



Proto-clusters: searches and studies

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Growing up at high redshift: from proto-clusters to galaxy clusters
ESAC Madrid • 10-13 September 2012

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?



What is a proto-cluster?

- Structure of galaxies that will evolve into massive cluster

Cluster of galaxies \rightarrow virialized \rightarrow 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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- Volume should contain $> 10^{14} M_{\odot}$
- $z \gtrsim 2$

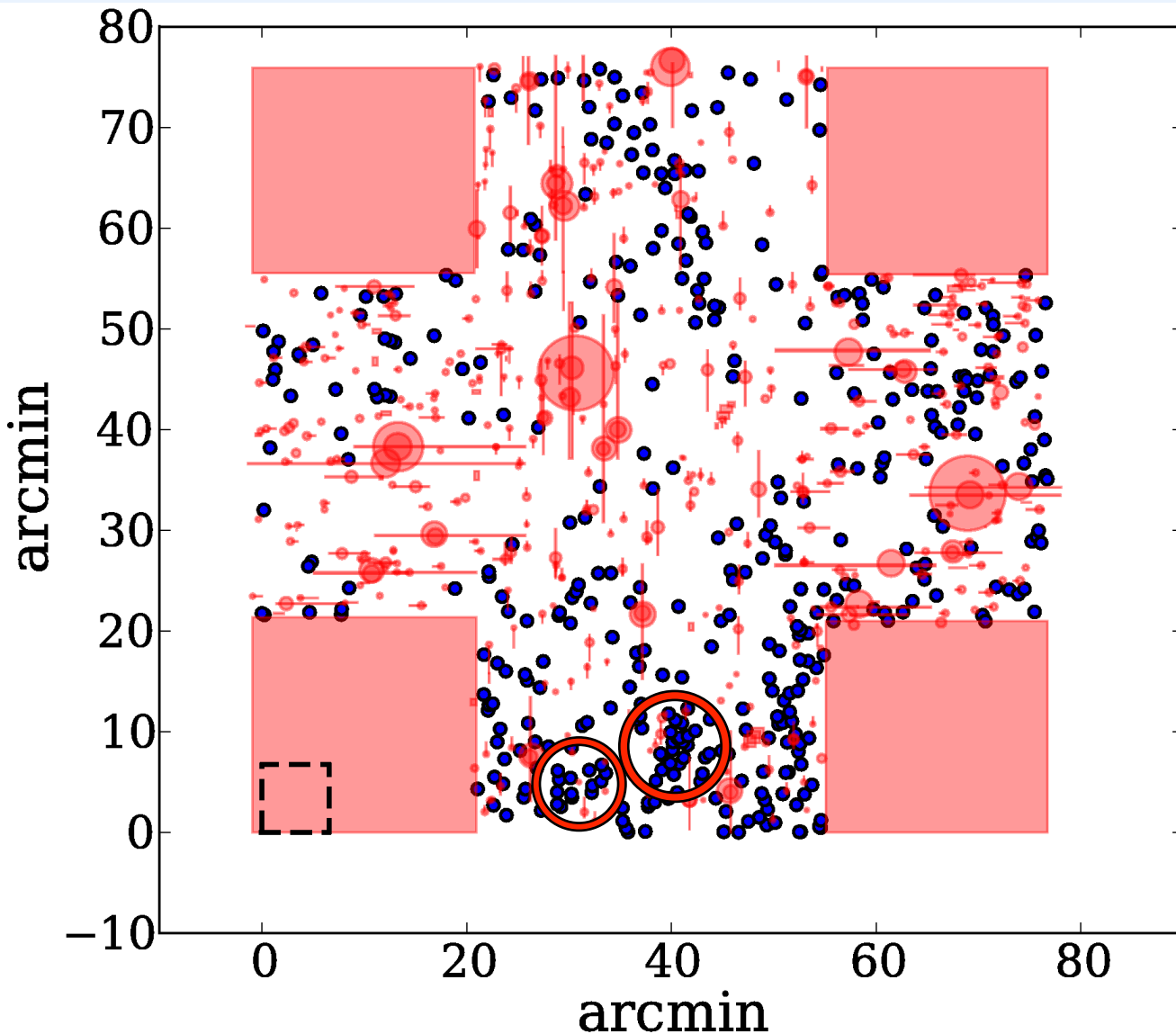
Ways to find proto-clusters

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

Proto-clusters in “blank” fields

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

Overdensities in “blank” fields (I)

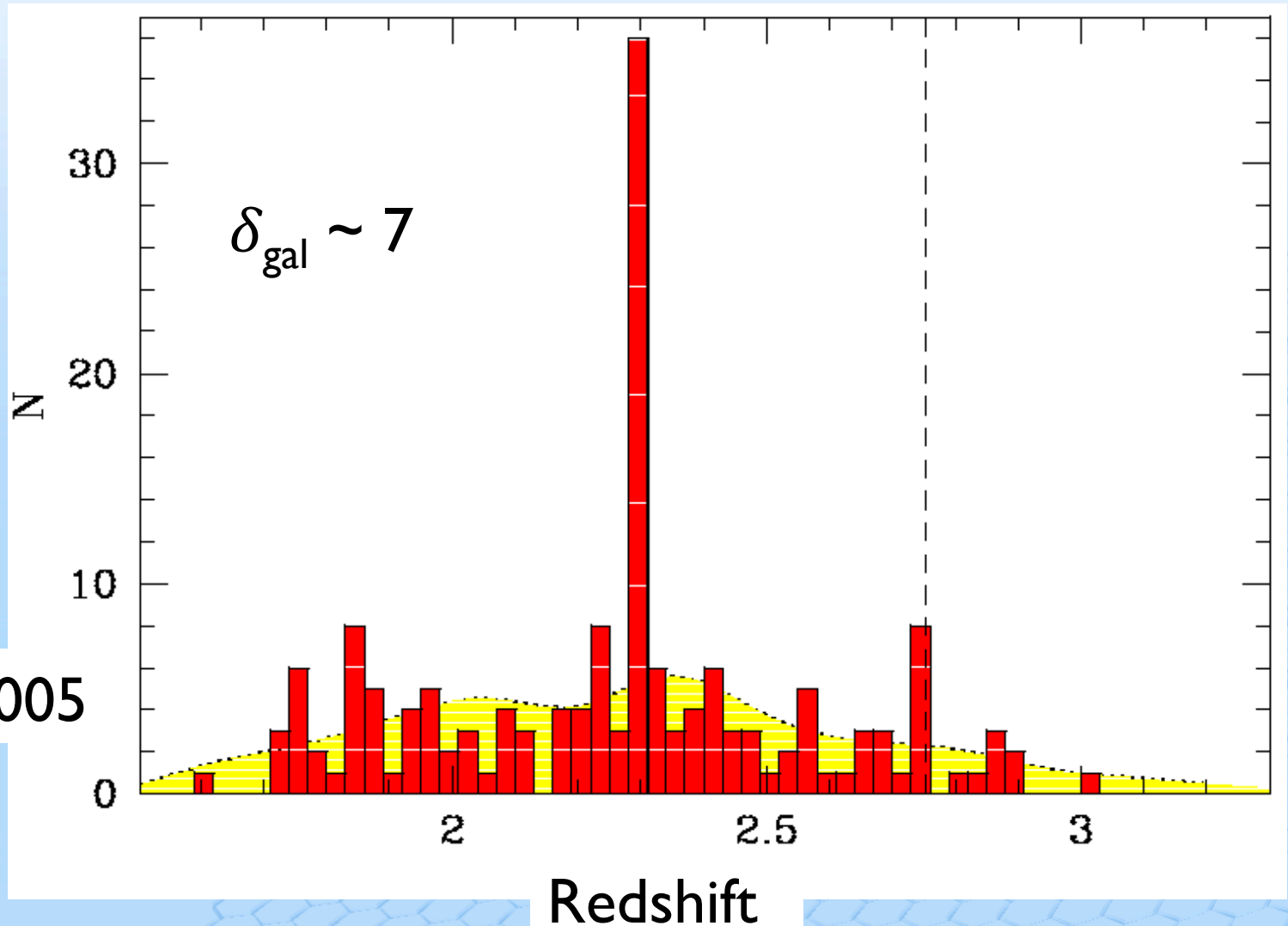


Lyman alpha
emitters at
 $z=5.7$

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

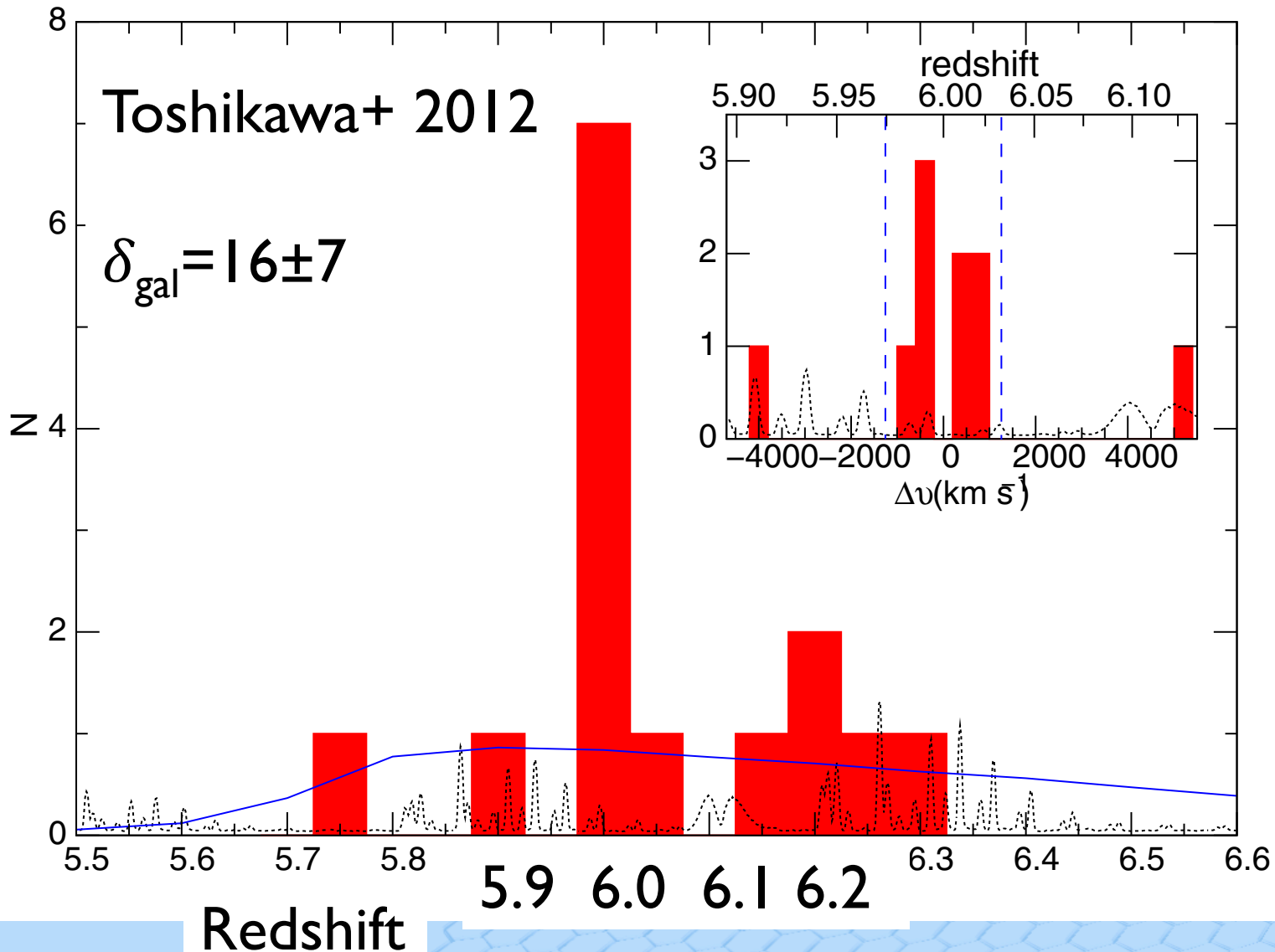
Ouchi+ 2005

Overdensities in “blank” fields (II)



Steidel+ 2005

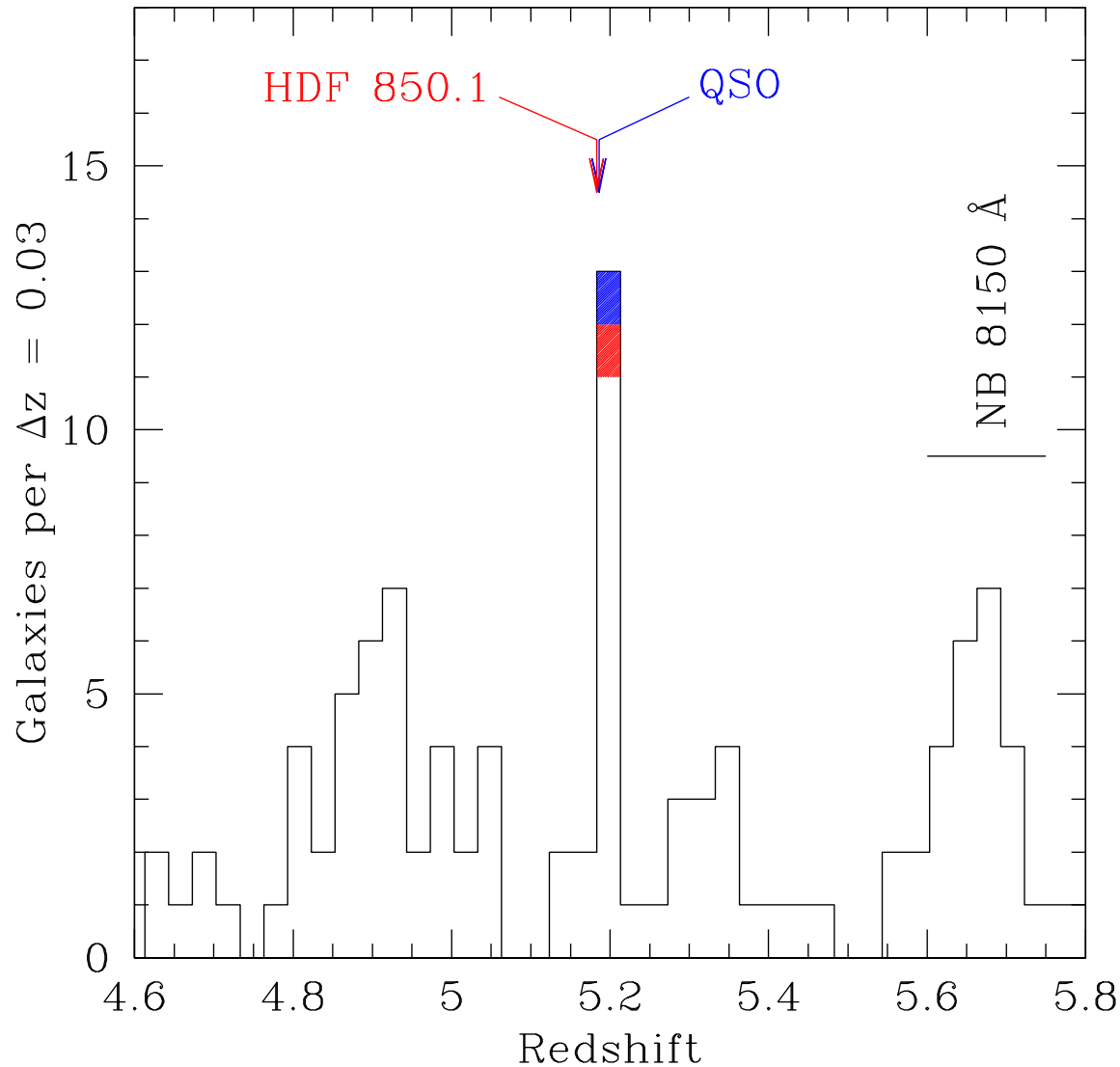
Overdensities in “blank” fields (II)



Tracers of galaxy overdensities

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

Overdensities around SMGs

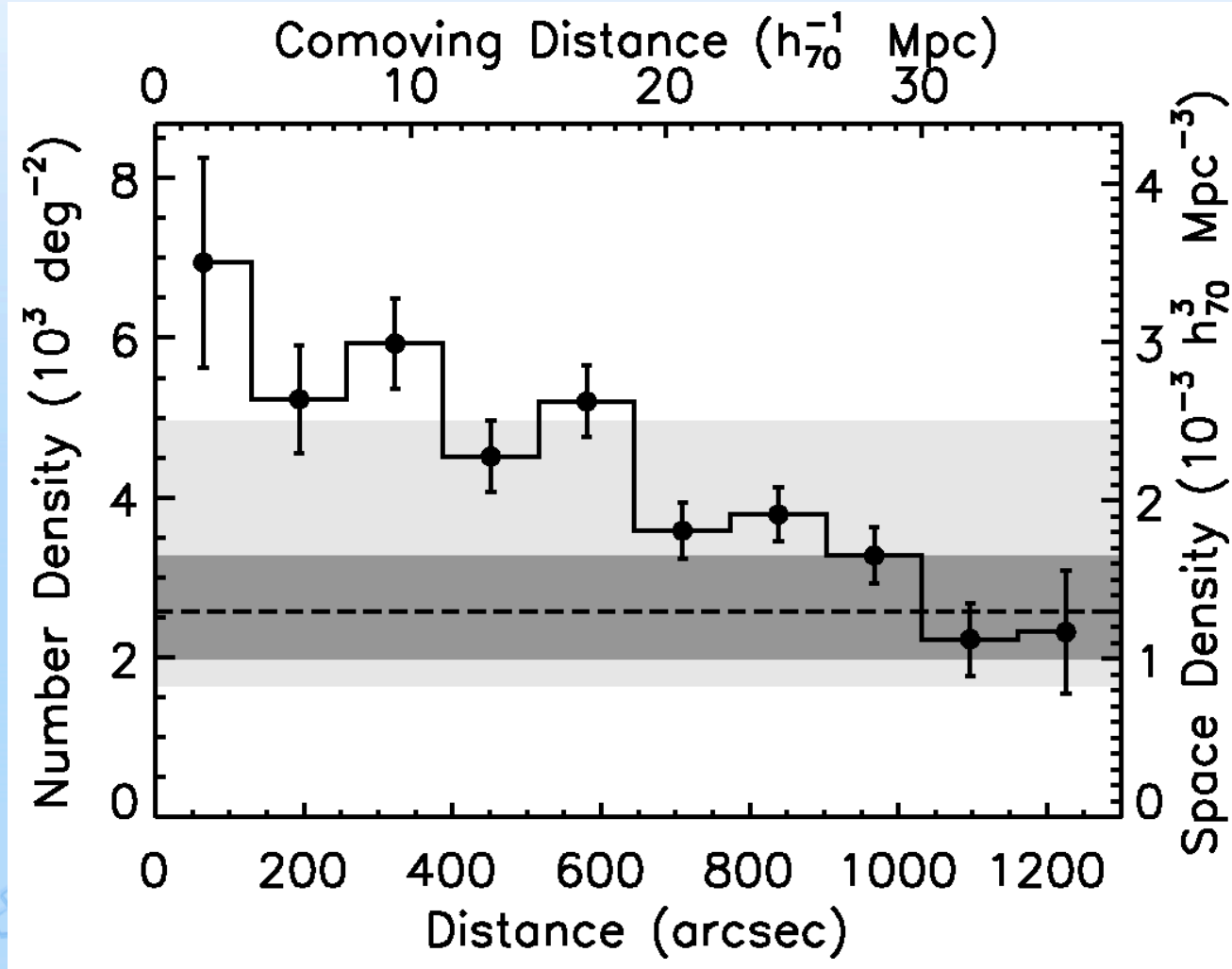


Walter+ 2012
Capak+ 2011

Overdensities around Ly α blobs

Prescott+ 2008

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

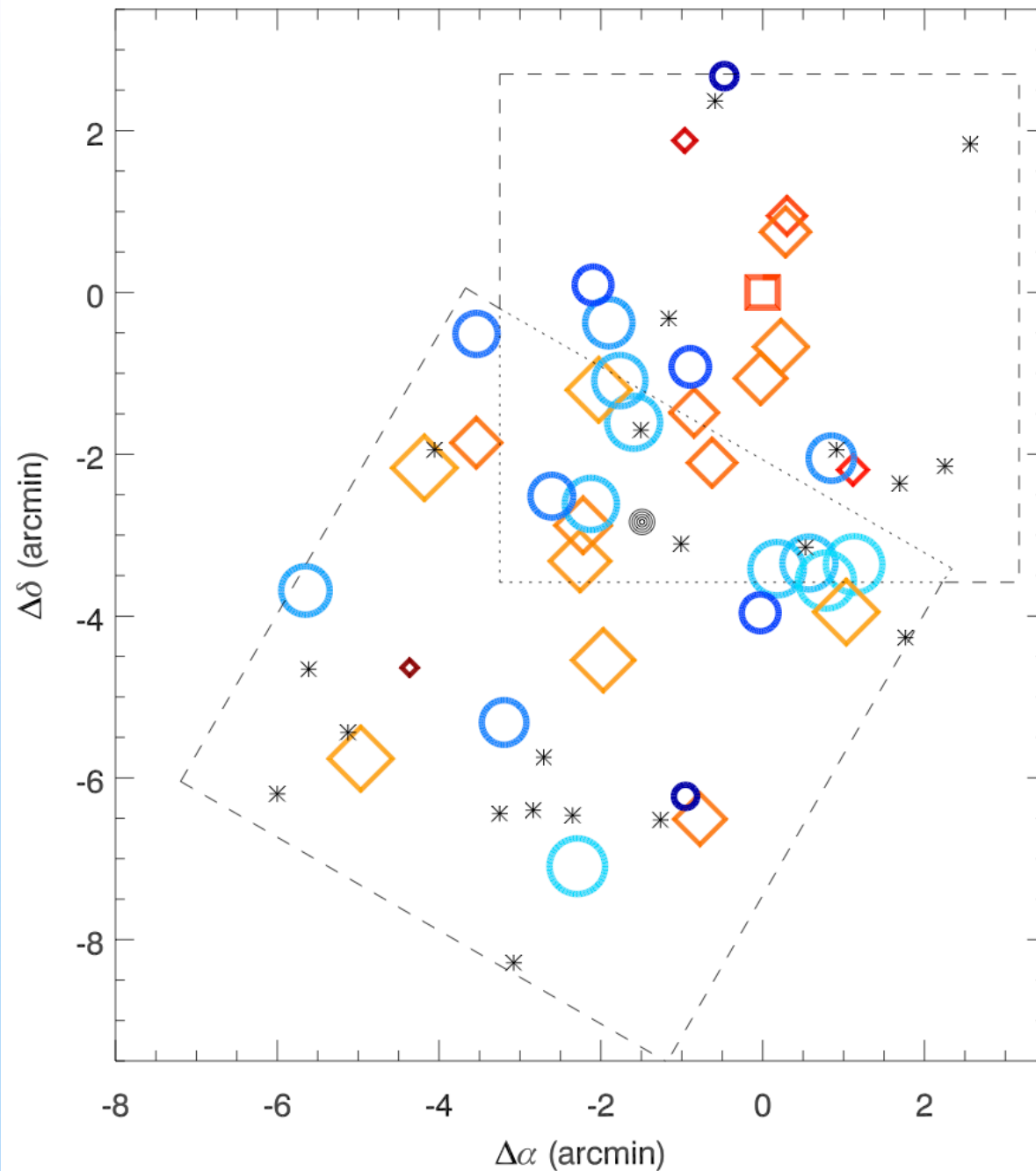


High redshift radio galaxies

- 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 $z \sim 3.7$ pc: $2-5 \times 10^{14} M_{\odot}$
- Toshikawa $z \sim 6$ 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 $z \sim 3$ LBG pc per $9' \times 18'$ field (Steidel+ 1998)

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

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

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

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

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

Characteristics of proto-clusters (II)

- Number density

- # radio galaxies at $z > 2$ + radio lifetime

- $n_{\text{proto-clusters}} \approx 6 \times 10^{-6} \text{ Mpc}^{-3}$ (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 @ $z=3-6$

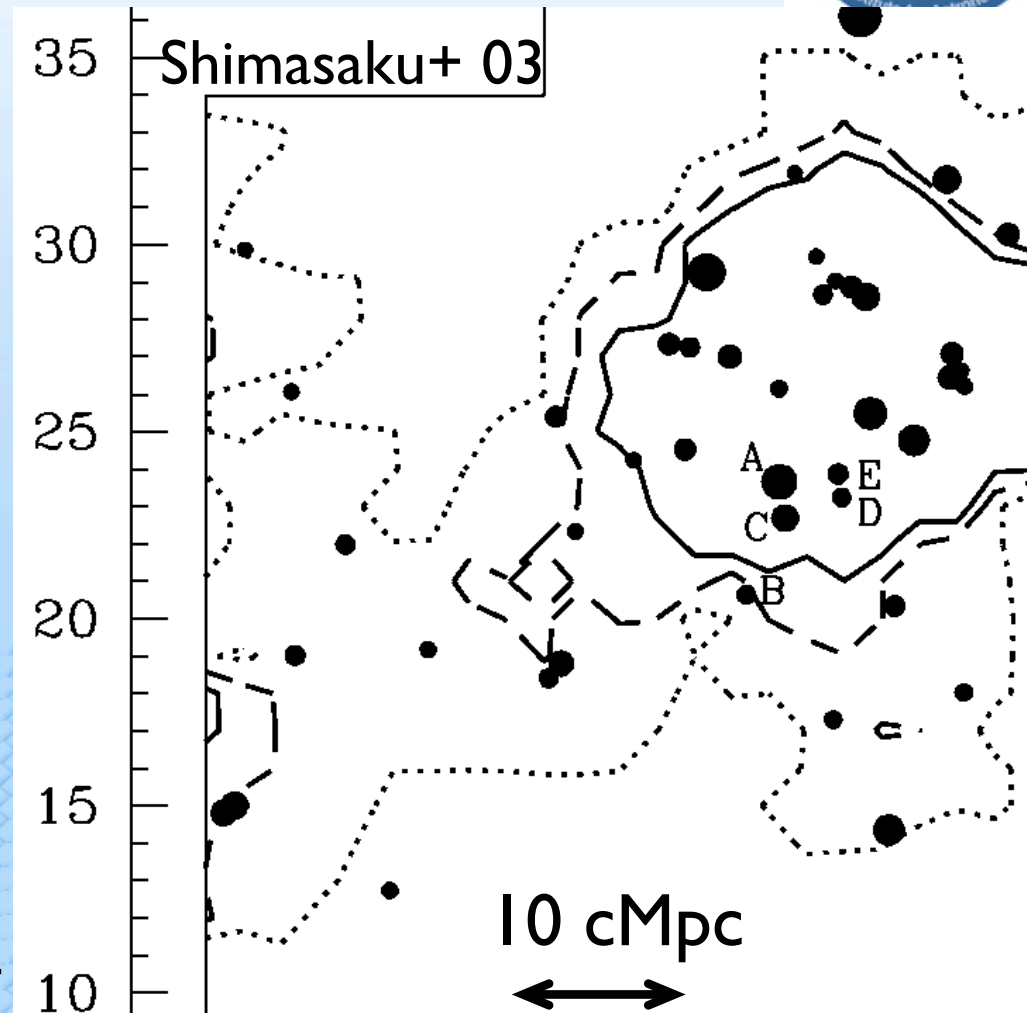
→ 7-20 cMpc

LBGs @ $z=2-6$

→ $\gtrsim 7-18$ cMpc

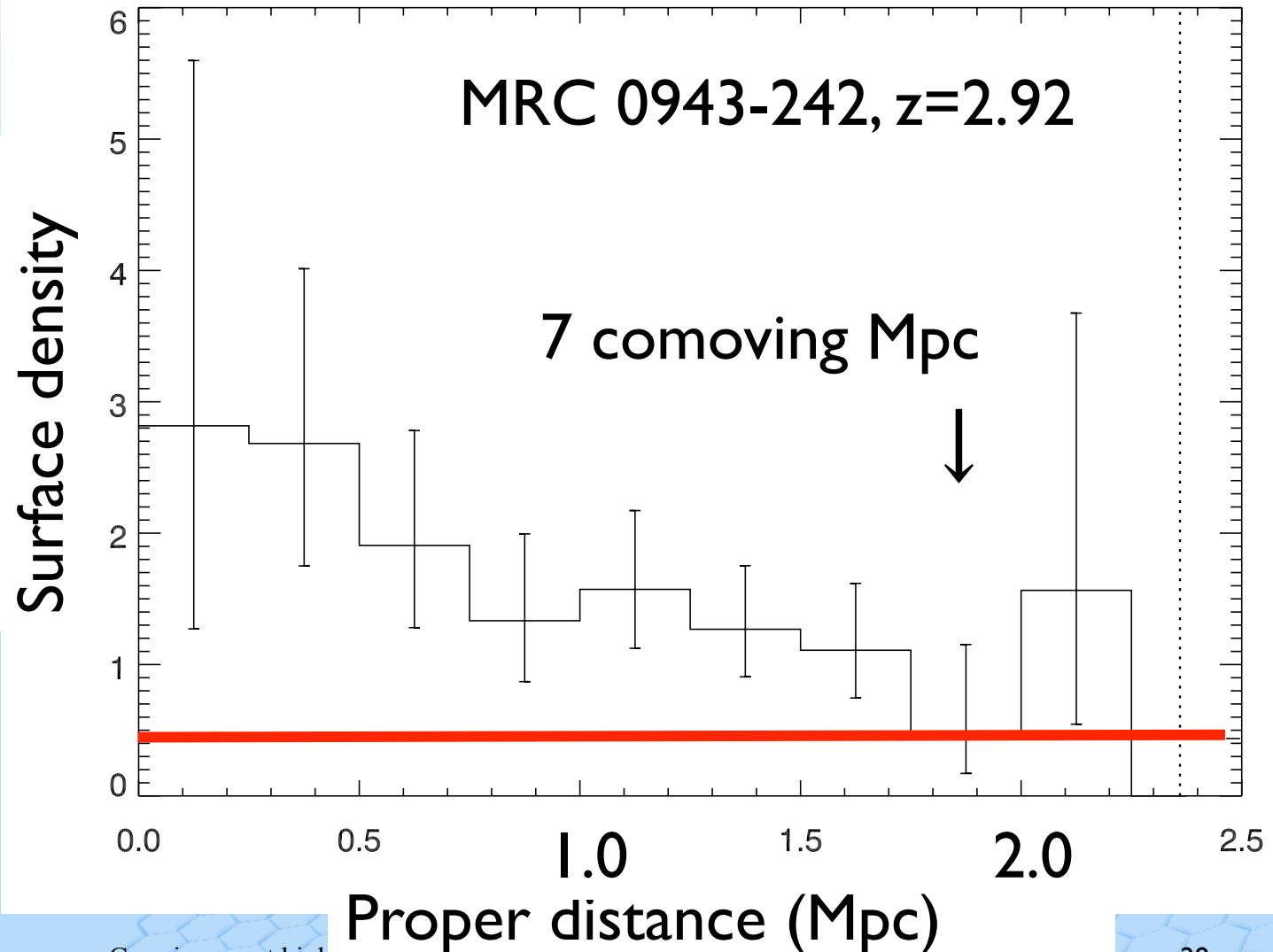
(e.g. Steidel+ 1998, 2005;
Shimasaku+ 2003; Hayashino+

2004; Ouchi+ 2005; Douglas+ 2010; Toshikawa+ 2012)



Characteristics of proto-clusters (III)

- Sizes



BV+ 2007

Characteristics of proto-clusters (III)

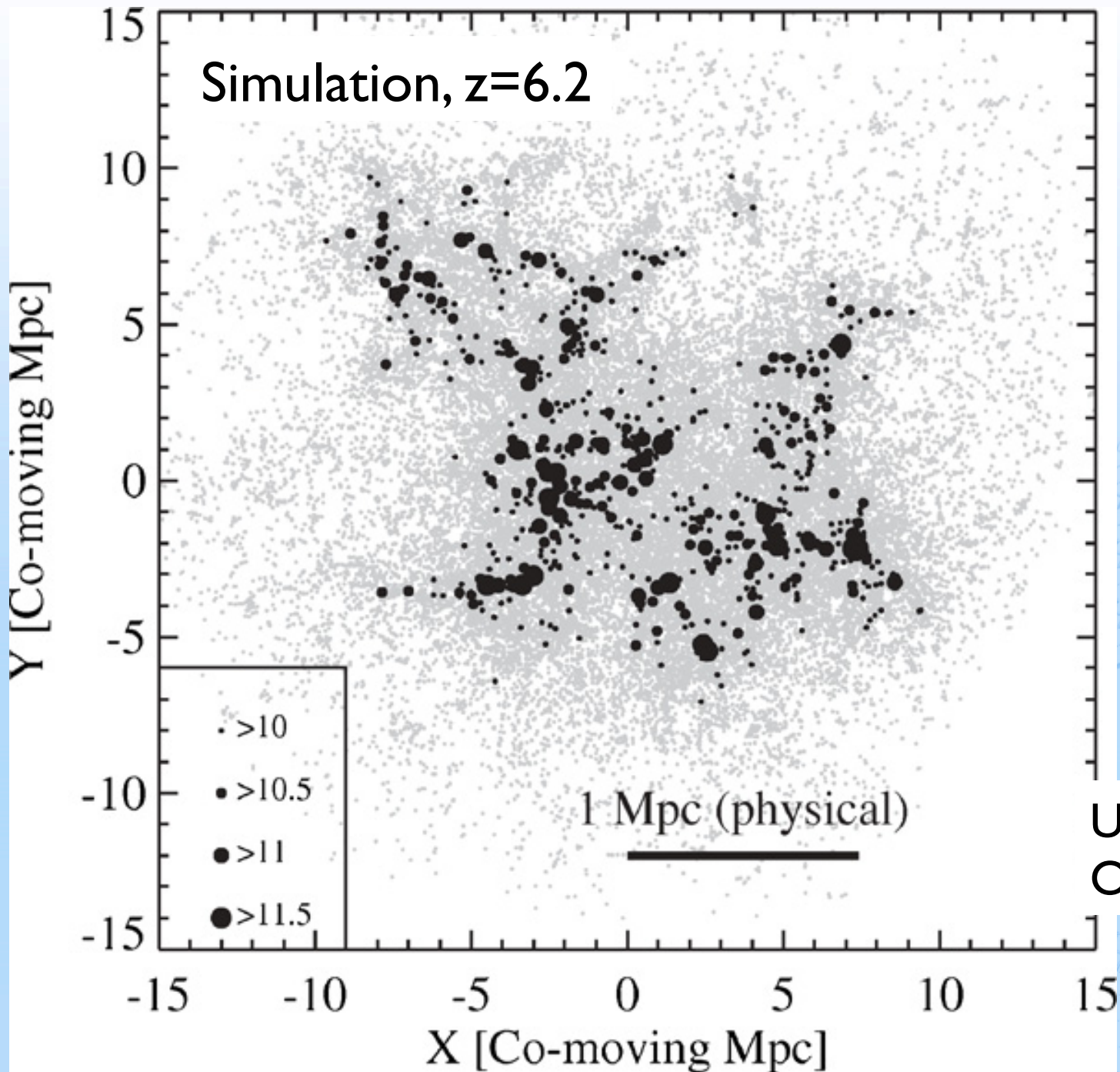
- Sizes

LAEs and LBGs around radio galaxies:

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

→ sizes up to >10 cMpc ($>1.5-3.3$ physical Mpc)

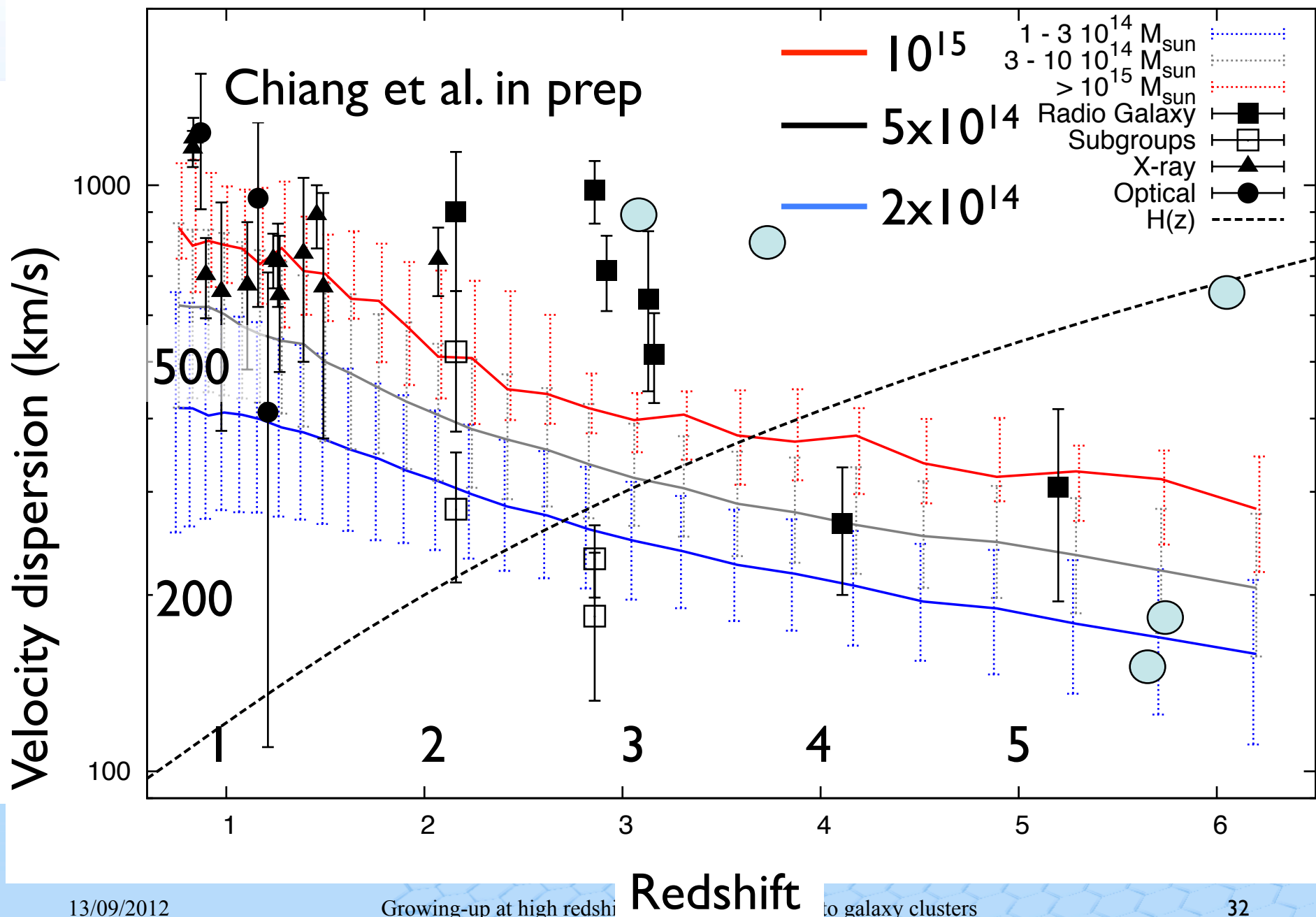
- Consistent with models
(e.g. Overzier+ 2009; Y.-K. Chiang's talk)



Utsumi+ 2010
Overzier+ 09

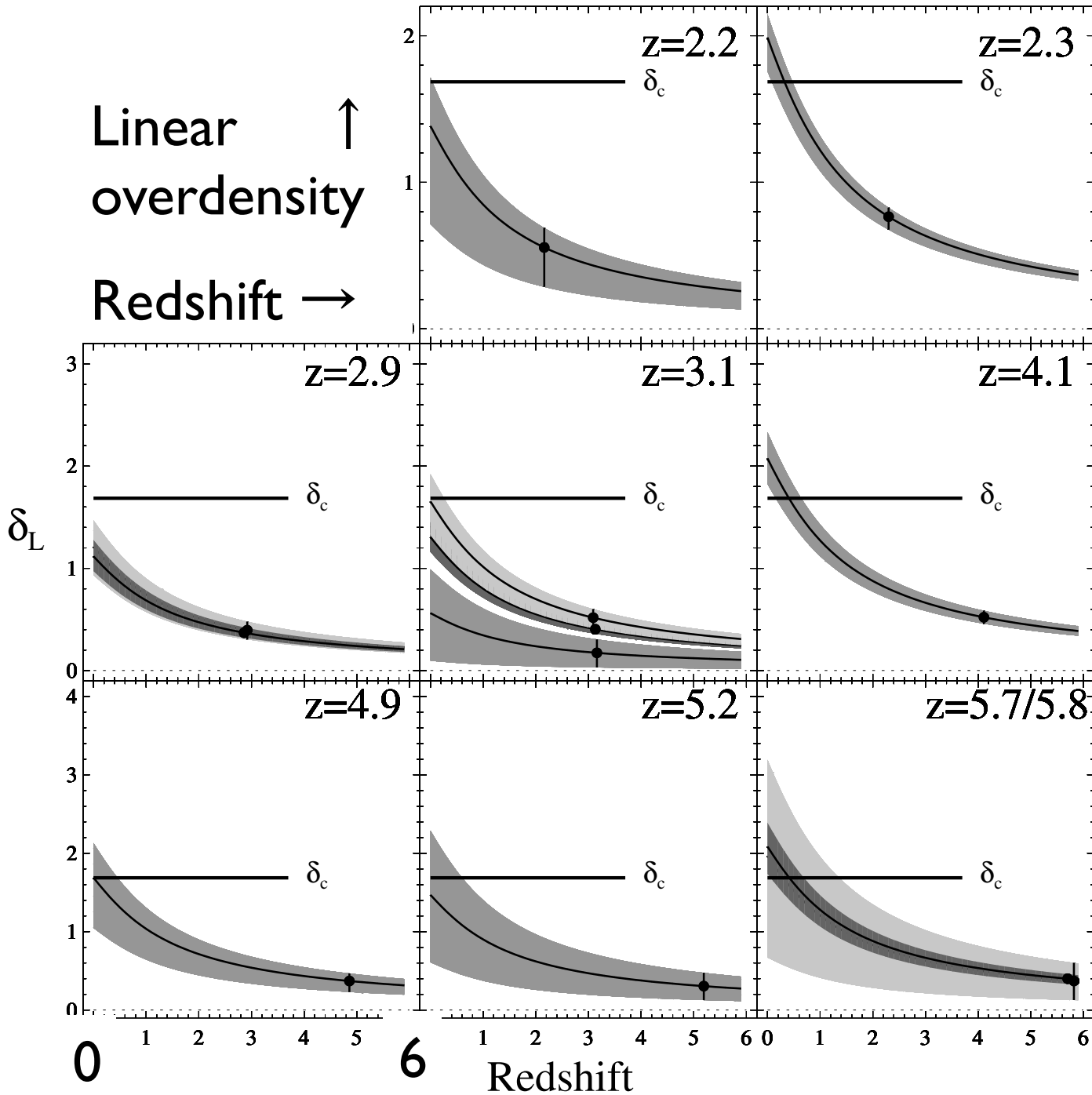
Characteristics of proto-clusters (IV)

- Velocity dispersion
 - Expensive
 - Contamination (field, subgroups)



Linear ↑
overdensity

Redshift →



← Collapse
threshold δ_c

R. Overzier
PhD thesis

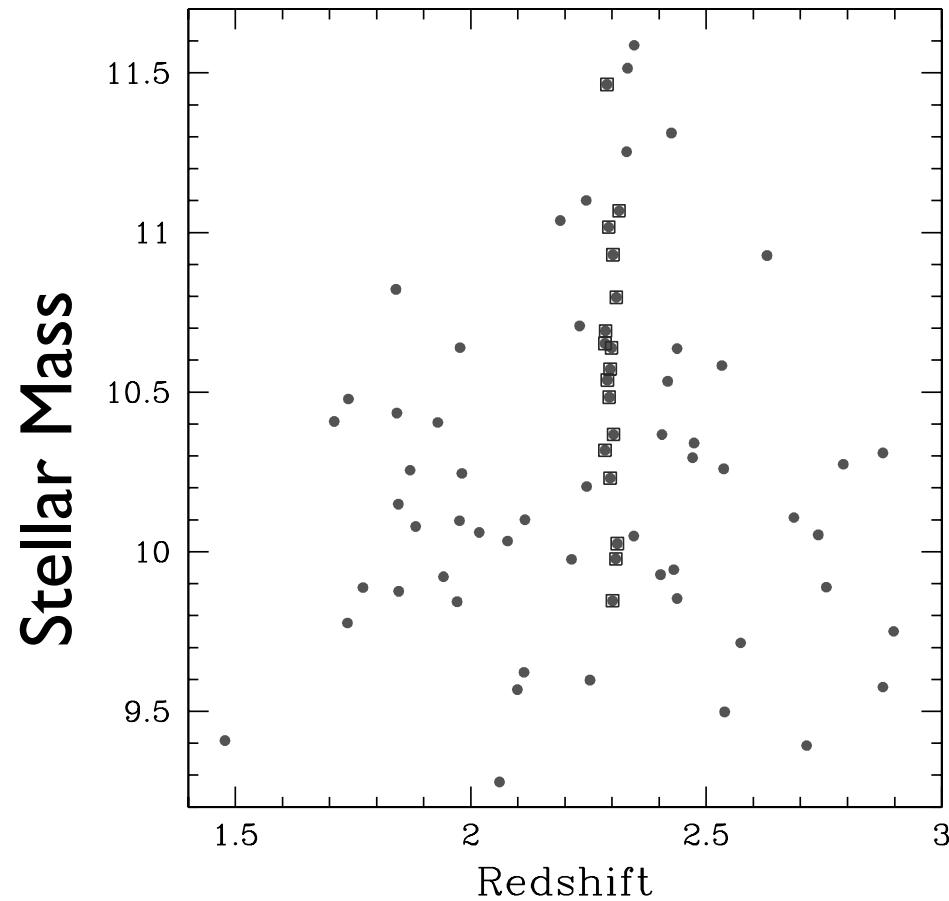
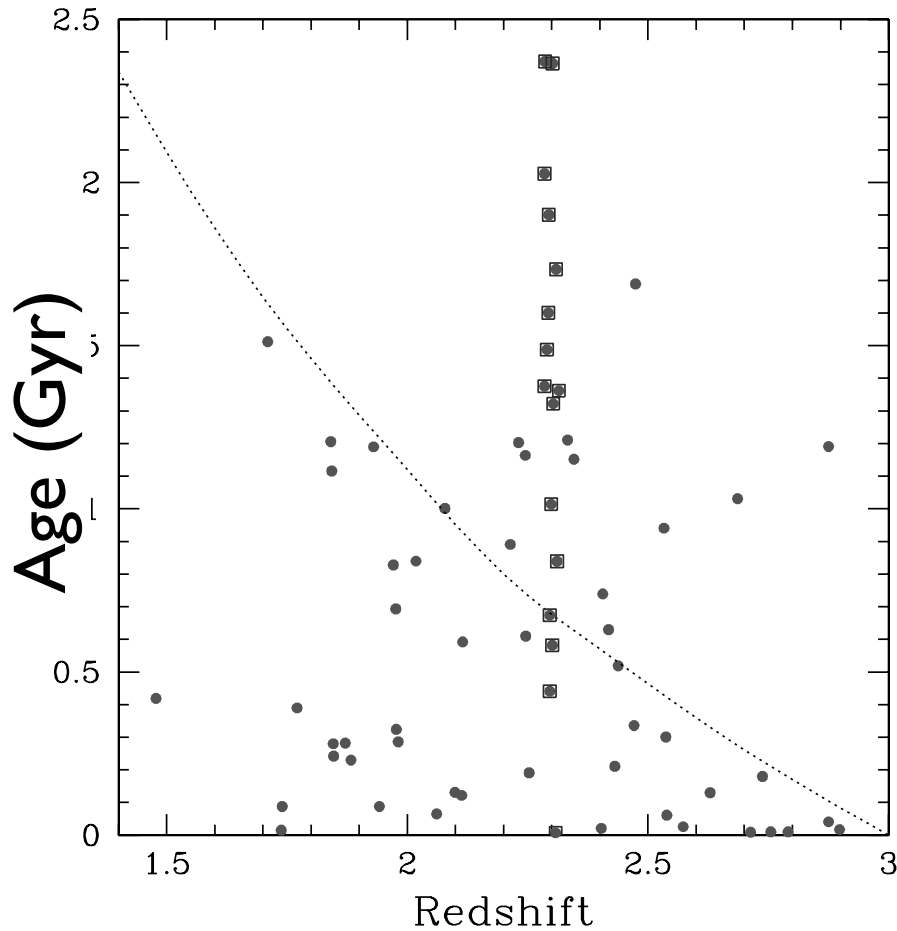
Steidel+ 2005

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