Lessons learnt from searches for distant galaxies

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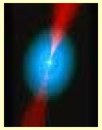
Relevant Questions

- When did the first galaxies form?
- What did they look like?
- What impact did they have on the rest of the Universe
- What kinds of observations can we carry out to explore them?

What do we know now?

- Reionization ended at z~6 (SLOAN QSOs, GP effect)
- Reionization *may* have been extended over several hundred Myr from z~15 or higher (WMAP)
- The main source of ionizing photons towards the end of reionization was starlight
- We can detect galaxies at z>5 using two main techniques with 8m and/or HST telescopes:

1. Dropouts (R or I band)
2. Narrow band imaging to search for Ly alpha



Dropouts: ground-based

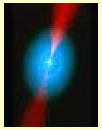
- Ground-based imaging(FORS2 on the VLT) to limit of R_{AB}=27.8, I_{AB}=26.5,Z_{AB}=26.

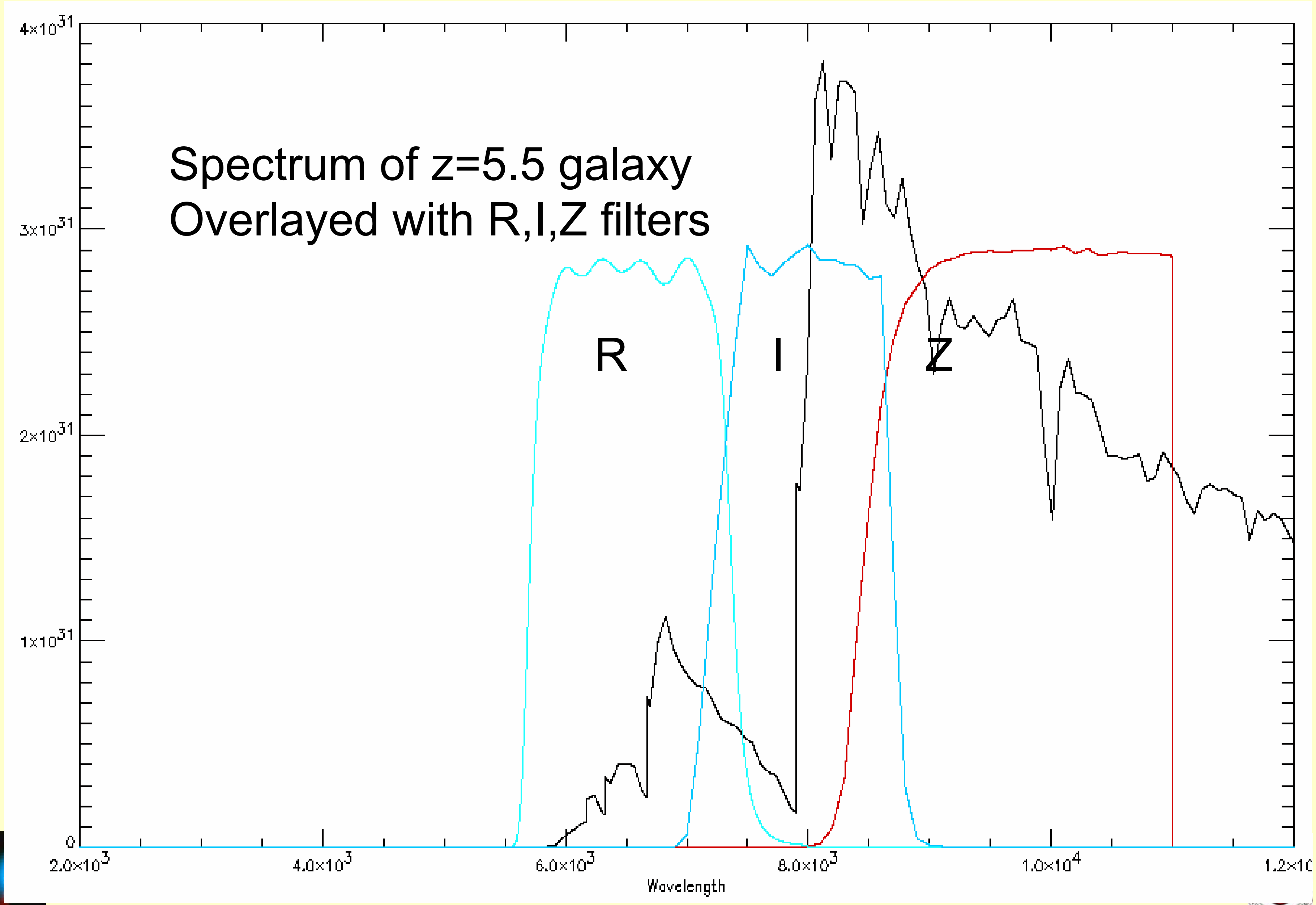
- Select objects with 25< I_{AB}<26.25 and R_{AB}>27.8

- Take spectra of these objects.

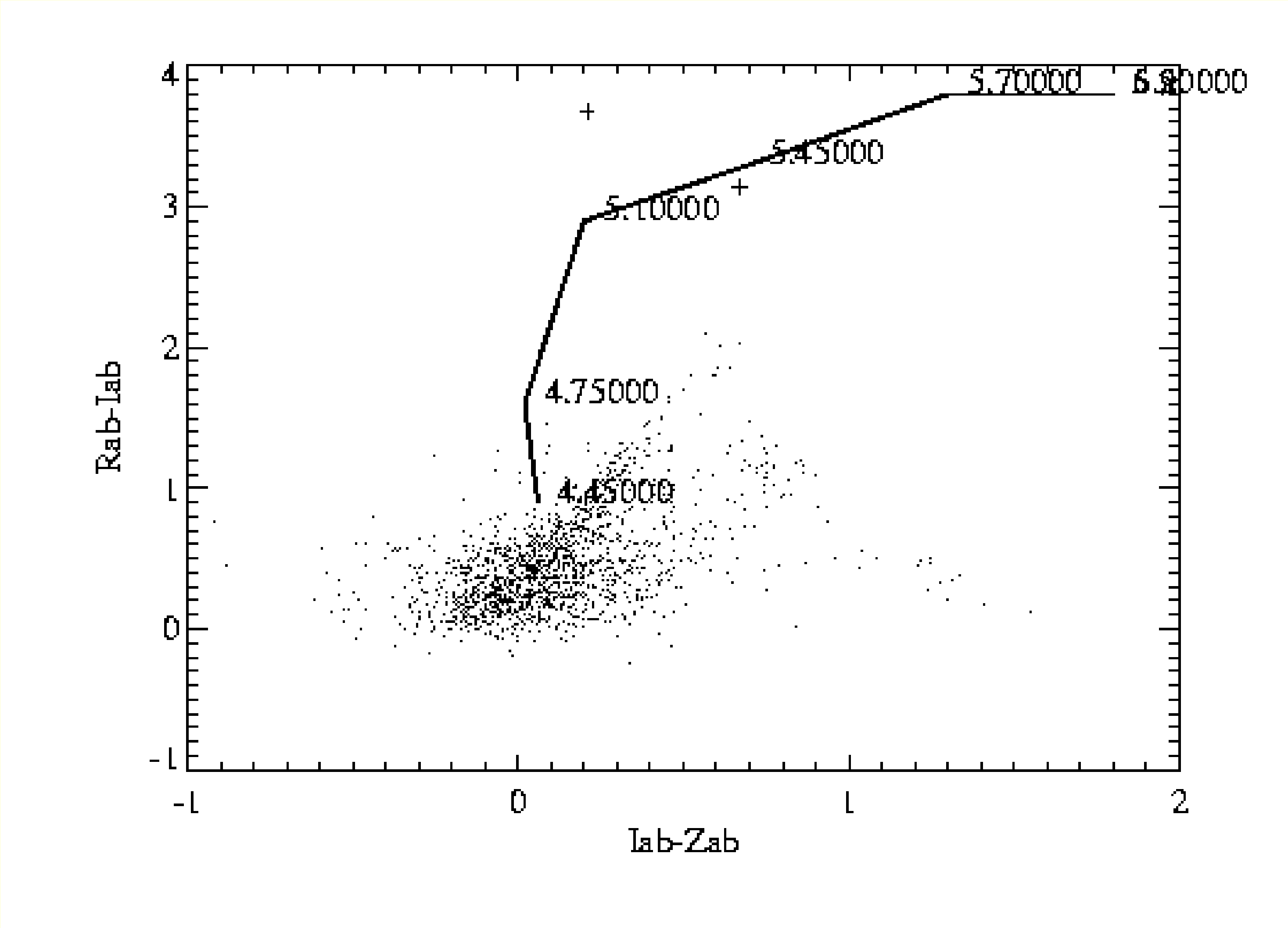
- To this level about 1 per 3 sq arcmin (80 sq arcmin).

- Half have Ly alpha emission lines, 4.8<z<5.8




Spectrum of z=5.5 galaxy
Overlayed with R,I,Z filters
R
I
Z
4×10^31
3×10^31
2×10^31
1×10^31
0
2.0×10^3
4.0×10^3
6.0×10^3
8.0×10^3
1.0×10^4
1.2×10
Wavelength

Elliptical galaxy formed in exponential burst starting z=9



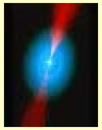
Results

- Lum (Ly alpha) ~ 10^{42} erg/s,
  flux ~ 10^{-17} erg/s/cm^2
  Rest Eq Width 30-50 Angstrom.

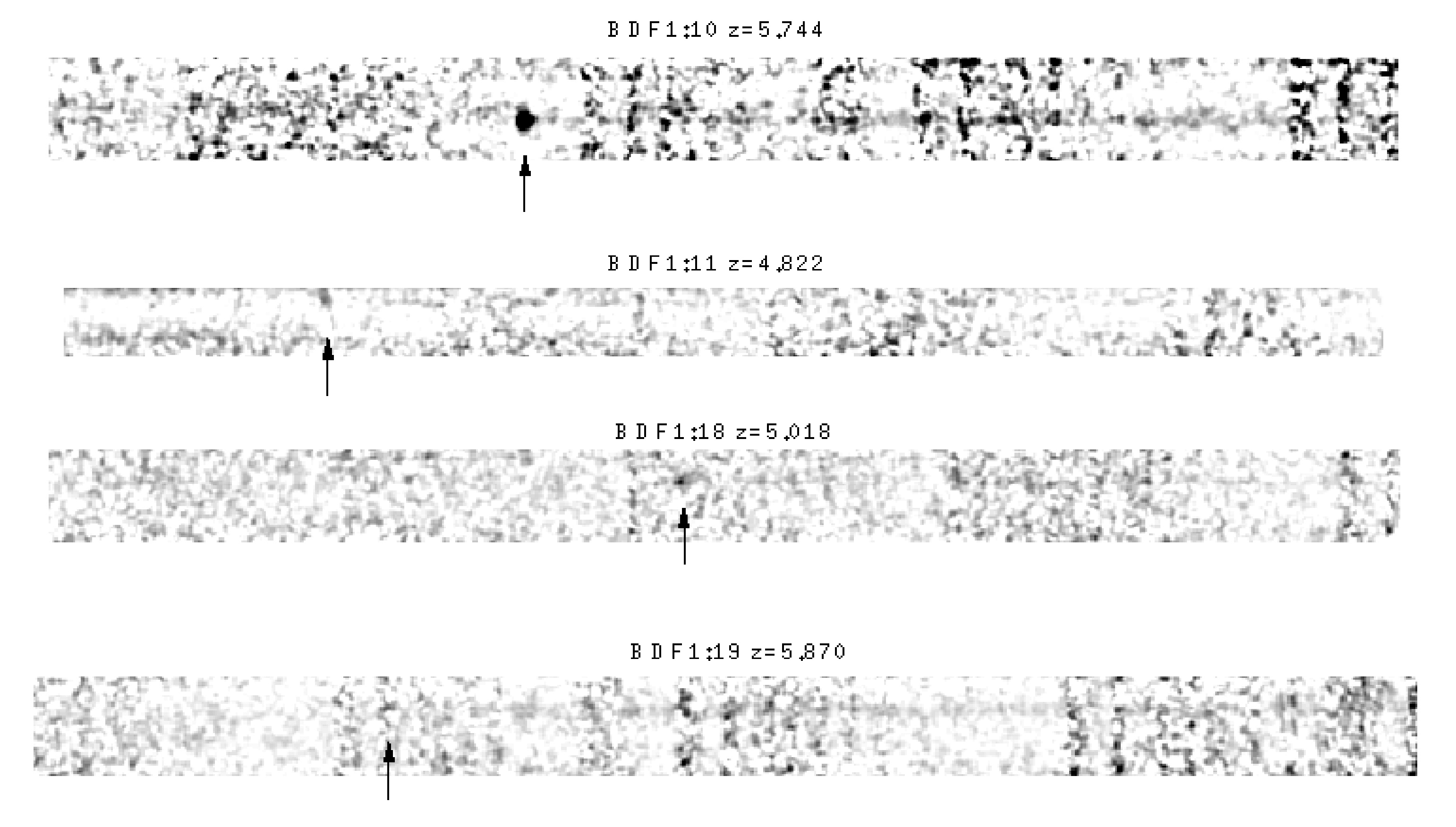
- Brighter sources with R-I>1.5 proved not to be at high redshift.

- See Lehnert & Bremer 2003, ApJ

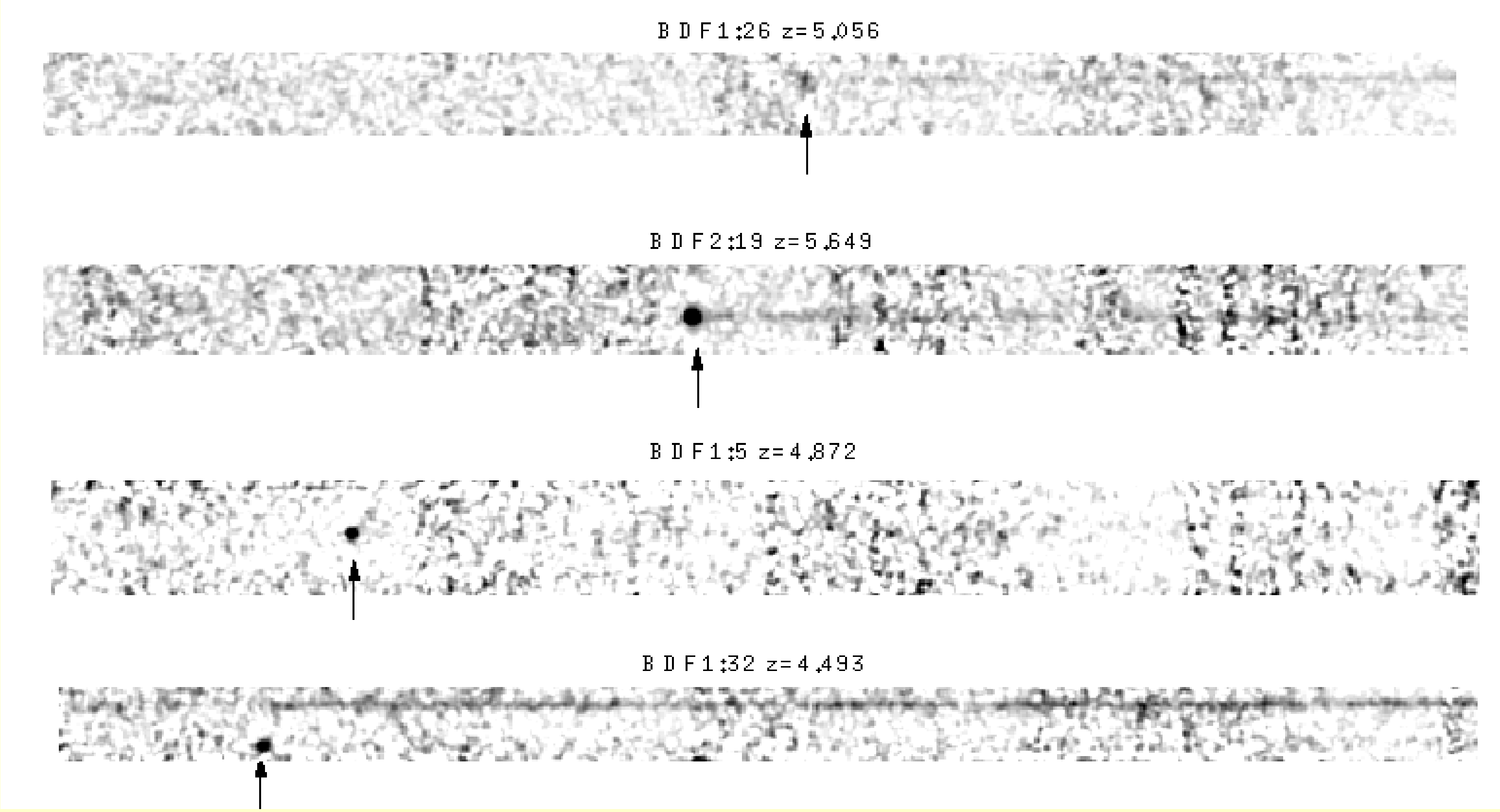
- Others (eg Bunker, Stanway etal have done I-drops: Similar results).



Some spectra

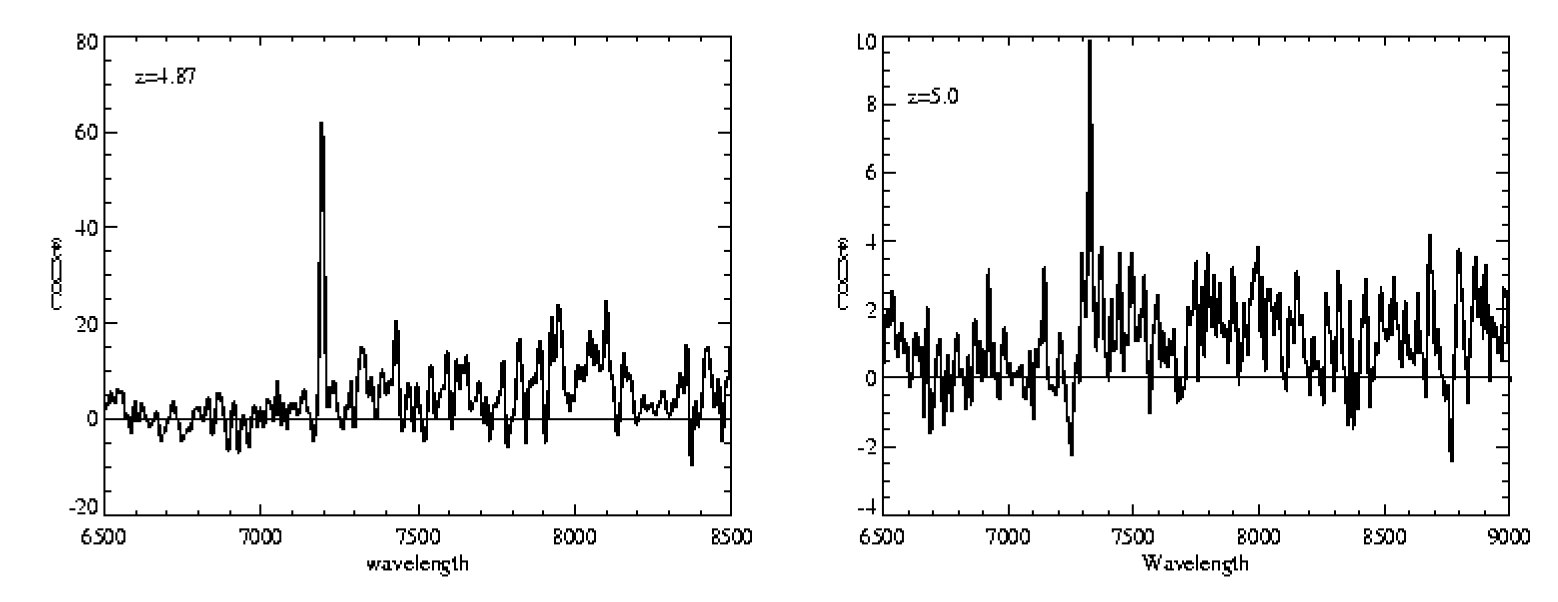


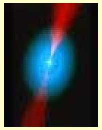
Some spectra



Galaxies: Some spectra

Z=4.9 and 5.0 Lyman break galaxy candidates with Lyα

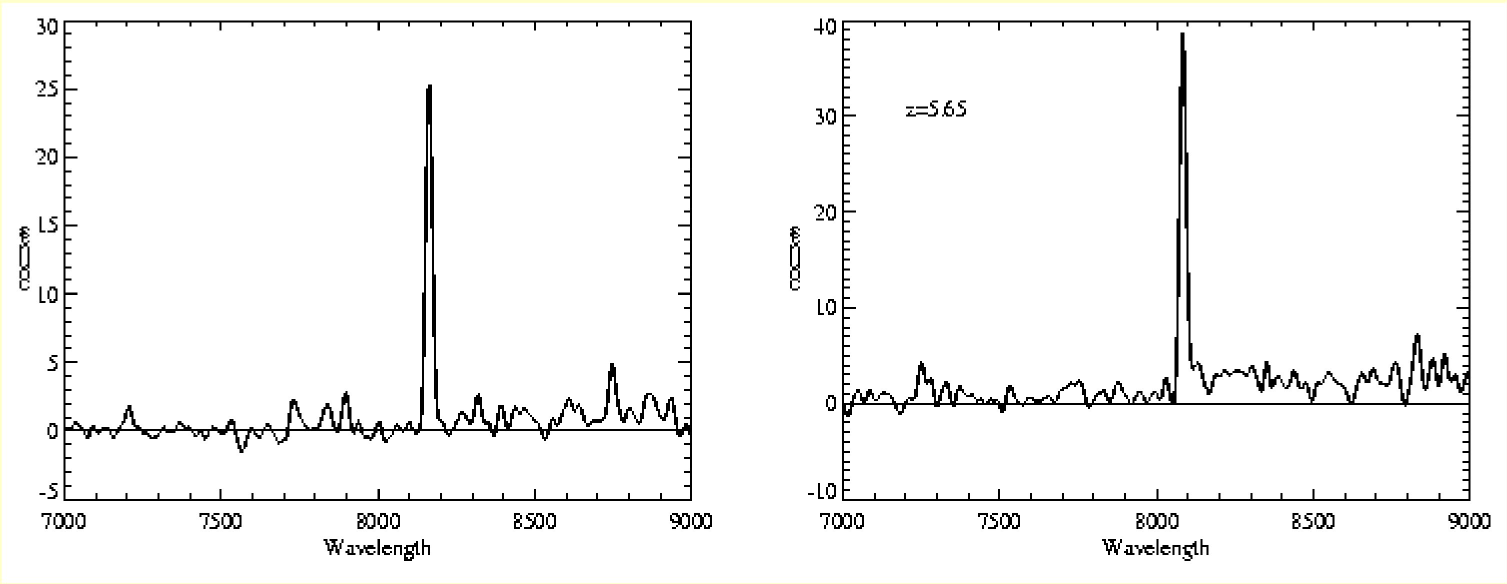


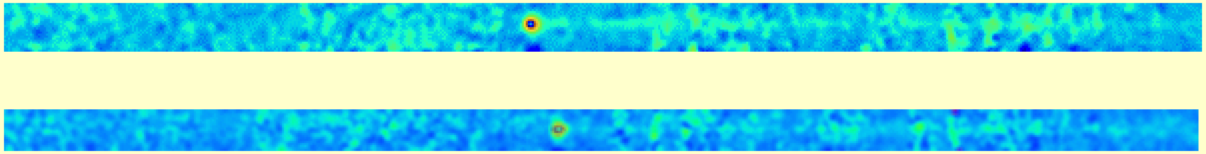


$R_{AB}>27.8, I_{AB}\sim26, Z_{AB}>25.8$

Some spectra

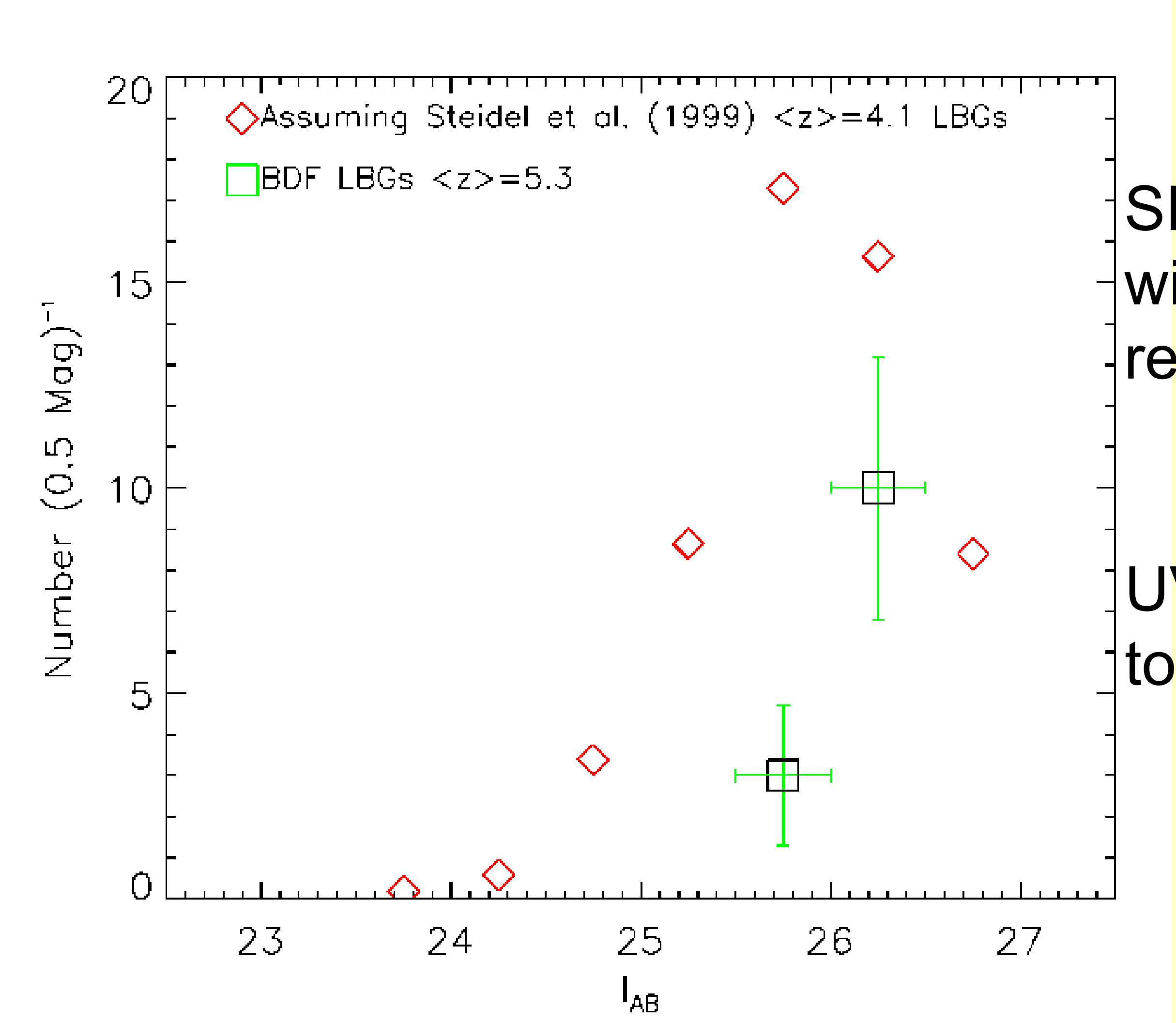
Z=5.6 and 5.7 Lyman break galaxy candidates with Lyα





R_{AB}>27.8, I_{AB}~26, Z_{AB}~25.3

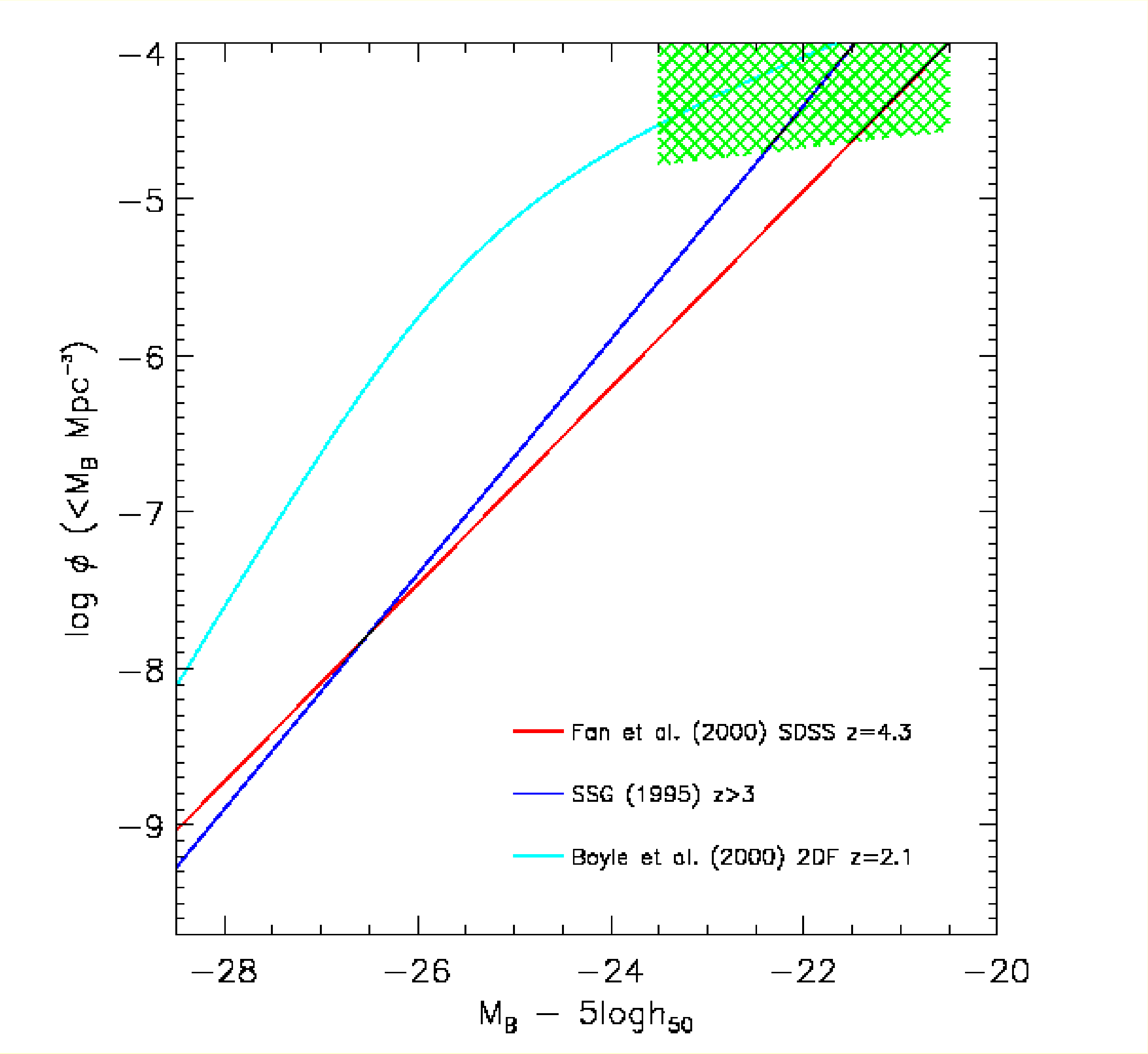
Number of detected sources relative to number of sources expected for no evolution



SFR decreasing with increasing redshift

UV flux 1/3 required to ionize volume

Constraints on AGN lum fn



Summary of ground-based results

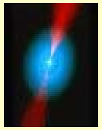
•No QSOs or AGN selected/spectroscopically confirmed at z>5. Lum fn does not steepen enough to give enough AGN to reionize universe.

•Star formation/UV density several times lower at z>5 than at z=3.

•UV emission from all detected objects that could be at z>5 is not enough to ionize the volume

•So universe is reionized by objects fainter than I_{AB}=26, or M_{1450}>-20.5.

•Number counts (lum fn) at bright end is steepening:- losing the most massive objects



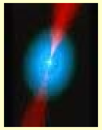
Dropouts: Space-based

- HST GOODS data can be used to identify objects over 160 $arcmin^2$ with CDF-S field.

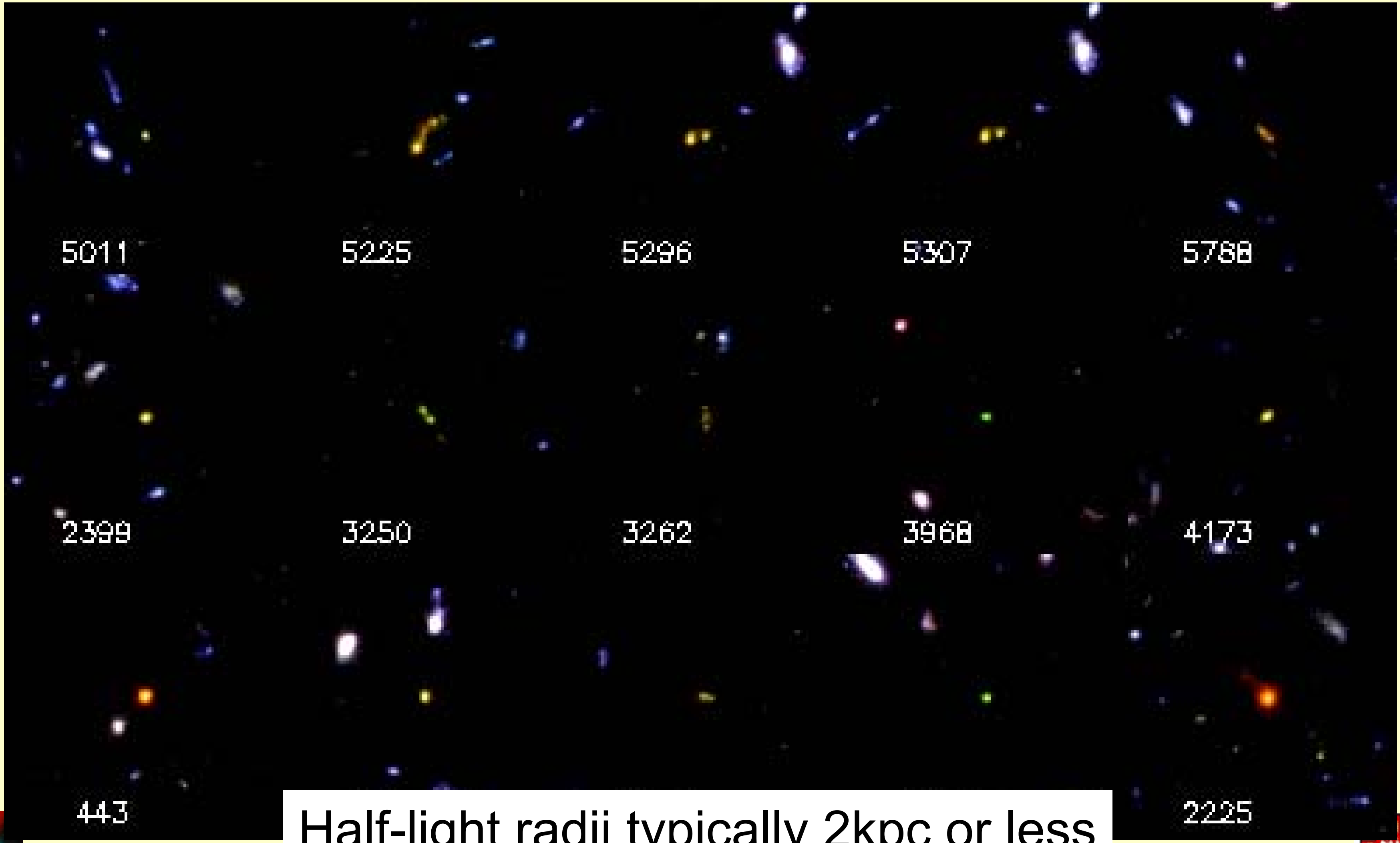
- GOODS and UDF data can be used to look at morphologies of sources.

- UDF data can be used to identify sources to I=29, and determine the (ionizing) flux from sources to M_{1500}~-17.5 in rest frame.

- UDF data can be used to look at colours of sources (I-z), indication of age of sources

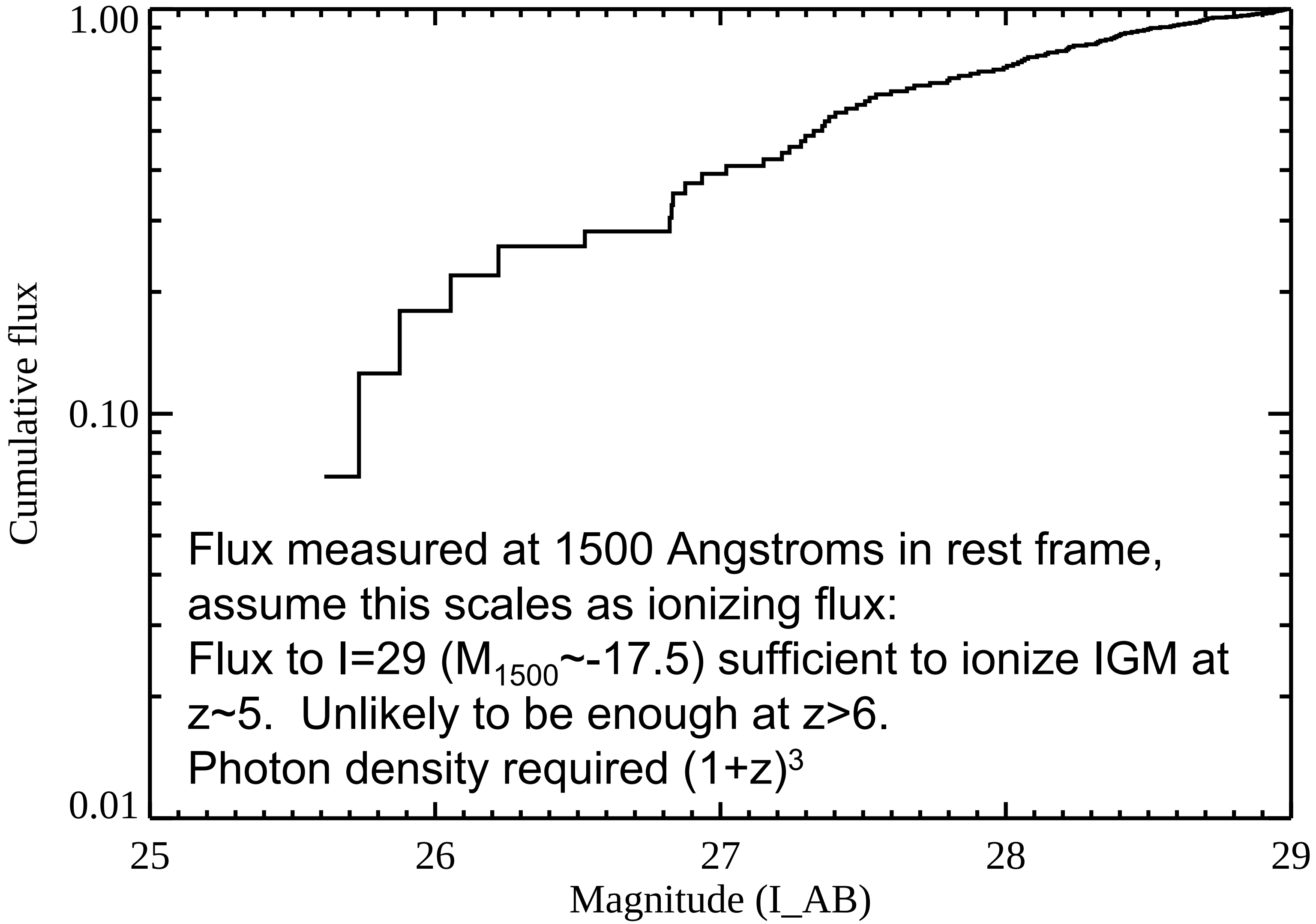


What do the high redshift galaxies look like in detail? HST-UDF data



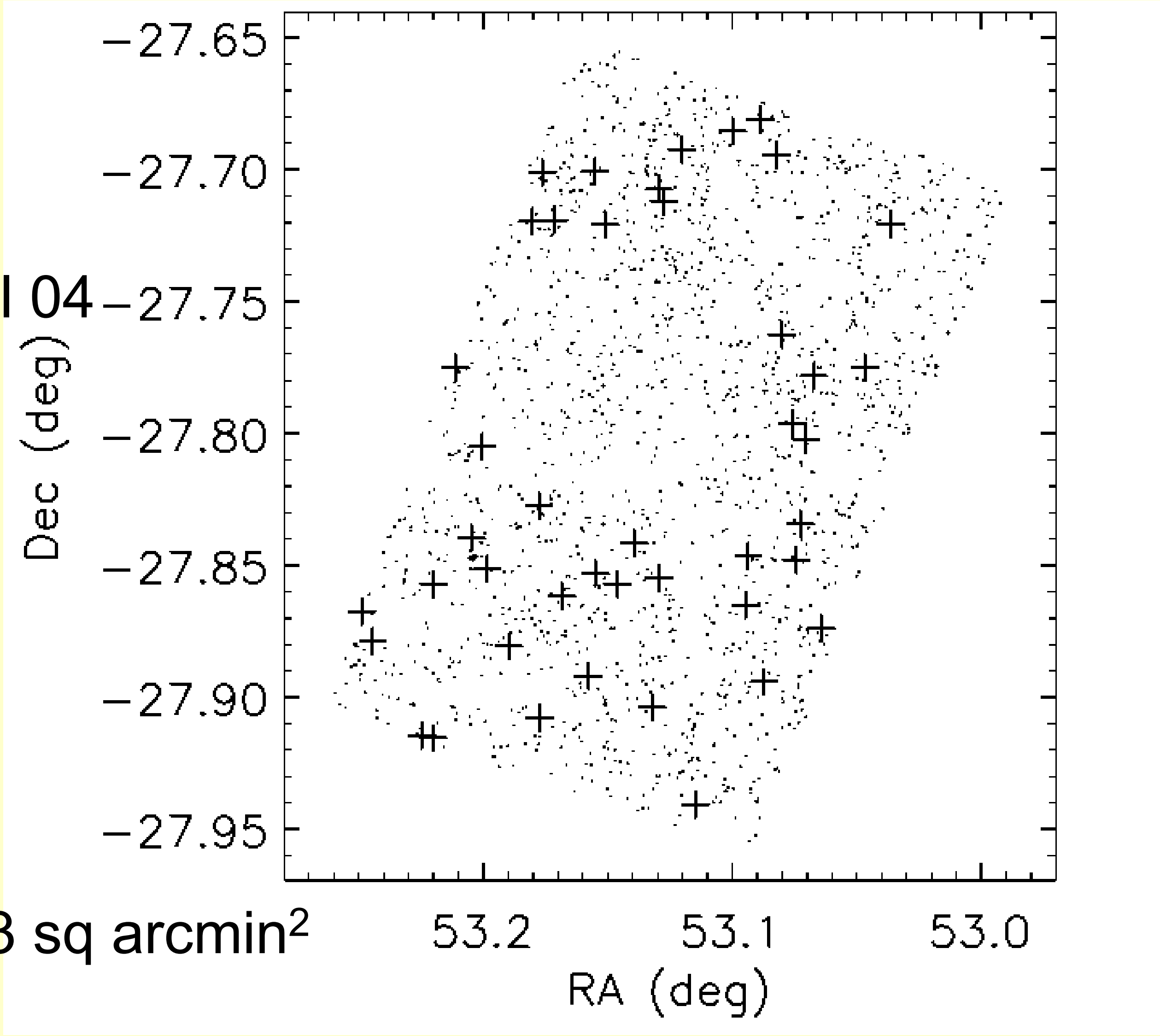
Half-light radii typically 2kpc or less

Cumulative flux from fainter galaxies



Are high redshift galaxies uniformly distributed?

Bremer etal 04

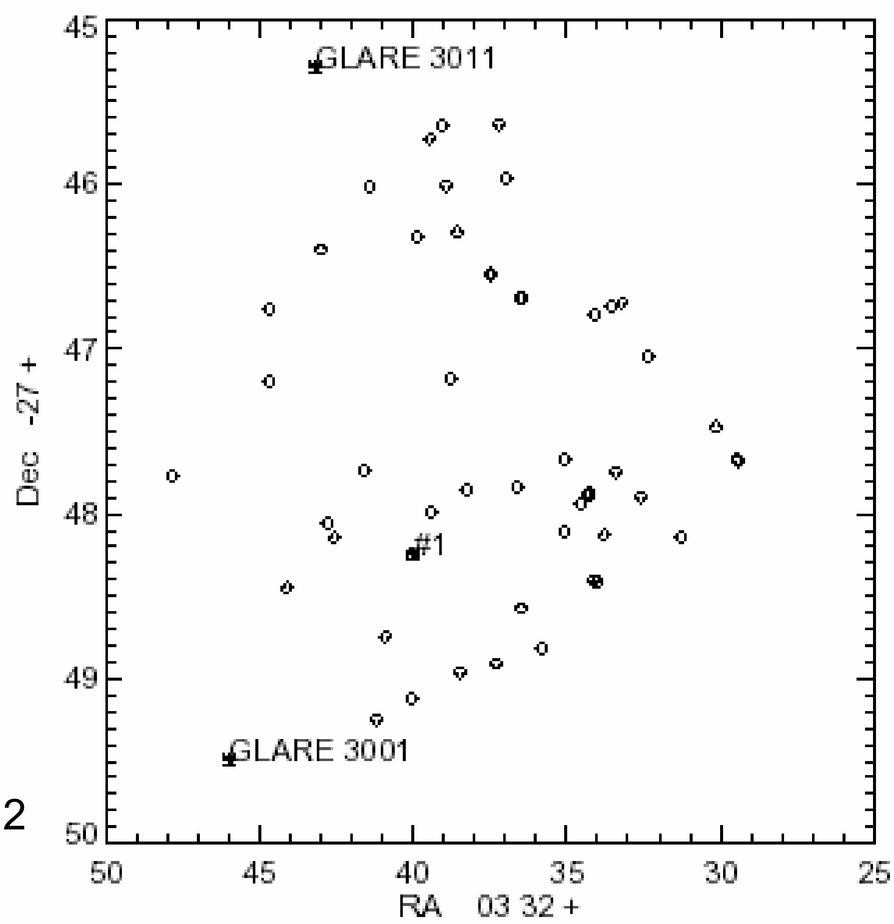


To m=26:

1 source / 3 sq arcmin^2

Are high redshift galaxies uniformly distributed?

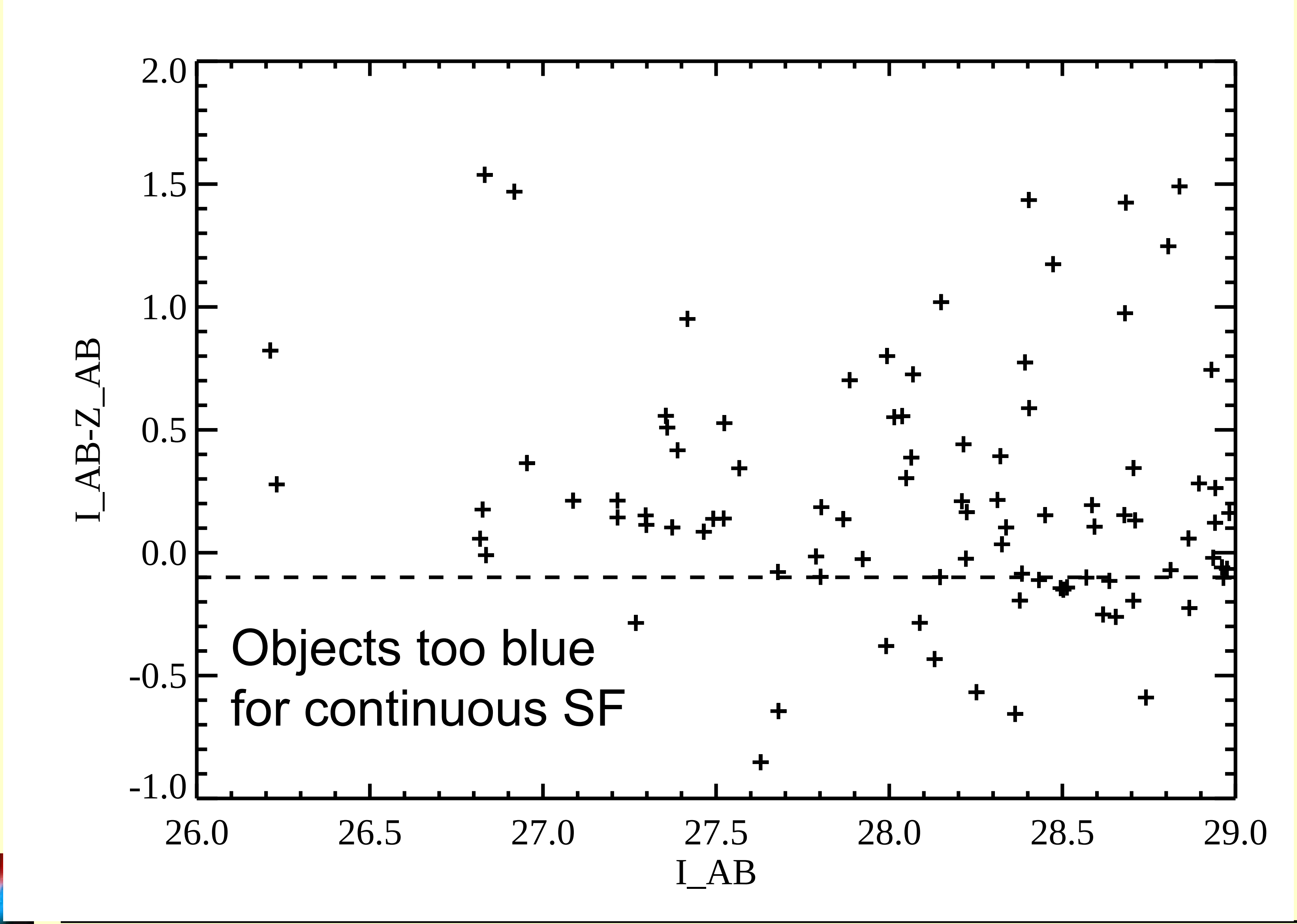
Bunker etal 04



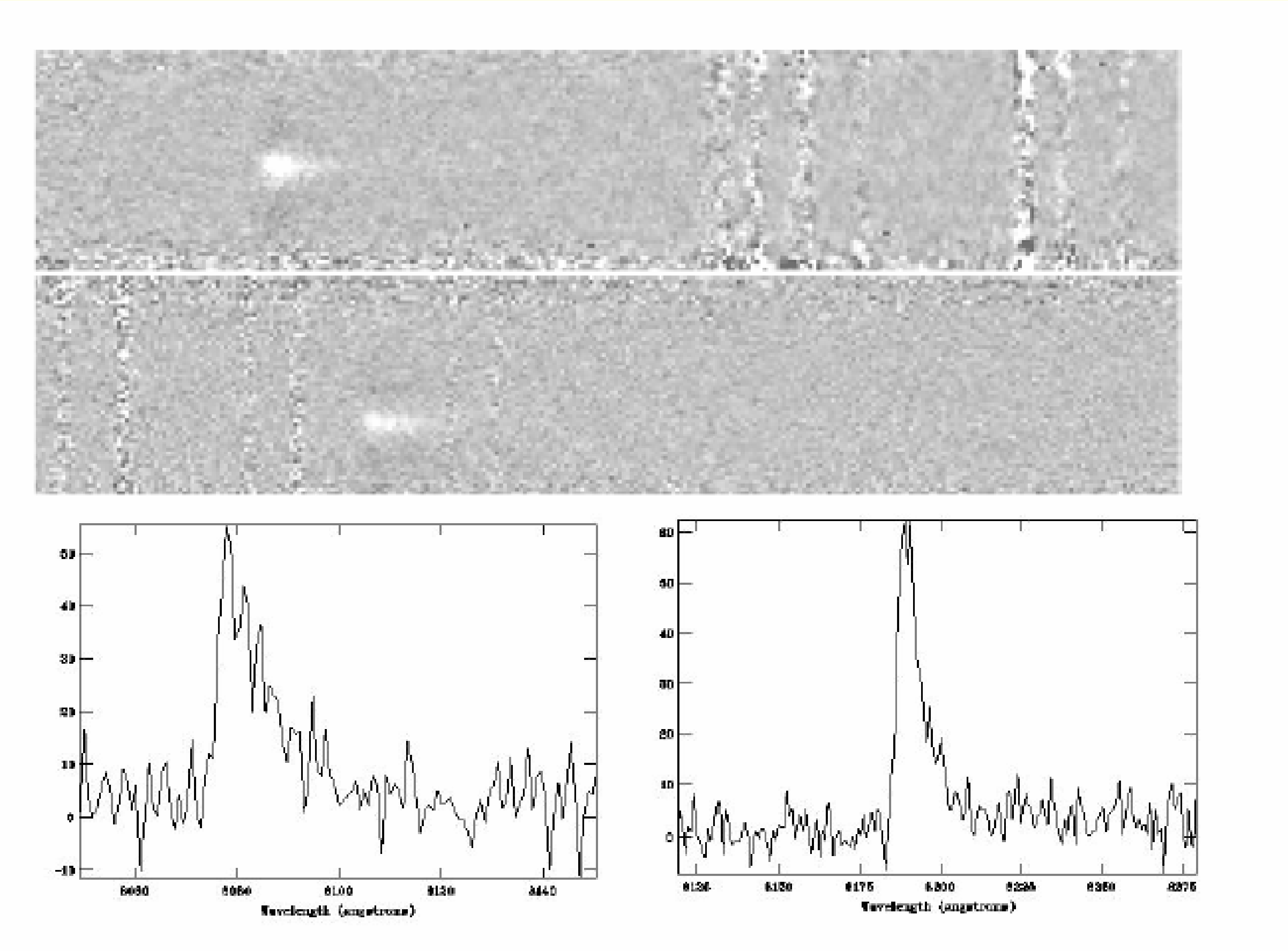
To m=28

5 sources/ $arcmin^2$

How old are the galaxies?

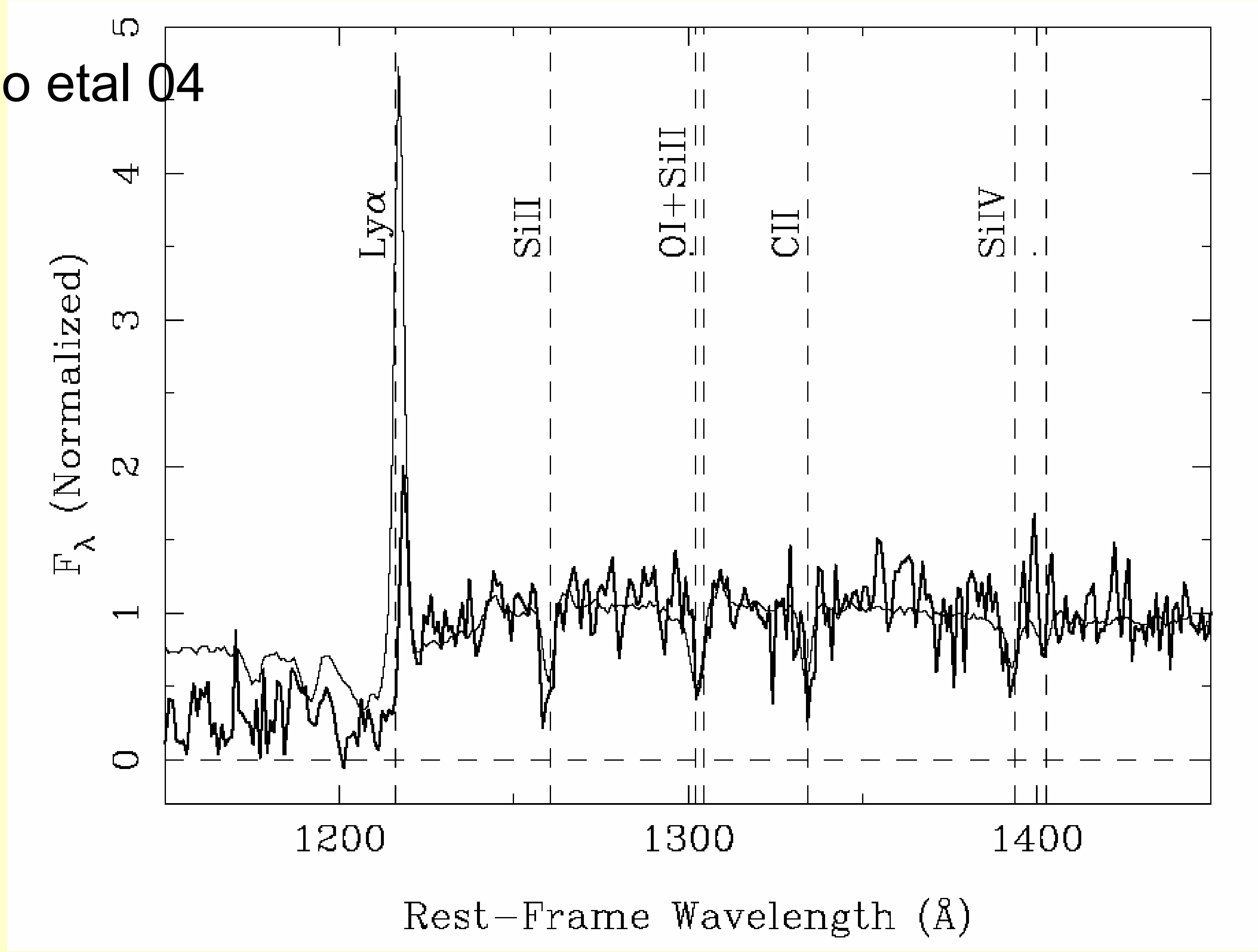


How old are the galaxies?



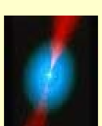
How old are the galaxies?

Ando etal 04



How old are the galaxies?

- All of this points to young starbursts, ~10Myr or younger
- Age of Universe 1 Gyr
- Will see similar objects back to z=10 at least, Several hundred Myr earlier than z=5-6



Line emitters

- NB imaging and follow-up spectroscopy by Rhoads and collaborators at z=5.7

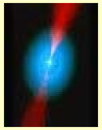
- Flux >1.5x10^{-17} erg s^{-1} cm^{-2}
500 per square degree per unit redshift

- Highly clustered

- Equivalent widths >150 Angstroms, higher than the Lyman break sources.

- Not X-ray detected so probably not AGN

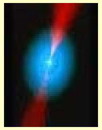
- Young, low metallicity starbursts, given the equivalent widths



Implications for 100m-class studies

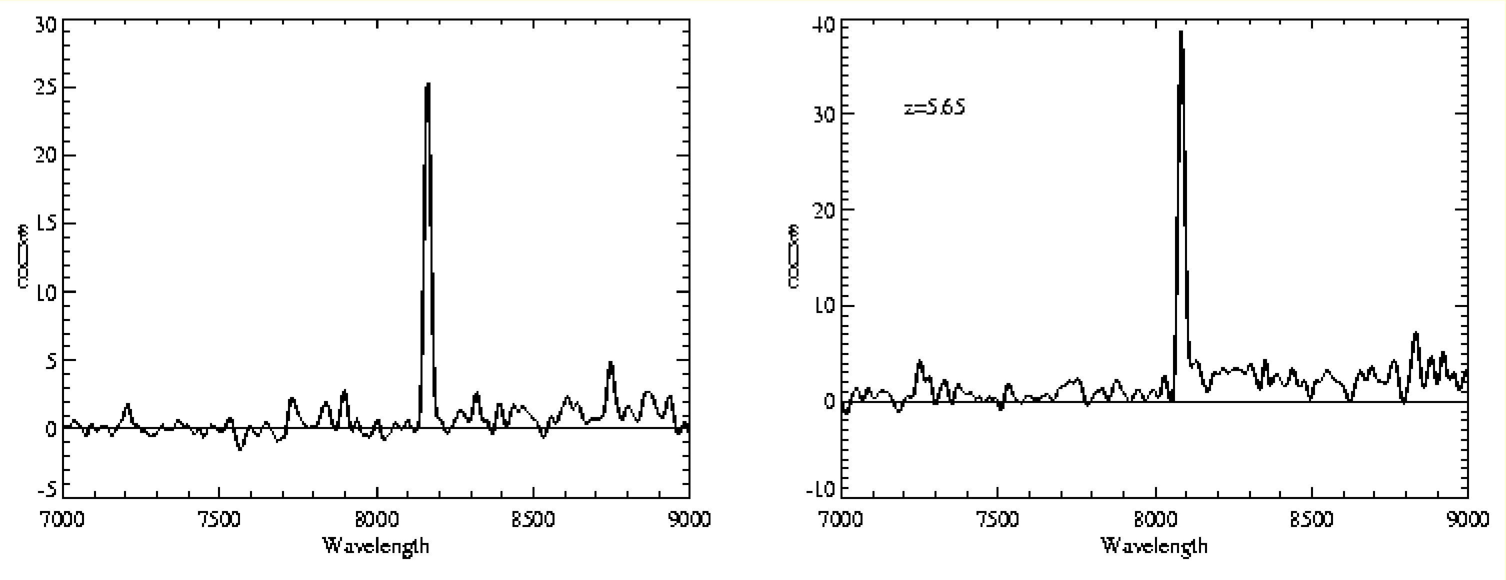
- Objects are spatially resolved, do not gain full advantage of diffraction limit for depth. Instrumentation needs to exploit the scale of these objects (typical half-light radii 0.2 arcsecs).

- JWST is “first light machine”. Smaller but above atmosphere. At low resolution 100m is more sensitive up to J band for resolved objects. At high (R>1000) resolution, 30 or 100m can win out over JWST depending on instrumentation.



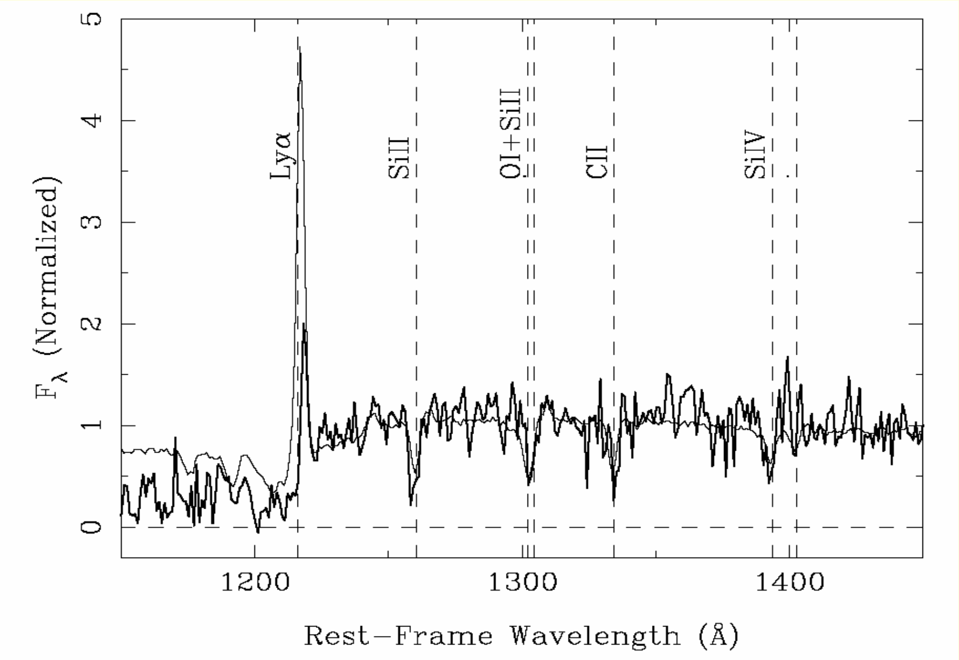
Implications for 100m-class studies Z=5-6 sources:

- Typical identification spectra today reach m=26, with 100m can reach m=29. 5-10 sources per sq arcmin



Implications for 100m-class studies Z=5-6 sources:

- Best spatially unresolved spectra today

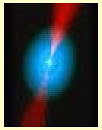


- Can be obtained on a 10 by 10 grid by a 100-m. Kinematics and spatially resolved metallicity/sfr variation in 100 hr exposures

Implications for 100m-class studies Z=5-6 sources:

•Can potentially use these sources to probe intervening IGM on arcminute scales. However, these sources are resolved.

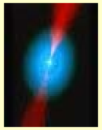
•Globular cluster-scale objects will be unresolved and therefore could benefit from diffraction limit (AO) on a 30m+ telescope.



Implications for 100m-class studies Z=8-10 sources:

- Into the J-band. Lose 2 mags at low resolution due to sky (1 mag between the sky lines at higher resolution). Lose nearly 1 mag due to luminosity distance.

- Above assumes no spatially unresolved regions in source. If a large fraction of light is emitted in sub-kpc regions of source sensitivity can dramatically increase-> R=10,000 spectra of subclumps to s/n=10 in 100 hrs.



Implications for 100m-class studies Z=15-20 sources:

- Into the H and K-bands. Lose >2-3 mags at low resolution due to sky (mag between the sky lines at higher resolution). Lose 1-2 mag due to luminosity distance.

- Studies limited to the most luminous sources unless they start to get very small and can start to benefit from the diffraction limit.

100-m observations

- Detection of break galaxies at z>8-10 as easily as z=5.5

- Detailed med-hi res spectra of Lyman break galaxies at z~6 and above→ star formation history, stellar pops, IMF…

- Direct detection of Pop-III supernovae→ key
- Unlikely to see Pop-III directly (m>35 in IR)

- Detailed measurements of ISM/IGM by abs lines ot to z=10?

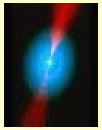
Instrumentation Drivers

•These objects are resolved, so probably cannot benefit from diffraction limit gain in sensitivity.

•Consequently, we need as large an aperture as possible to really do better than JWST.

•Also need flexible pixel scale, not just optimised to diffraction limit. Need to optimize pixel scale to get good s/n per spectral resolution element.

•Source densities “easy” for multiplexing faint sources in a small field. Brighter objects required for best s/n, require 5-10 arcmin field for multiplex



Conclusions

•On their own 100m-class telescopes can carry out key observations of the earliest galaxies (certainly to z=10 (J-band) , probably to z=20 (K-band).

•Our main instument to understand these sources in detail, regardless of what is in orbit.

•The bigger the telescope the better!

•Choice of pixel scale and field size important to optimise such studies.