A Systematic Approach to Cluster Formation in the Early Universe - Observations, Simulations, and New Surveys

Yi-Kuan Chiang

Roderik Overzier

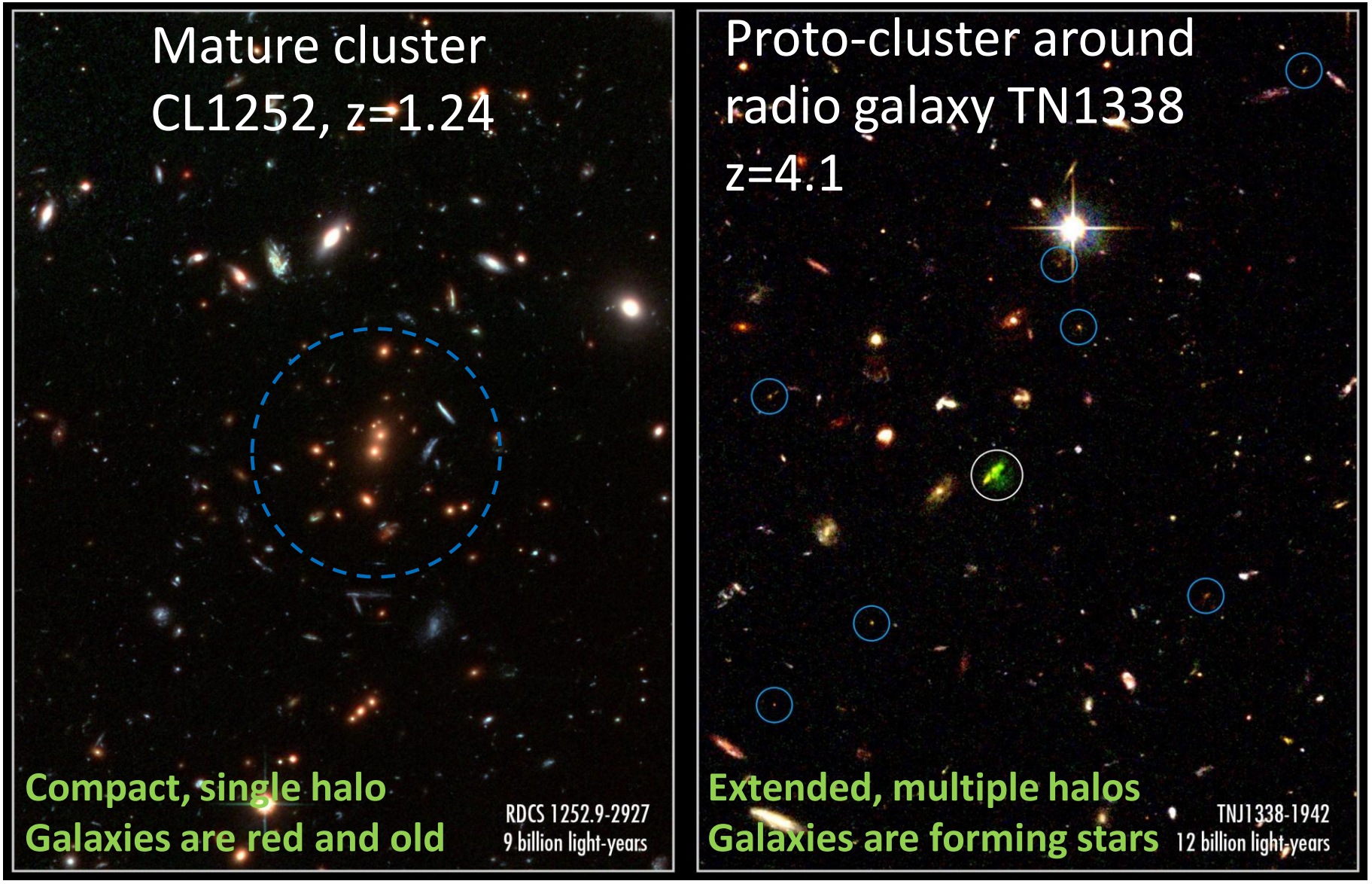
Karl Gebhardt

University of Texas at Austin

09/10/2012

From proto to mature, how?

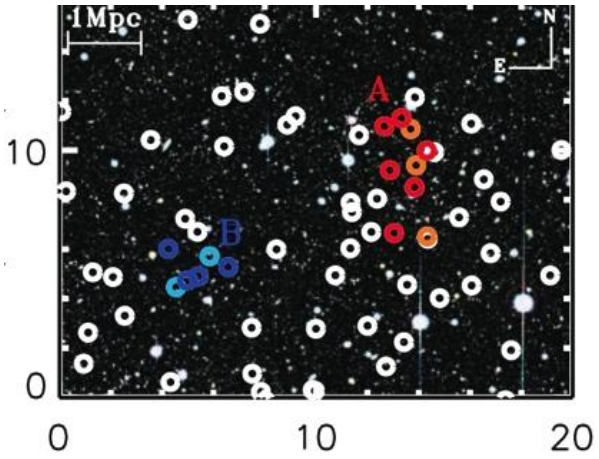
~ 1/3 t_H ~ 1/10 t_H



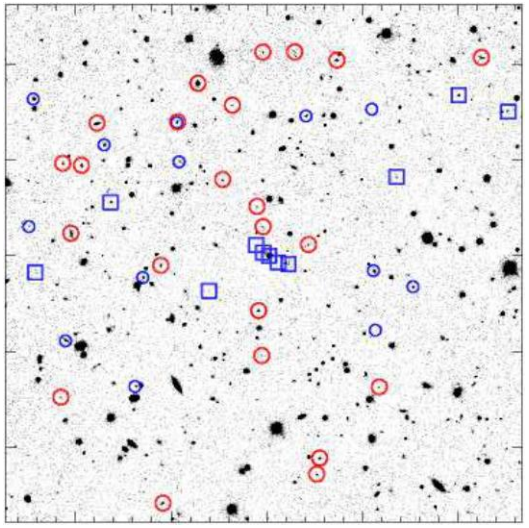
Blakeslee et al. 2003 Miley et al. 2004

The Proto-cluster "Zoo"…

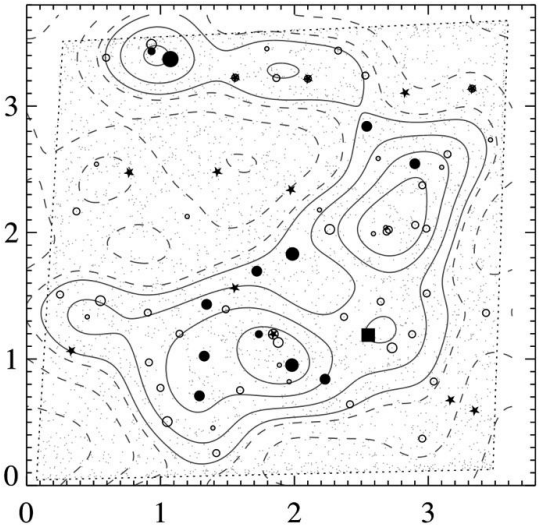
Ouchi et al. 2005, LAE, z=6



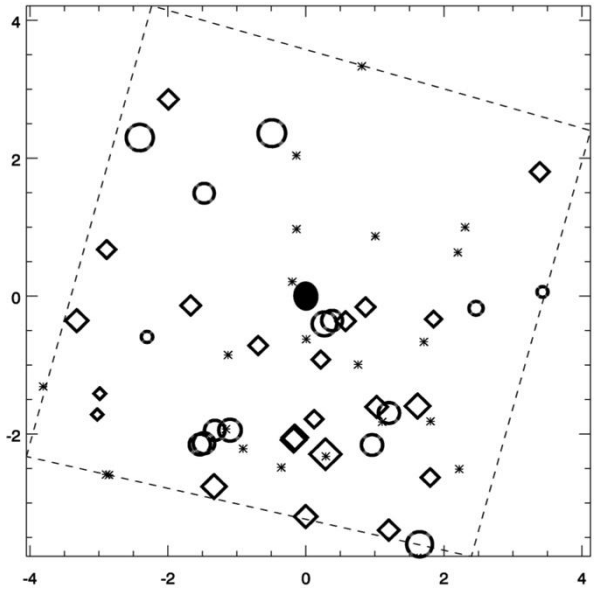
Hatch et al. 2011, Hα, z=2.35



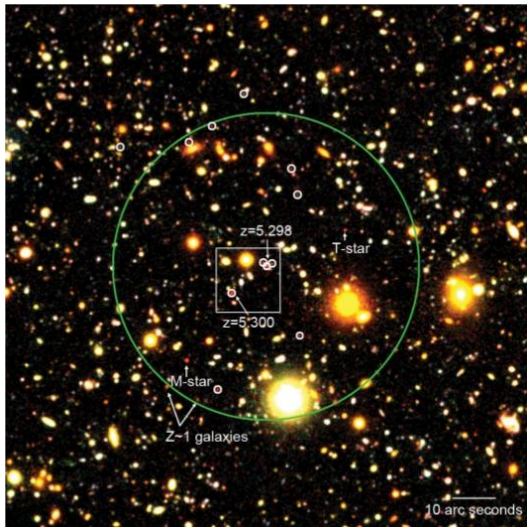
Overzier et al. 2008, LBG, z=4.1



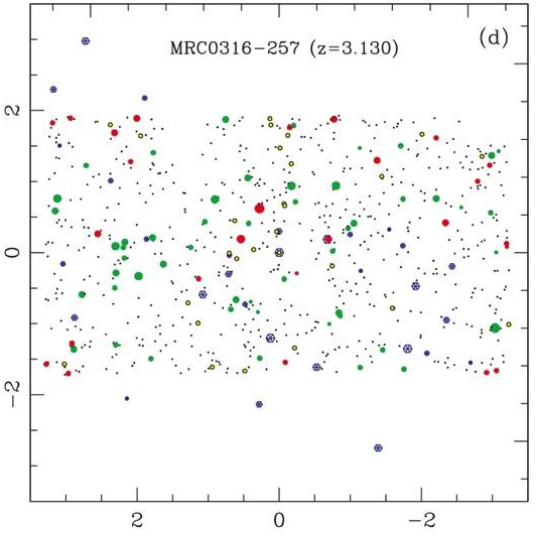
Venemans et al. 2007, LAE, z=2.86



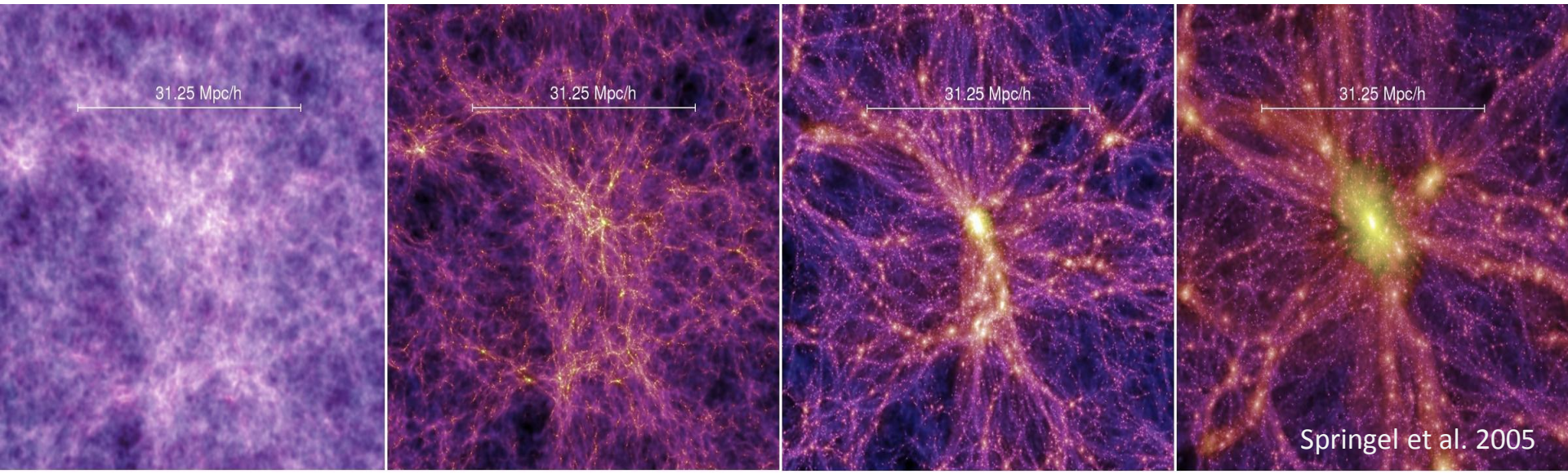
Capak et al. 2011, sub-mm, z=5.3



Kodama et al. 2007, JHK, z=3.13



Galaxy clusters in cosmological simulation



We think this is gonna work

Observables δ_{galaxy} **(properties)** ⟷ **LCDM SAM galaxy** ⟷ **Environments** δ_{mass}

Over 3000 clusters extracted from the MR (Springel+05)

Allows us :

- **Make predictions**
- **Compare structures observed with different methods**
- **Identify new proto-clusters**

Statistical, simulations-assisted study of (proto-)cluster evolution from z=6 to z=0

Practical definition:

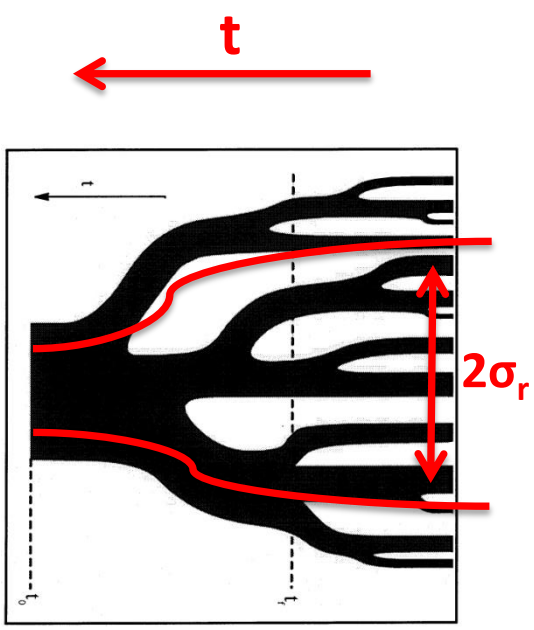
- **Galaxy cluster – gravitational bound DM halo with mass > 10^{14} M_{sun}/h and its associated galaxies and gas**
- **Proto-cluster – a collection of DM halos and their associated galaxies which will evolve into a galaxy cluster by z=0**

Tools:

- **DM density fields (δ_{mass} as the basic quantity for environments)**
- **Halo catalogues (M_{halo} > ~10^10 M_{sun})**
- **Semi-analytic galaxy catalogs (SAM) (Guo et al. 2011) (M_{star} > ~10^9 M_{sun}) (δ_{galaxy} as the observables)**
- **Multi-Wavelength Lightcone catalogues (Henriques et al. 2011)**
- **WMAP1 Cosmology (WMAP7 coming soon)**
- **Millennium Run Observatory (Overzier et al.2012)**

Properties of proto-clusters in Millennium

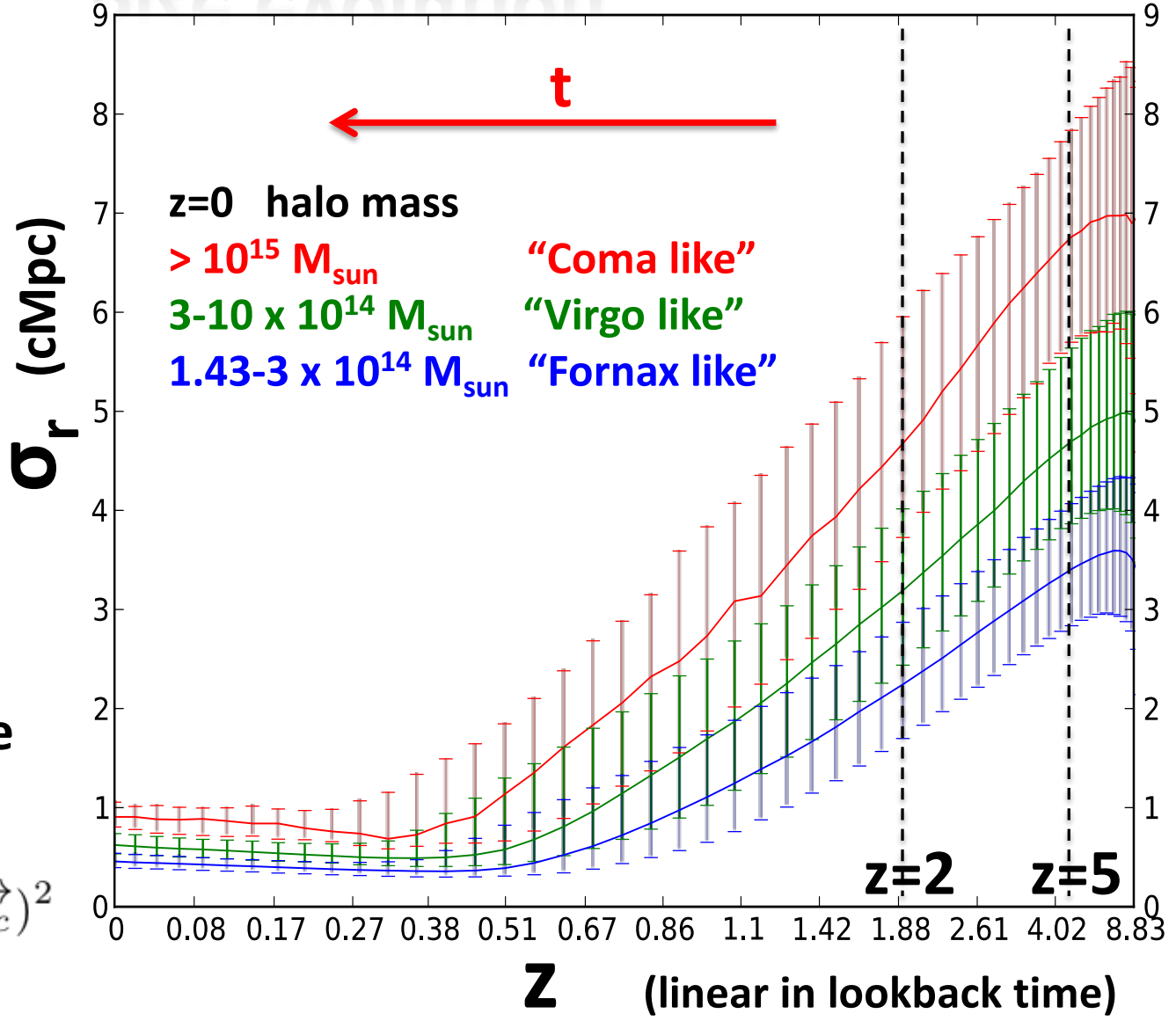
Size evolution



Effective radius, σ_r

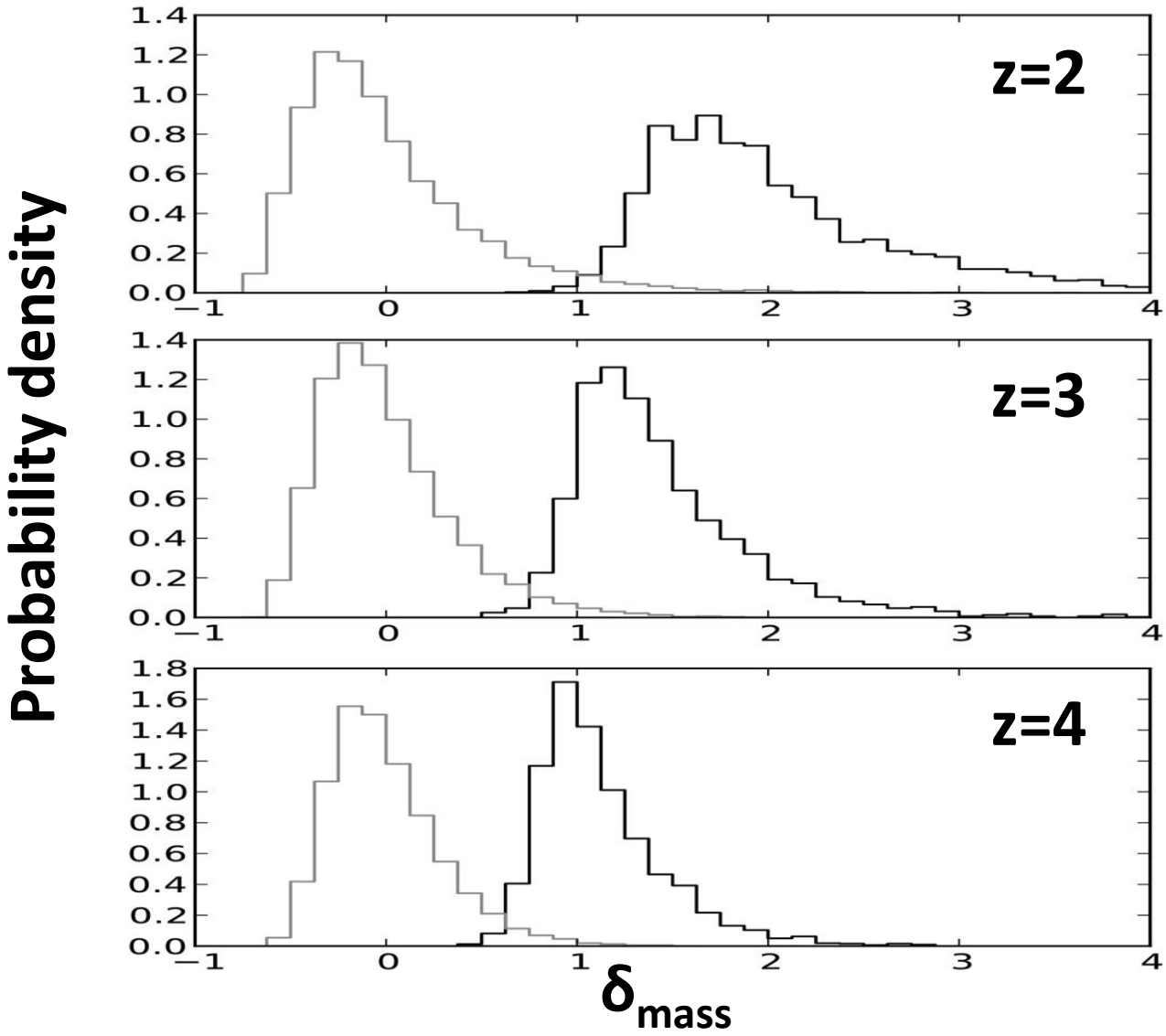
2nd moment of the mass distribution

$$\sigma_r^2 \equiv \frac{1}{M}\Sigma_i m_i(\overrightarrow{r_i} - \overrightarrow{r_c})^2$$



Physical quantity of environments

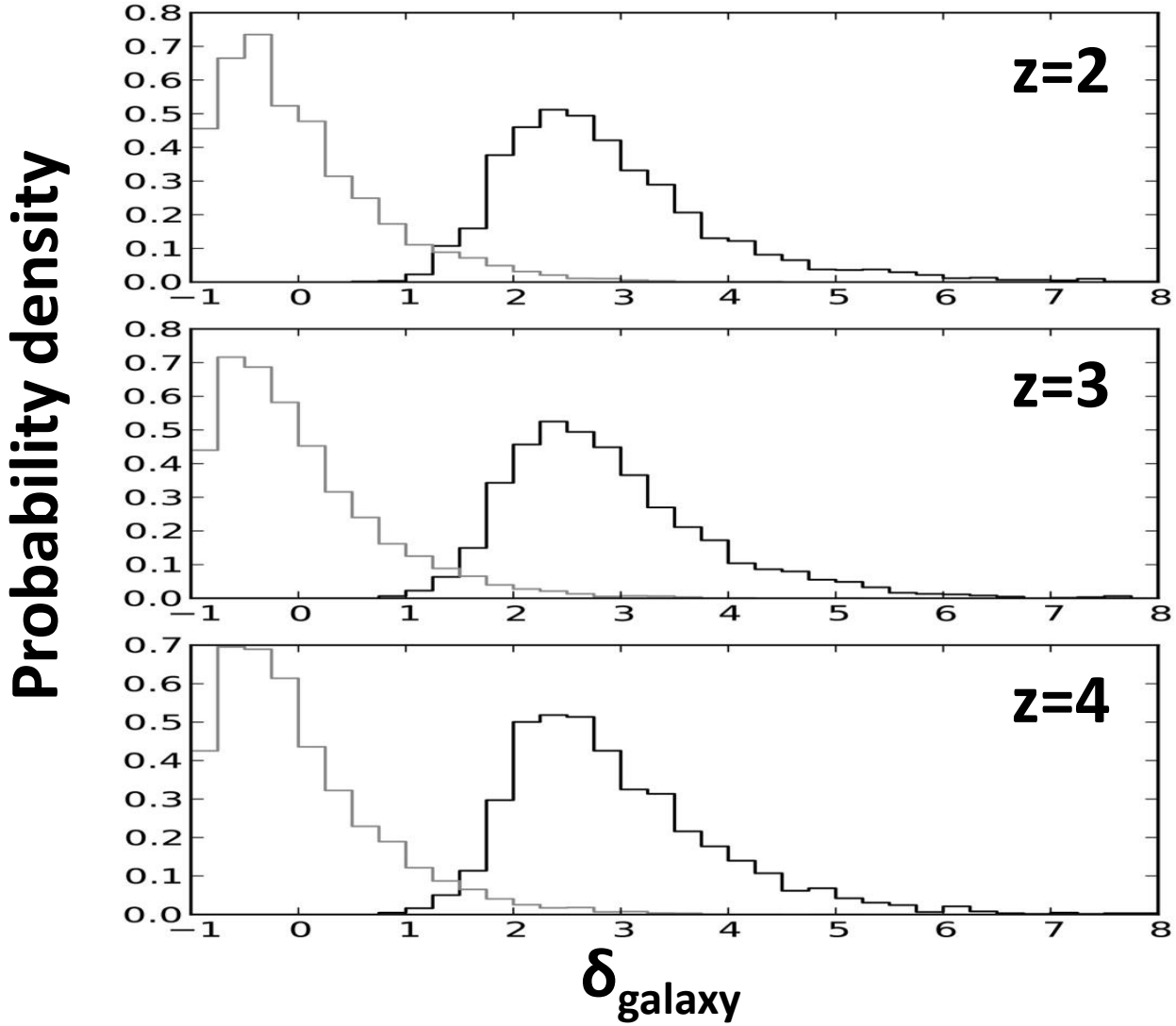
Mass overdensity evolution



Observables of proto-clusters

Galaxy overdensity evolution

SFR > 1 M_{sun}/yr galaxies



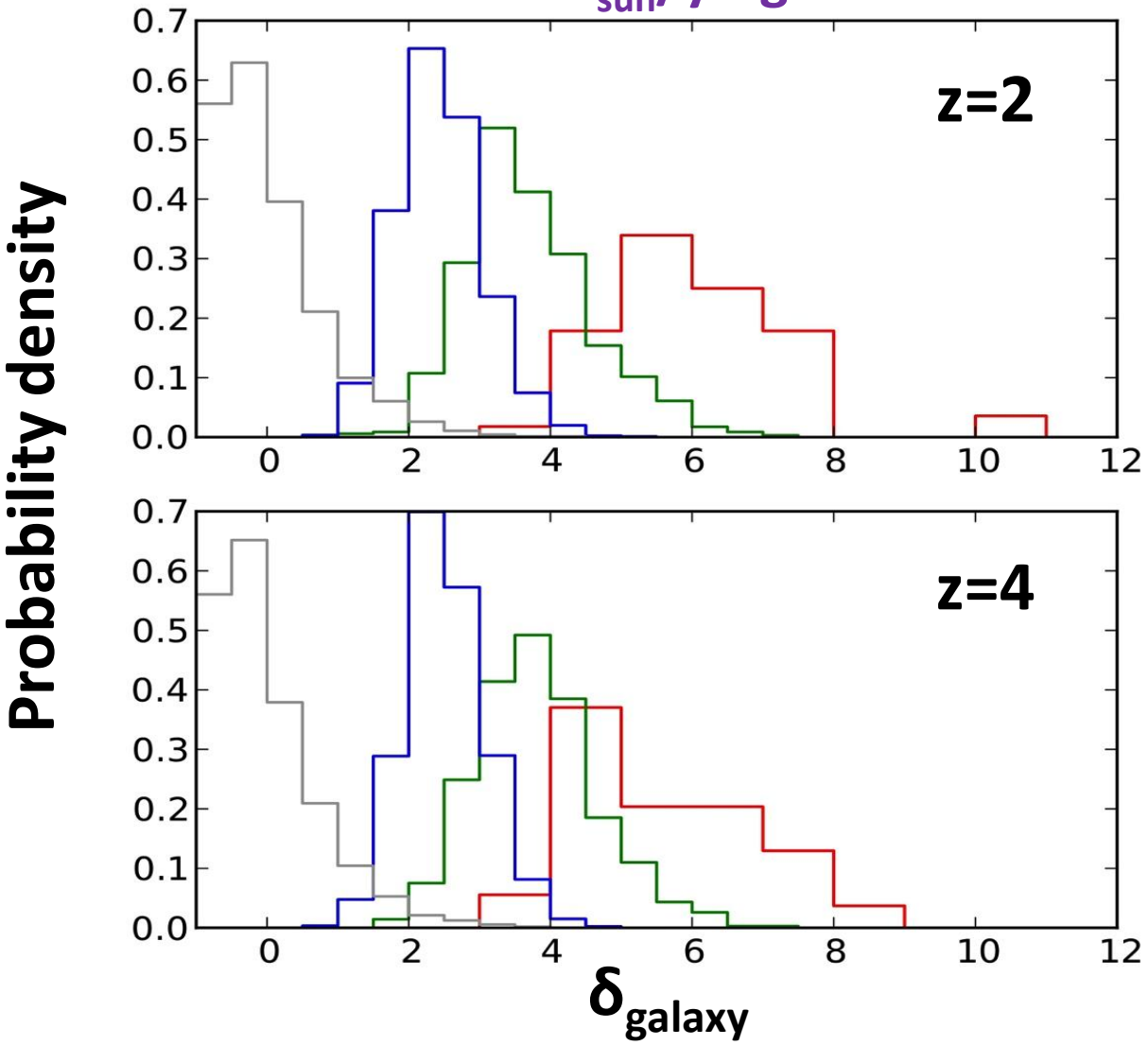
Gray: Random

Black: Proto-cluster

Properties of proto-clusters in Millennium

Galaxy overdensity versus Cluster Mass

SFR > 1 M_{sun}/yr galaxies



Gray:
Random

Red:
> 10^{15} M_{sun}
"Coma like"

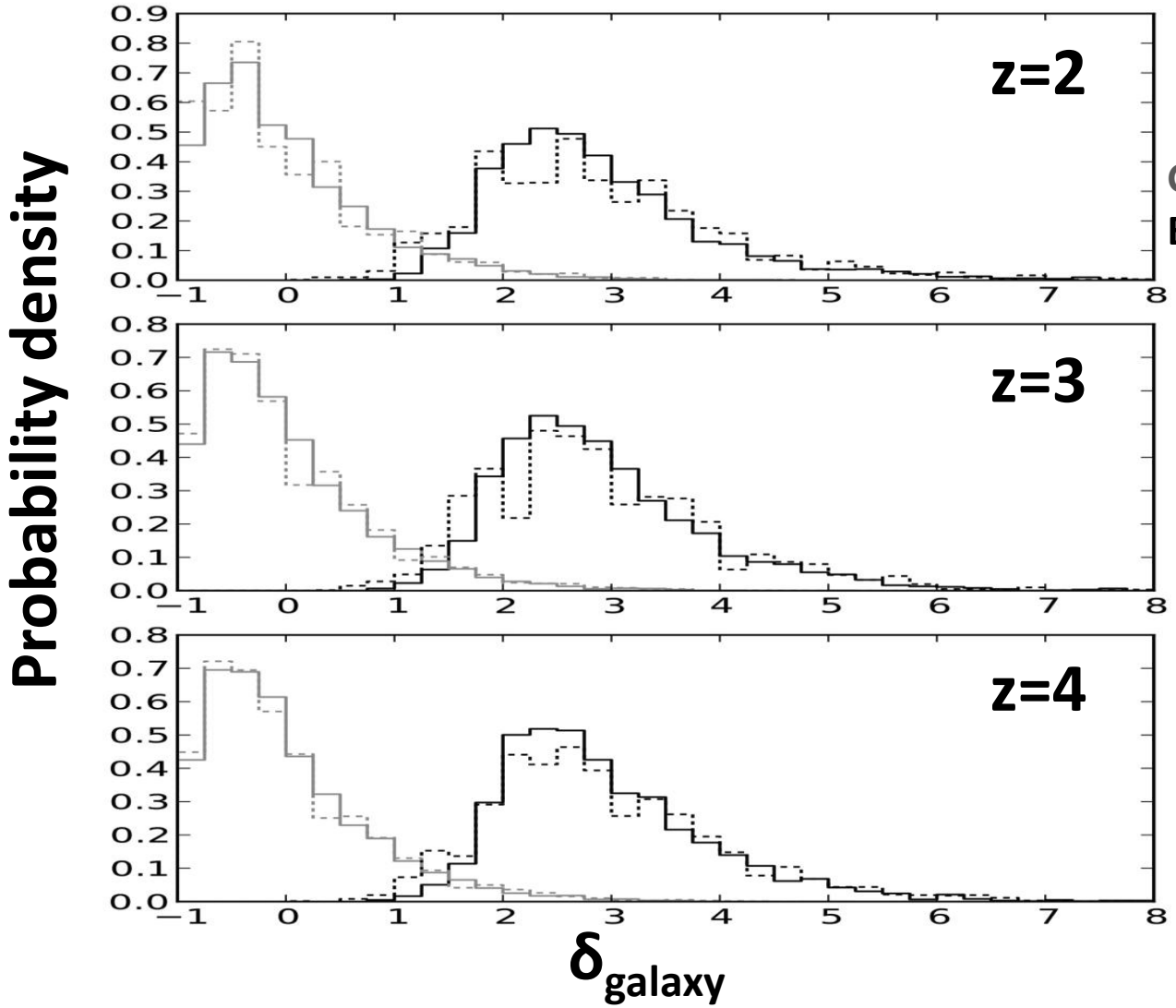
Green:
3-10 x 10^{14} M_{sun}
"Virgo like"

Blue:
1.43-3 x 10^{14} M_{sun}
"Fornax like"

Observables of proto-clusters

LAE overdensity evolution

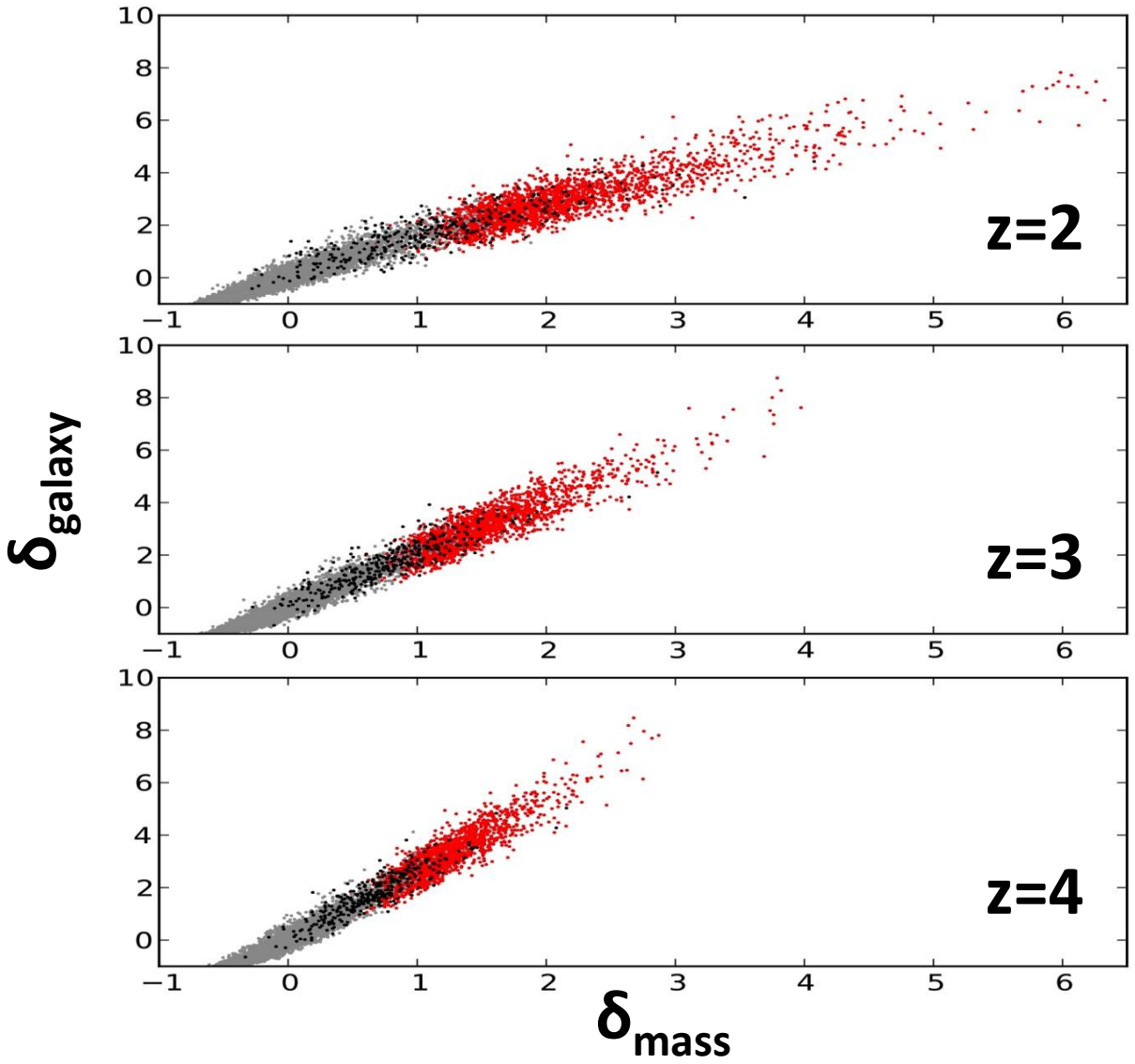
Solid: SFR > 1 M_{sun}/yr galaxies **Dotted: LAEs**



Gray: Random
Black: Proto-cluster

Galaxy bias – δ_{mass} vs. δ_{galaxy}

SFR > 1 M_{sun}/yr galaxies

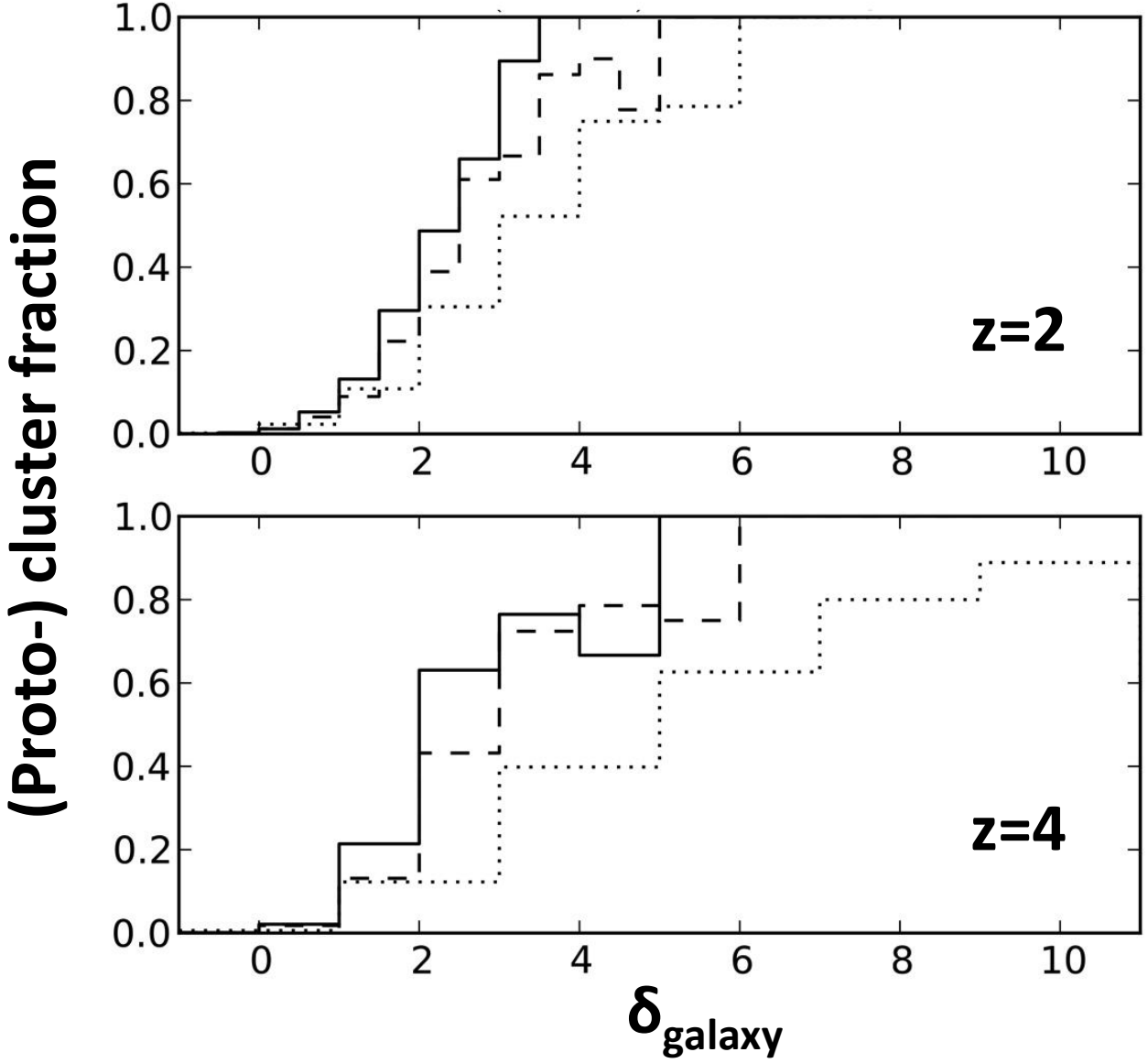


Gray: Random

Black: Random regions which cover significant parts of proto-cluster

Red: Proto-cluster

Proto-cluster fraction vs. δ_{galaxy}



Solid:
SFR > 1 M_{sun}/yr galaxies

Dashed:
$M_{star} > 10^9 M_{sun}$ galaxies

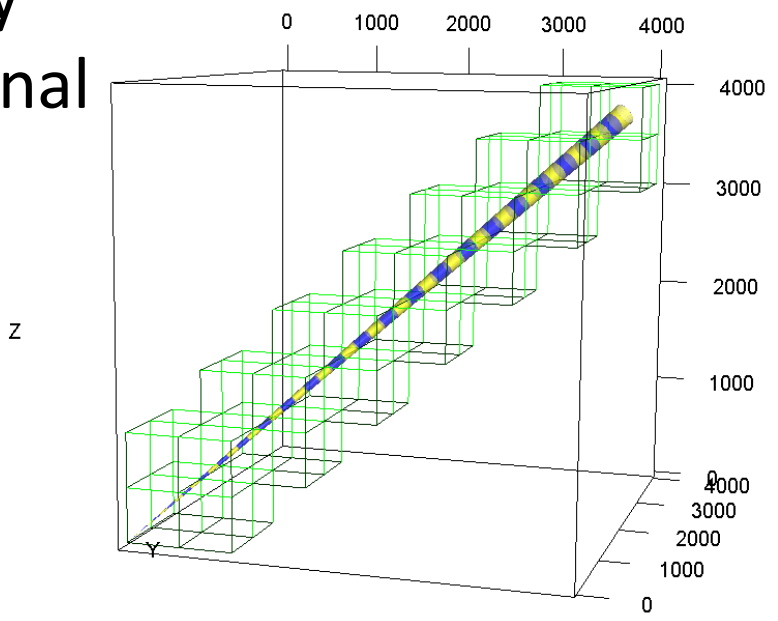
Dotted:
$M_{star} > 10^{10} M_{sun}$ galaxies

More biased

Simulated observations - Example JHK selection on synthetic lightcone

- **Idea:**
  Where is the sweet spot to maximize the ability to identify proto-clusters with observational selections applied
- **Example - JHK selection:**
  Get very rough "photometric redshift" using 3 bands to **select 2.2<z<3 galaxies**

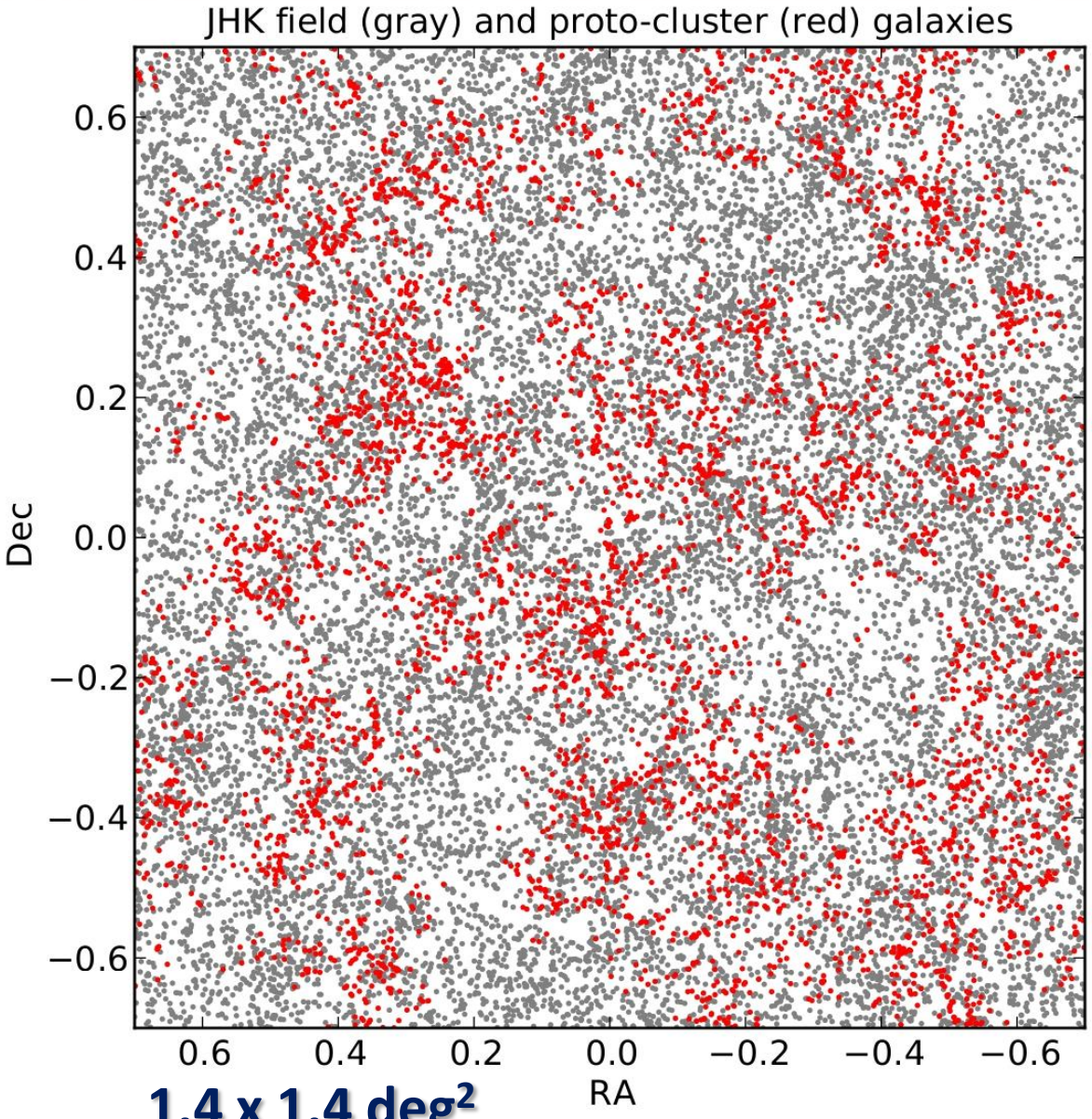
- **Synthetic lightcone of Millennium+SAM galaxies with IGM correction**



Kajisawa et al. 2006
Kodama et al.2007
Hatch et al. 2011

SAM: **Guo et al. 2011**
Lightcone: **Henriques et al. 2012**
IGM correction: **Overzier et al. 2012**

JHK selection on synthetic lightcone

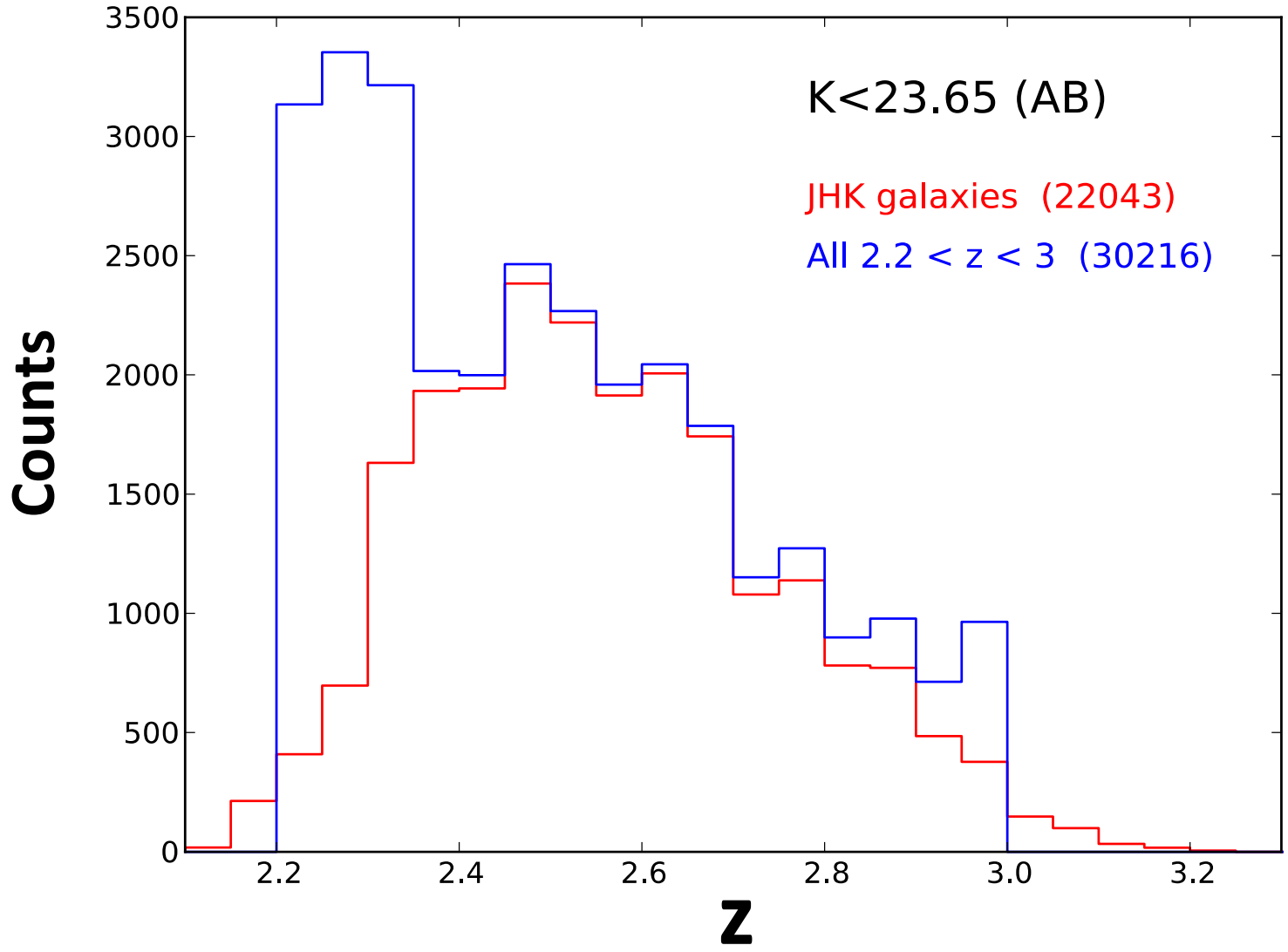


1.4 x 1.4 deg²

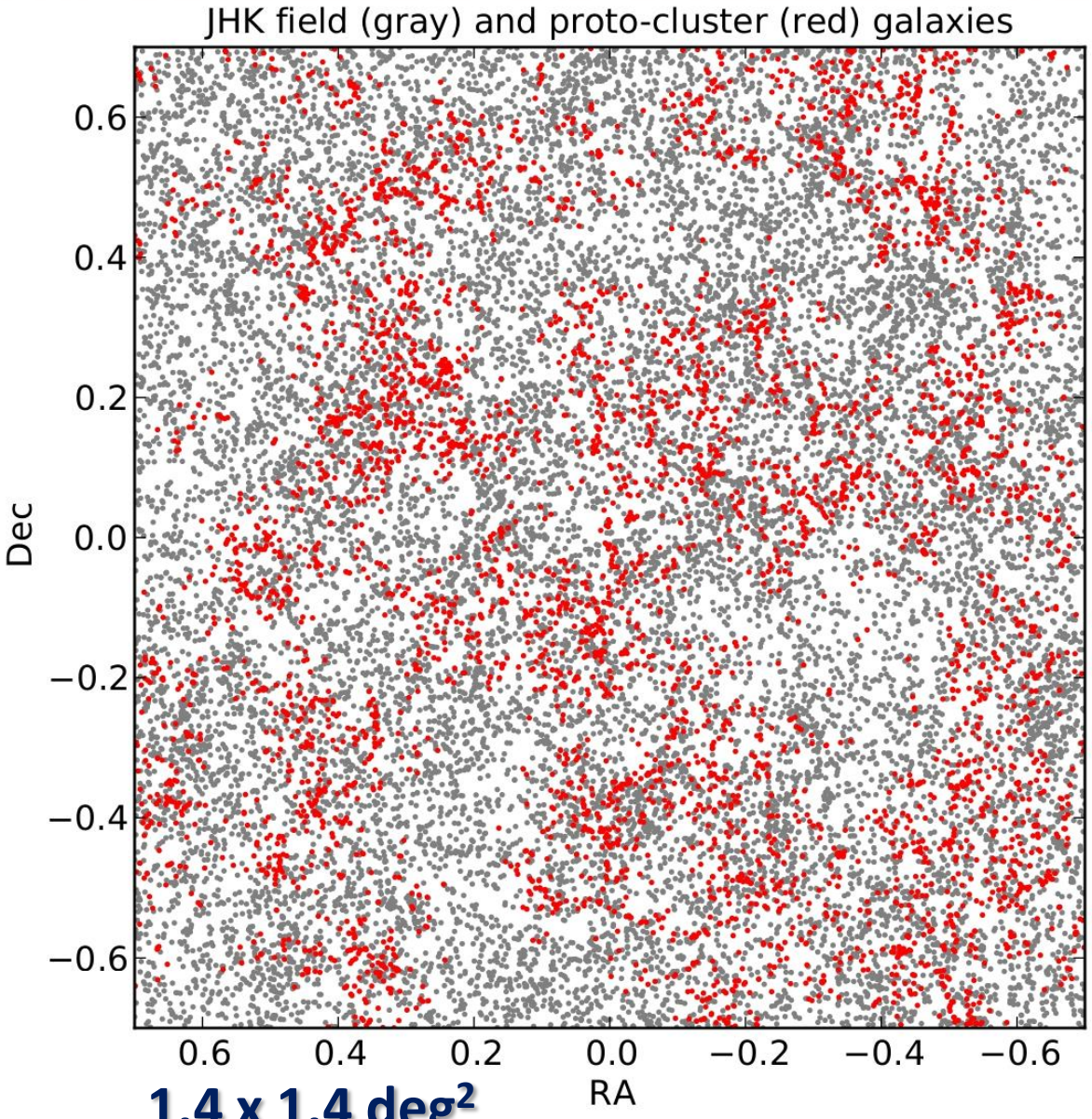
Gray:
Field galaxies

Red:
Proto-cluster galaxies

Selection effects
-We know it in simulated observations



JHK selection on synthetic lightcone

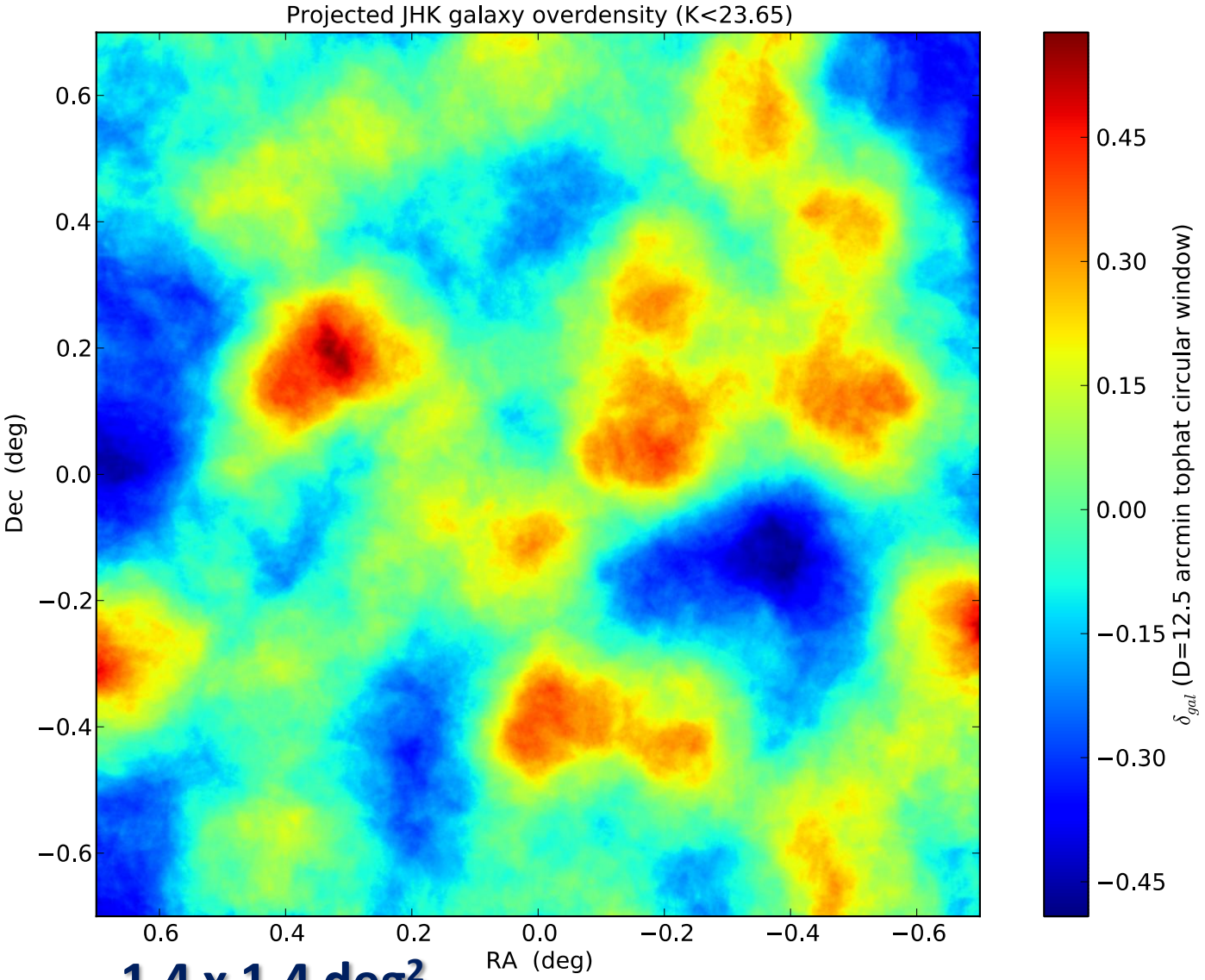


1.4 x 1.4 deg²

Gray:
Field galaxies

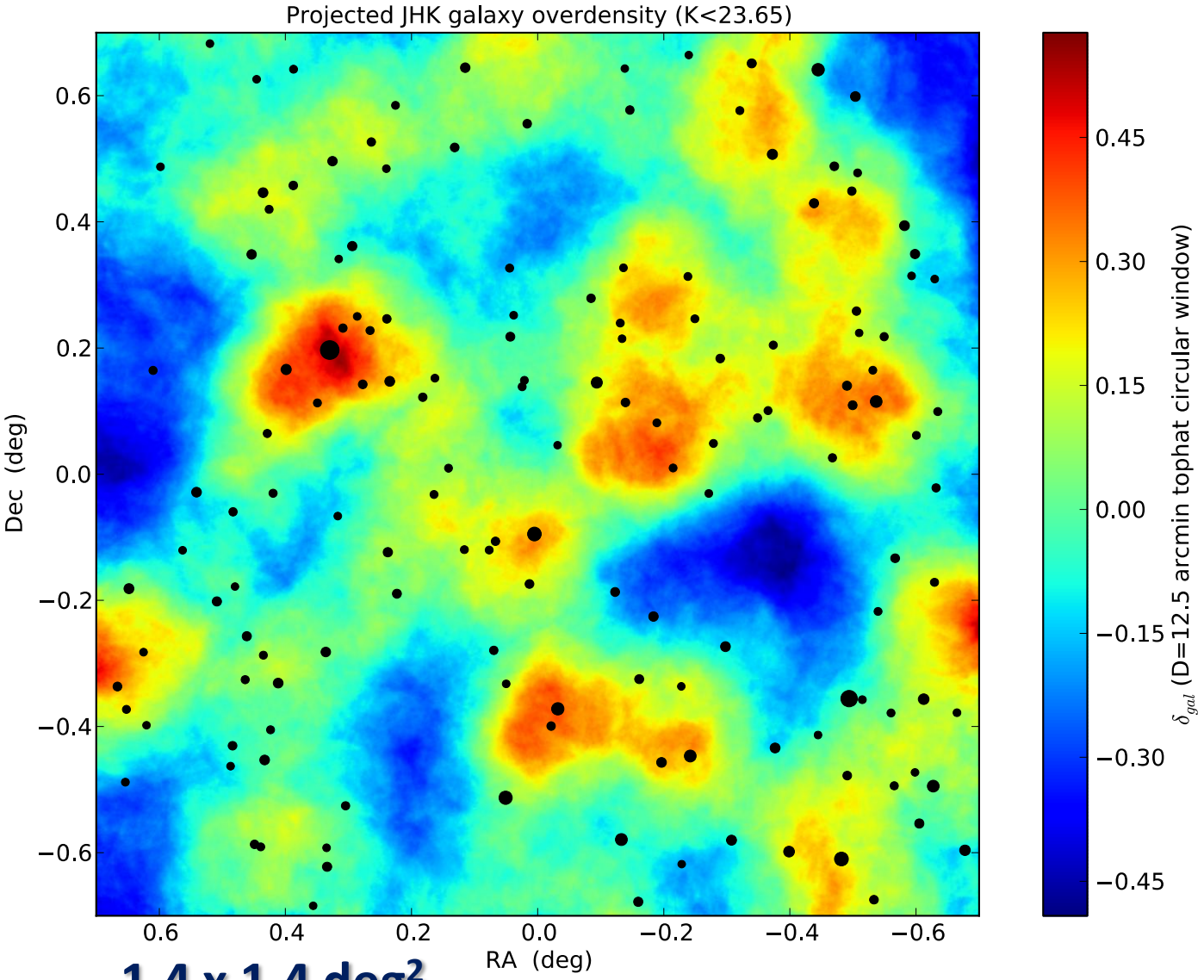
Red:
Proto-cluster galaxies

Projected overdensity of JHK galaxies



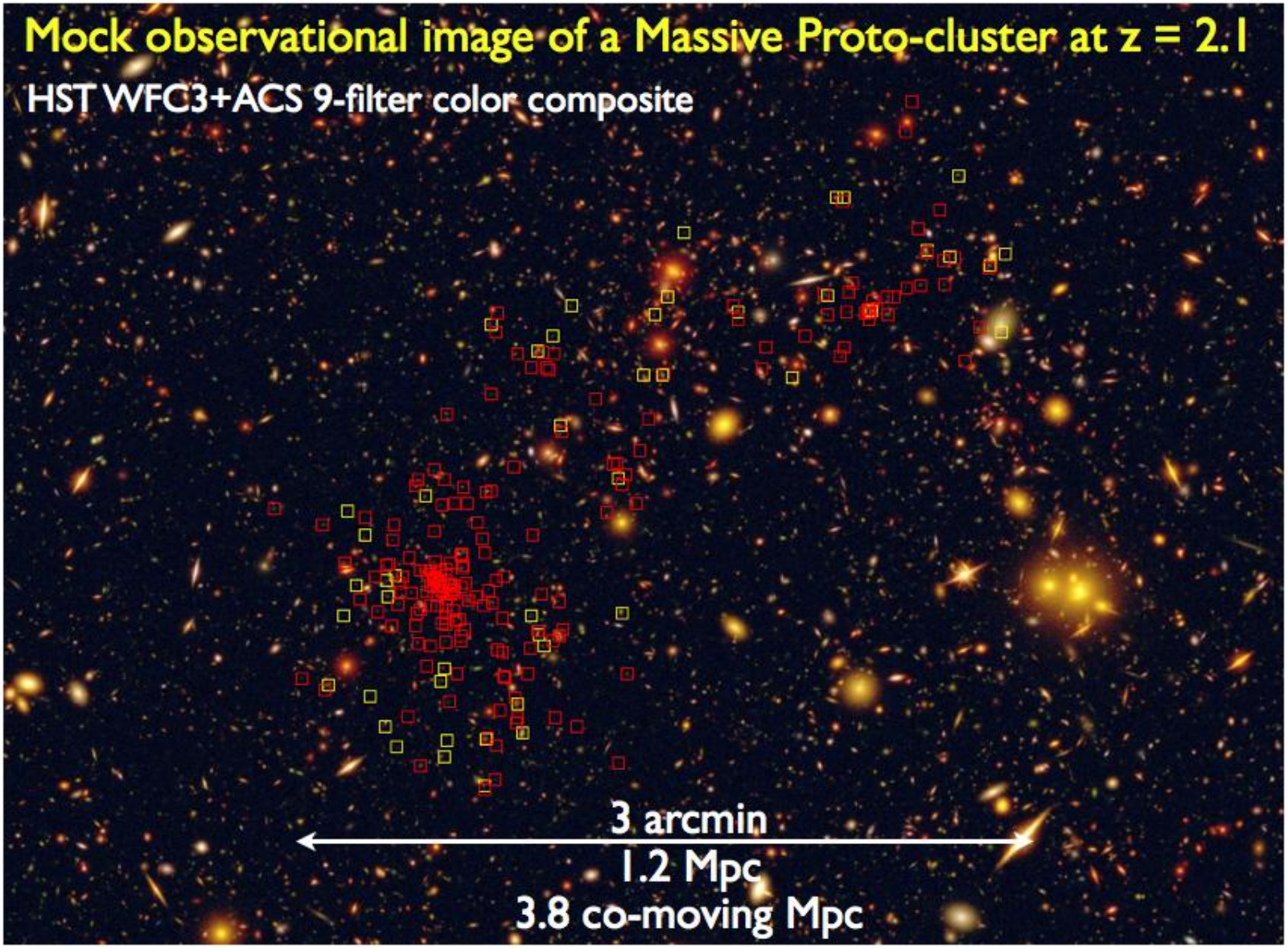
1.4 x 1.4 deg^2

Centers of proto-clusters



1.4 x 1.4 deg^2

Precise predictions from the *Millennium Run Observatory*

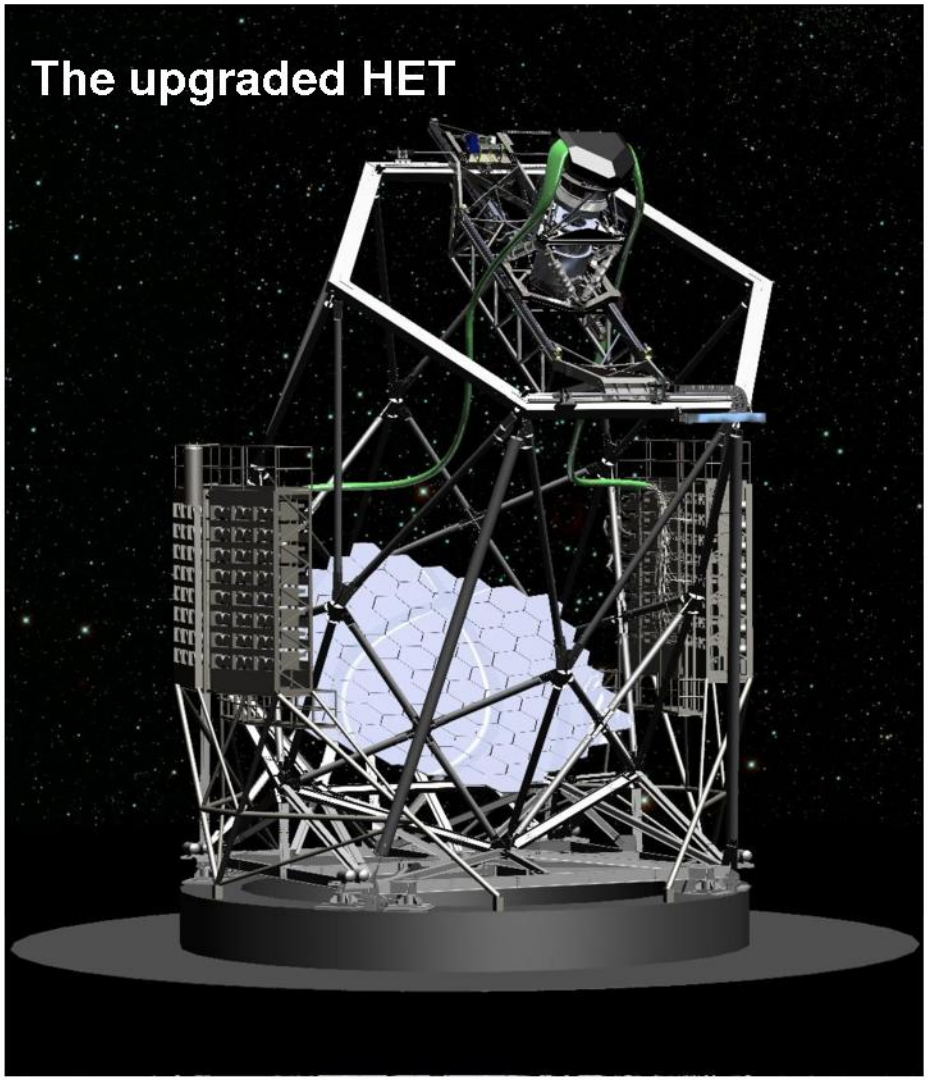


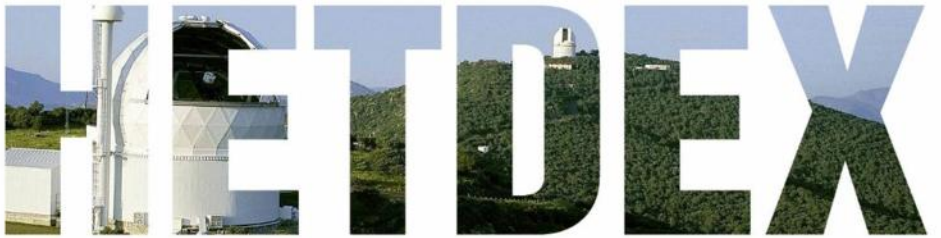
Overzier, Lemson et al. (arXiv:1206.6923)
http://galformod.mpa-garching.mpg.de/mrobs/

HETDEX
Hobby-Eberly Telescope Dark Energy Experiment

THE UNIVERSITY OF TEXAS AT AUSTIN
Department of Astronomy
1 University Station, C1400 • Austin, Texas 78712-0259

McDonald Observatory
THE UNIVERSITY OF TEXAS AT AUSTIN





Hobby-Eberly Telescope
Dark Energy Experiment

MPE

PENNSTATE
1855

AIP

LMU
USM

ATM

Summary

- Proto-clusters have sizes of few to tens of Mpc
- Correspond to mass overdensities of a few that separate clearly from the field up to high redshifts
- Same is true for galaxy overdensities (SFR, M*, Lya,…), with overdensities of >~4 indicating proto-cluster identification success rate of ~100%
- Progenitors of different mass clusters are distinct in size, galaxy (mass) overdensity, and velocity dispersion
- But: the projection/selection effects increase the scatter between observables and physical properties
- These effects can now be understood/quantified by using accurate lightcone predictions from simulations
- Our detailed comparison with a large number of protoclusters from the literature and own observations is underway
- HETDEX is going to observe LAEs in a volume 15 times of Millennium

Chiang et al., in prep.

Thank You