



Proto-clusters: searches and studies

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Growing up at high redshift: from proto-clusters to galaxy clusters
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Overview

- Introduction
- Finding proto-clusters
- Characteristics of proto-clusters
- Proto-cluster galaxies
- Summary

Progenitors of low z massive clusters

- Properties of clusters in formation
- Redshift evolution of large scale structures
- Emergence of red sequence
- Influence of environment on galaxy properties
- Many galaxies at single redshift

What is a proto-cluster?

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- Structure of galaxies that will evolve into massive cluster

Cluster of galaxies → virialized → hot gas

What is a proto-cluster?

- Structure of galaxies that will evolve into massive cluster
- High density of galaxies, clustered in α, δ, z
- Minimum size $\gtrsim 1$ physical Mpc
- Not virialised
 - no extended X-ray emitting gas
- Red sequence: still forming?

What is a proto-cluster?

- The grey area: $1 \lesssim z \lesssim 2$

For example: ISCS cluster Stanford+ (2005):

- clustering of galaxies in α, δ and z space
 - 5 members confirmed
- high redshift cluster of galaxies

What is a proto-cluster?

- The grey area: $1 \lesssim z \lesssim 2$

For example: ISCS cluster Stanford+ 2005:

- clustering of galaxies in α, δ and z space

- 5 members confirmed

- high redshift cluster of galaxies

or proto-cluster?

What is a proto-cluster?

- Do we really care? No
- We can still study the effects of environment on galaxy properties

What is a proto-cluster?

- Structure of galaxies that will evolve into massive cluster
- High density of (SF) galaxies, clustered in α, δ
- $\delta_{\text{galaxy}} \gtrsim 2$
- Minimum size $\gtrsim 1$ physical Mpc
- Volume should contain $> 10^{14} M_{\odot}$

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- Minimum size $\gtrsim 1$ physical Mpc
- Volume should contain $> 10^{14} M_{\odot}$
- $z \gtrsim 2$

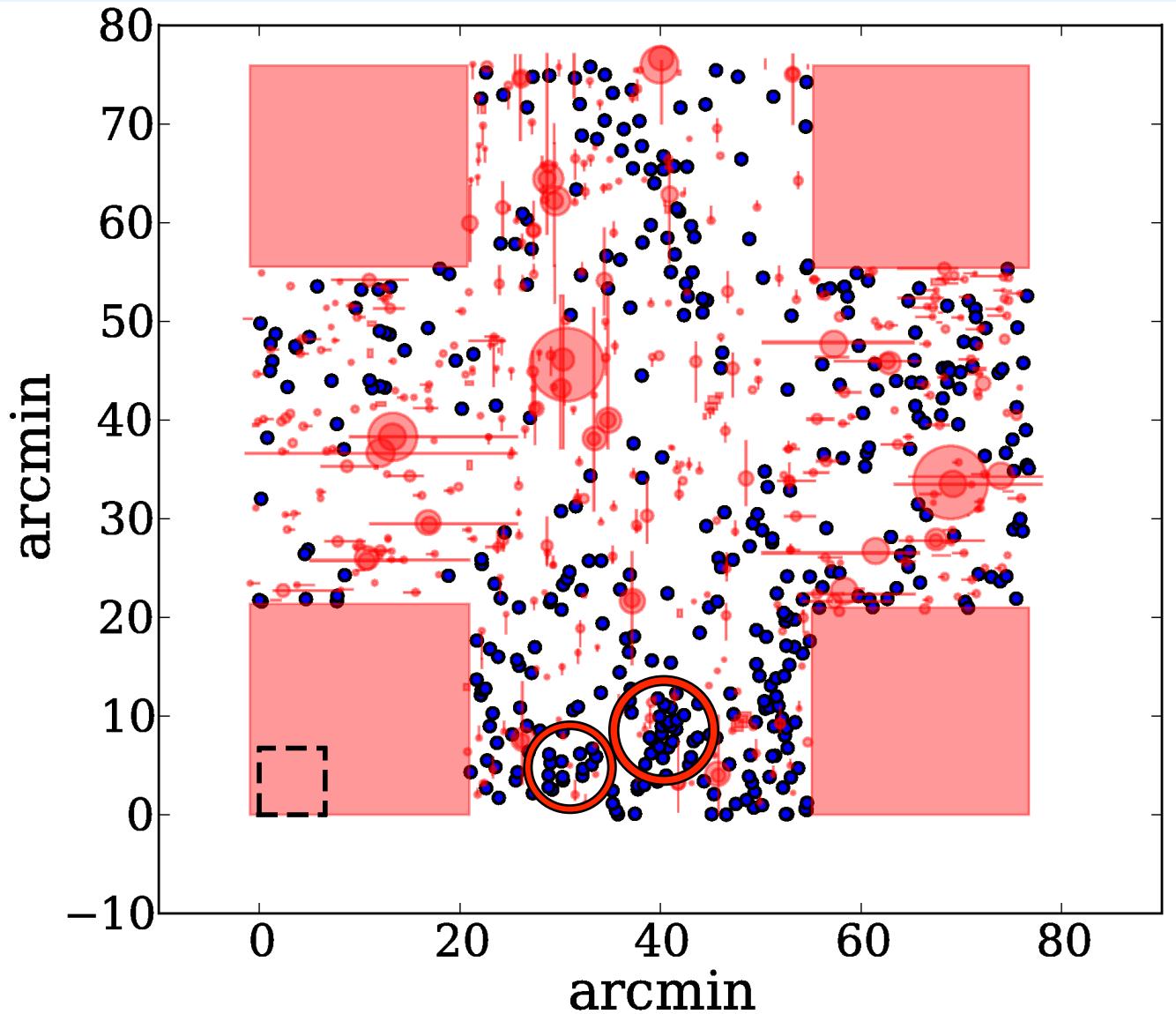
Ways to find proto-clusters

- Galaxy overdensities in “blank” fields
- Galaxies associated with high density tracers

Proto-clusters in “blank” fields

- Need to probe large volume
 - small area → cover large z range (photo-z)
 - large area, small z range (e.g. NB imaging)

Overdensities in “blank” fields (I)

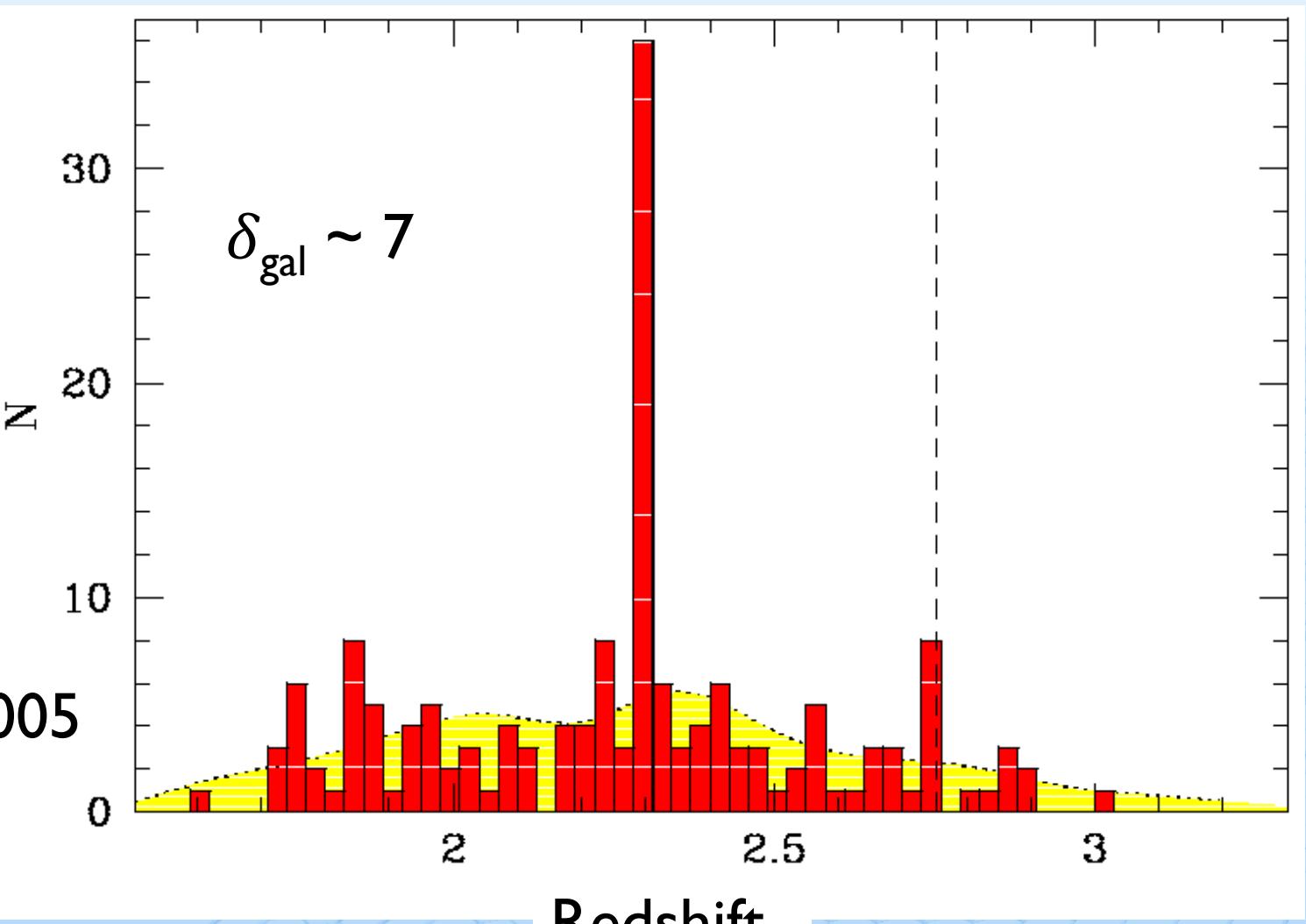


Lyman alpha
emitters at
 $z=5.7$

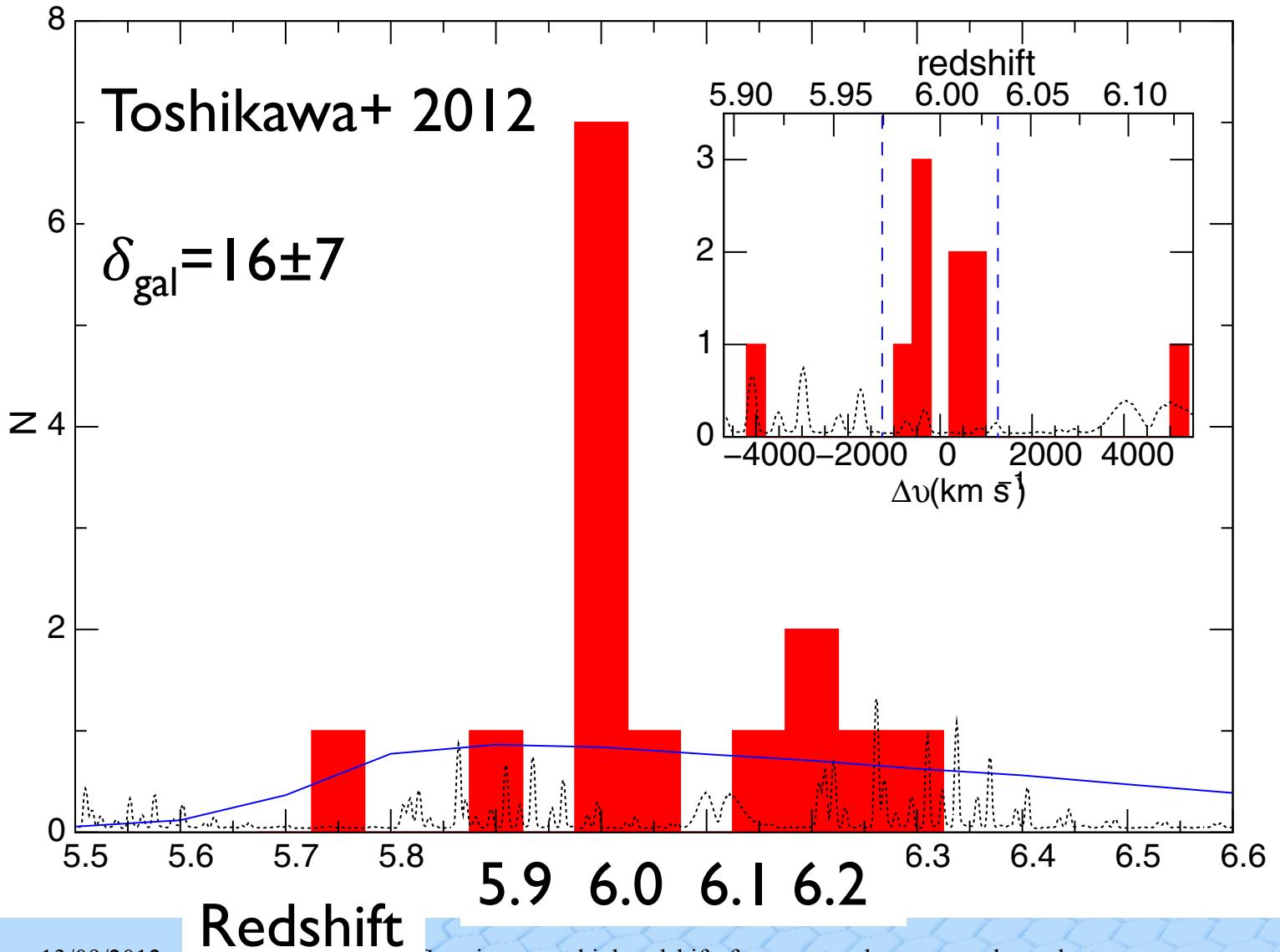
At least two
overdensities
 $\delta_{\text{gal}} > 3$

Ouchi+ 2005

Overdensities in “blank” fields (II)



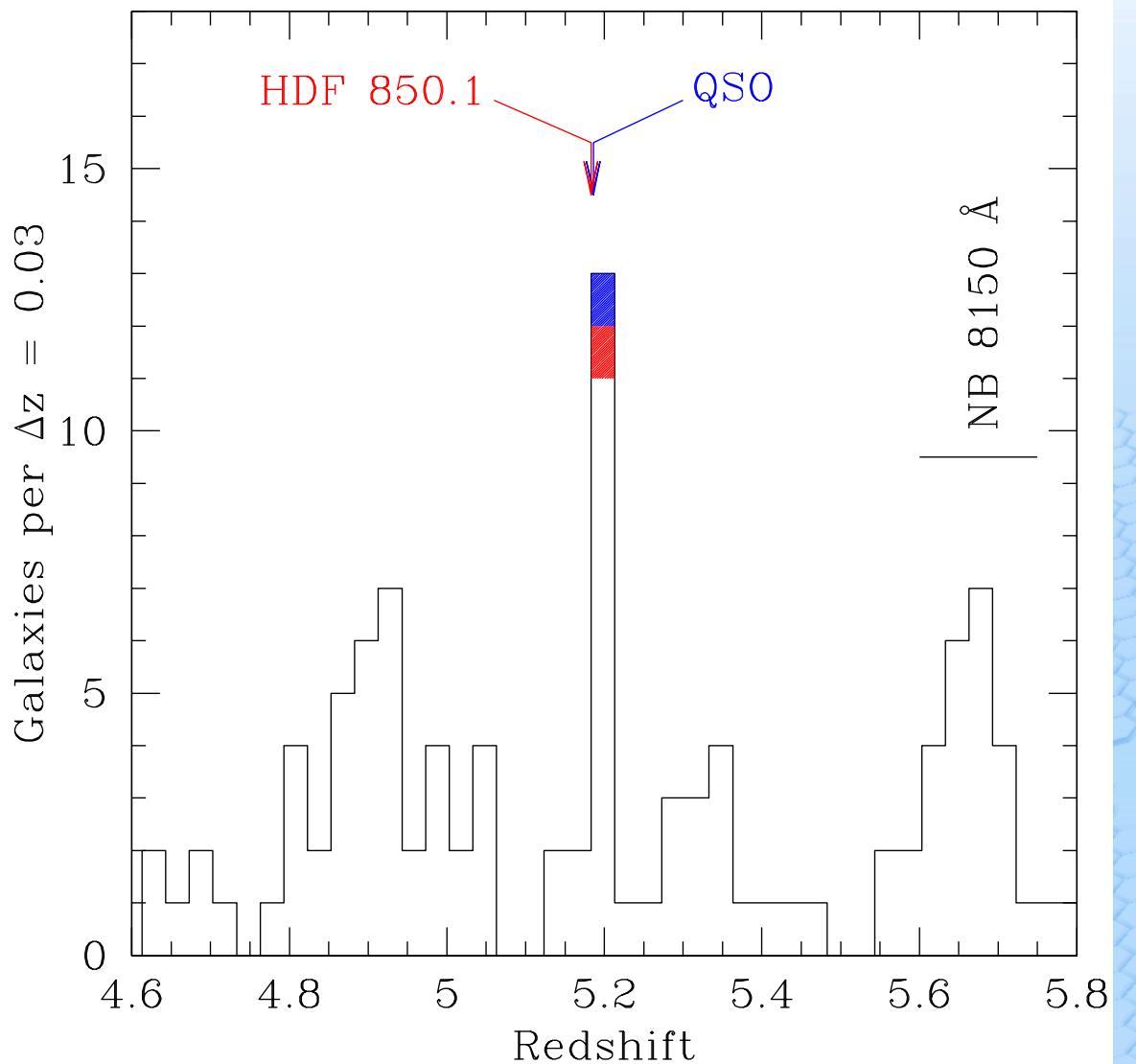
Overdensities in “blank” fields (II)



Tracers of galaxy overdensities

- Progenitors of BCGs / massive galaxies / ...
 - Quasars
 - Radio galaxies
 - Lyman alpha blobs
 - Sub-millimeter galaxies (SMGs)
 - ...

Overdensities around SMGs

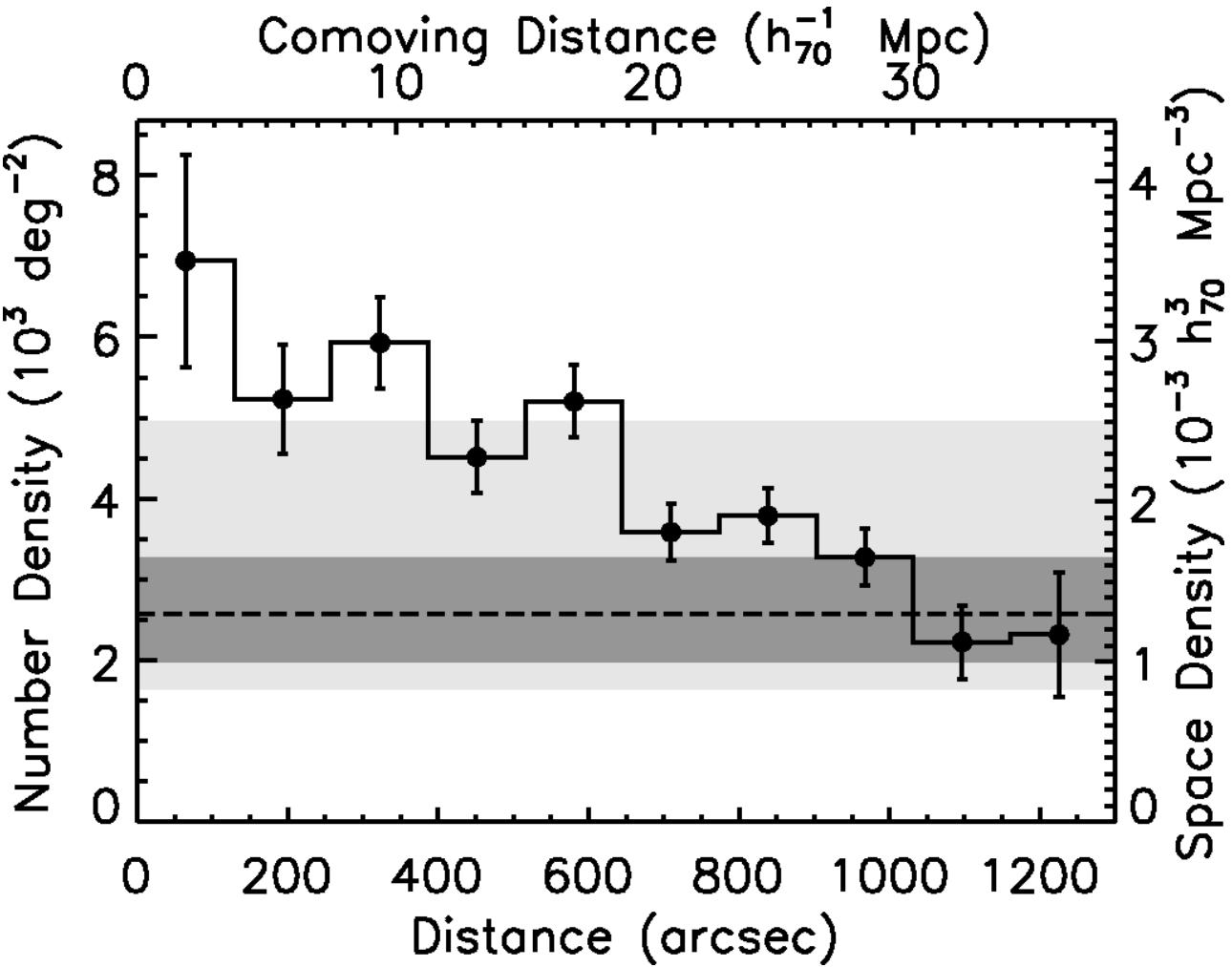


Walter+ 2012
Capak+ 2011

Overdensities around Ly α blobs

Prescott+ 2008

$\delta_{\text{gal}} \sim 2$

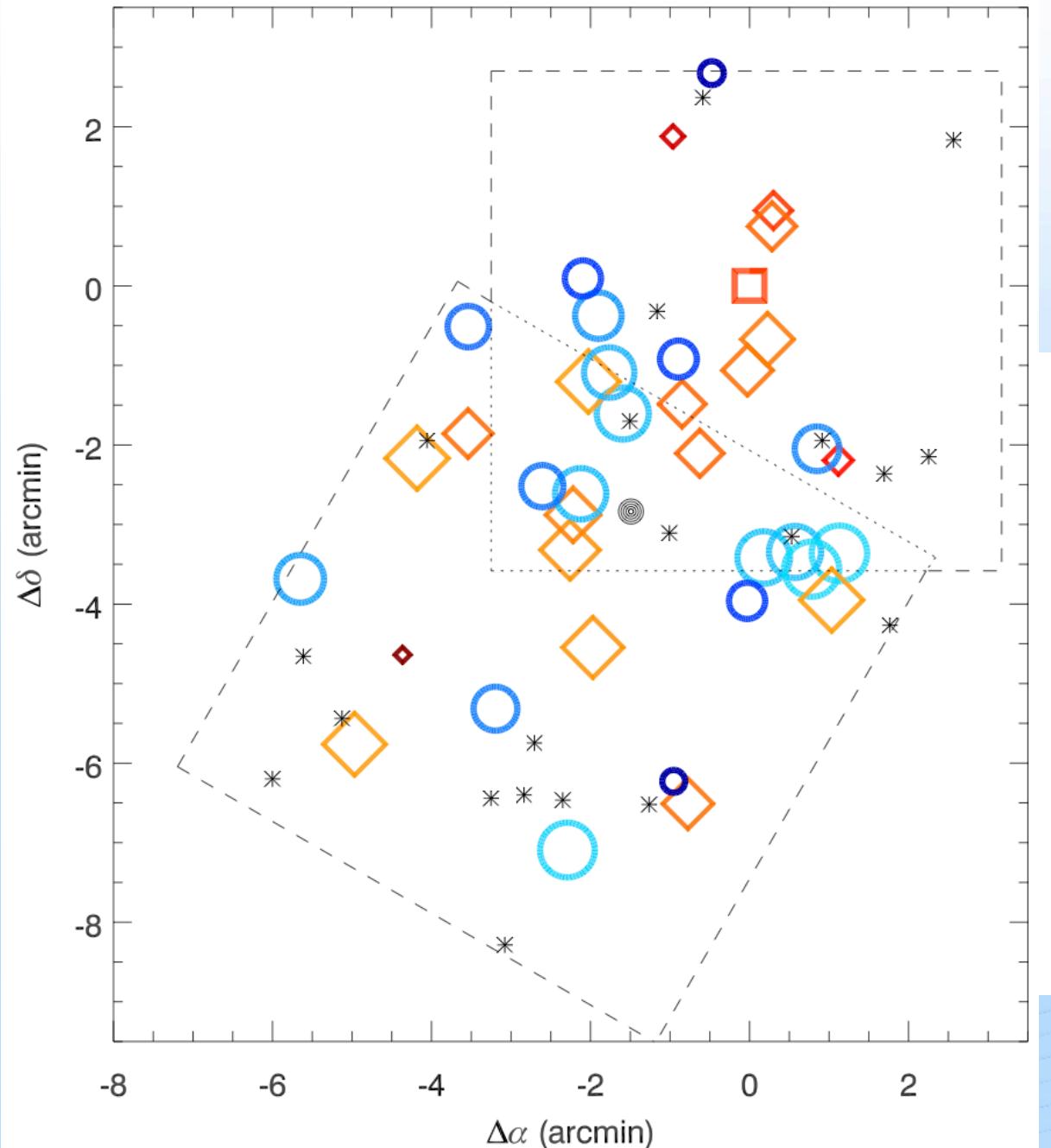


High redshift radio galaxies

- D. Stern and J. Vernet's talks:
 - radio galaxies among most massive galaxies
 - high SF; surrounded by large halos gas
- Many objects at $z > 2$, known redshifts
 - Lyman alpha imaging
 - H alpha imaging
 - Broad band imaging straddling break

Overdensities around radio galaxies

- Some results already presented this week
- Project: radio galaxies for which Lyman alpha imaging was feasible with VLT/FORS2
 - overdensity easy to catch
 - spectroscopy quick
 - not much contamination



field of I338 at $z=4.1$

37 spec. members

$\delta_{\text{gal}} > 4$

**6/8 radio galaxies in
overdensities**

Characteristics of proto-clusters (I)

- Mass

$$M_{pc} = \rho V (1 + \delta_m)$$

ρ = mean density

V = Volume

δ_m = mass overdensity

- related to δ_{gal} via bias parameter

- + add redshift space distortions

Characteristics of proto-clusters (I)

- Mass

- Steidel et al. pc: $\sim 10^{15} M_{\odot}$
- Kang & Im z~3.7 pc: $2-5 \times 10^{14} M_{\odot}$
- Toshikawa z~6 pc: $3 \times 10^{14} M_{\odot}$
- radio galaxy pc: $2-9 \times 10^{14} M_{\odot}$

→ enough mass for a massive cluster

Characteristics of proto-clusters (II)

- Number density

- 1 z~3 LBG pc per 9'x18' field (Steidel+ 1998)

$$\rightarrow n_{\text{proto-clusters}} \approx 3 \times 10^{-6} \text{ Mpc}^{-3}$$

- ~1 LAE pc per S-CAM field (Ouchi+ 2005)

$$\rightarrow n_{\text{proto-clusters}} \gtrsim 2 \times 10^{-6} \text{ Mpc}^{-3}$$

- 5-8 LBG pc per S-CAM field (Intema+ 2006)

$$\rightarrow n_{\text{proto-clusters}} \sim 5 \times 10^{-6} \text{ Mpc}^{-3}$$

Characteristics of proto-clusters (II)

- Number density
 - # radio galaxies at $z > 2$ + radio lifetime
 $\rightarrow n_{\text{proto-clusters}} \approx 6 \times 10^{-6} \text{ Mpc}^{-3}$ (BV+ 2007)

Various surveys: $n = \text{few} \times 10^{-6} \text{ Mpc}^{-3}$

Locally: comparable to $M_{\text{cluster}} \gtrsim 2 \times 10^{14} M_{\odot}$

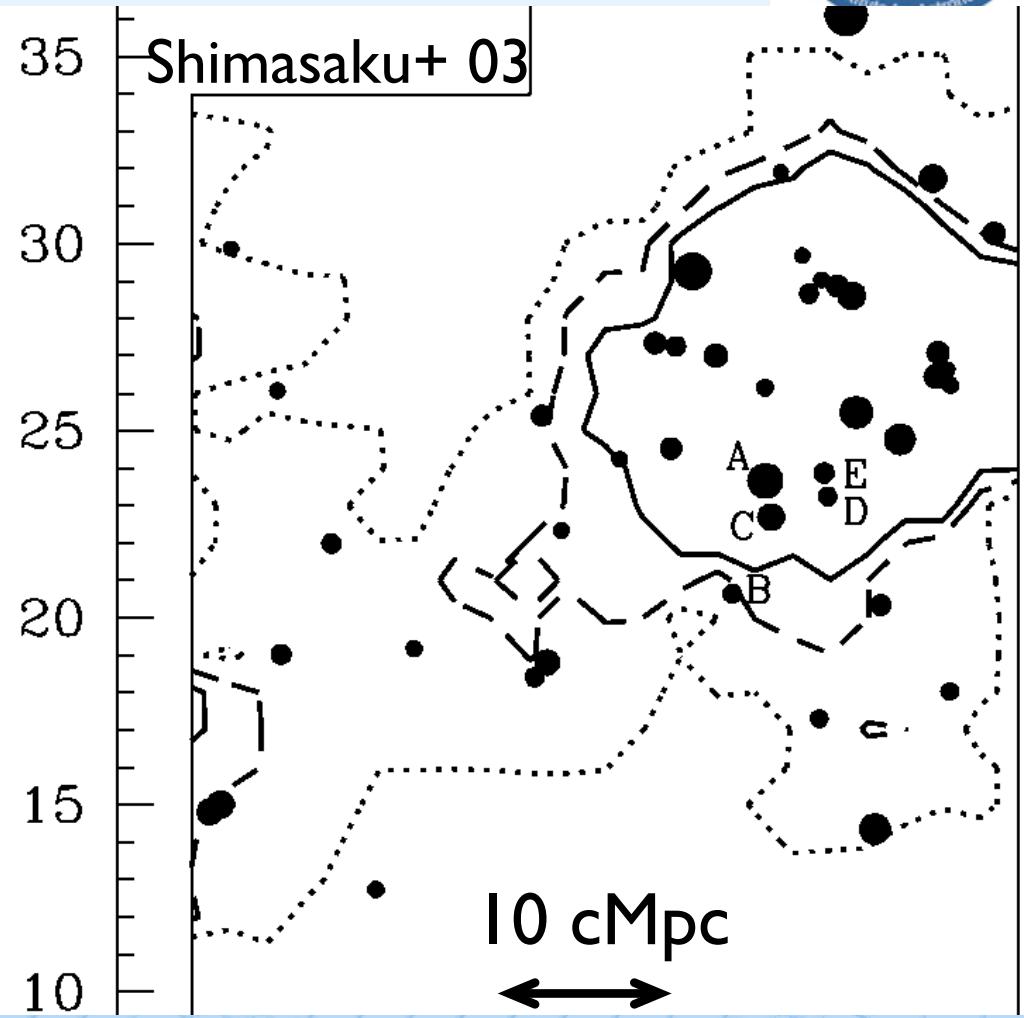
Characteristics of proto-clusters (III)

- Sizes

LAEs @ $z=3-6$
 $\rightarrow 7-20 \text{ cMpc}$

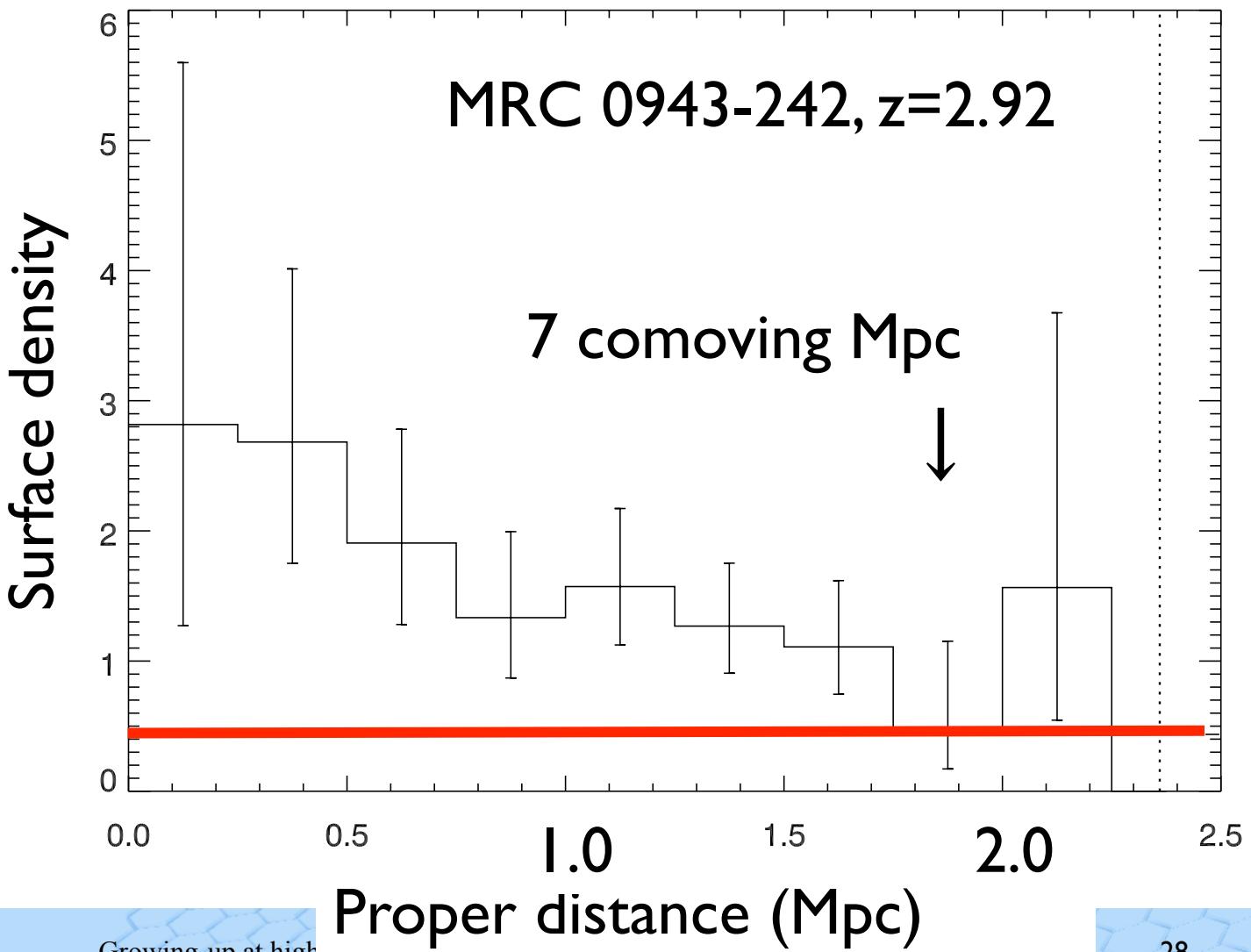
LBGs @ $z=2-6$
 $\rightarrow \gtrsim 7-18 \text{ cMpc}$

(e.g. Steidel+ 1998, 2005;
 Shimasaku+ 2003; Hayashino+
 2004; Ouchi+ 2005; Douglas+ 2010; Toshikawa+ 2012)



Characteristics of proto-clusters (III)

- Sizes



Characteristics of proto-clusters (III)

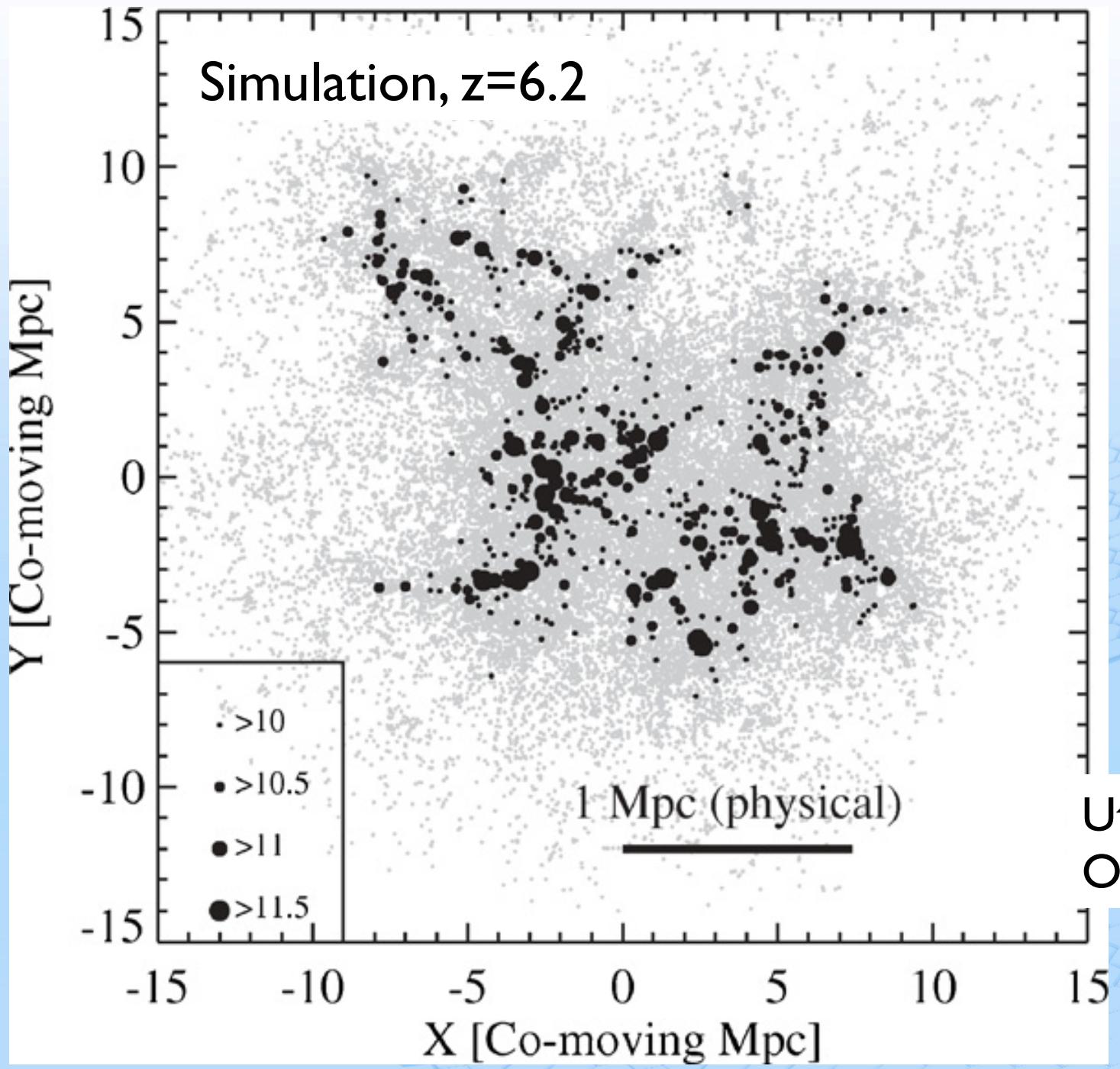
- Sizes

LAEs and LBGs around radio galaxies:

- $>6\text{-}10 \text{ cMpc}$ (e.g. Keel+ 1999; Intema+ 2006; BV+ 2007)

→ sizes up to $>10 \text{ cMpc} (>1.5\text{-}3.3 \text{ physical Mpc})$

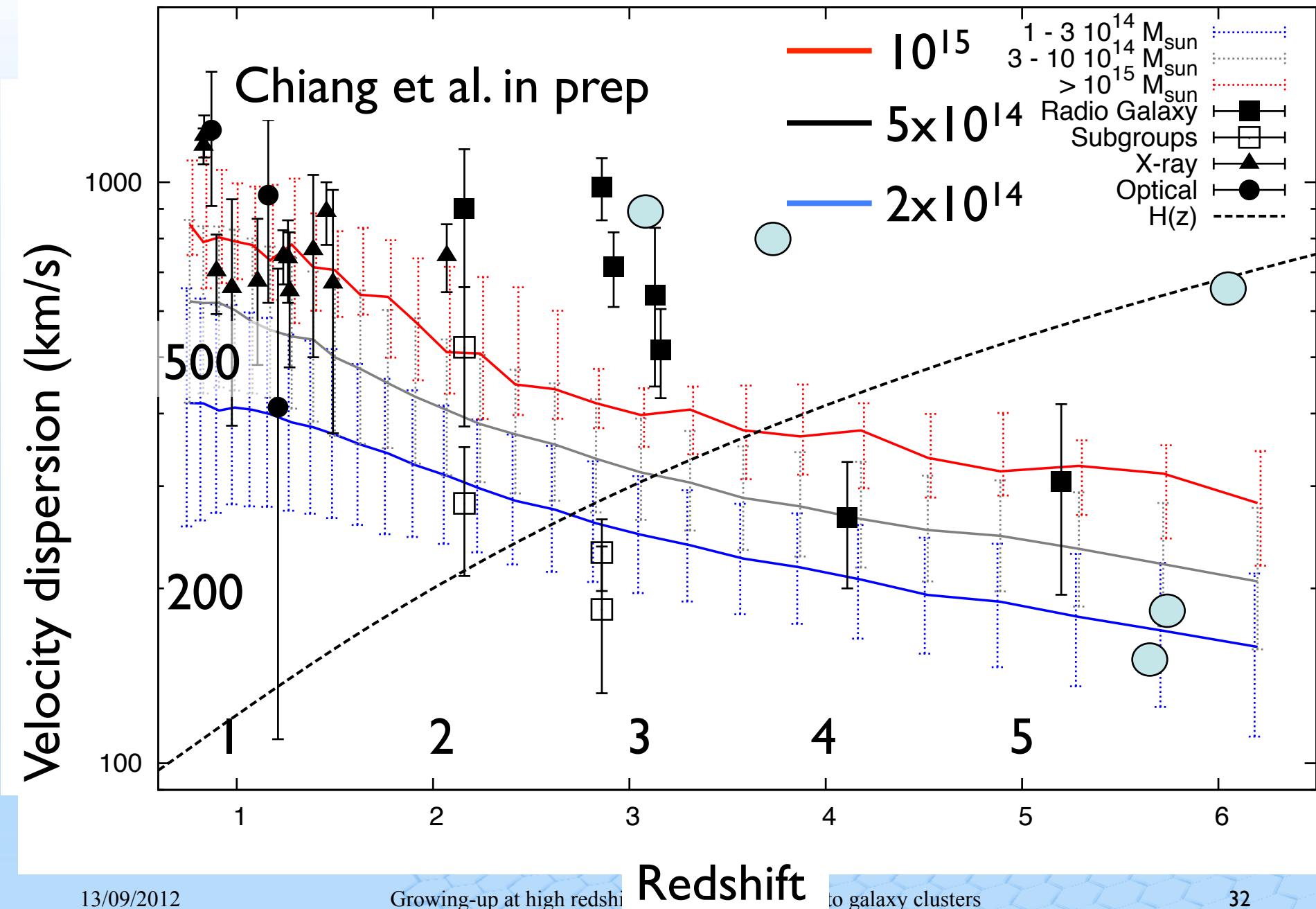
- Consistent with models
(e.g. Overzier+ 2009; Y.-K. Chiang's talk)



Characteristics of proto-clusters (IV)

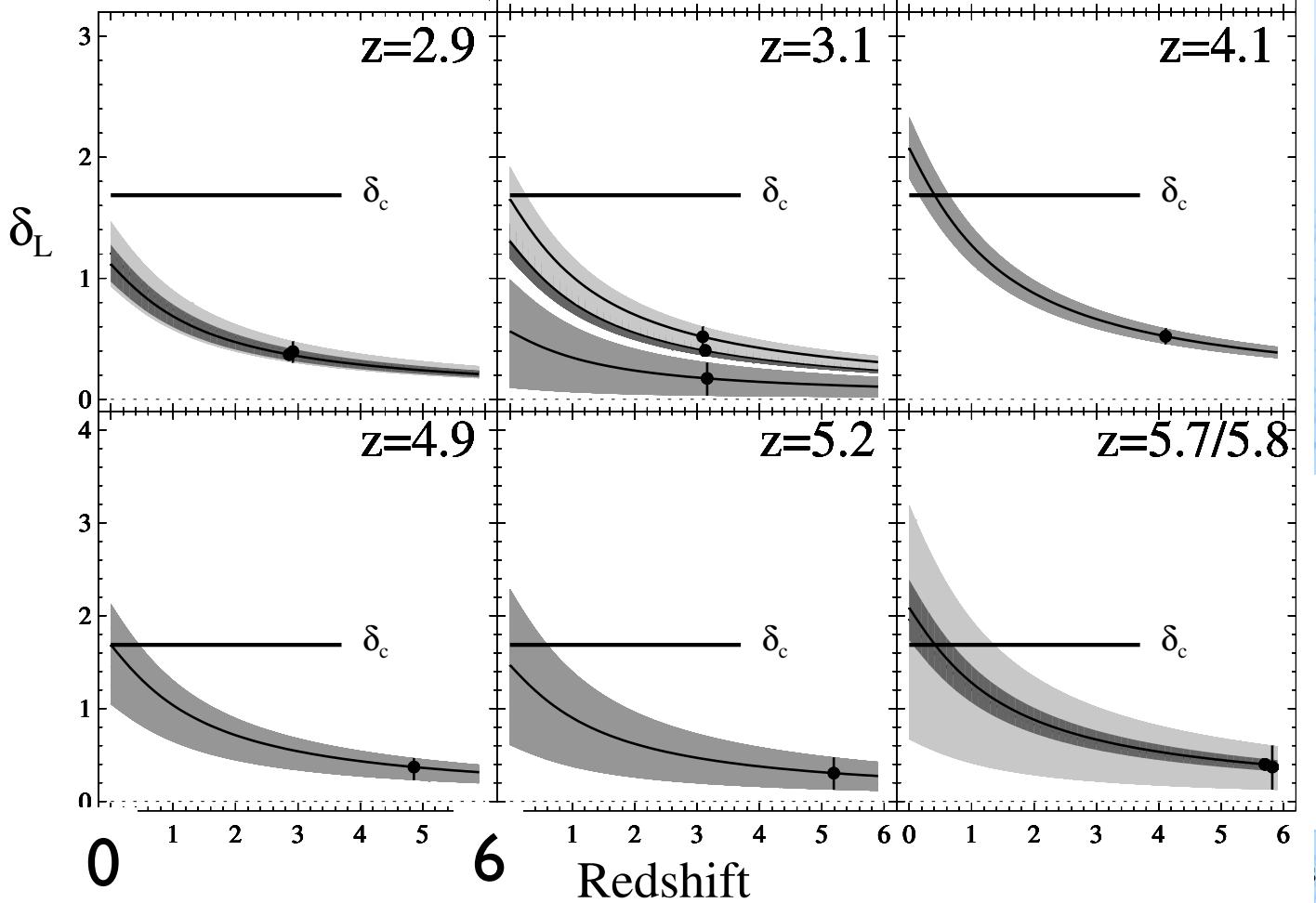
- Velocity dispersion

- Expensive
- Contamination (field, subgroups)



Linear
overdensity ↑

Redshift →



← Collapse
threshold δ_c

R. Overzier
PhD thesis

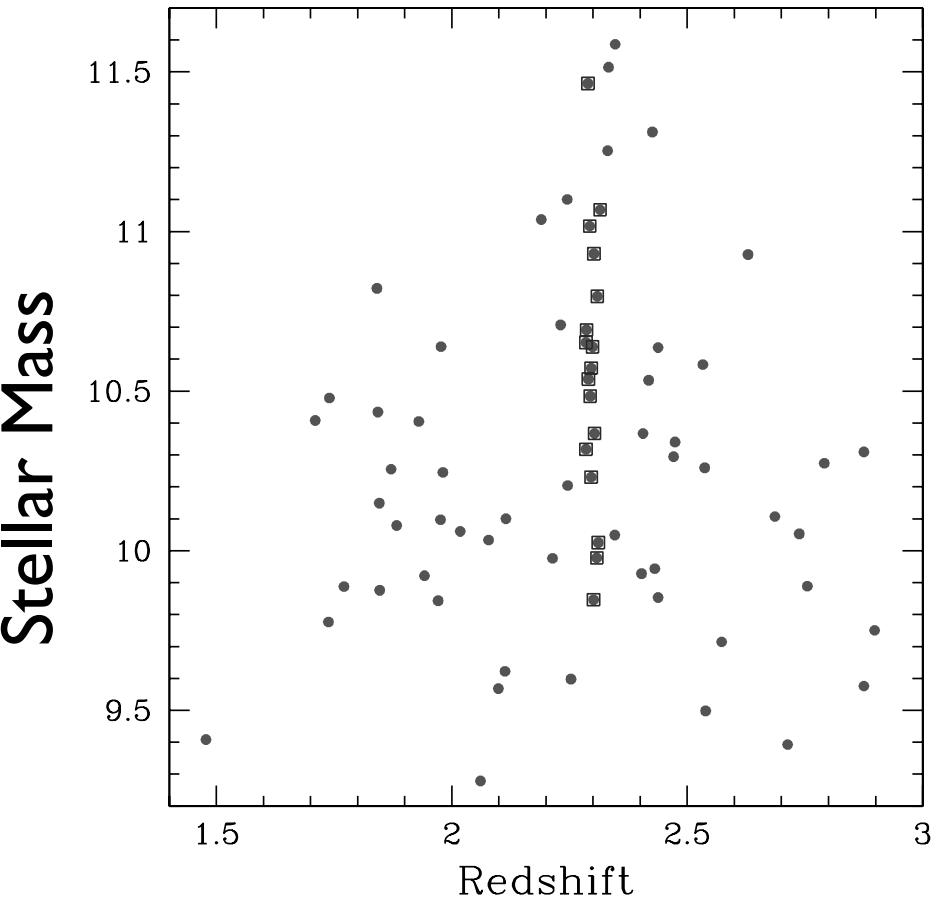
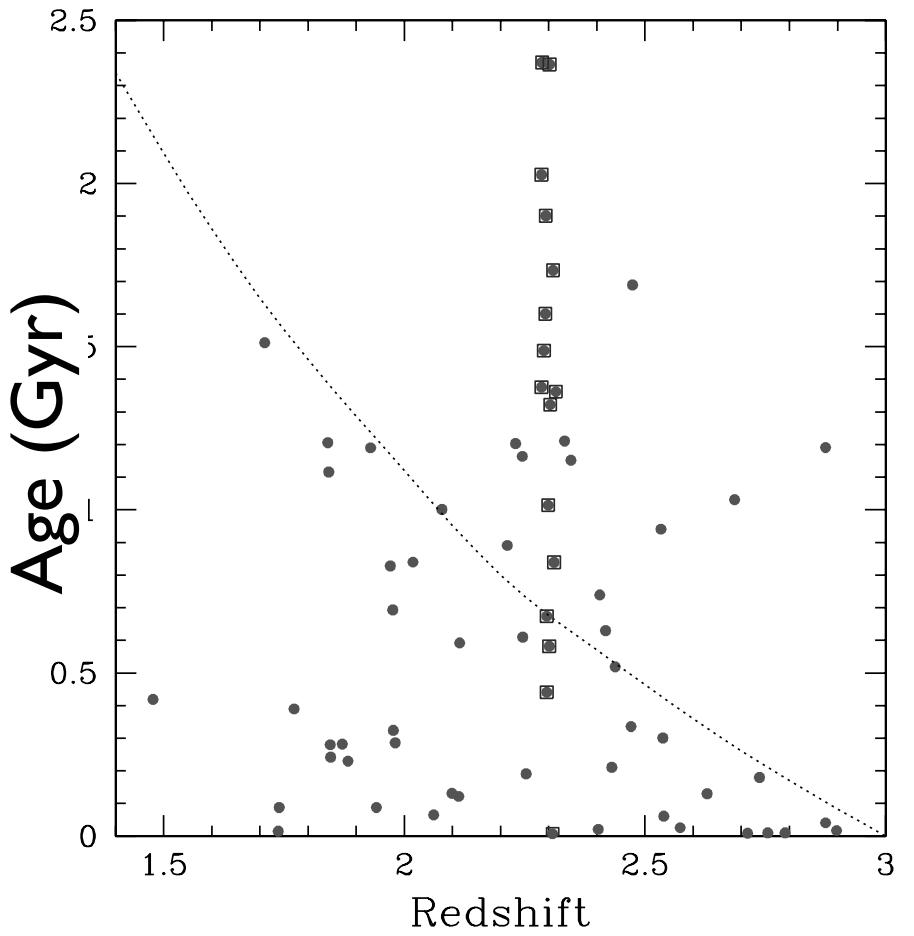
Steidel+ 2005

Effect of environment on galaxies

- Already presented in various talks
- Higher AGN fraction in proto-clusters
(e.g. Pentericci+ 2002; Lehmer+ 2009; Digby-North+ 2010)
- Galaxies older and more massive
(e.g. Steidel+ 2005; Hatch+ 2011)

Galaxies older and more massive

Steidel+ 2005



Summary

- Caution linking high-z pc with low-z cluster
- Differences found between pc / field galaxies
 - in place at high-z, cluster still forming
- Need large samples to trace redshift evolution

End