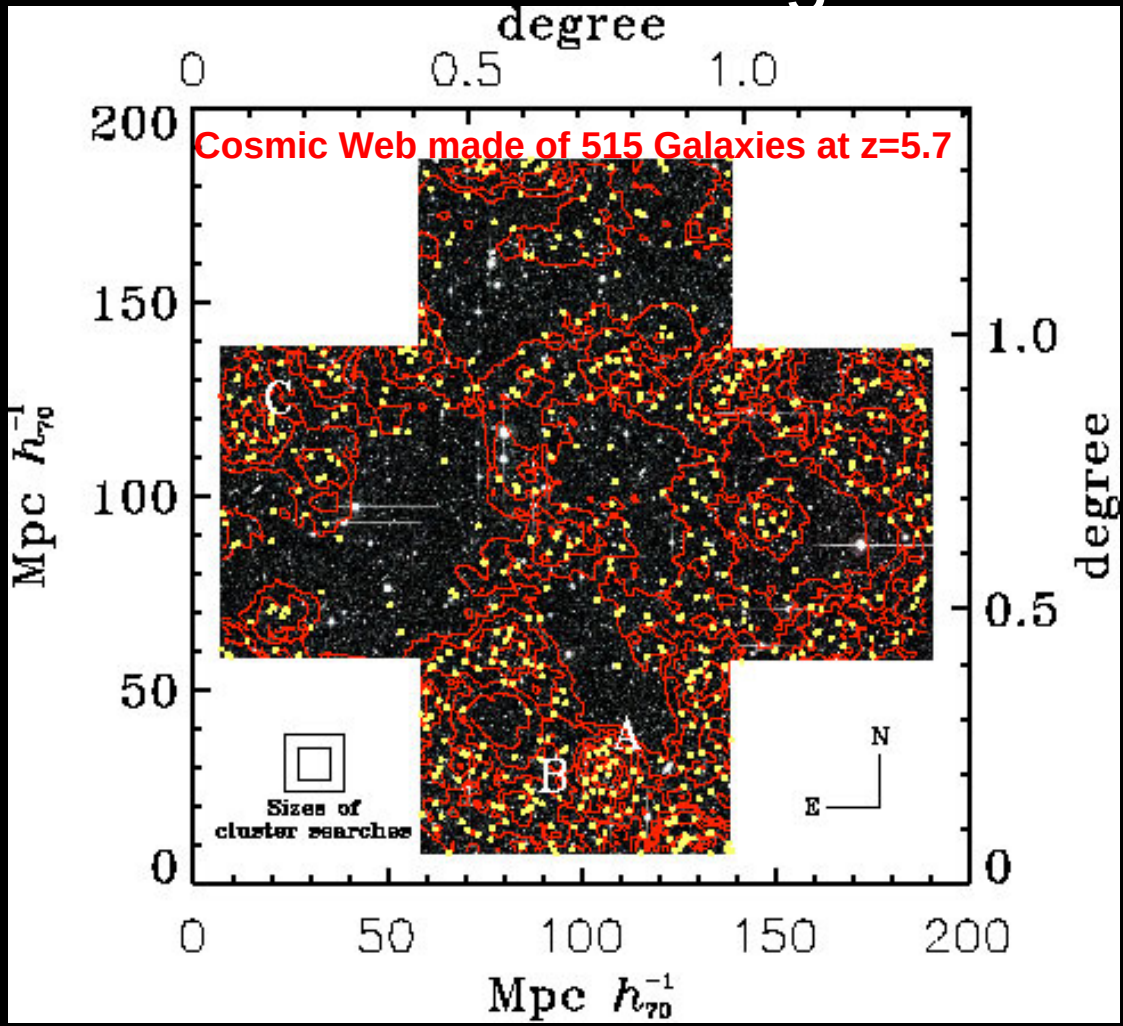
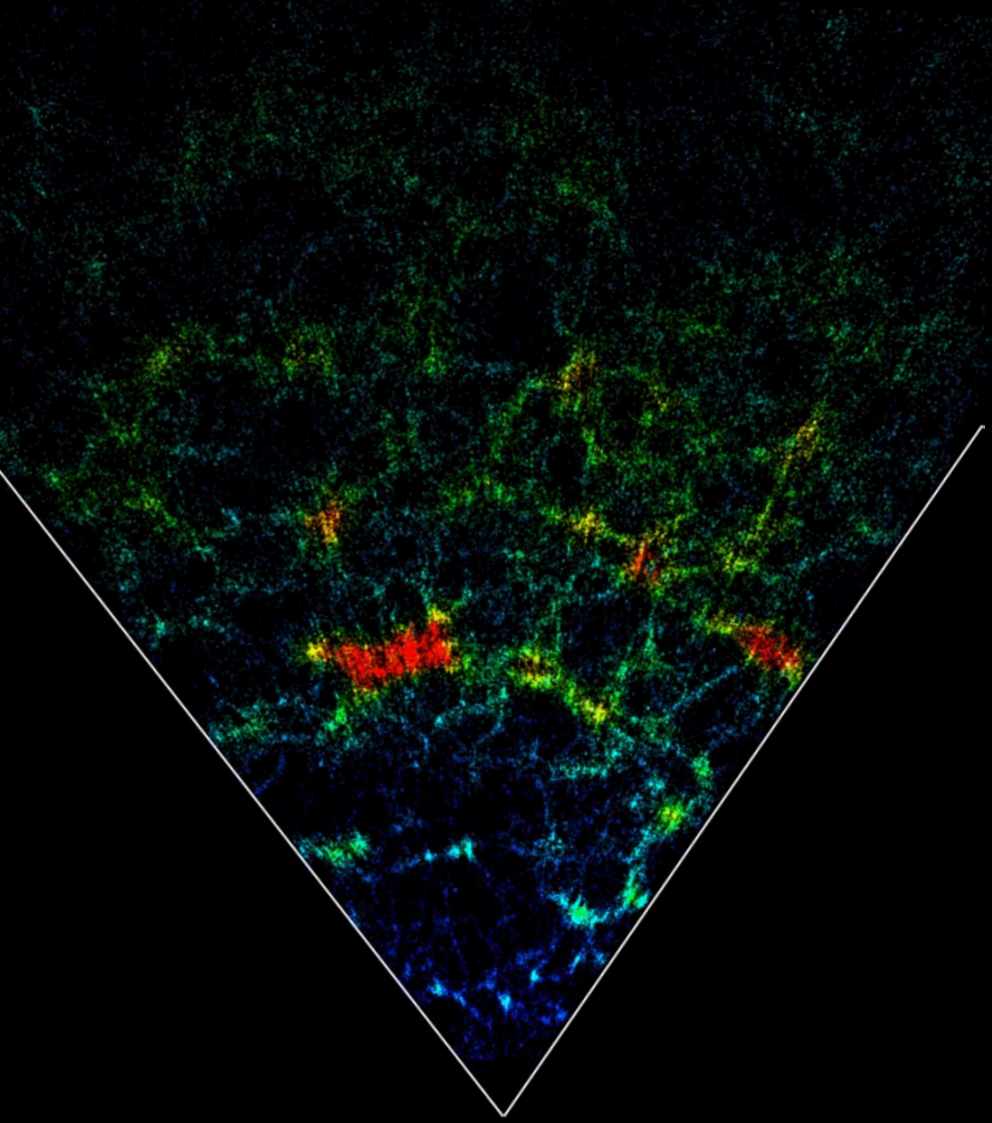
Origin of Clusters and Large-Scale Structures: Panoramic View of the High-z Universe



Masami Ouchi
(Space Telescope Science Institute)
for the SXDS Collaboration

22nd Texas Symposium at Stanford

Origin of Clusters & Large-scale structures



Clusters and large-scale structures in the Local Universe (2dFGRS)

The standard CDM model says,

"Initial density perturbation grows up by gravitational instability"

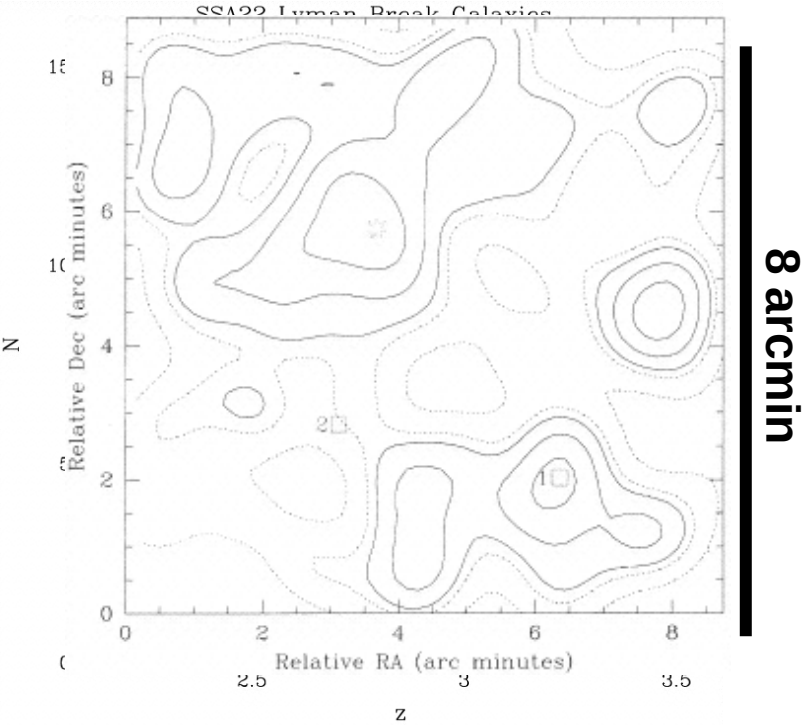
It is true for the mass (CDM) distribution

It is not obvious for structures made of galaxies, because complicated physics of star-formation is involved.

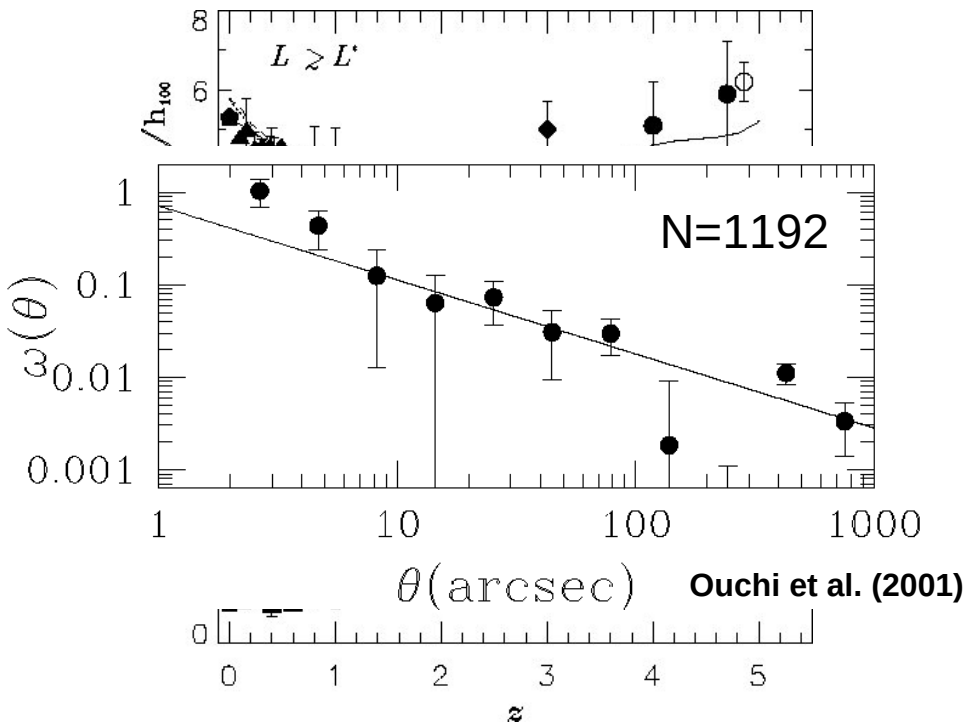
When, how and where clusters and LSSs of galaxies formed??

High-z galaxy clustering should be investigated.

Highly Biased High-z Universe



Proto-cluster: Redshift spike of Ly break galaxies at z=3.1
(Steidel et al. 1998)

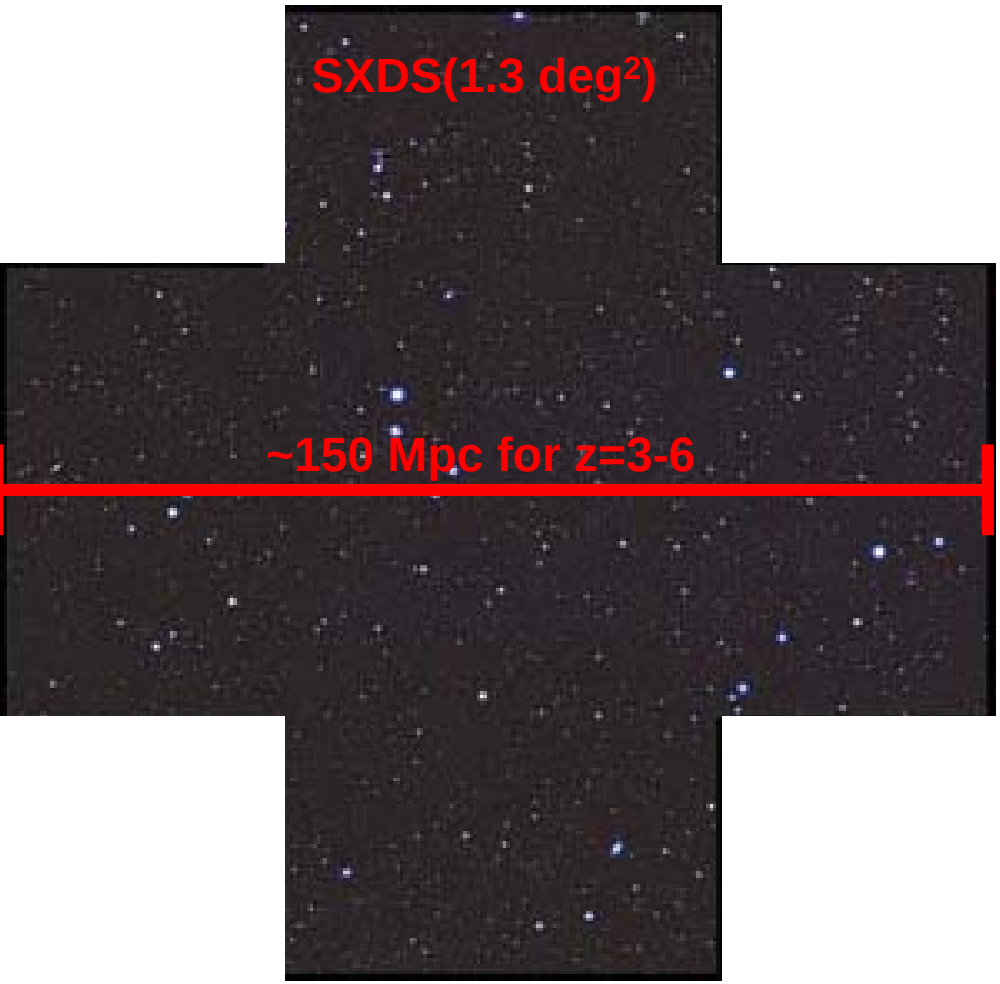


Ouchi et al. (2001)

r_0 and bias of Ly break galaxies with L>L* (Ouchi et al. 2004)

- Dense galaxy concentrations←Understood with DH distribution (+GF bias).
- Distribution of High-z galaxies are highly biased against DM (b=3-5 at z=3-5).
- **How does the large-scale structure of high-z galaxies look like?**
- **How do galaxies relate to dark halos?**
  → Wider & deeper survey is needed.

Mapping the high-z Universe
Subaru/XMM Deep Survey



- Subaru Observatory Key Project (Sekiguchi et al. 2004)
  - **BVRiz with Subaru** (Furusawa et al. in prep) ~5hr/band/pointing

B	V	R	i'	z'
28.2	27.2	27.6	27.5	26.5

  - **FOCAS/MOS** Optical Spectroscopy (Akiyama et al. in Prep.)
    - See Iye et al.(2004) PASJ, 56, 381
      Miyazaki et al.(2002): PASJ, 54, 833
  - **VIMOS 62 hours** (Simpson et al. in Prep.)
  - **VIMOS 10 hours** (Saito et al. in prep)
- UKDISS; **JHK (K_{AB}=25)** (Almaini et al.)
- The other wavelength (with international collaboration)
  - **X-ray:XMM** (Watson et al.)
  - **UV: GALEX**
  - **IR: Spitzer/IRAC** (*Swire:* Lonsdale et al.)
  - **Sub-mm:SCUBA** (SHADES;Dunlop et al.)
  - **Sub-mm:BLAST** (Hughs et al.)
  - **Radio:VLA** (Rawlings et al.)
    (**GMRT**; Rawlings et al.)

Very deep + wide-field images (Unique data set)

Comparison of Surveyed Areas in the Very Deep Surveys (i'~27)

GOODS (0.09 deg^2)

FDF(0.01deg^2)

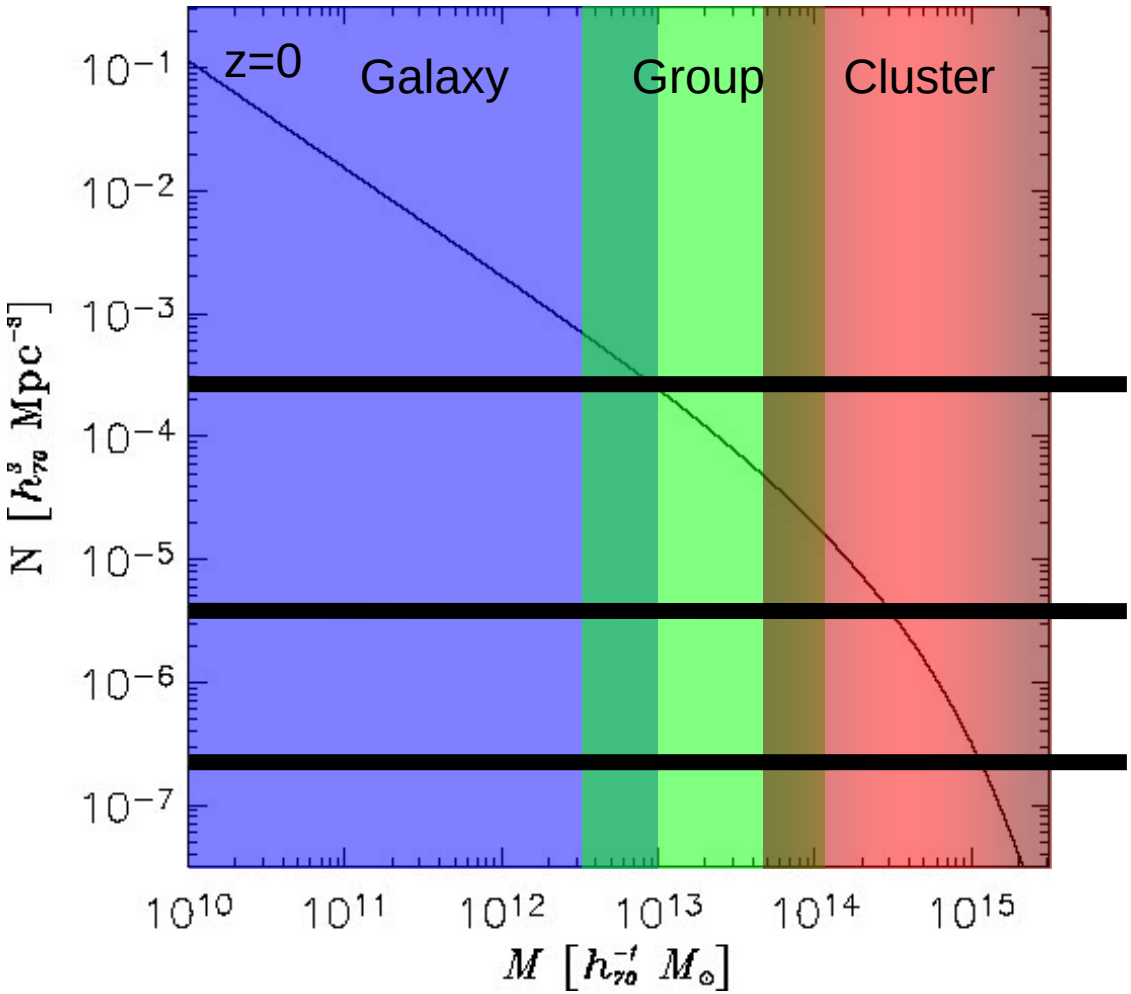
HUDF(0.002deg^2)

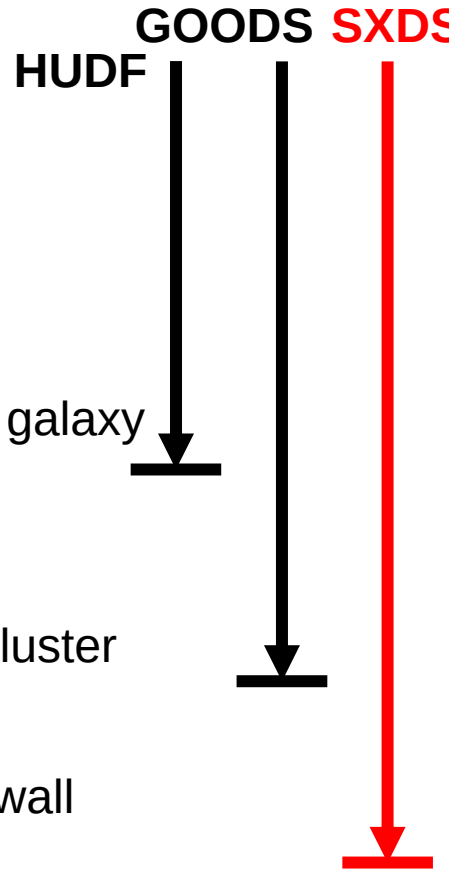
HDF(0.001deg^2)

- The widest-sky coverage among the very deep surveys

Number Densities v.s. Survey Volumes (comoving)

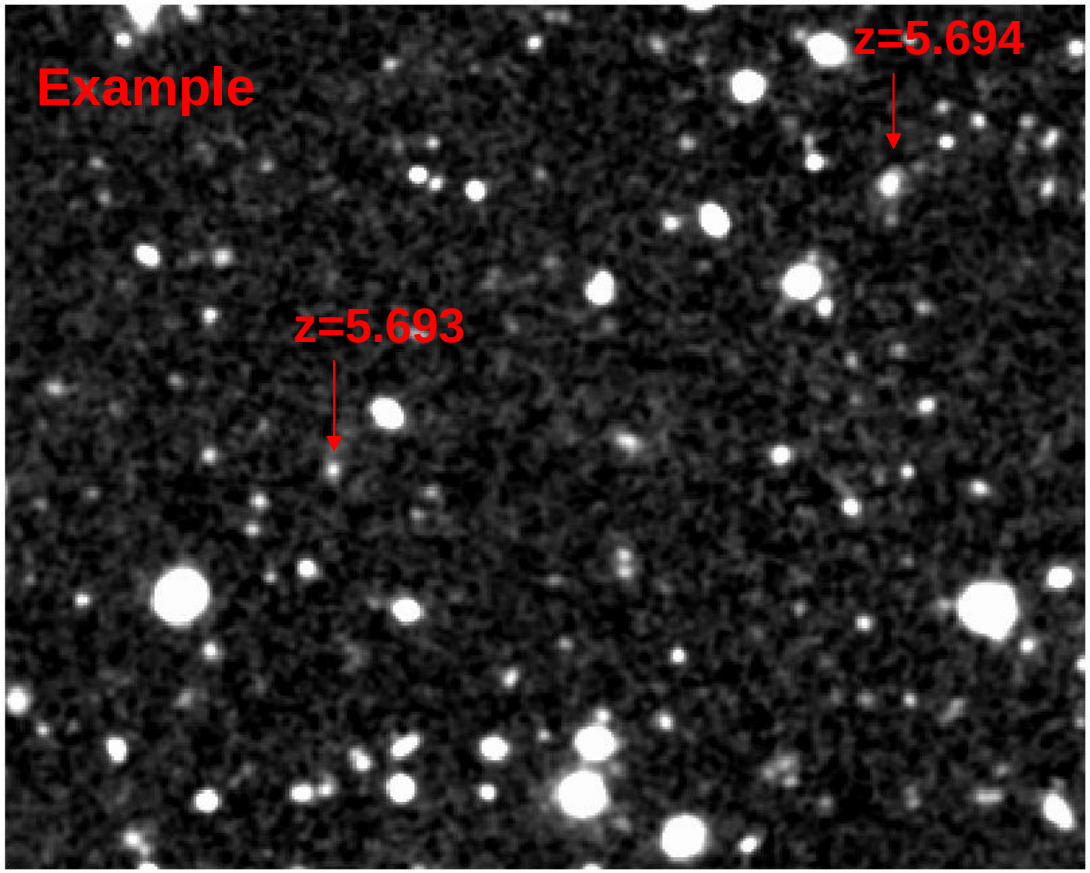
1/V par $\Delta z=1$





You can study galaxies, clusters, and LSSs at high-z with SXDS.

Limitation of the SXDS data
poor spatial resolution



Galaxies are marginally resolved with these ground-based images. (c.f. GOODS, HUDF etc.)

You cannot study morphologies of galaxies.

Large High-z Galaxy Samples

- Lyman Break Galaxy (LBG)
  - z~4: 16,920 (i'<27.5; BRi 2 colors)
  - z~5: 2,768 (z'<26.5; Viz 2 colors + B>2 σ)
  - z~5: 1,293 (z'<26.5; Riz 2 colors + B,V>2 σ)
  - z~6: 133 (z'<26.0; iz 1 color + B,V,R>2 σ)
- Lyman α Emitter (LAE)
  - z~3: 332 (NB503<25.2; BRNB 2 colors)
  - z~4: 175 (NB570<25.0; BRNB 2 colors)
  - z~6: 515 (NB816<26.0; RiNB 2 colors)

- Thanks to the deep & wide field imaging data, we have obtained ~20,000 LBGs and ~1,000 LAEs at z=3.5-6.2

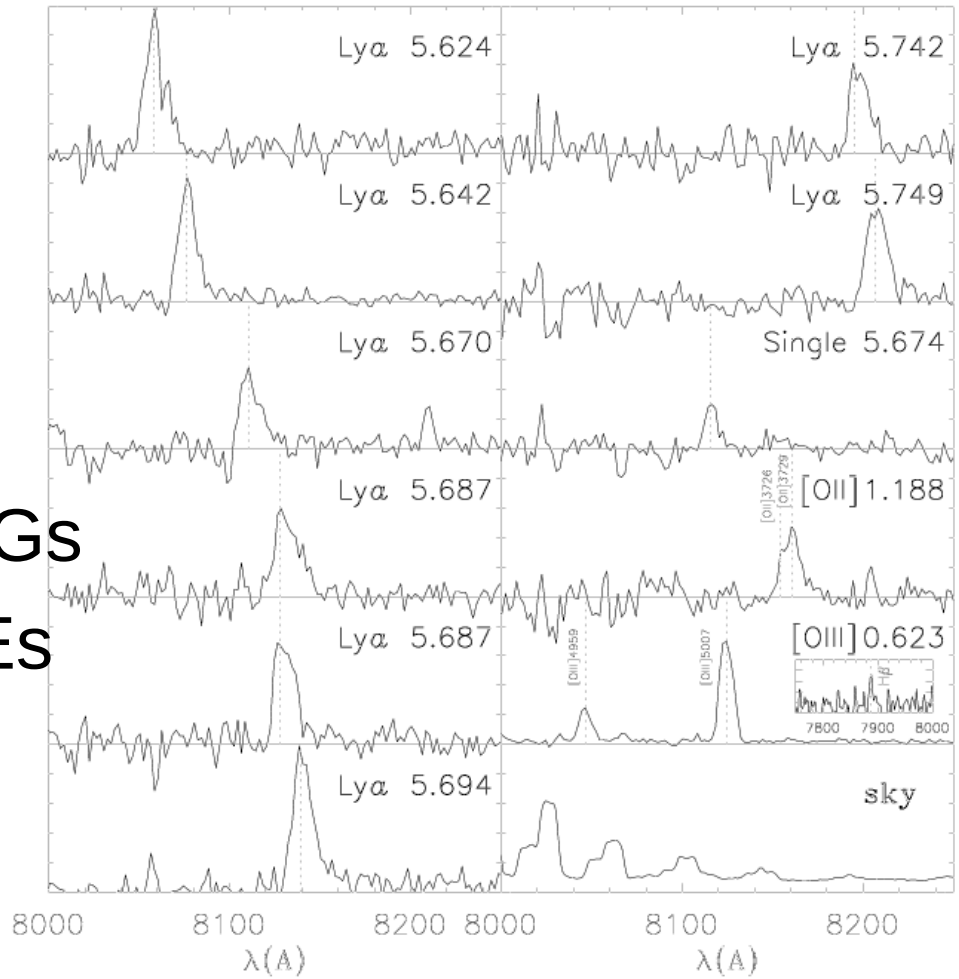
Results of Spectroscopic Follow-ups

- Part of galaxies in these samples are spectroscopically confirmed.

e.g. results in 2003

- 40/16920 for z=4 LBGs
- 19/515 for z=5.7 LAEs

- Contaminants<30%

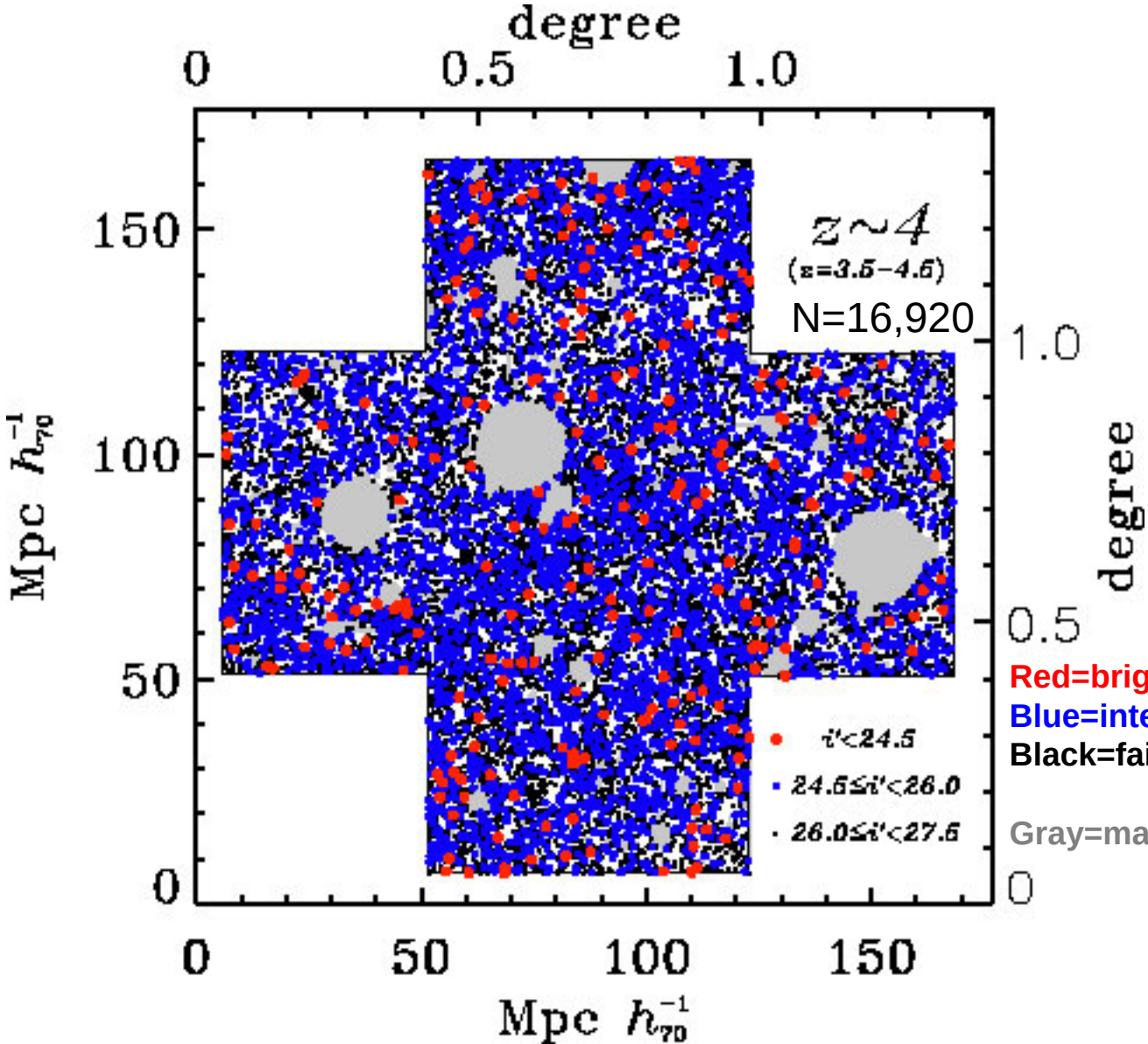


Part of results (for z=5.7 Ly α emitters)

Ouchi et al. 2004, ApJ submitted

Sky Distribution

z~4 BRi-LBGs (z=3.5-4.5)

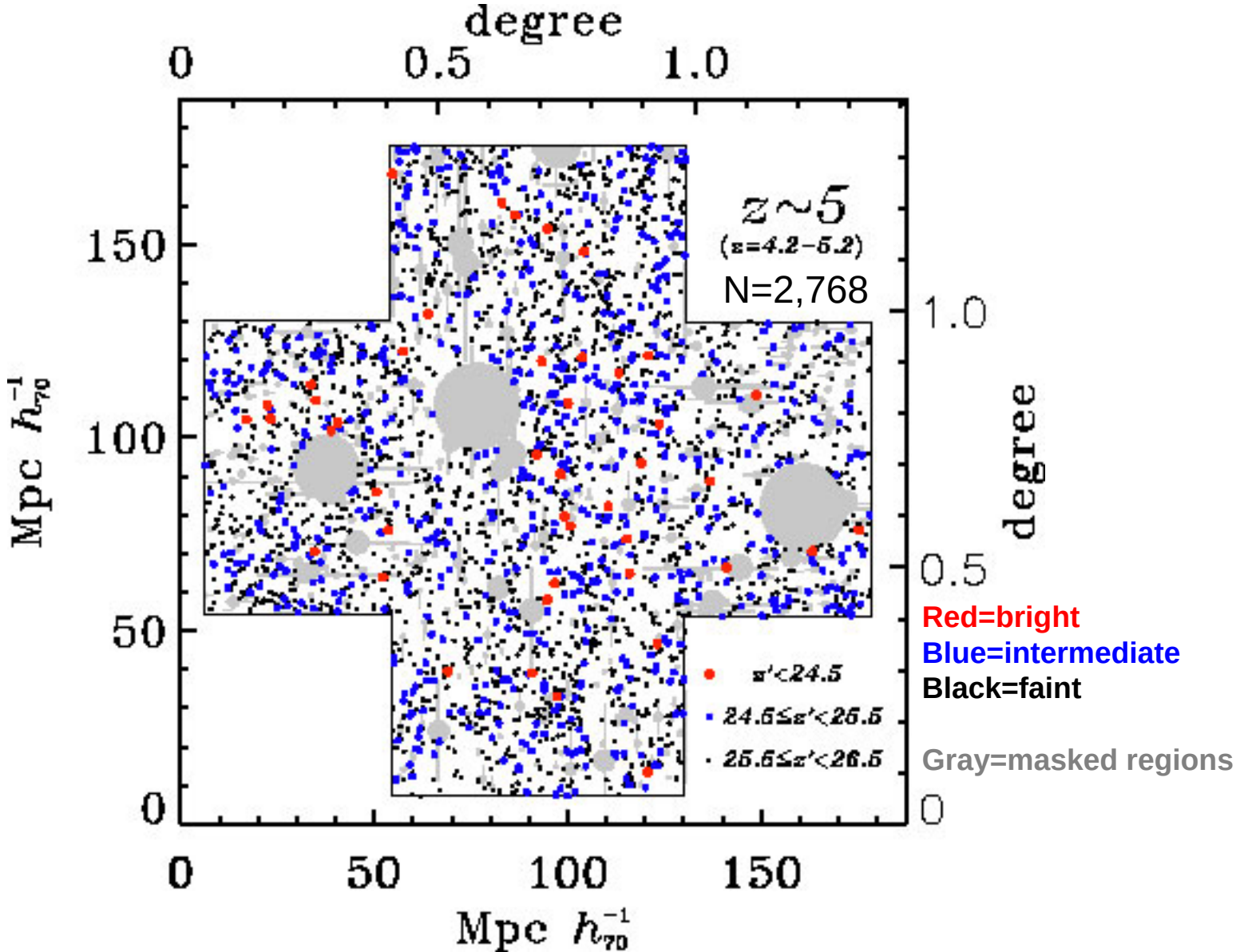


Red=bright
Blue=intermediate
Black=faint

Gray=masked regions

Sky Distribution

z~5 Viz-LBGs (z=4.2-5.2)

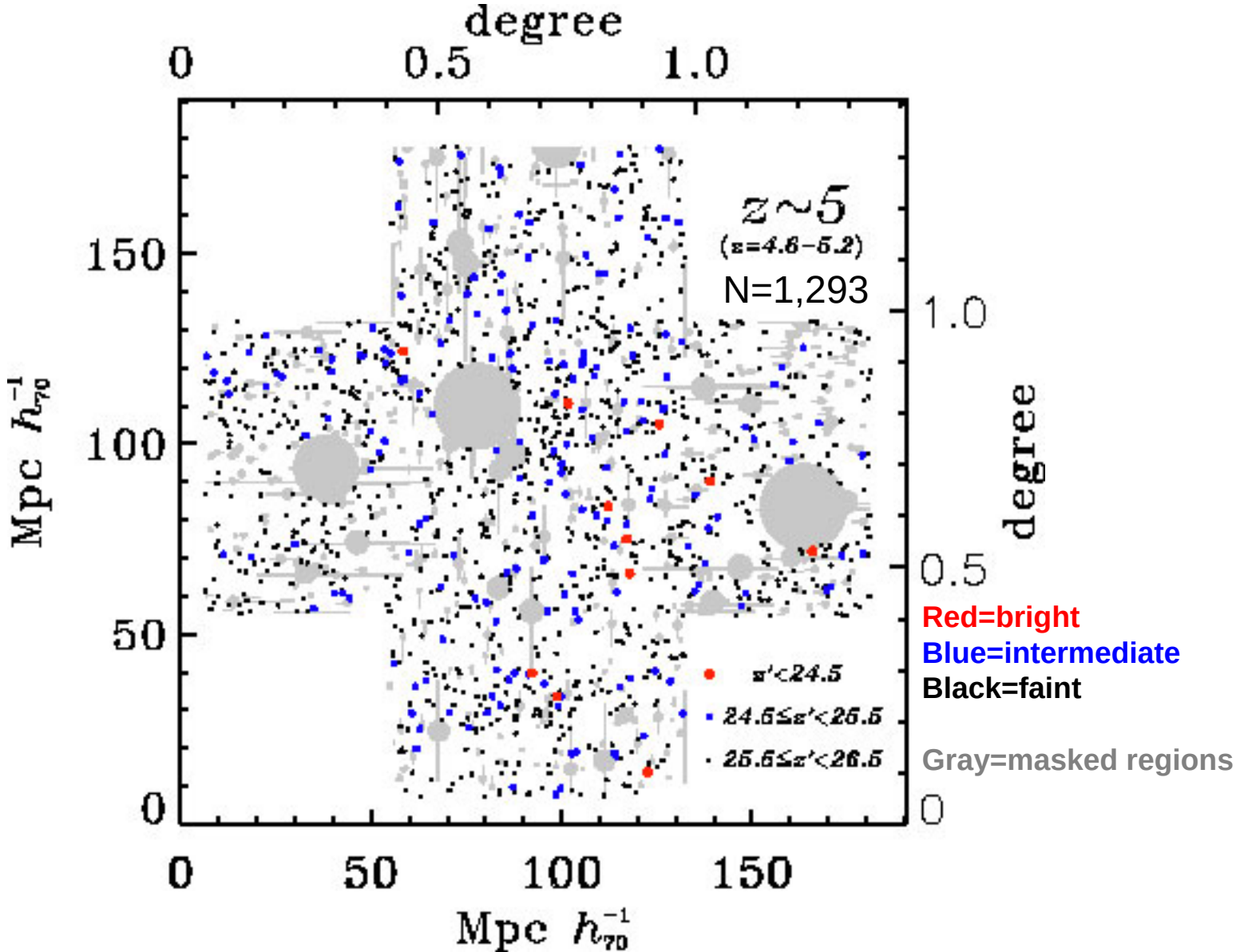


Red=bright
Blue=intermediate
Black=faint

Gray=masked regions

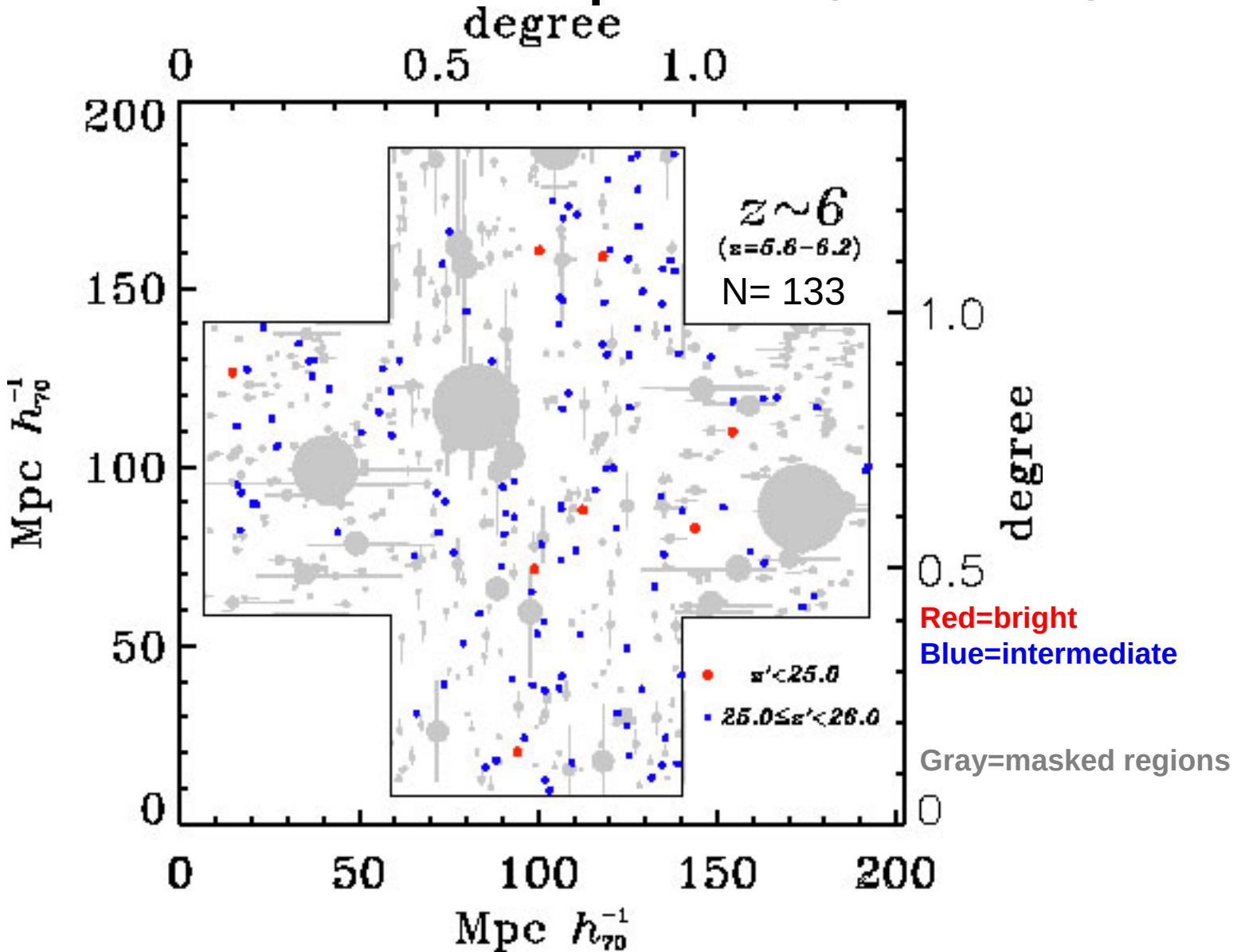
Sky Distribution

z~5 Riz-LBGs (z=4.6-5.2)



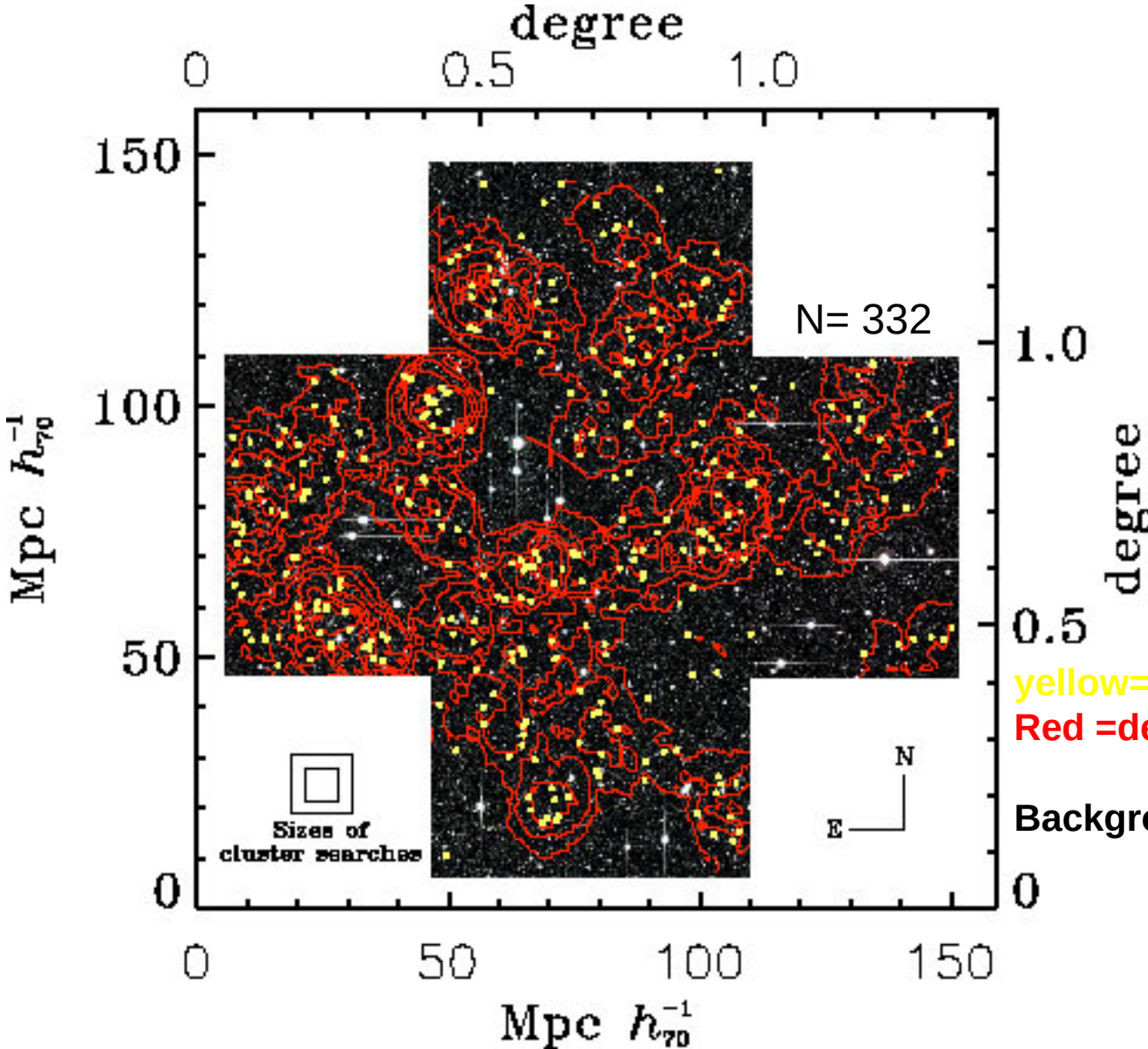
Sky Distribution

z~6 i-dropouts (z=5.6-6.2)



Sky Distribution

z=3.1 LAEs



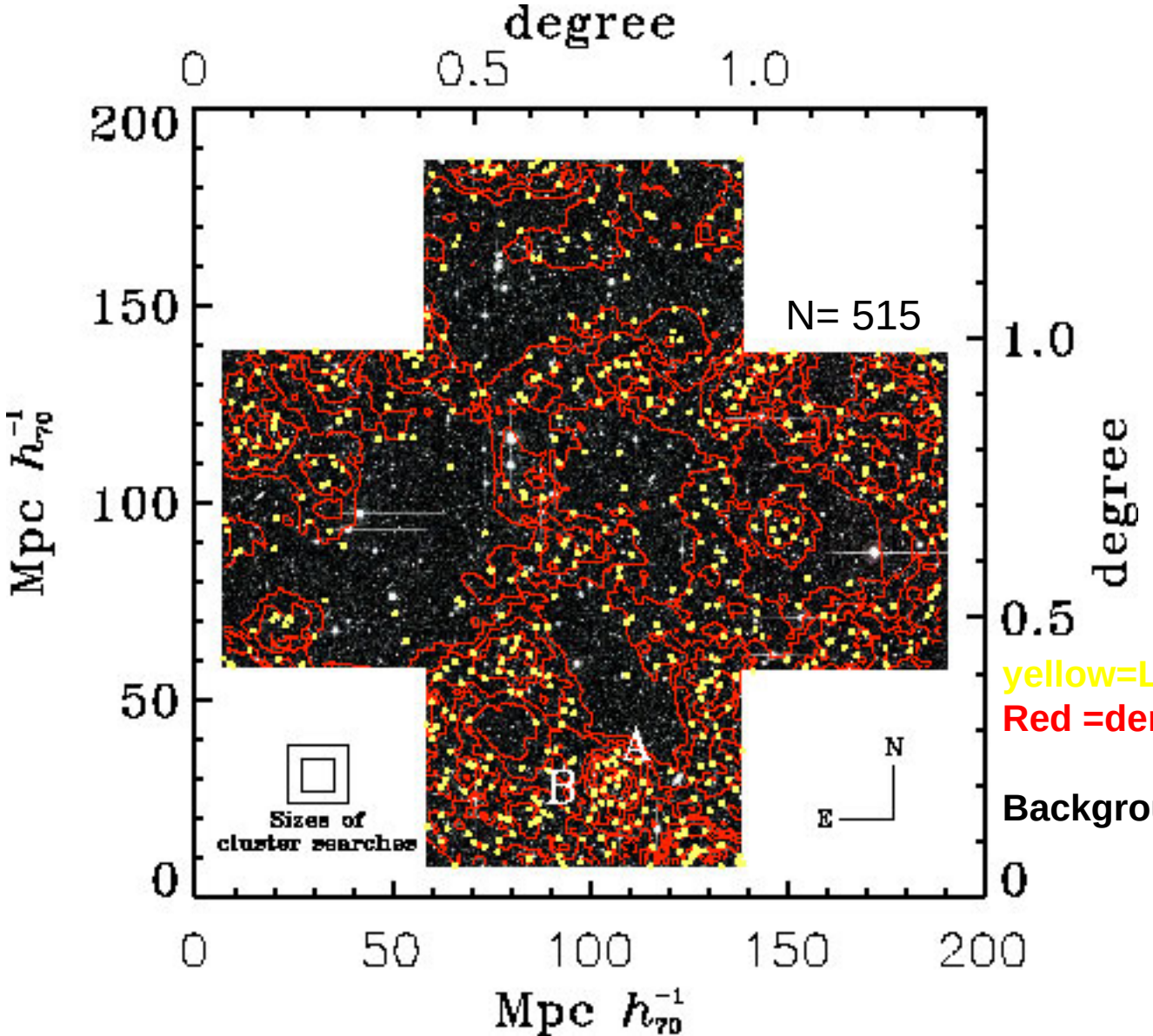
yellow=LAEs

Red =density contour

Background: Image

Sky Distribution

z=5.7 LAEs



yellow=LAEs

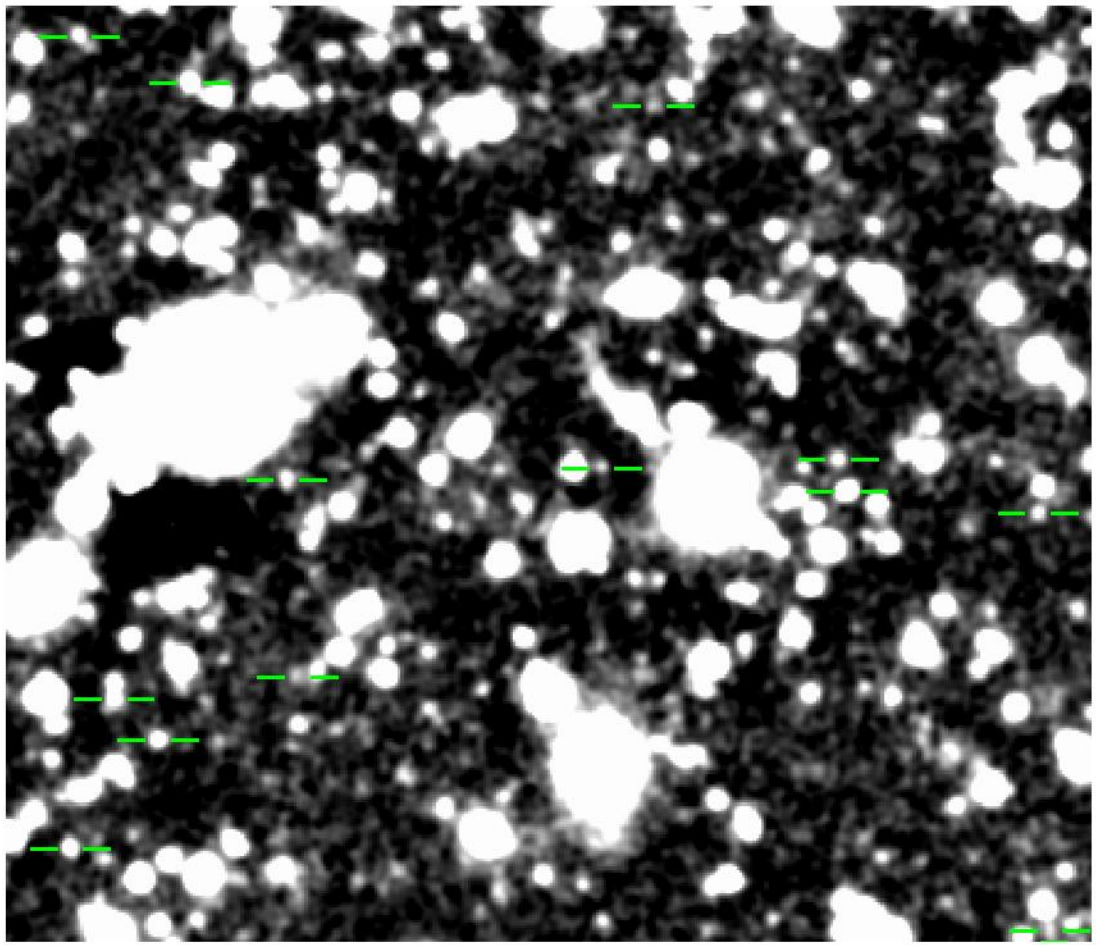
Red =density contour

Background: Image

Galaxy-Scale Clustering

Close Companions
z=4 LBGs : example

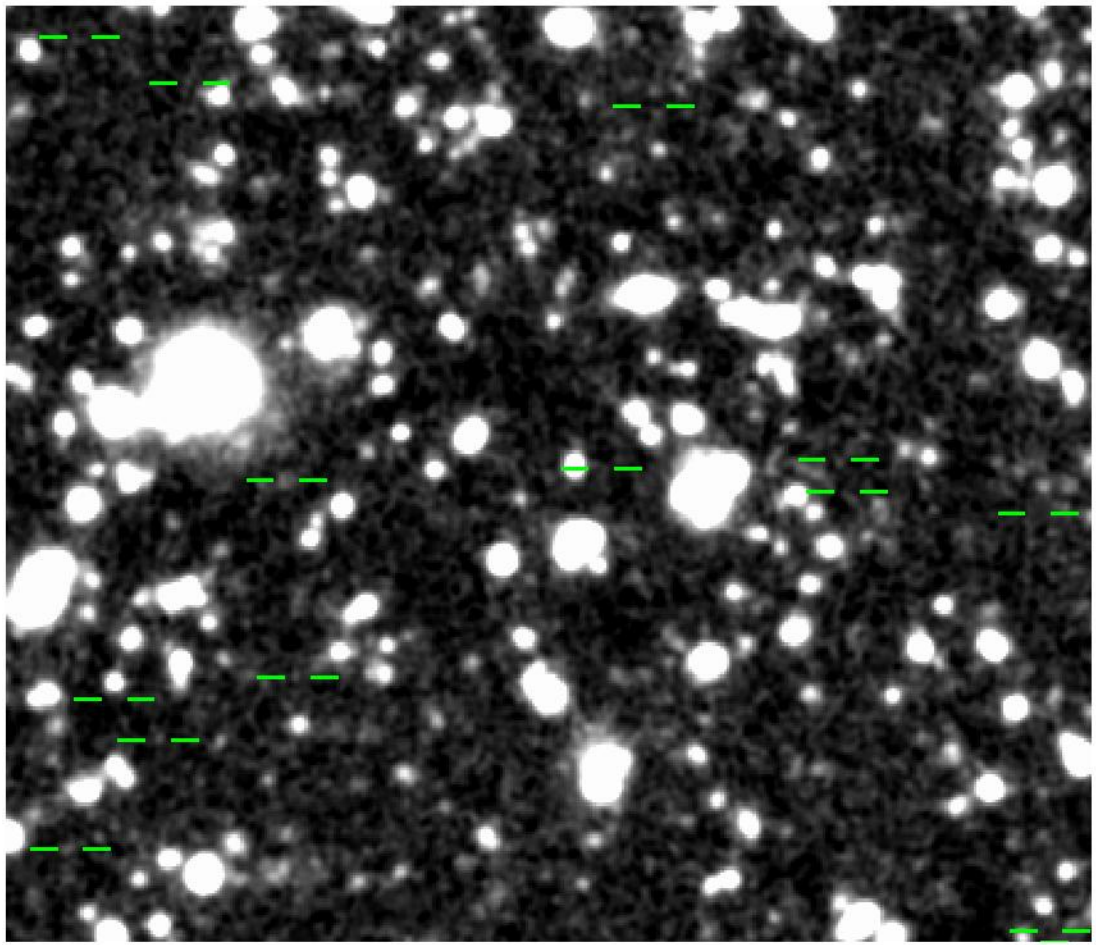
i’ band



10”=350kpc
(comoving)

Close Companions
z=4 LBGs : example

B band



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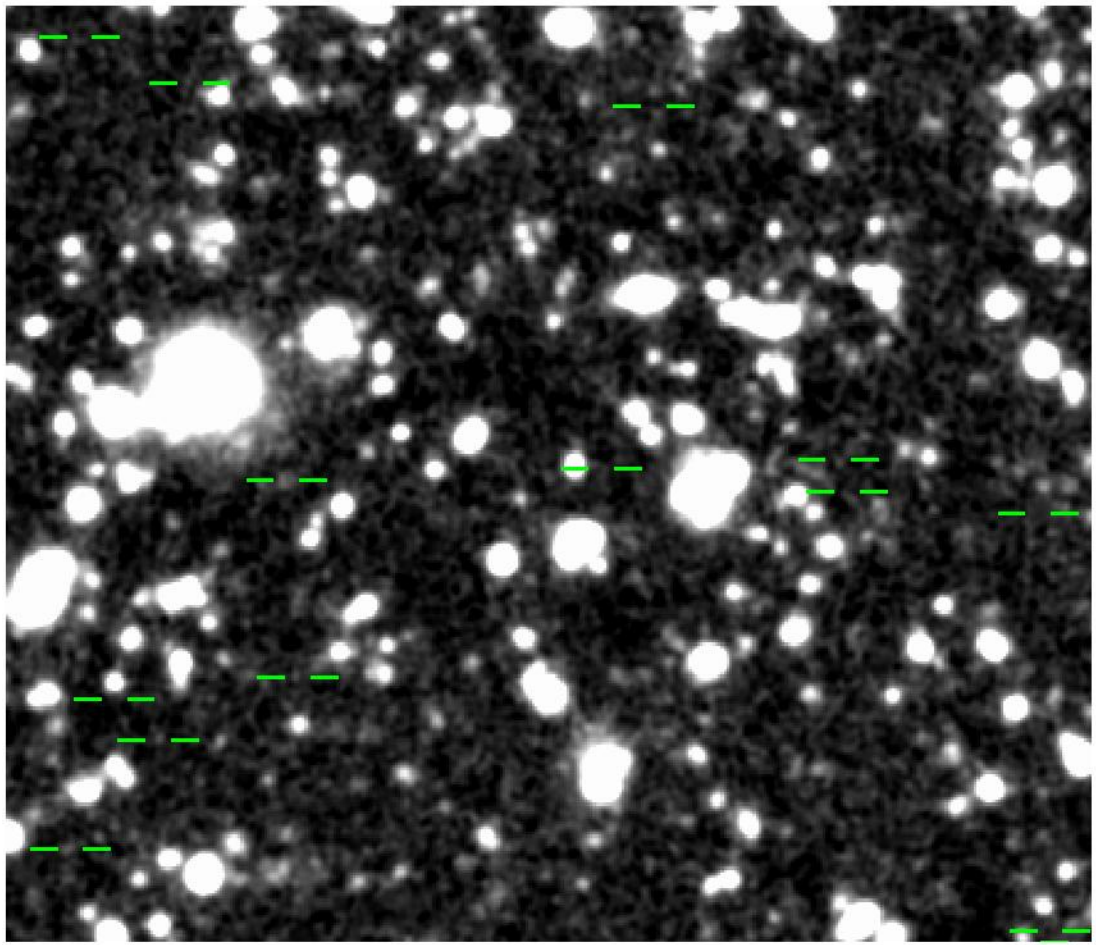
Close Companions
z=4 LBGs : example

B band



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Close Companions
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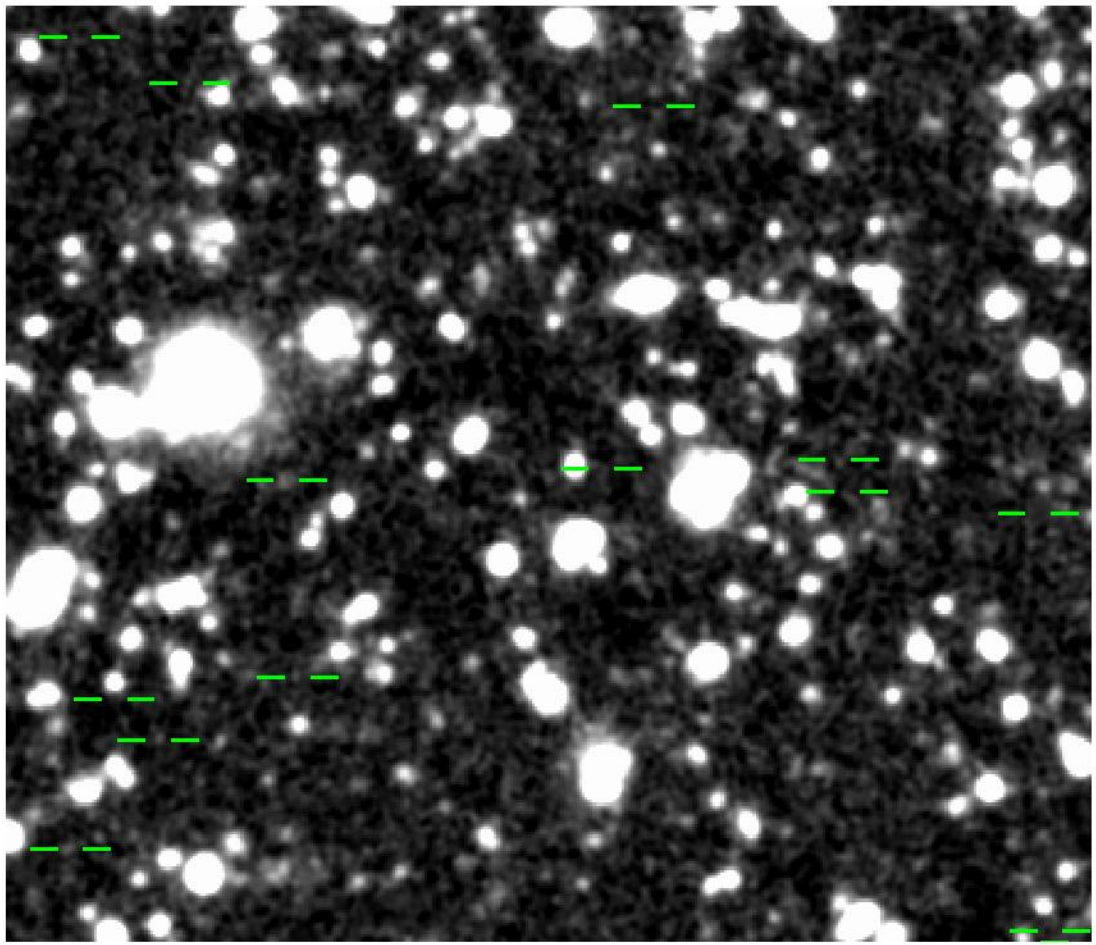

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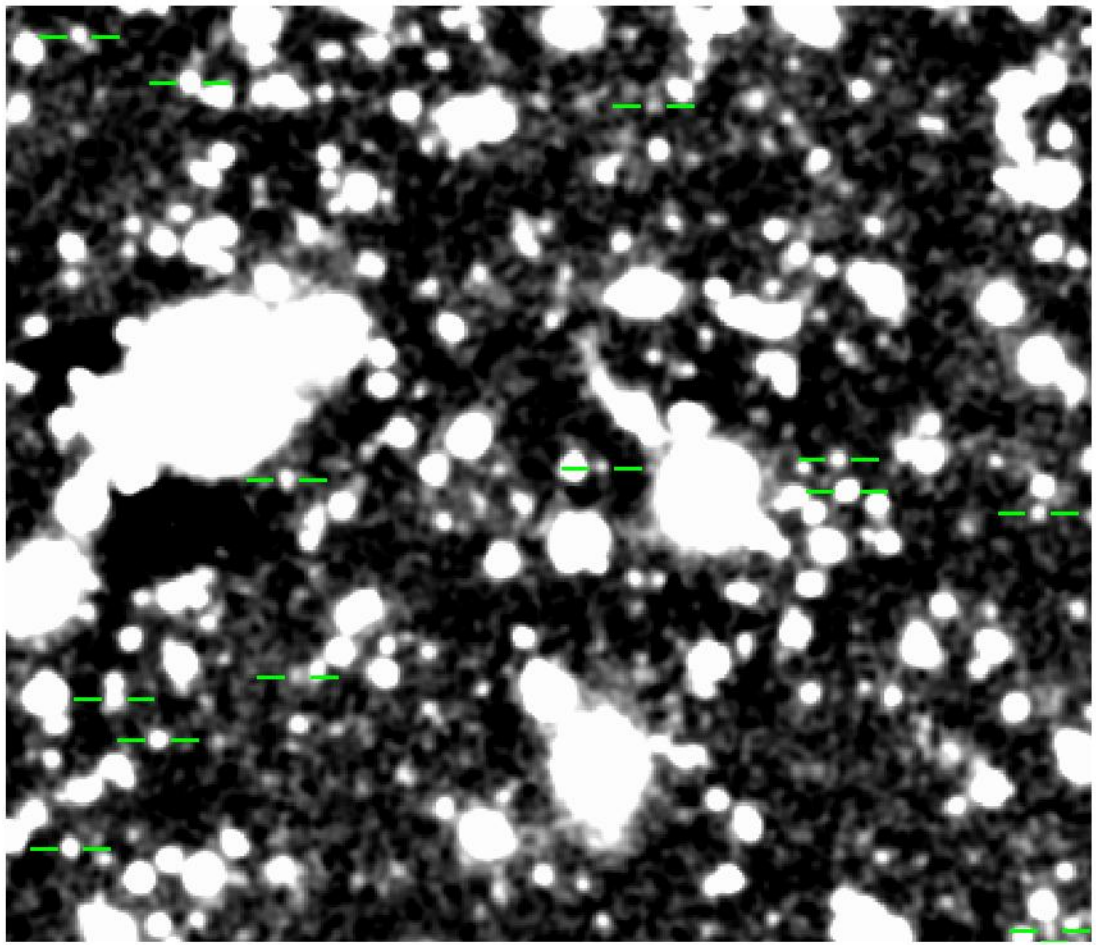
Close Companions
z=4 LBGs : example

i’ band



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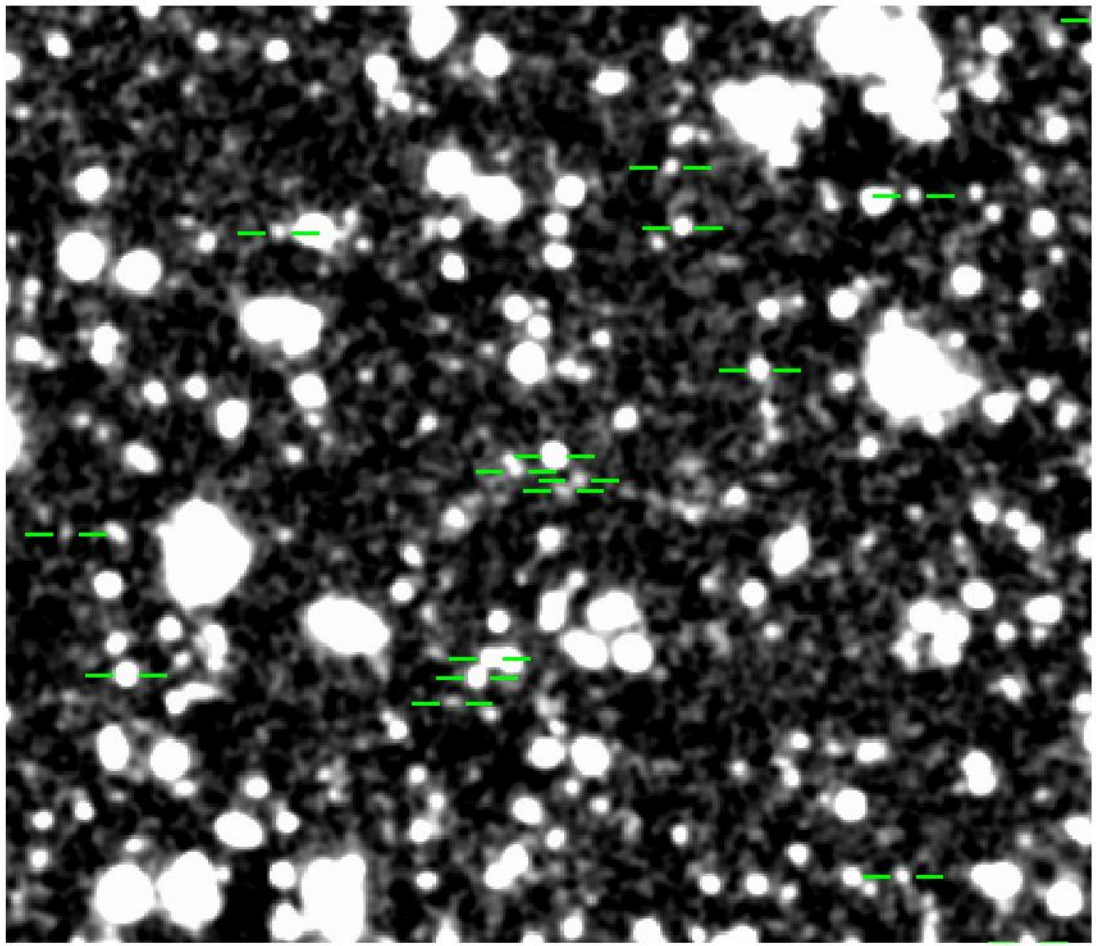
Close Companions
z=4 LBGs : example

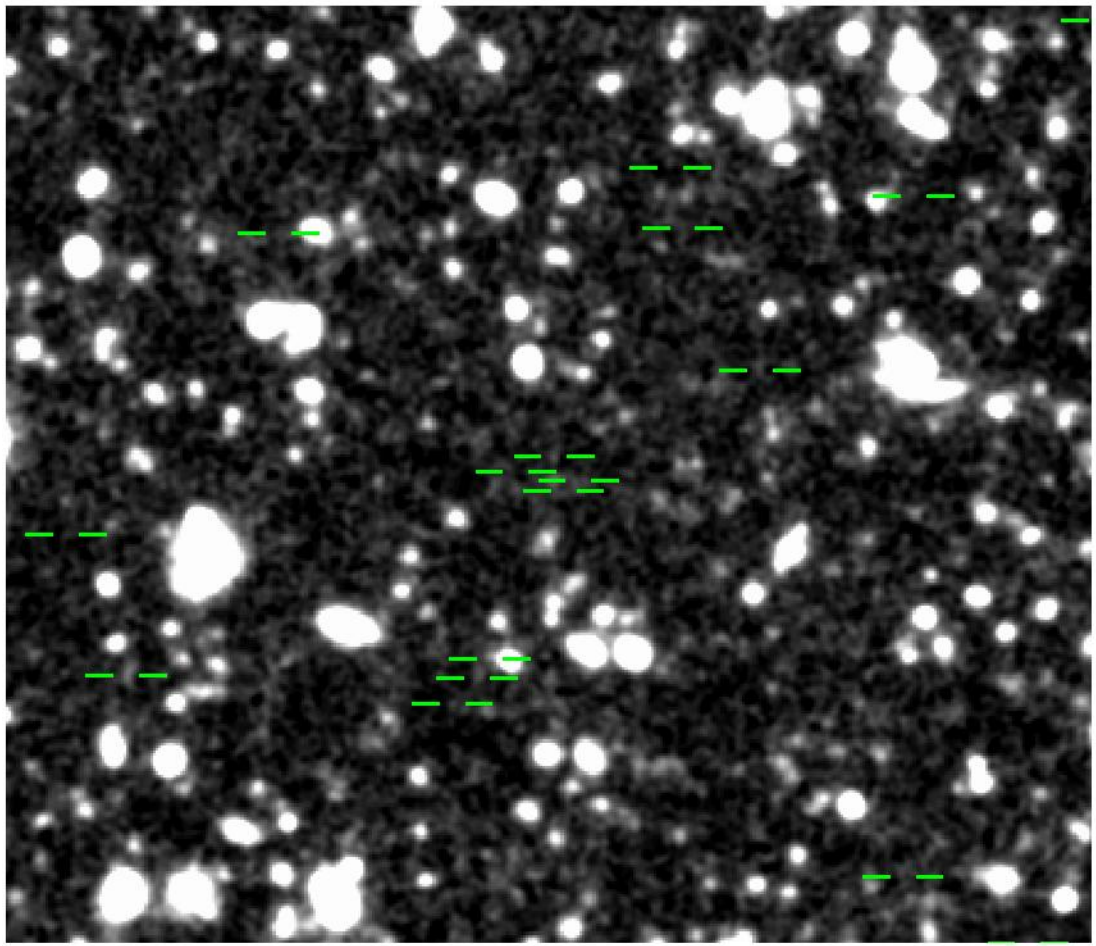
i' band



10"=350kpc
(comoving)

Close Companions
z=4 LBGs : example

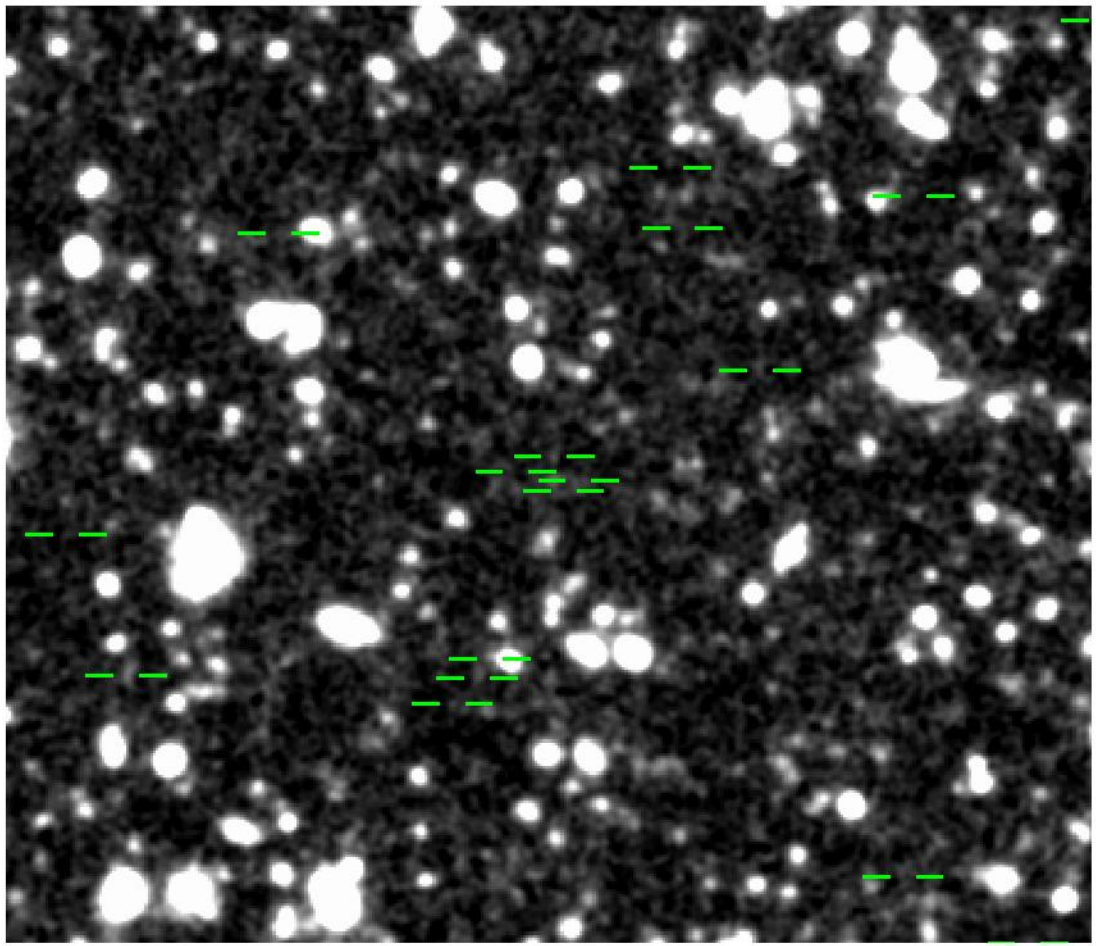
B band



10”=350kpc
(comoving)

Close Companions
z=4 LBGs : example

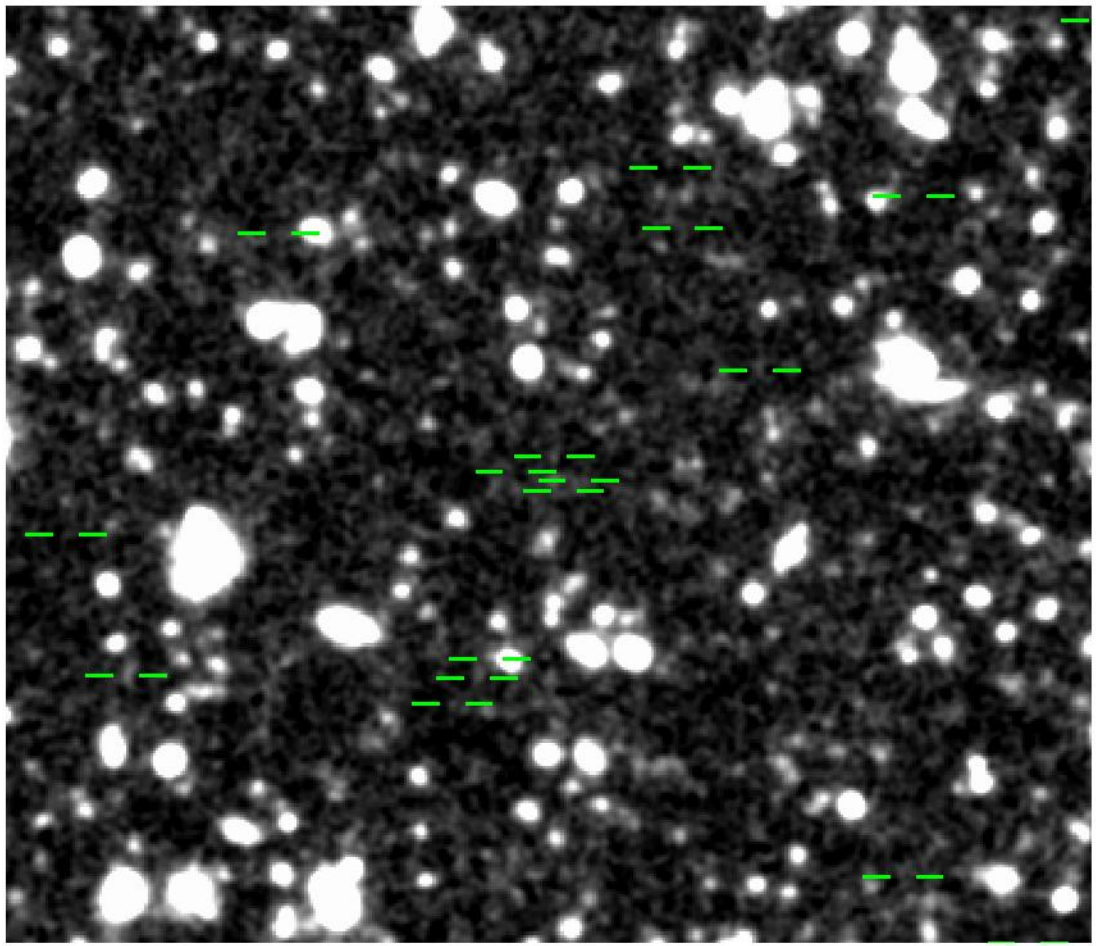
B band



10”=350kpc
(comoving)

Close Companions
z=4 LBGs : example

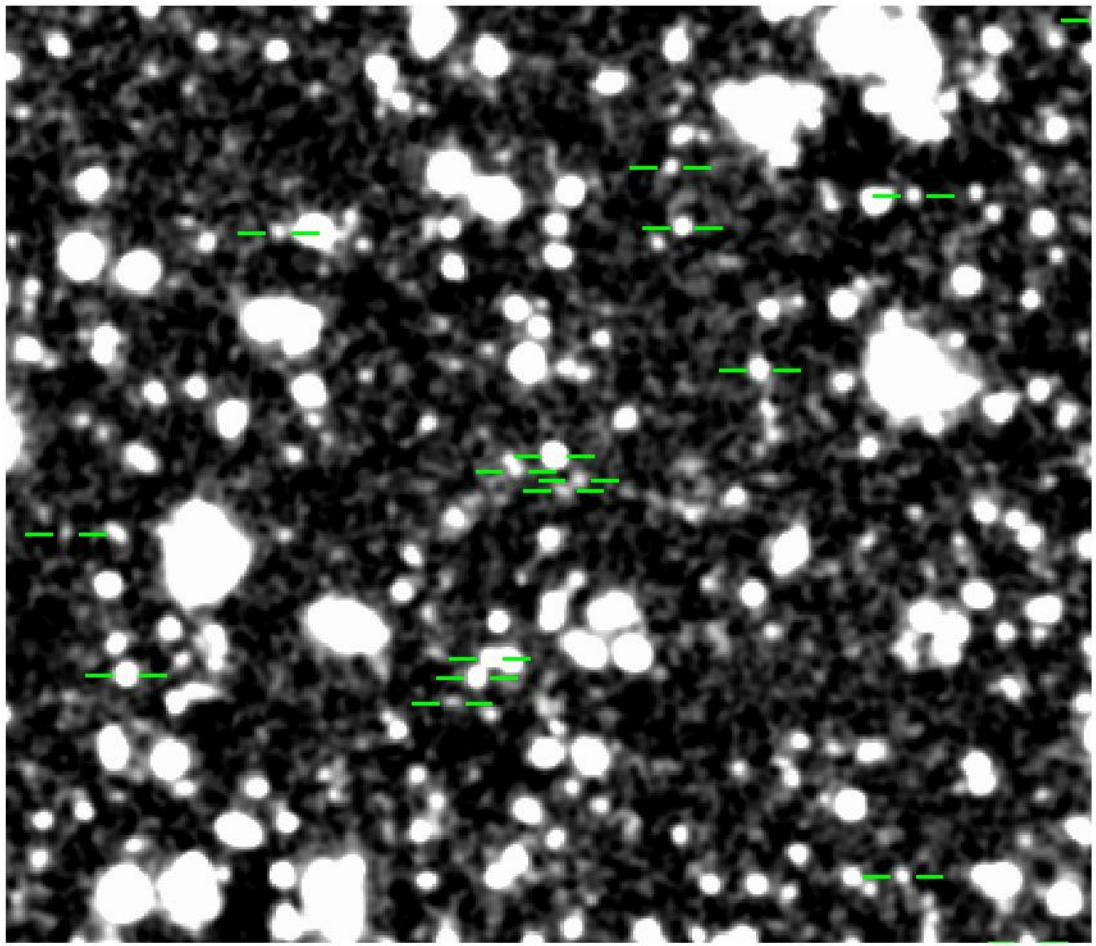
B band



10”=350kpc
(comoving)

Close Companions
z=4 LBGs : example

i' band



10"=350kpc
(comoving)

Close companions

- Many LBGs have (a) close companion(s).
- N_{pairs}~1,000

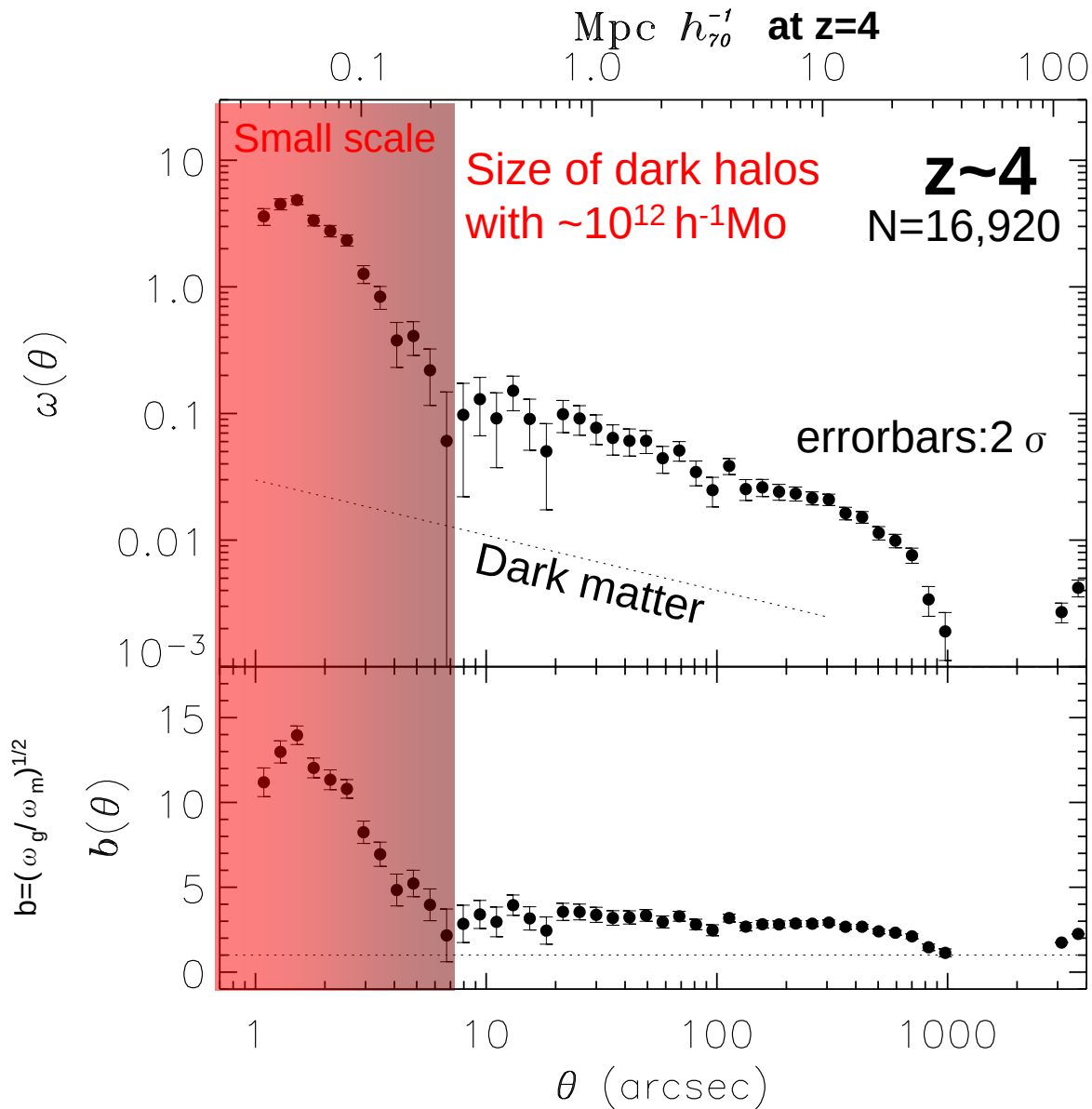
for 1”< θ <4”

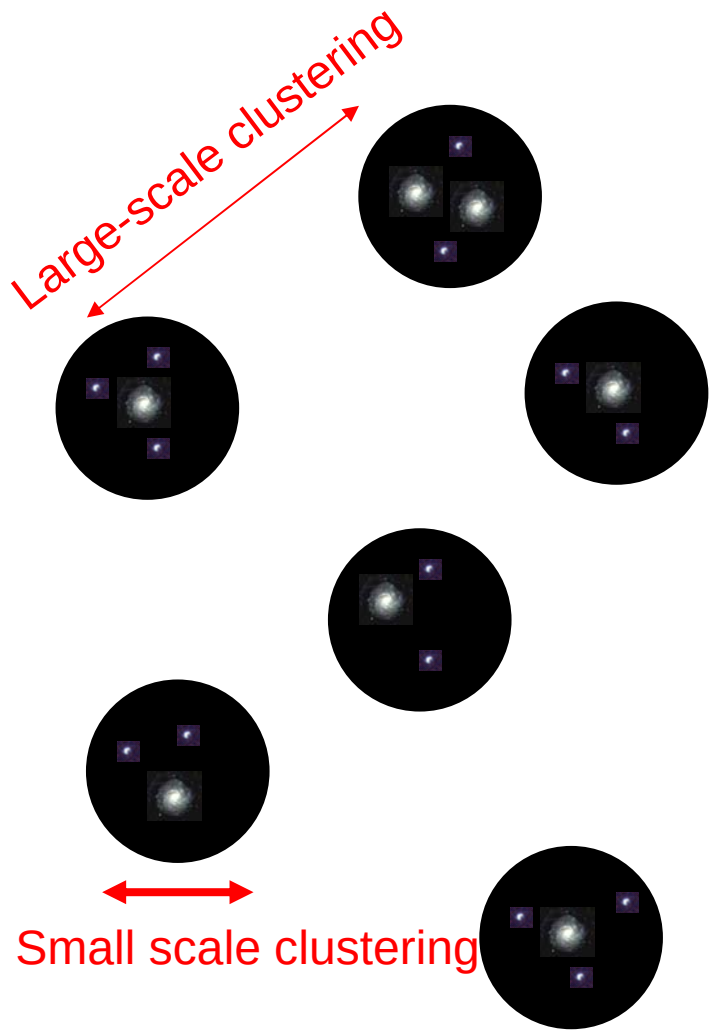
i.e, 40-150 h_{70}^{-1}kpc (comoving)

10- 30 h_{70}^{-1}kpc (physical)

→ for more quantitative analysis, we derive the angular correlation function

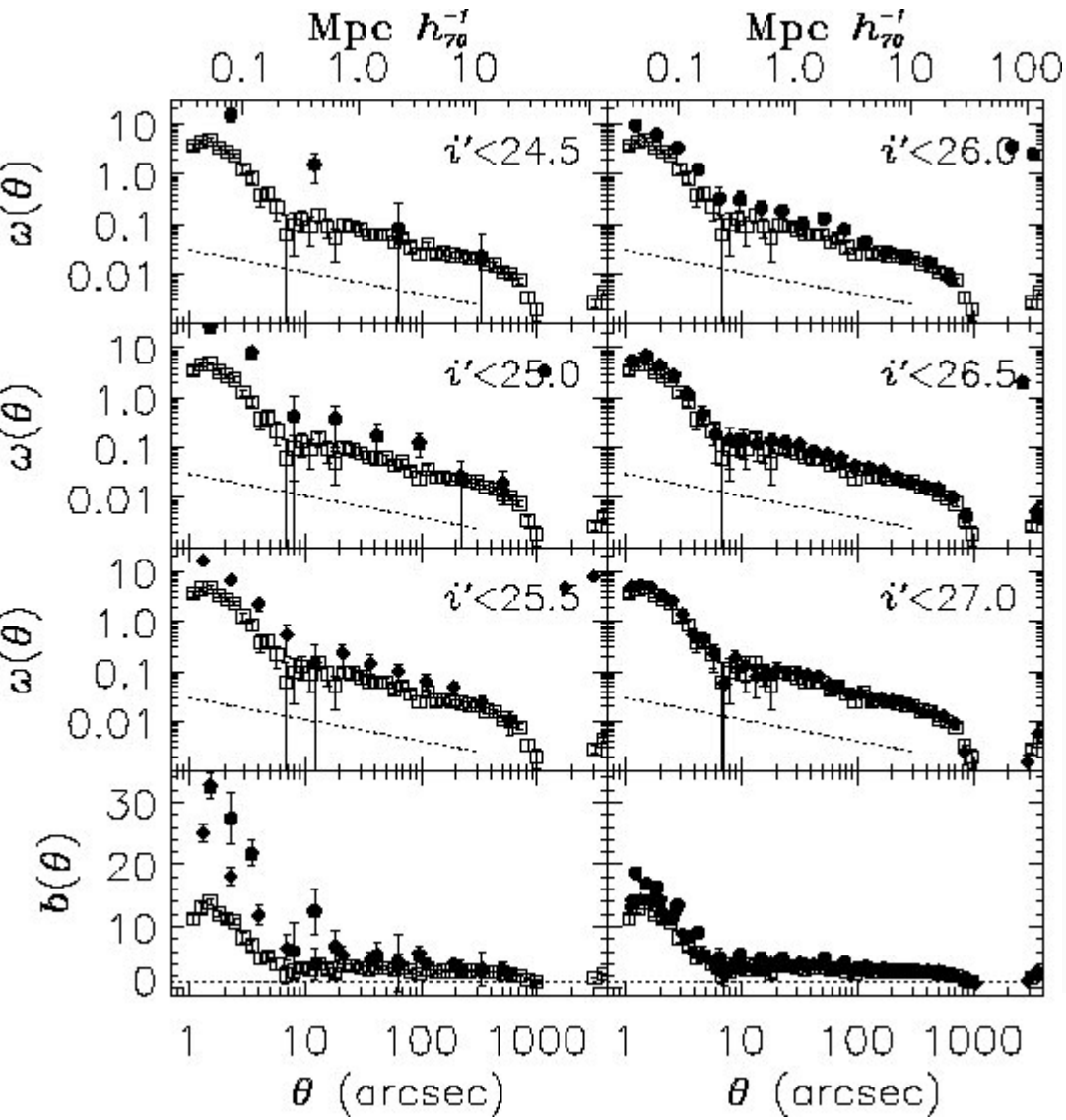
Definitive Detection of the transition from one-halo to halo-halo clustering

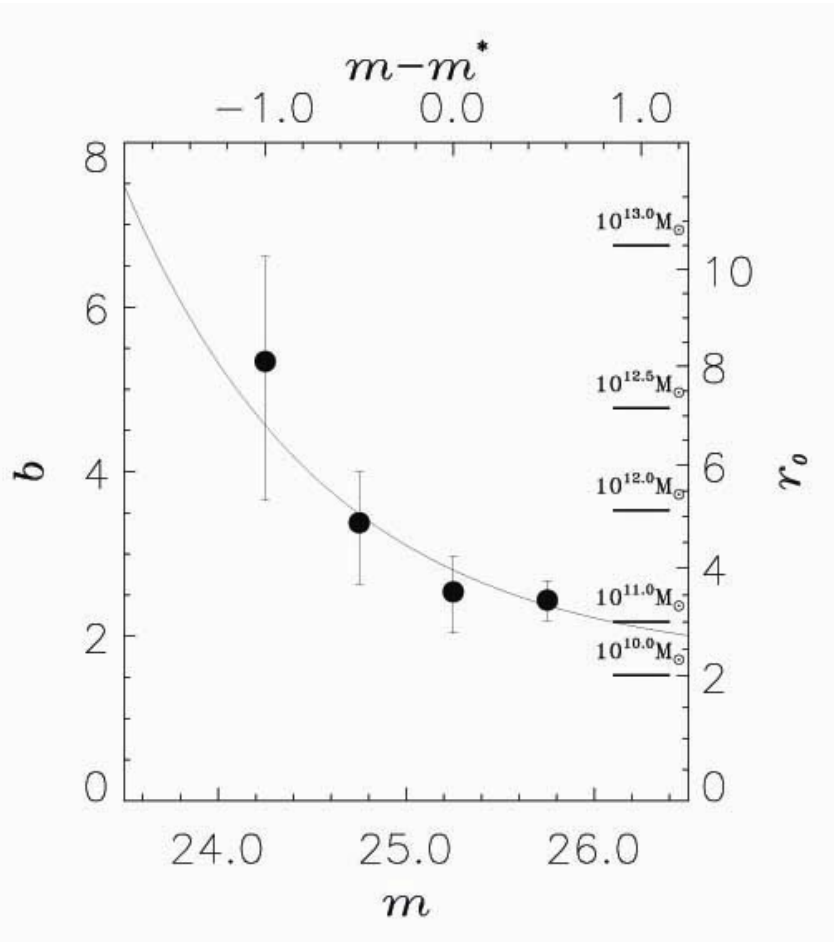




See, e.g., Hamana et al. (2004) for the theoretical predictions

Luminosity Dependence of LBG Clustering



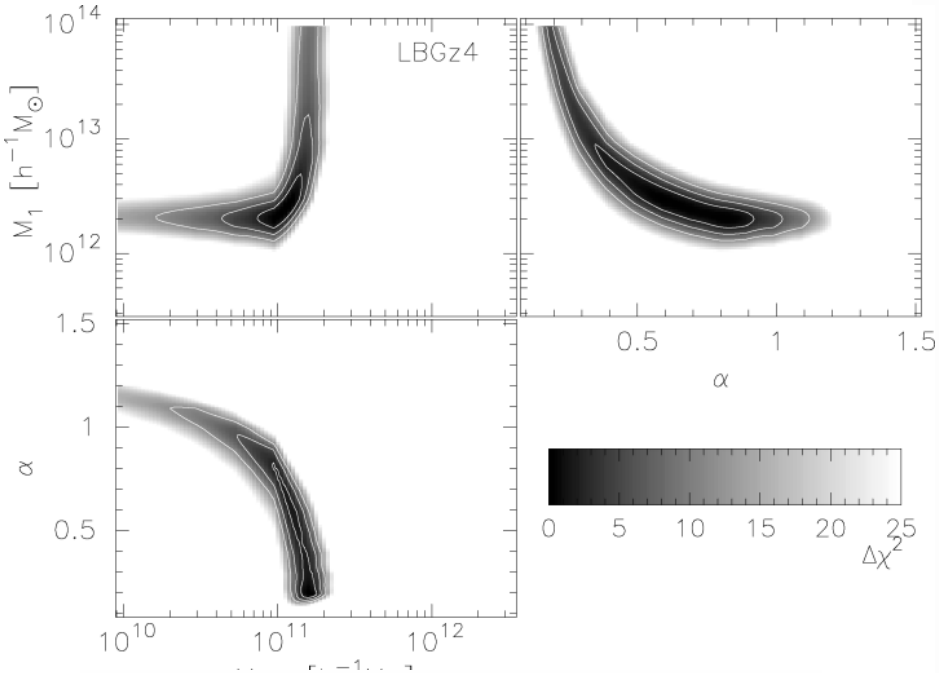


Ouchi et al. 2004, ApJ, 611, 685

- Large-scale bias (at ~8Mpc)= 2-5
- Small-scale bias (at ~0.1Mpc)=10-30

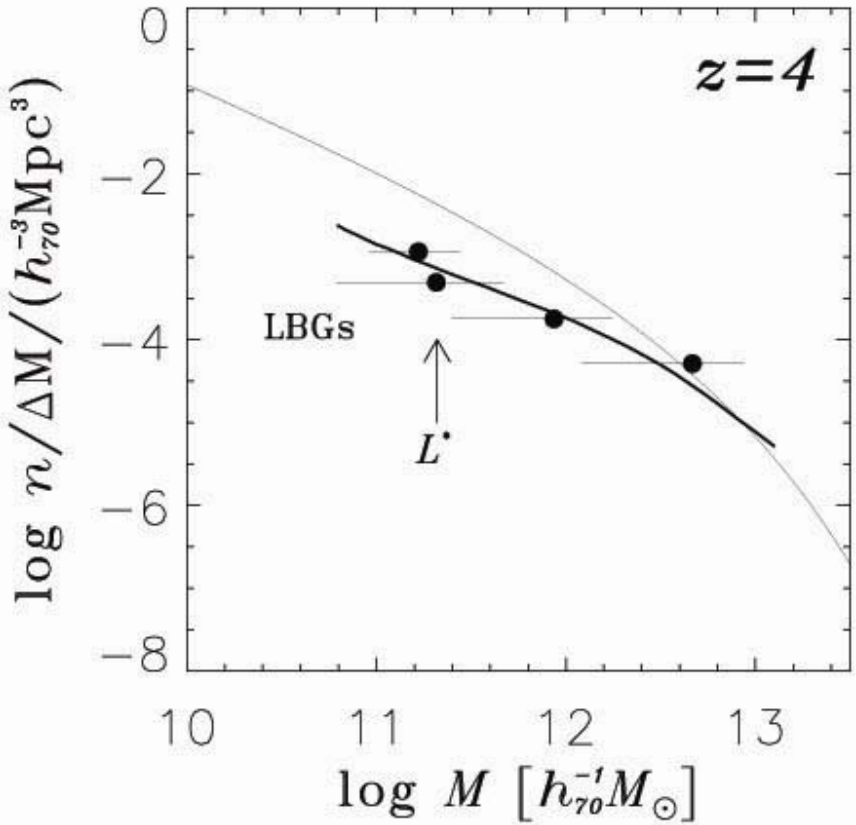
c.f. 2dF galaxies (Norberg et al. 2002 MNRAS,336, 907)

Comparison with the CDM model



$$N_g(M) = \begin{cases} (M/M_1)^\alpha & \text{for } M > M_{\rm min}, \\ 0 & \text{for } M < M_{\rm min}. \end{cases}$$

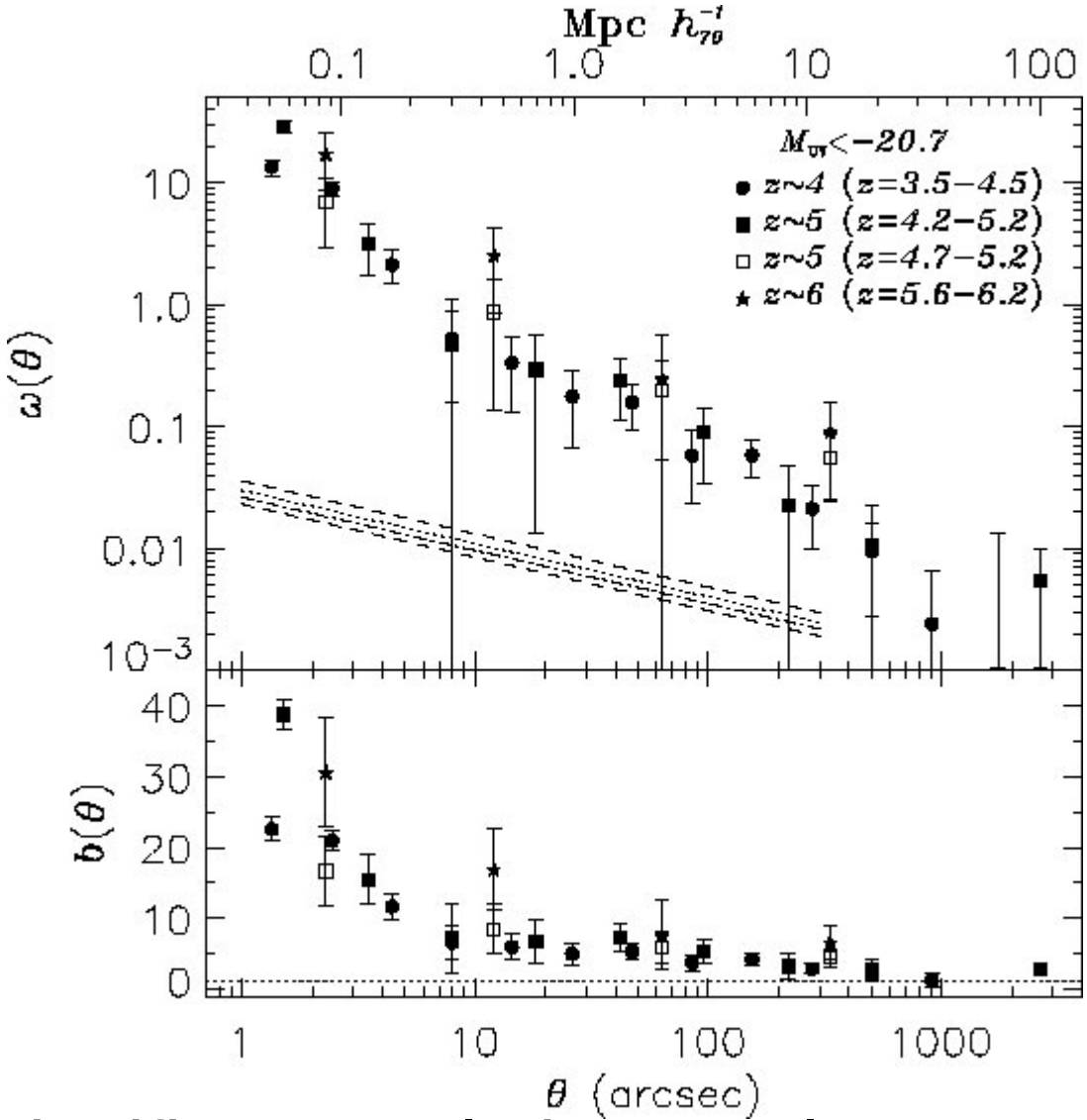
Hamana et al. 2004, MNRAS, 347, 813

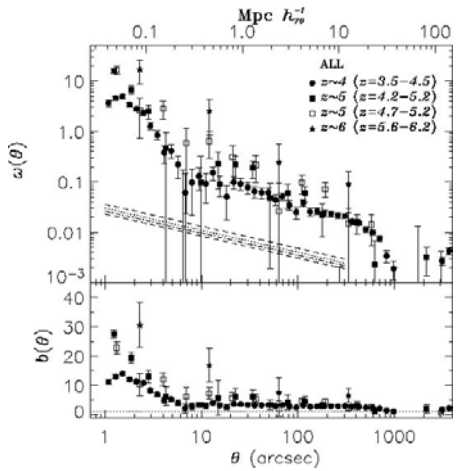


Ouchi et al. 2004, ApJ, 611, 685

- L>L* LBGs at z=3-5 reside in <M>~10^{12} $M_\odot$ (comparable mass to the MW Galaxy).
- Number density of L>L* LBGs is about ~1/10 of that of dark halos. Existence of dark halos without galaxies??

Evolution of the Angular Correlation Functions at z=3.5-6.2



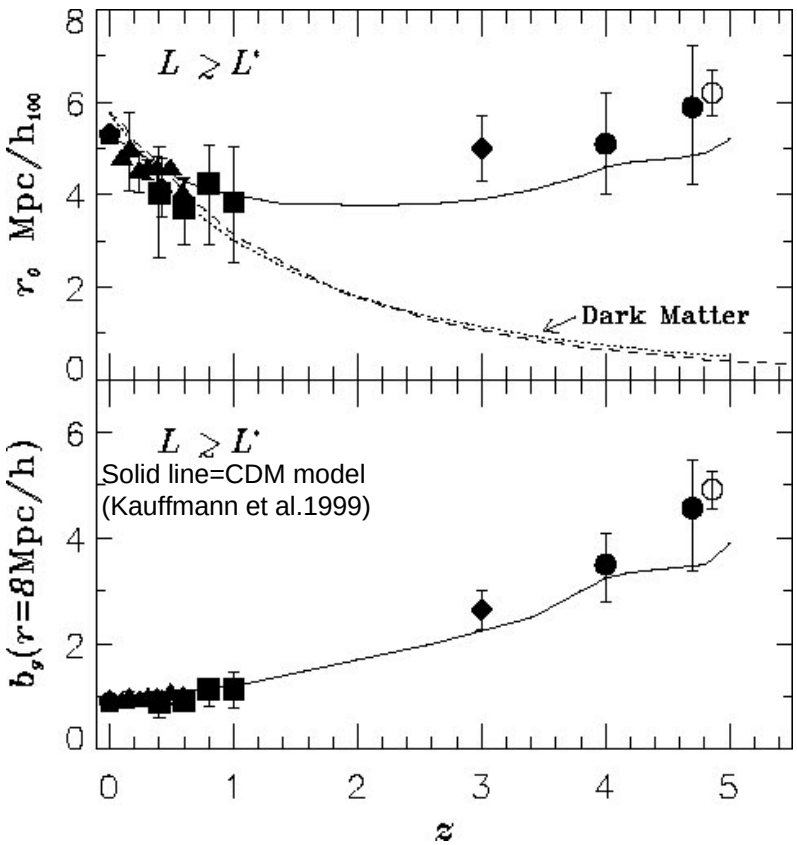


All LBGs at z=4,5, and 6

- No significant evolution at a large scale for L>L* LBGs

Evolution of Galaxy-Matter Bias

- $\xi_g(r)=(r/r_0)^{-\gamma}$
  - r_0 : correlation length (=typical scale of clustering)
- Correlation amplitudes are almost constant at z=3-5.
- →consistent with predictions of the CDM models for dark halos with a mass of ~10^{12}Mo
- Bias of the galaxy clustering $b=(\xi_g/\xi_m)^{1/2}$
  - We find that the bias becomes larger at higher z



Ouchi et al. 2003, ApJ, 582, 60

Ouchi et al. 2004, ApJ, 611, 685

Cluster- to Large-Scale Clustering

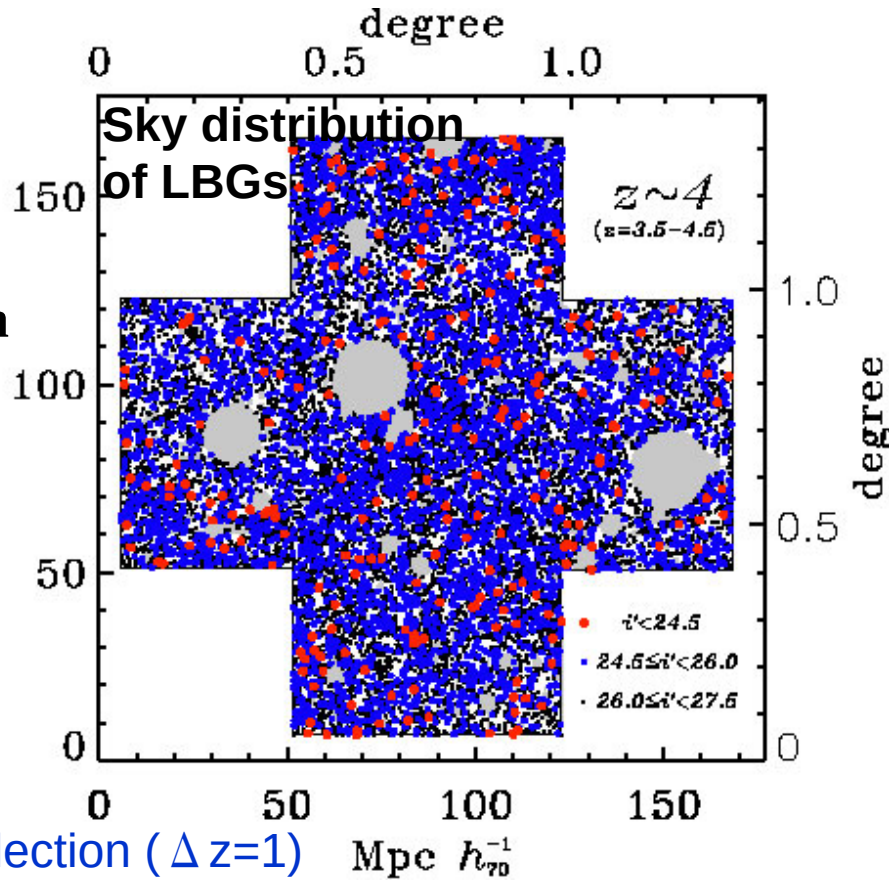
clustering for large-scales

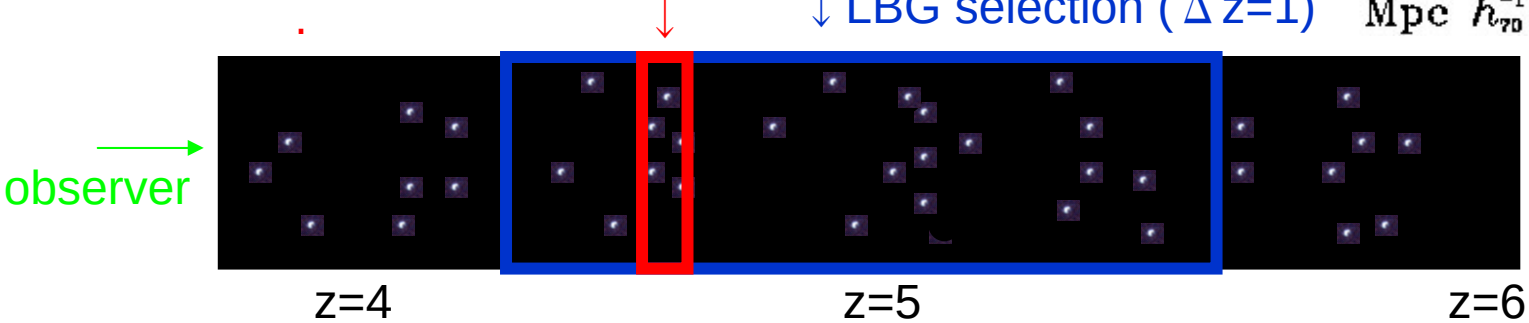
LAE: Powerful probe in identifying LSSs

- **LBGs have a wide redshift distribution** ($\Delta z \sim 1.0$).
  →Individual clustering properties are erased.

- **LAEs have a narrow redshift distribution** ($\Delta z < 0.1$). Galaxies located in a slice of Universe ($\Delta \sim 40$Mpc) can be obtained.

- Look at the clustering properties of LAEs.





Primeval Large-Scale Structures at z=5.7

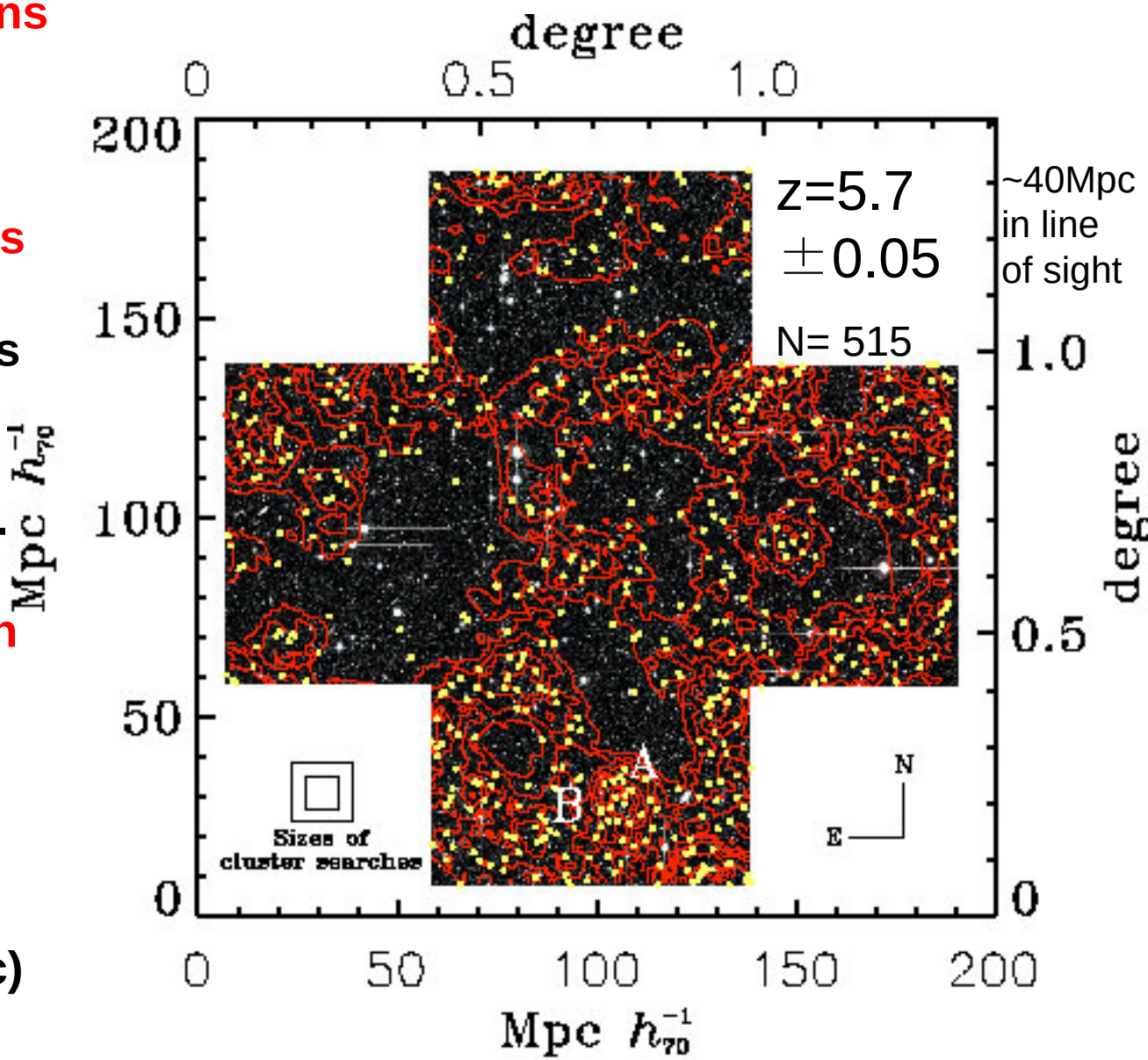
- Galaxy concentrations connected with filaments

-10-40 Mpc scale voids

Large-scale structures of LAEs are quite similar to those of present-day Universe.

→Very early formation of filamentary LSSs made of galaxies

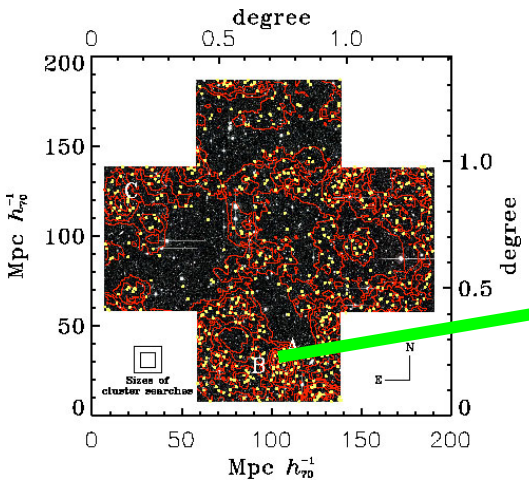
The large-scale bias b=3.4 ±1.8 (σ_{20} =0.4 for r=20Mpc) is consistent with the LBG clustering (b=2-5)

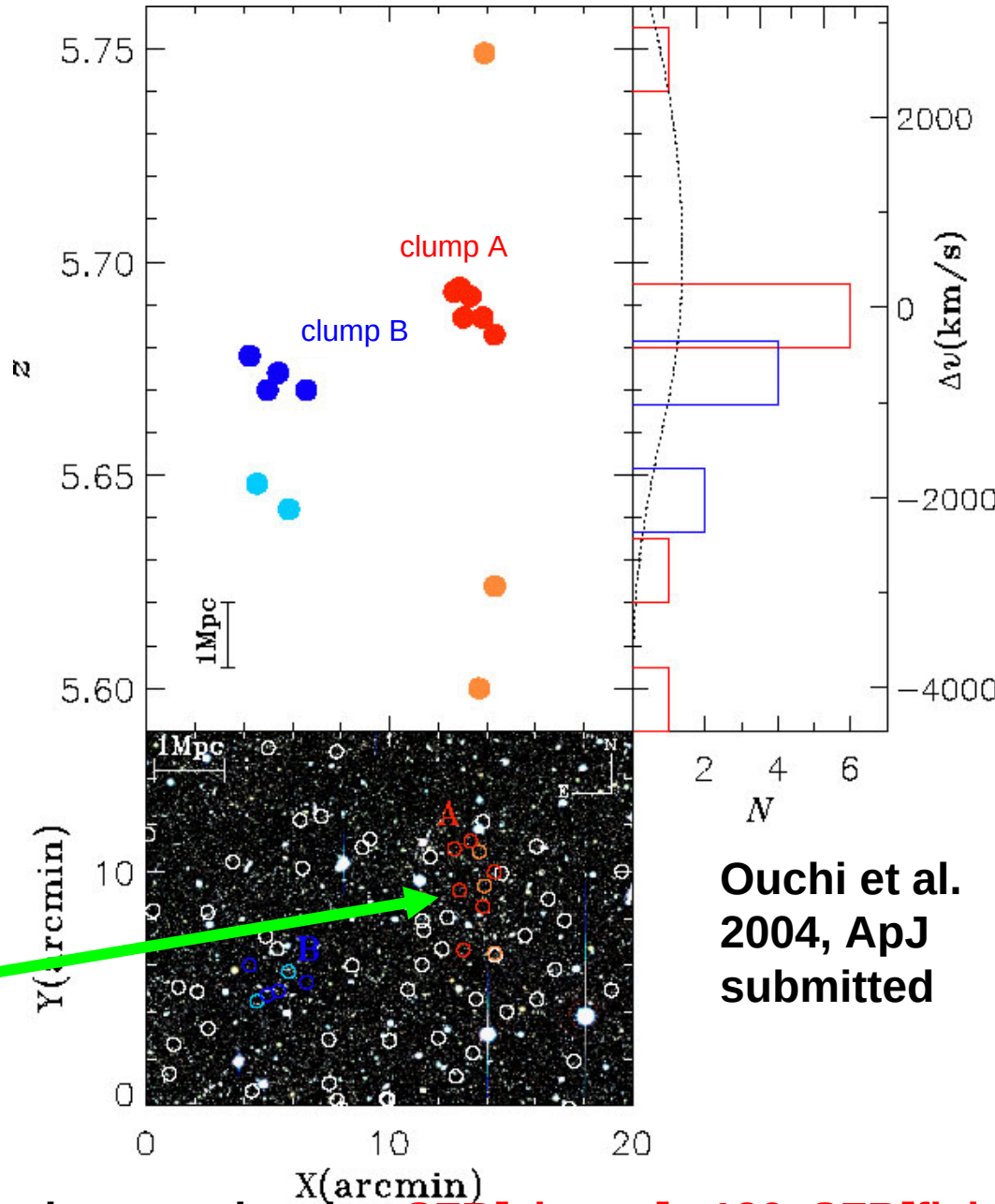


Ouchi et al. 2004, ApJ submitted

Progenitors of massive clusters

Forming Clusters involving a burst of galaxy formation??



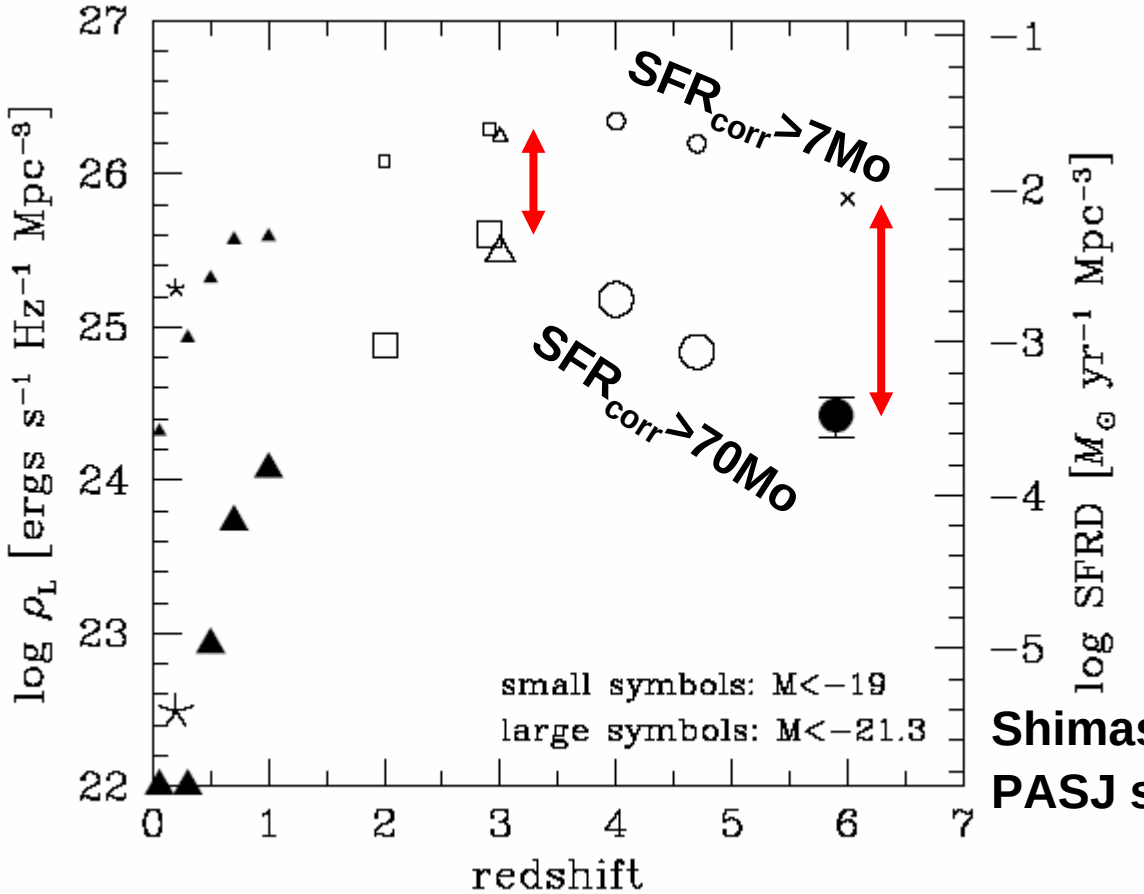


Ouchi et al. 2004, ApJ submitted

Dense clumps have a large star-formation rate density: SFR[cluster] =130xSFR[field

Do we witness the origin of cluster by a burst of galaxy formation?

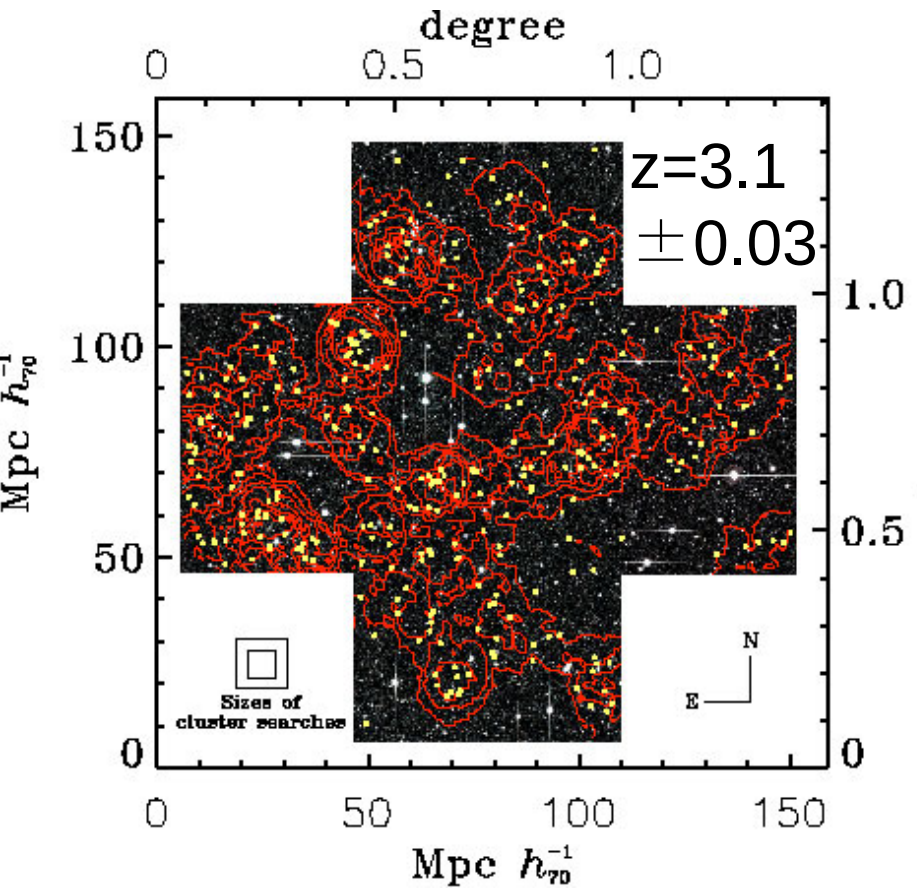
SFR Density of Bright LBGs Significantly Drops from z=3-6

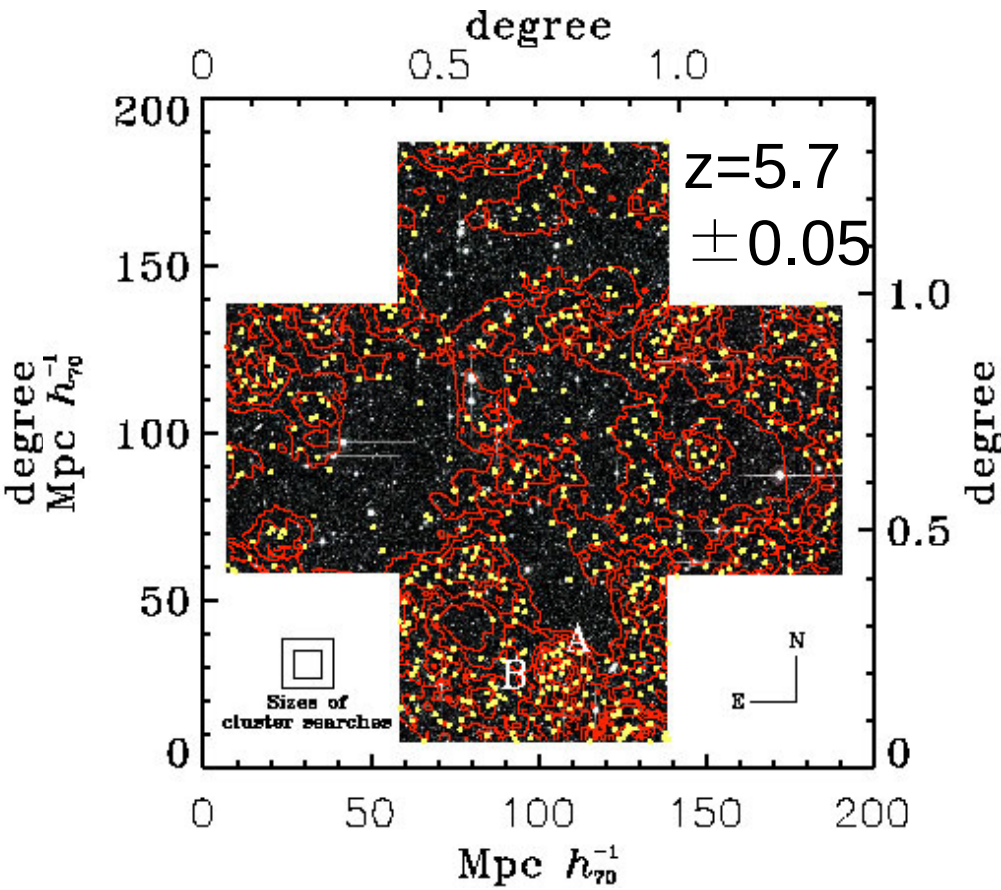


Shimasaku et al. 2004, PASJ submitted

- Starburst galaxies (with high SFR) do not contribute to the balk of the cosmic SFR at z=5.7.
- Cluster may form with a number of galaxies with an intermediate SFR?

Evolution of Large-Scale Structures





Large-scale structures of LAEs do not show a significant difference qualitatively.

But quantitative analyses (counts-in-cell etc.) should be made.

Summary

- I introduced the large samples of galaxies (LBGs and LAEs) at z=3.5-6.2 distributed in a very wide area (1deg2) of SXDS. Our initial results from these data show
  - Galaxy scales: Small scale clustering of z=4 LBGs are significantly enhanced.
    →**Multiple galaxies in one halo.**
  - Cluster scales: Concentration s of LAEs at z=5.7 are found. The SFRD is enhanced by 100 times.
    →**Galaxy clusters in a formation phase?**
  - LSS scales: Large-scale structures at z=5.7 (and z=3.1) are similar to those at present-day.
    →**The early formation of LSSs of galaxies.**