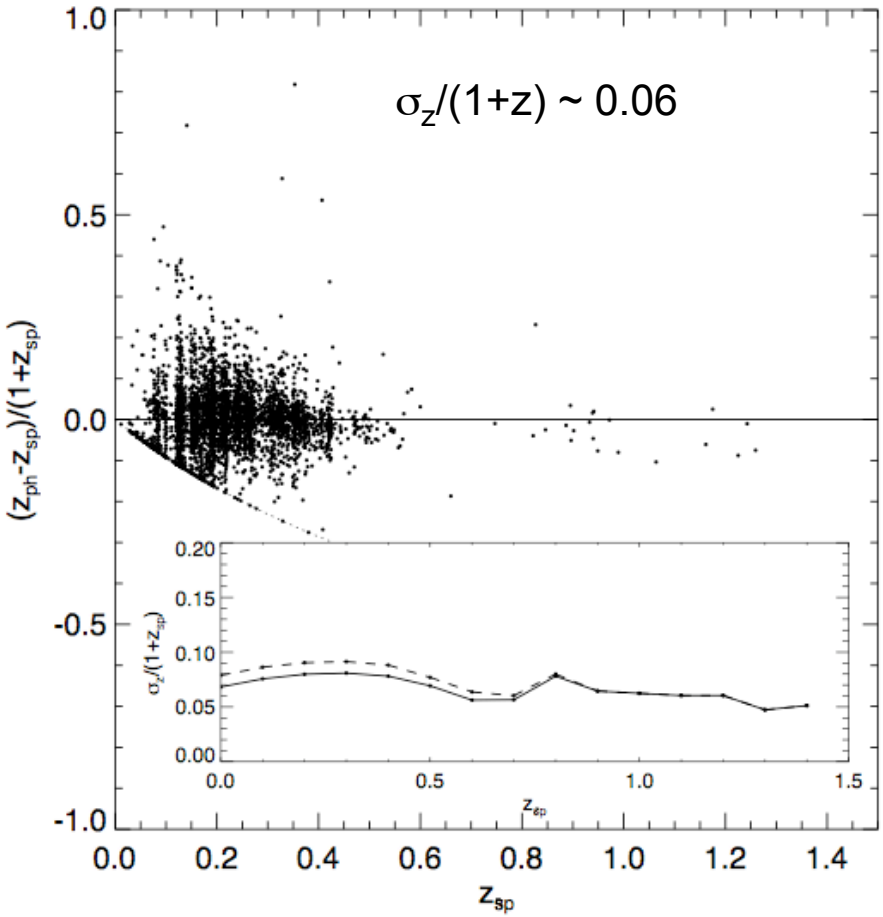
IRAC Shallow Survey

- Predictions extrapolate measured K (2um) luminosity in z = 0 - 1 clusters to 4.5 um and z=2, using models which also fit the color-magnitude relation.
- Negative K correction plus passive evolution mean $F_{4.5}$ = K *luminosity for 0.7 < z < 2 cluster galaxies
- Nice selection function
  - Don't assume red sequence

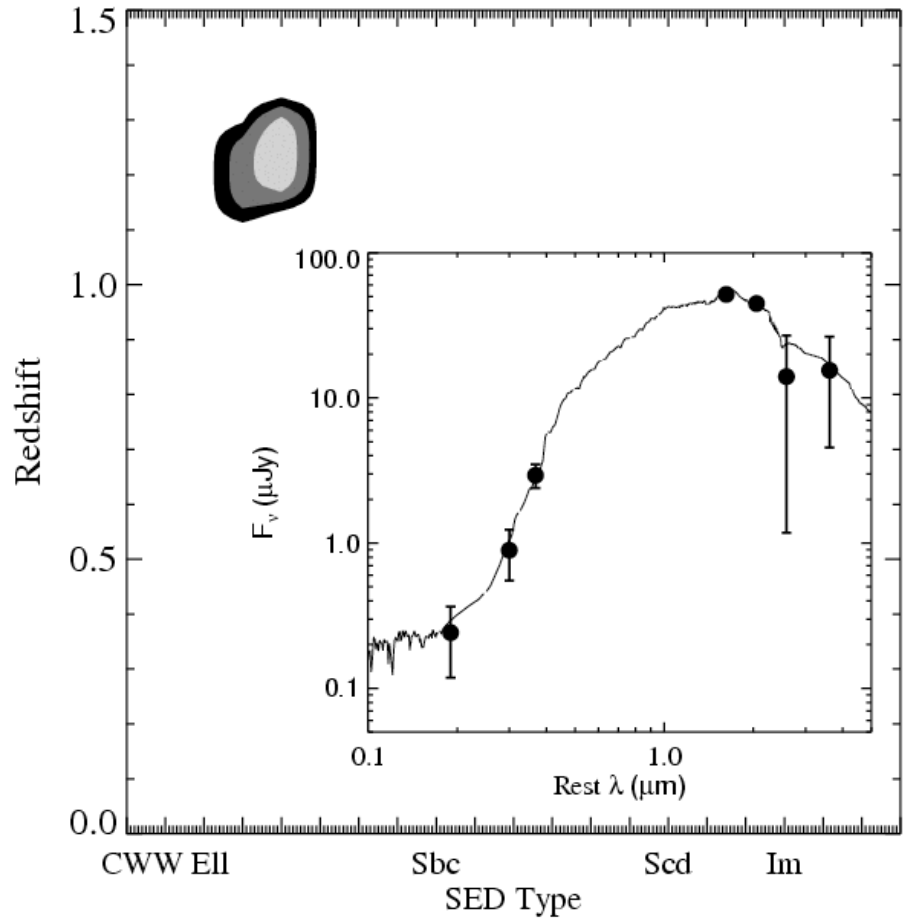


Phot-z's from NDWFS+ IRAC+AGES (Brodwin et al 2005)

(AGES=AGN and Galaxy Evolution Survey; Kochanek, Eisenstein, Caldwell, Cool et al.)
(NDWFS=NOAO Deep Wide Field Survey; Jannuzi, Dey, Brown, Tiede et al.)



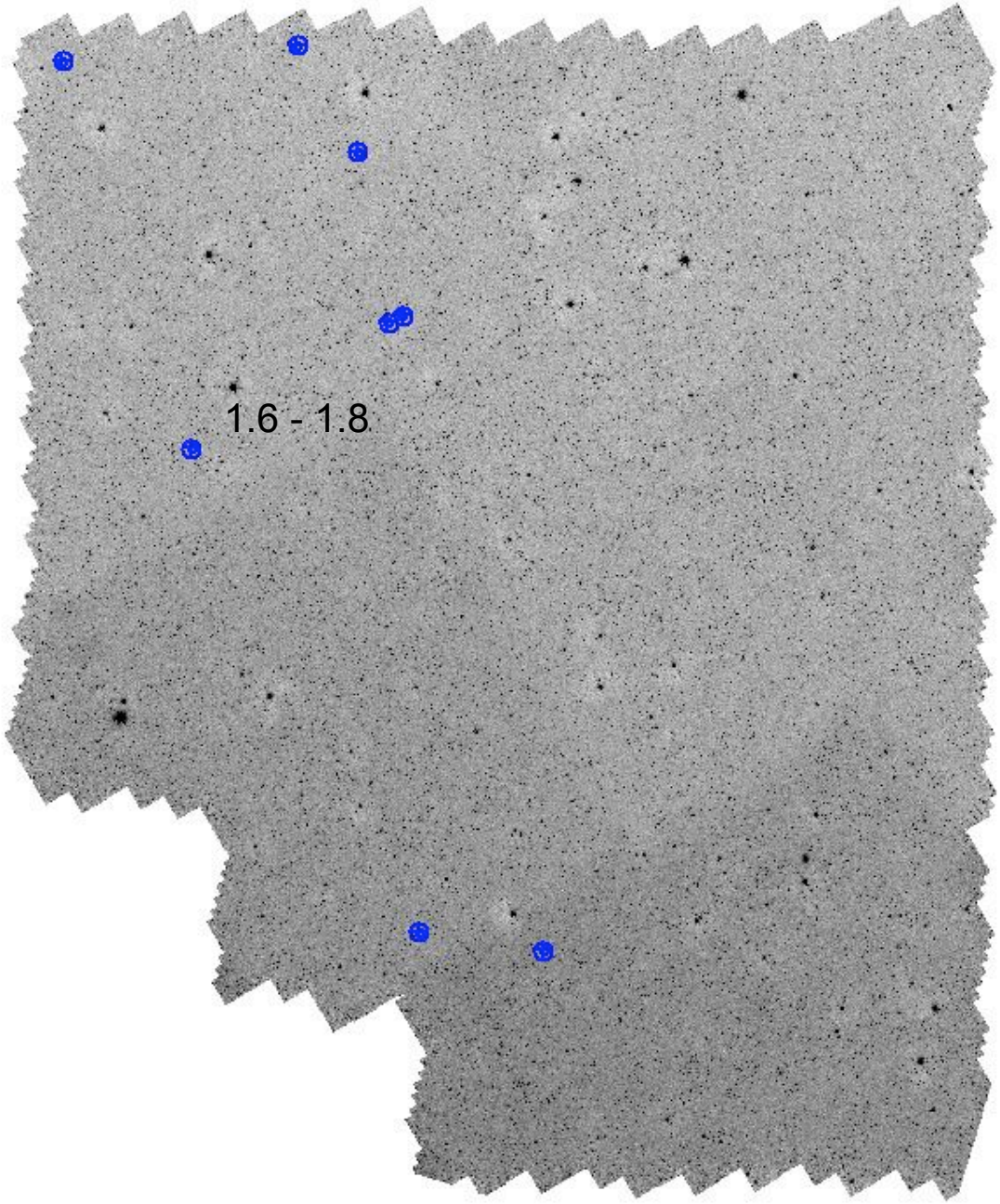
Phot-z's vs. AGES etc.



Z > 1 Cluster Candidates

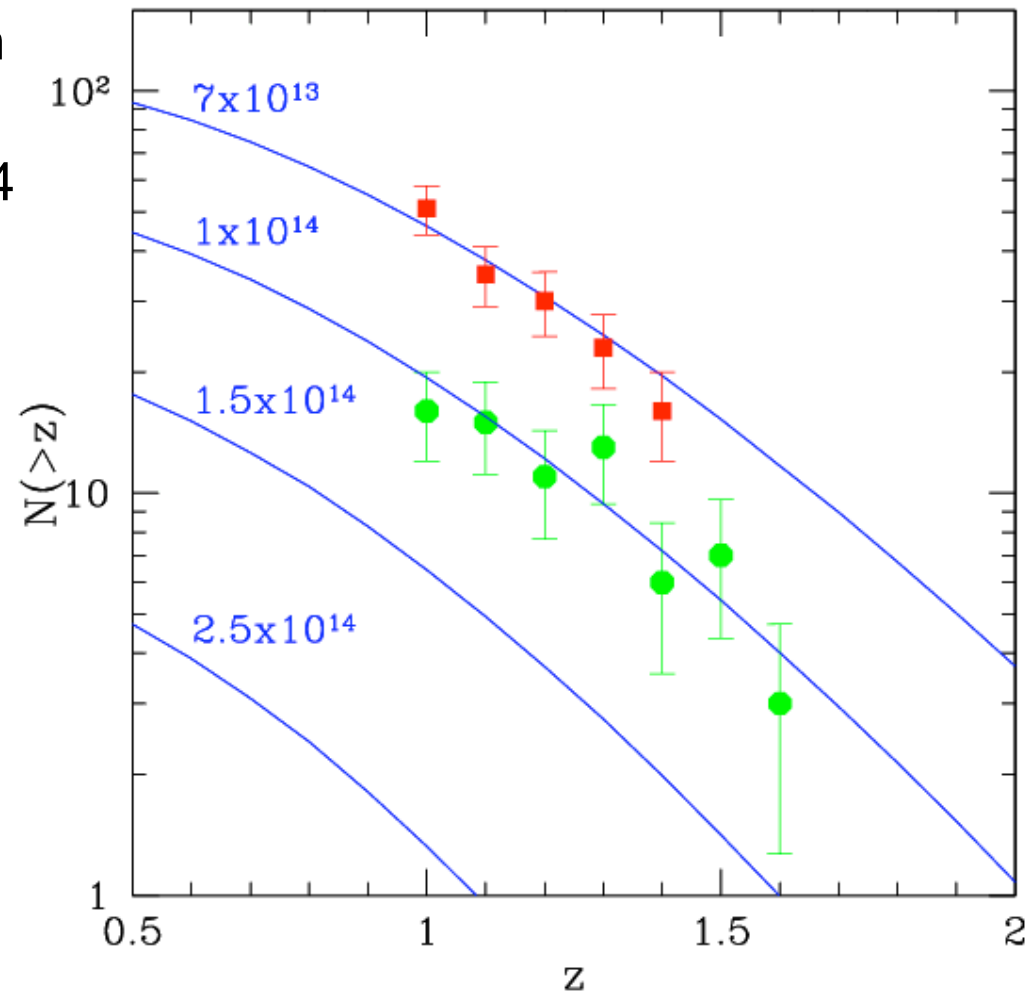
- Slice into overlapping dz = 0.2 bins from z = 1 to 2
- Run wavelet search for overdensities on 200 - 800 kpc scales
- 152 high significance candidates

Z range	Number Candidates
1.0 - 1.2	48
1.1 - 1.3	37
1.2 - 1.4	24
1.3 - 1.5	18
1.4 - 1.6	14
1.5 - 1.7	8
1.6 - 1.8	3

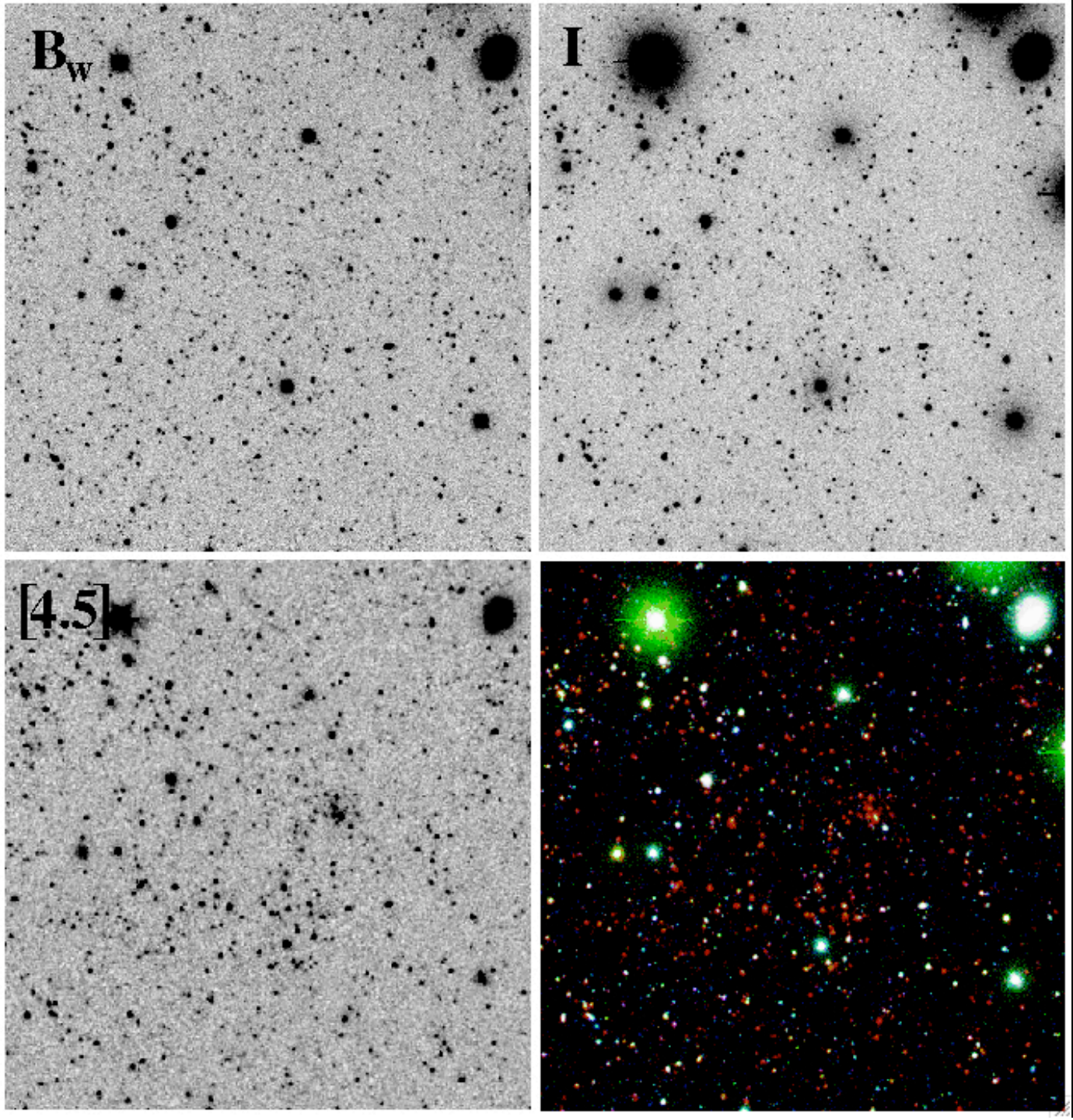

1.6 - 1.8

N(z) vs. z (Anthony Gonzalez)

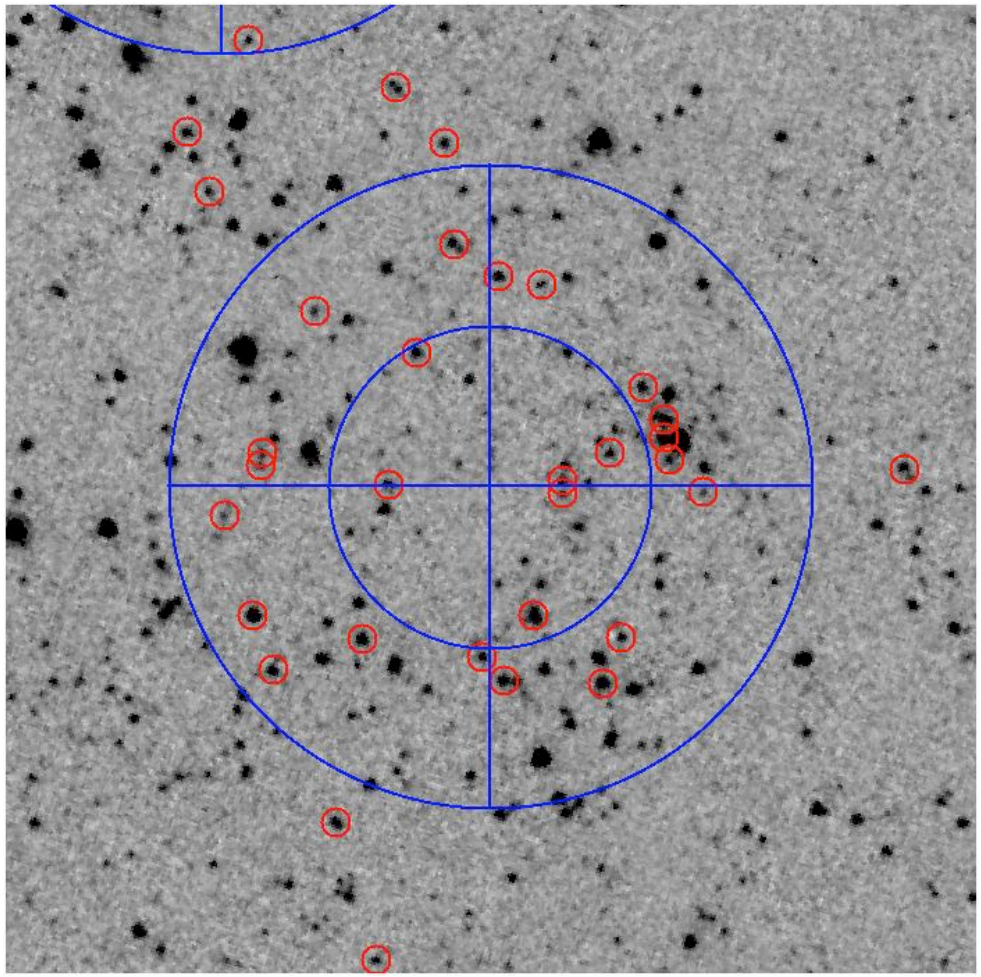
- N per IRAC Shallow Survey with $\langle f_{4.5} \rangle_{2Mpc} / \langle f_{4.5} \rangle_{10Mpc} > 2.5$
- N with $\langle f_{4.5} \rangle_{2Mpc} / \langle f_{4.5} \rangle_{10Mpc} > 4$
- Sheth - Tormen DM vs z Λ CDM σ_8=0.9

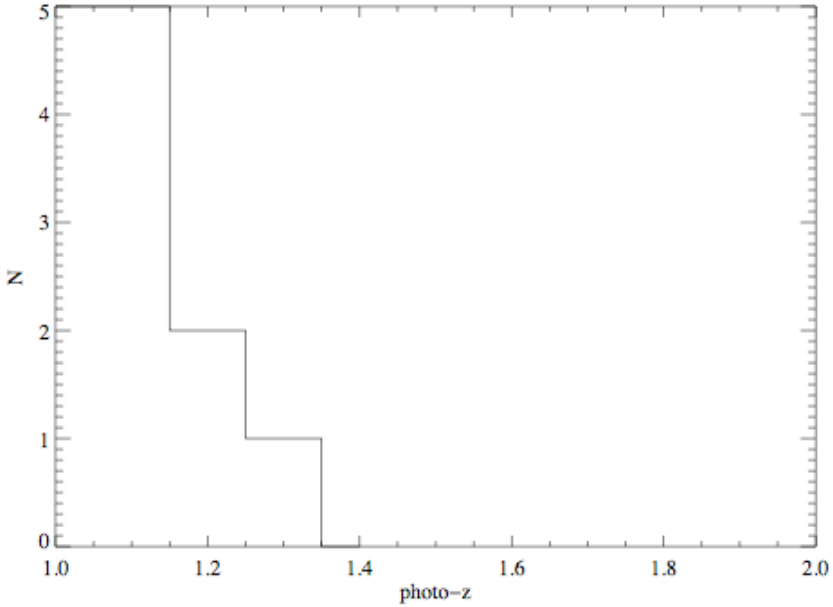


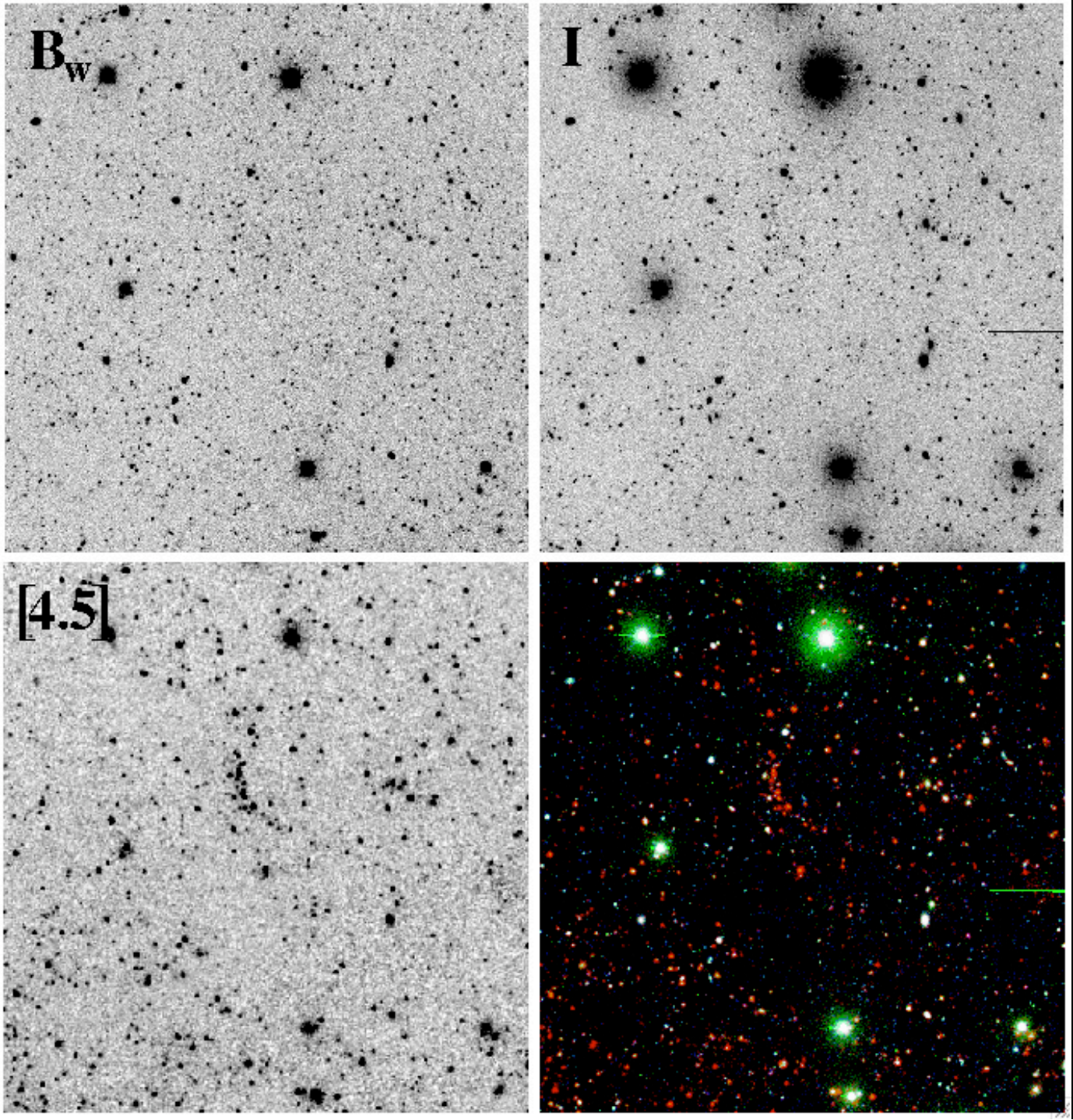
- Suggests we are recovering ~1 x 10^{14} $M_\odot$ systems
- But drop at higher z may be from reqt. for optical detection
  - redoing selection using optical limits


B_W
I
[4.5]

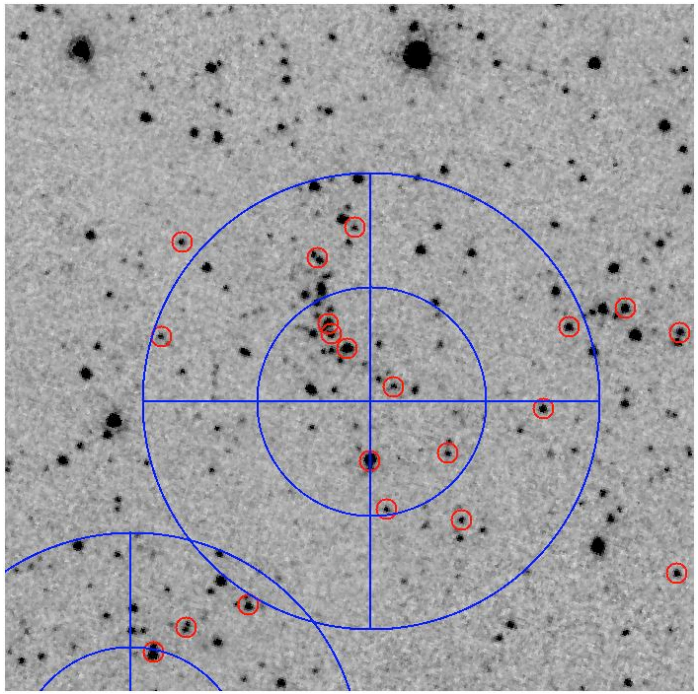
z ~ 1.1

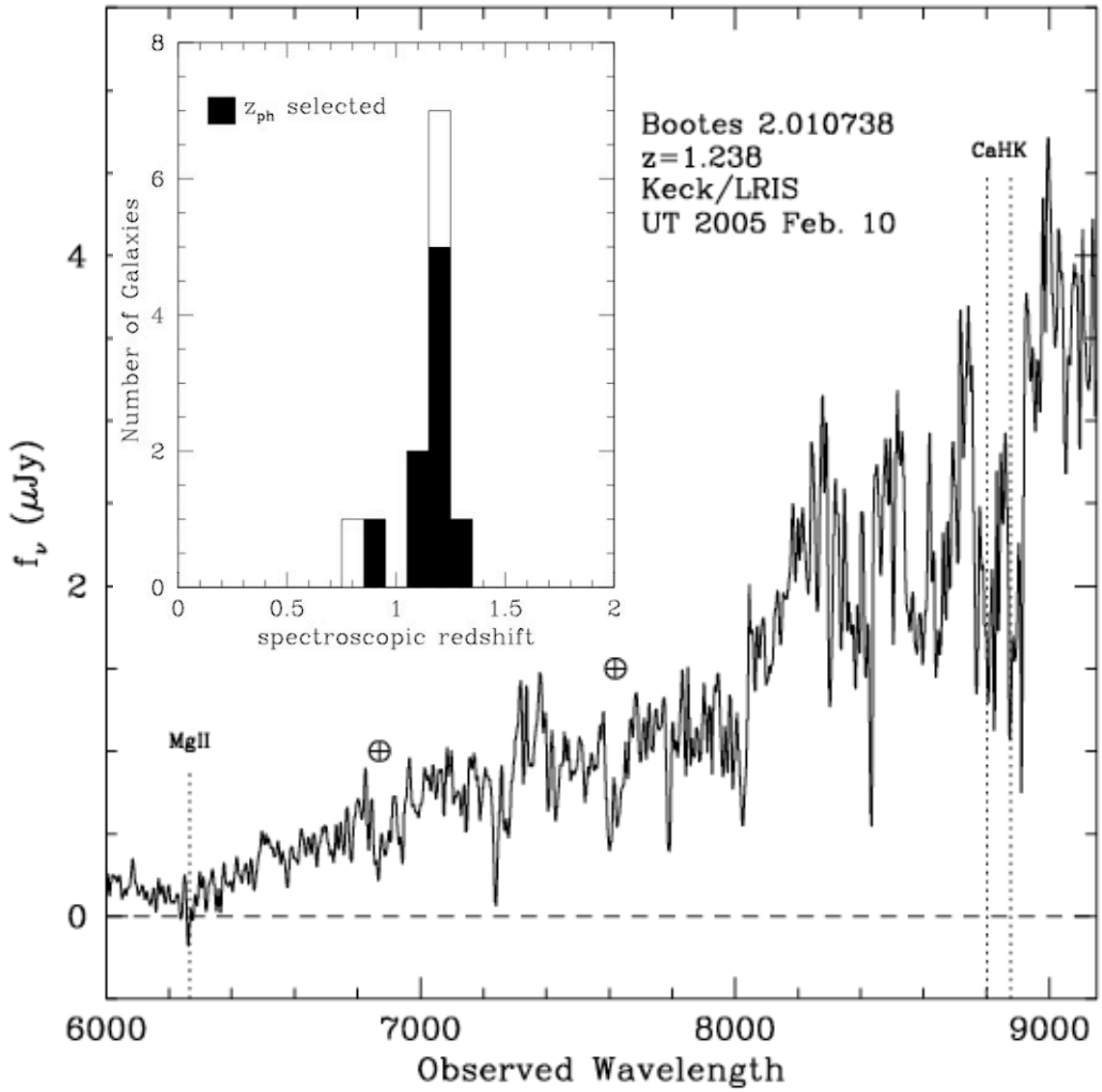




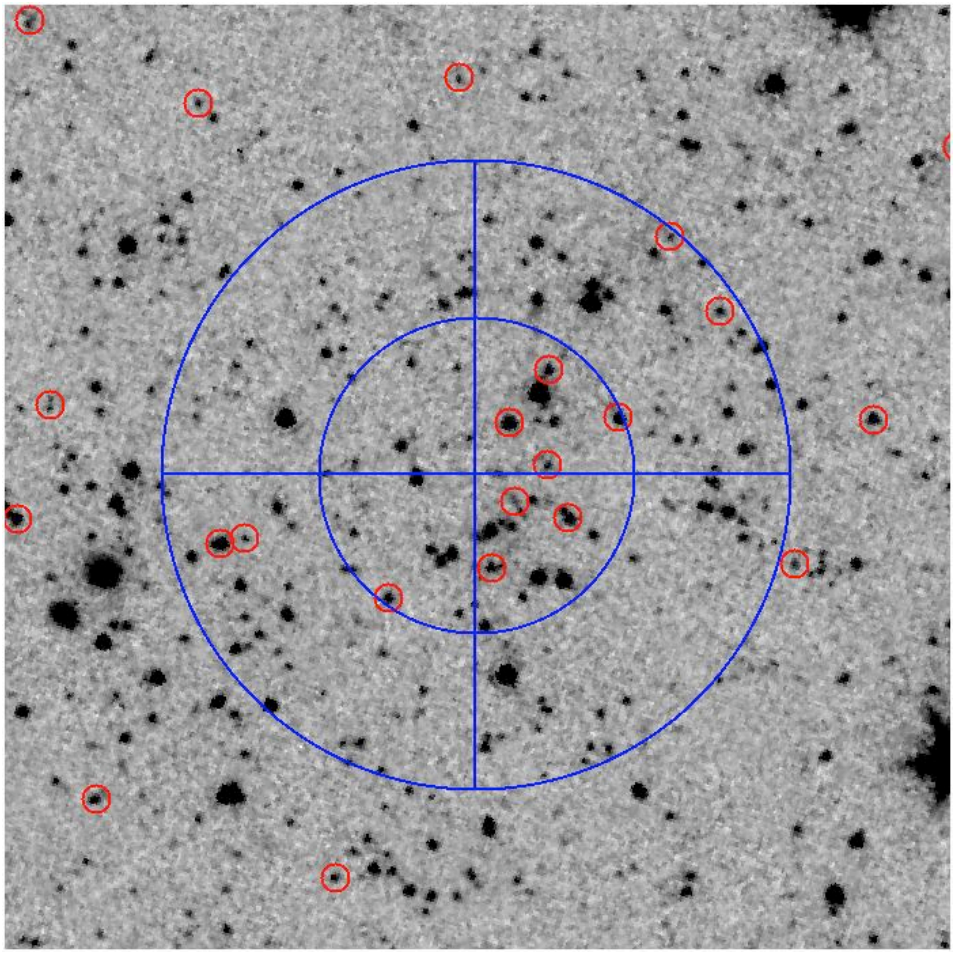

B_w
I
[4.5]

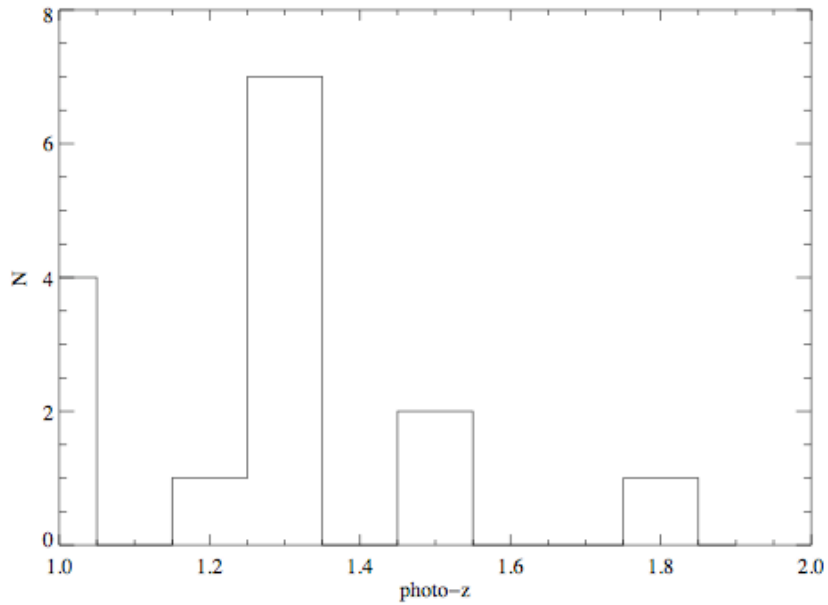
Spectroscopic <z> = 1.2 (courtesy Adam Stanford)

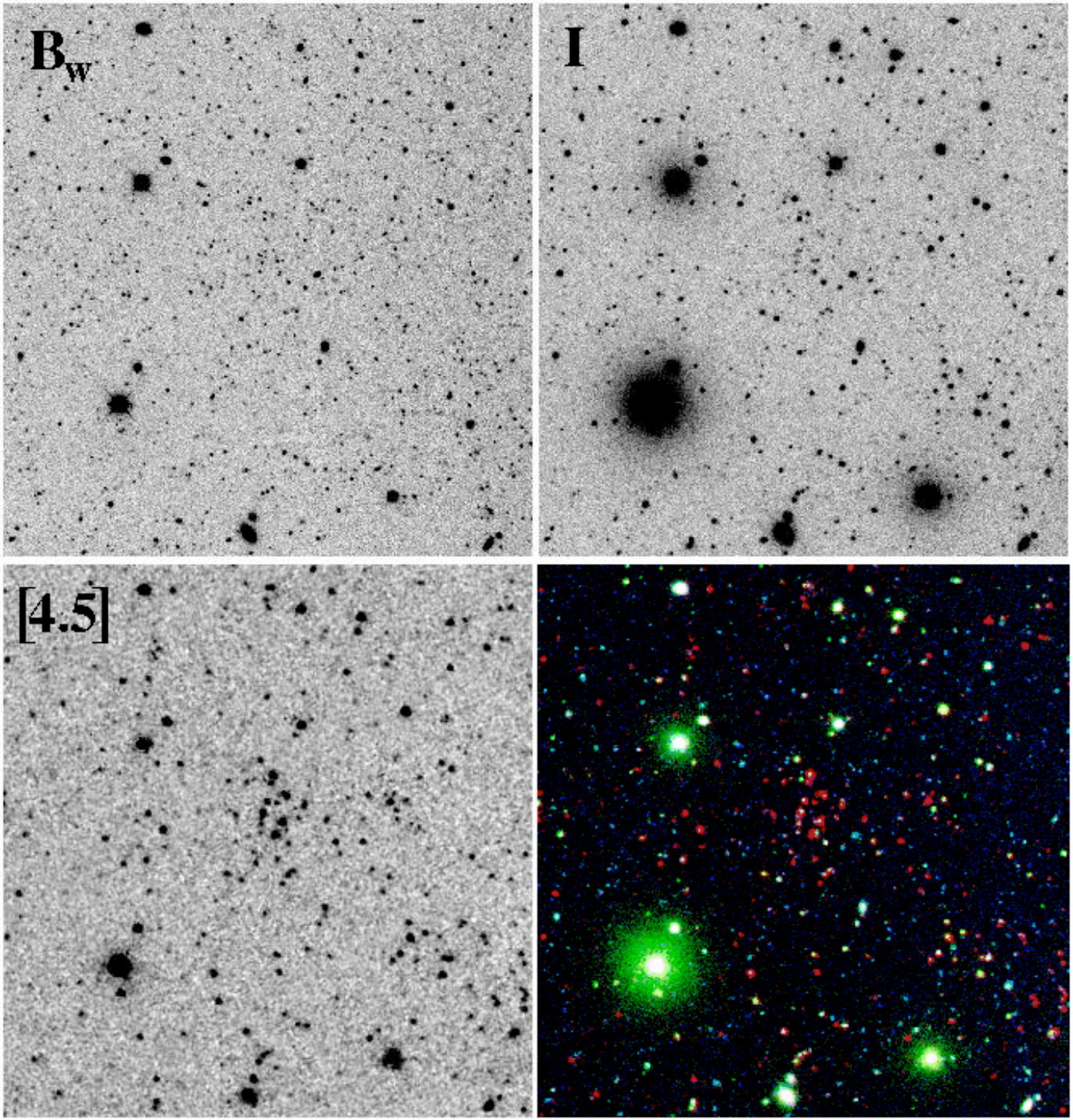




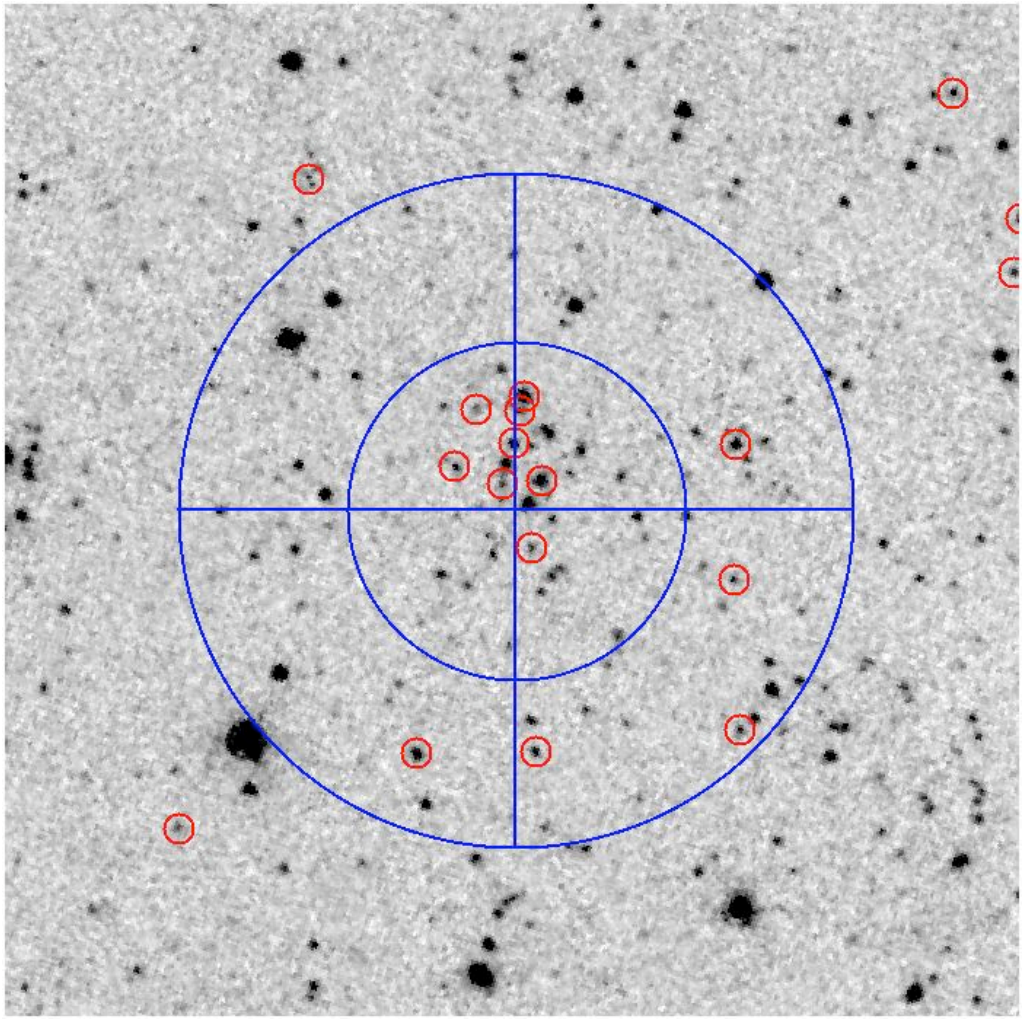
z ~ 1.3

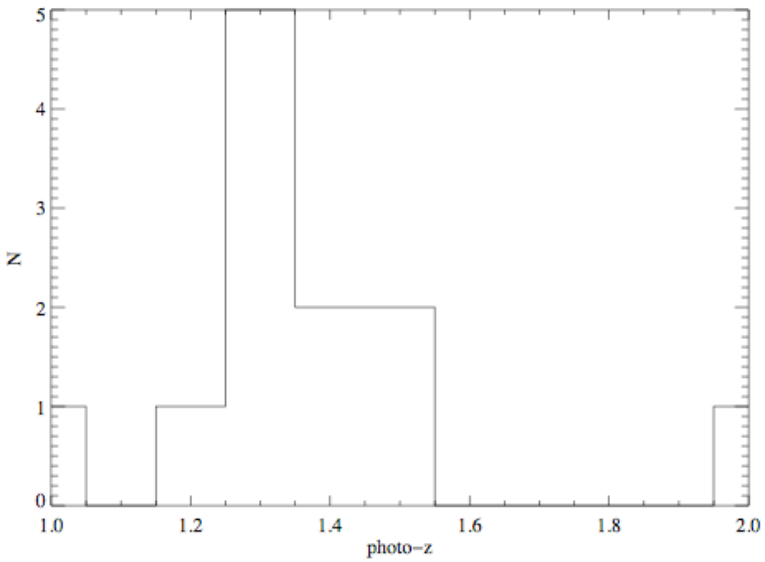




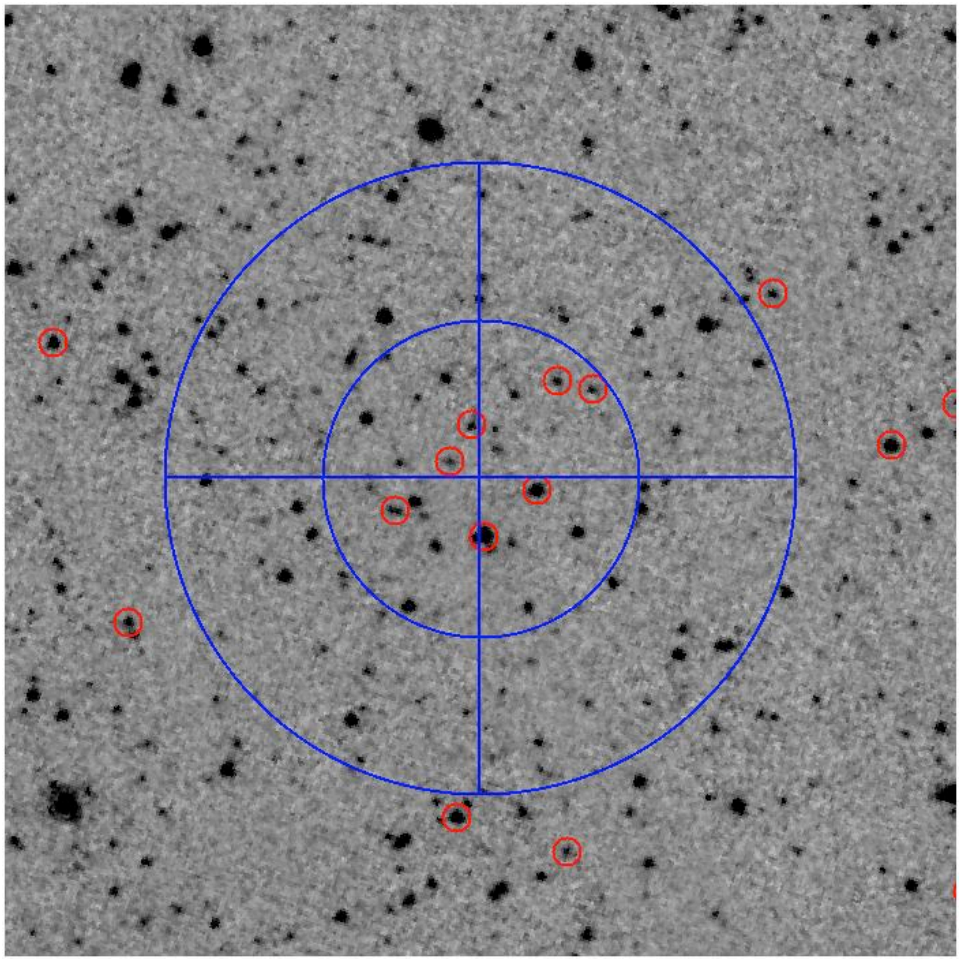

B_w
I
[4.5]

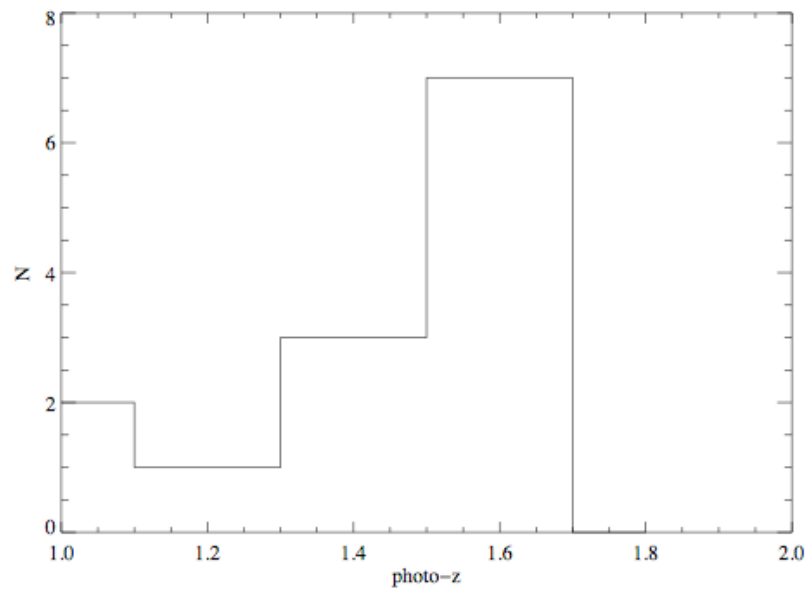
z ~ 1.4





z ~ 1.6



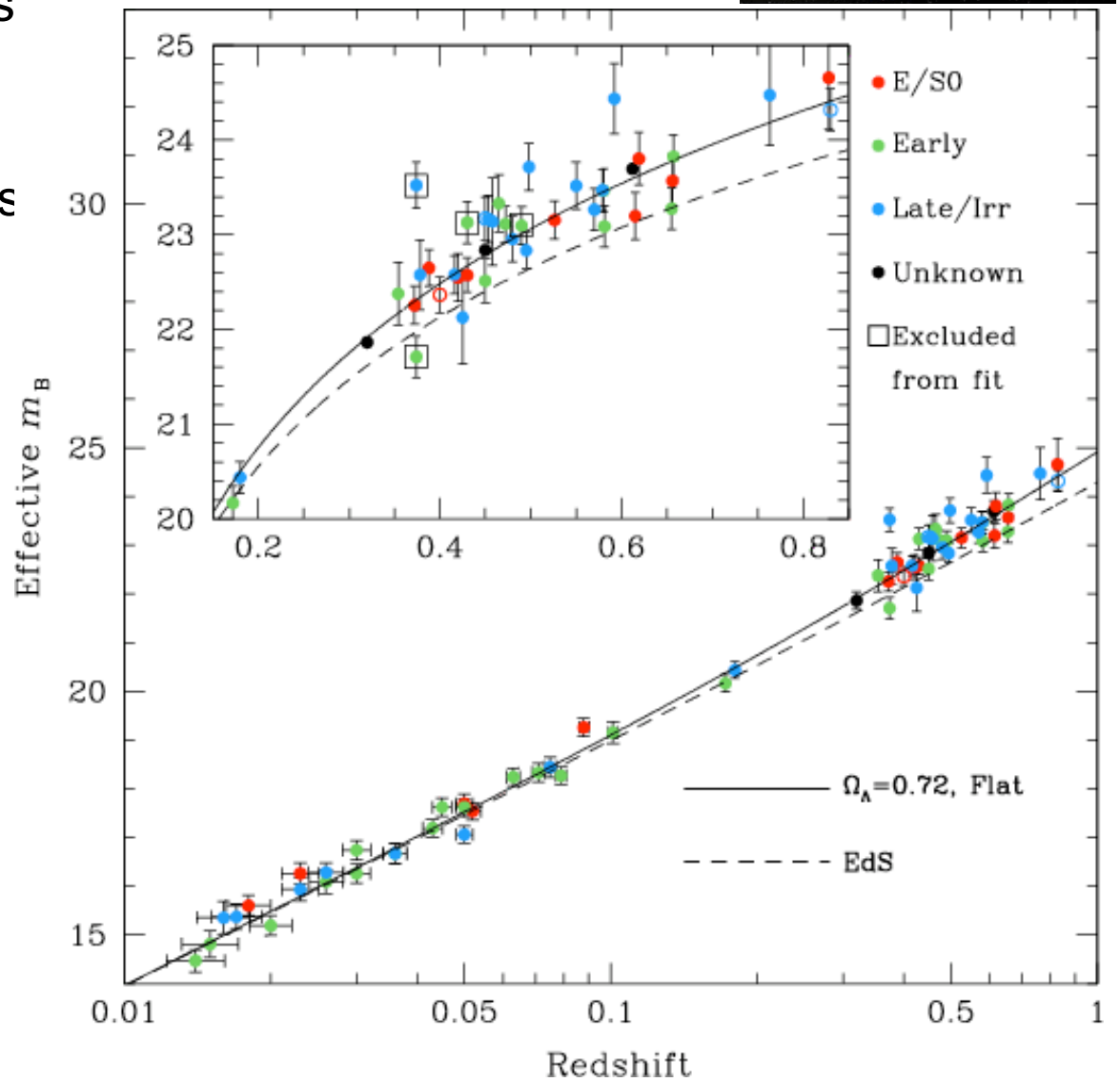


Candidate z > 1 clusters

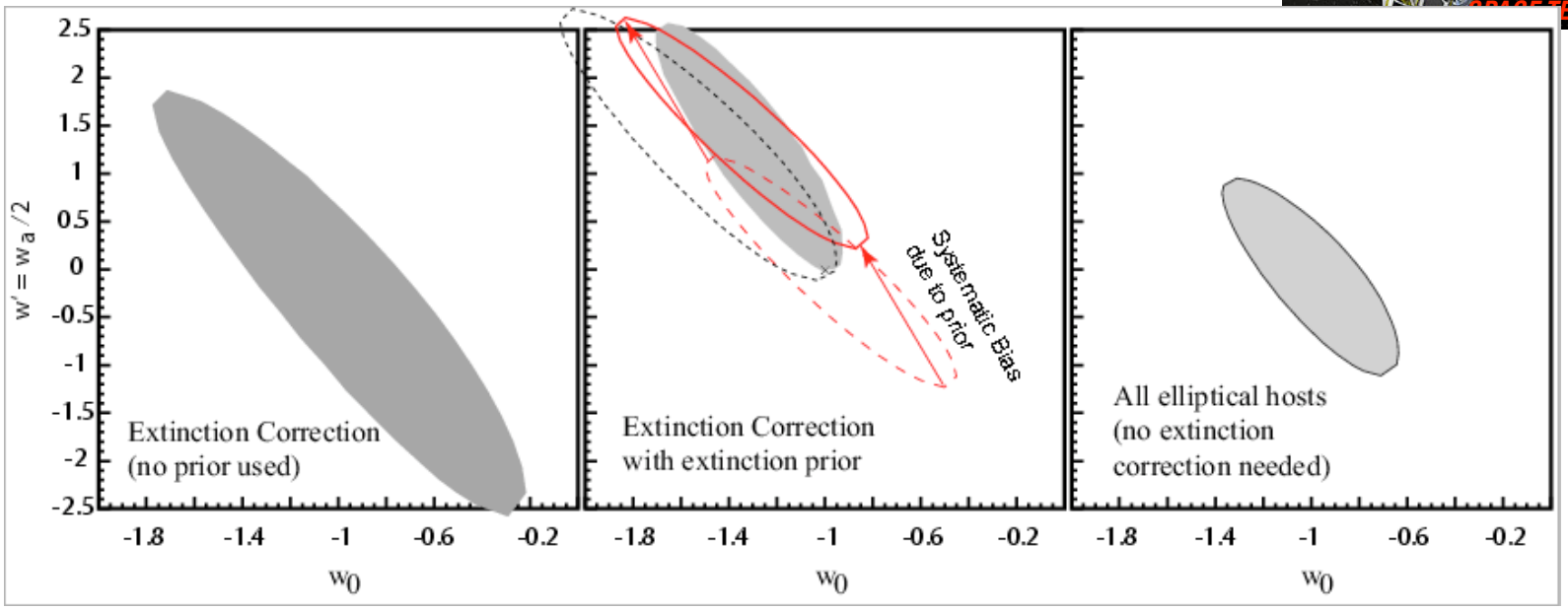
$\langle z_{ph} \rangle$	R < 0.5 Mpc			0.5 < R < 1 Mpc		
	N	M_{max}	<sed>	N	M_{max}	<sed>
1.09	16	4.5E+11	4.5	16	4.0E+11	8.4
1.13	7	6.8E+11	1.6	14	4.4E+11	7.0
1.26	8	4.2E+11	5.6	10	4.8E+11	6.4
1.36	9	4.2E+11	5.9	9	2.3E+11	6.2
1.59	7	7.5E+11	7.9	3	3.7E+11	11.0

Cosmology with Cluster SNe (Perlmutter)

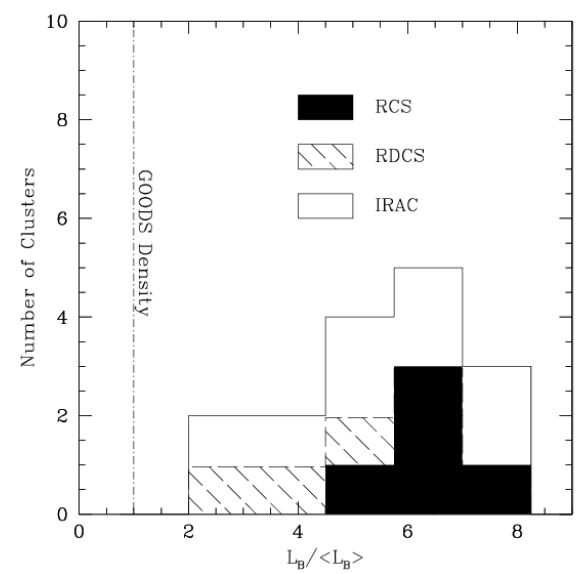
- Type Ia SNe in E/S0 hosts show much less scatter (Sullivan et al 2003).
- Each E/S0-hosted Ia SN is statistically worth many times those in later type hosts.



Cosmology with Cluster SNe



- Extinction corrections to SNe introduce uncertainty and bias in w', w_0 determination
- Elliptical-hosted SNe avoid this problem
- Galaxy clusters are 5x more likely to have elliptical-hosted z > 1 SNe than the field



Summary

- Clusters to z ~ 1 match PLE z_f=3 models
- Higher redshift things look redder
- The IRAC shallow survey (90s with 85cm telescope) detects L-band sources ~ 9,000 times faster while reaching ~ 5 times deeper than the deepest previous work with Keck
  - Advantage increases at longer wavelengths
- Clusters are being found to z ~ 1.6
  - "Morphology" (SED class) density relation present
  - <sed> increases (ie later types) with increasing z
  - Decline in numbers vs. z *may* be consistent with ΛCDM
    - Need to be careful about biases against high z clusters
- Clusters are good places to find lots of Type Ia SNe in low-dust hosts