IR-Selected Clusters at z > 1: Current Status and Future Prospects

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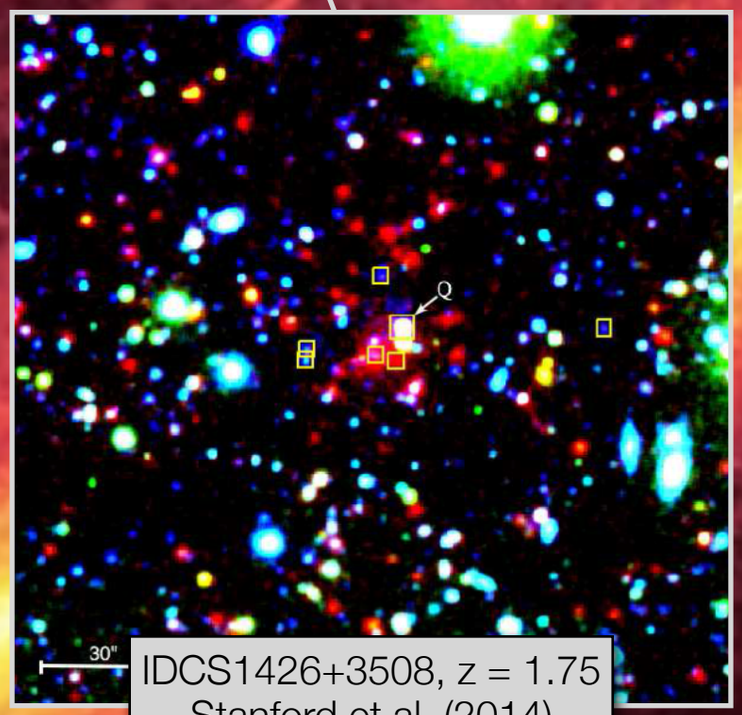
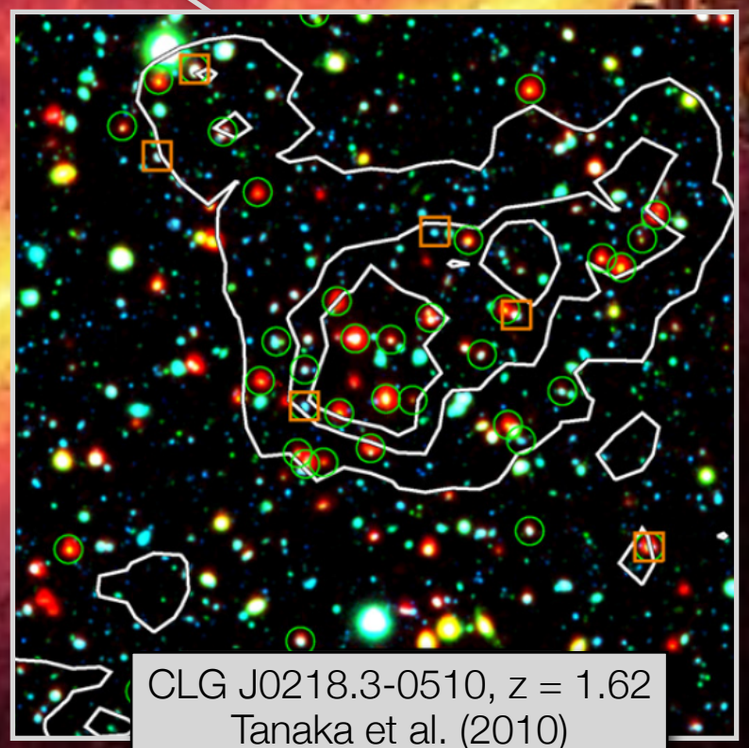
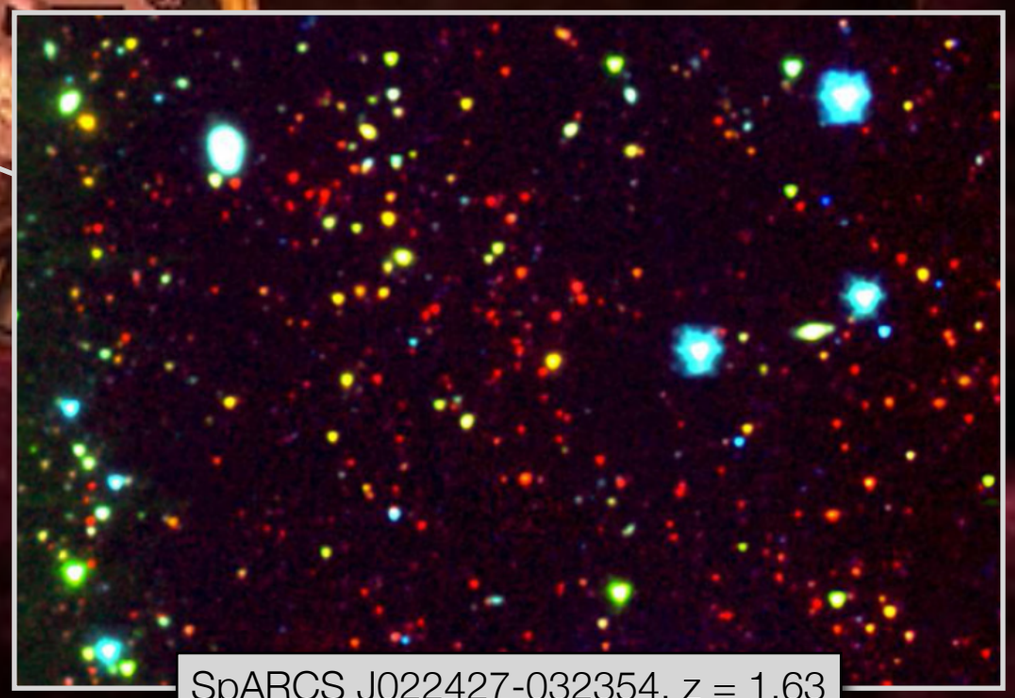


IDCS1426+3508, z = 1.75
Stanford et al. (2014)



CLG J0218.3-0510, z = 1.62
Tanaka et al. (2010)
Papovich et al. (2010)



SpARCS J022427-032354, z = 1.63
Muzzin et al. (2013)

Two things I need to say…

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1. THANK YOU!

2. I'M SORRY!

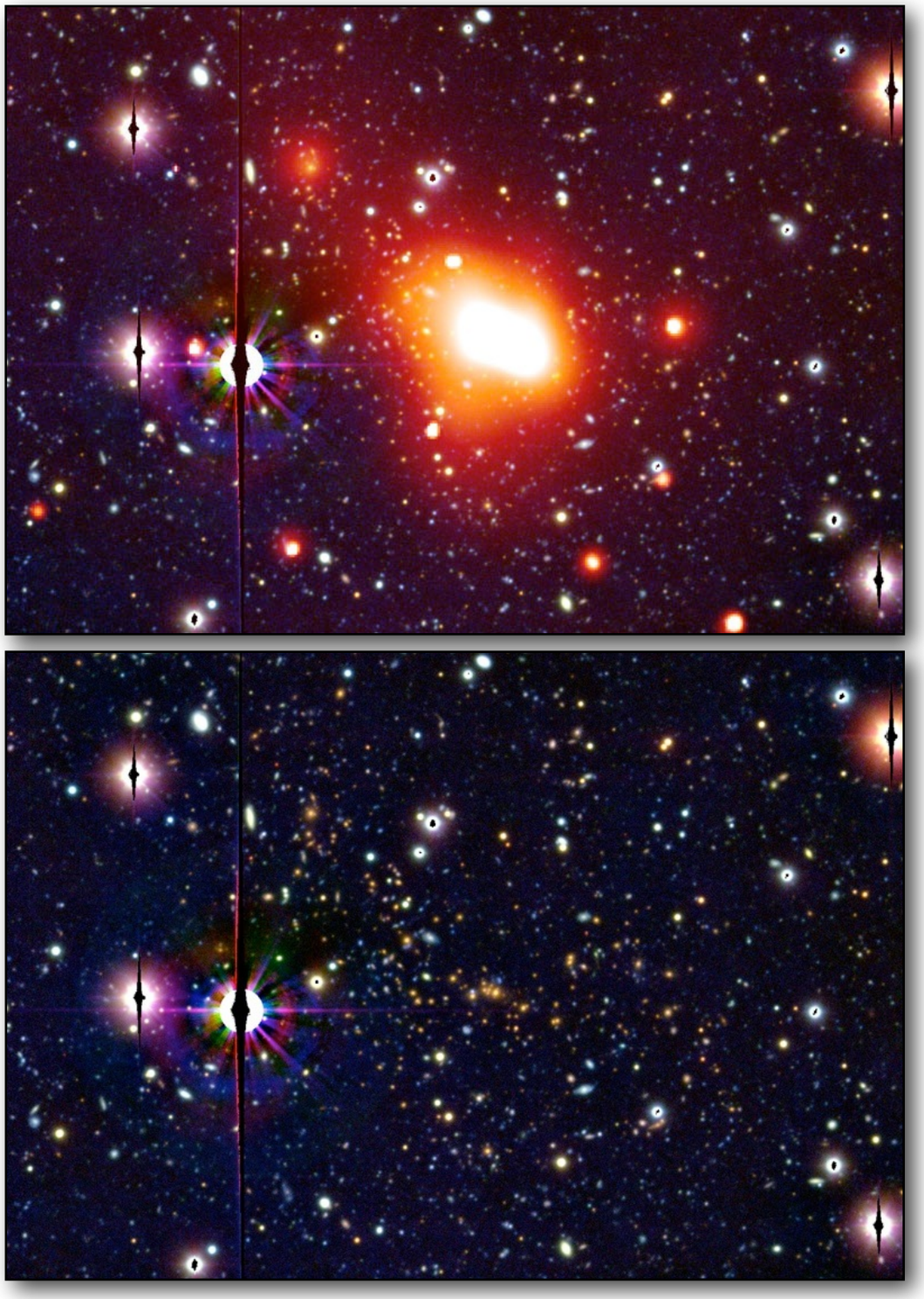
The Two Major “Signposts” for Distant Clusters

1. Hot Cluster Gas

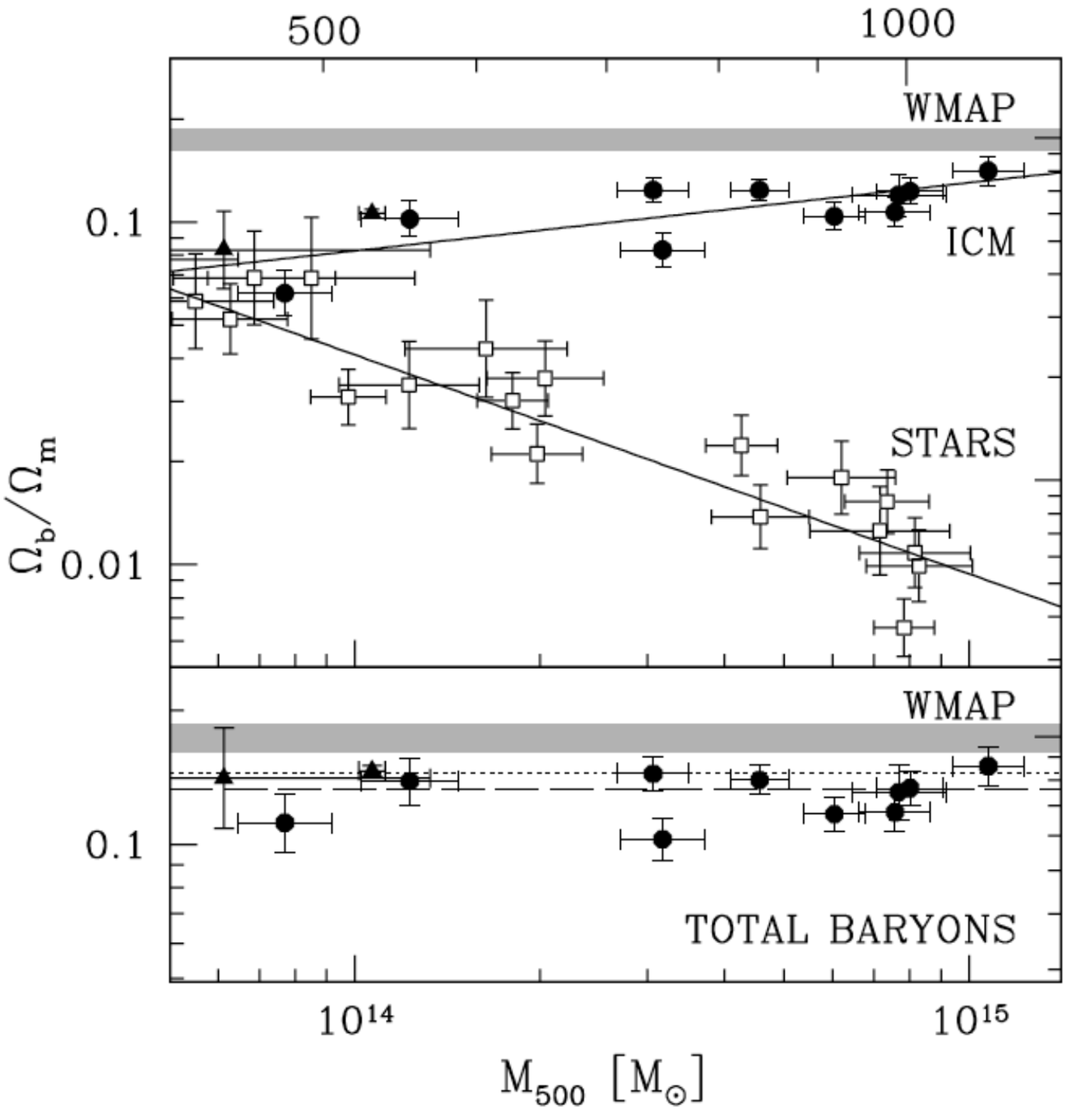
- X-ray surveys
- Sunyaev-Zeldovich Effect

2. Overdensities of Galaxies

- Color-selection methods
- Photometric redshifts



Why Select Galaxy Clusters on Galaxies (IR)?



Gonzalez+2007

- Low-mass clusters/groups contain as much stars as hot gas
- There is a scatter in gas/stellar content
- Selecting on gas and stars provides more comprehensive samples
- **Detection of high-redshift clusters is still easier for IR selection compared to X-ray/SZ**

Several Advances in the Last 10 Years Have Made IR Cluster Selection Possible…

1. Launch of the Spitzer Telescope in 2004

2. Launch of the Spitzer Telescope in 2004

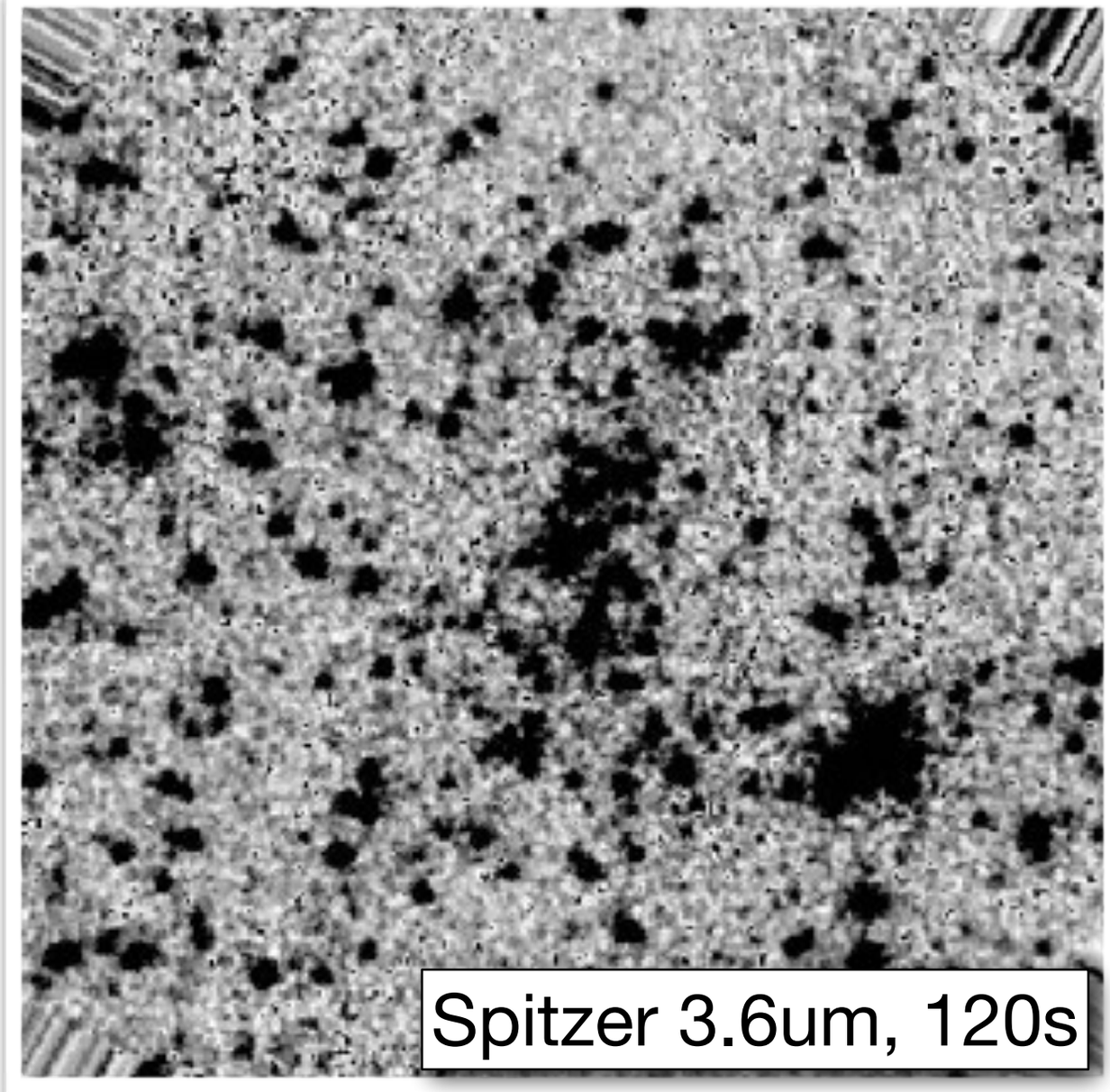
3. Launch of the Spitzer Telescope in 2004

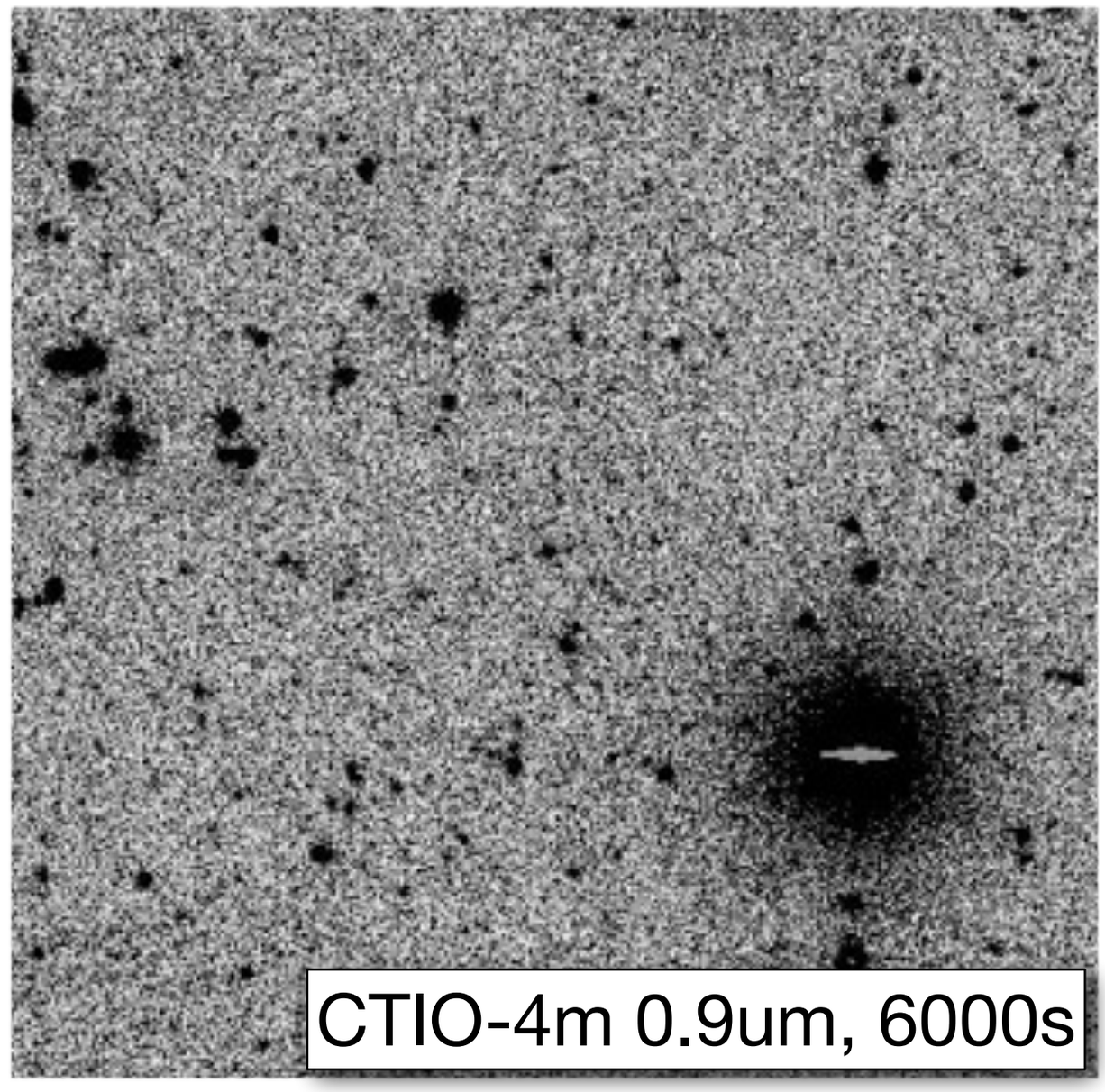
IR Cluster Selection is Driven 95% by Spitzer Surveys

- Cluster galaxies are RED, need an IR telescope to detect them at $z > 1$
- Spitzer is the most efficient IR survey telescope

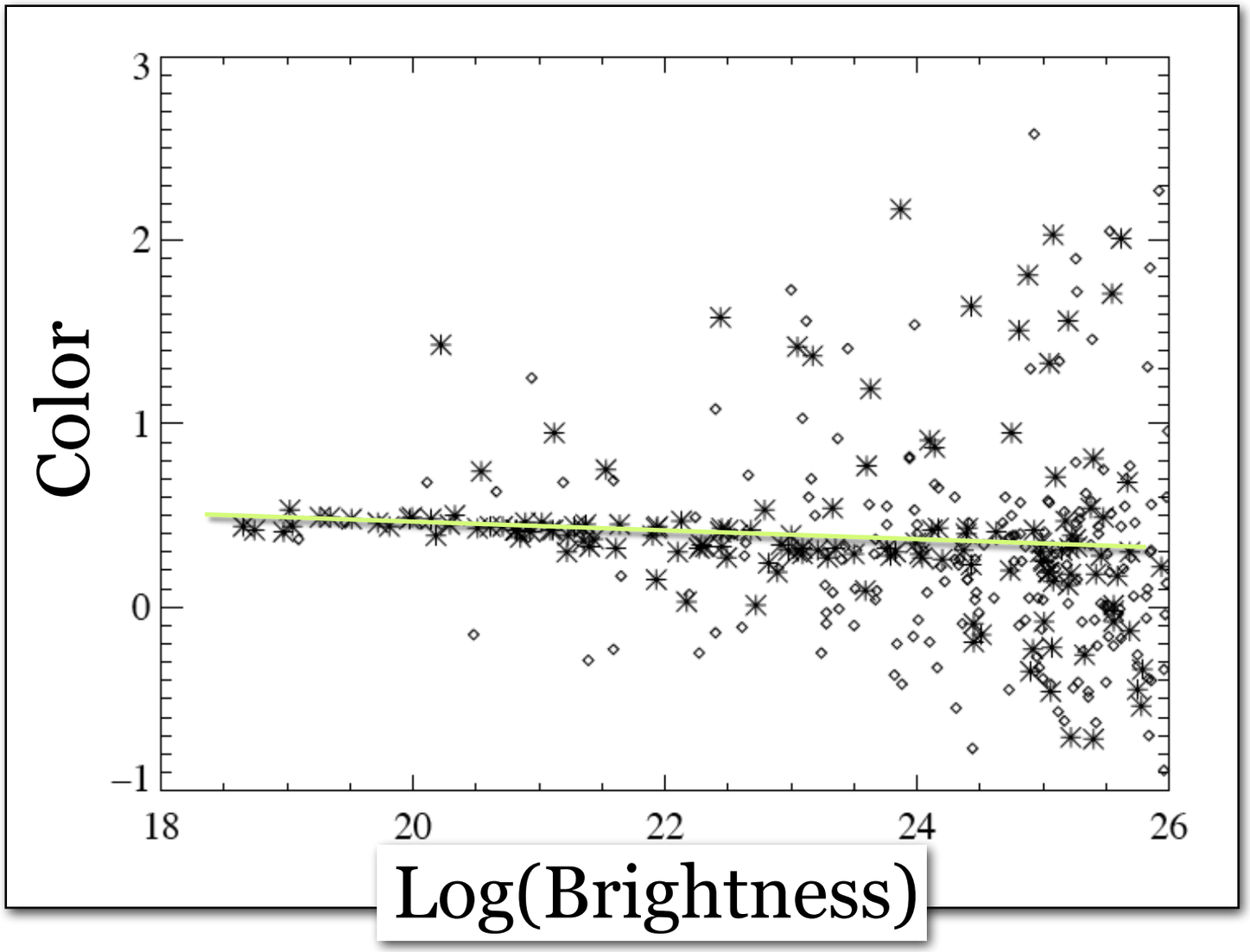
z > 1 Clusters in the Optical vs. IR

SpARCS J003550-431224, z = 1.335





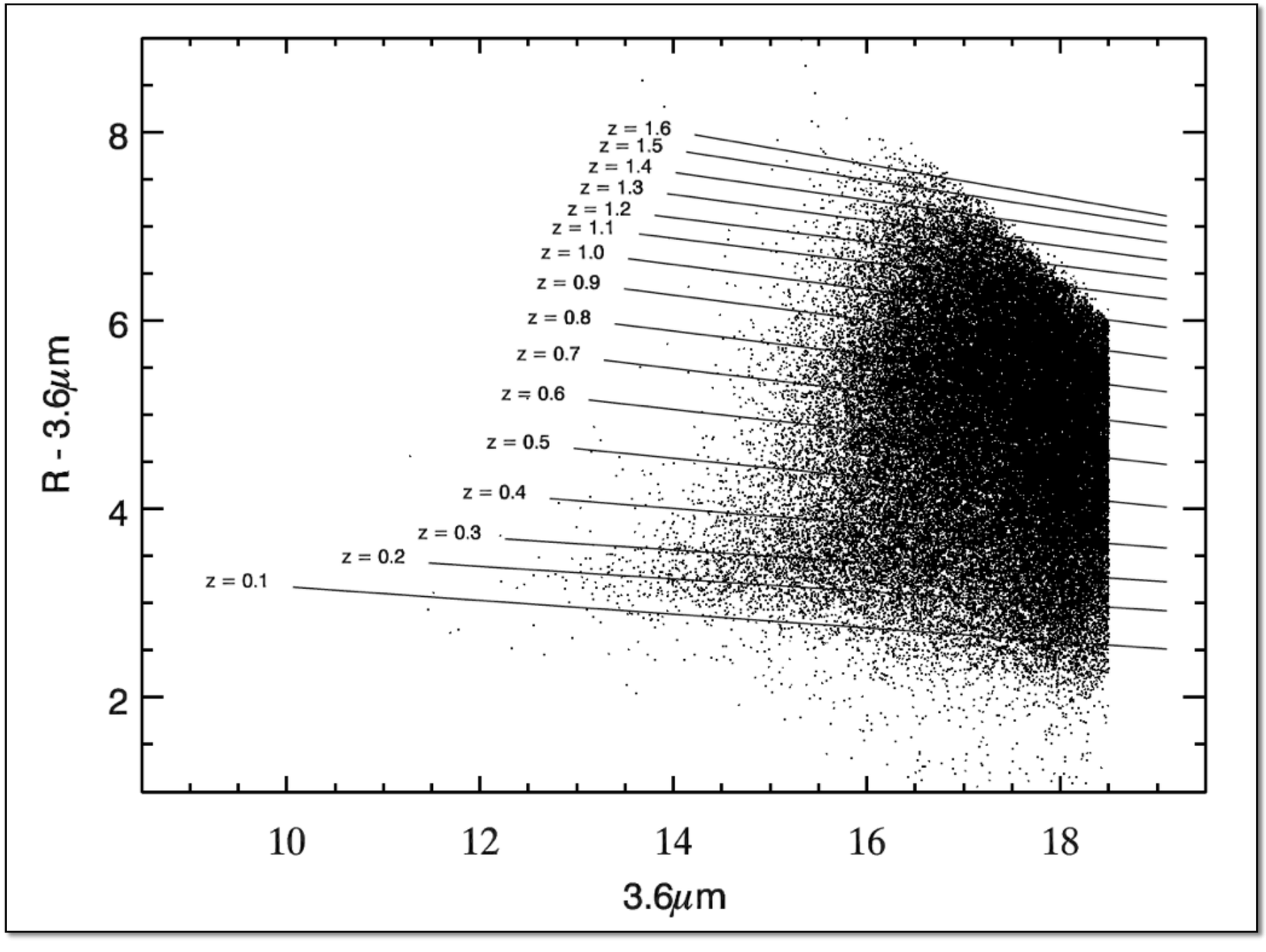
Quick Illustration of Optical/IR Cluster Selection



Abell 2390, z = 0.22
Gladders et al. (1998)

- Cluster galaxy populations show a “red-sequence” due to the dominance of old and dead galaxies
- Two filter imaging is an efficient way to find galaxy clusters!

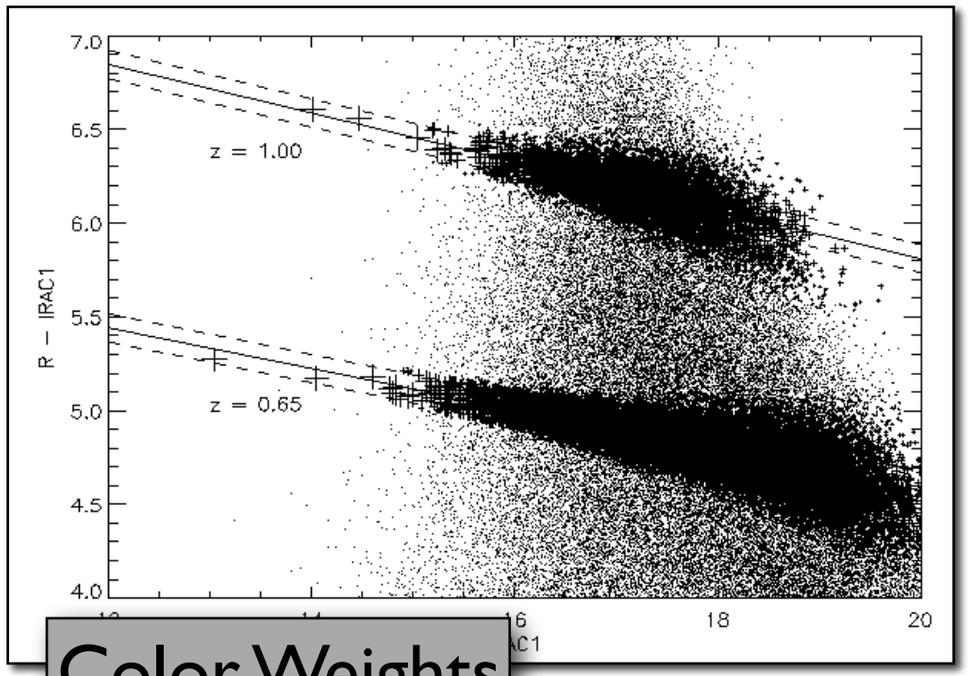
Quick Illustration of Optical/IR Cluster Selection

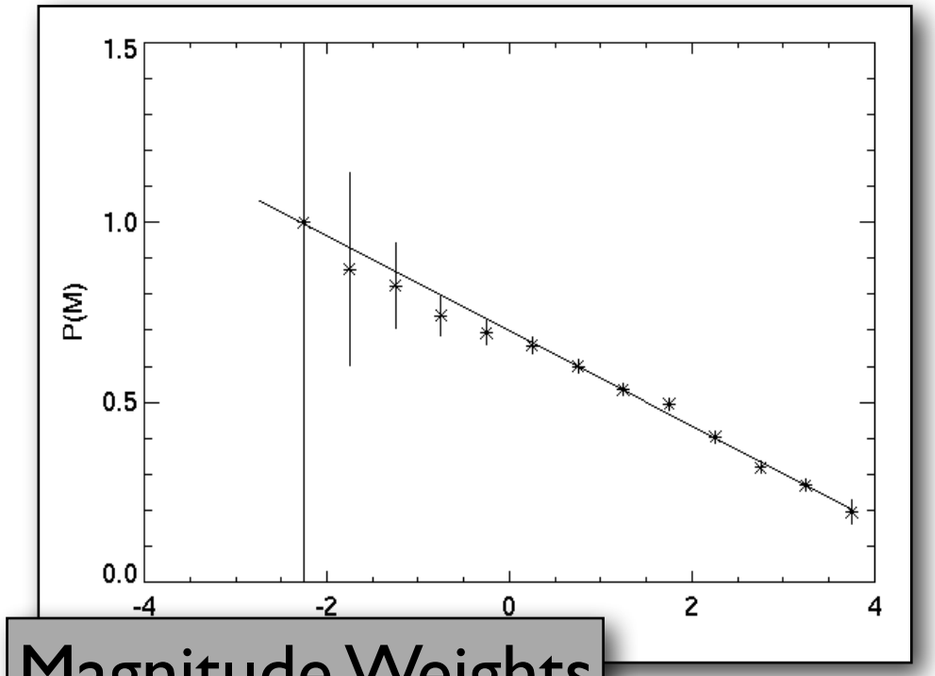


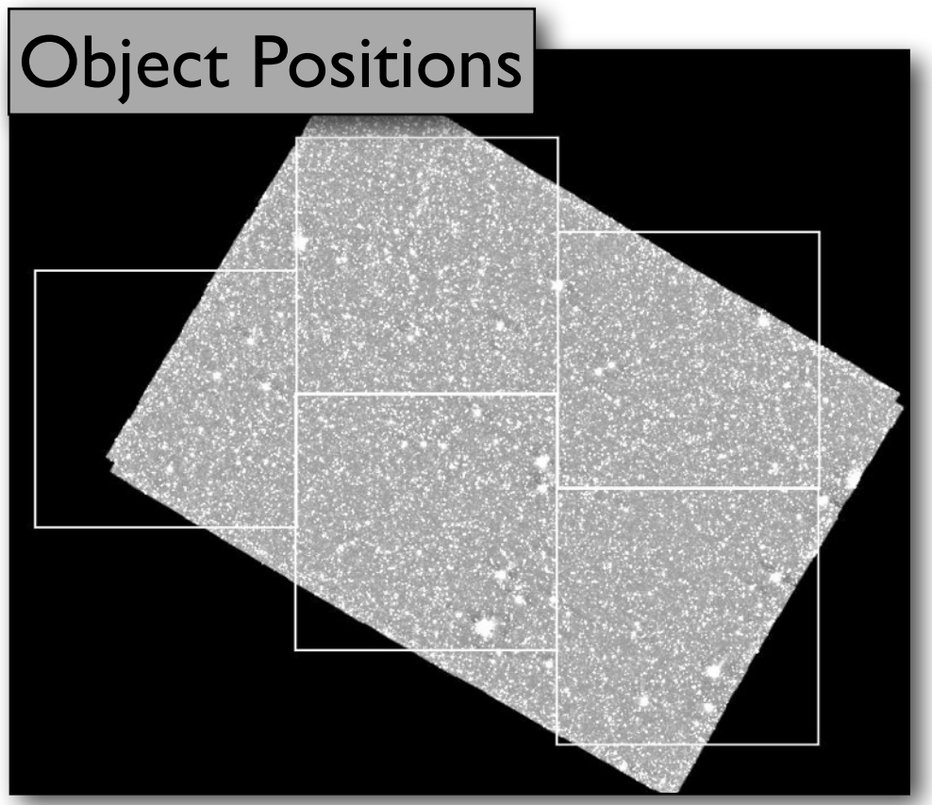
- Color-magnitude diagram of all galaxies in 4 deg survey
- Model red-sequences from BC03 passively evolving galaxy calibrated to Coma cluster CMR

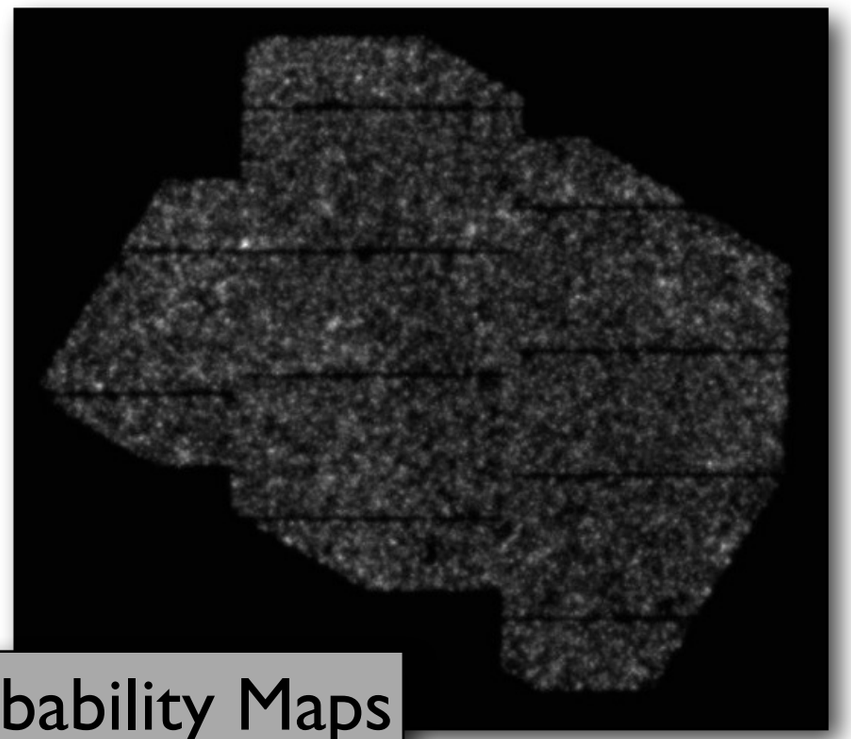
Muzzin+2008

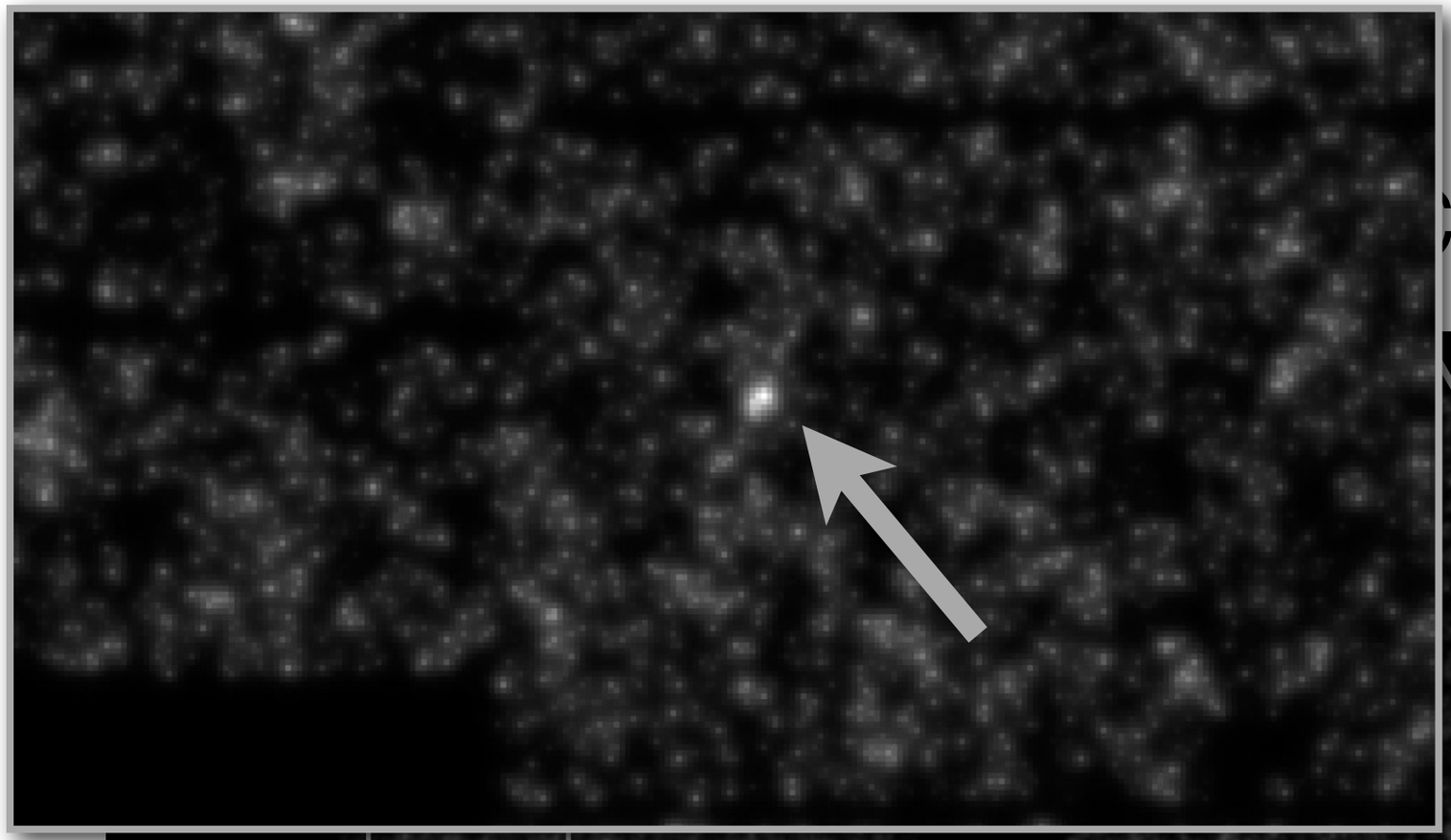
Quick Illustration of Optical/IR Cluster Selection

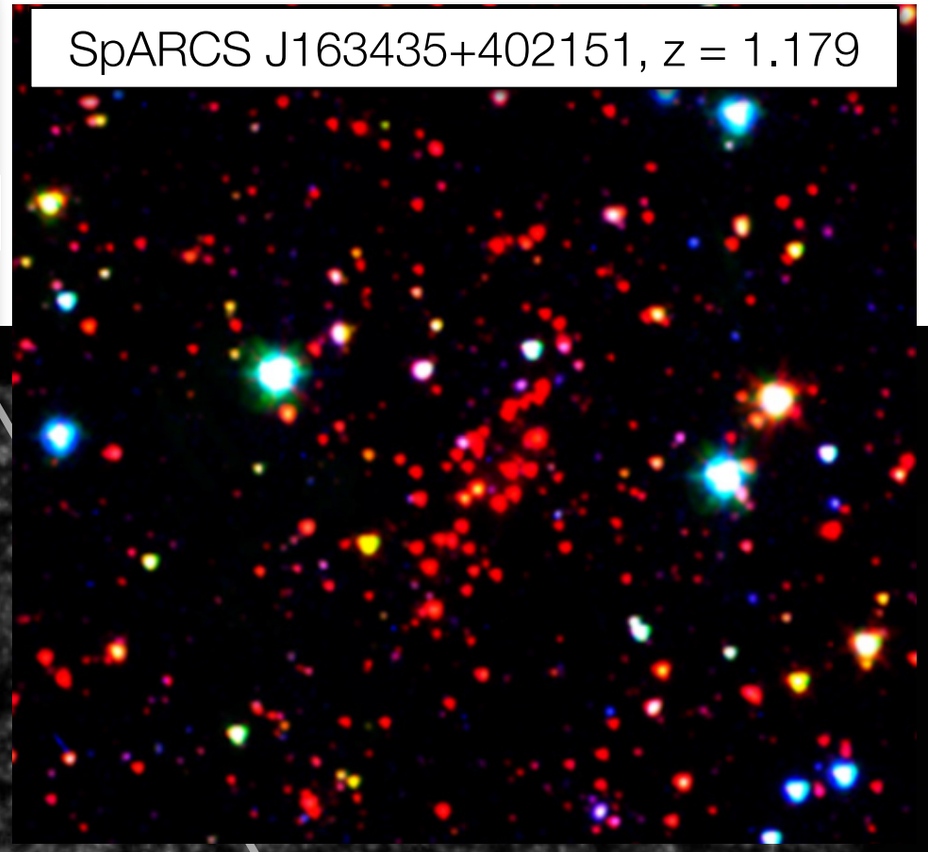











SpARCS J163435+402151, z = 1.179

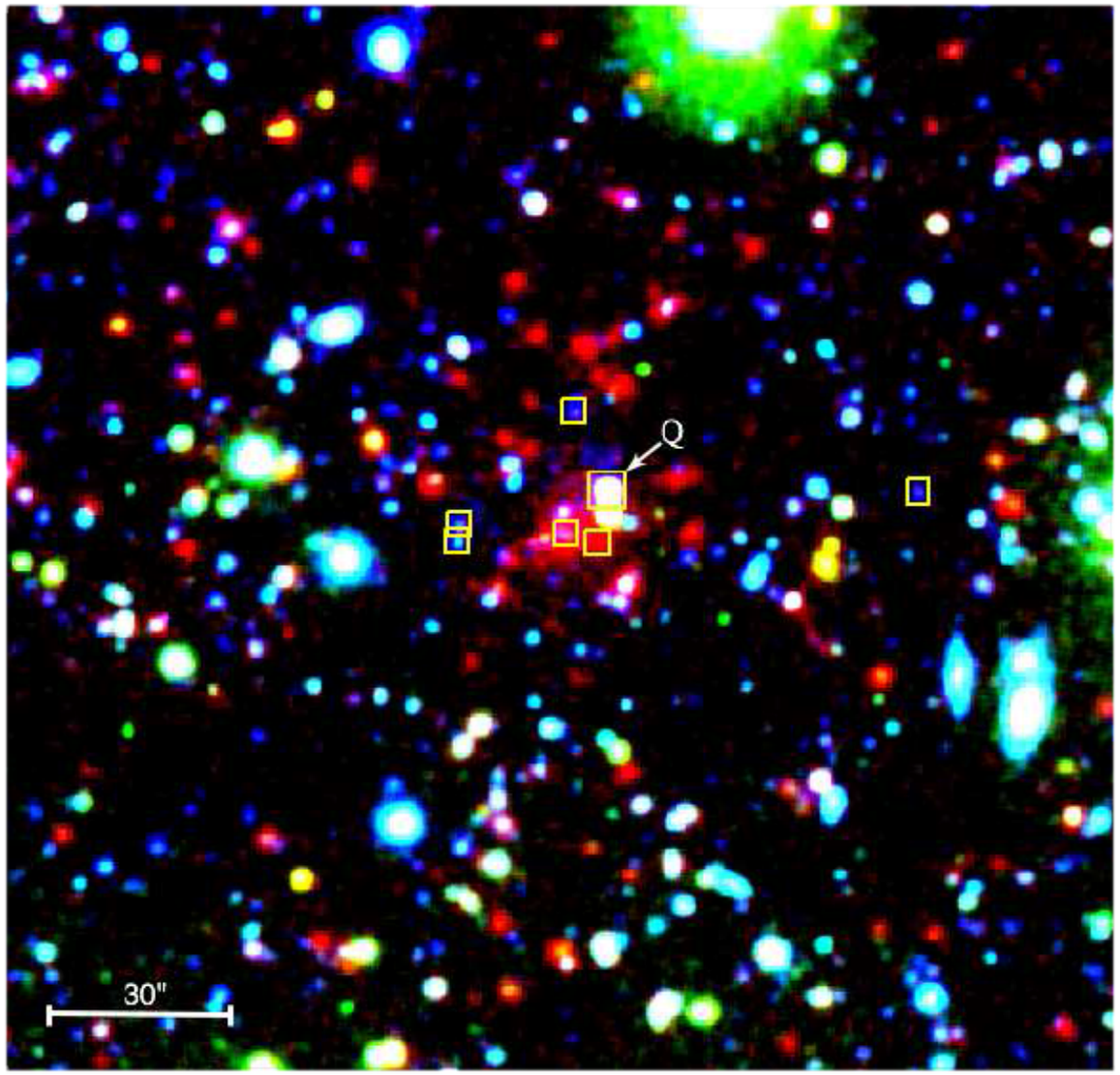
SpARCS J163852+403843, z = 1.196

Spitzer Surveys for Distant Clusters

- IRAC Shallow Cluster Survey (ISCS) - Eisenhardt et al. (2008), **8 Degree^2**
- Spitzer Adaptation of the Red Sequence Cluster Survey (SpARCS) - Muzzin et al. (2009), Wilson et al. (2009), **42 Degree^2**
- Spitzer SWIRE Survey - Papovich et al. (2008, 2010), **50 Degree^2**
- Spitzer Hetdex Exploratory Large Area Survey (SHELA)- Papovich et al. (2016), **35 Degree^2**
- Spitzer SPT Deep Field (SSDF) - Rettura et al. (2013), **100 Degree^2**
- Clusters Around Radio-Loud AGN (CARLA) - Wylezalek et al. (2013), **4 Degree^2**
- Various other small field successes (COSMOS, zFOURGE), **3 Degree^2**

Total Area Surveyed by Spitzer~ 200 Degree^2

The IRAC Shallow Cluster Survey (ISCS)



IDCS1426+3508, z = 1.75
Stanford et al. (2014)

- Clusters detected using optical +IRAC photometric redshift over densities
- 8 Square Degrees in NOAO Bootes Deep Wide-field Survey
- 15 clusters spectroscopically confirmed at $z > 1$
- Highest-redshift cluster, $z = 1.75$, Stanford et al. (2014)

Stanford+2005, Brodwin+2006, Eisenhardt+2008, Mancone+2010, Stanford+2012, Brodwin+2013, Zeimann+2013, Alberts+2014, Stanford+2014, Gonzalez+2015, Brodwin+2016, Mo+2016, Alberts+2016

The Spitzer Adaptation of the Red Sequence Cluster Survey (SpARCS)

Astronomers find galaxy cluster with bursting heart

Hubble, Spitzer, and the Canada-France-Hawaii Telescope join forces for rare cosmic find

10 September 2015

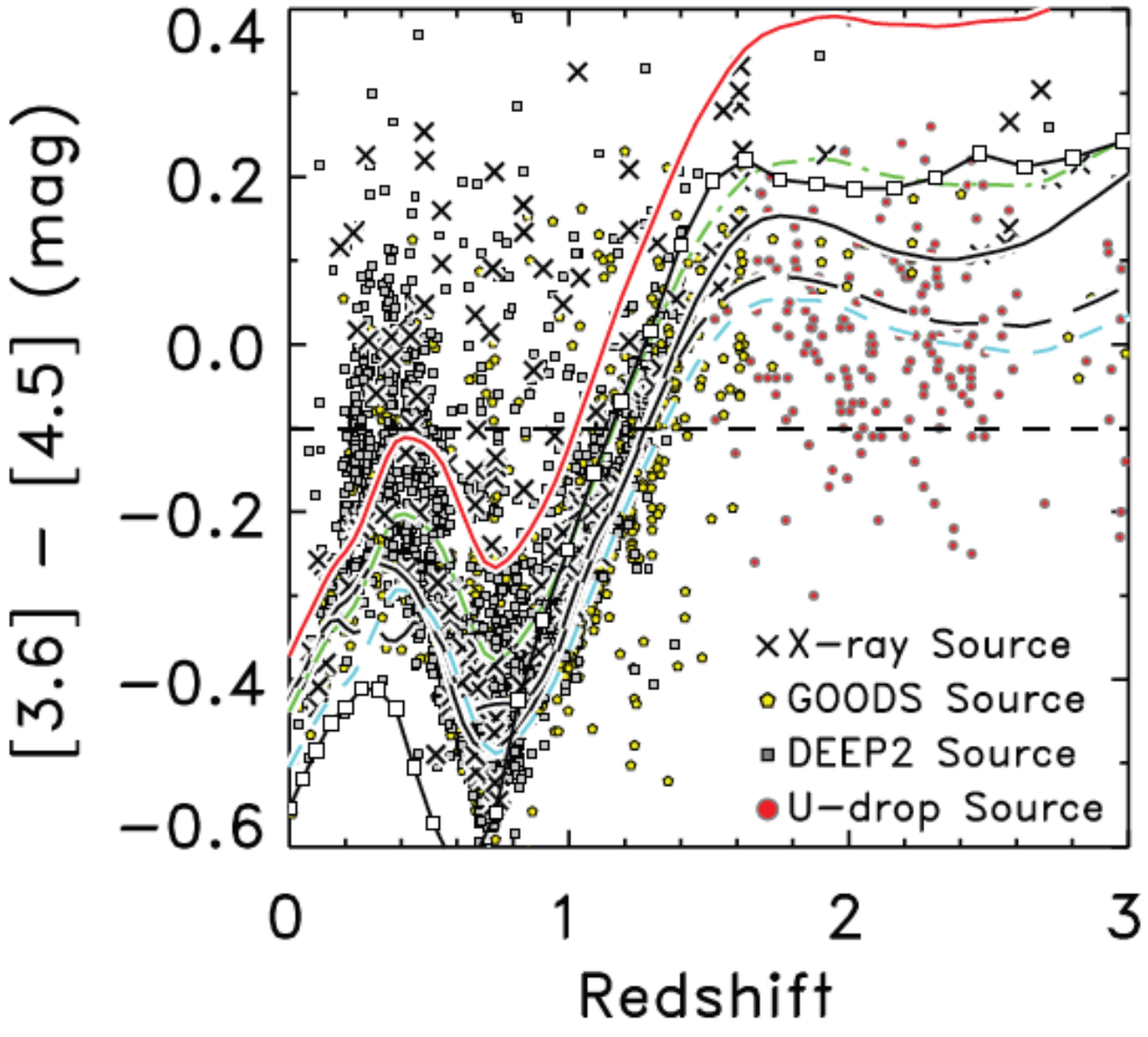
An international team of astronomers has discovered a gargantuan galaxy cluster with a core bursting with new stars — an incredibly rare find. The discovery, made with the help of the NASA/ESA Hubble Space Telescope, is the first to show that gigantic galaxies at the centres of massive clusters can grow significantly by feeding off gas stolen from other galaxies.

SpARCS J104922+564032, z = 1.70
Webb et al. (2015)

- Clusters detected using red-sequence selection moved to z' - 3.6um color selection
- 42 square degree survey of the Spitzer SWIRE fields
- 12 clusters spectroscopically confirmed at z > 1
- Highest-redshift cluster, z = 1.70, Webb et al. (2015)

Muzzin+2009, Wilson+2009, Demarco+2010, Hildebrandt+2011, Muzzin+2012, Lidman+2012, Muzzin+2013, Lidman+2013, van der Burg+2013, Muzzin+2014, van der Burg+2014, Webb+2015a, 2015b, Nantais+2016

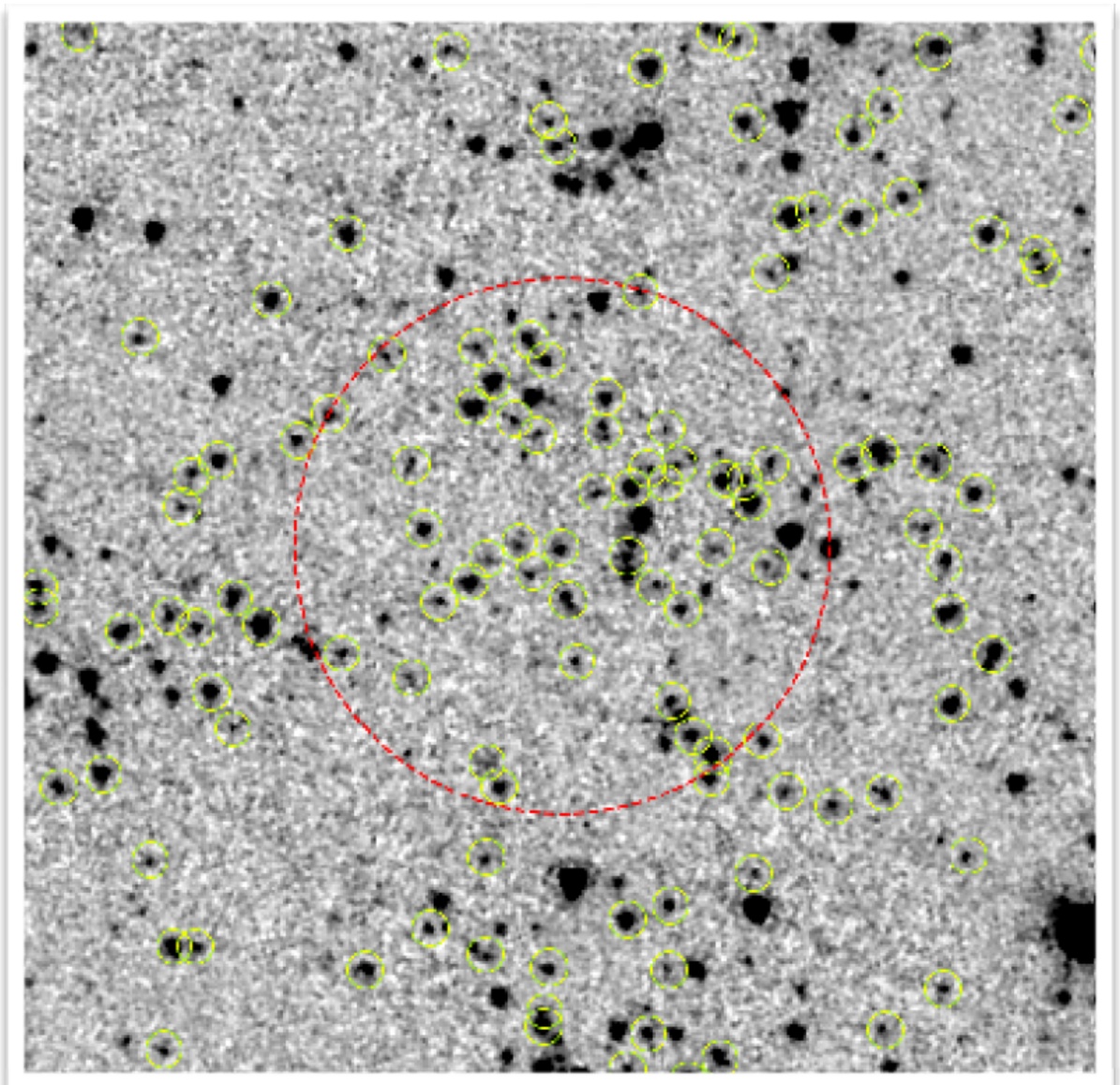
Spitzer SWIRE Survey



- Clusters detected using pure IRAC 3.6um - 4.5um color selection
- 50 square degree survey of the Spitzer SWIRE fields
- 1 clusters spectroscopically confirmed at $z > 1$
- Highest-redshift cluster, $z = 1.62$, Papovich et al. (2010)

Papovich+2008, Papovich+2010, Tran+2010, Papovich+2012, Rudnick+2012, Pierre+2012, Tadaki+2012, Lotz+2013, Bassett+2013, Wong+2014

The Spitzer SPT Deep Field (SSDF)

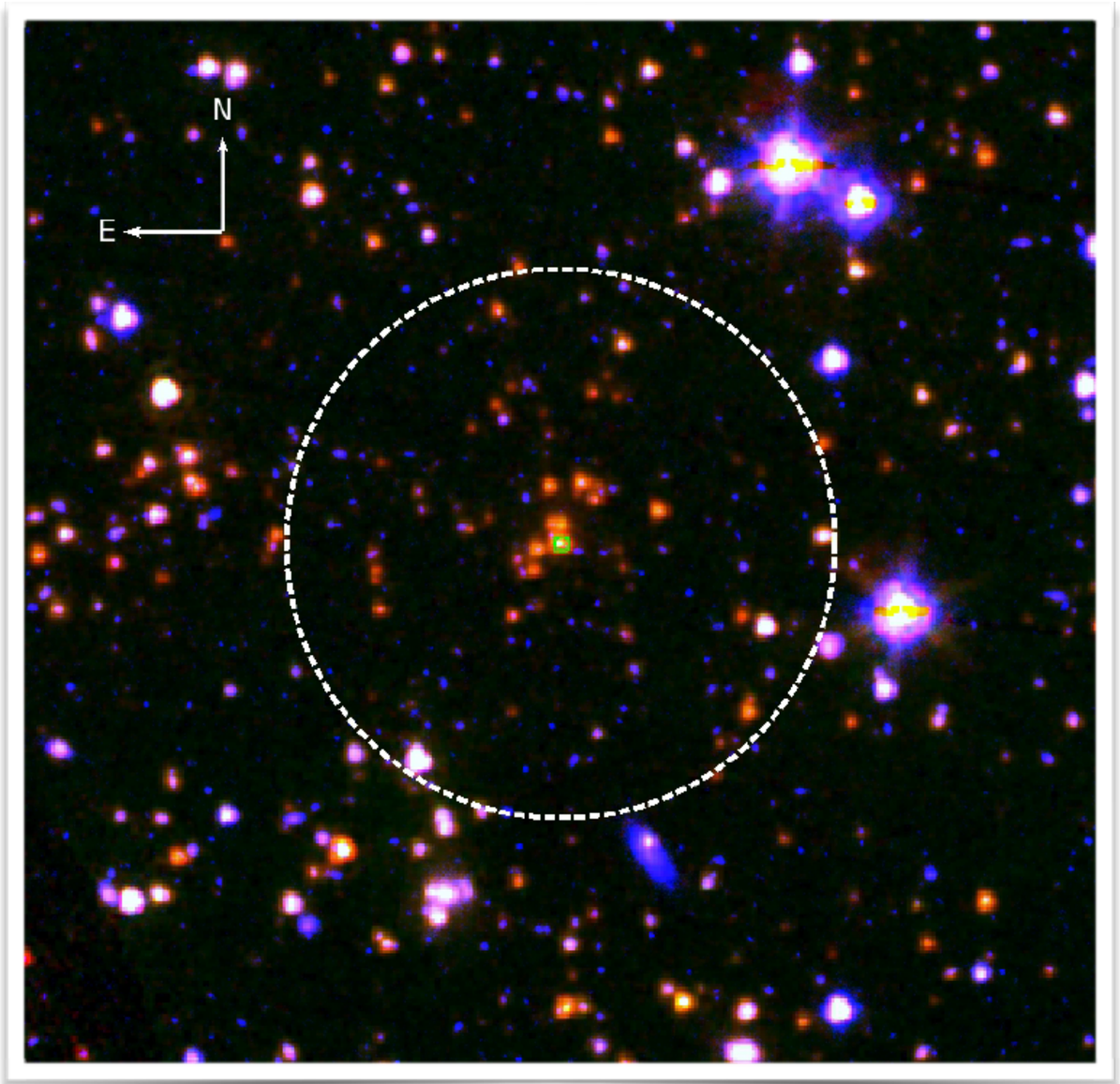


SSDF J2339-5531, z > 1.3
Rettura et al. (2013)

- Clusters detected using pure IRAC 3.6um - 4.5um color selection from Papovich
- 100 square degree survey of the SPT field and XXL southern field
- 10 Candidates published, 0 clusters spectroscopically confirmed at z > 1 (so far)

Talk by Alessandro Rettura

Clusters Around Radio-Loud AGN (CARLA)

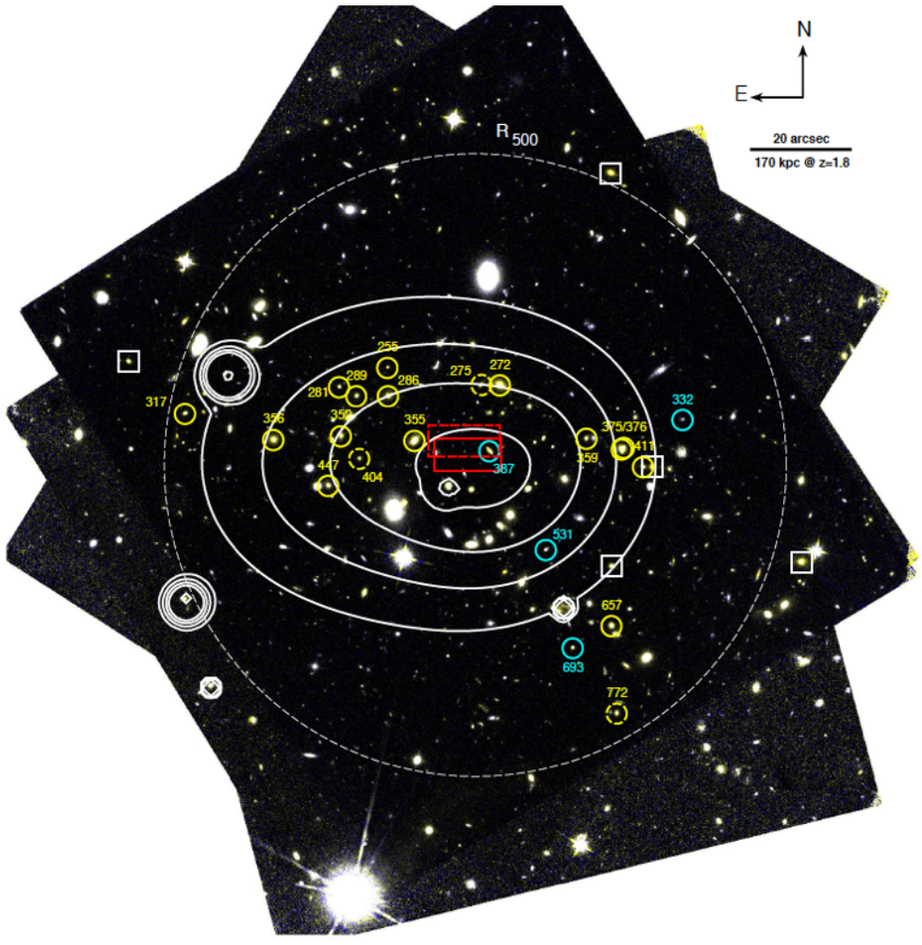


CARLA J1753+6311, z = 1.58
Cooke et al. (2016)

- Clusters detected using pure IRAC 3.6um - 4.5um color selection
- 400 individual radio galaxies surveyed, 200 candidate clusters
- 2 clusters spectroscopically confirmed at $z > 1$
- Highest-redshift cluster, $z = 1.58$, Cooke et al. (2016), Rettura et al. (2016)
- Several more confirmations at $z > 2$ near submission

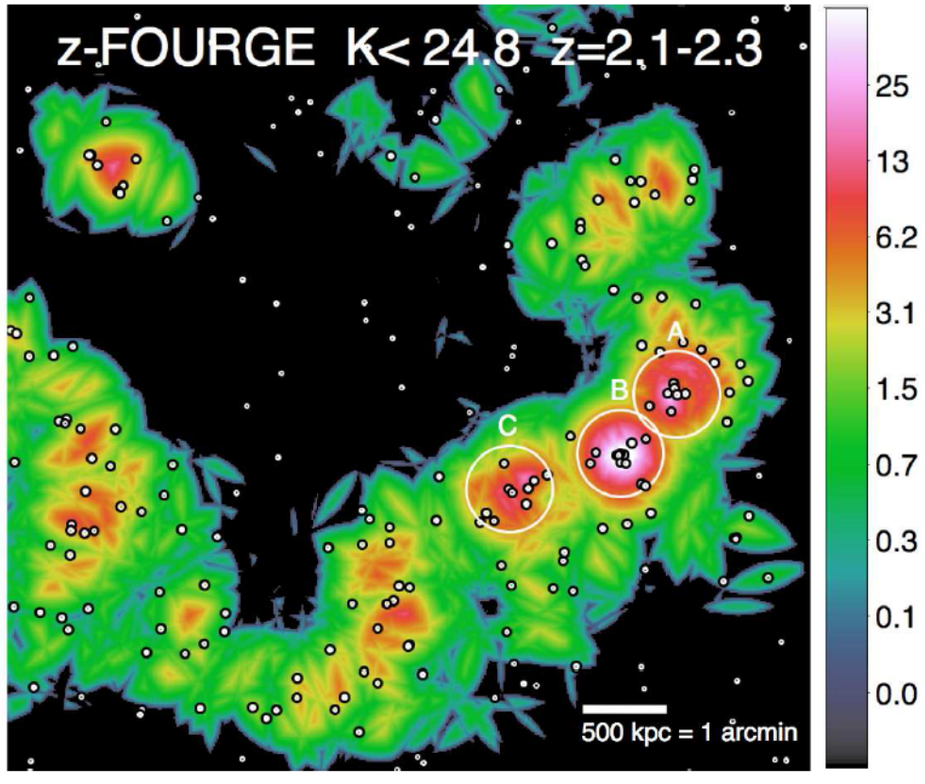
Galametz+2012, Wylezalek+2013, Wylezalek+2014, Cooke+2015, Cooke+2016, Rettura+2016

Various other IR-clusters in smaller fields

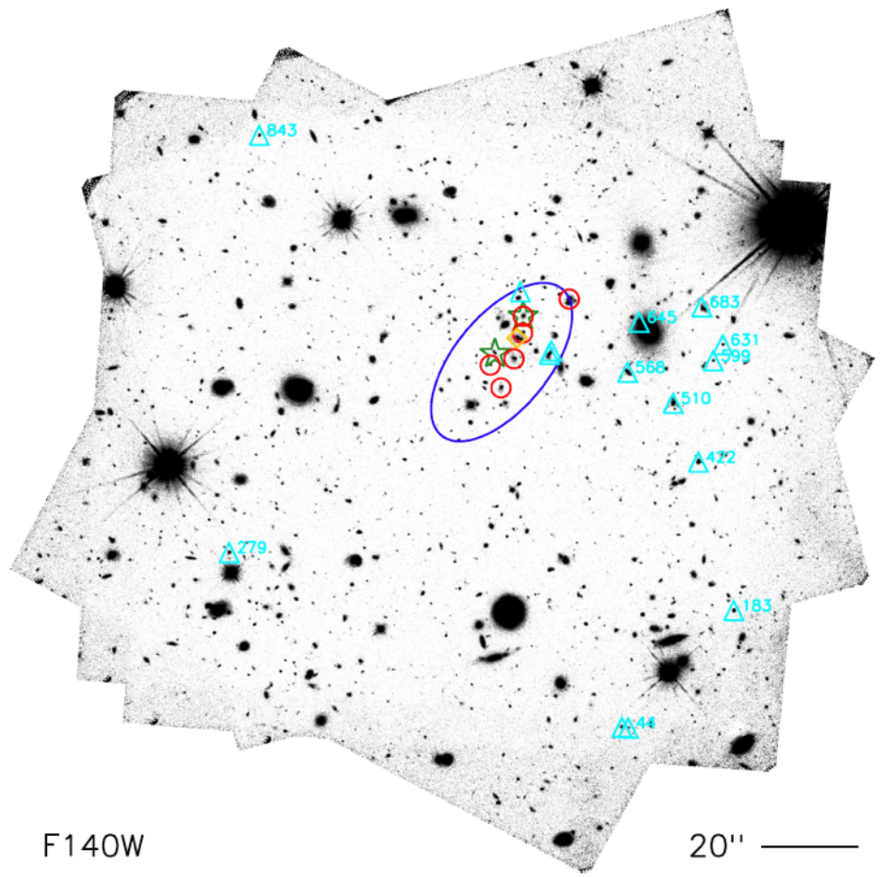


- JKS041, z = 1.80, Andreon et al. (2005,2014), Newman et al. (2014)

- zFOURGE J100015+021539, z=2.16, Spitler et al. (2012)

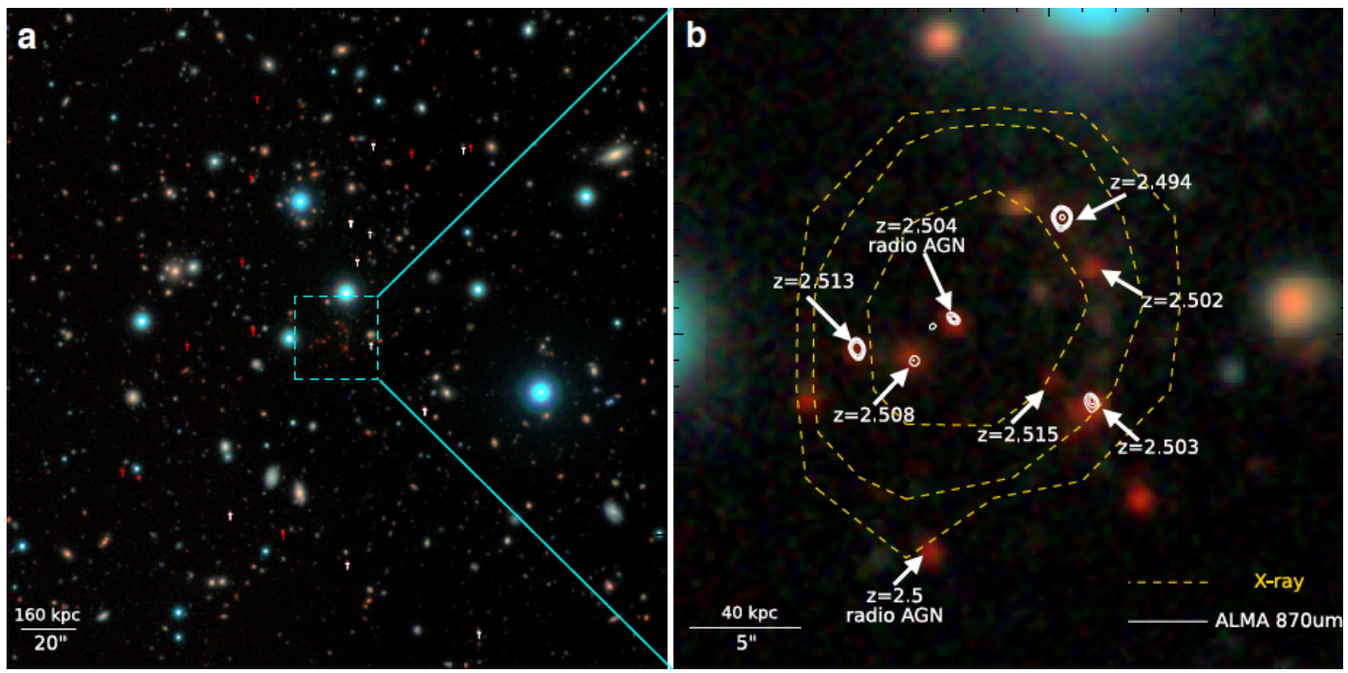


Various other IR-clusters in smaller fields



- CL J1449+0856, z = 2.01, Gobat et al. (2011, 2013), also X-ray detection

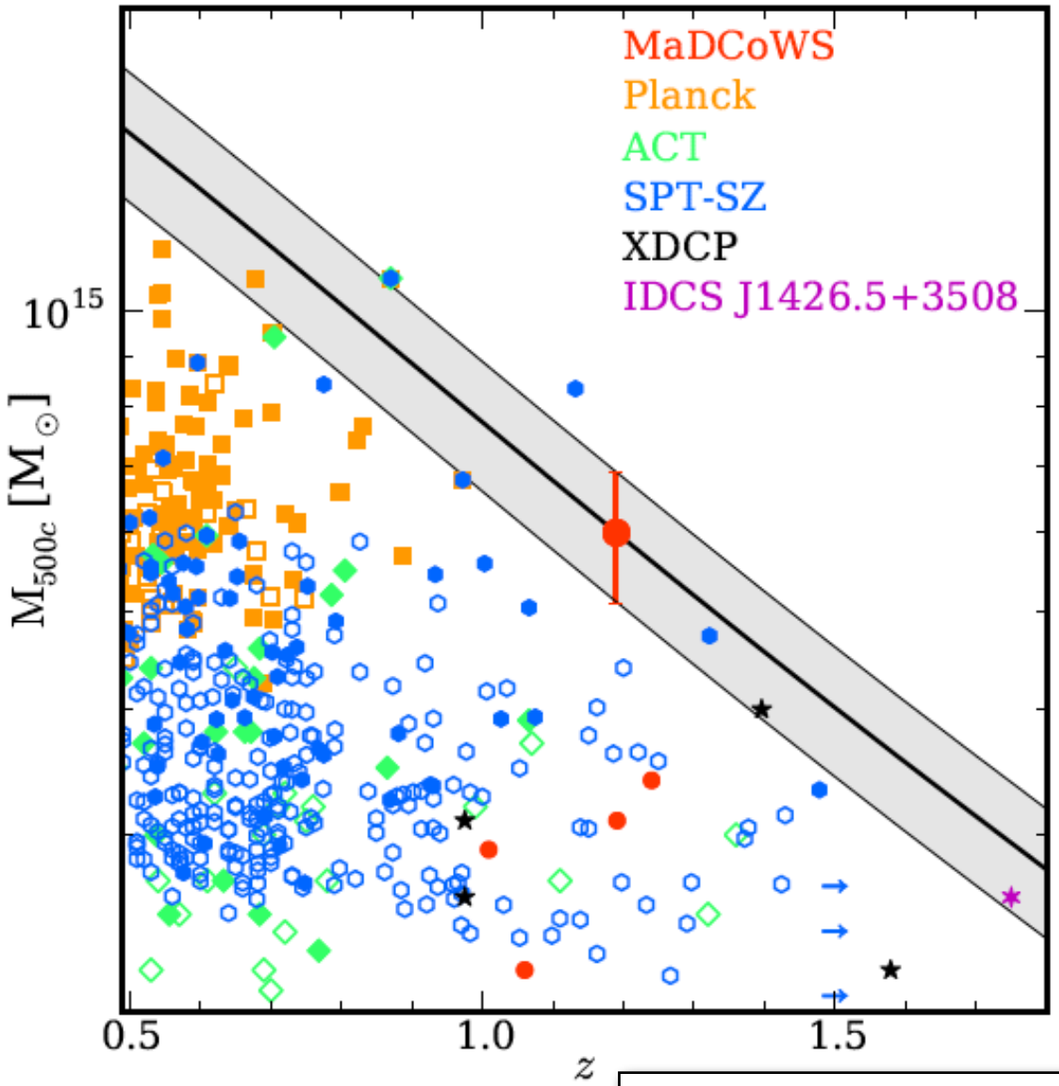
- COSMOS J100057+022011 z = 2.56, Wang et al. (2016) also X-ray detection

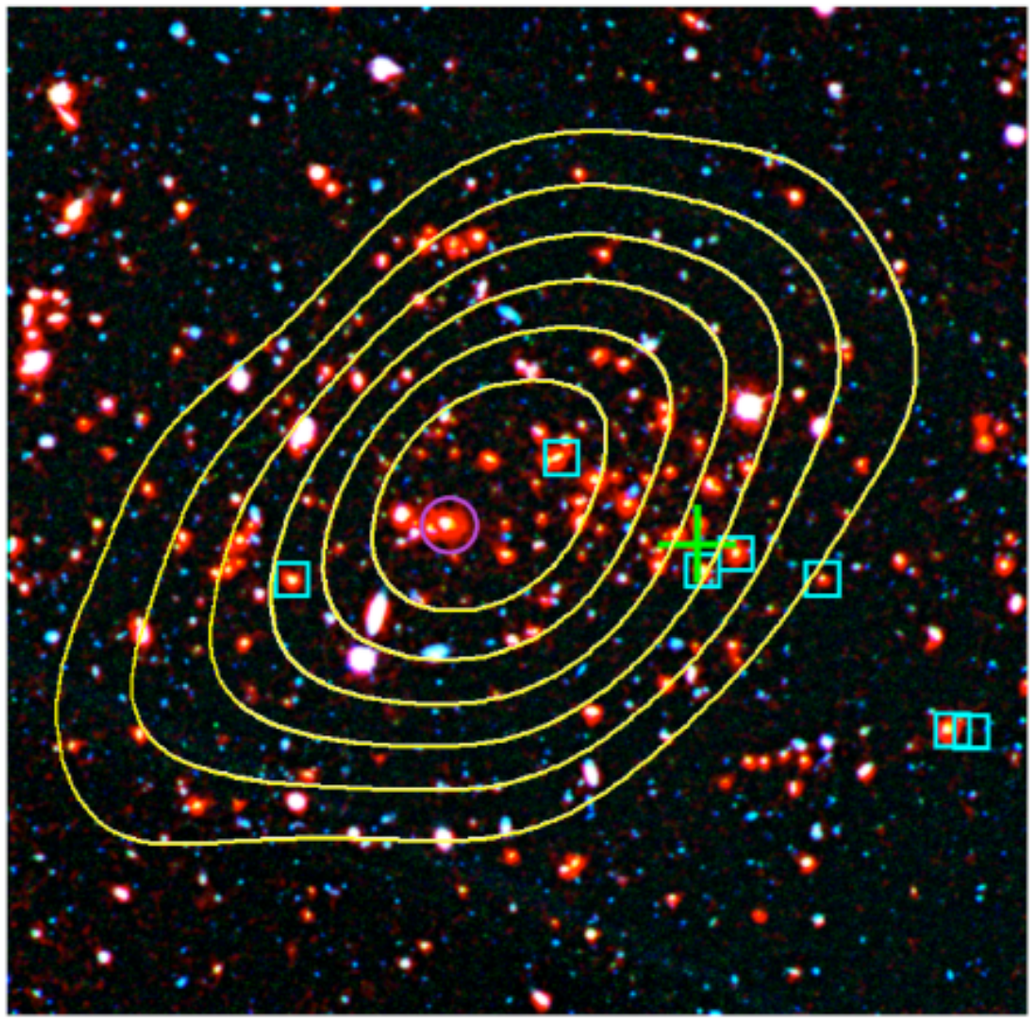


Current Combined Status of IR-selected Clusters

Name	Redshift	Reference
COSMOS J100057+022011	$z = 2.56$	Chun et al. (2016)
zFOURGE J100015+021539	$z = 2.16$	Spitler et al. (2012)
CL J1449+0856	$z = 2.01$	Gobat et al. (2011)
JKS 041	$z = 1.80$	Andreon et al. (2014)
IDCS J1426+3508	$z = 1.75$	Stanford et al. (2014)
SpARCS J104922+564032	$z = 1.70$	Webb et al. (2015)
SpARCS J022427-032354	$z = 1.63$	Muzzin et al. (2013)
CL J0218.3-0510	$z = 1.62$	Papovich et al. (2010)
CARLA J1753+6311	$z = 1.58$	Cooke et al. (2016)
Various	$1.0 < z < 1.6$	~ 30 clusters

Is Spitzer the Only IR-telescope Doing Cluster Surveys? NO! WISE!



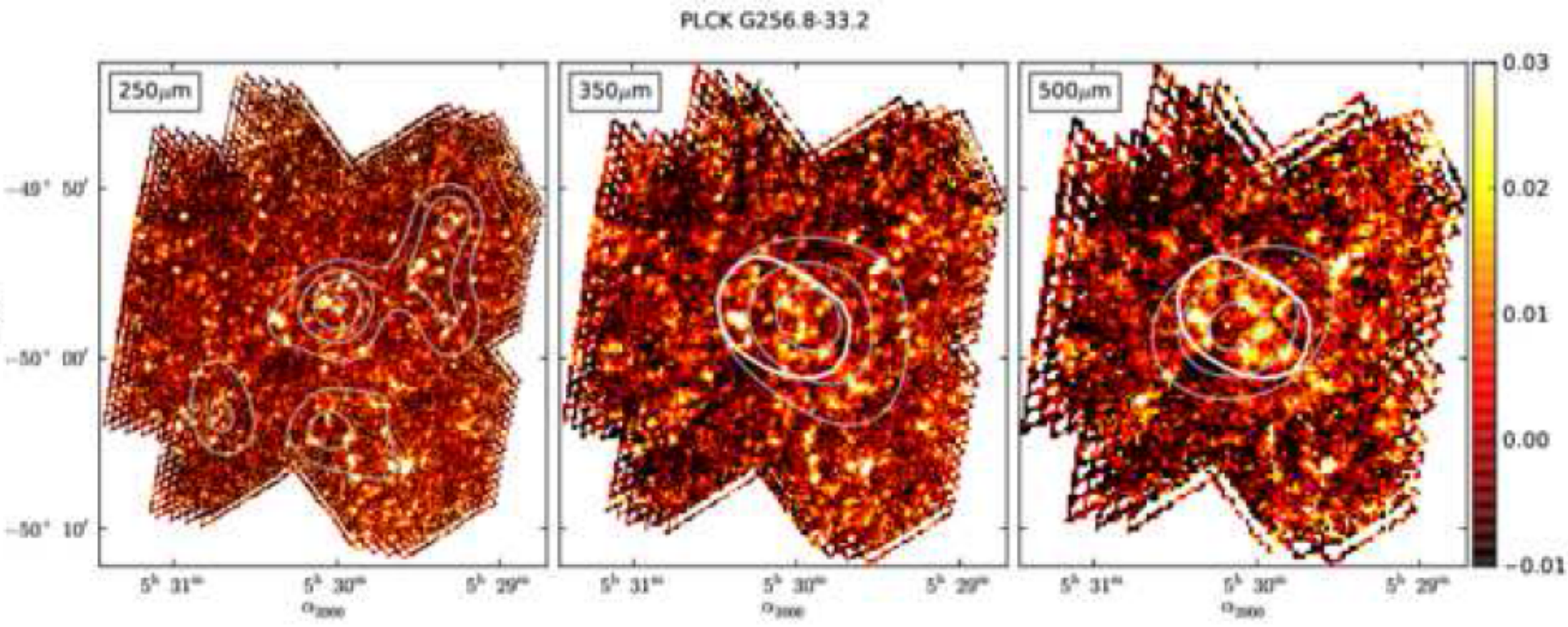


MOO J1142+1527, z = 1.19
Gonzalez et al. (2015)

Gettings+2012, Stanford+2014, Brodwin+2015, Gonzalez+2015

… and Planck and Herschel

See Next Talk by Bruno Altieri



The Planck Collaboration+2015

- Herschel Followup of “cold” spots in the Planck map reveals over densities of dusty starburst galaxies, candidate proto-clusters at z > 2

- Blank-field Herschel Surveys also find candidates (e.g., Casey+, Rigby+)

There Are Now Many High-z Clusters….

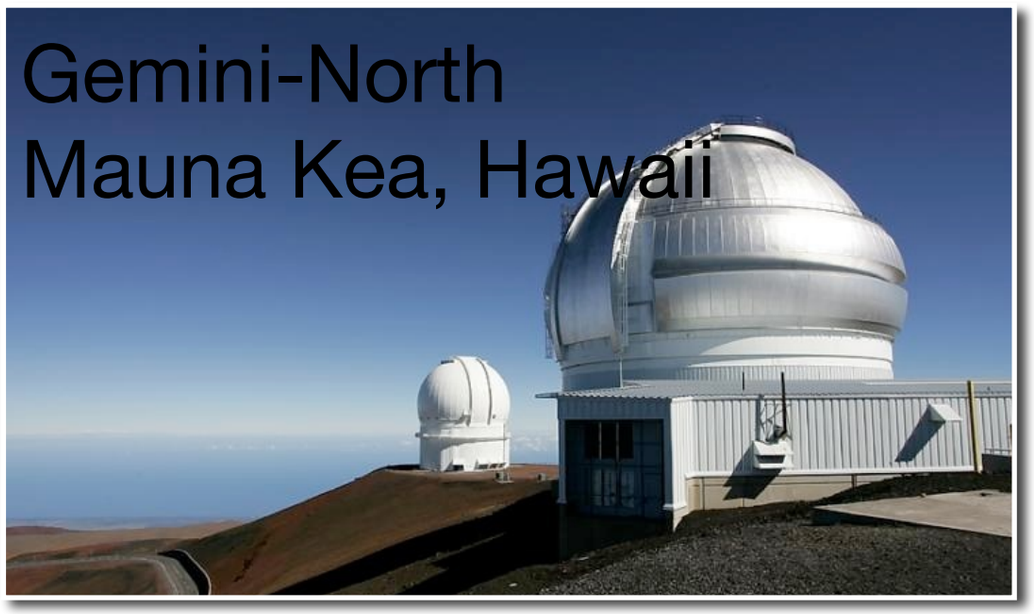
Name	Redshift	Reference
COSMOS J100057+022011	z = 2.56	Chun et al. (2016)
zFOURGE J100015+021539	z = 2.16	Spitler et al. (2012)
CL J1449+085		al. (2011)
JKS 041		et al. (2014)
IDCS J1426+35		et al. (2014)
SpARCS J104922+564032	z = 1.70	Webb et al. (2015)
SpARCS J022427-032354	z = 1.63	Muzzin et al. (2013)
CL J0218.3-0510	z = 1.62	Papovich et al. (2010)
CARLA J1753+6311	z = 1.58	Cooke et al. (2016)
Various	$1.0 < z < 1.6$	~ 30 clusters

What have we learned from high-z IR clusters?

The **G**emini **C**luster **A**strophysics **S**pectroscopic **S**urvey (GCLASS)

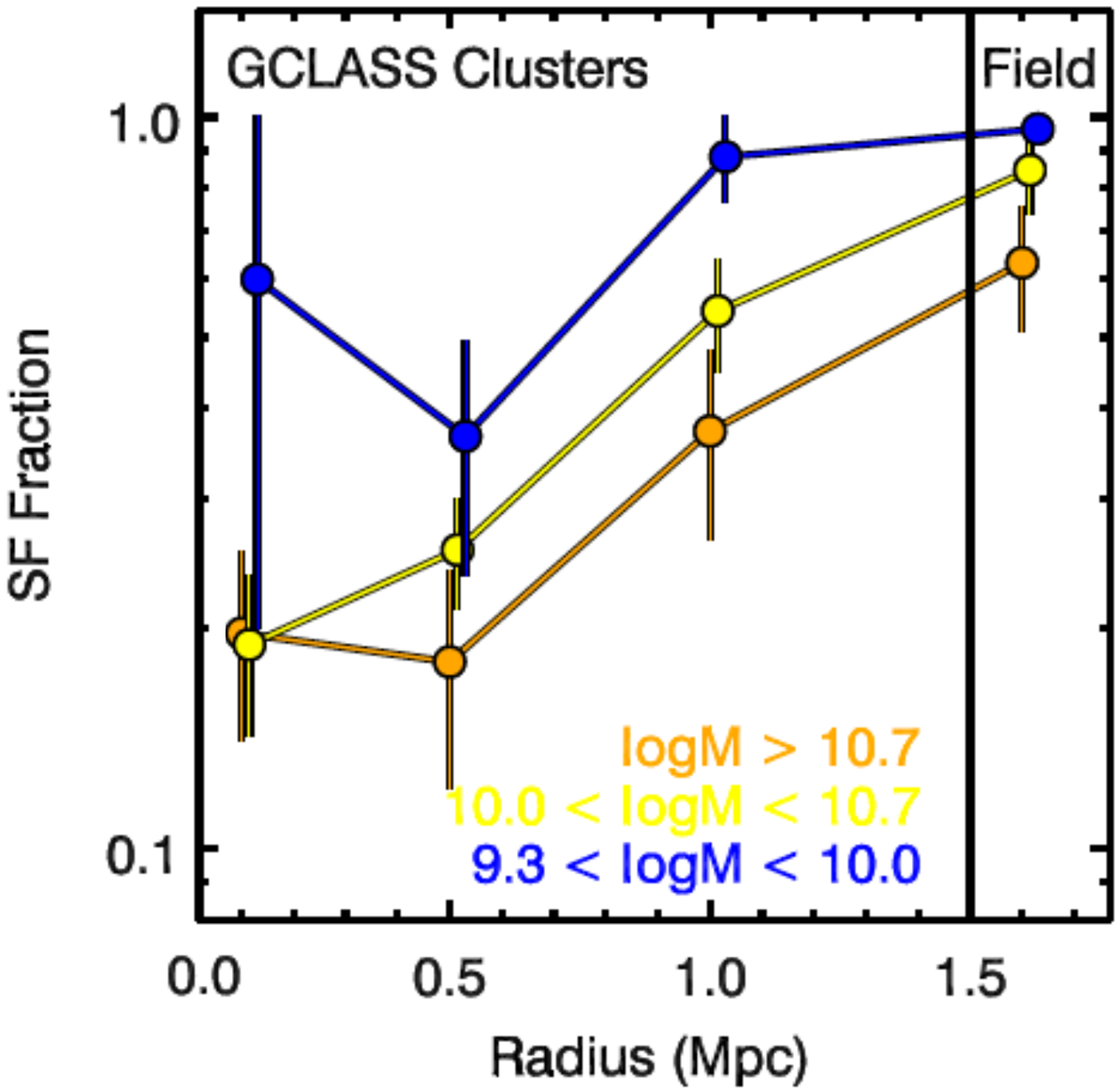
Spectroscopic survey of 10 rich, IR-selected clusters at $0.86 < z < 1.34$ with Gemini/GMOS

High spectroscopic completeness, ~500 members across 10 clusters



222-hour project from 2009-2012 with Gemini/GMOS (8 allocations)

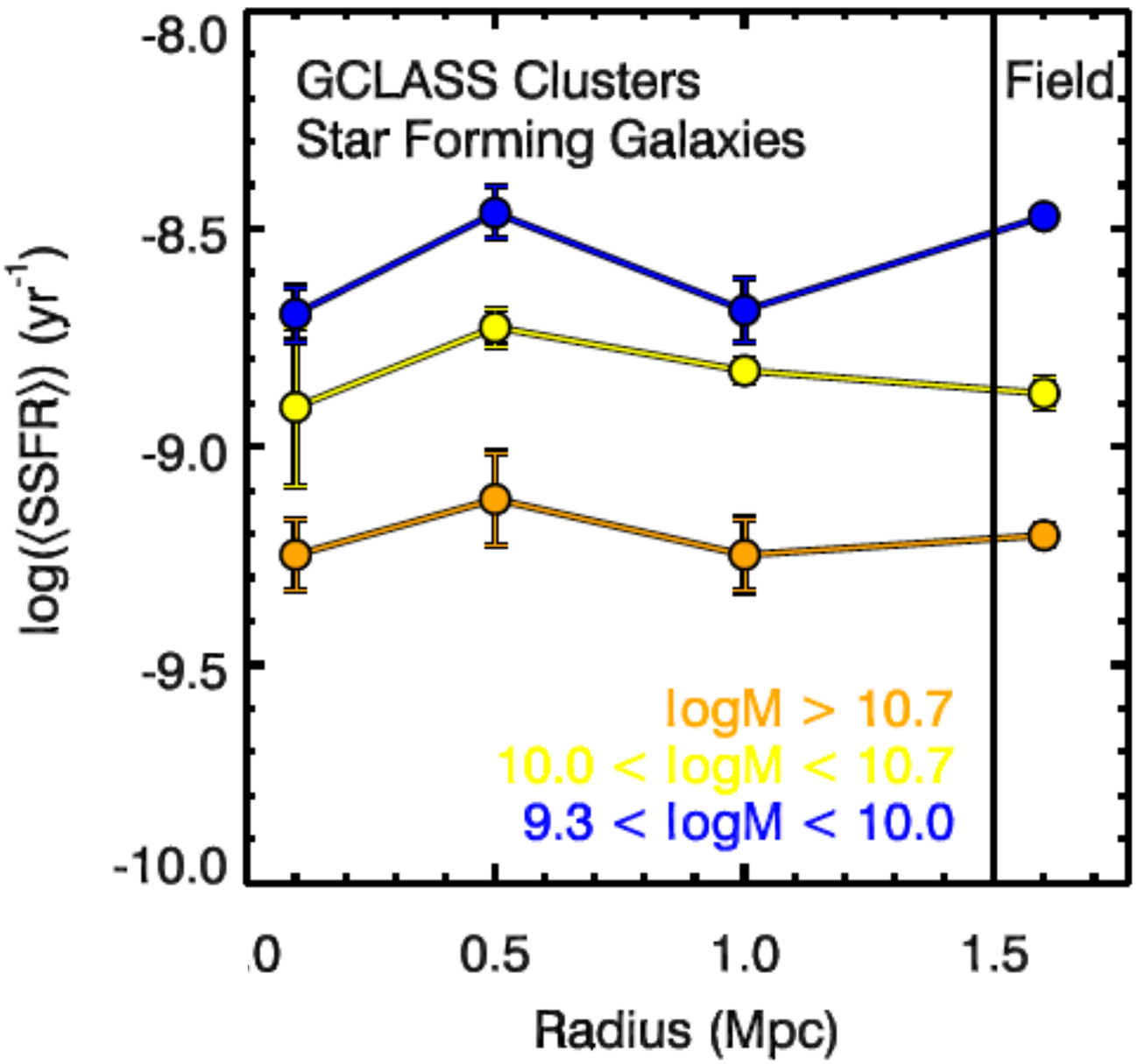
Star-forming Fraction at Fixed Stellar Mass



Muzzin+2012

Star-forming fraction correlates with both stellar mass and environment

Specific Star Formation Rates of SF-Galaxies



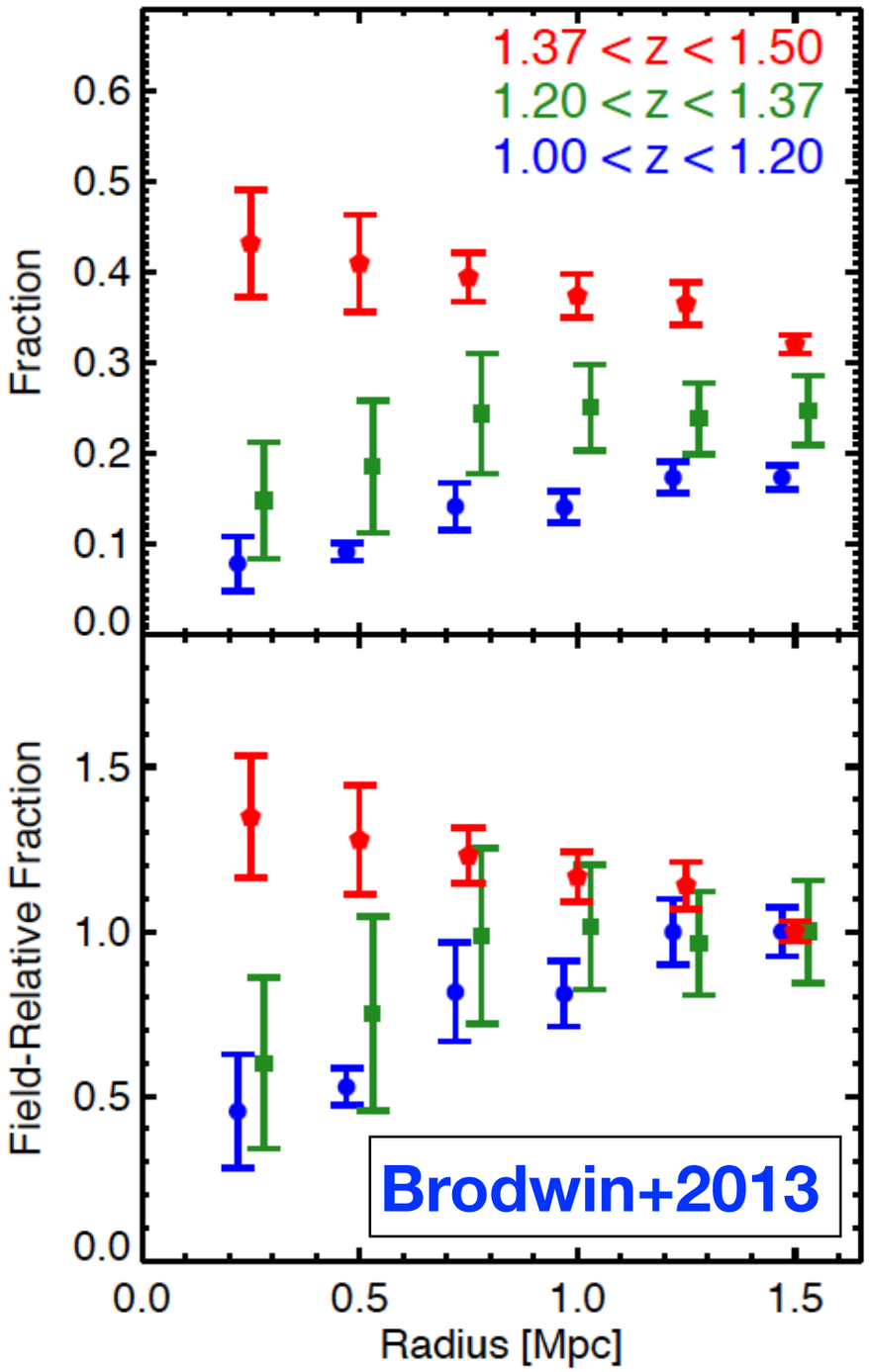
Muzzin+2012

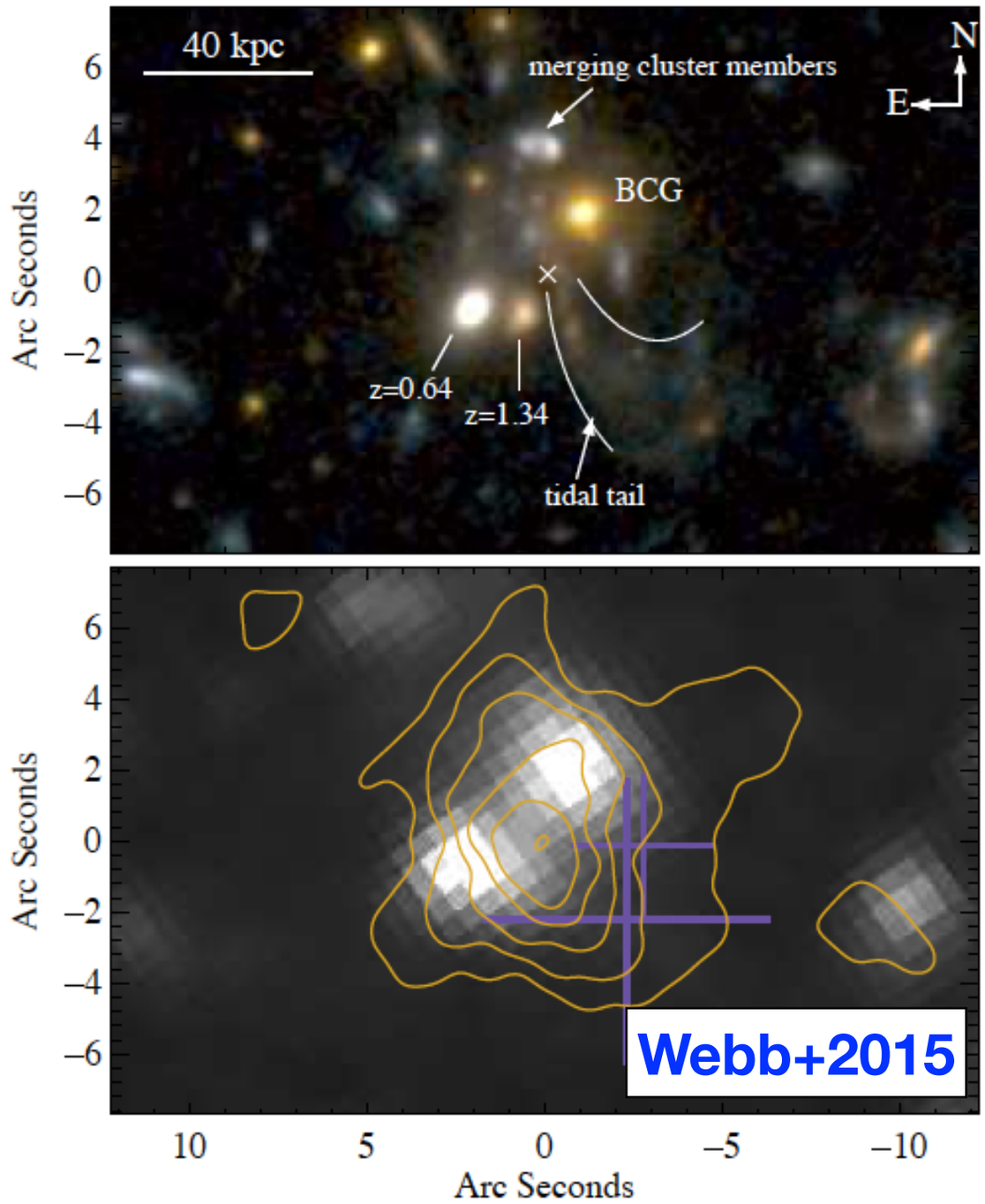
Specific star formation rate of star-forming galaxies correlates with stellar mass, **not** environment

The take home message:

<u>The effects of the cluster environment on galaxy evolution are the same at z = 0 and at z = 1</u>

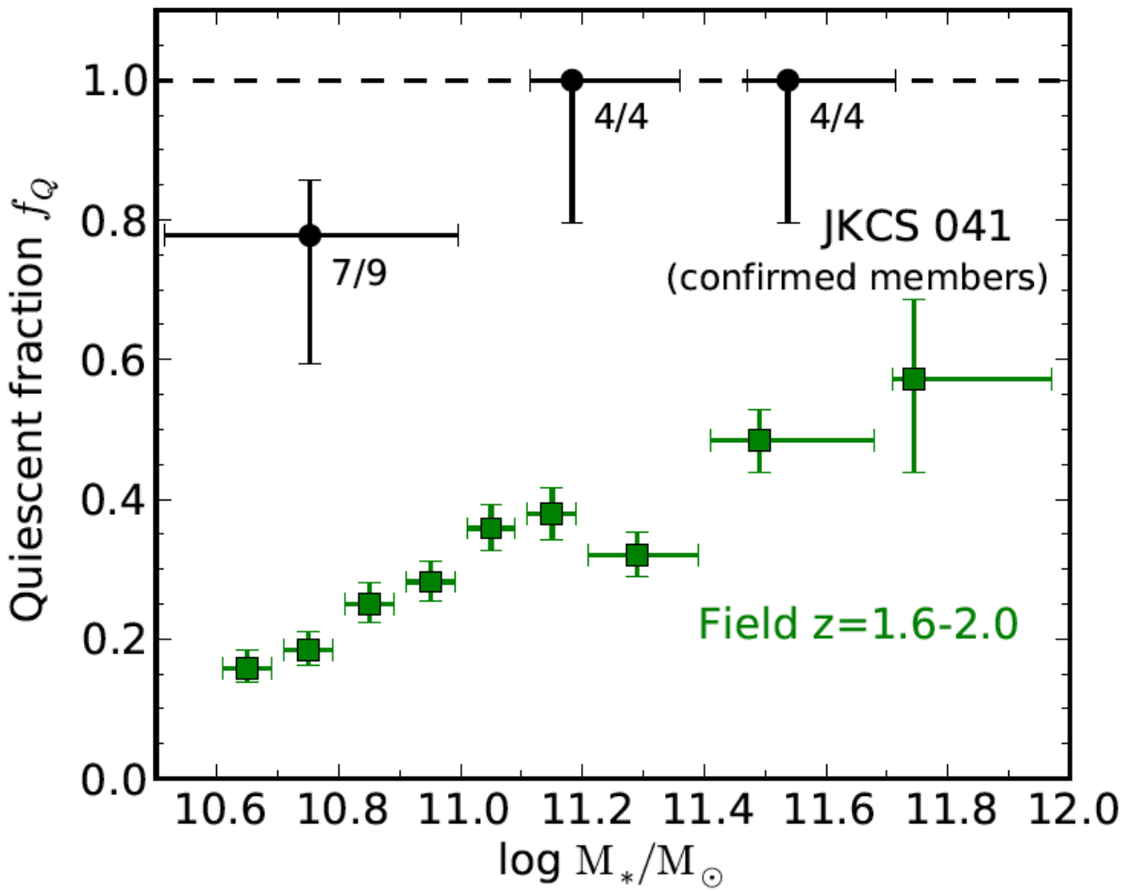
Evidence That Clusters at z > 1.5 are Significantly Increasing in Star Formation



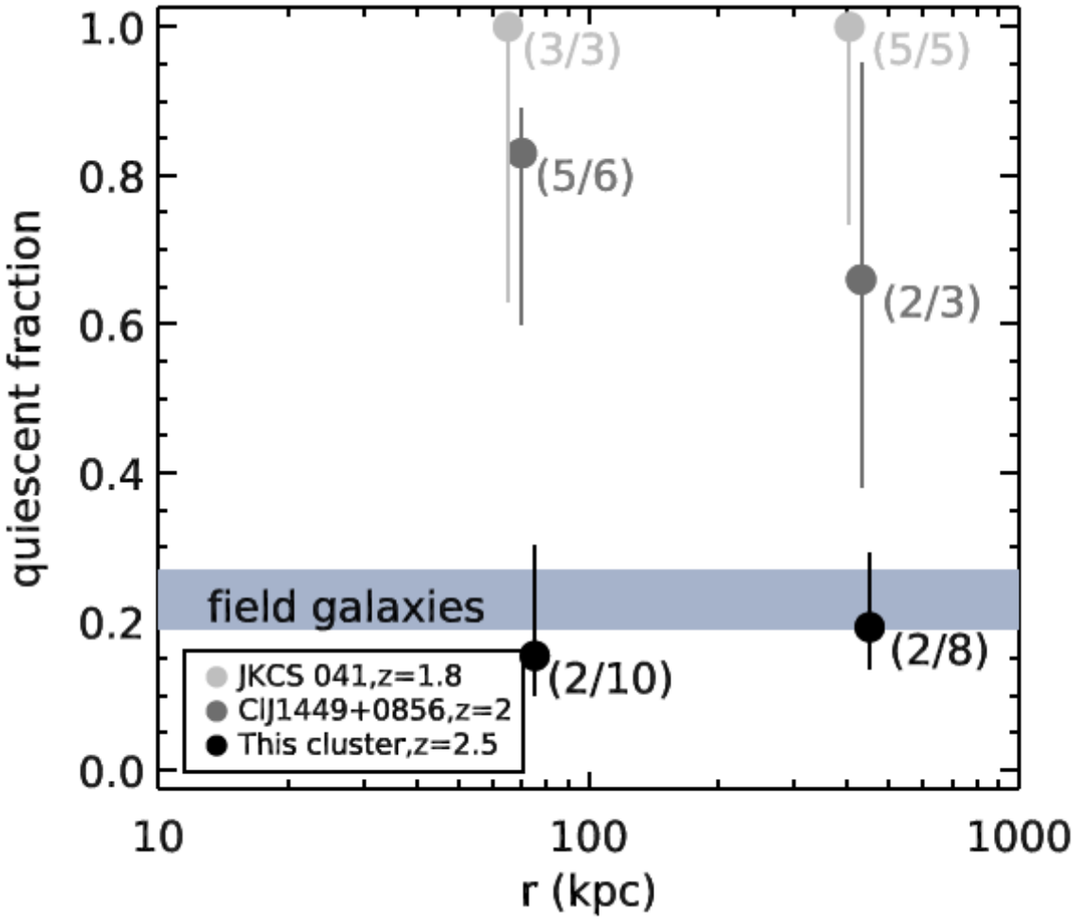


Although there are counter-examples

Clusters that are LESS active than the field at z ~ 2



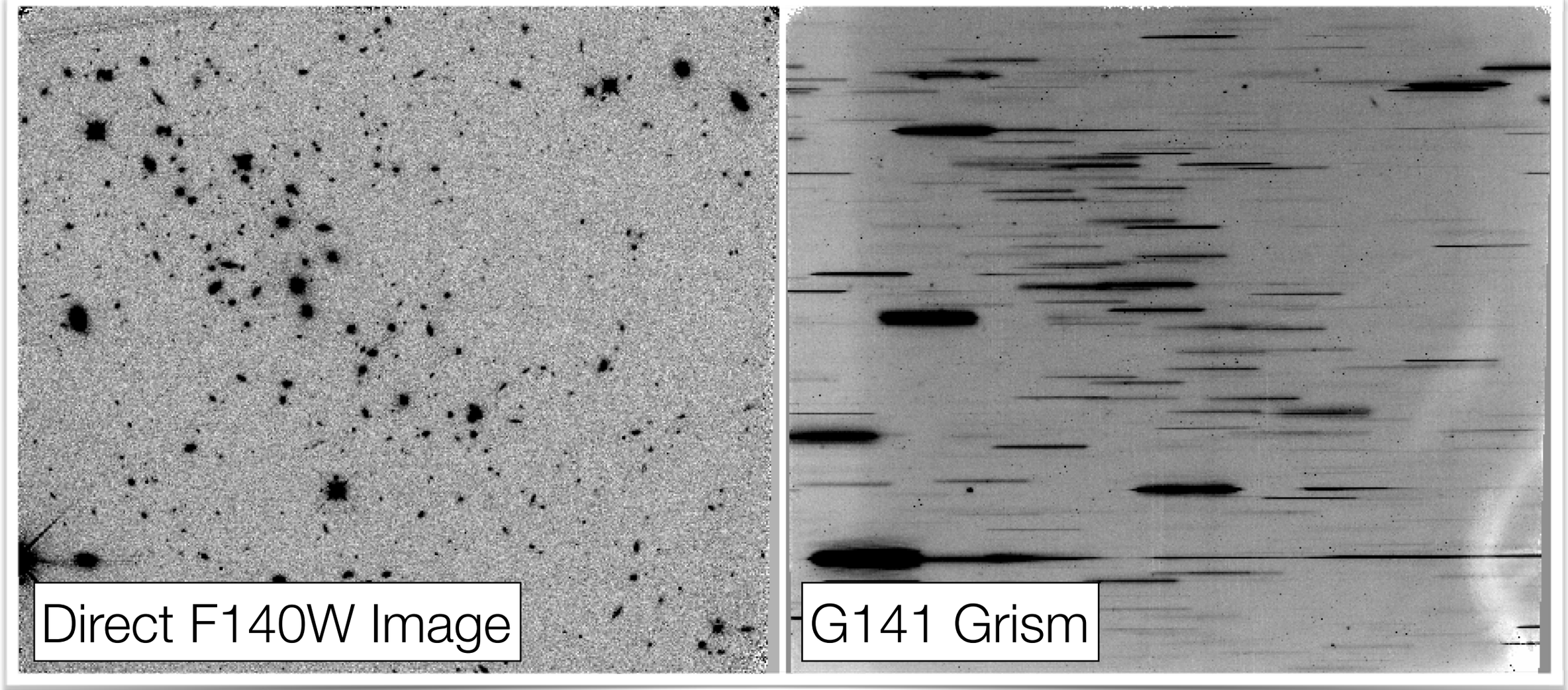
Newman+2014



Wang+2016

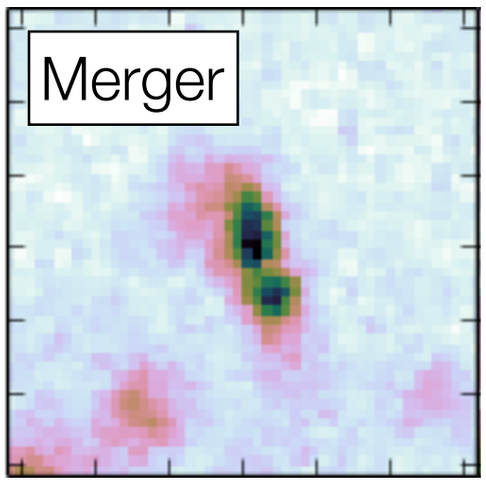
GCLASS WFC3 Grism Program (PI: Muzzin)

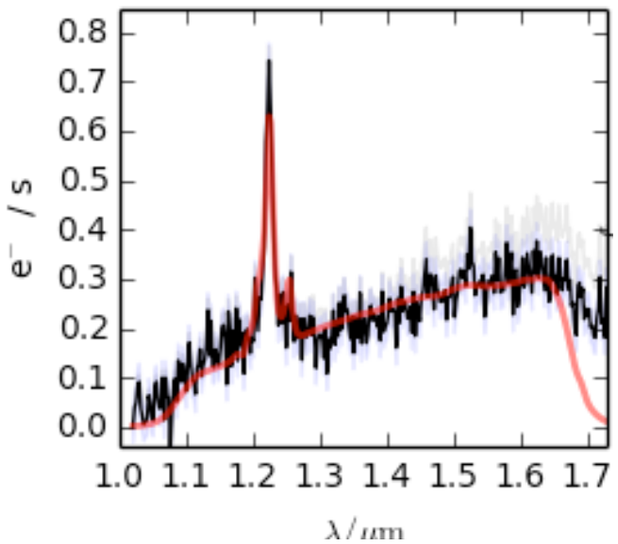
A 38-orbit G141 grism program to get resolved H-alpha maps of cluster galaxies

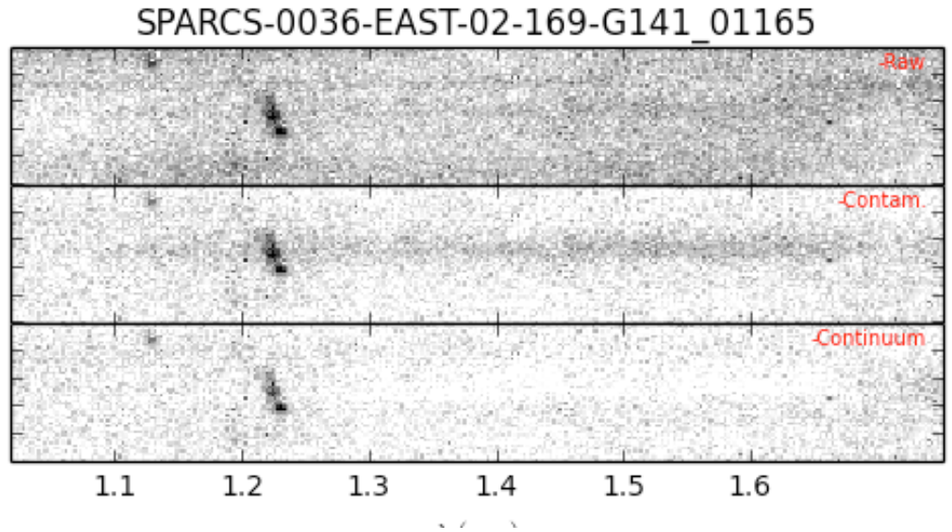


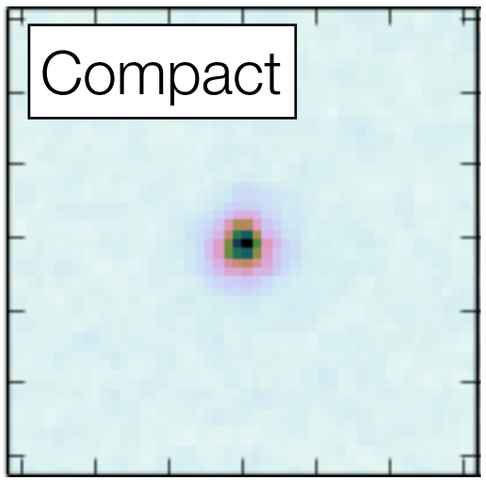
SpARCS J1638+4038, z = 1.179

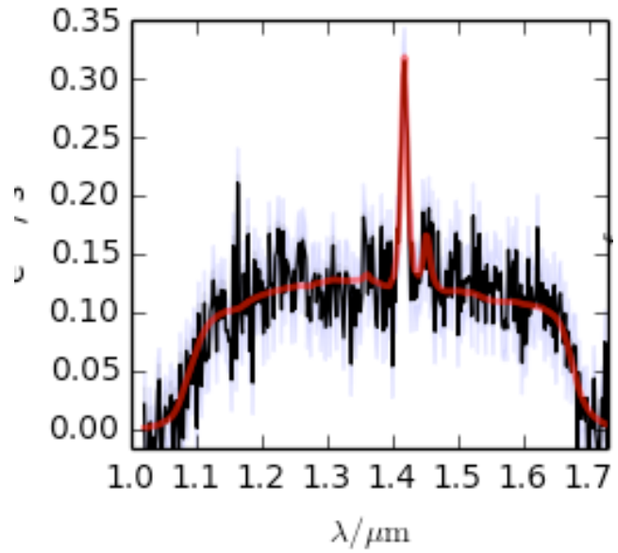
Examples of GCLASS Grism Spectra with H-alpha

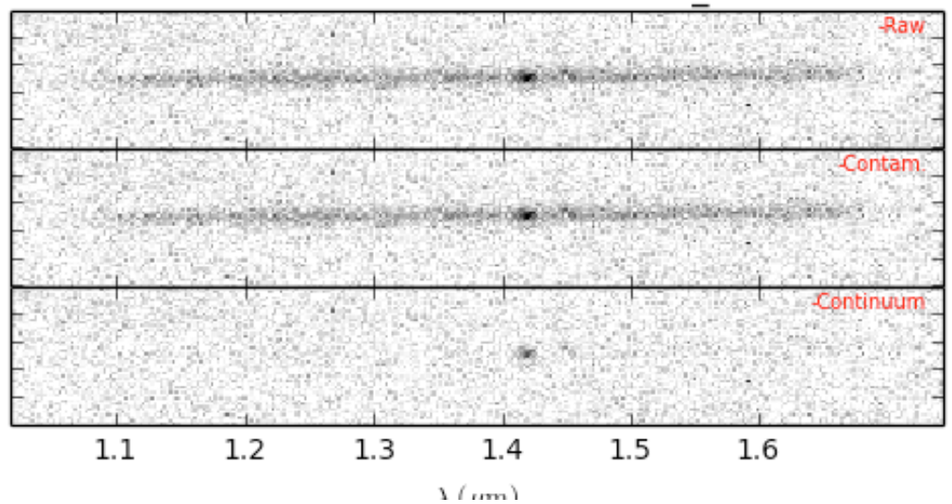


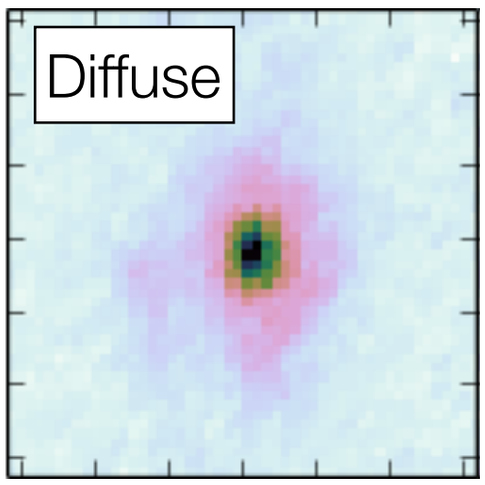


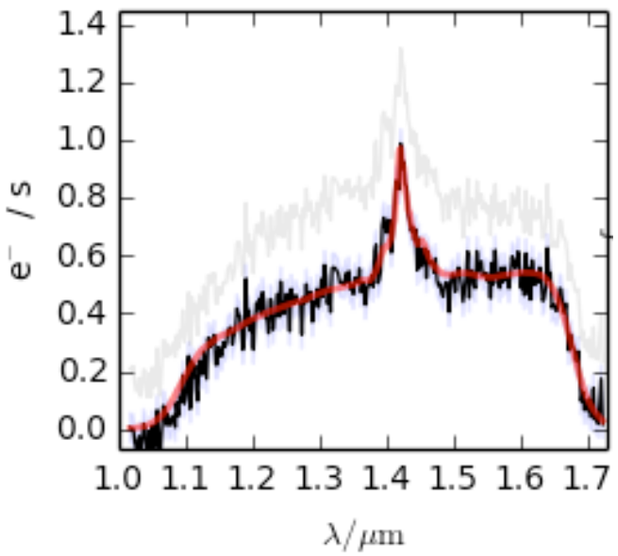


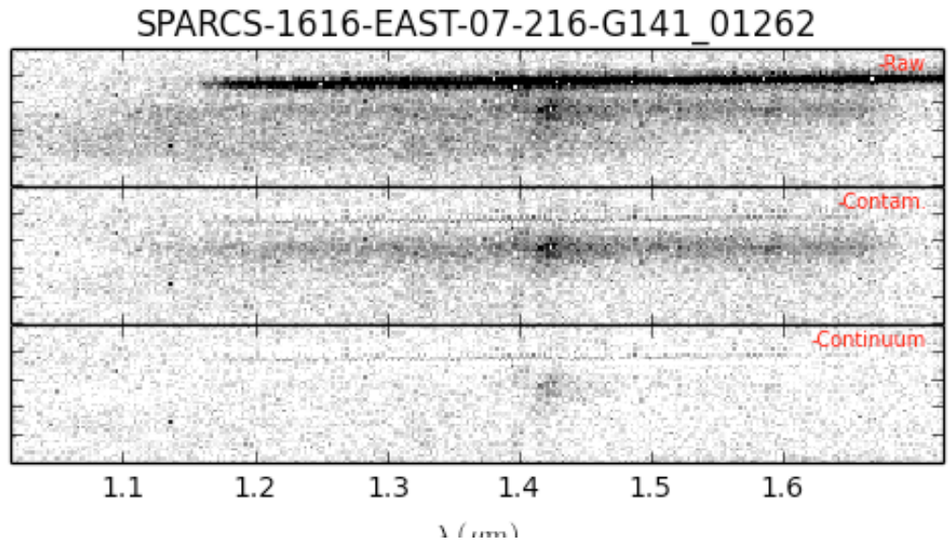




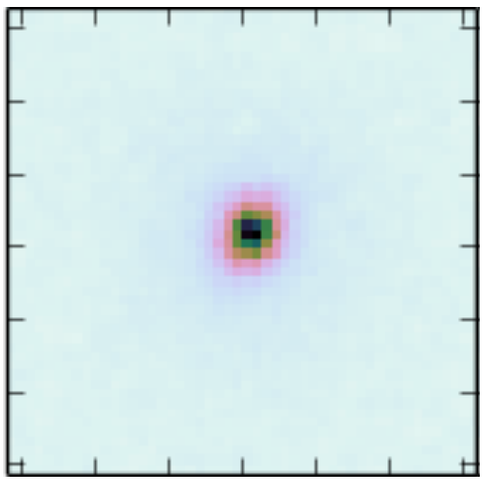


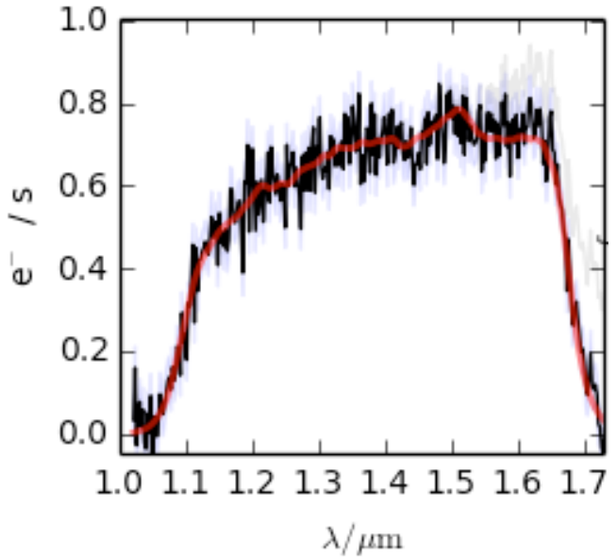


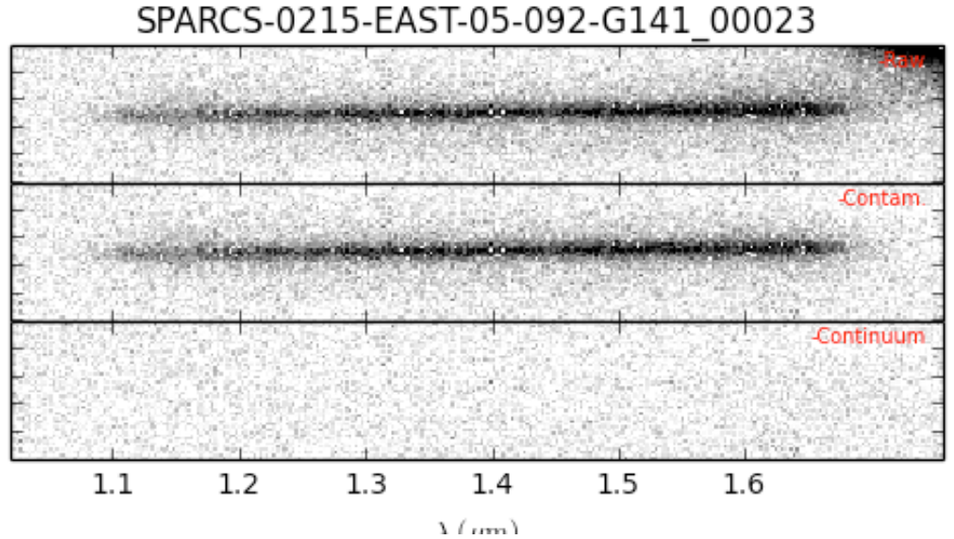


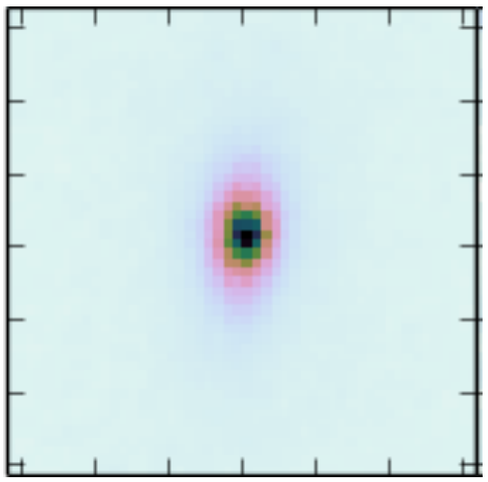


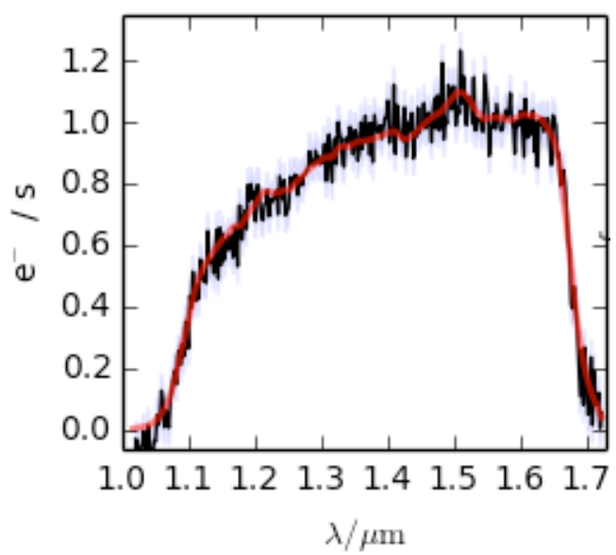
Examples of GCLASS Grism Spectra **without** H-alpha

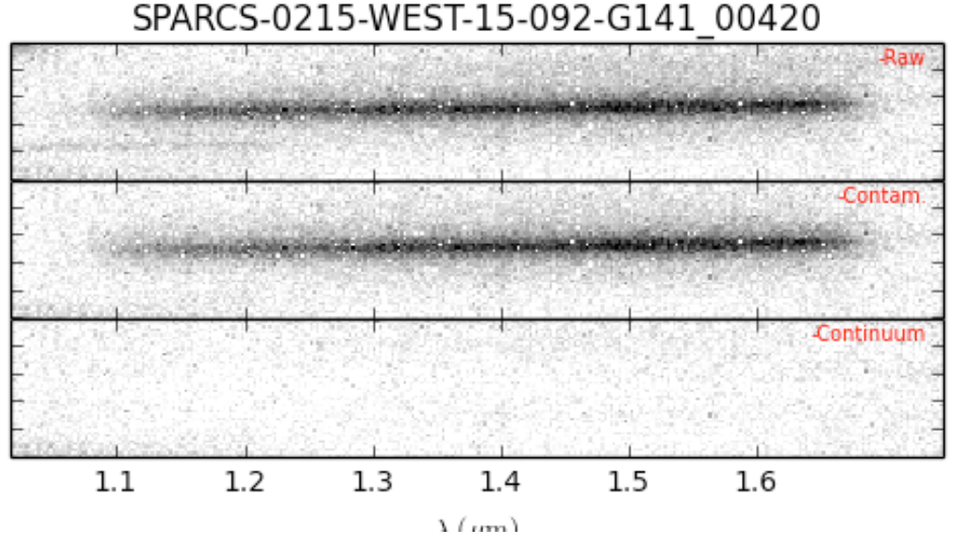


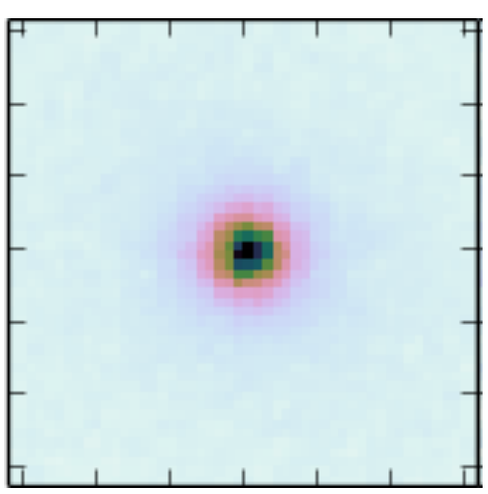


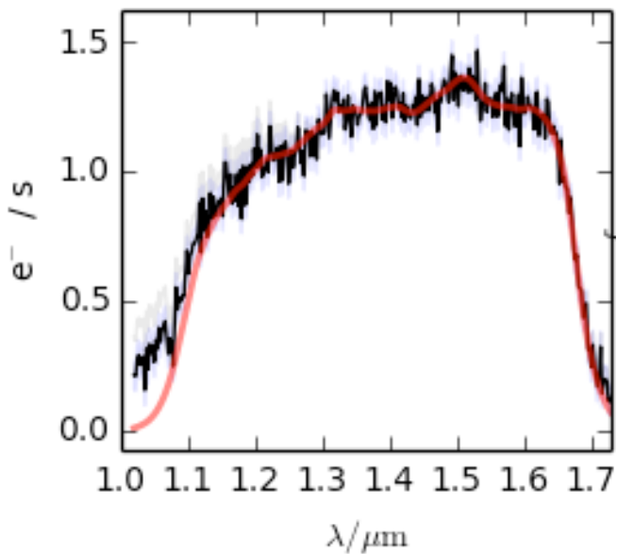


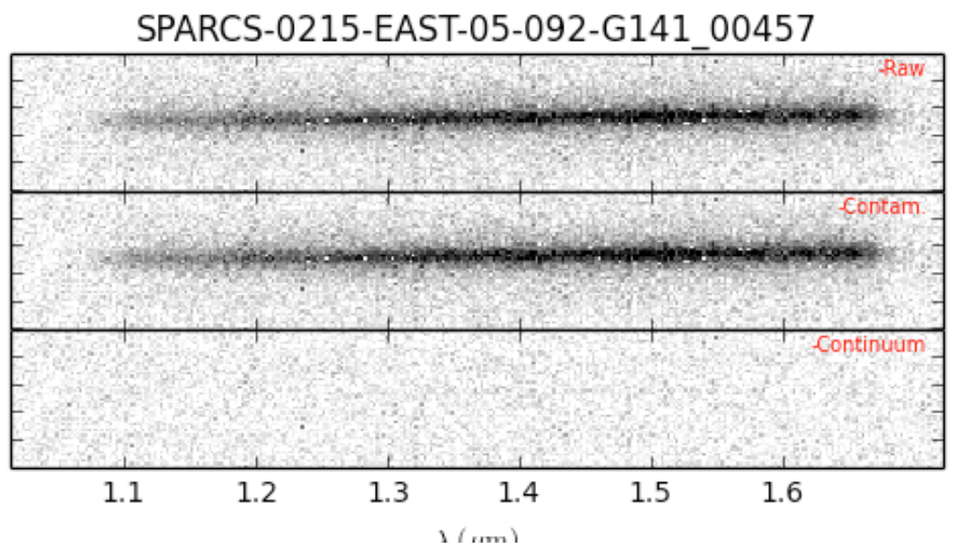


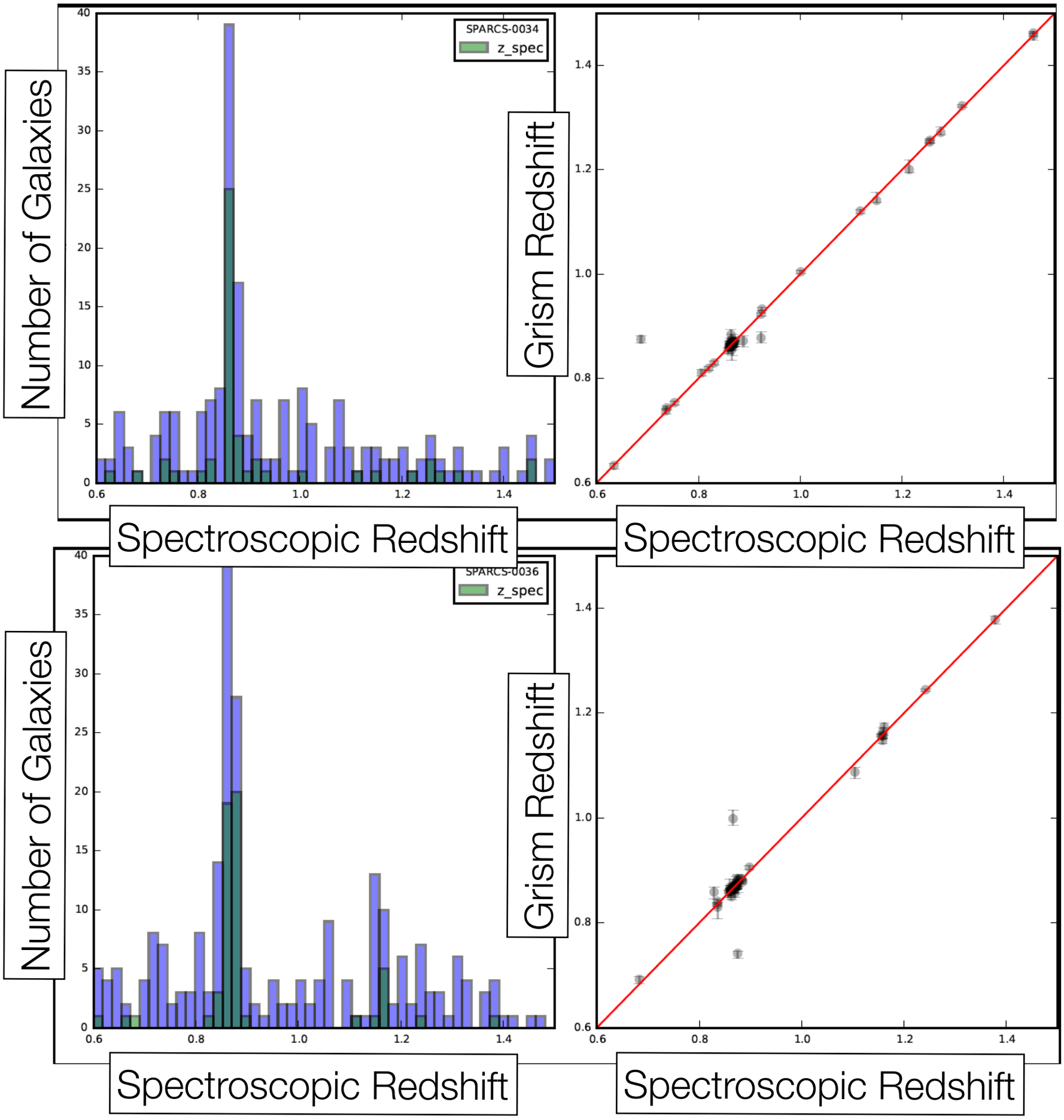












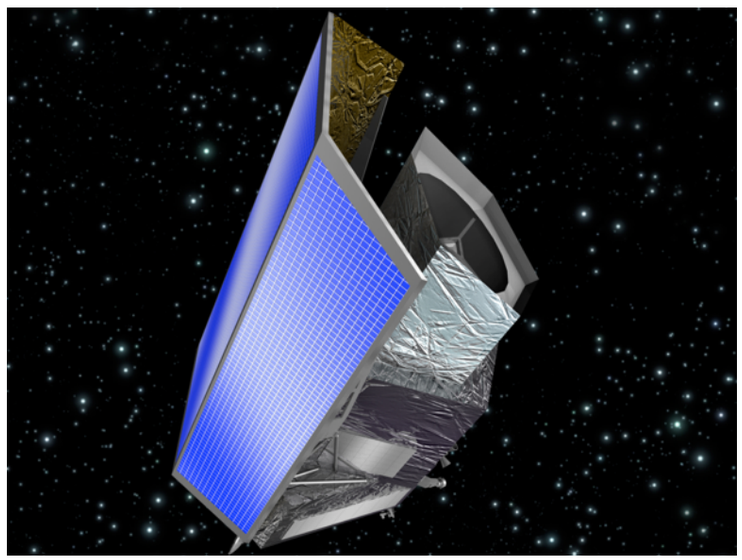
How many spectra do we get?

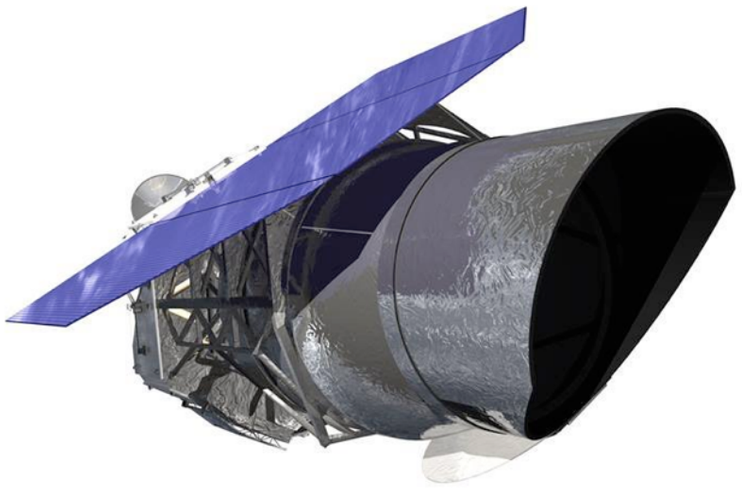
- GCLASS Gemini spectra has ~500 cluster members
- Grism redshifts are good enough for membership and double this to ~1000 cluster members at z = 1!!

“Game Changing” Telescopes: The Bright Future of IR Cluster Detection with Slitless IR spectroscopy!

- EUCLID will survey 15,000 deg with NIR slitless grism spectroscopy (R = 250)

See talk by Barbara Sartoris





- WFIRST will survey 2,400 deg with NIR slitless grism spectroscopy (R = 600)

See talk by Megan Donahue

Conclusions

- IR-Selection has become a competitive method of selecting high-redshift clusters

- Spitzer has been by far the most important telescope for most detections

- Other IR telescopes such as Planck, Herschel, and WISE have detected proto-clusters with active star formation

- The spectroscopic capabilities of EUCLID and WFIRST will be extraordinary for detecting thousands of clusters at $1 < z < 2$