The First Galaxies

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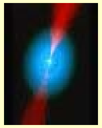


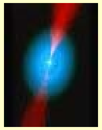
Relevant Questions

- When did the first galaxies form?
- What did they look like?
- 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 telescopes:

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



Dropouts

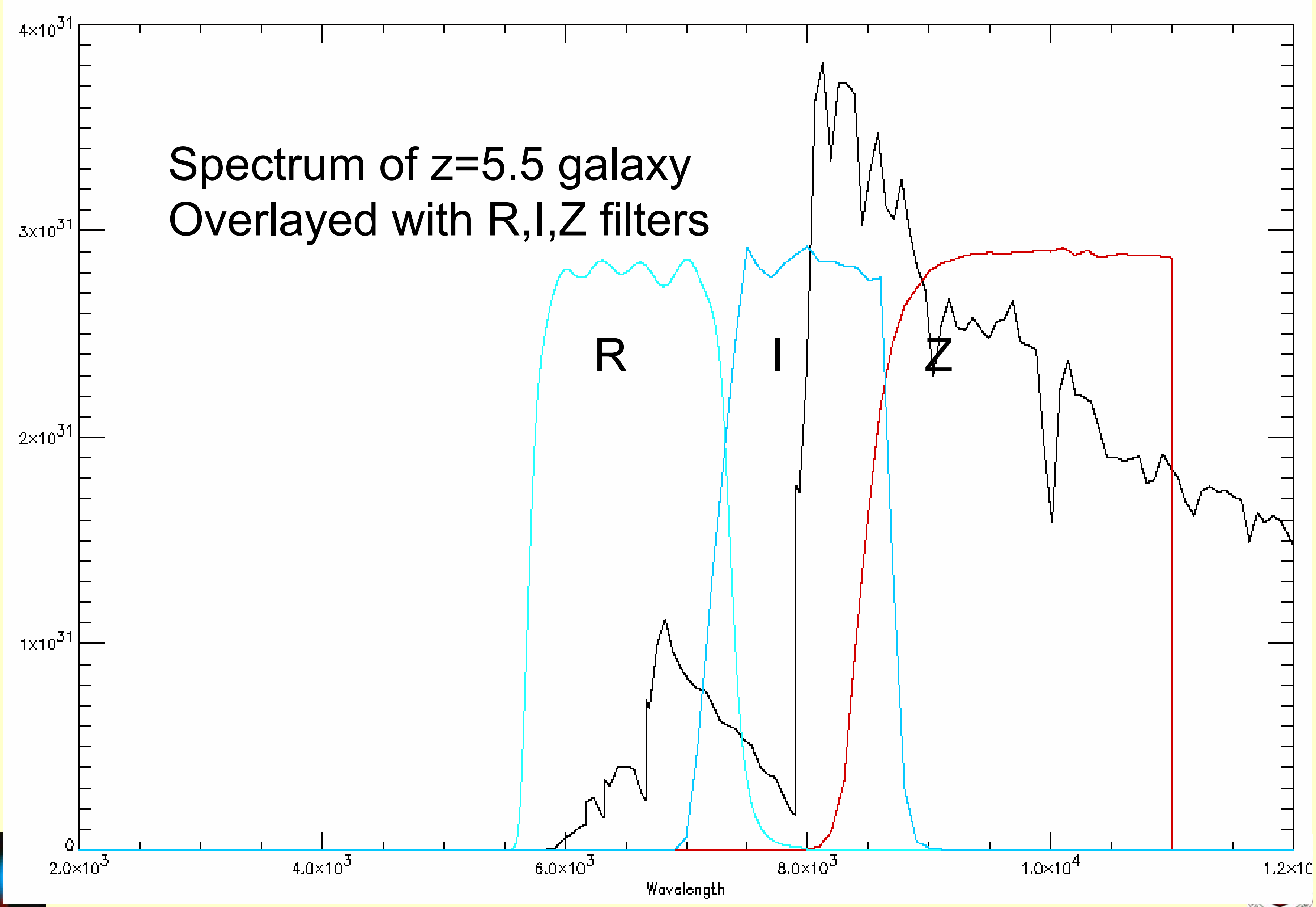
- Image a 80 arcmin^2 field with FORS2 on the VLT to limit of $R_{AB}=27.8$, $I_{AB}=26.5$,$Z_{AB}=26$.

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

- Take spectra of these objects.

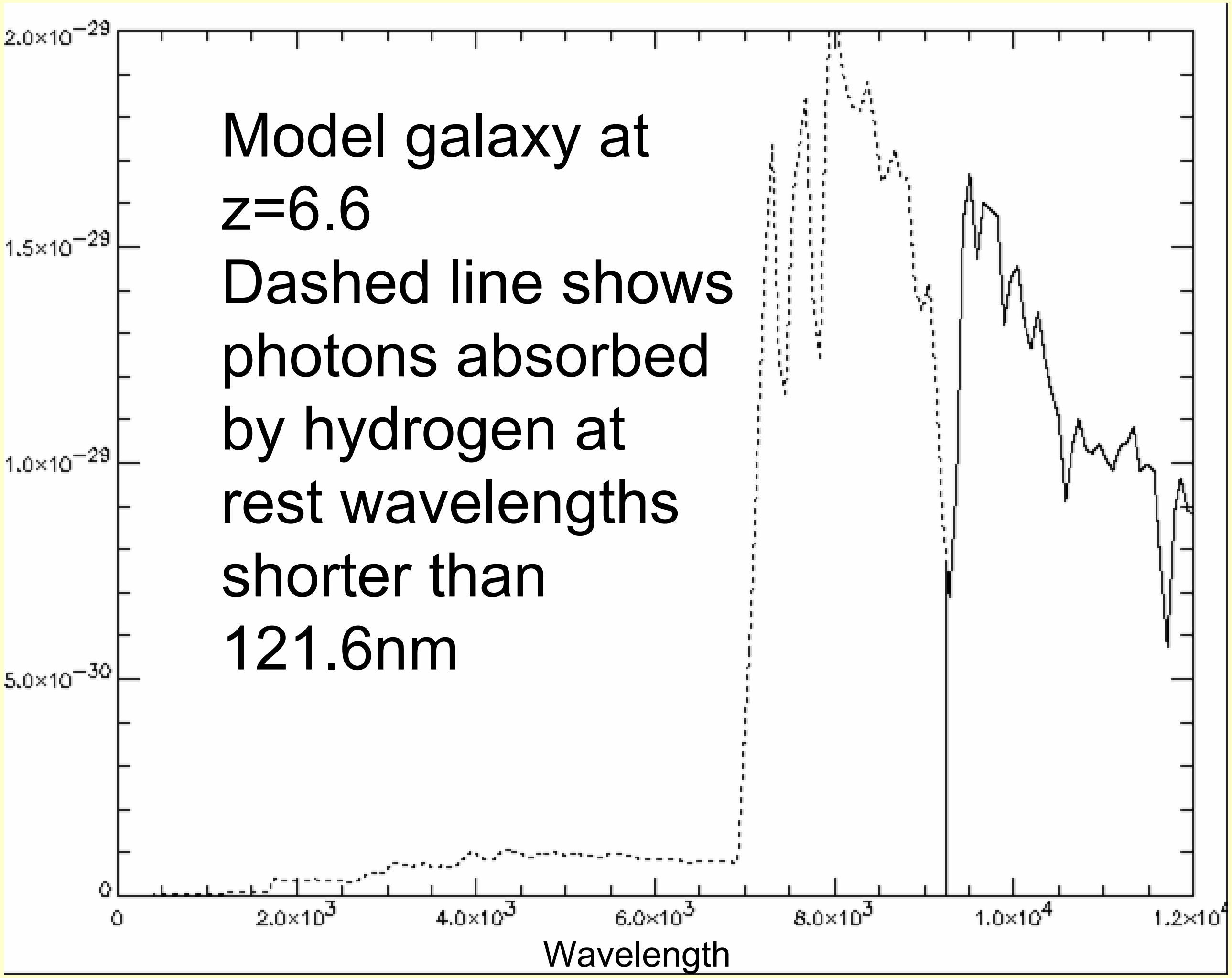
- Between $4.8<z<5.8$ the volume probed by this field is ~$2*10^5$ Mpc^3.

- Scaling from the mass density of the universe at $z=0$, require about $5x10^{56}$ ionizing photons per sec to keep this volume ionized (one SLOAN QSO, typically with I=22ish at $z=5.5$).

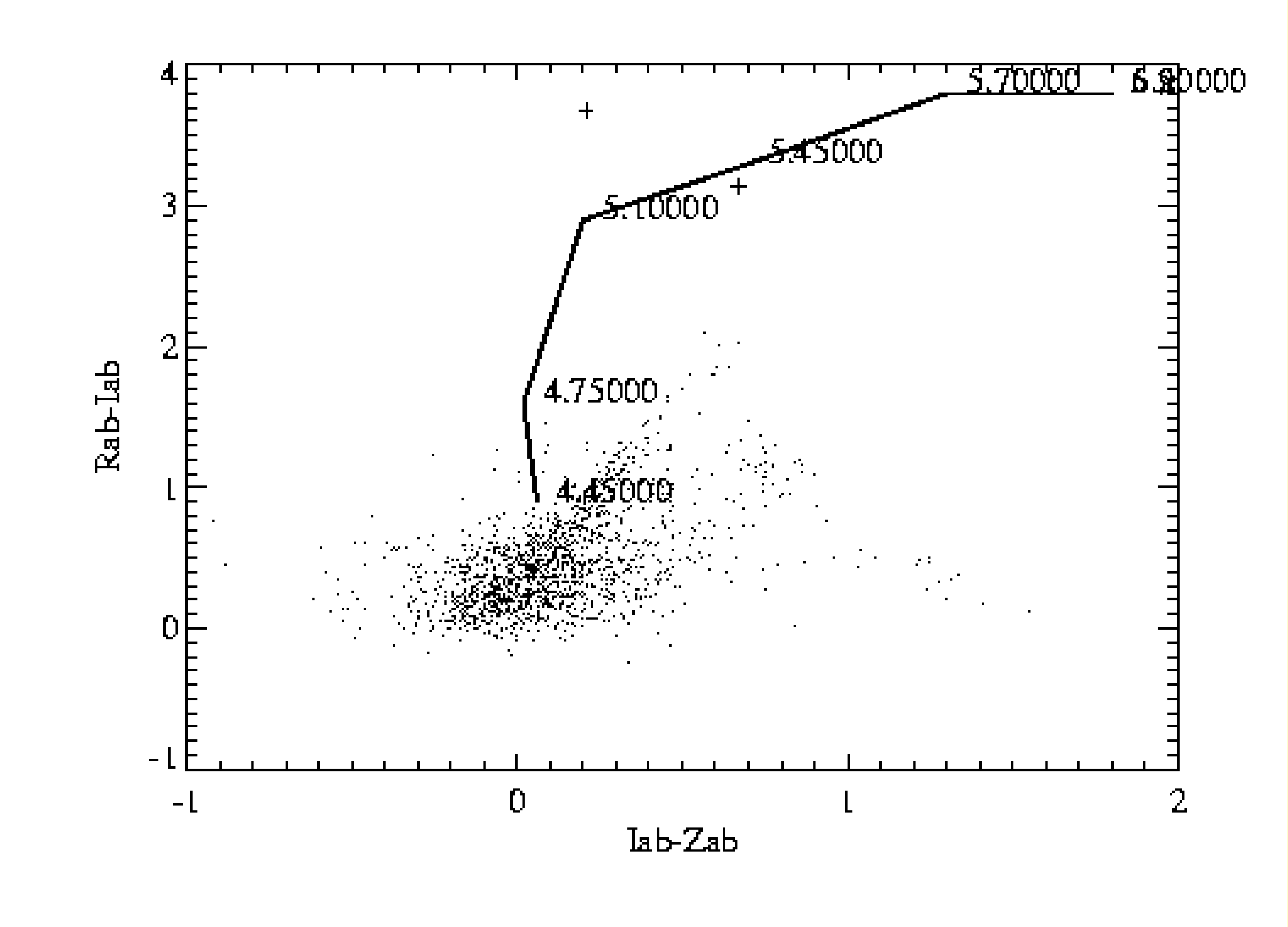


Spectrum of z=5.5 galaxy
Overlayed with R,I,Z filters
R
I
Z
4×10^31
3×10^31
2×10^31
1×10^31
0
2.0×10^3
4.0×10^3
6.0×10^3
8.0×10^3
1.0×10^4
Wavelength

High redshift sources reddened by H opacity



Elliptical galaxy formed in exponential burst starting z=9



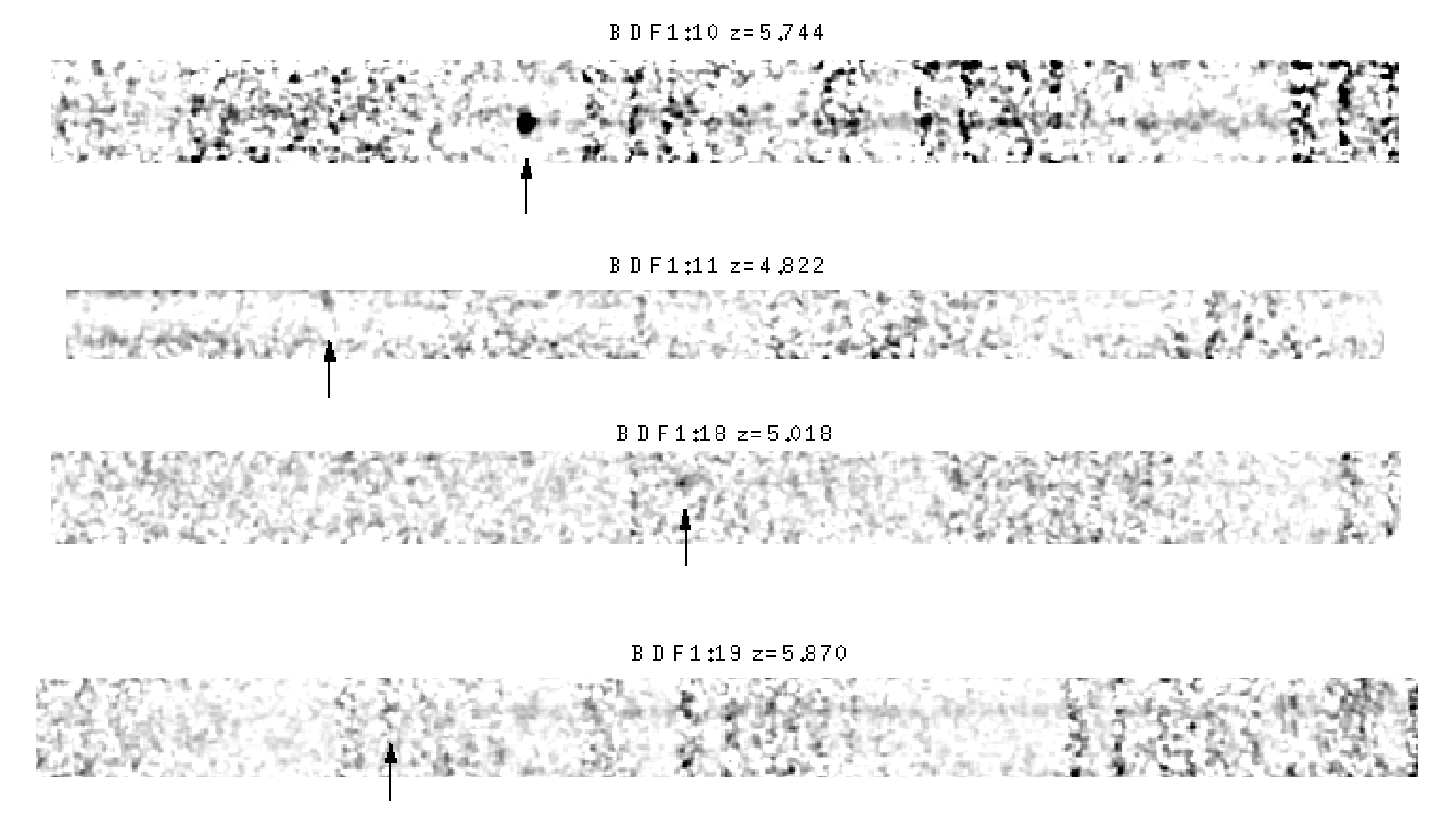
Results

- Of 26 sources with $25<I<26.25$, $R-I>1.5$, got spectra of 26. Twelve showed single emission line at break in continuum. Redshifts $4.8<z<5.8$. Another showed a break at $z=5.2$

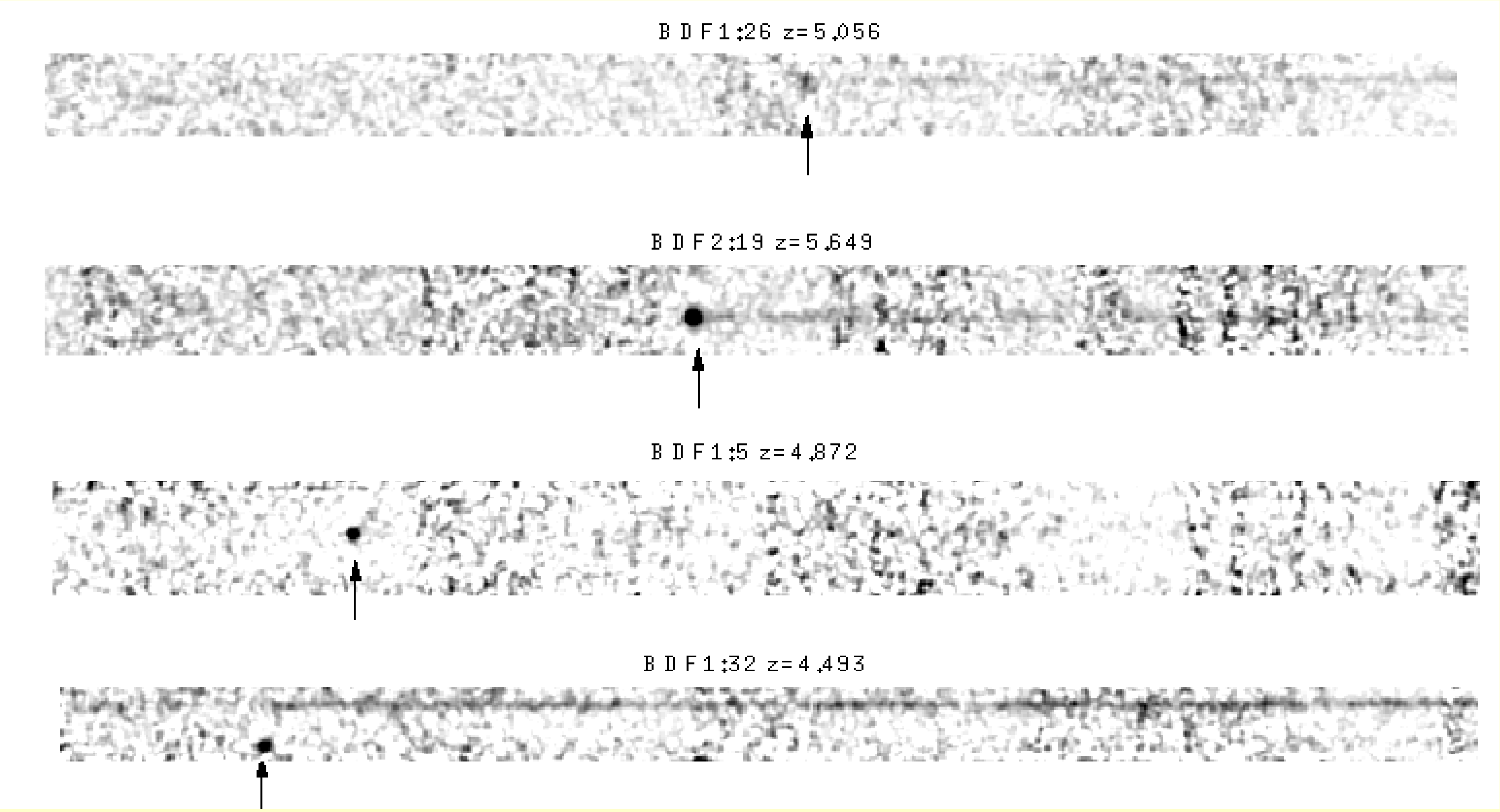
- Lum (Ly alpha)~ 10^{42} erg/s (flux 10^{-17} erg/s/cm^2) Rest Eq Width 30-50 Angstrom.

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

Some spectra

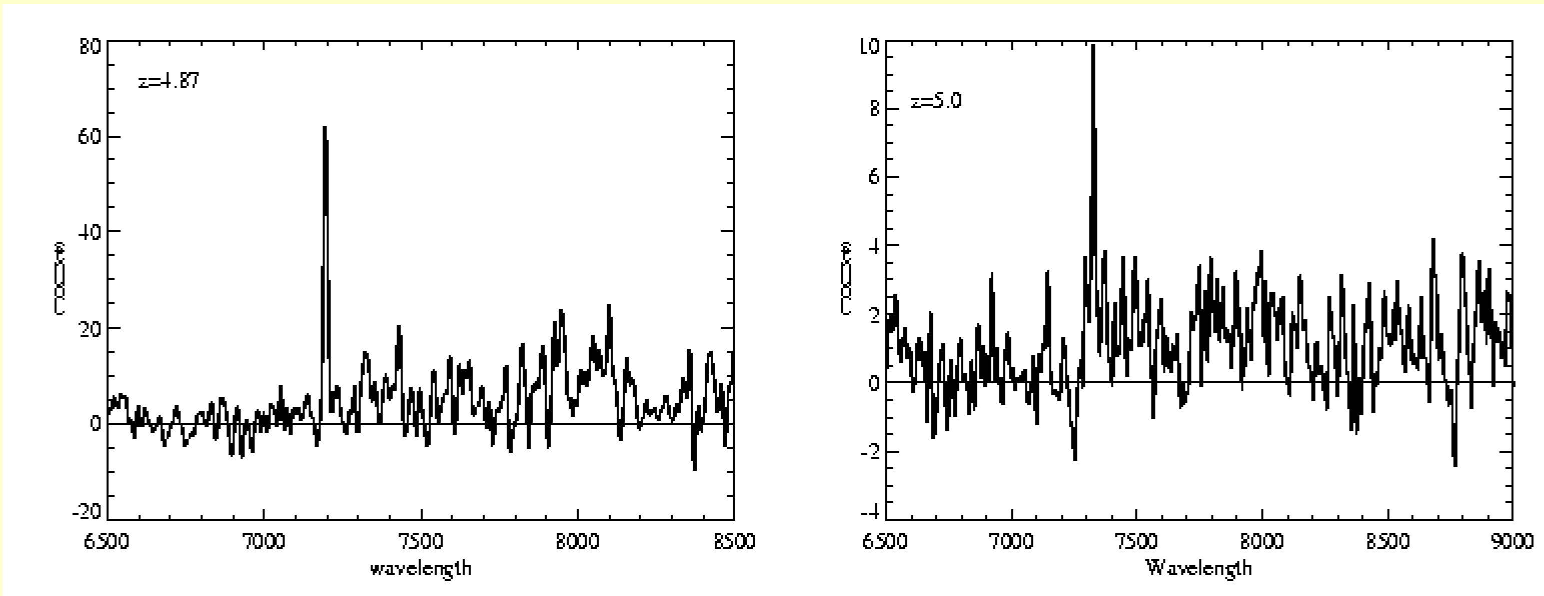


Some spectra

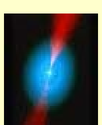


Galaxies: Some spectra

Z=4.9 and 5.0 Lyman break galaxy candidates with Lyα

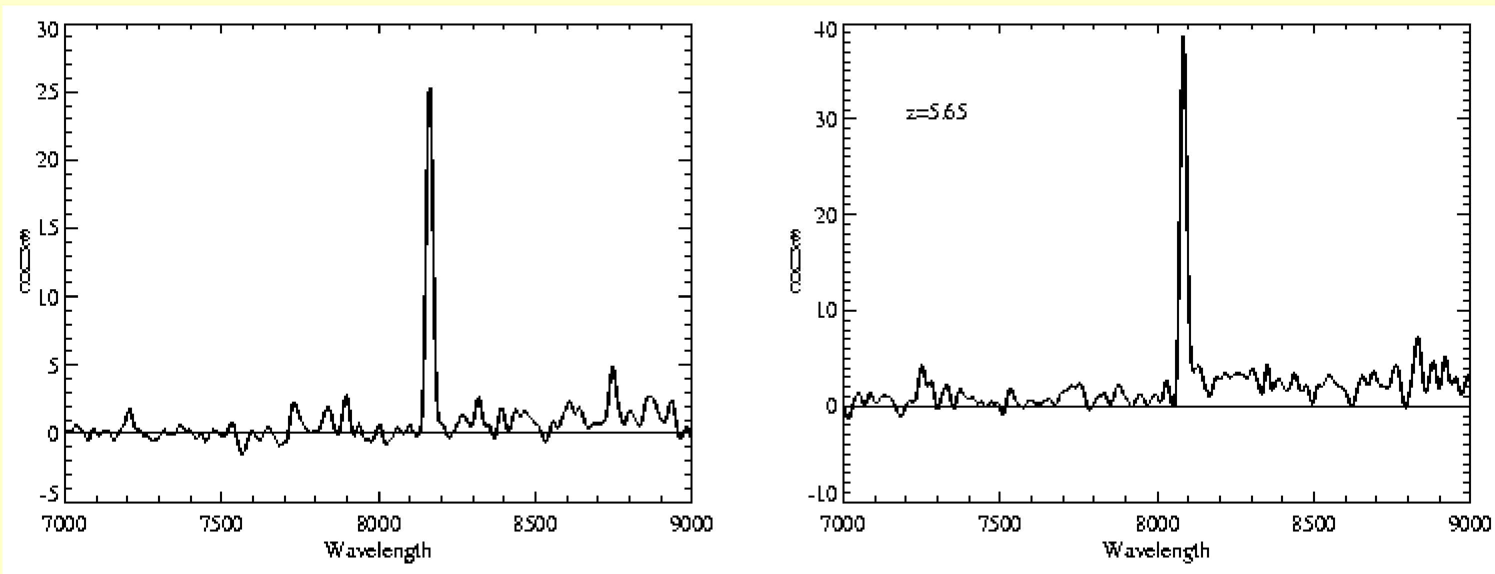


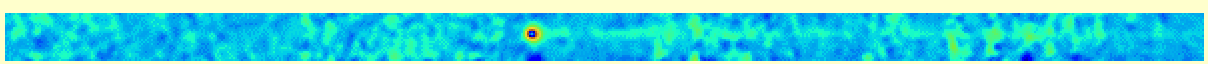
$R_{AB}>27.8, I_{AB}\sim 26, Z_{AB}>25.8$

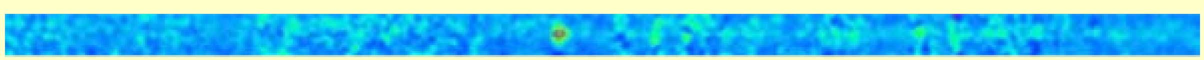


Some spectra

Z=5.6 and 5.7 Lyman break galaxy candidates with Lyα

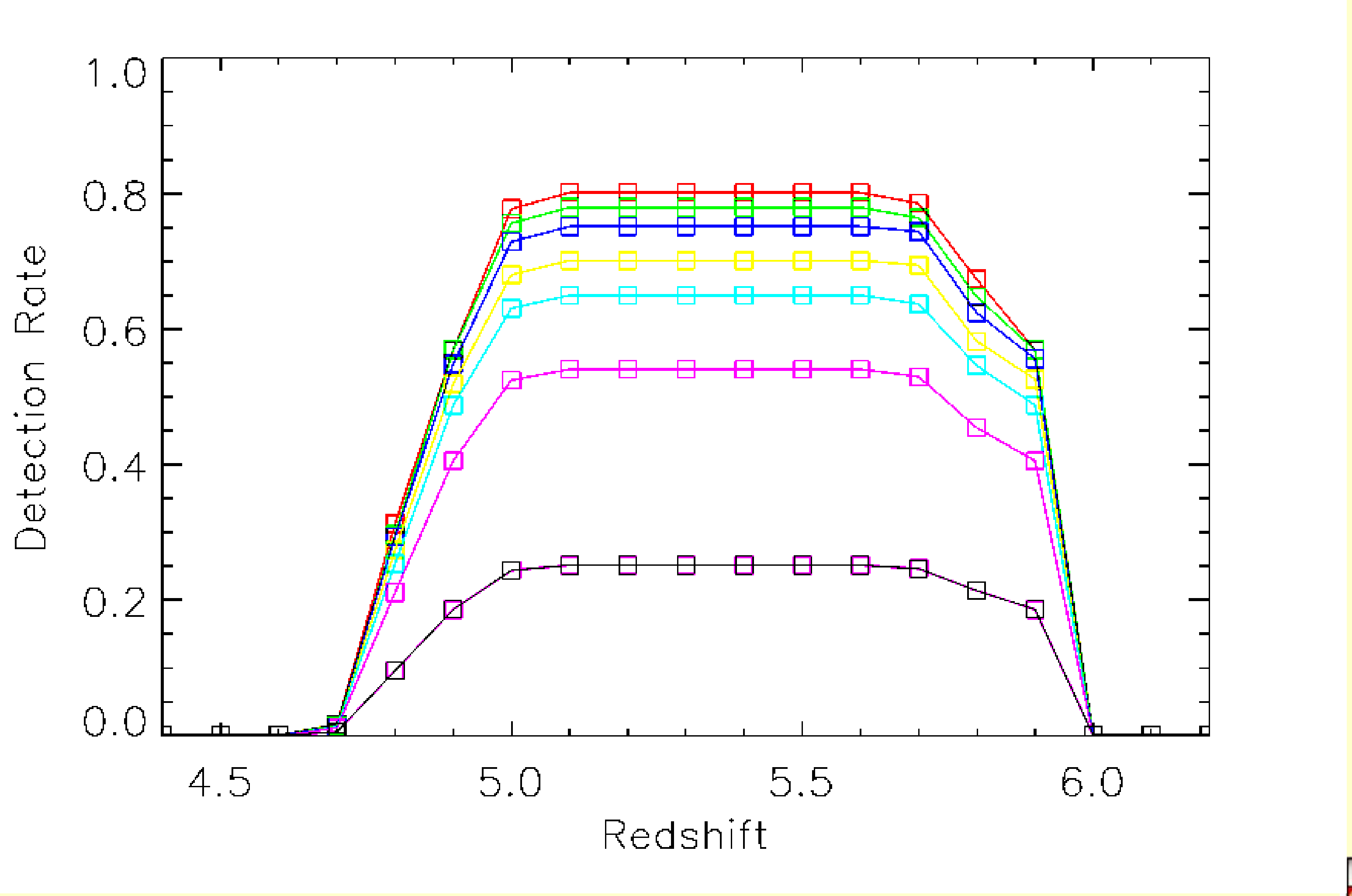




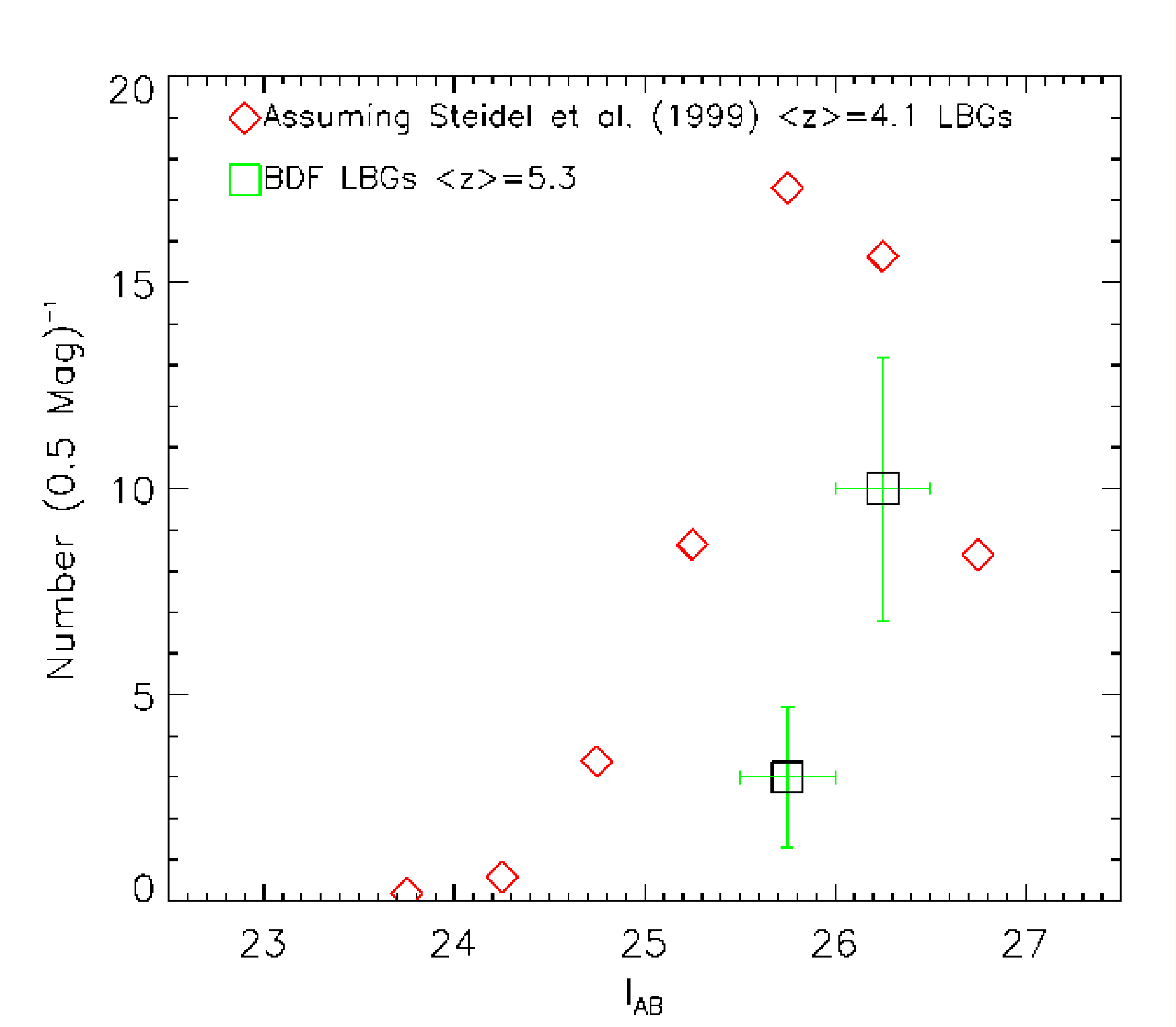


R_{AB}>27.8, I_{AB}~26, Z_{AB}~25.3

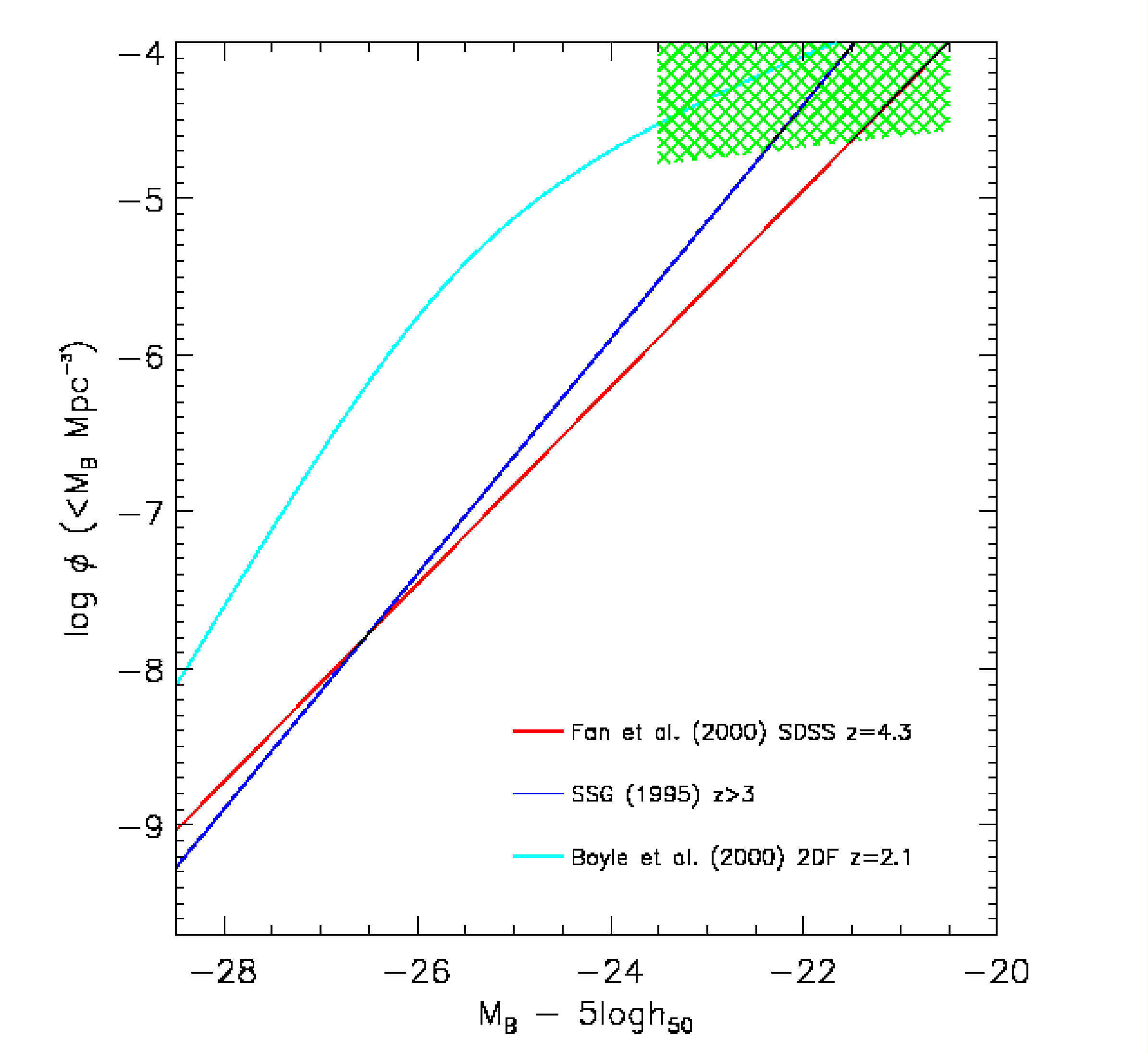
Interpretation: Source detectability



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



Constraints on AGN lum fn



Summary of results

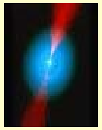
•No QSOs or AGN selected/spectroscopically confirmed at z>5. Lum fn does not steepen enough to give enough AGN to reionize universe.

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

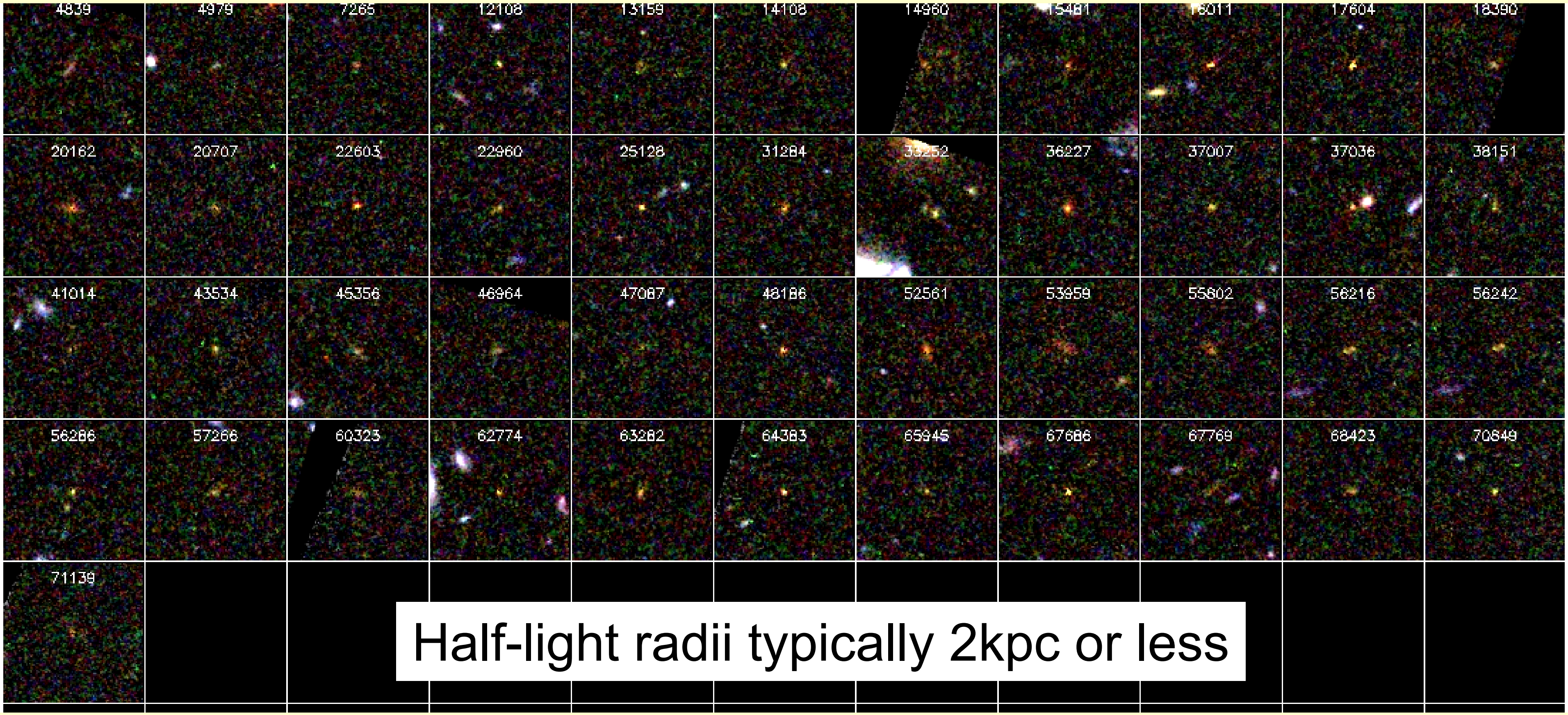
•UV emission from all detected objects that could be at z>5 is not enough to ionize the volume

•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

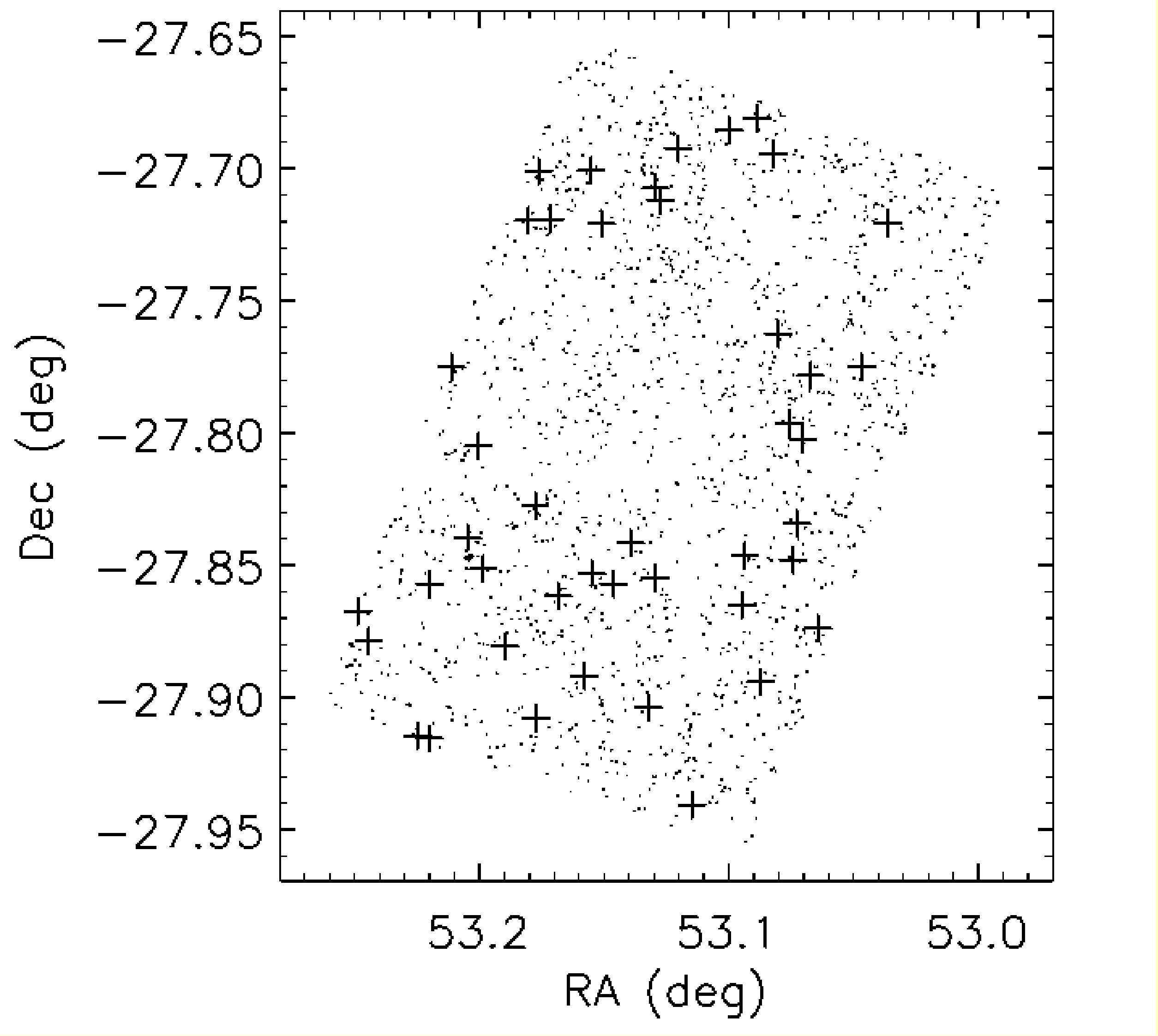


What do the high redshift galaxies look like in detail? GOODS ACS data



Sources undetected in 1Msec Chandra: $L<2x10^{43}$ erg/s

Are high redshift galaxies uniformly distributed?



Line emitters

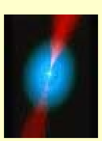
•NB imaging and follow-up spectroscopy by Rhoads and collaborators at $z=5.7$

•~12 emitters with $f>1.5\text{x}10^{-17}$ erg s^{-1} cm^{-2} .in 0.5 square degree through a 1% filter ->
•540 per square degree per unit redshift

•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



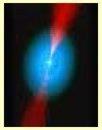
Theoretical and modelling results

•Pop III IMF must be top-heavy if WMAP is to be consistent with thermal history of IGM (Wythie & Loeb).

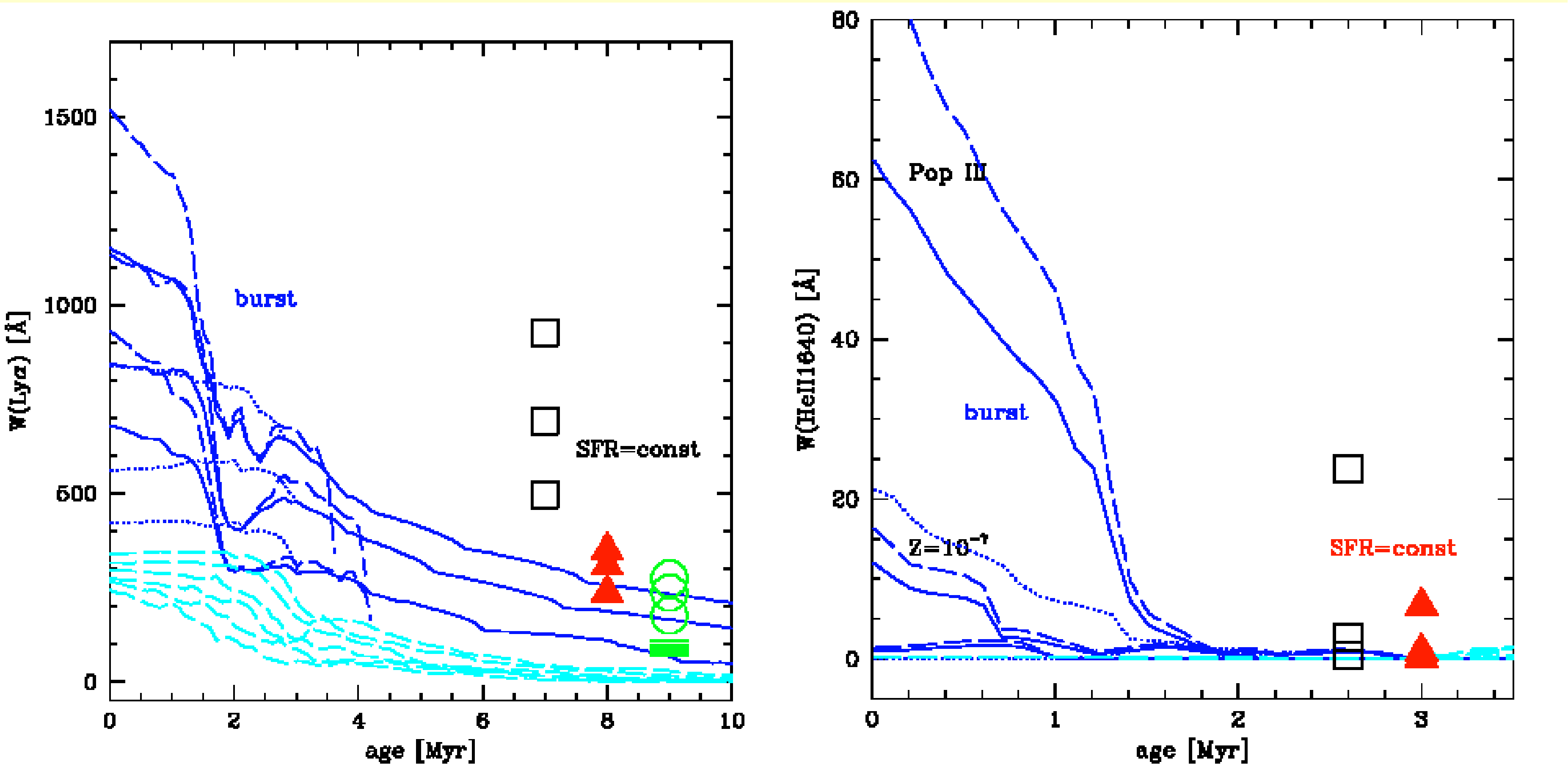
•Reionization & first star/galaxy formation is patchy (Barkana & Loeb). Faintest sources heavily absorbed by the surrounding IGM. A jump in the number of the faintest sources gives the real reionization epoch for that volume.

•Pop-III-> Pop-II at metallicity of 10^{-4} Solar.

•Pop III are high equivalent width Ly alpha emitters and are relatively strong in HeII for the first 1-2 Myr of life (Schaerer)

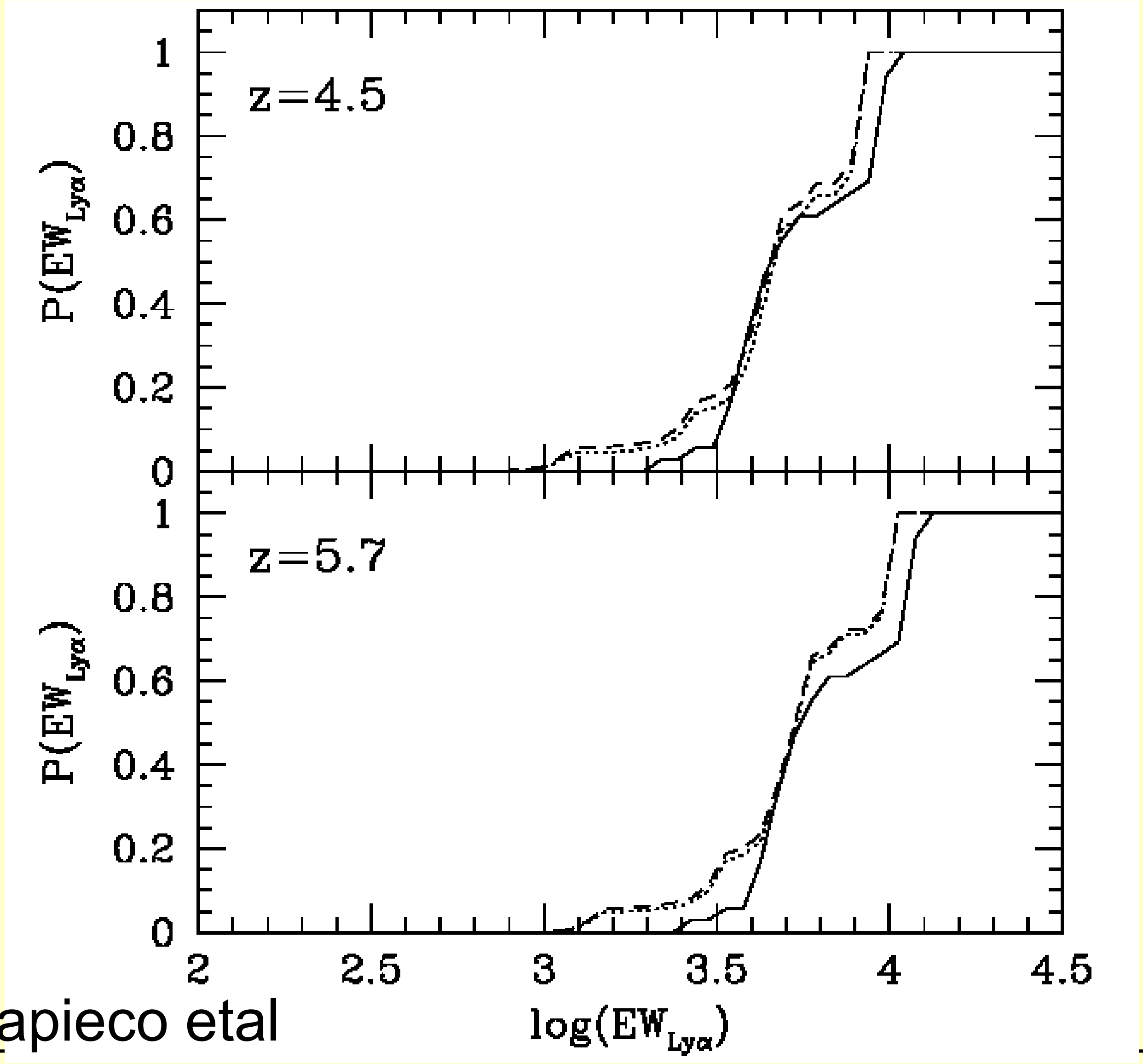


Theoretical and modelling results



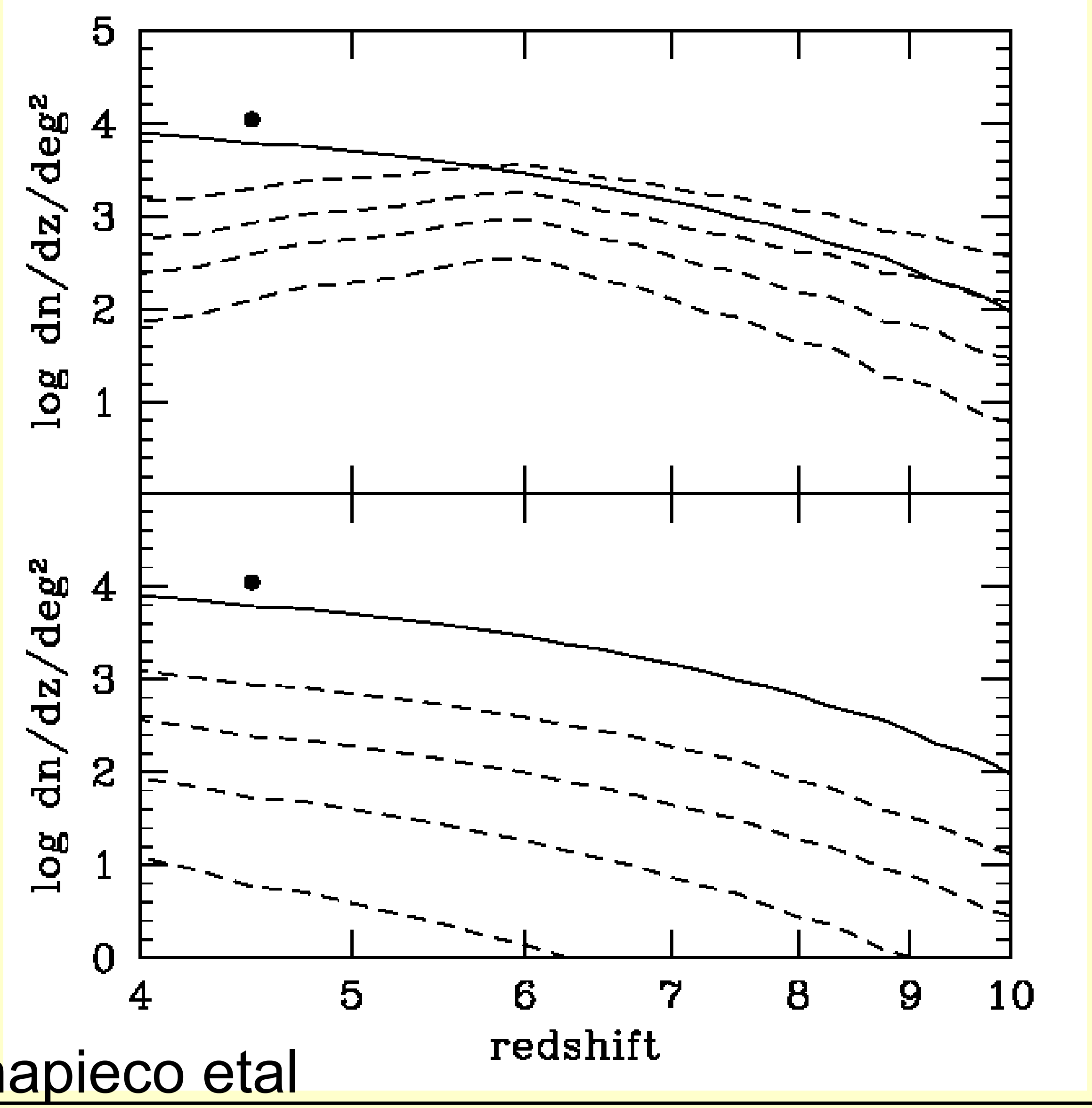
Schaerer

Theoretical and modelling results



Scannapieco etal

Theoretical and modelling results



Scannapieco etal

Strawman formation model

- What is the progenitor of the objects we see at z=5.8? Assume these have 10^8 Solar masses of Pop-II stars-> 10^5 Solar masses of metals.
- For now assume *all* metals produced by Pair-production Pop-III SNe end up in stars, so 10^3 Pop 3 objects of a few hundred solar masses each (this is wrong!!!).
- Formed over a period of 100 Myr (?), each lasts 0.1Myr (?), so at any time we see 1 pop-III object when looking at the z>6 progenitor of the dropouts we see at z=5.8.
- To detect this, we need to detect the Ly alpha emitted due to this single 100-1000 solar mass object at z>7:- 10^{36} erg/s, 10^5 times fainter than known Ly alpha emitters.

Strawman formation model

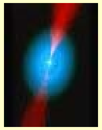
•Vary some of the parameters

•Say only 1 per cent of metals end up in the Pop-II stars, and say Pop-III starburst lasts 10 Myr,.

•This pushes luminosity up by 10^3. So luminosities of 10^{39} erg/s/cm^2

•Detectable by 100m in 100 hrs with 0.1 arcsec resolution.

•BUT… why should all of the metals seen in z=6 dropouts be produced by Pop-III objects?



100-m observations

•Direct detection of Pop-III from Ly alpha
→ line shapes, lum fn….. Look for HeII

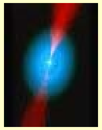
•Detection of break galaxies at z>6 as easily as z=5.5

•

•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

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



Conclusions

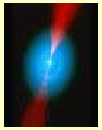
•Using the Lyman dropout technique is reliable way of finding star forming galaxies at z>5. Gets hard at z>5.8

•Star formation reionized the universe. Star formation in less luminous (less massive?) galaxies dominates.

•Star formation/ UV density decreases by factor 3-10 from z=3 to z>5 at bright end of LF.

•Individual sources small, r_h~2kpc. No X-ray emission brighter than that expected from strong starburst.

•The sources cluster, this will eventually help determine their nature and let us better understand early galaxy formation. Need a lot more area to do this properly.



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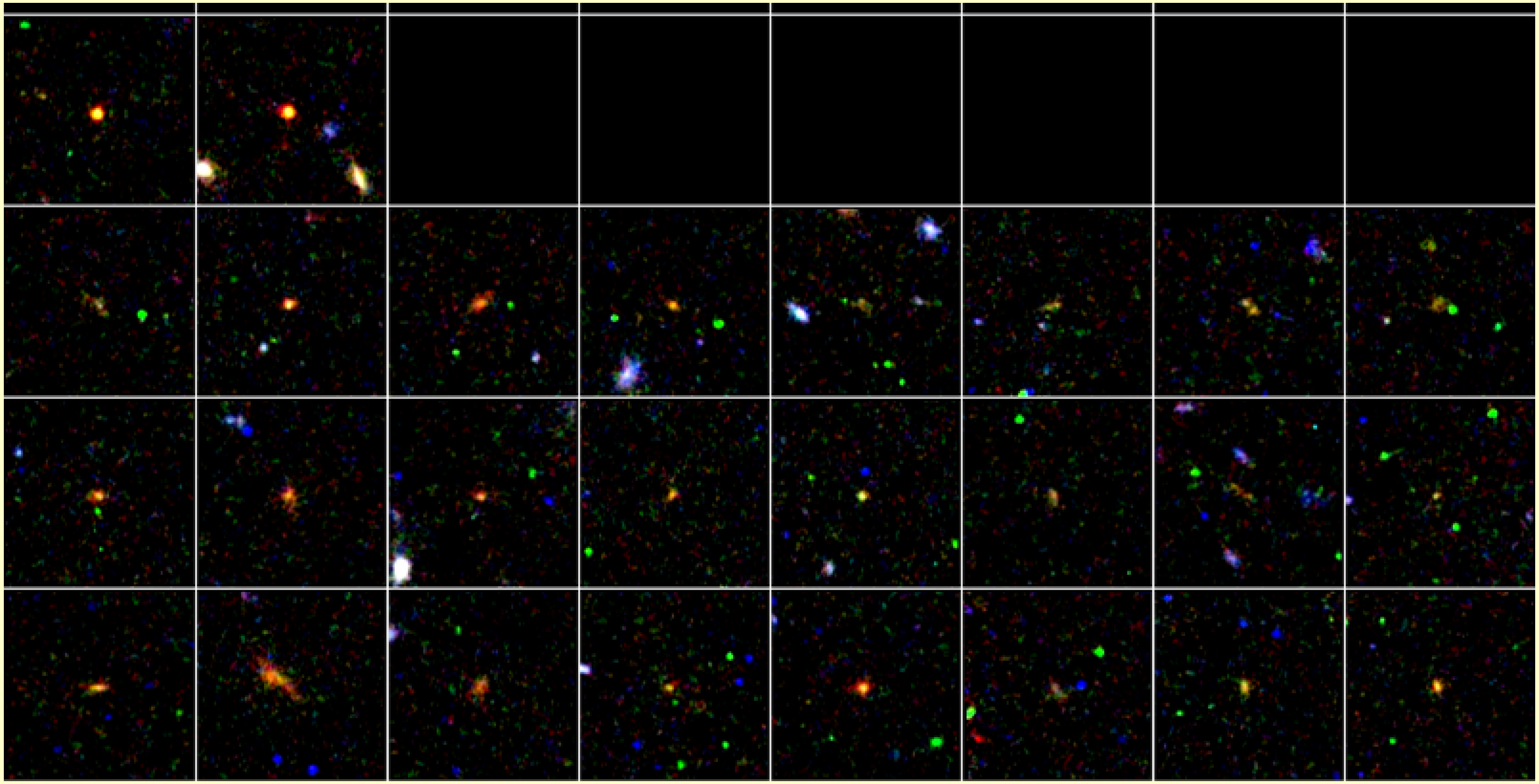
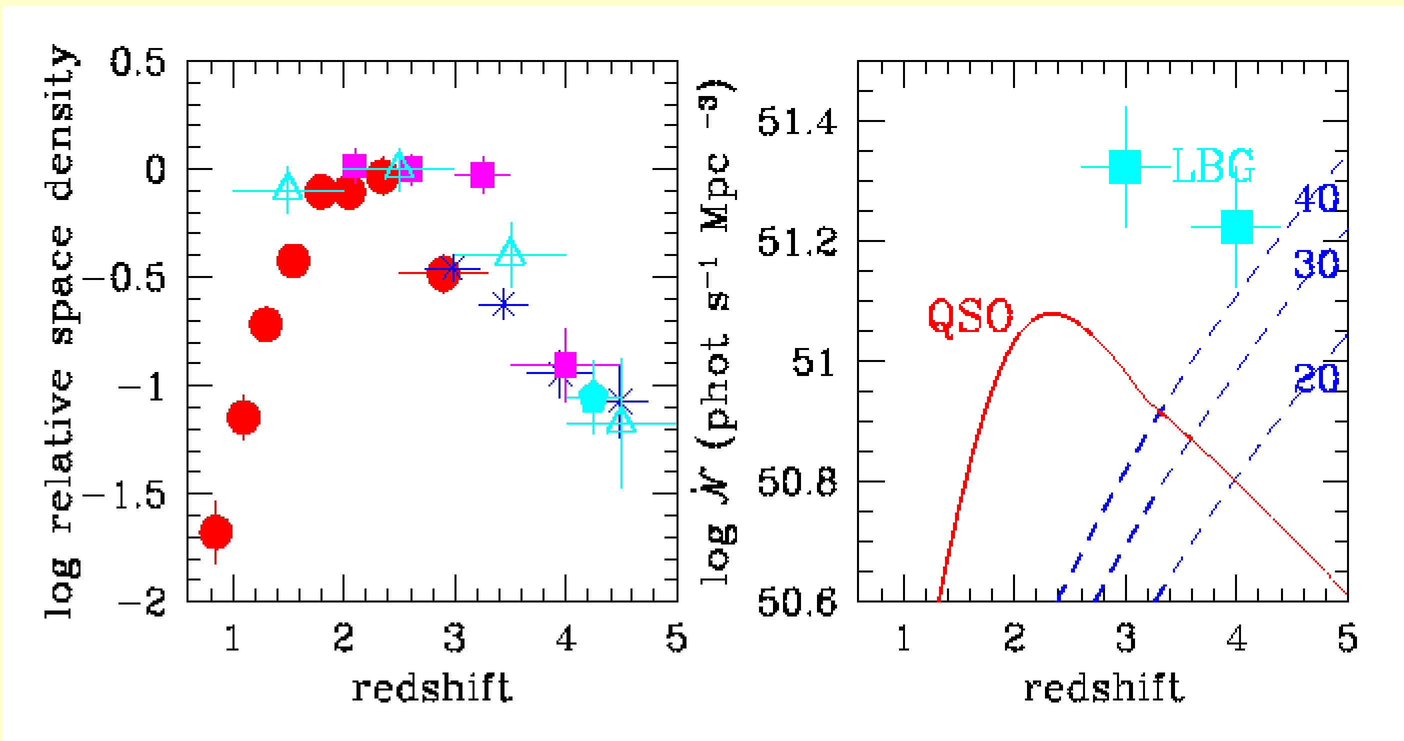
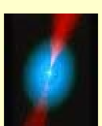


What causes the Reionisation
or
How do quasars and galaxies evolve at z>5?

(1) Quasars:





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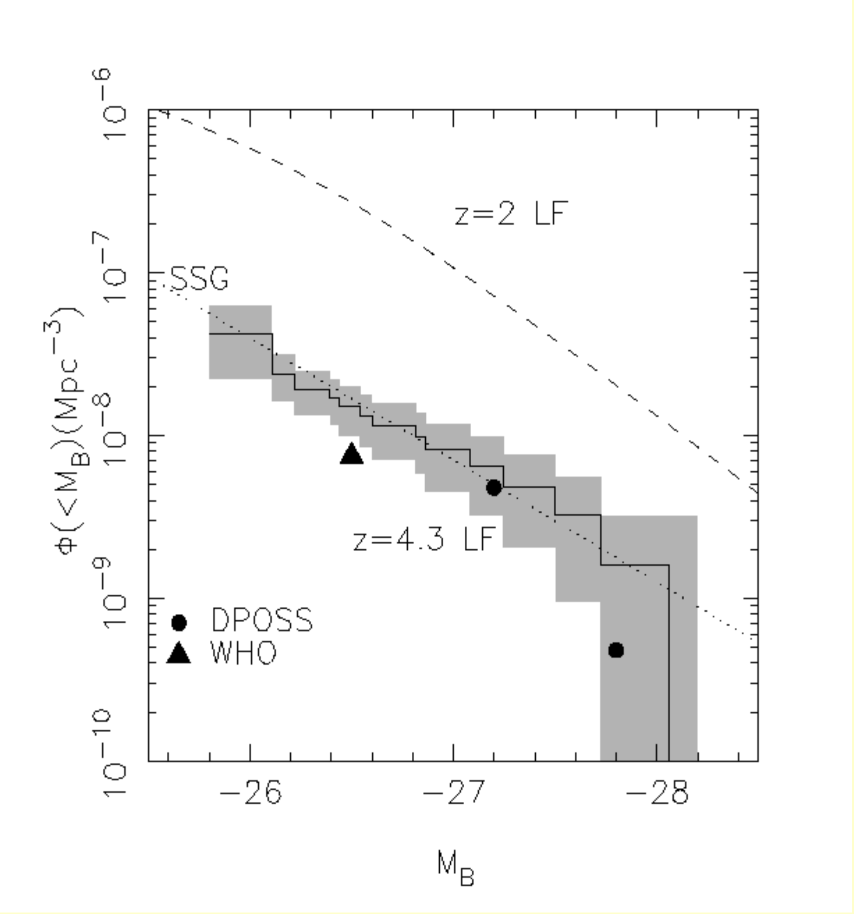

What causes the Reionisation
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(2) Galaxies: