The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

Protoclusters in formation

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ING La Palma

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Outline

- Intro to clusters
- High z protoclusters
- MRC2104-242
- CARLA survey
- Red sequences

Intro– clusters at low z

- Useful tools
  - Probes of history of galaxy and structure formation
  - Cosmology
  - Galaxy evolution–labs of 1000s of galaxies
  - Representative sample of the Universe

- Galaxies in clusters differ from field:
  - Redder (e.g. Bamford et al., 2009)
  - Predominantly early types (e.g. Dressler et al., 1980)
  - Older ellipticals (e.g. Rettura et al., 2010)

Intro– clusters at high z

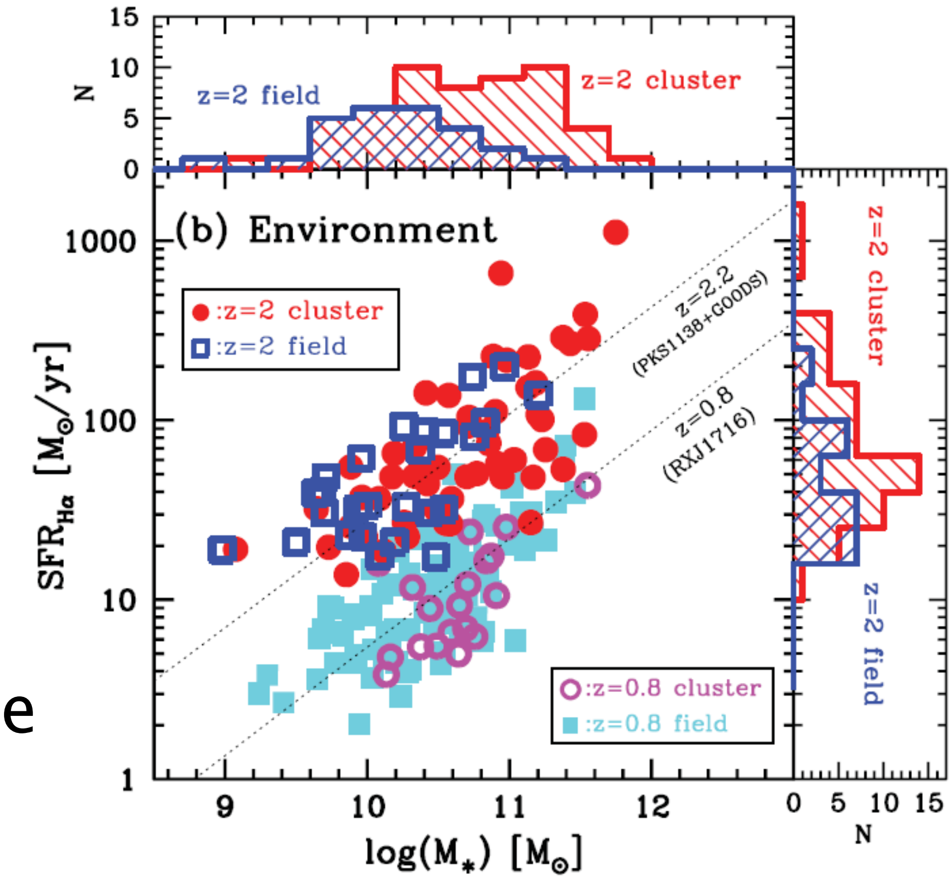
- Larger (e.g. Papovich et al., 2012)
- More massive (e.g. Steidel et al., 2005)
- Redder (e.g. Hayashi et al., 2012)
- More metal rich (e.g. Kulas et al., 2013)
- High z (proto)clusters can help constrain what physical processes are going on

How to find high z clusters

- Usual methods (X-ray, red sequence...) don't work
- Radio-loud AGN (RLAGN) tend to reside in overdense environments (Venemans et al. 2007)
- Act as beacons for protoclusters

Previous studies' findings

- No difference in sSFR between (proto)cluster and field
- Used K band flux to estimate masses
- $A_V \propto M$
- Do these results change with more robust measures of mass/A_V?



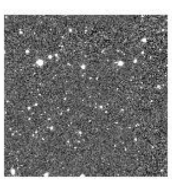
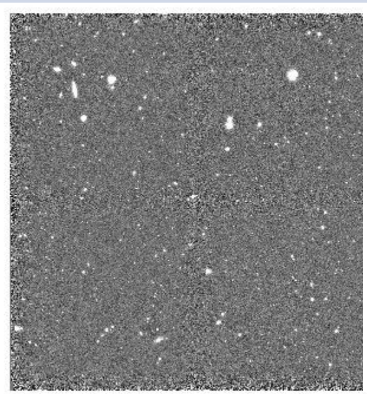
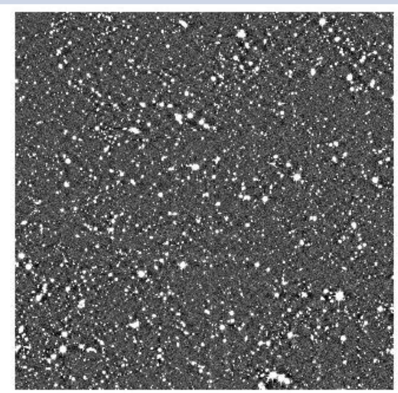
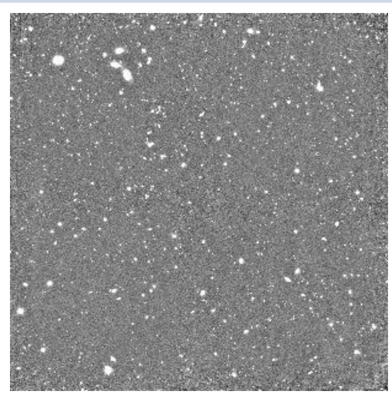
From Koyama et al., 2013a

MRC2104-242

- z = 2.49
- 2.5′ x 2.5′

- Study properties of any galaxies with respect to environment at this redshift

MRC2104	COSMOS	UDS	GOODS-S
A = 7.09 sq arcmin	A =170.4 sq arcmin (total)		

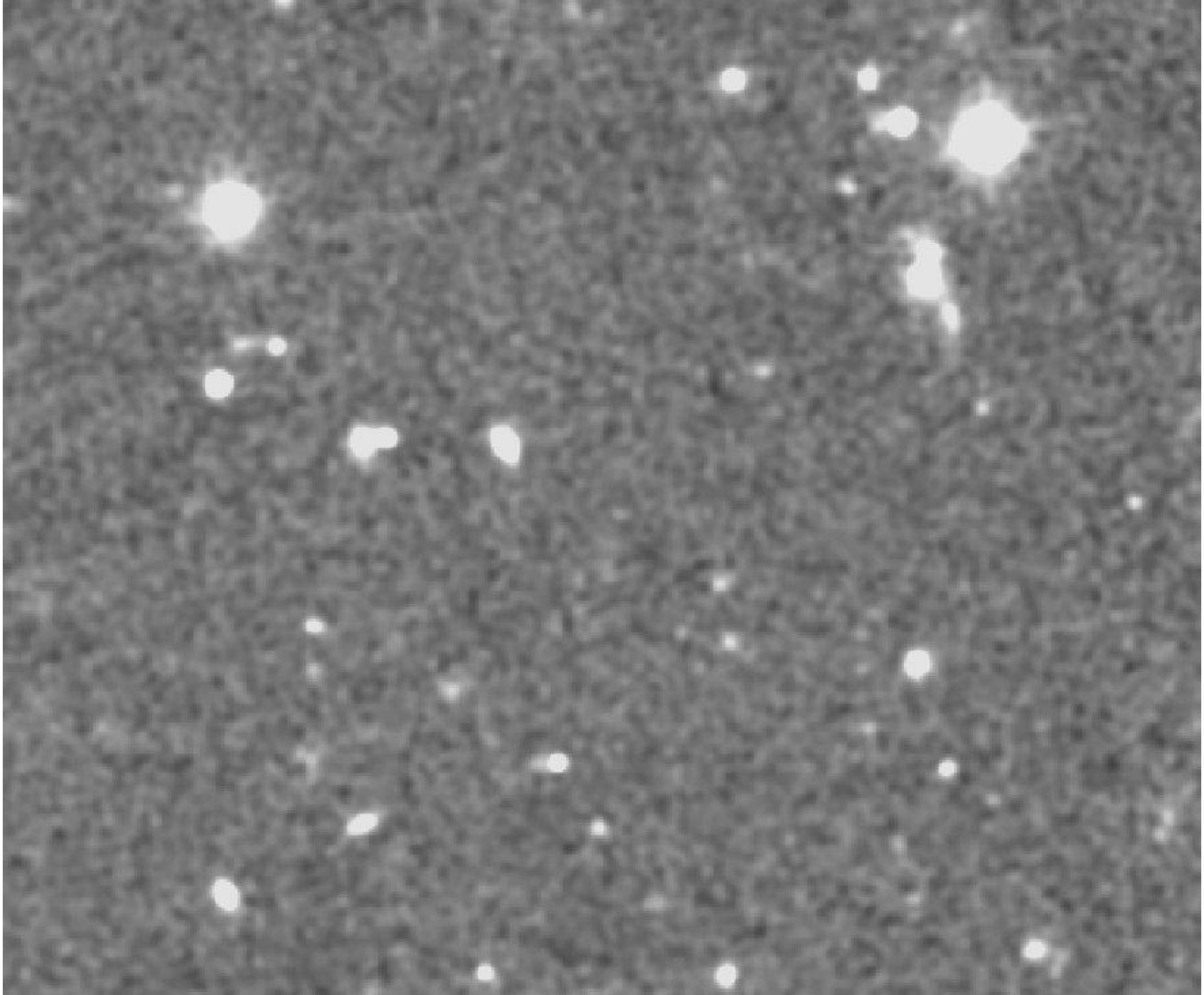





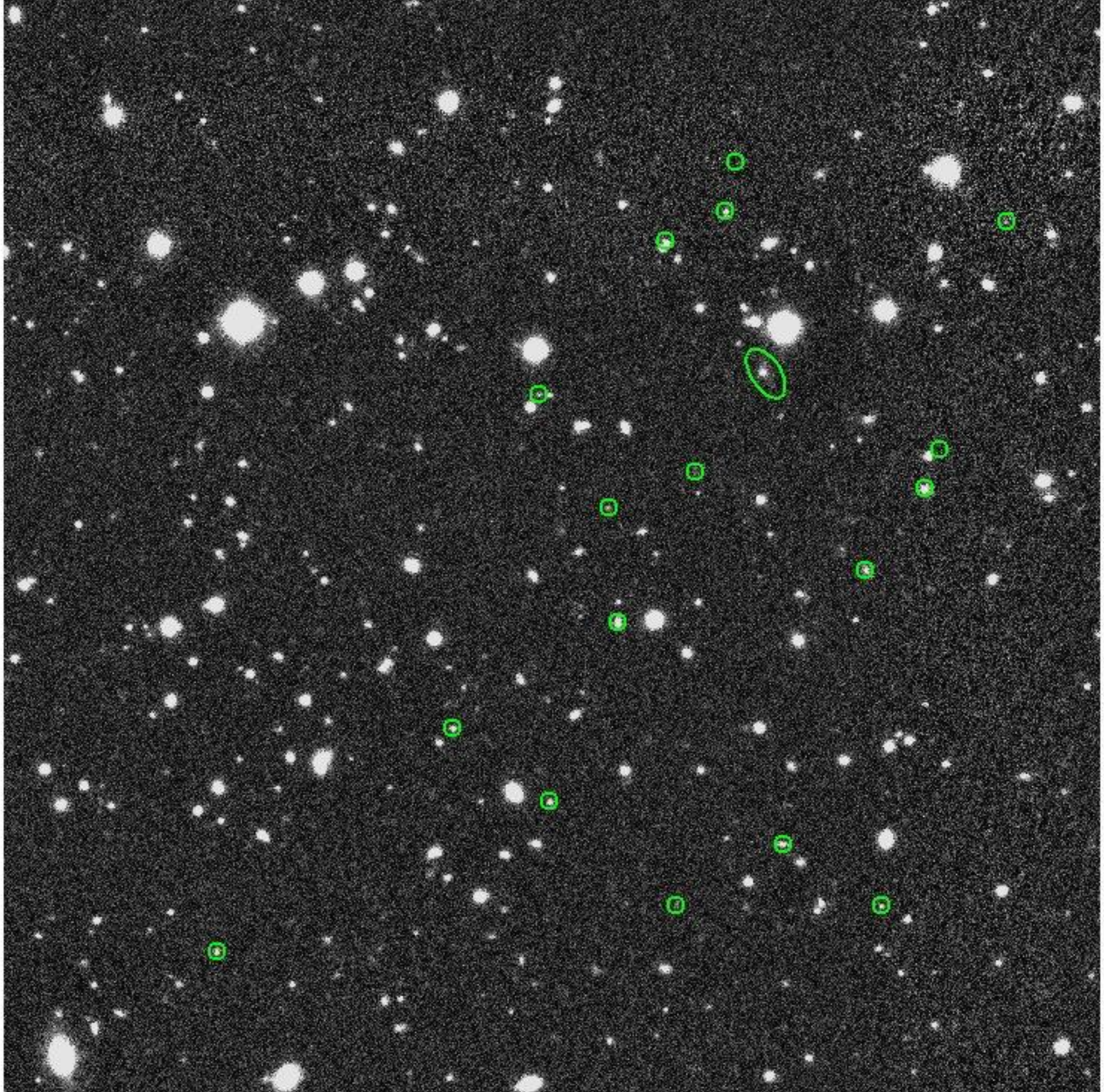
Observations/data

- NB survey
  - VLT: ISAAC NB λ_{cen} = 2.29μm
- VLT HAWK-I: K, J, H
- Gemini GMOS: g′, z′
- IRAC: 3.6μm, 4.5μm
- MIPS: 24μm
- Herschel: 250μm

Selecting Hα emitters

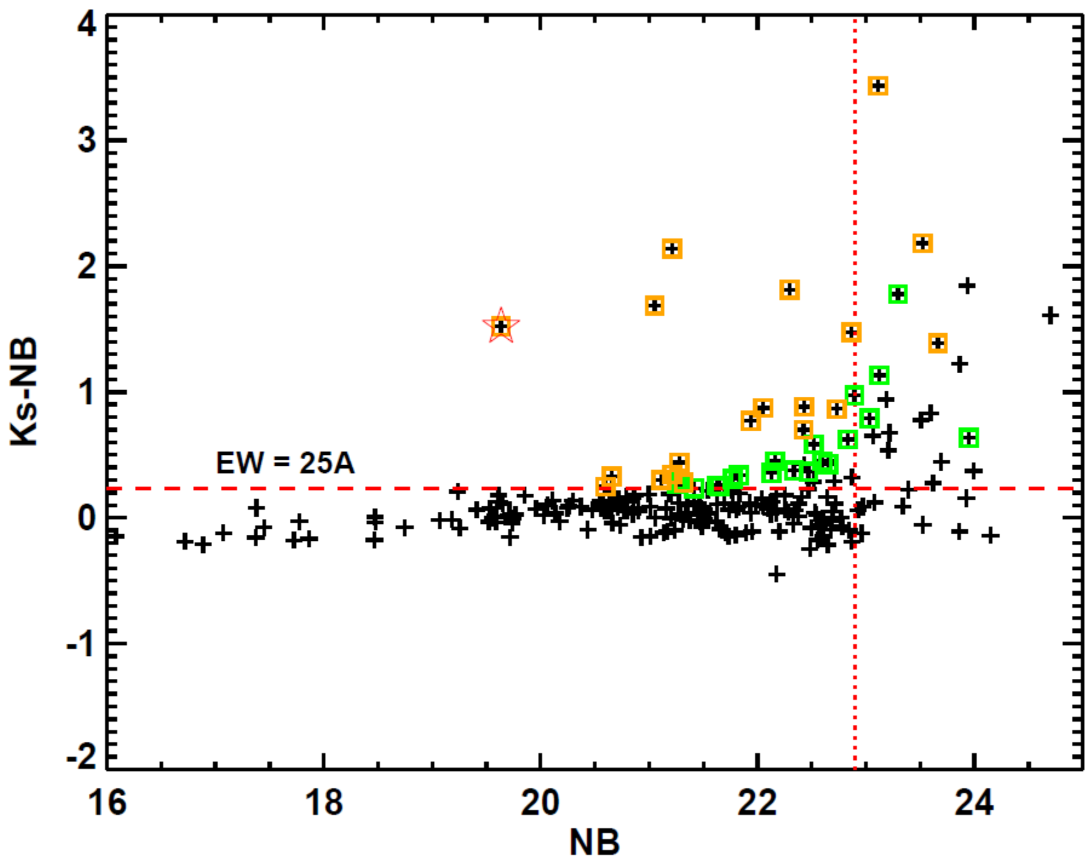
- Look for excess NB flux compared to K_s image





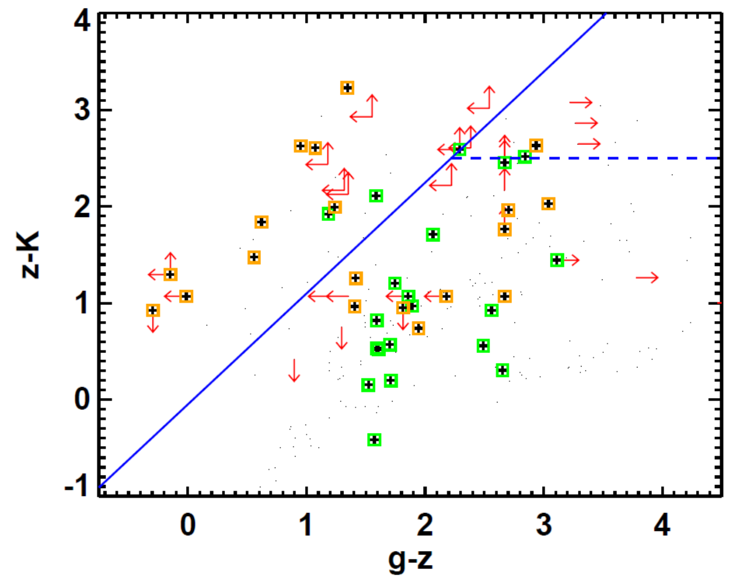
Sample selection

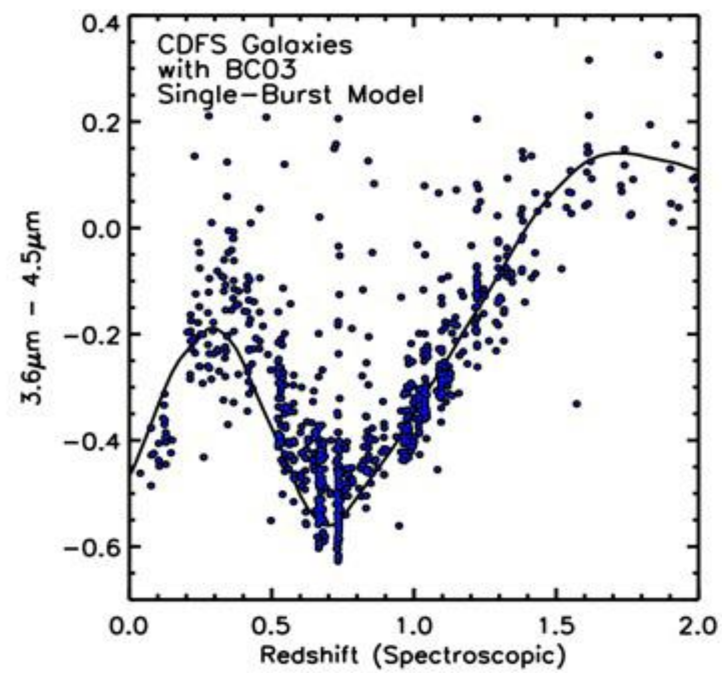
- Ks−NB colour vs NB magnitude
- $\Sigma > 2$
  - Selection in SFR



Sample selection

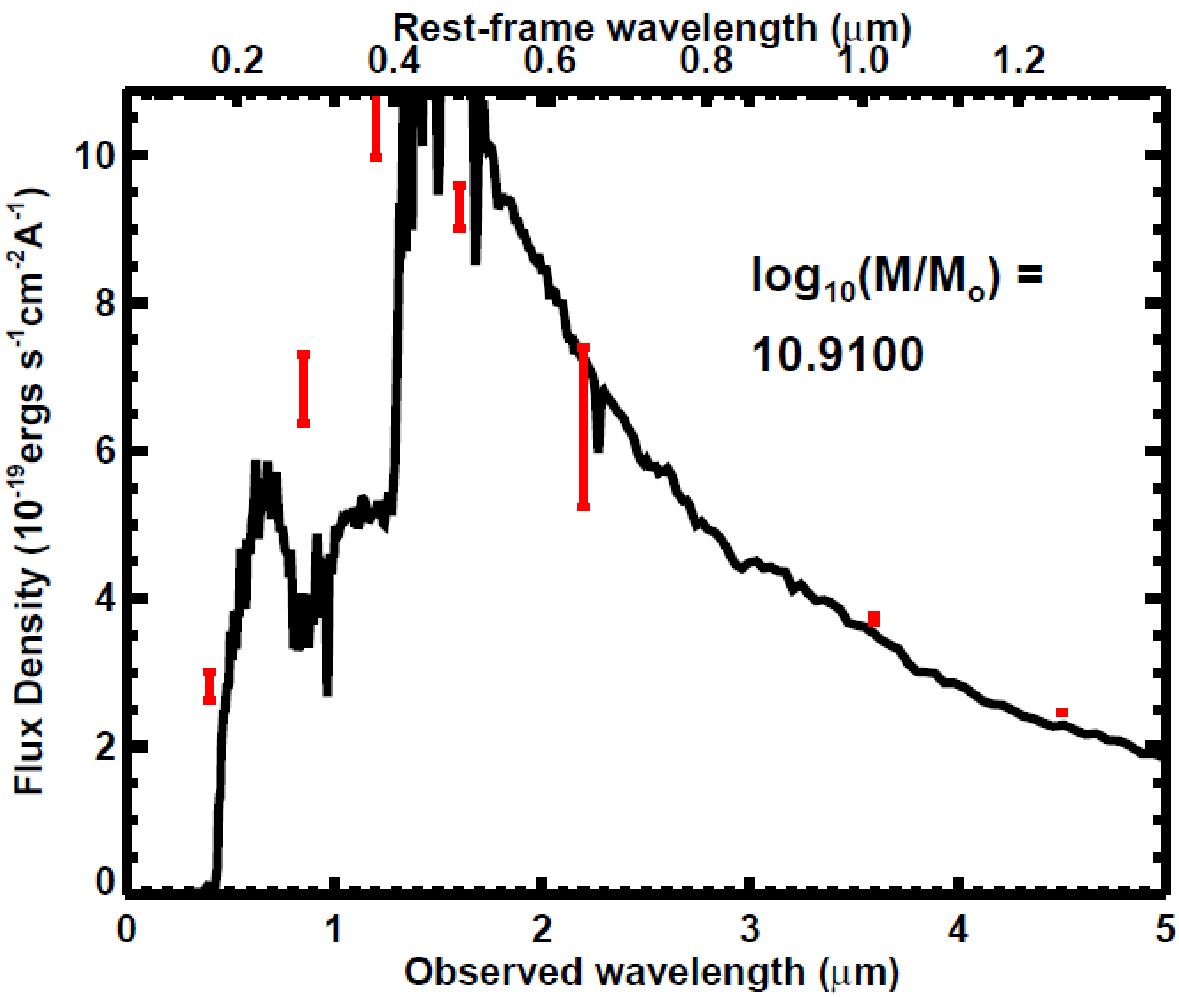
- Remove low-z contaminants
- BzK
  $(B-z) - (z-K) > -0.2$
  (Daddi et al., 2004)
- IRAC
  $[3.6]-[4.5] > -0.1$
  (Papovich et al., 2008)



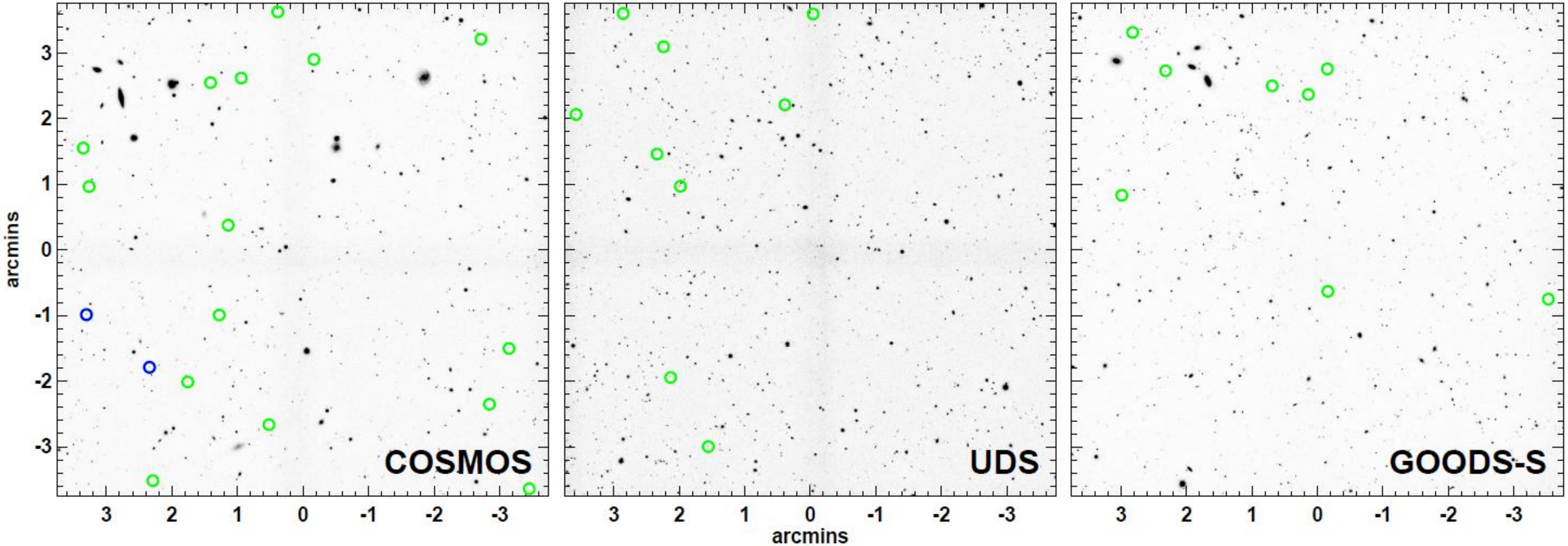


SED fitting

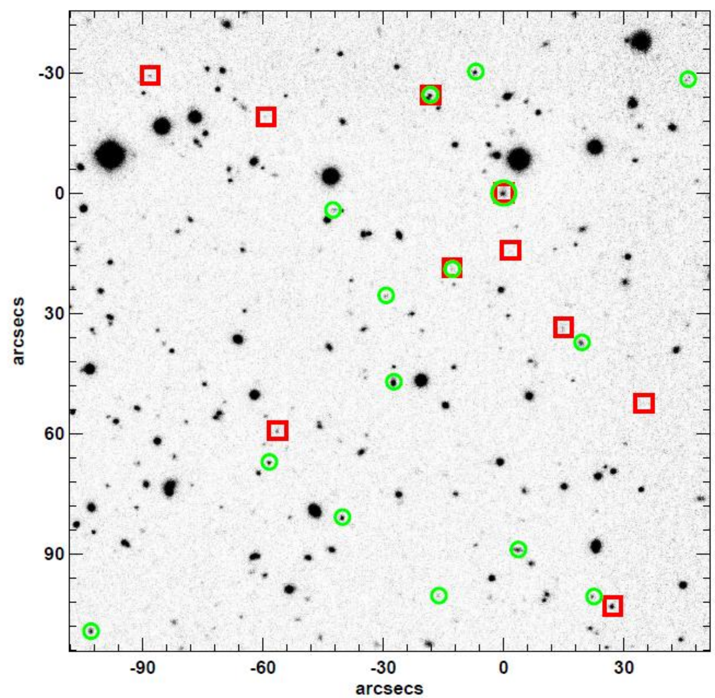
- FAST
  (Kriek et al., 2009, *ApJ*)
- SEDs robust measure of mass
- Line emission not accounted for
- Constrained redshift to centre of NB filter

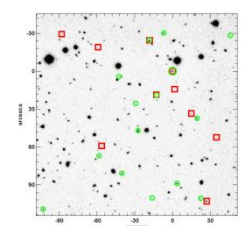


Results



Green : Hα emitters
Blue : AGN
Red : red galaxies





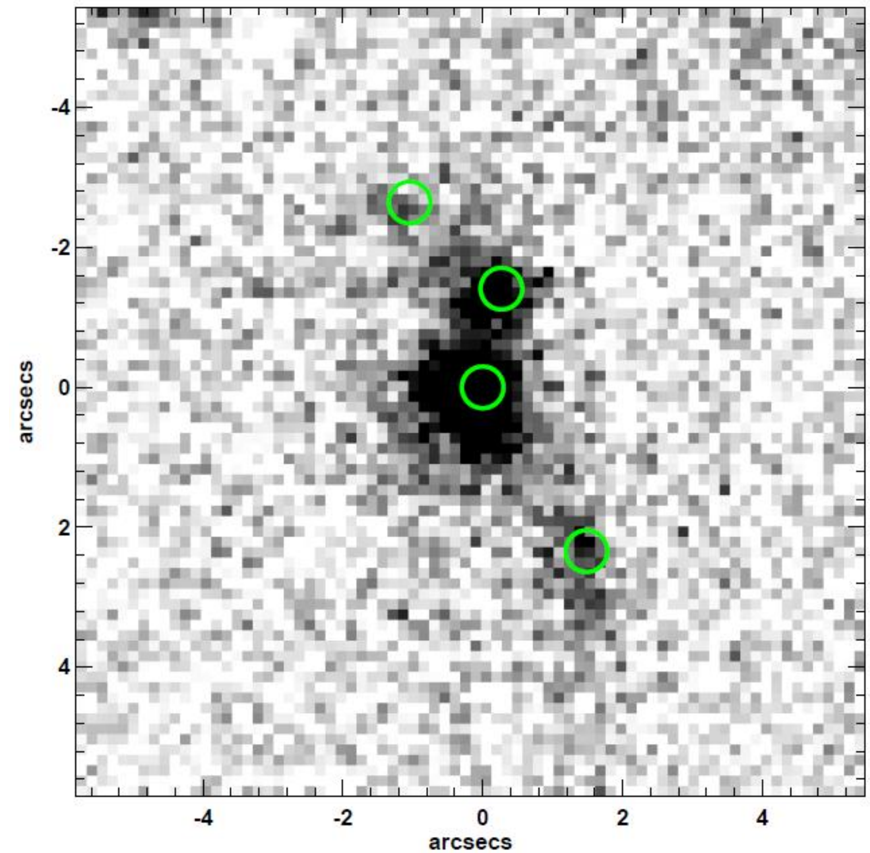
Overdense

- Spatial density of 8 x control field density
- Overdensity of same order as other protoclusters (e.g. Hayashi et al., 2012; Hatch et al., 2011b; Kurk et al., 2004)

MRC2104	COSMOS	UDS	GOODS-S
17 sources	34 sources (total)		
A = 7.09 sq arcmin	A =170.4 sq arcmin (total)		

Properties

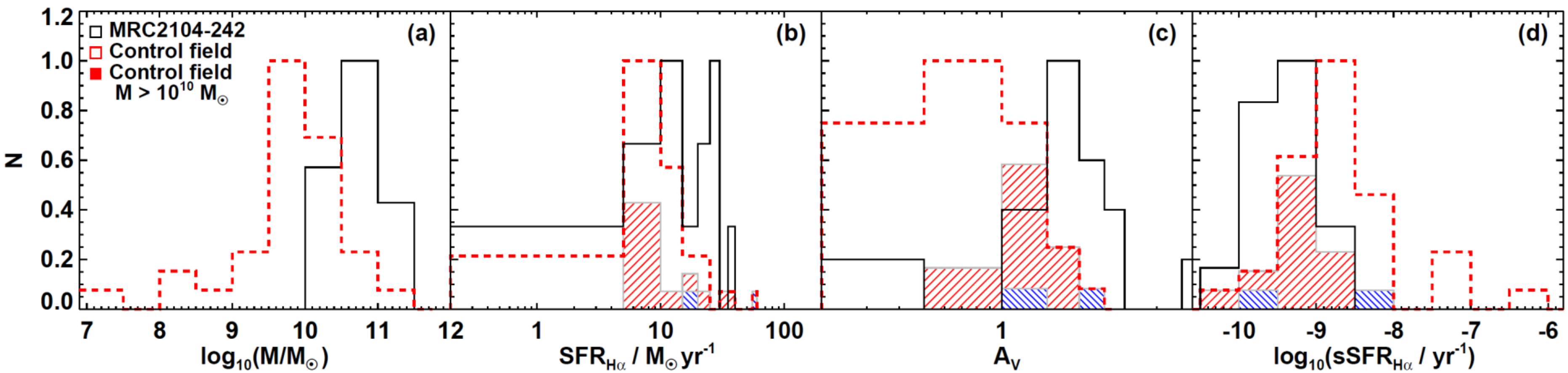
- Radio galaxy and “companions” not included



Properties

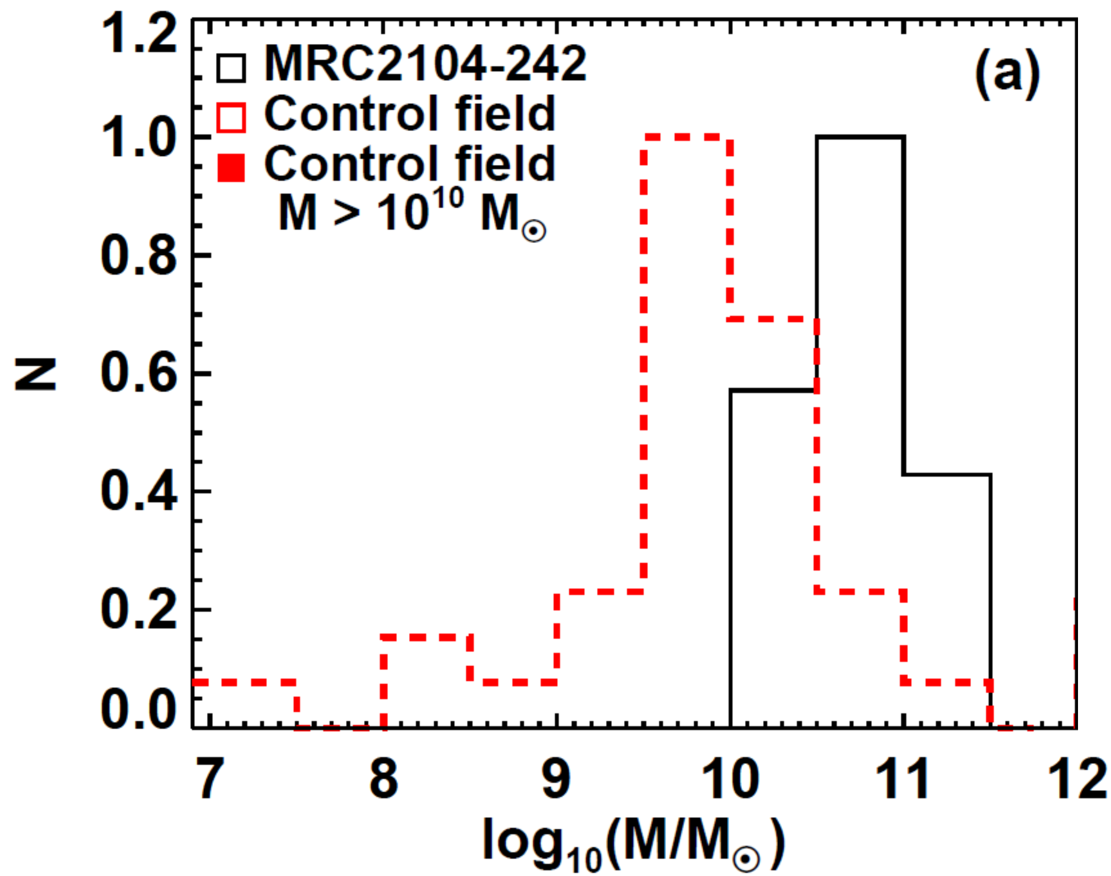
- Radio galaxy and “companions” not included
- Suspected AGN in blue

Mass	SFR	A_V	sSFR



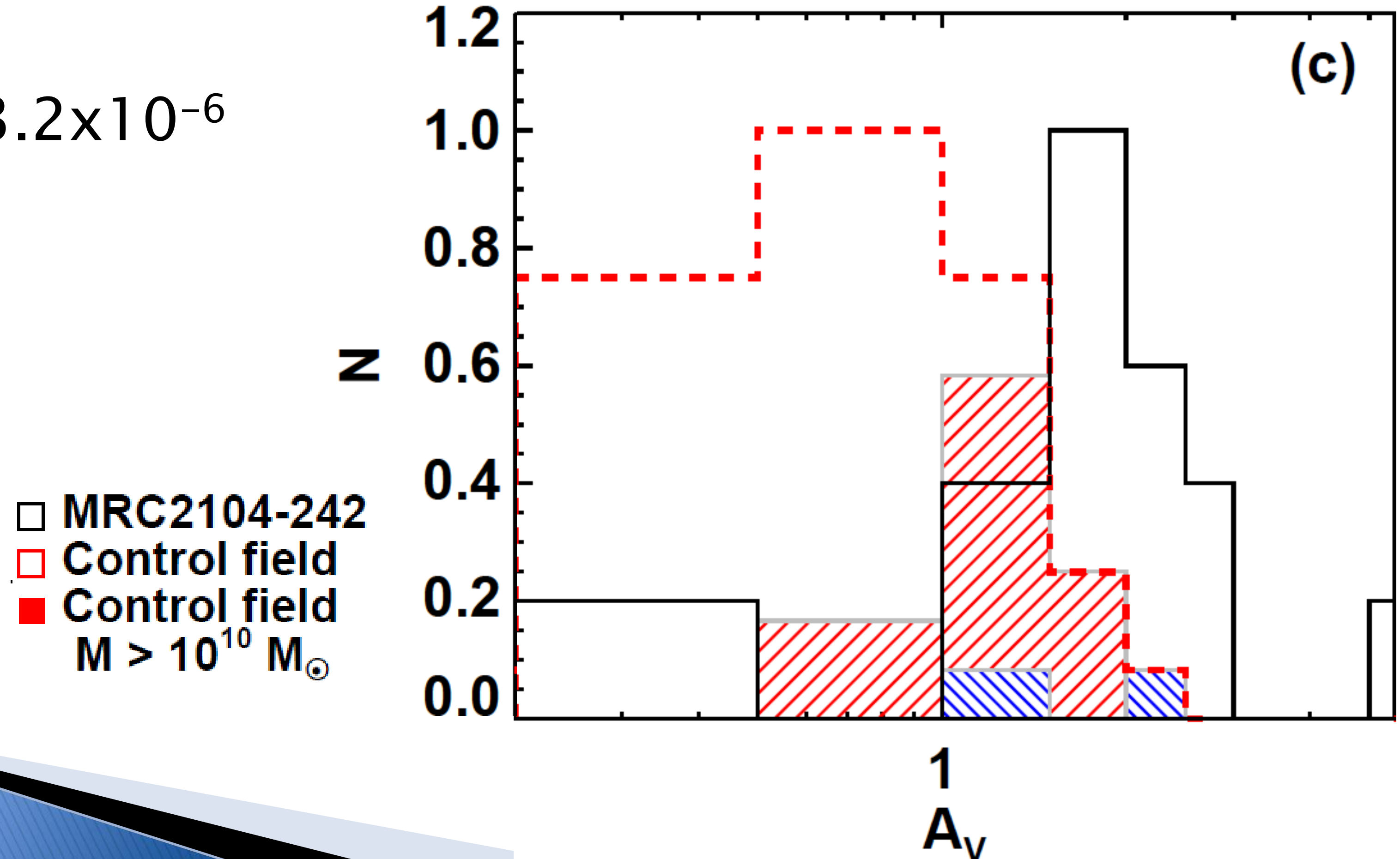
Properties

- Masses from SED fits
- KS = 2.2×10^{-5}
- Consistent with previous surveys
  - Steidel et al., 2005
  - Hatch et al., 2011b
  - Koyama et al., 2013



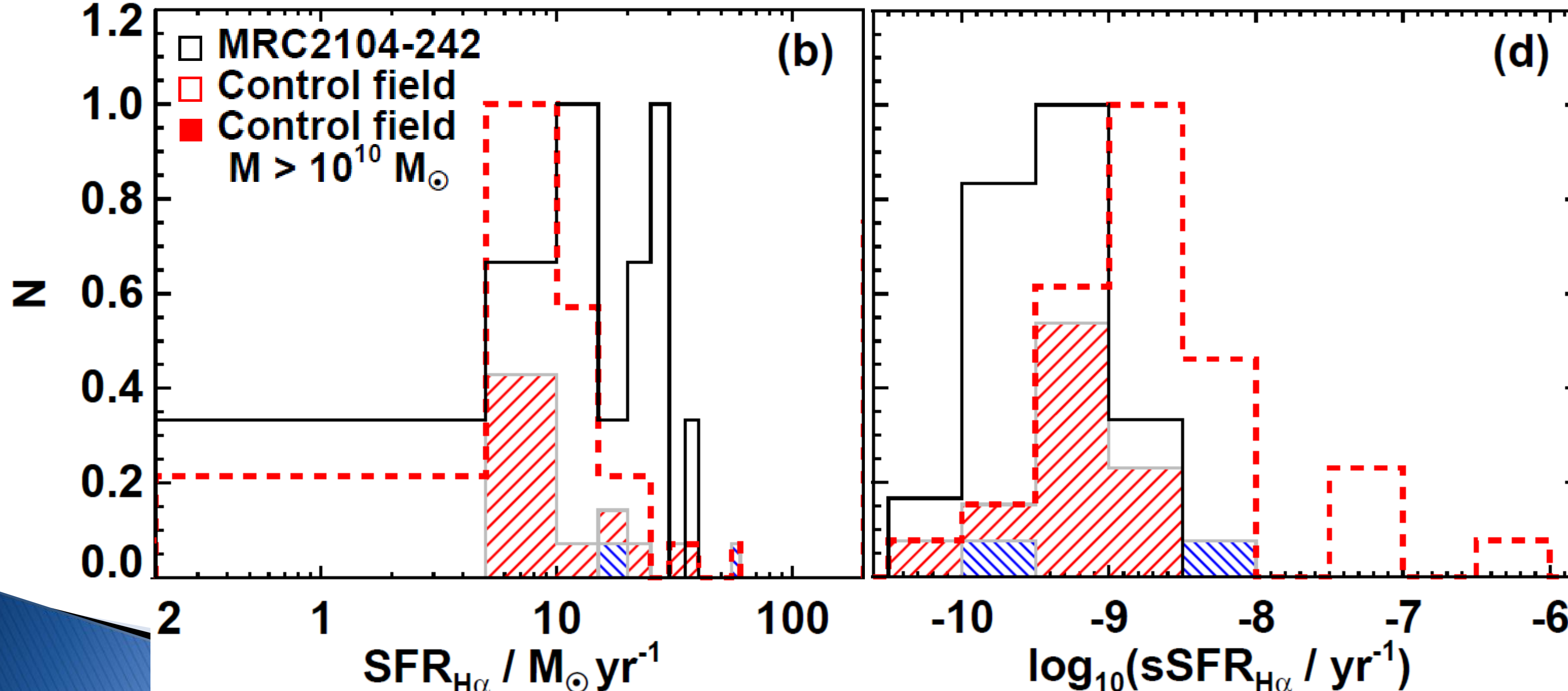
Properties

- A_V from UV slope
  - $E(B-V) = 0.25(B-z + 0.1)_{AB}$ (Daddi et al., 2004)
- KS = 3.2×10^{-6}



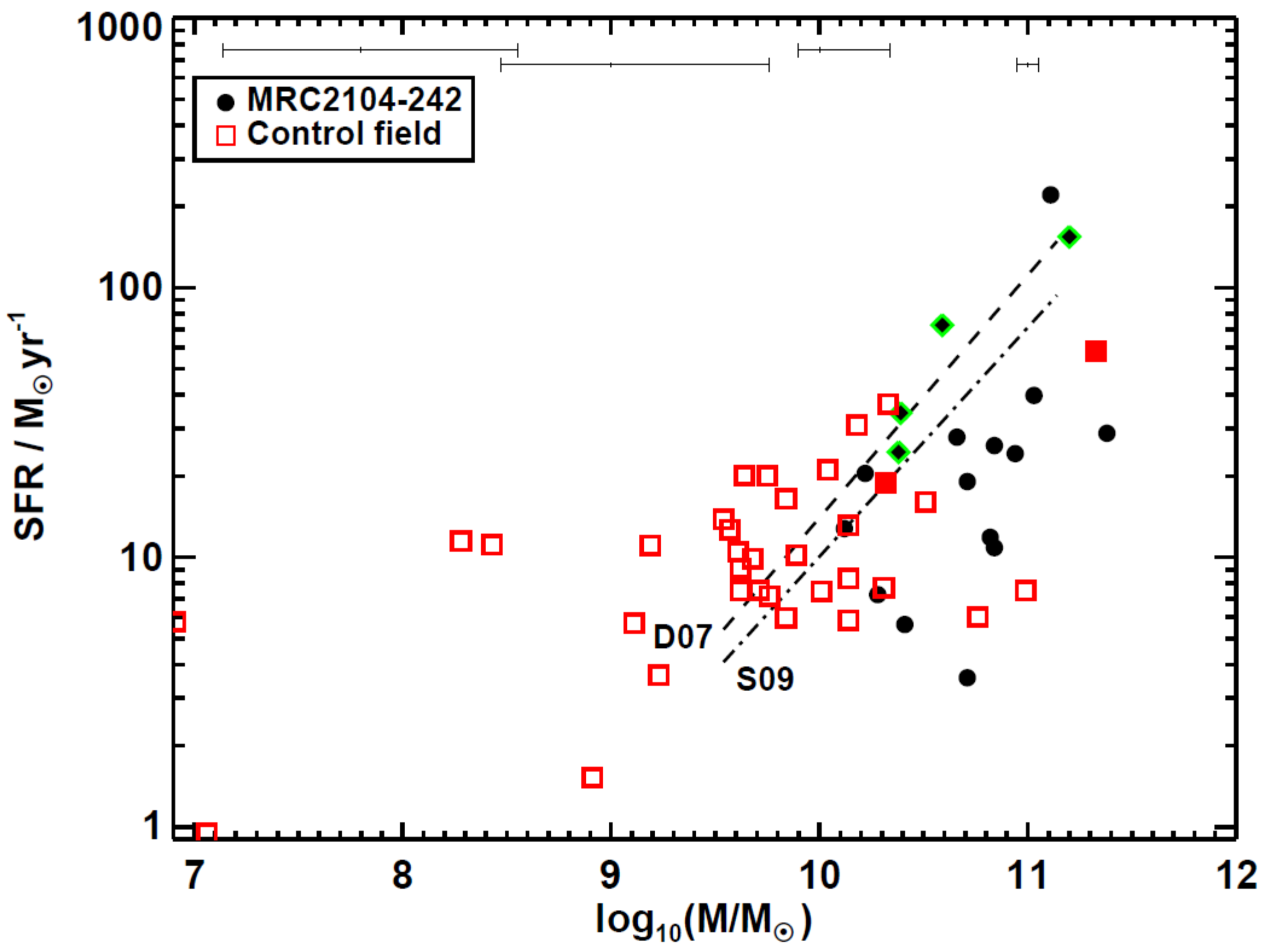
Properties

- SFR/sSFR from Hα fluxes
- KS >0.05 for $M > 10^{10} M_{\odot}$



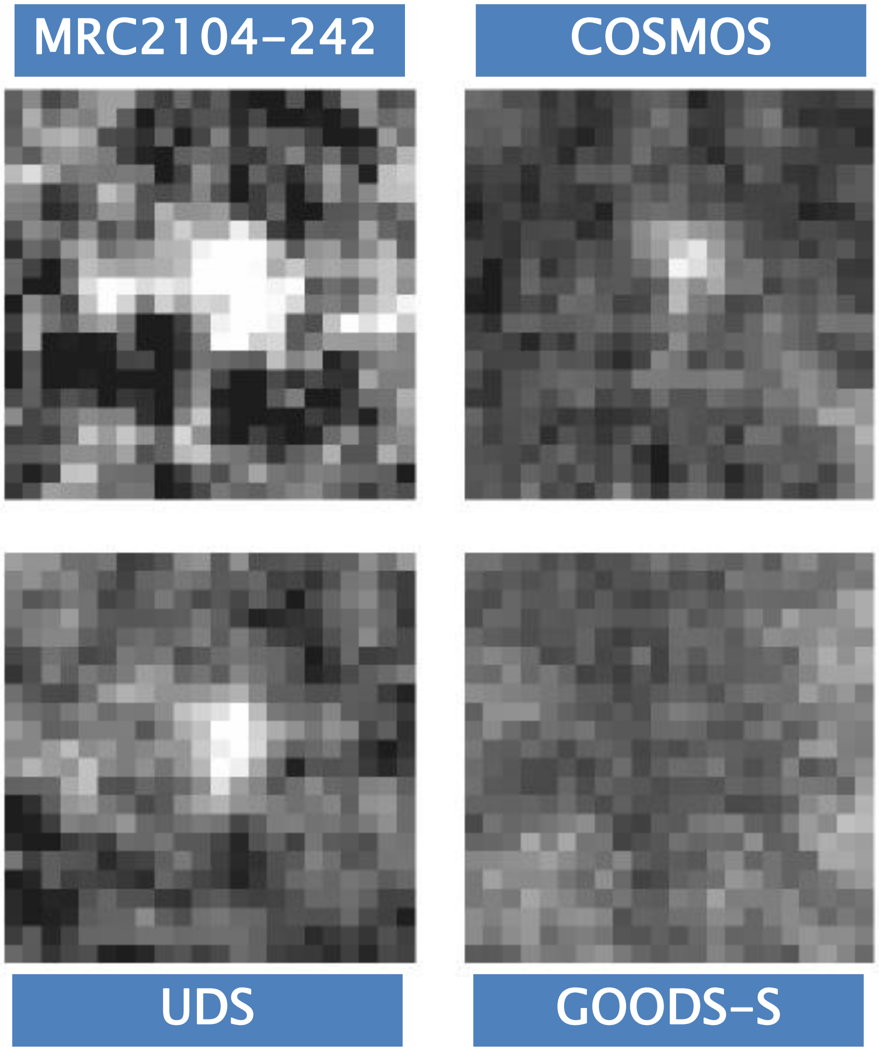
SFR–mass relation

- Hα SFR
- Corrected for extinction
- Same sSFR– no starbursts
- MRC2104 galaxies more massive/star forming



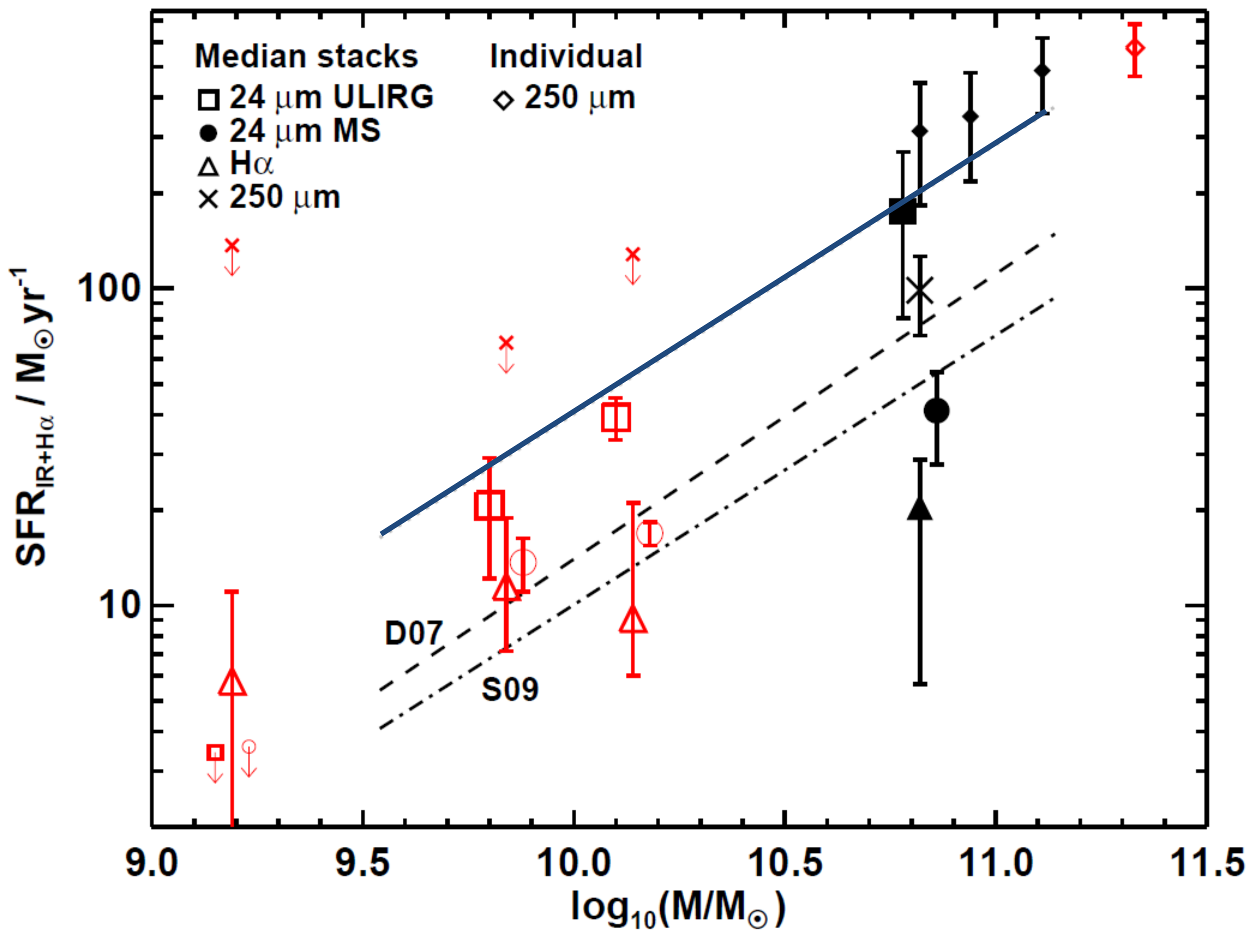
IR SFRs

- Stacked MIPS 24μm images
- Calculate SFR in 2 ways:
  - ULIRGs (Reike et al., 2009)
  - Main sequence (Rujopakarn et al., 2013)



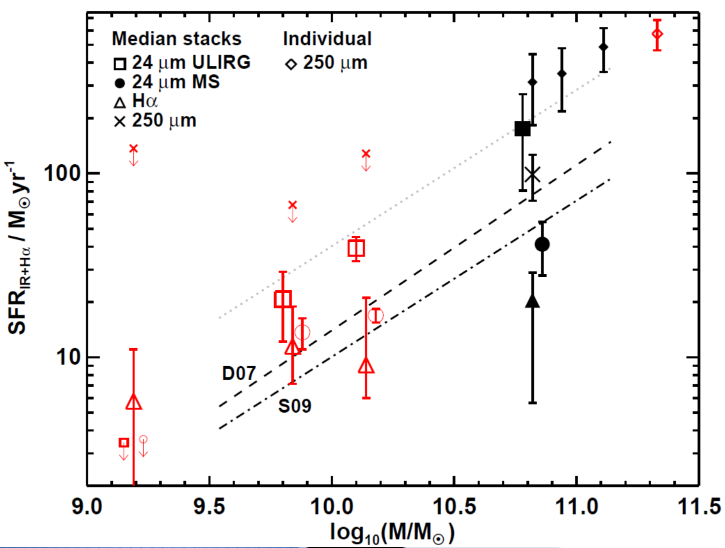
SFR–mass relation

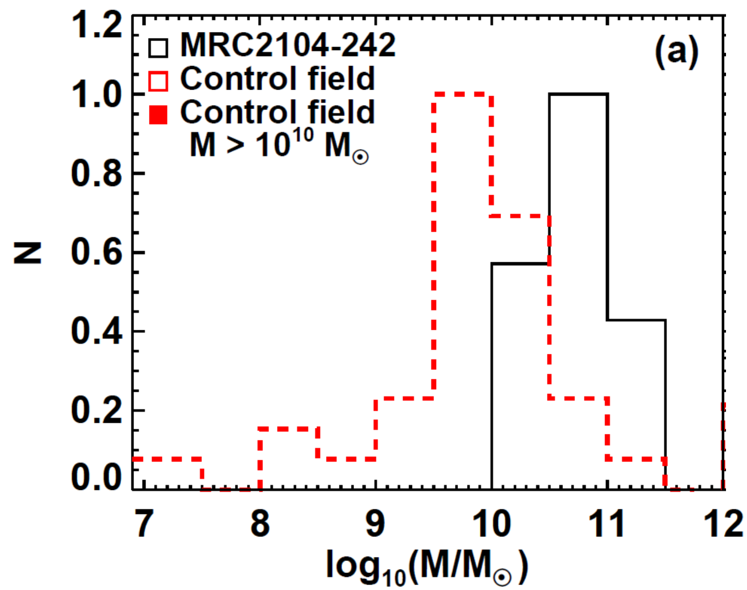
- IR+Hα SFR
- More hidden SF in protocluster
- Possible starbursts (2σ)



Discussion

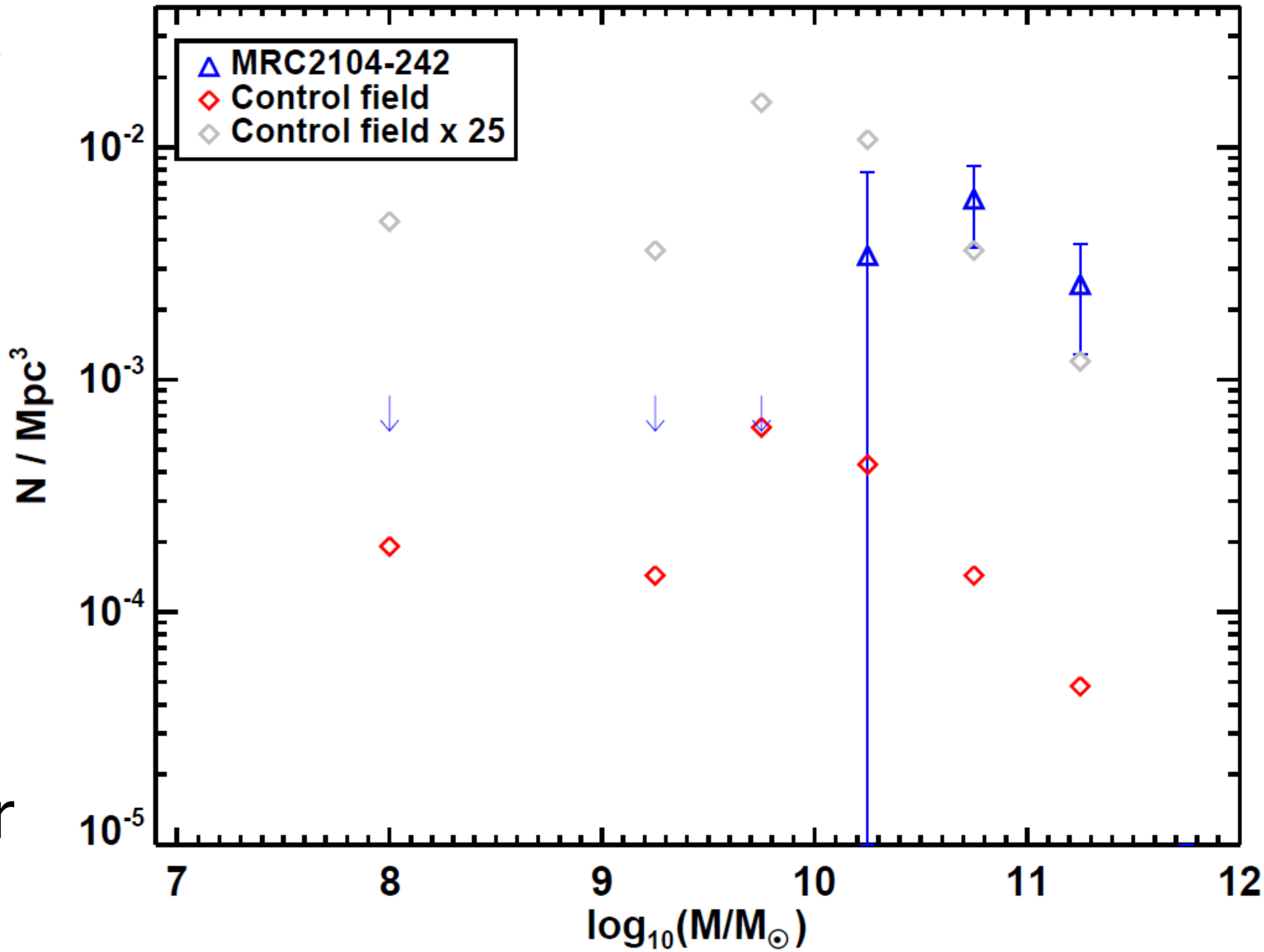
- SFR–mass relation of protocluster and control field galaxies are consistent
- Observed mass distributions very different
  - Overdensity function of mass





Mass distributions

- At $M>10^{10}M_{\odot}$ protocluster is 25x control field density
- Lack of low mass objects seen in protocluster



Where are the low mass objects?

- Mass functions
- Observational effects
  - Dust
  - Quenching
- Mass segregation

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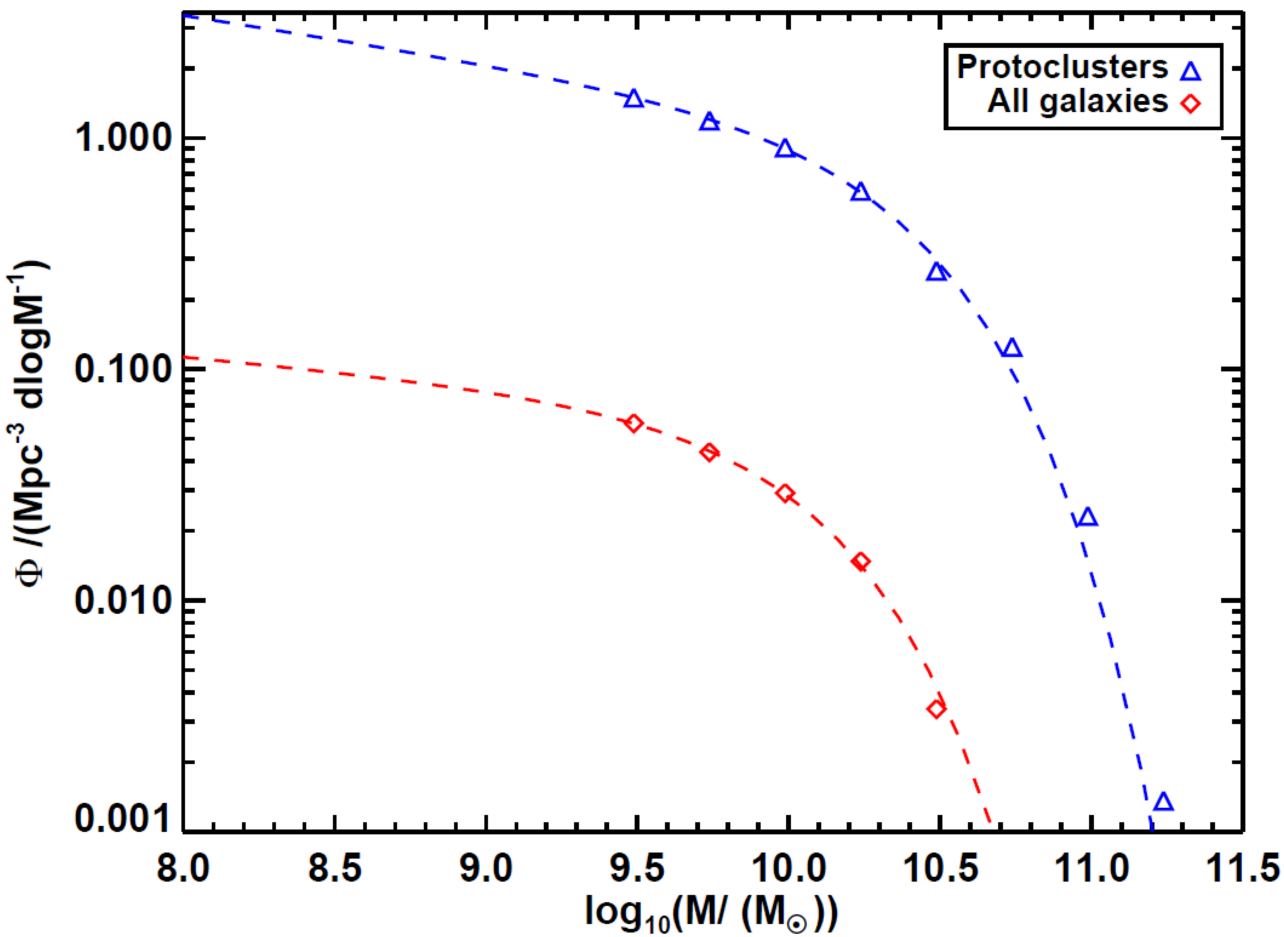

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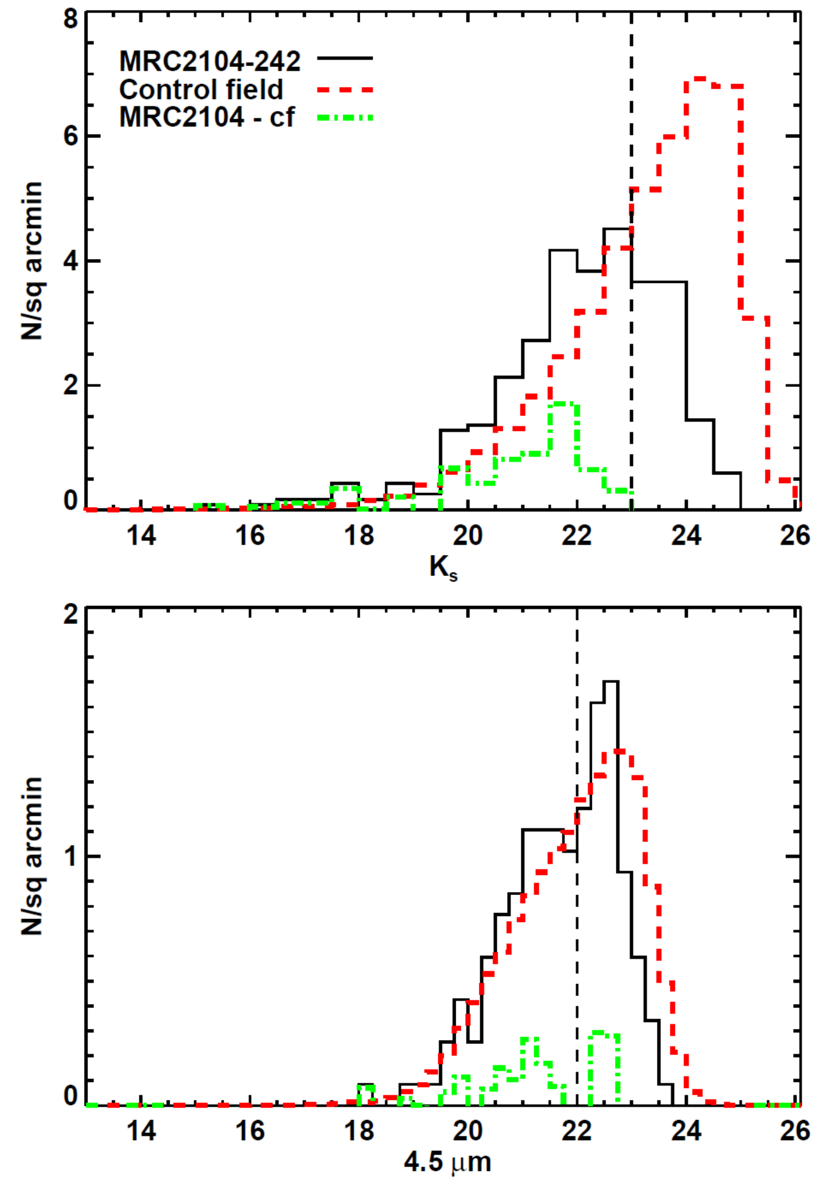

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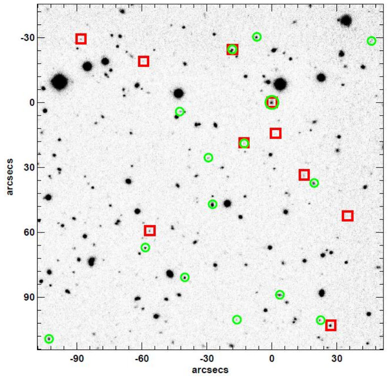


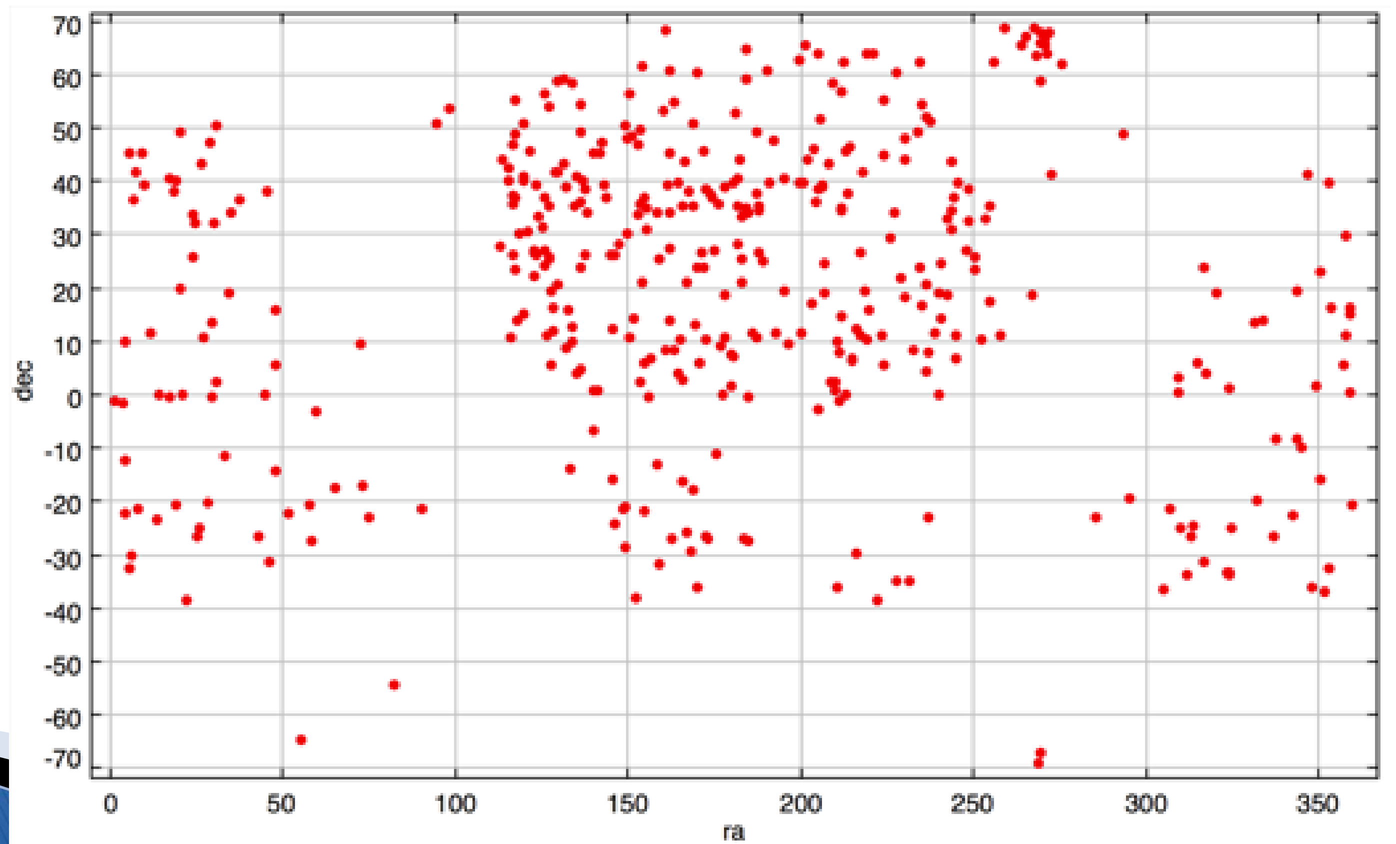
Circle = 10 Mpc diameter, comoving

Conclusions on MRC2104

- 8x density of control field – protocluster
- Protocluster galaxies are more massive and have more hidden star formation
  - Mass effect
- Average SFR–mass relations are the same in both environments
- Large difference in the mass distributions
  - Expect 21–22 galaxies in the protocluster at $M < 10^{10} M_\odot$
  - Higher level of dust extinction in low mass galaxies in the protocluster?
  - Protocluster forming more high mass galaxies
    - monolithic collapse ?
    - undergoing more mergers in the early stages of their growth?
- Tentative evidence of a larger fraction of starburst galaxies in the protocluster than in the control field
  - Further data required to confirm 250μm detections
- Need a larger selection of protoclusters

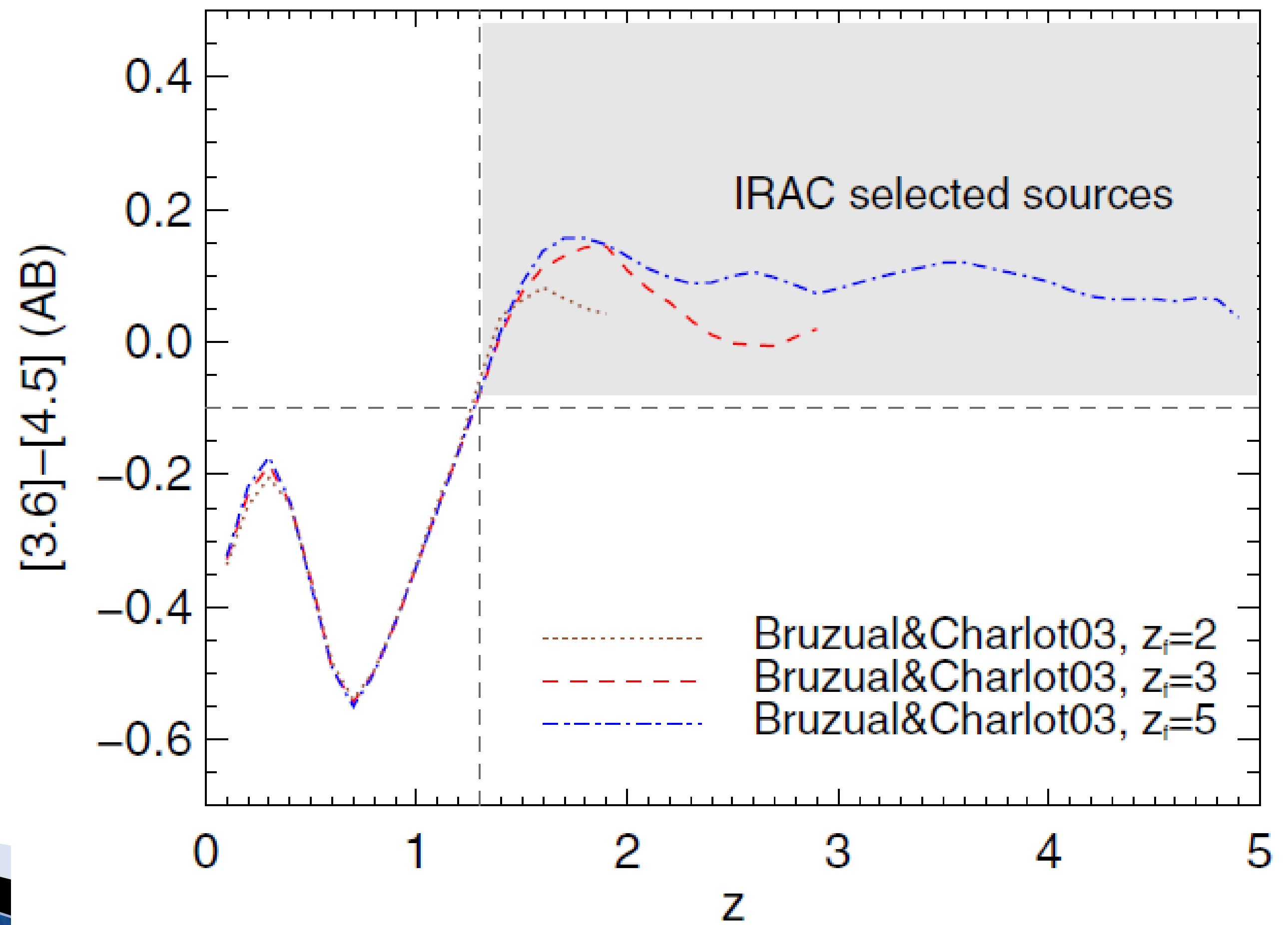
CARLA

- **C**lusters **A**round **R**adio-**L**oud **A**GN
- Spitzer: ~400 hours
- 419 RLAGN



CARLA

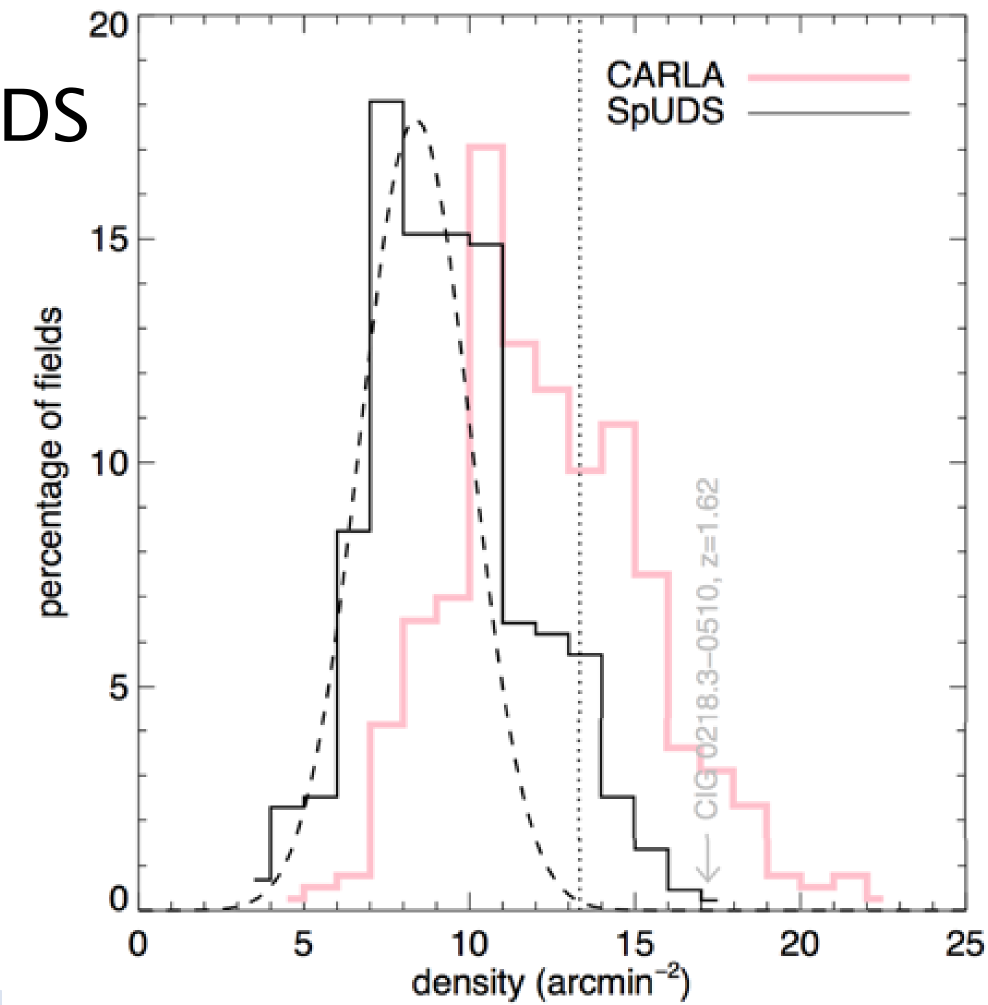
- Spitzer IRAC selection
  - [3.6] – [4.5] > −0.1



CARLA

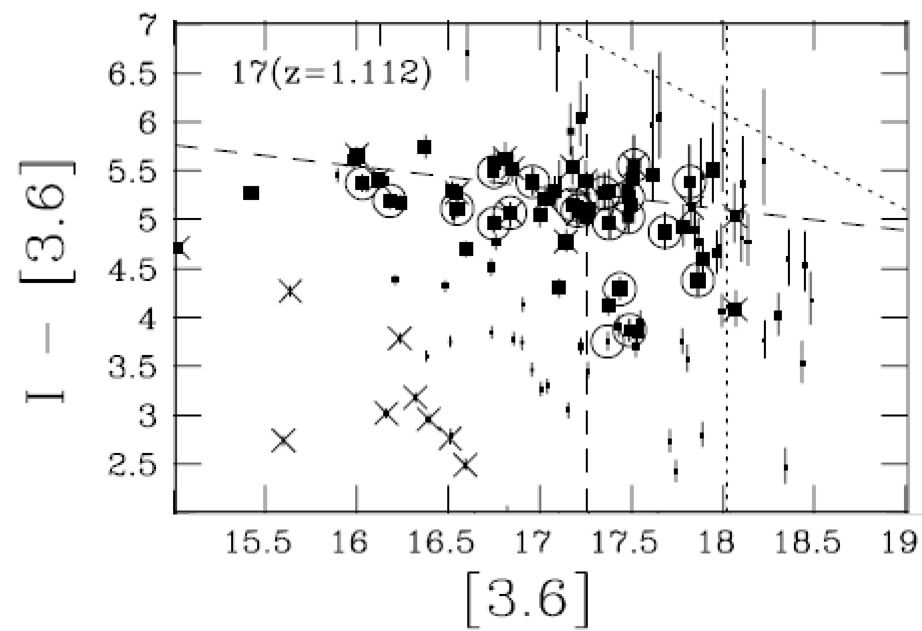
- Density- RLAGN in overdense environments
- 92% denser than SpUDS peak
- 55% >2σ
- 37% >3σ

(Wylezalek et al. 2013)



Optical follow-up

- i′ band
  - looking for evolved galaxies that have quenched SF and moved onto the red sequence

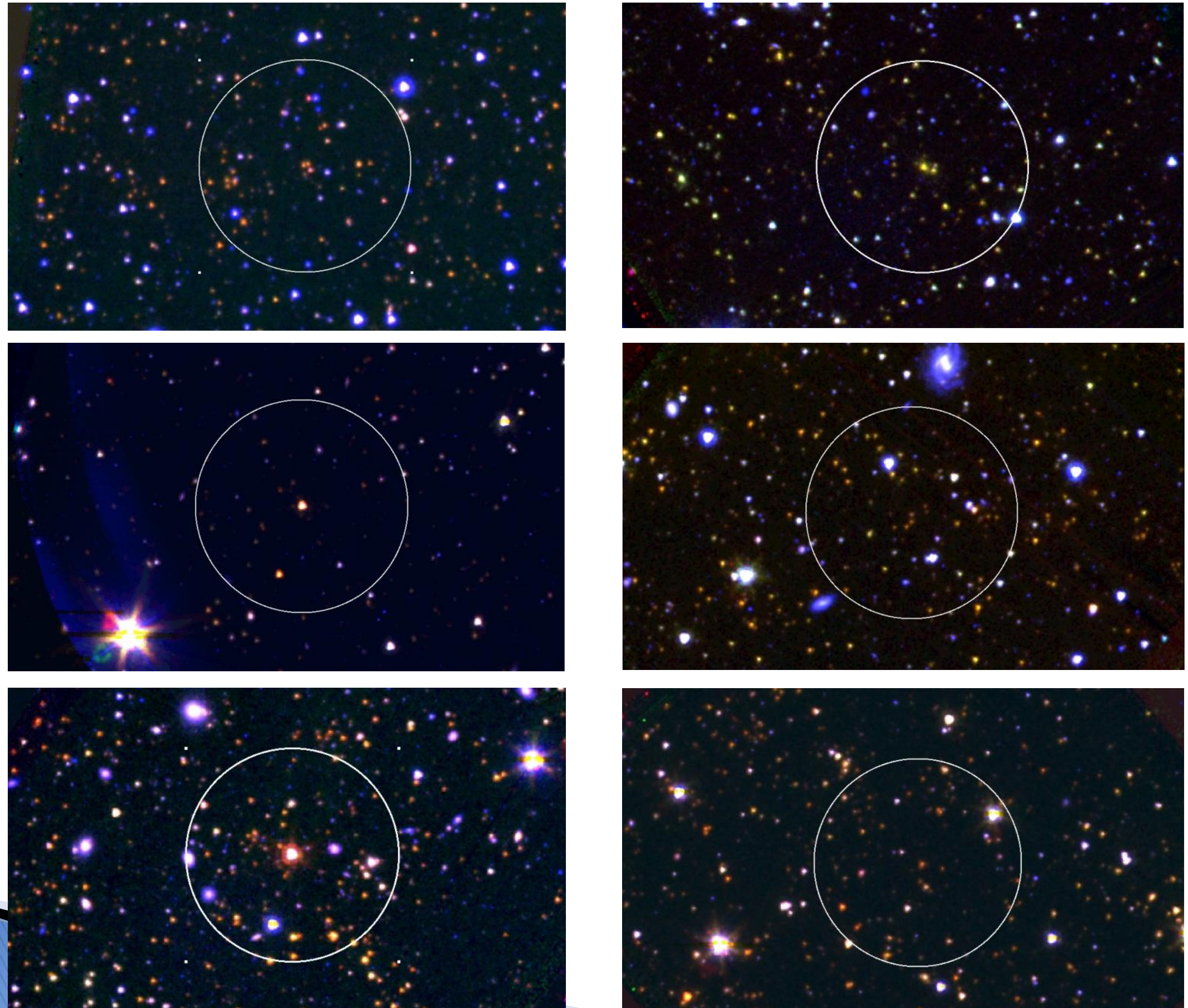


(From Eisenhardt et al., 2008)

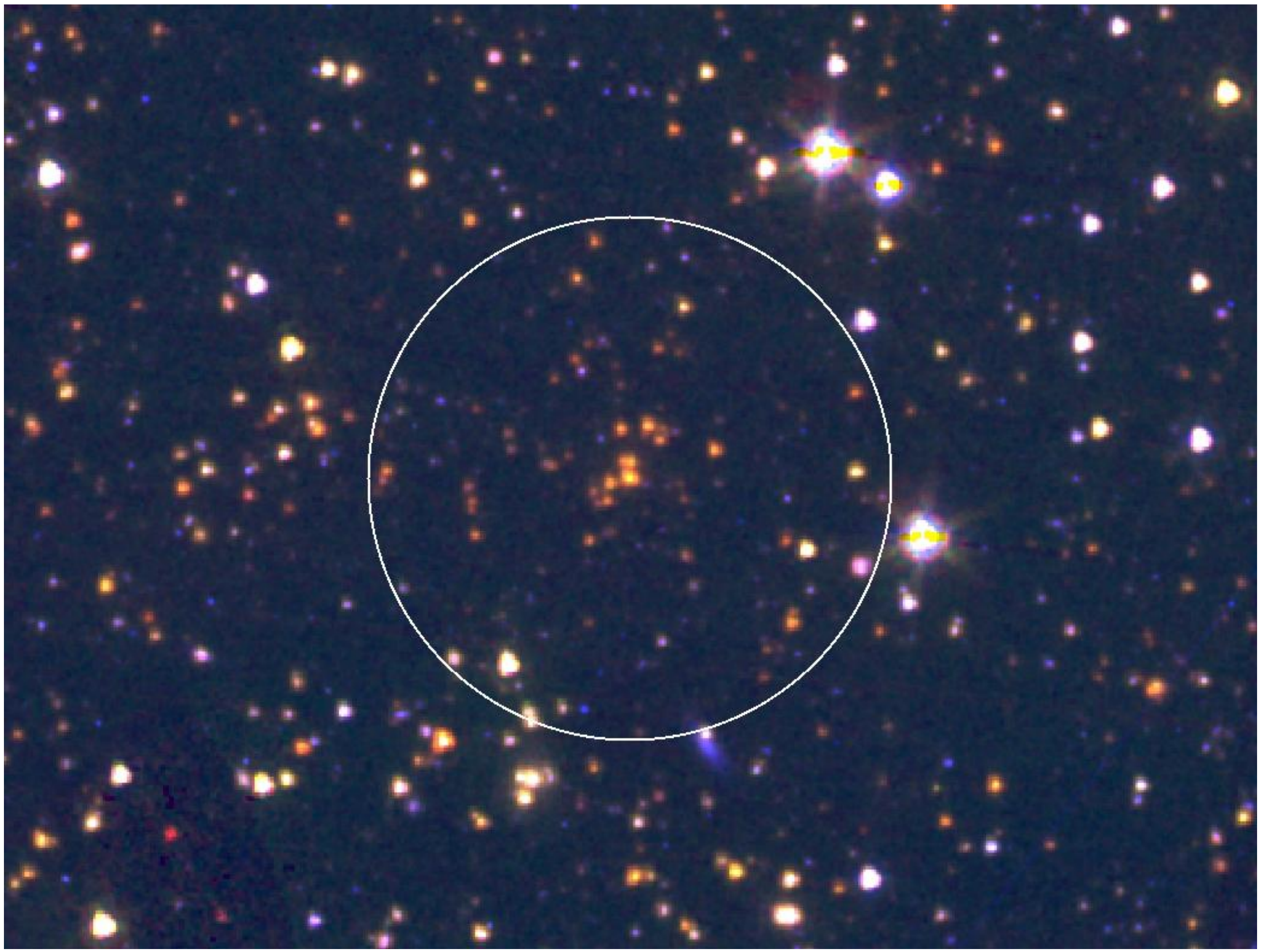
i′ band imaging

- WHT: ACAM
- 2 hours per target
- ~30 targets in total

i′, [3.6], [4.5]

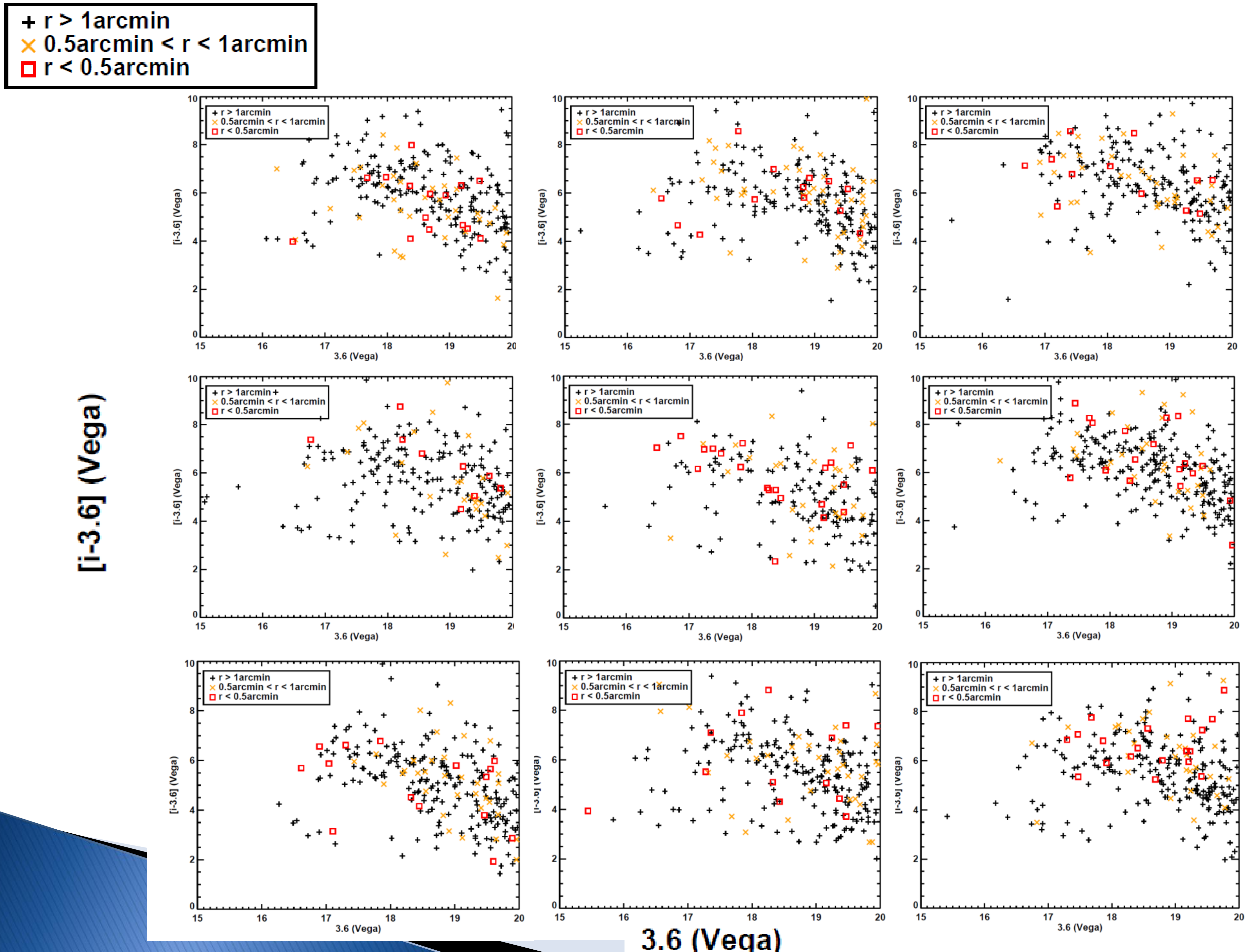


i′, [3.6], [4.5]

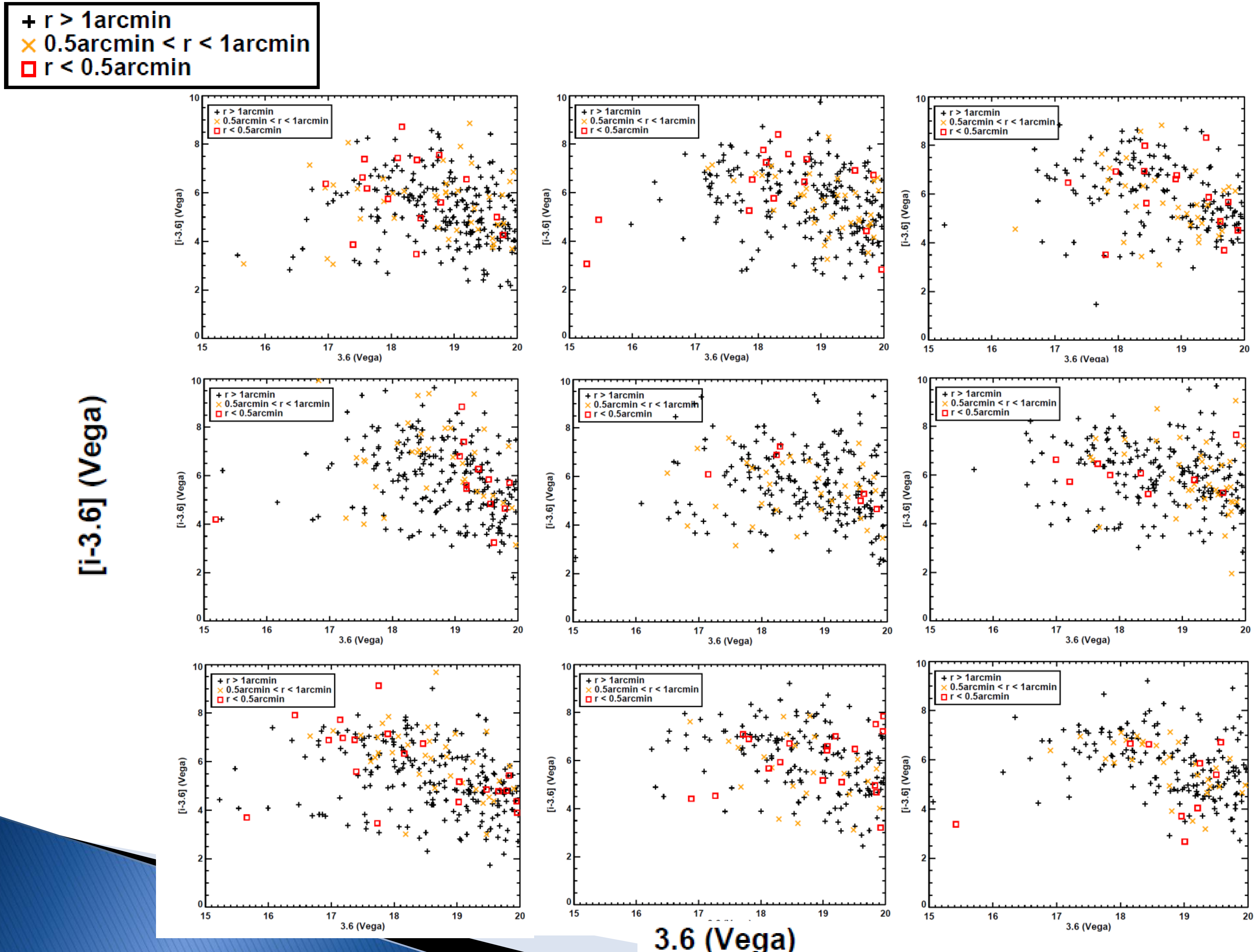


Circle = 1 arcmin

Colour–Magnitude diagrams



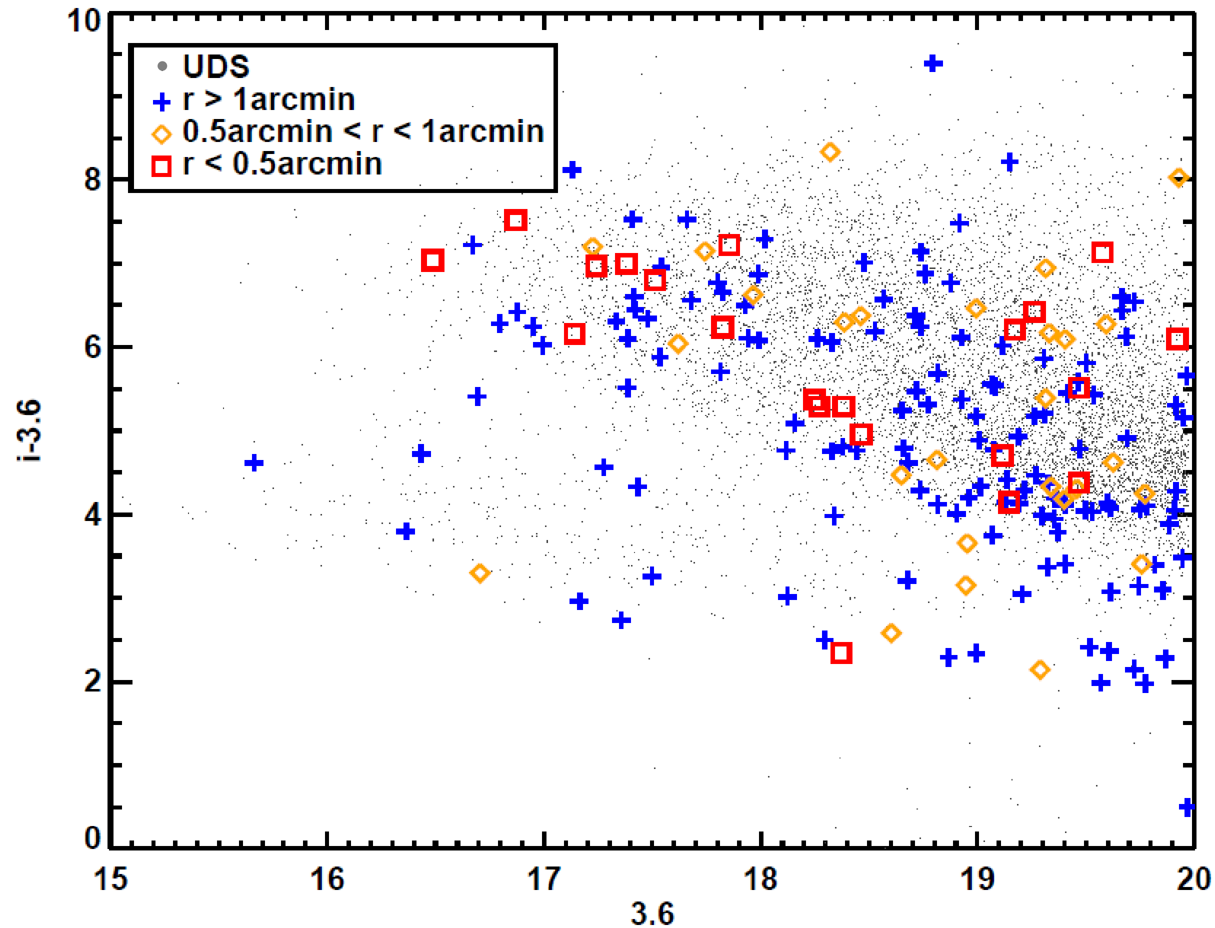
+ r > 1arcmin
× 0.5arcmin < r < 1arcmin
□ r < 0.5arcmin
[i-3.6] (Vega)
3.6 (Vega)



+ r > 1arcmin
× 0.5arcmin < r < 1arcmin
□ r < 0.5arcmin
[i-3.6] (Vega)
3.6 (Vega)

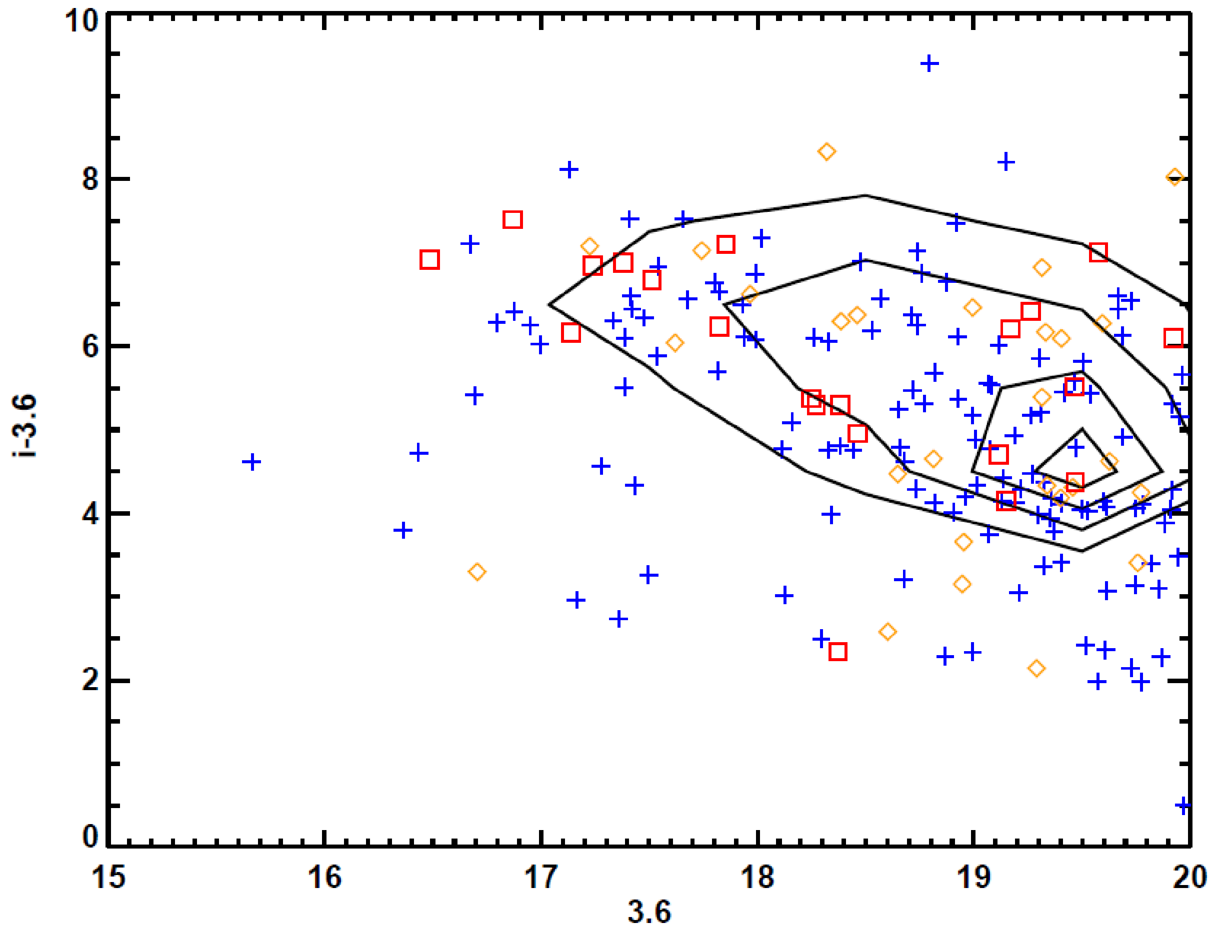
Colour–Magnitude diagrams

- Control field = UDS (1 sq.deg)



Colour–Magnitude diagrams

- Statistically subtract contaminants



Colour–Magnitude diagrams

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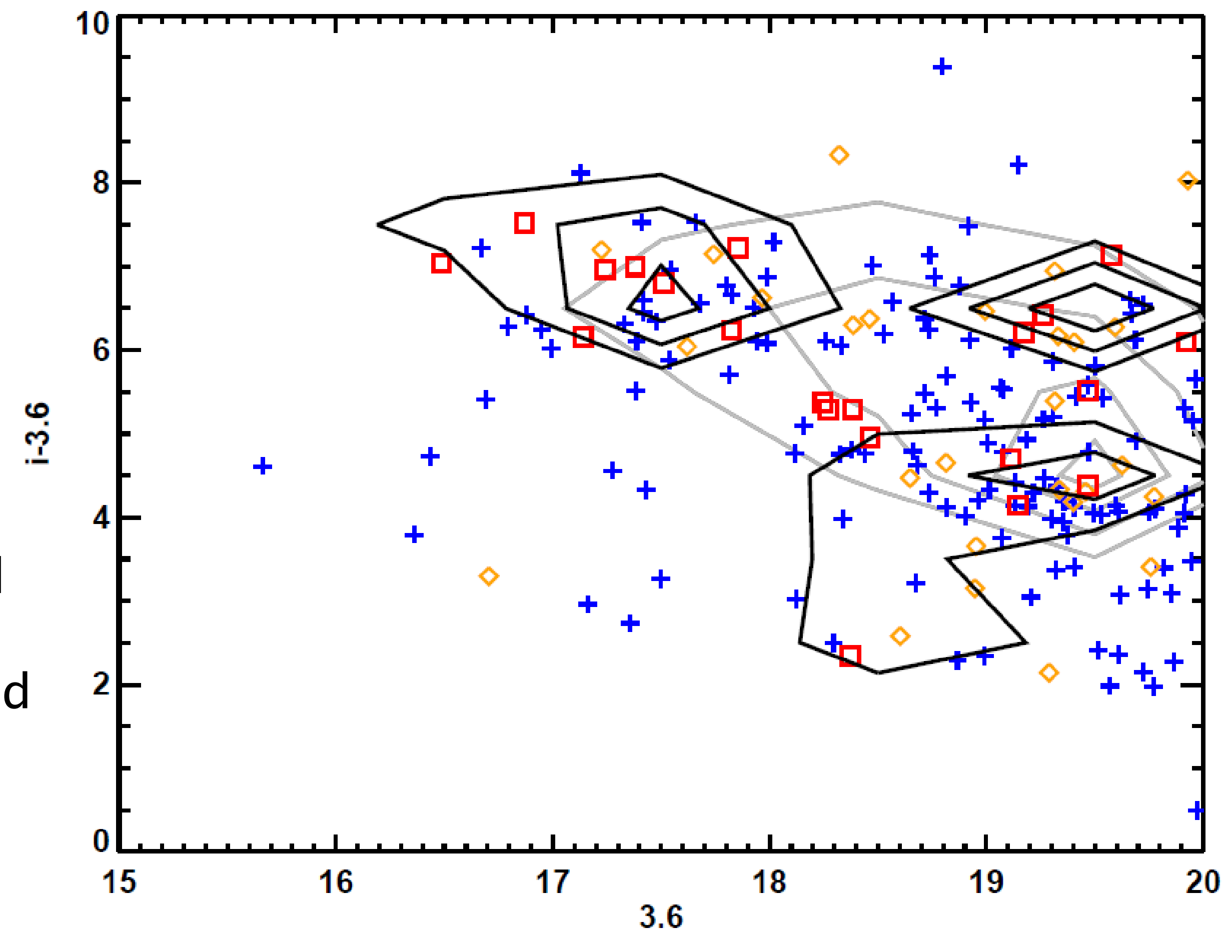
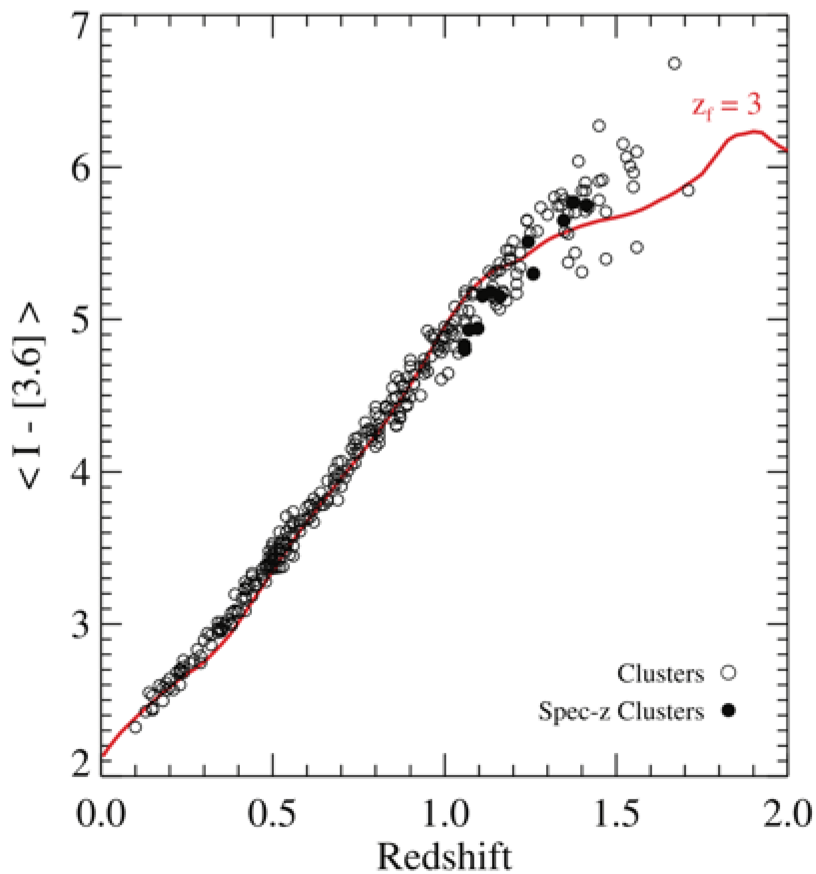


Grey = UDS control field
Black =
target field – control field

Lower z

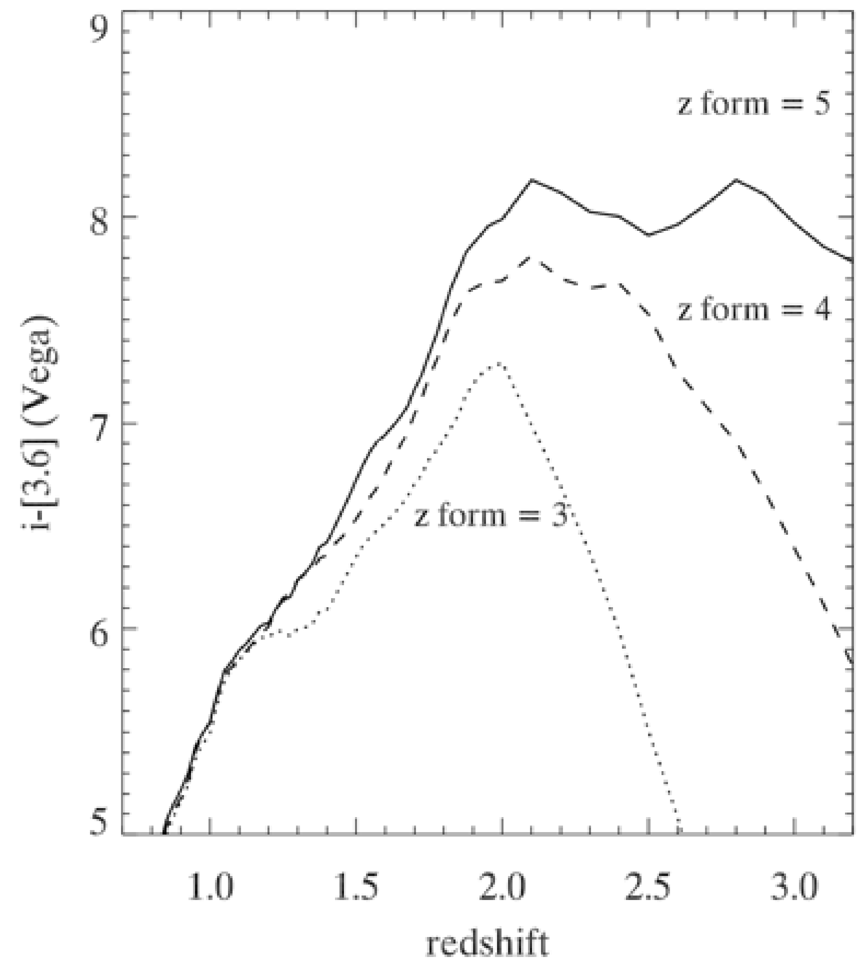
- Low z <i–[3.6]>

(Eisenhardt et al. 2008)



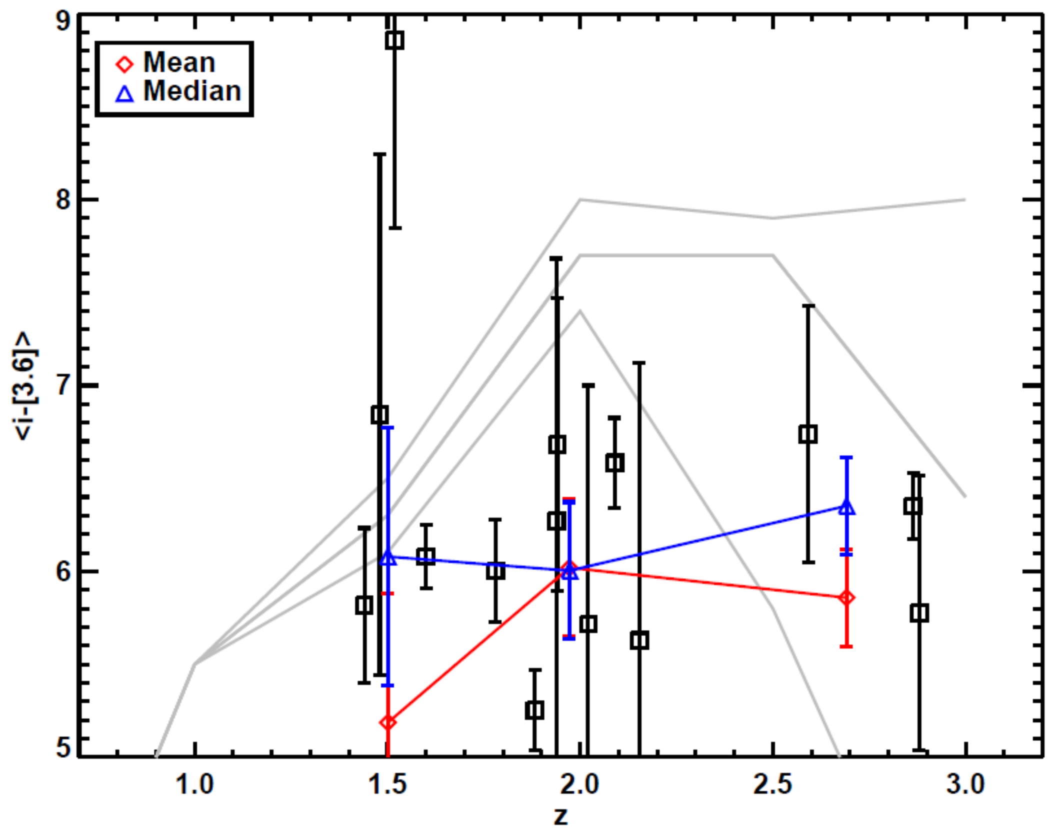
High z

- <i–[3.6]> can distinguish between different formation redshifts



Results so far

- First look: difficult to see any trend



Conclusions

- Average RS galaxy colour can indicate z_f for cluster
- Large sample of clusters required due to hugely varying cluster to cluster properties
- Work in progress, next steps:
  - Improve contamination subtraction
  - Measure strength/scatter of any red sequences