Lyman alpha emitters from redshift zero to seven

or… can we use the properties of low redshift galaxies to improve our probes of high redshift galaxies?

Len Cowie

ASIAA: October 2011

Introduction

Very limited set of z>6 diagnostics: L break, GRB, L alpha, X-ray

In the absence of AGN all of these are measures of massive star formation and are expected to be proportional to the star-formation rate if the IMF is invariant.

But… all are metallicity dependent and may be expected to rise for younger galaxies

Only the L alpha is affected by the IGM properties so it's a natural diagnostic of reionization… particularly if ratioed to other diagnostics

- A neutral IGM may suppress the number of observed Lya emitters beyond the redshift corresponding to the end of the EoR and even subsequently the neutral fraction may leave an imprint on the observed flux

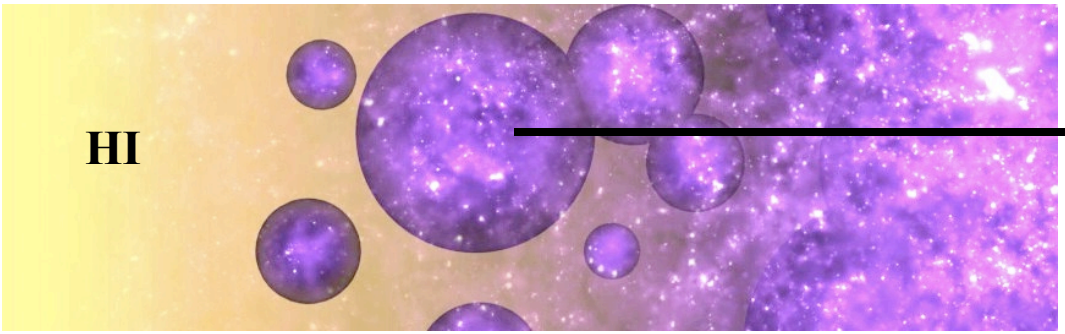


Illustration from Dijkstra

Lyman alpha line by K Nillson

SOME BACKGROUND: high redshift L alpha galaxies were predicted almost 50 years ago!

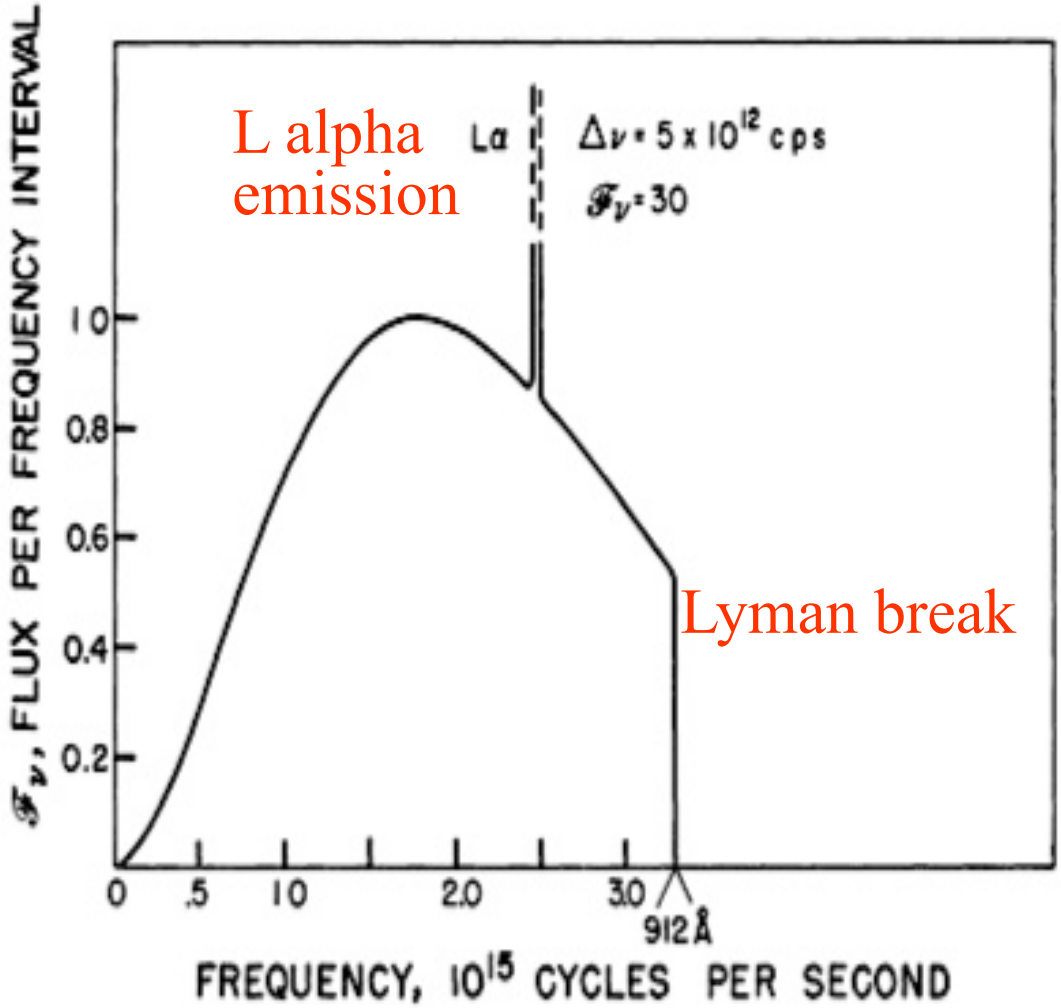
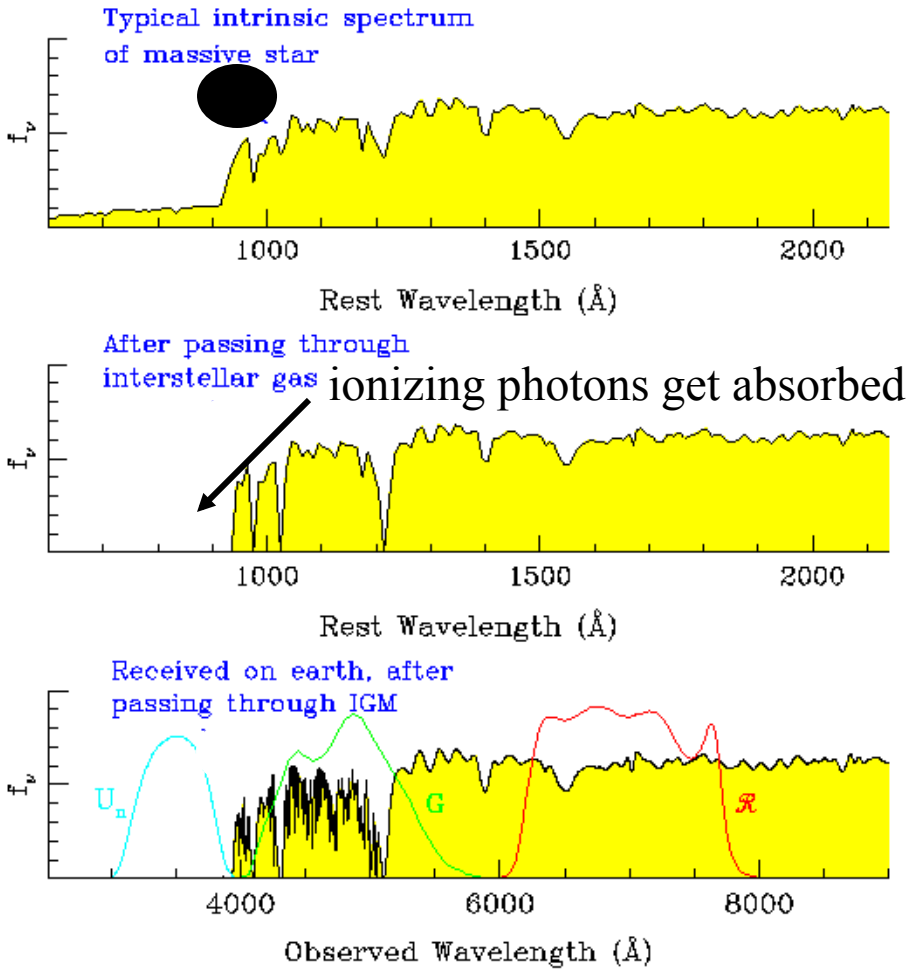
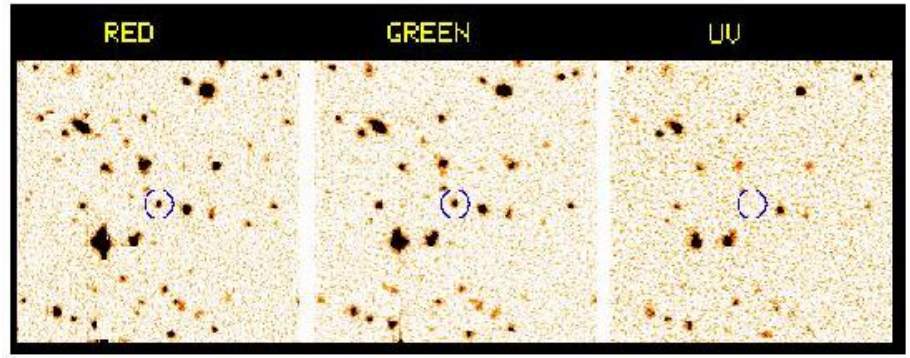


FIG. 3.—This curve represents semi-quantitatively the expected spectra of young galaxies in the extreme case that all photons of ionizing radiation have been converted to Lyman photons (§ II*e*). The expected Lyman-α flux is calculated with $\Delta\nu = 0.002\ \nu$ for the line.

Partridge & Peebles (1967)

Finding Star-Forming Galaxies





Lyman continuum discontinuity particularly powerful for isolating star-forming, high-redshift galaxies

IG gas becomes denser and more neutral as go to higher z, so higher effect of scattering photons out of galaxy spectrum

Steidel et al. 1999, ApJ, 462, L17

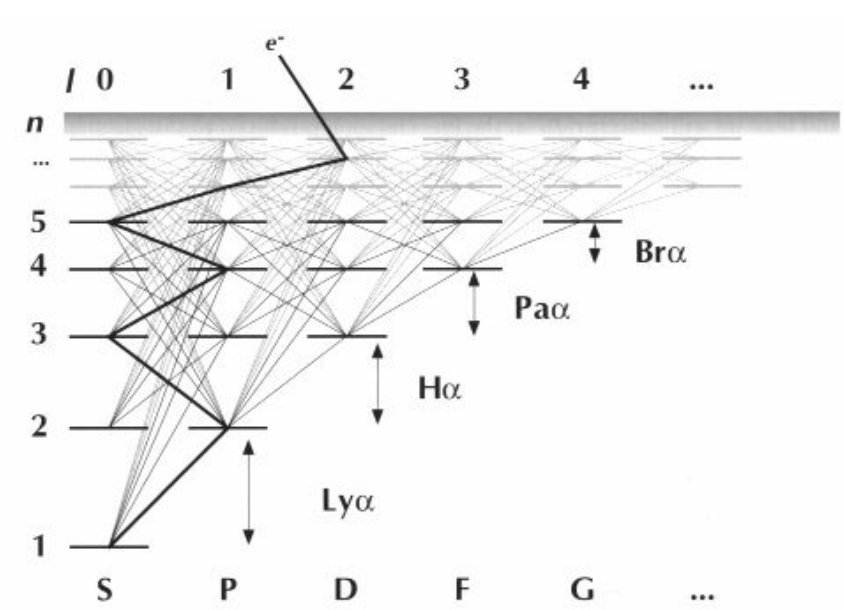
Steidel et al. 1999, ApJ, 519, 1

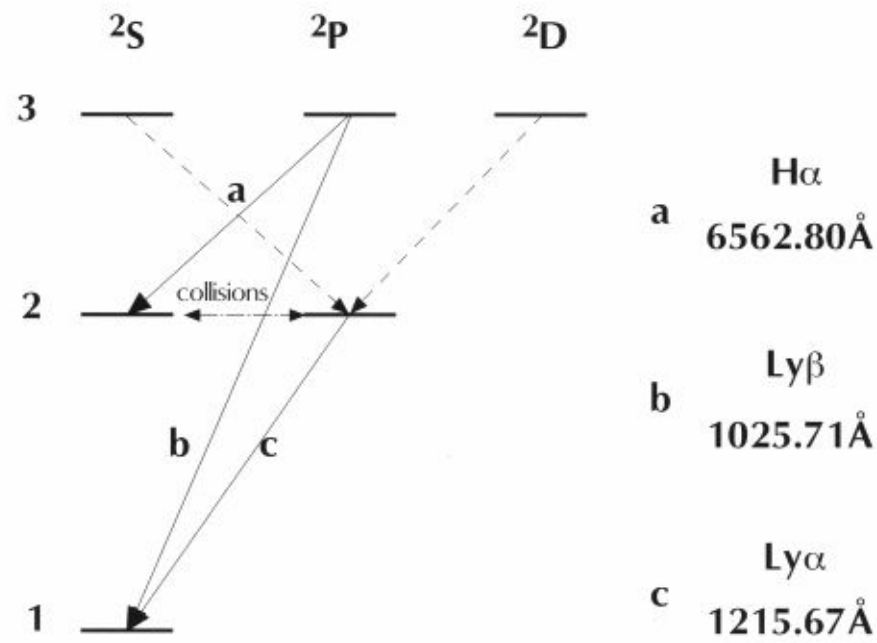
Steidel et al. 2003, ApJ, 592 728

Formation of L alpha line and continuum break are tightly related:

Intense UV radiation, ionising flux (>13.6 eV) is absorbed in
HII regions and diffuse ionised ISM
→ H, He recombination lines, [semi-]forbidden metal lines …
→ case B: **$L(Ly\alpha, H\alpha, \ldots) = c_l * Q_H$** and **$I(Ly\alpha)/I(Hn) = c(T,n_e)$**

2/3 of recombinations lead to the emission of a Ly alpha photon





Lyman alpha flux is a substantial fraction of the bolometric flux: should be easy!!!

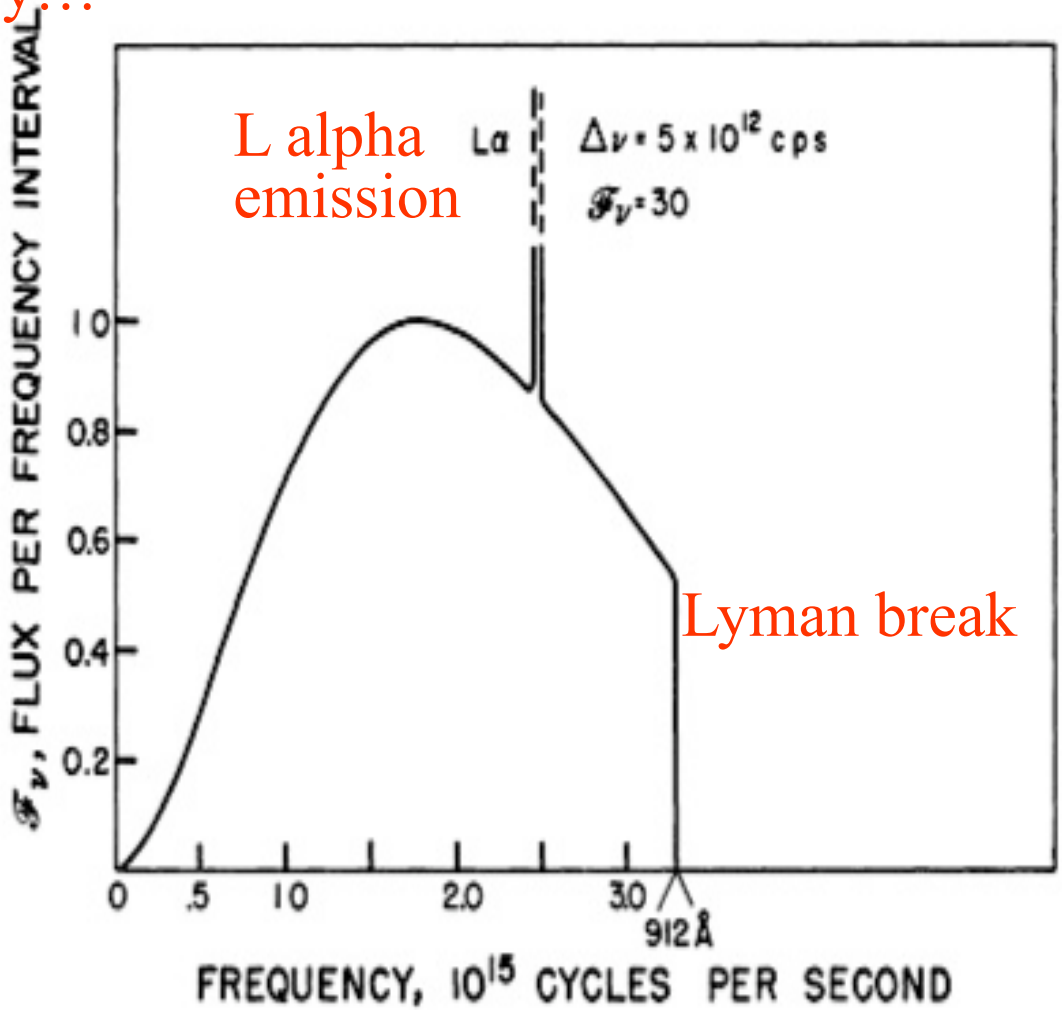


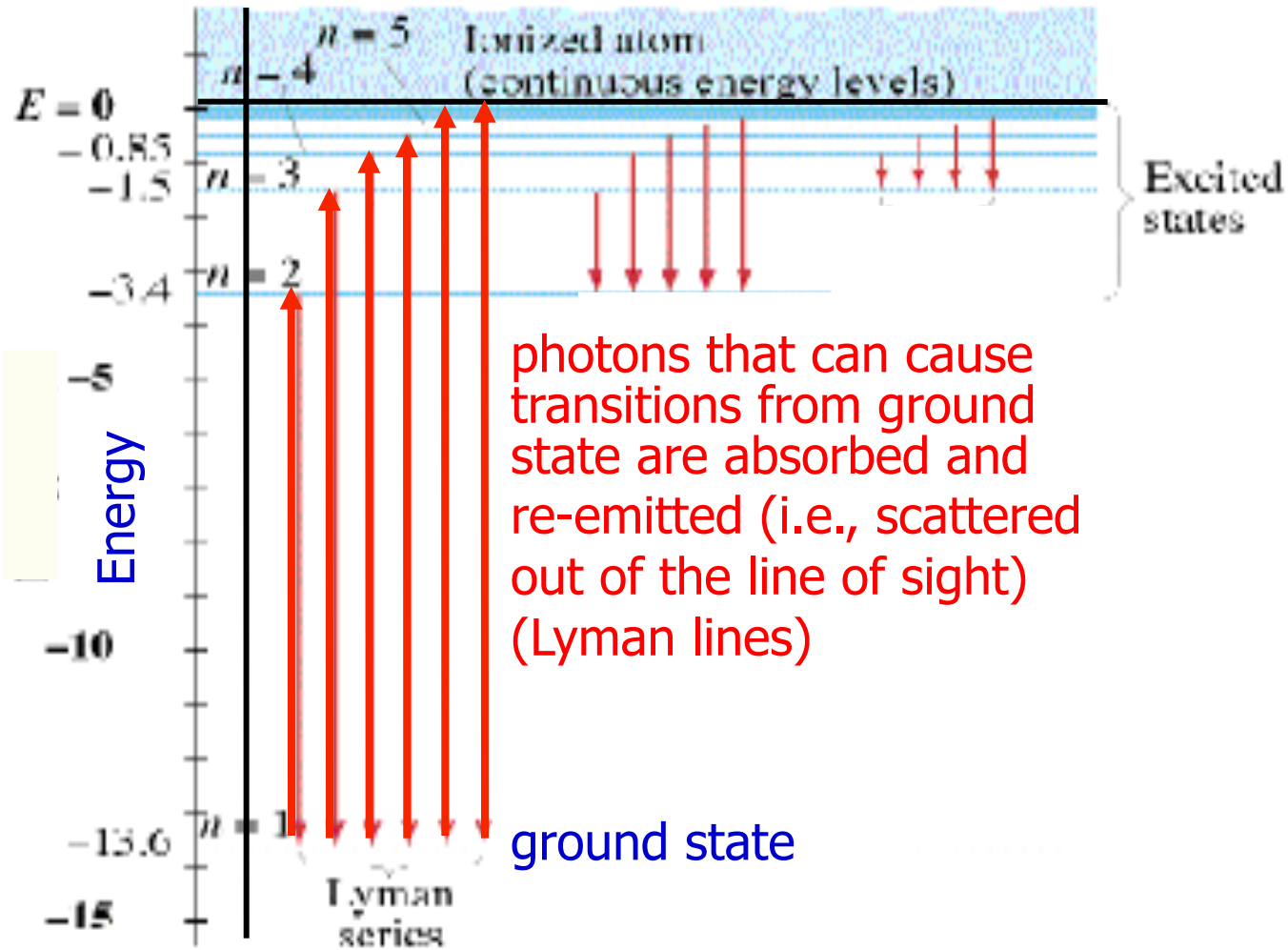
FIG. 3.—This curve represents semi-quantitatively the expected spectra of young galaxies in the extreme case that all photons of ionizing radiation have been converted to Lyman photons (§ II*e*). The expected Lyman-α flux is calculated with $\Delta\nu = 0.002\,\nu$ for the line.

Partridge & Peebles (1967)

Its harder than it looks however:

- In practice it turned out to be very difficult to find L alpha lines (indeed for a long time it was thought they wouldn't be found!)
- Weak/no L alpha was found in local blue compact galaxies in the 1980s with IUE (Meier & Terlevich 1981)
- First discovery of high redshift (z=3) LAEs was not until 1998 (Cowie and Hu 1998 ApJ 115 1319) almost 30 years after Partridge and Peebles
- Why is this?

Scattering of the Lyα Photons



photons that can cause transitions from ground state are absorbed and re-emitted (i.e., scattered out of the line of sight) (Lyman lines)

ground state

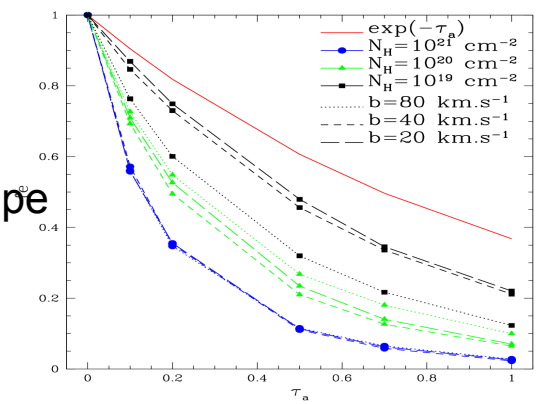
the problem

- Observable UV (>912 Ang): galaxies optically thin
- But they are optically thick in the Lyα line (N_{HI} >~ 10^{13} cm^{-2})

--> Complex radiative transfer within the galaxy determines the emergent line profile and Lyα transmission

- **The long path length makes it easy for dust to destroy Lyα photons**

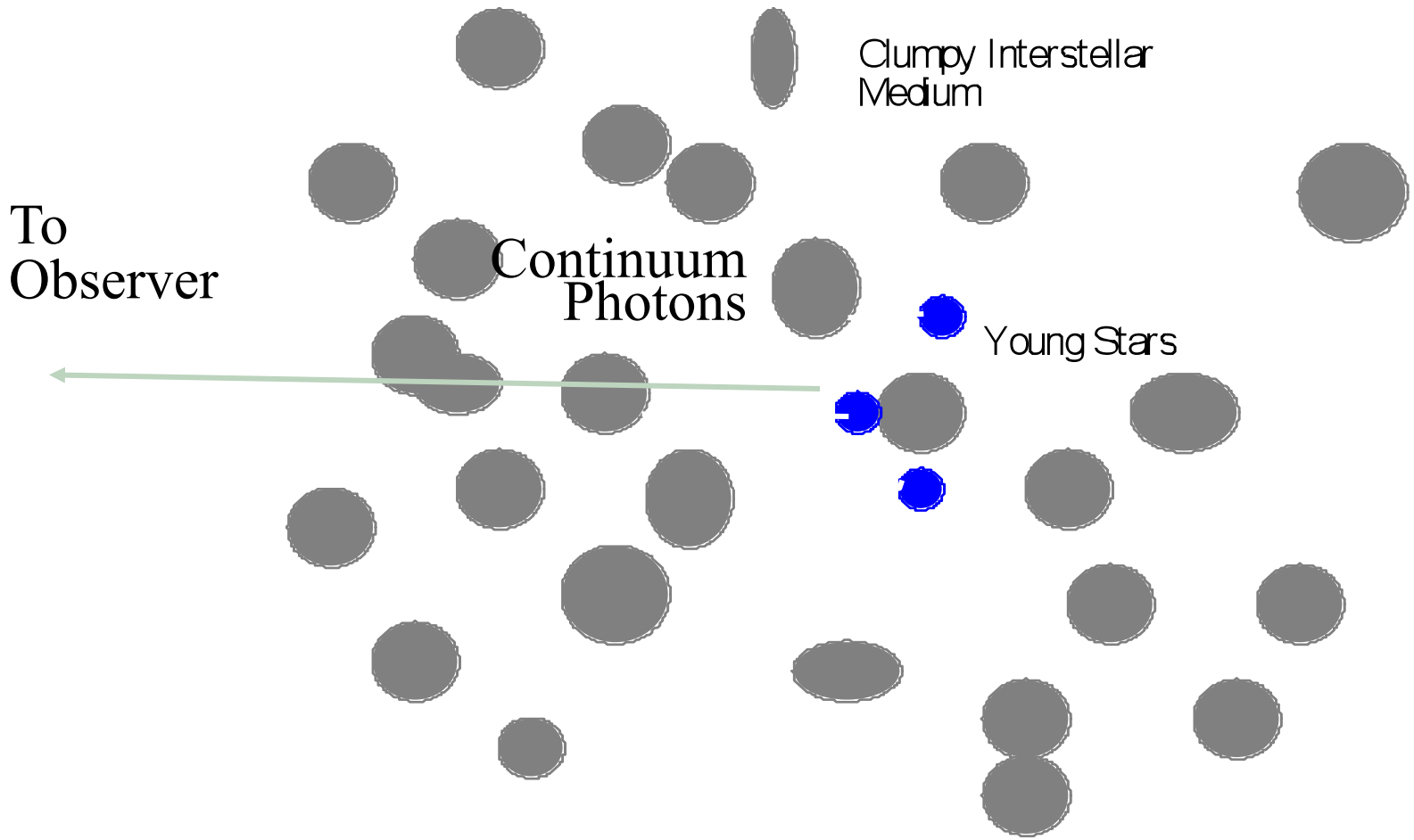
Lyα escape fraction



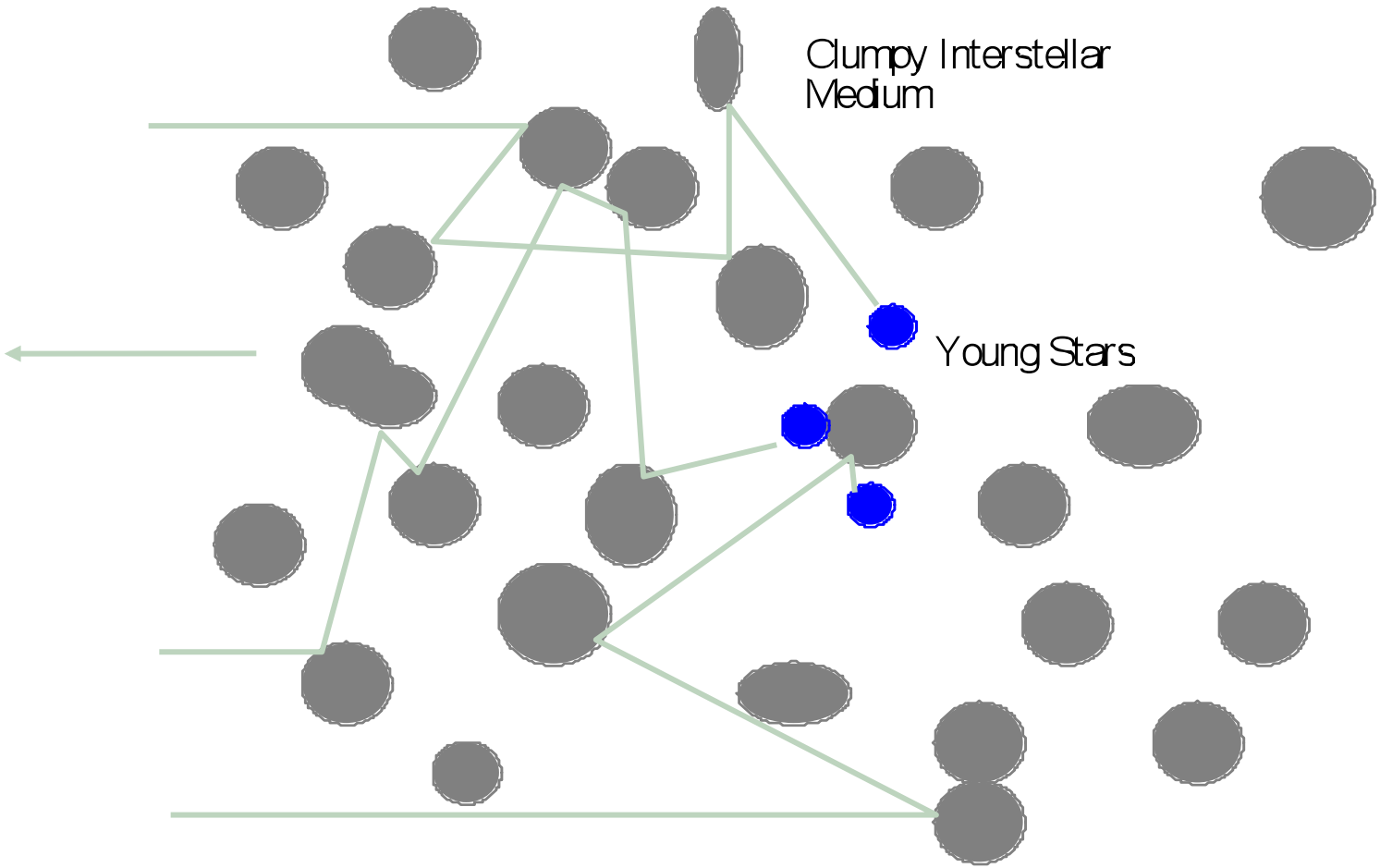
0 E_B-V 0.1

Plane slab (Salpeter) photons scatter in velocity space till they finally escape or are destroyed by dust.

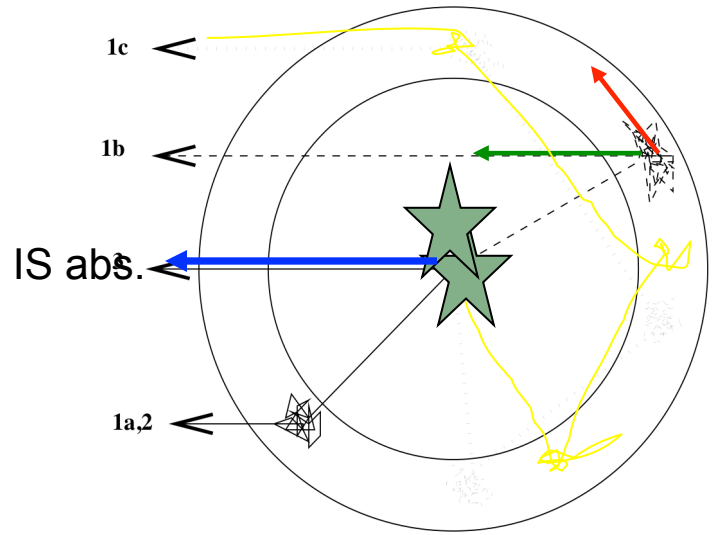
Continuum photons (>912A)



Lyman alpha photons:

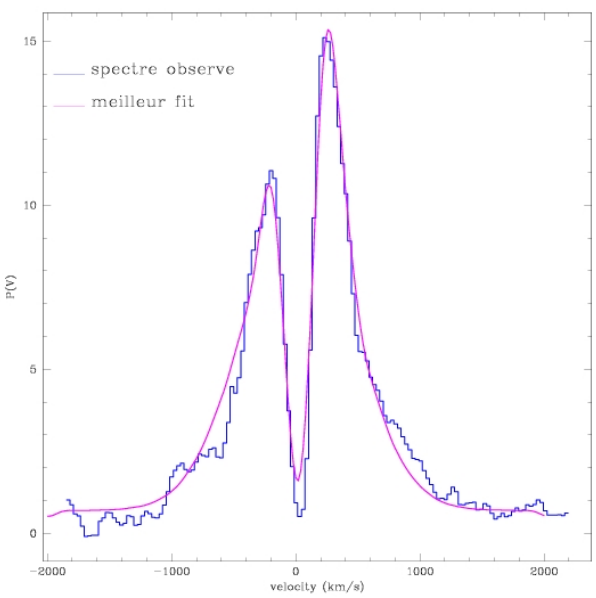


Lyα emission profiles depend sensitively on the kinematics

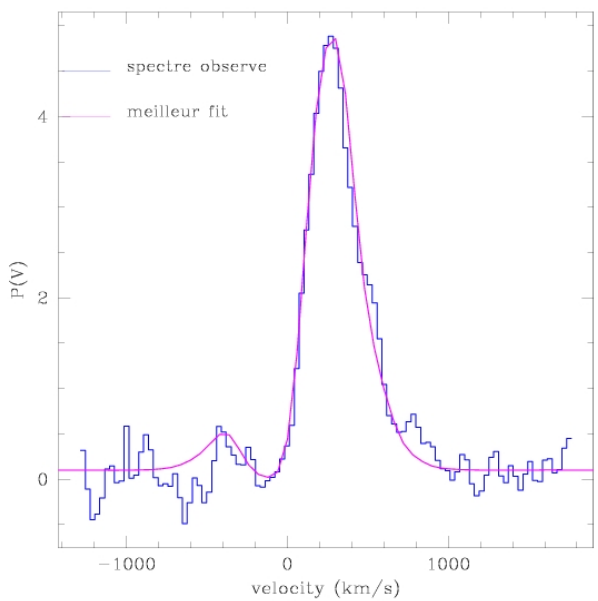


Verhamme et al. (2007)

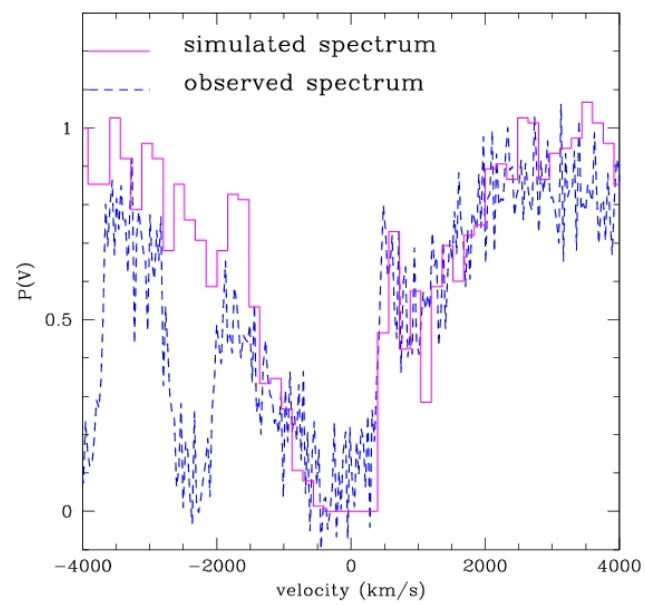
FDF 4691: ~ static



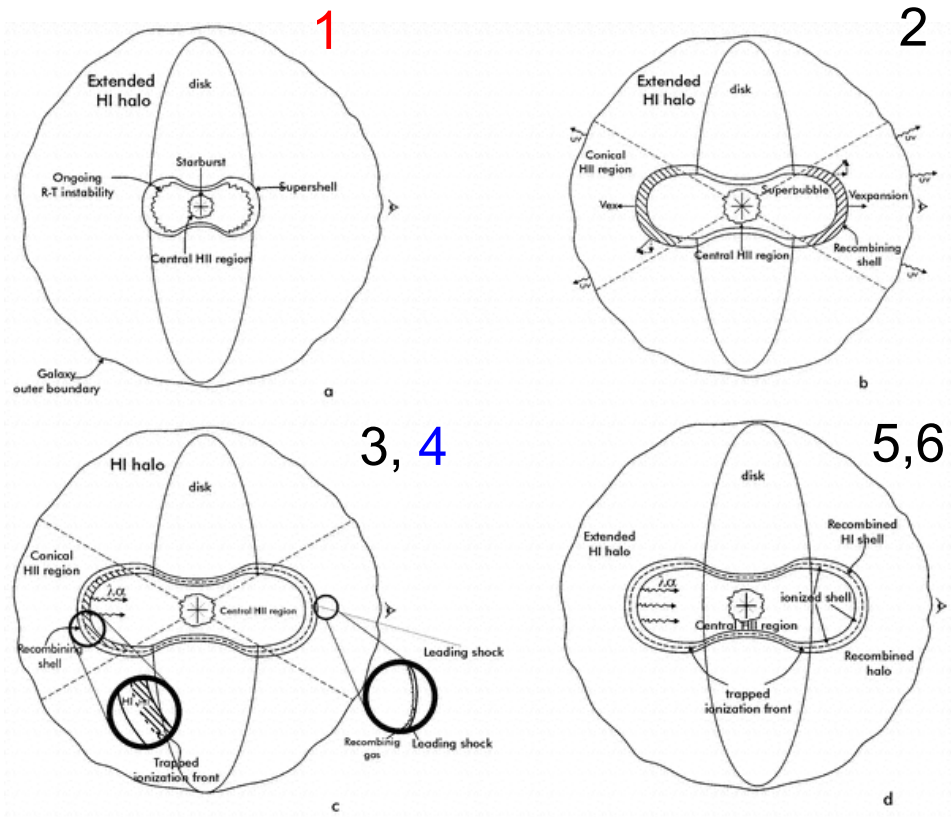
FDF 4454: v_{exp} ~220 km/s, low extinction

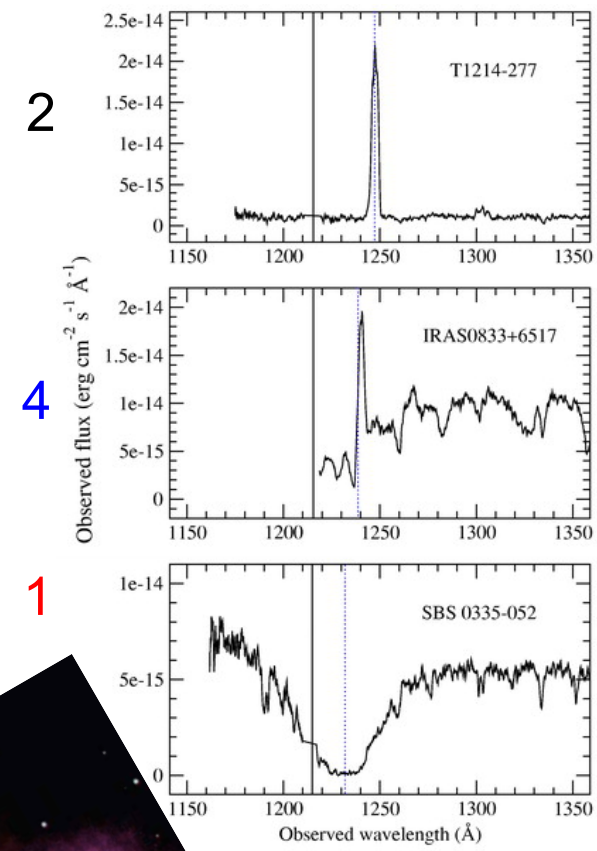


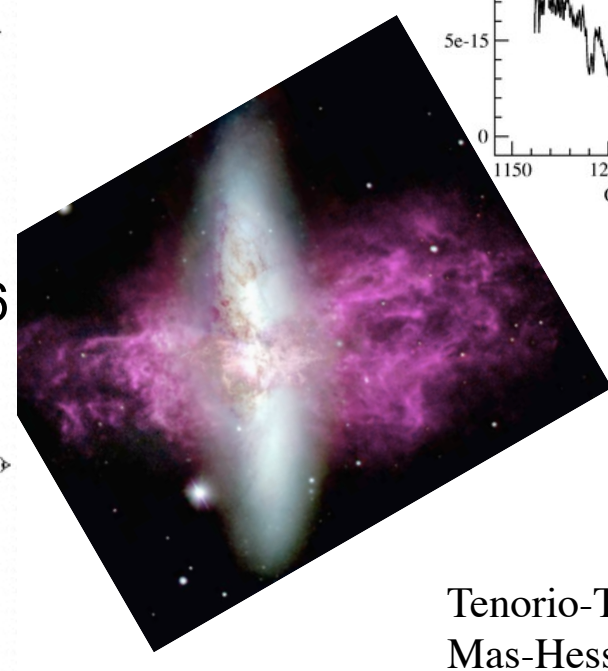
cB58: v_{exp} ~255 km/s, E_{B-V}=0.3



Complex kinematics and winds can make L alpha escape easier depending on the geometry....







M82

Tenorio-Tagle et al. (1999)
Mas-Hesse et al. (2003)

Scattering of the Lyα Photons

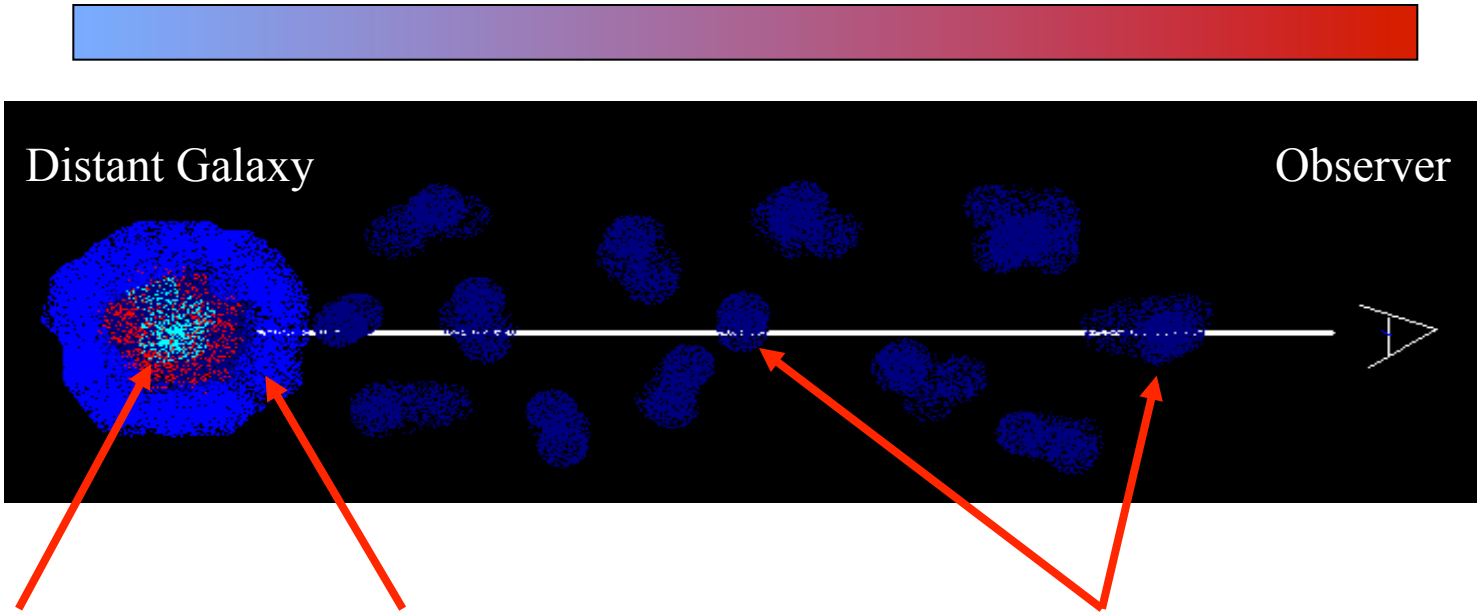
- The escape of Lyα light from high-redshift galaxies is determined by two processes:
  - the escape from the galaxy itself
  - the subsequent propagation through the neighboring IGM
- In the case of the escape from the galaxy, if no dust is present, scattering preserves number of Lyα photons
- However, if dust is present, since Lyα takes so long to get out (it undergoes many scatterings, which extends the escape path), it is likely to get absorbed by dust

- The level of destruction is dependent on the exact escape route, which depends on the structure of the ISM, so it is difficult to know how much escapes, making modelling very hard

- This was one of the reasons why people thought we would not find Lyα emitters!

- The shape and width of the final Lyα spectrum will also depend on the escape process, and observations and modelling of low-z galaxies suggest that there will be considerable variation in the output Lyα line

Hydrogen Absorption in the Spectra of Distant Galaxies



Stellar continuum emission

Absorption and emission by associated ISM and outflows close to rest-frame wavelength

⇒ Asymmetric emission-line profiles

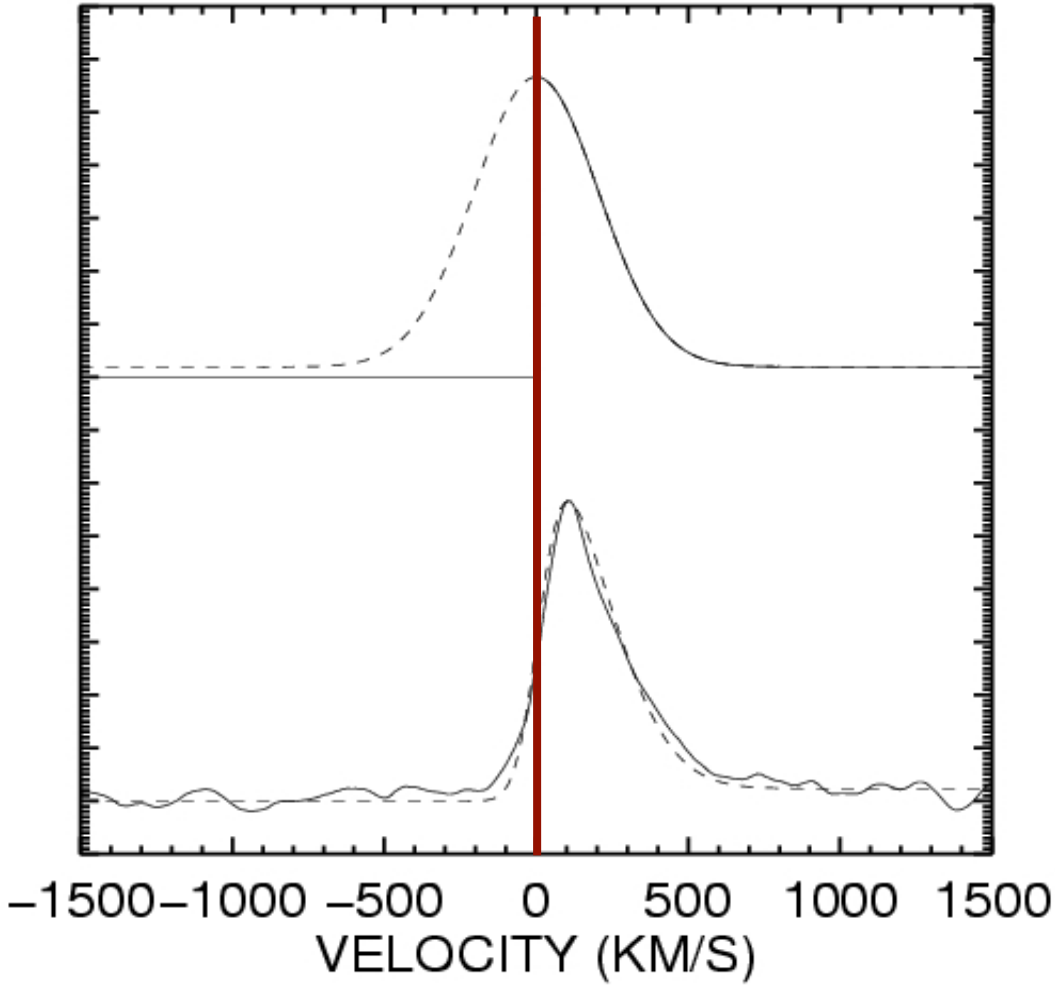
Absorption by clouds of HI in the IGM at $\lambda_{line}(1+z_{cloud})$

⇒ Forest of absorption lines

- The subsequent propagation of the Lyα line through the IGM also reduces the strength of the emitter and modifies its shape

- The blue side of the Lyα line scatters on the neutral hydrogen in the IGM

- The net effect is to truncate the shorter wavelength light in the line and hence leave a red component, but the exact effect and the fraction of the line which will be observed depend on numerous modeling parameters: infall velocity of gas to the galaxy, density profile, peculiar velocity, whether there is enhanced ionization around the galaxy from ionizing photons from the galaxy or its neighbors



Initial symmetric profile broadened by the scattering as the Lyα photons escape from the galaxy; thus, width not a good measure of the kinematics of the galaxy

Observed profile truncated by scattering in the associated ISM

- Variations in the intrinsic Lyα line profiles may be important

- In particular, redder and wider galaxy Lyα profiles will be more likely to produce observable Lyα emission lines after the subsequent IGM propagation

- These processes will determine both the output shape of the line and the distribution of line widths; measurements of these can constrain the modeling

- Might also expect a progressive reduction in the fraction of galaxies having strong Lyα as we move to higher neutral fractions in the IGM at higher redshifts

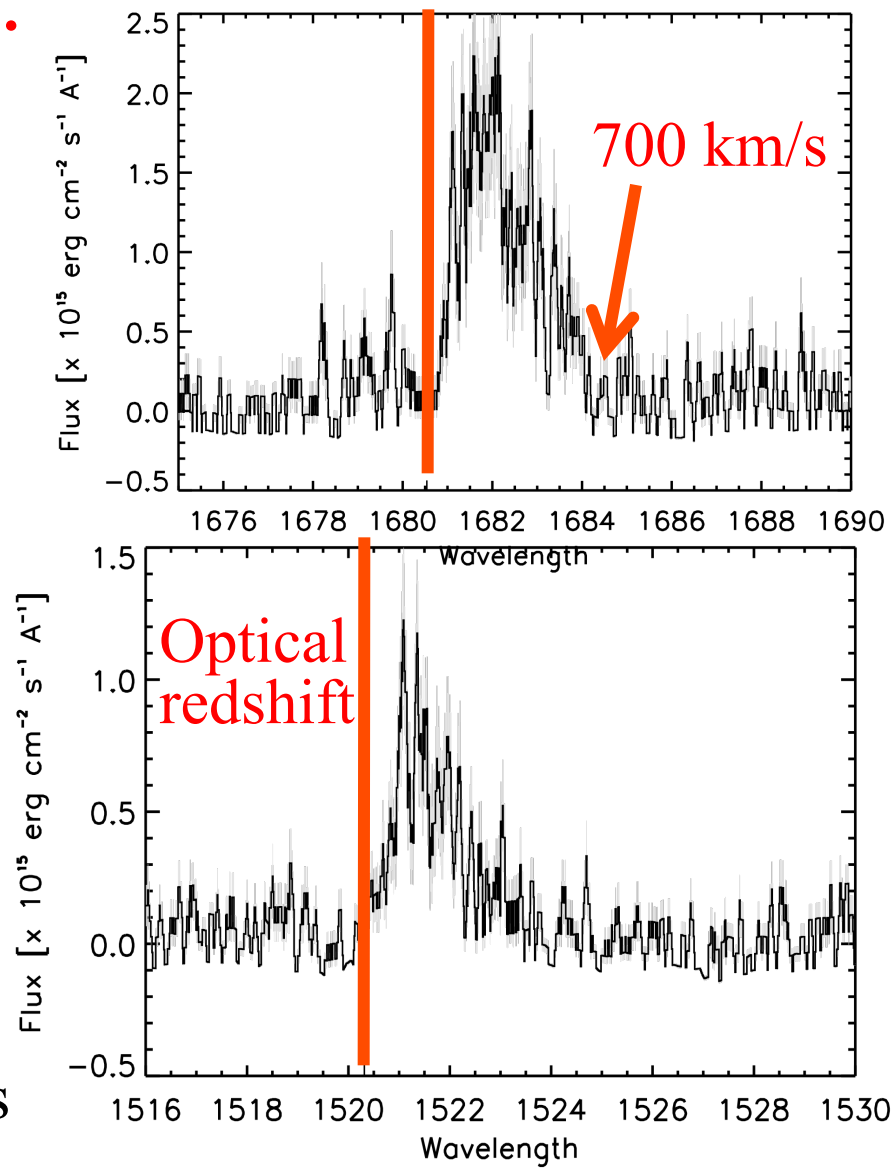
Complicated however…

Lyman alpha line emerging from the galaxy is most often redshifted , sometimes complex and multi-peaked, occasionally blue shifted

How it is affected by the IGM depends critically on the form of the output line from the galaxy but also on the local structure and ionization of the IGM gas and the galaxy proper motion.
(e.g. Zheng et al. 2011)

In z=0.3 LAEs line shifts are not large enough to escape the damping wings at full neutrality at z=7 (needs about 1000 km/s) before EOR so almost all LAEs may be suppressed.

Z=0.3 L alpha profiles:
COS on HST… 2 of 25 profiles



Scarlata et al. 2011

2-3 D studies of Lyα in nearby starbursts

Imaging (ACS)+ kinematics (Hα Integral Field, Lyα long-slit STIS)

ESO 350-IG038:

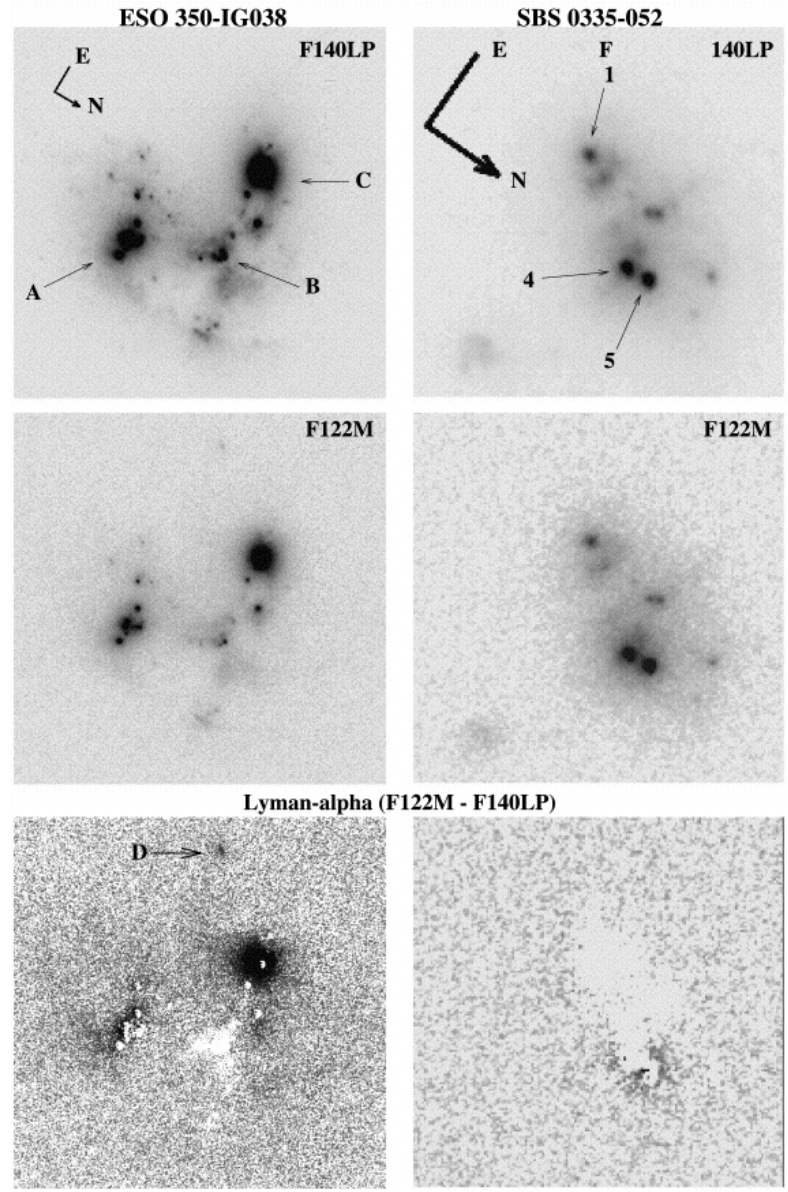
knots B + C: similar, high extinction

→ one shows emission other not.

Kinematics, NOT DUST, dominant

SBS 0335-052:

only absorption seen. If dust affects Lyα, it must do so at small scales (1 pixel ~ 6-9 pc!)



Kunth et al. (2003)

Lessons from nearby starbursts

- W(Lyα) and Lyα/Hb < case B prediction !
- No clear correlation of Lyα with metallicity, dust, other parameters found.
- Strong variation of Lyα observed within a galaxy
- Lyα scattering « halo » observed
- Starbursts show complex structure (super star clusters + diffuse ISM); outflows ubiquitous

Lyα affected by:

- **ISM kinematics**
- **ISM (HI) geometry**
- **Dust**

Precise order of importance unclear!

Shaerer 2008

So…..

Most galaxies are optically thick to ionizing photons… getting some out requires odd geometry

The escape of L alpha is also dependent on the geometry, the kinematics, the internal micro-structure and the dust content

We need to empirically calibrate the escape of the ionizing continuum and the L alpha photons

This is all most easily done with low redshift observations where we have lots of other information

Low redshift LAEs: can they be used as templates for high redshift LAEs?

- We would like to find large homogeneous samples of low redshift galaxies that might be broadly similar to the z=6-7 LAEs.

- Use these to understand how LAEs work in detail.

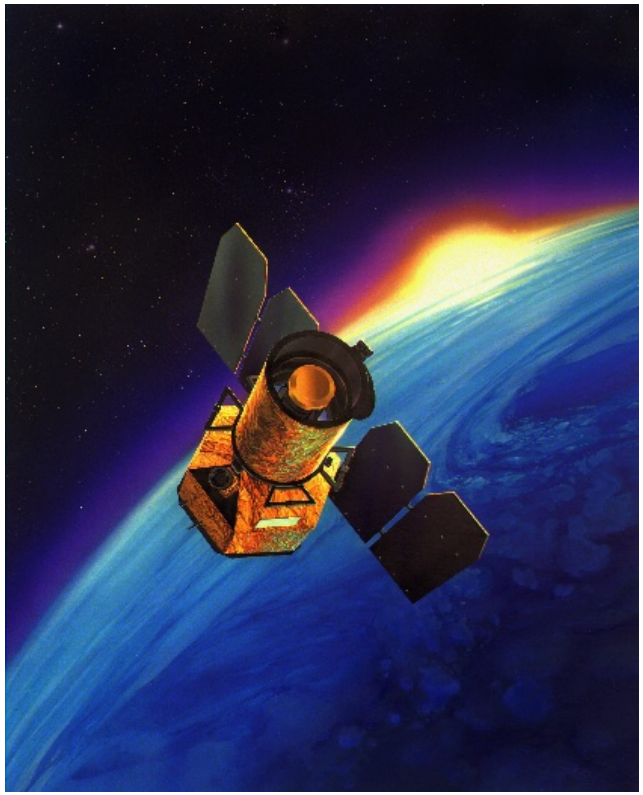
- Up until a few years ago there was no way to do this.

So how do we find low redshift Lyα galaxies?

This is where GALEX came in…

- GALEX: Galaxy Evolution Explorer
- Small explorer NASA mission, led by Caltech
- LAUNCH: April 28th, 2003

- The first all-sky imaging and spectroscopic surveys in the space ultraviolet
- Wavelength: 1350-2750 A



GALEX Lyα emitters

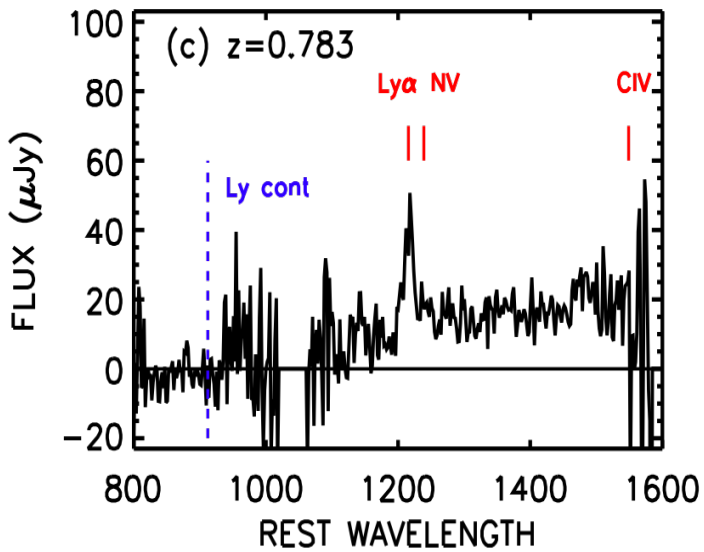
- Deharveng et al. (2008) showed that a few percent of the GALEX spectra have emission lines and can be identified as Lyα emitters. (The precise fraction depends on the field depth.)

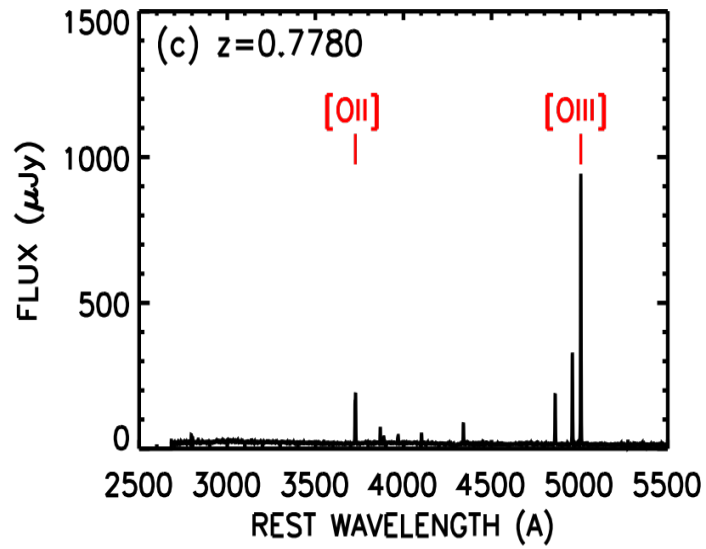
- These are divided between objects which only show a single line (assumed to be Lyα) and those which show high excitation lines and which are clearly AGN.

Lyα emitters

- Can find low redshift (z = 0.2-1.25) LAEs using GALEX grism spectroscopy (Deharveng et al. 2008, Cowie et al.,2010, 2011, Barger and Cowie 2011, Wold et al. 2011)
- About 80 z~0.3 LAEs, 84 z~1 LAEs
- Combine with optical spectroscopy (and other data like X-ray) to determine the properties of the LAEs, particularly the extinction and **metallicity. (**Atek et al. 2009, Scarlata et al. 2010, Finkelstein et al. 2010,2011, Cowie et al. 2010,2011**)**
- Compare the population with the high-redshift samples to see how similar they are.

Low redshift LAEs (z=0-1)

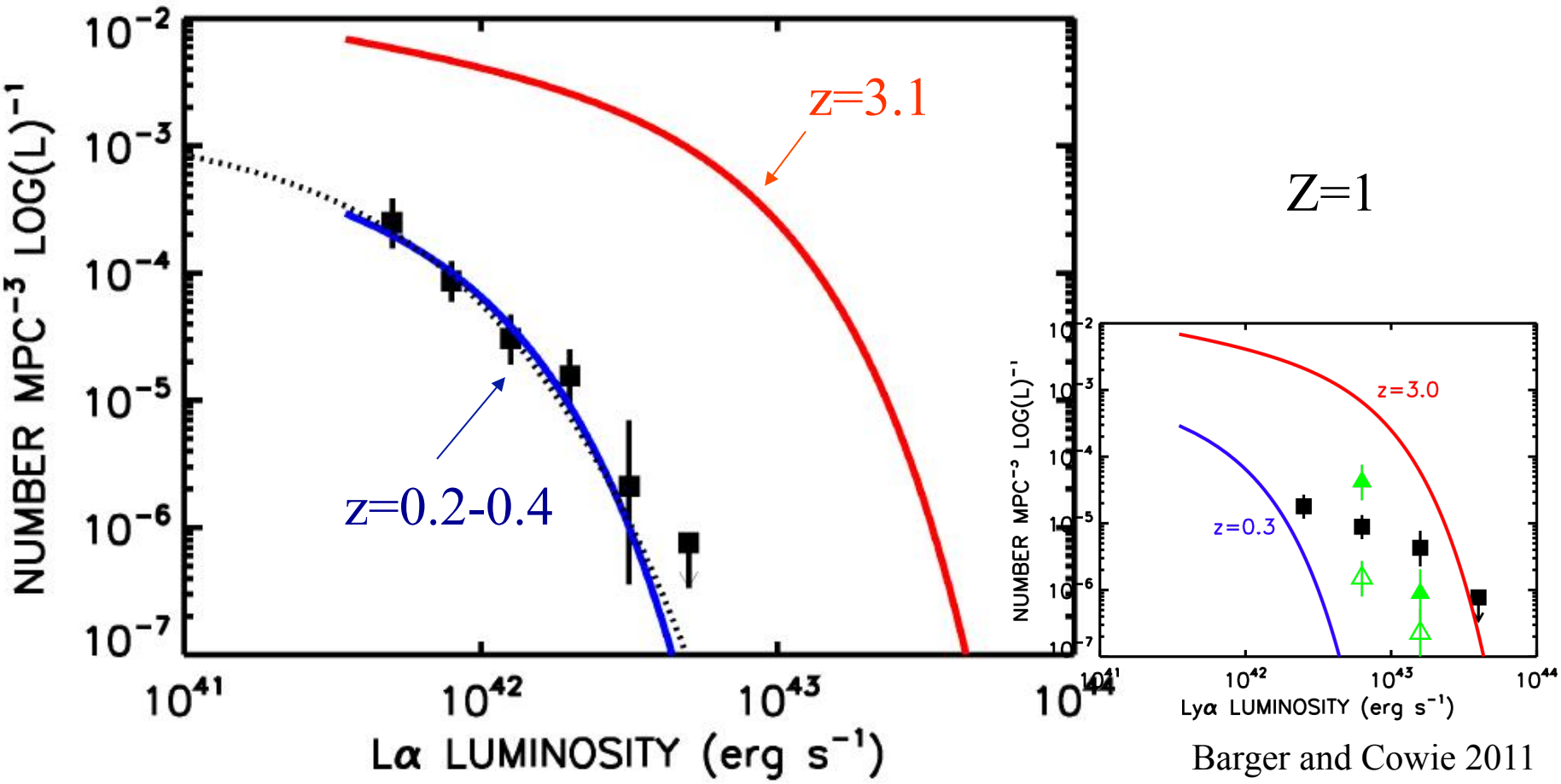




Found with the grism spectra from the GALEX satellite: followed up with optical spectroscopy

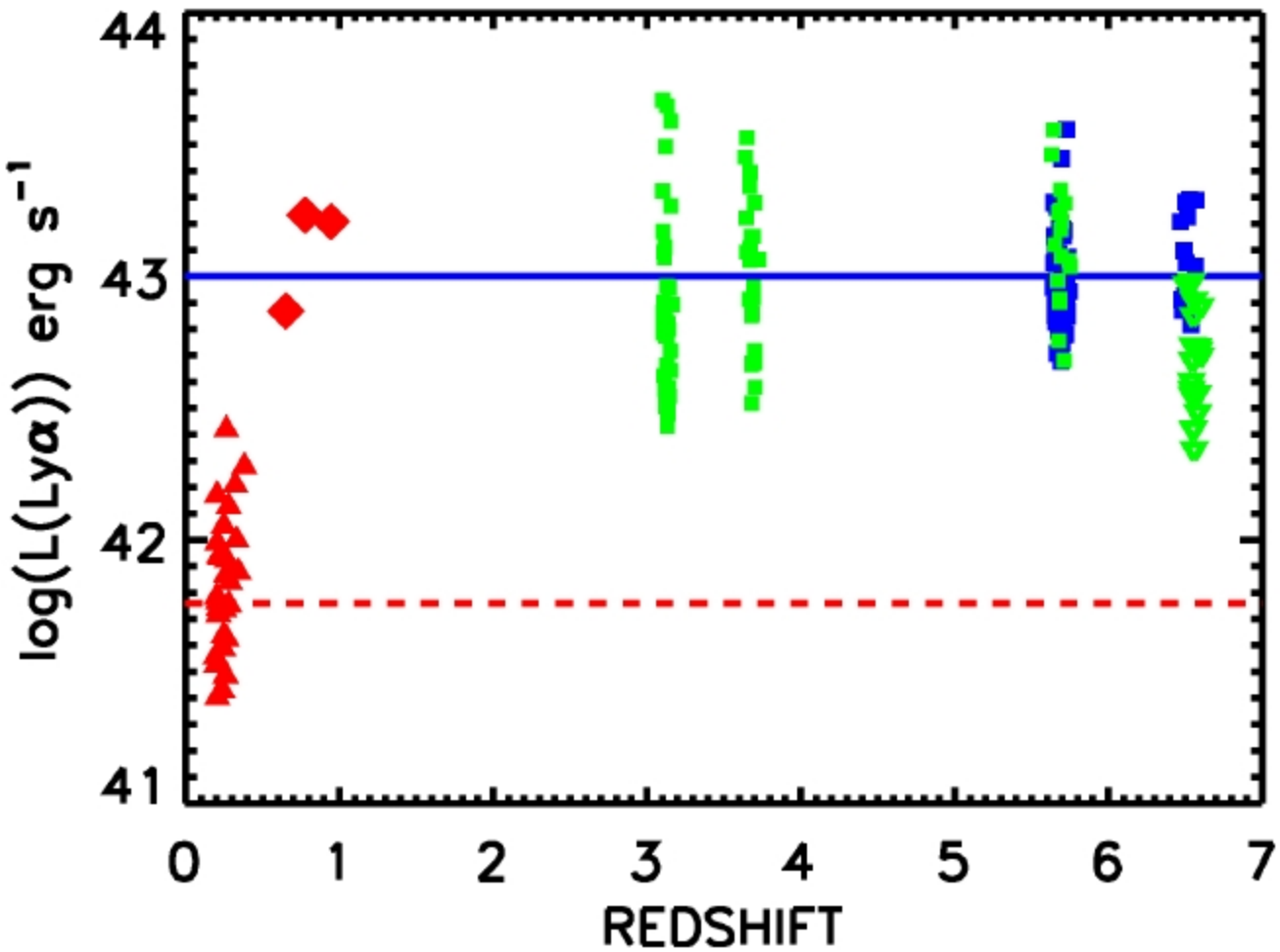
z = 0.2-0.4 LAE LF vs. z = 3.1 LAE LF

Drop in luminosity density by factor 50-60



Barger and Cowie 2011

High luminosity Lyα emitters only appear at ~ z = 0.8



Cowie et al 2011

Low redshift LAEs: can they be used as templates for high redshift LAEs?

- We need to go to the z=1 samples to get LAEs that are luminous enough to be high-z analogs.
- However, most of the current work is on the z=0.3 samples
- What does this z=0.3 work tell us about how LAEs are drawn from the underlying UV continuum selected population. (LBG analogs)

Z=0.3 LAEs: (Cowie , Barger and Hu, 2011 ApJ 738 136)

We compare LAEs with objects with the same UV continuum luminosity but without Lyman alpha in emission. (Use standard rest frame EW(L alpha) >20 A to distinguish).

In particular are LAEs primarily:

Old, dusty and red (e.g. Shapley et al. 2001, Lai et al. 2008 ,Finkelstein et al. 2009, Kornei et al. 2010)

OR:

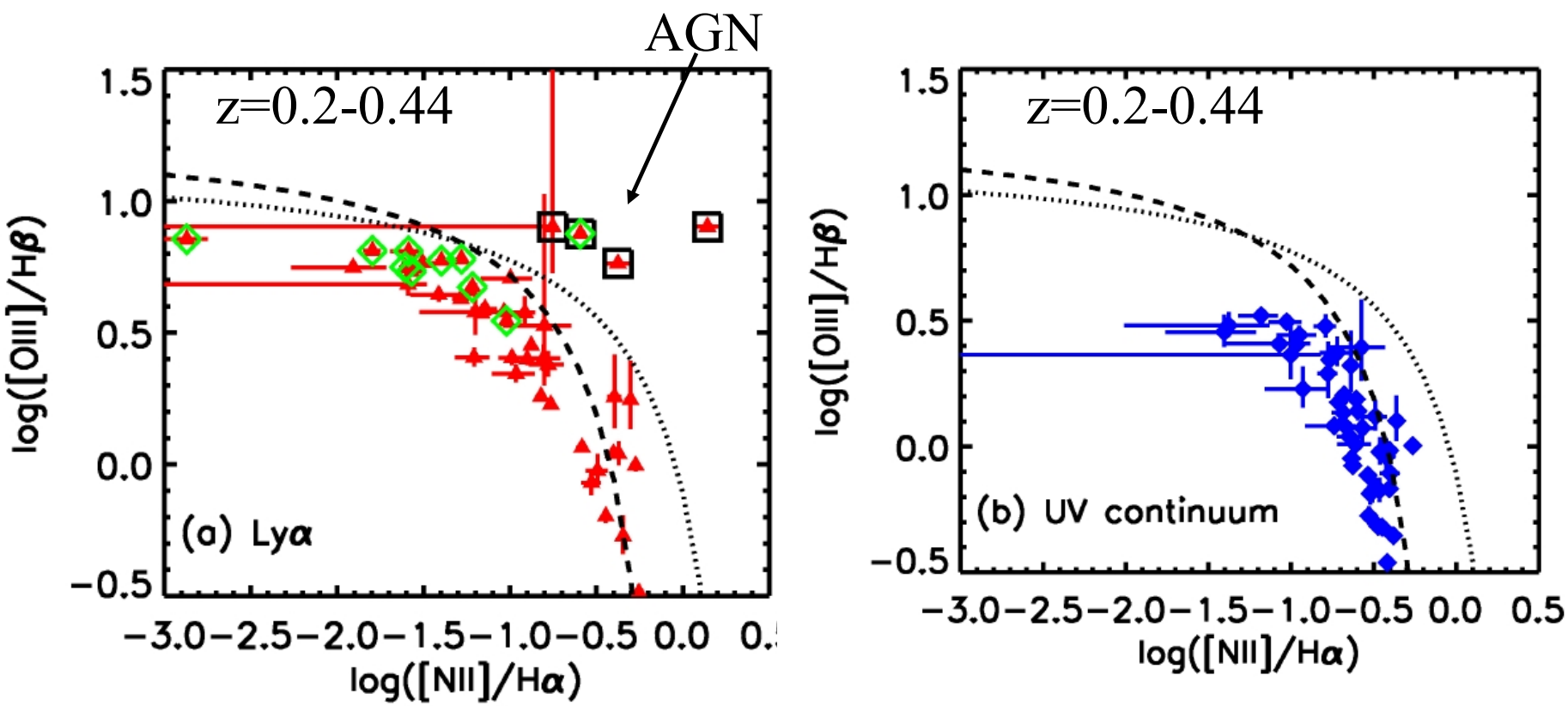
Young, low metallicity and low extinction (e.g. Hu et al. 1998; Nilsson et al. 2007; Gawiser et al. 2007)

This has been surprisingly controversial and it has major implications for our understanding of the high z LAEs

It also has implications for finding young low metallicity galaxies.

Lyα selected galaxies have much lower NII/Hα than other UV galaxies at the same redshift

They are lower metallicity



Green triangles have strong [OIII]4363

Cowie Barger and Hu 2011

Red=LAE
Blue=UV continuum

Low z LAEs are small and have low metallicity and low extinction

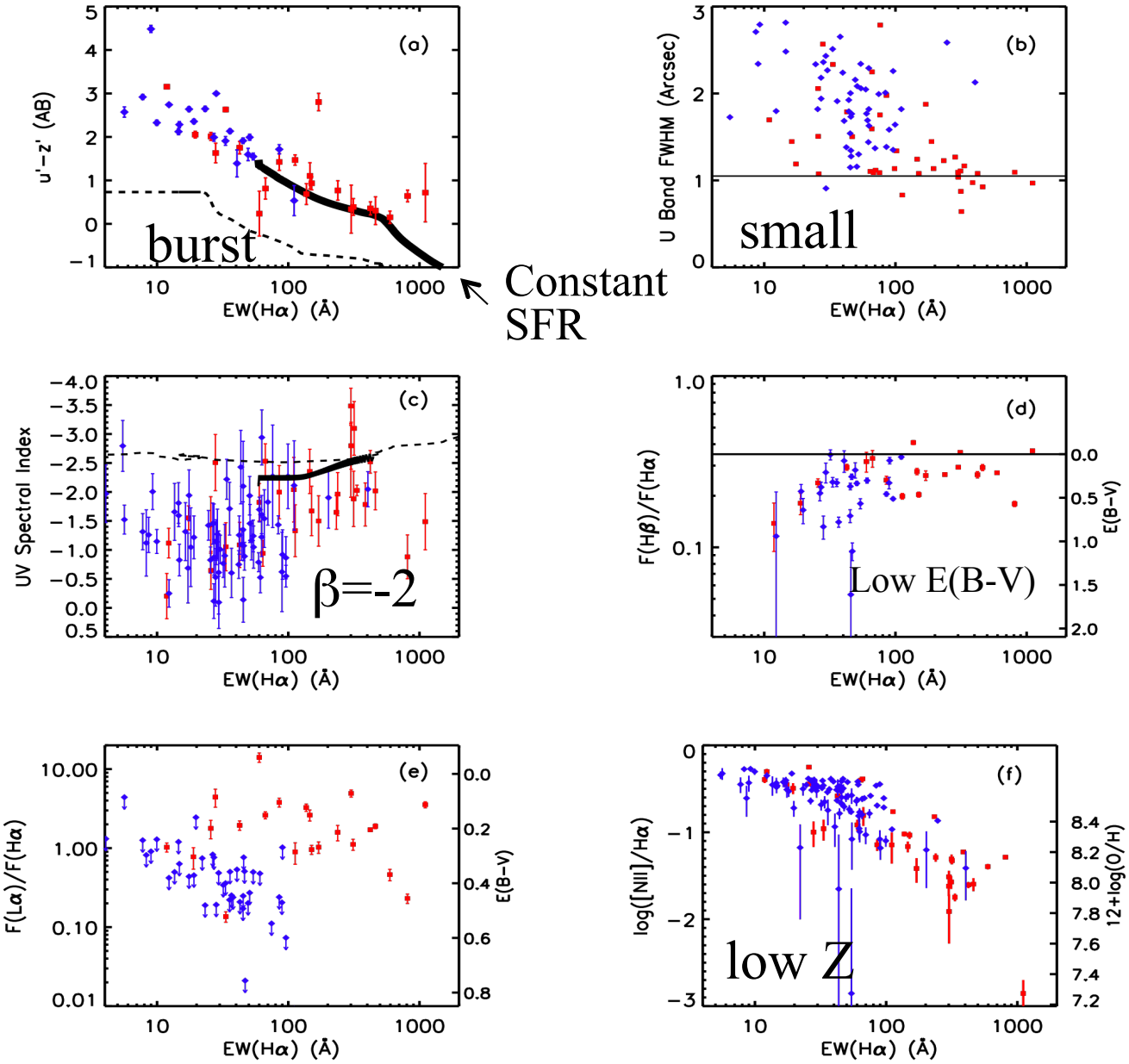


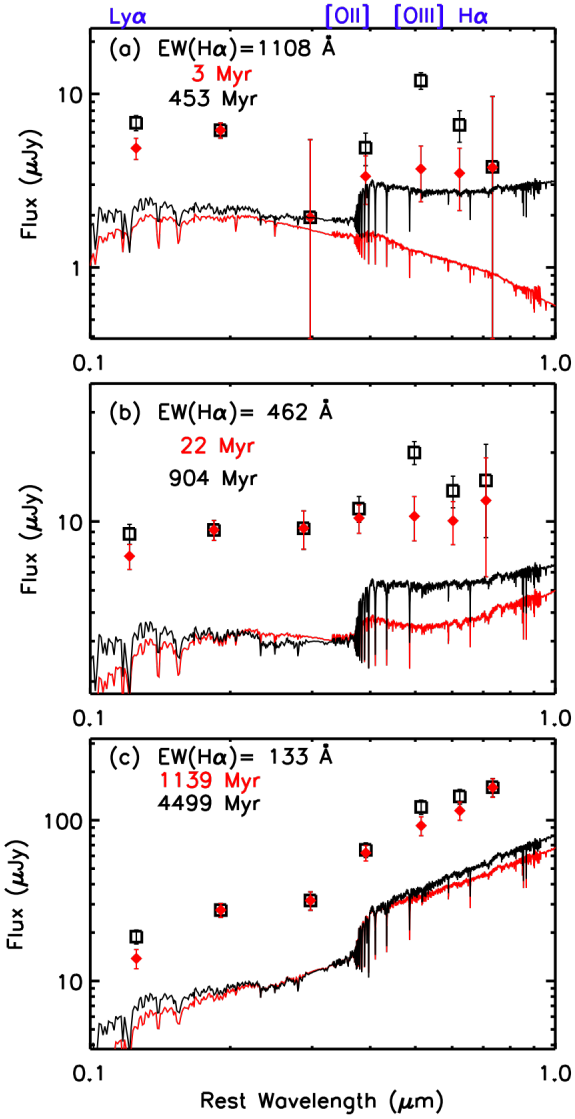
FIG. 9.— The (a) SDSS $u' - z'$ color, (b) FWHM in CFHT MegaPrime U-band images, (c) UV power law slope, (d) $f(\mathrm{H}\beta)/f(\mathrm{H}\alpha)$, (e) $f(\mathrm{Ly}\alpha)/f(\mathrm{H}\alpha)$, and (f) $\log(f([\mathrm{NII}]\lambda6584)/f(\mathrm{H}\alpha))$, all plotted vs. the rest-frame EW(Hα). The red squares show the LAE galaxies with EW(Lyα) $\geq$ 20 Å. The blue diamonds show the UV-continuum sample. Error bars are $\pm1\sigma$. In (a) we have used the spectra to correct for the emission-line contributions to the z' magnitude (see Section 5.2). In (a) and (c) the black curves show solar metallicity models from

Are they young?

- Need to correct for emission-line contributions

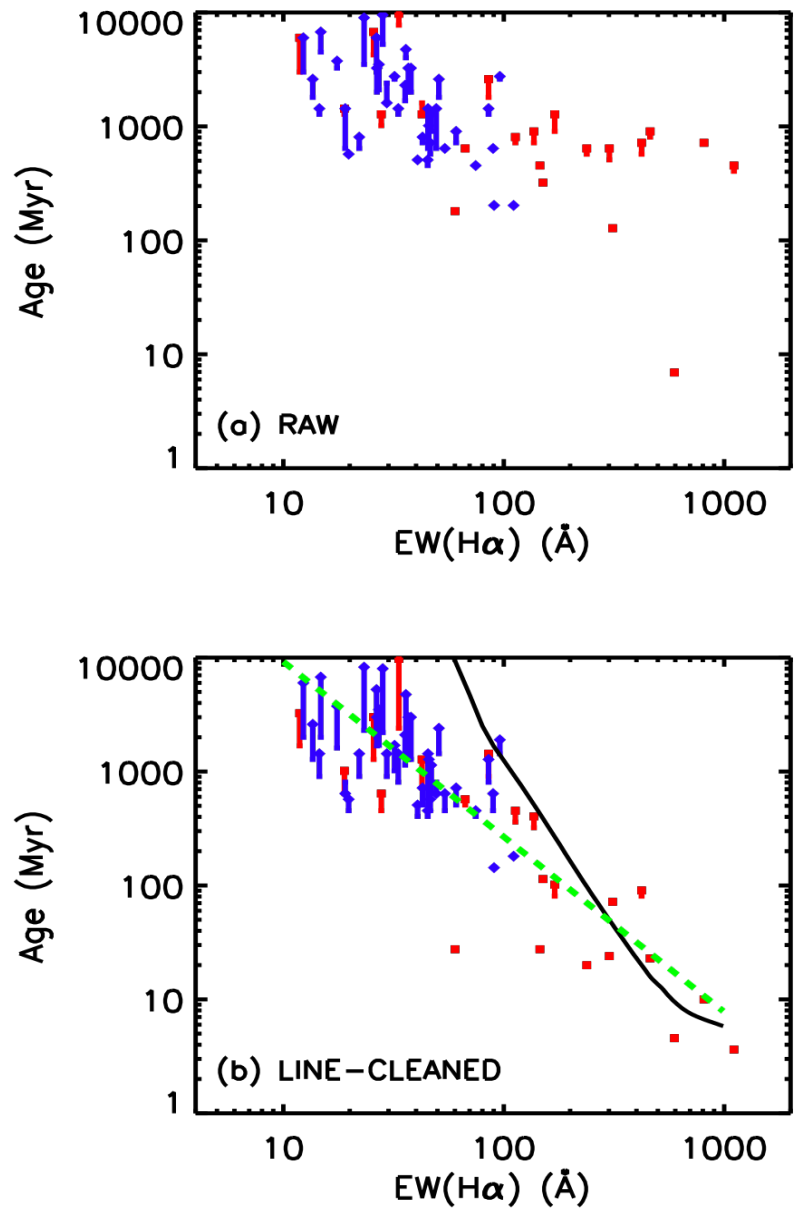
(e.g. Schaerer and deBarros 2009)

For these data sets where we have both spectra and colors we can correct the broad band colors for the known emission lines. These corrections can be very large for the LAEs

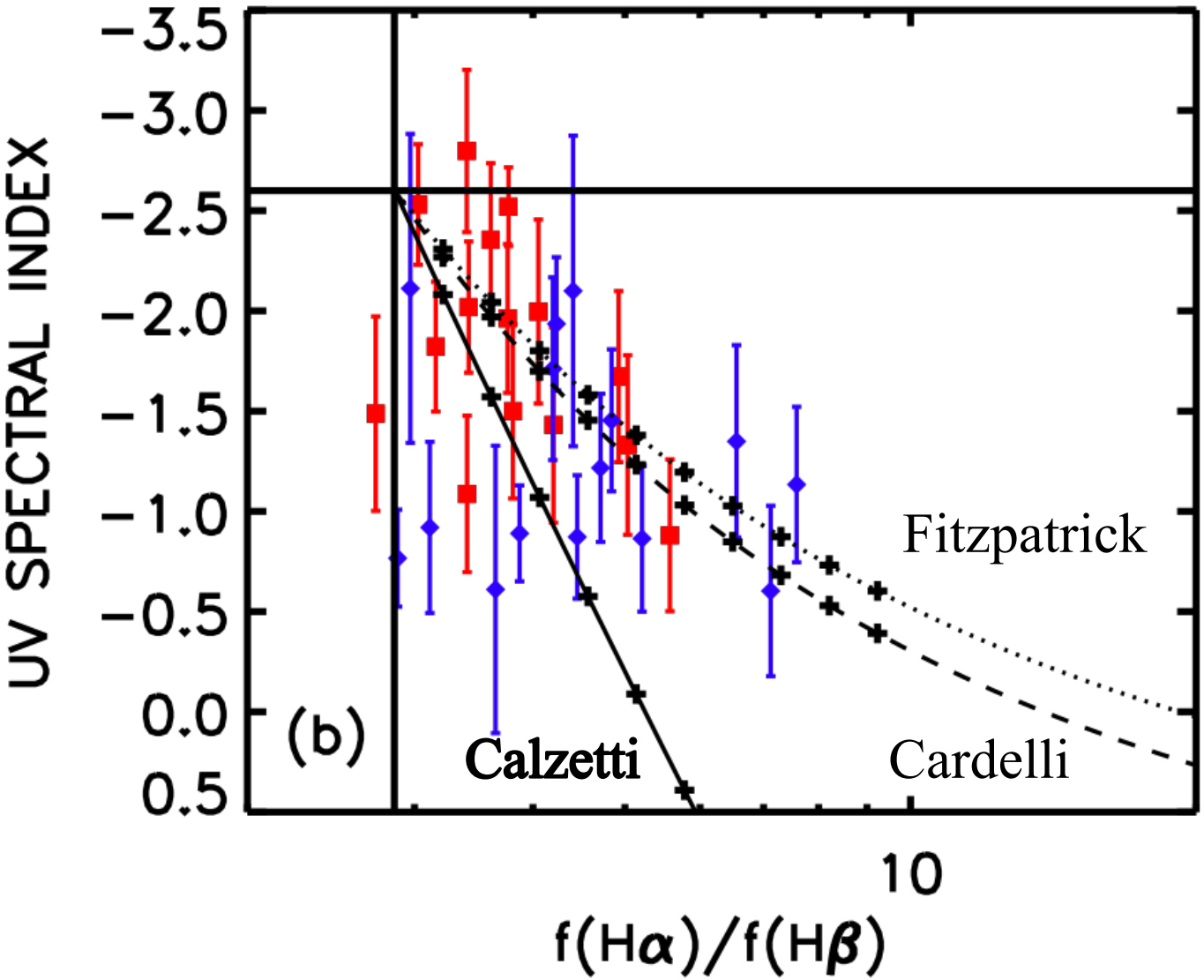


Cowie Barger and Hu 2011

- Without line correction galaxies are misinterpreted as old and red:
- Really the bulk of LAEs are young and relatively dust free.



Is there a preferred extinction law? (Milky way line of sight seems to work better than Calzetti screen)



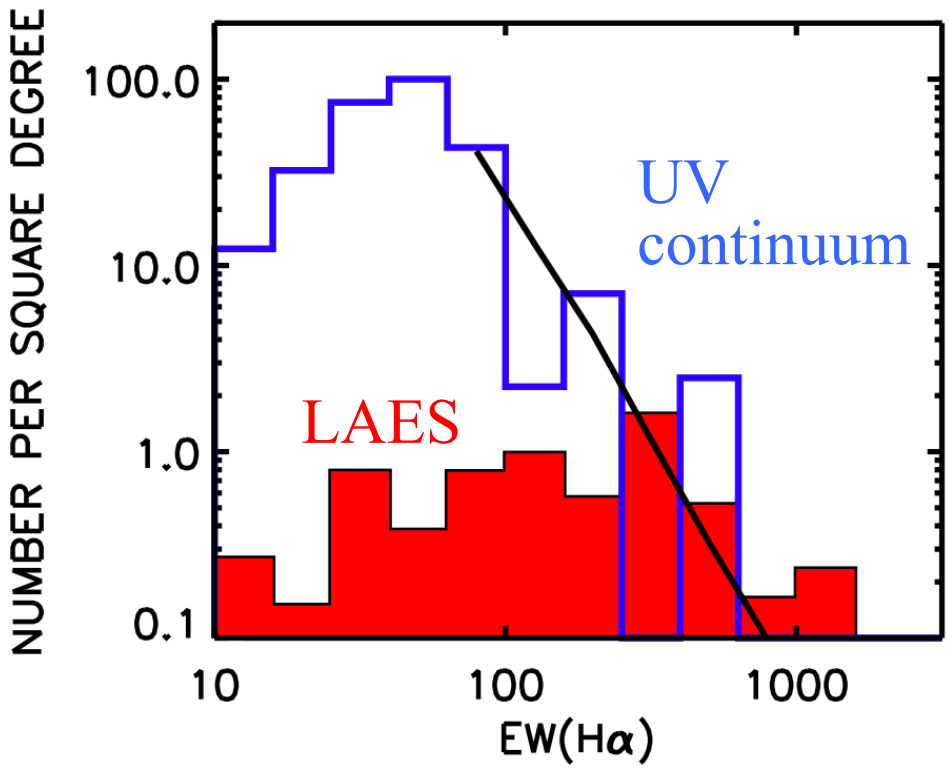
The LAE population corresponds to a high Hα equivalent width selection

LAEs at z = 0.2-0.4 <EW(Hα)> = 54 A

Non-LAES, z=0.2-0.4 <EW(Hα)> = 24 A

The LAEs overlap Kakazu' et al (2007)'s USEL selection limit of EW(Hα) >150 A and seem to comprise the high luminosity tail of her USEL population.

Fraction of UV continuum galaxies that are LAEs as a function of EW(H alpha)

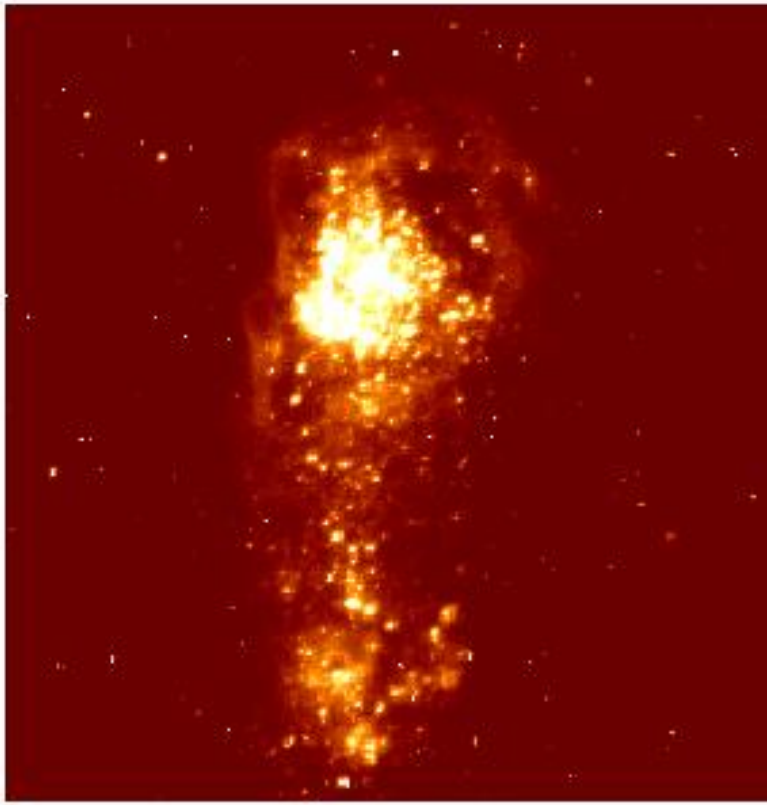


We've known since Sargent and Searle's work in the 1970s that there are some very low metallicity galaxies in the local universe. The lowest metallicities known are about 12+log(O/H)=7.2 or about 1/40th of the solar metallicity.

But these are generally small galaxies and we still only know of a handful of them.

Does this mean that we have stopped making new galaxies?
If so when did this happen?
Also is there really a floor on the galaxy metallicity?

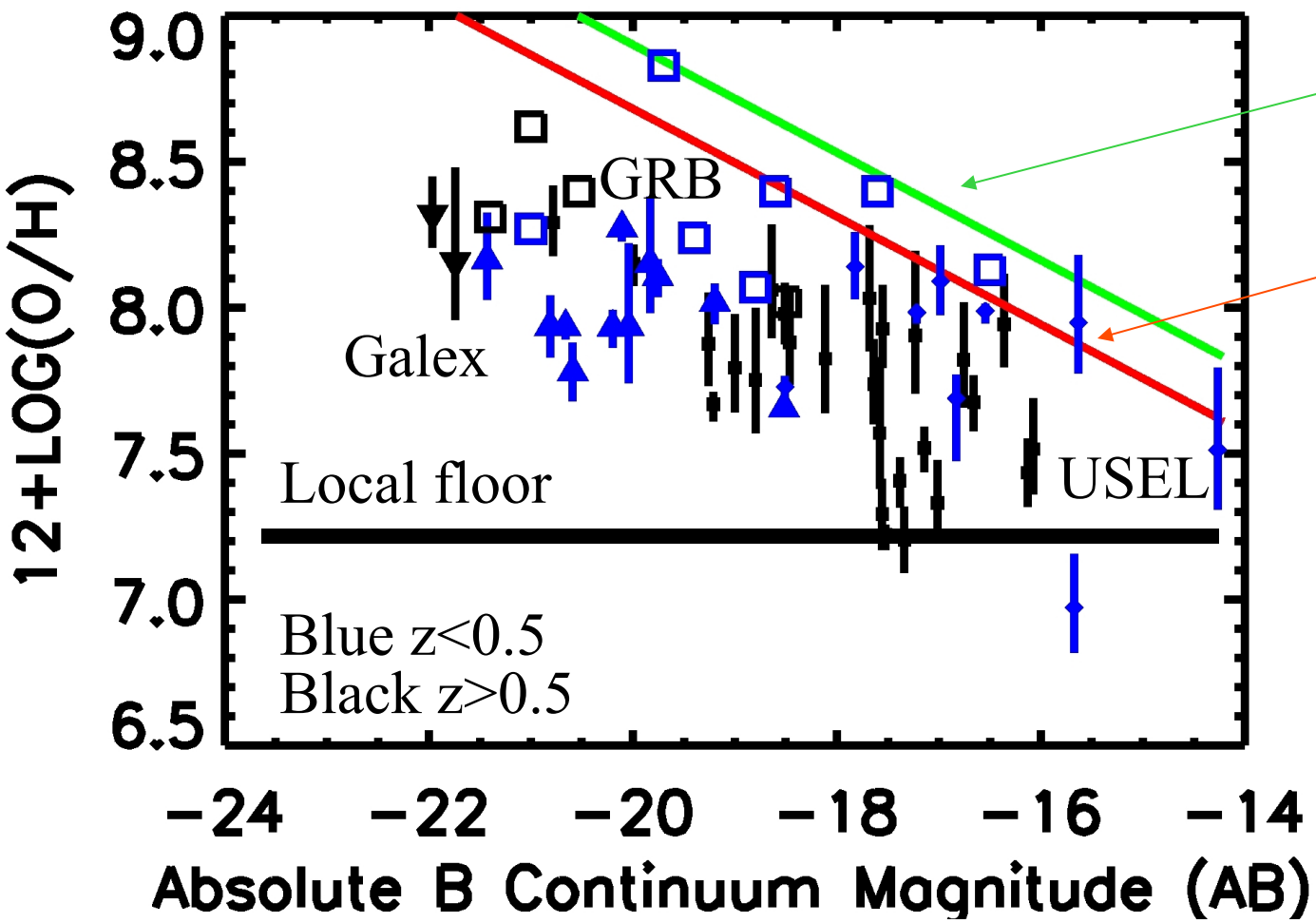
I Zw 18 - HST PC image (F555W)



Kunth et al. (1994)

The lowest metallicity galaxy known for almost 3 decades
I Zw 18 has 12+log(O/H)=7.17
or about 1/40th of the solar metallicity

Metallicity-luminosity

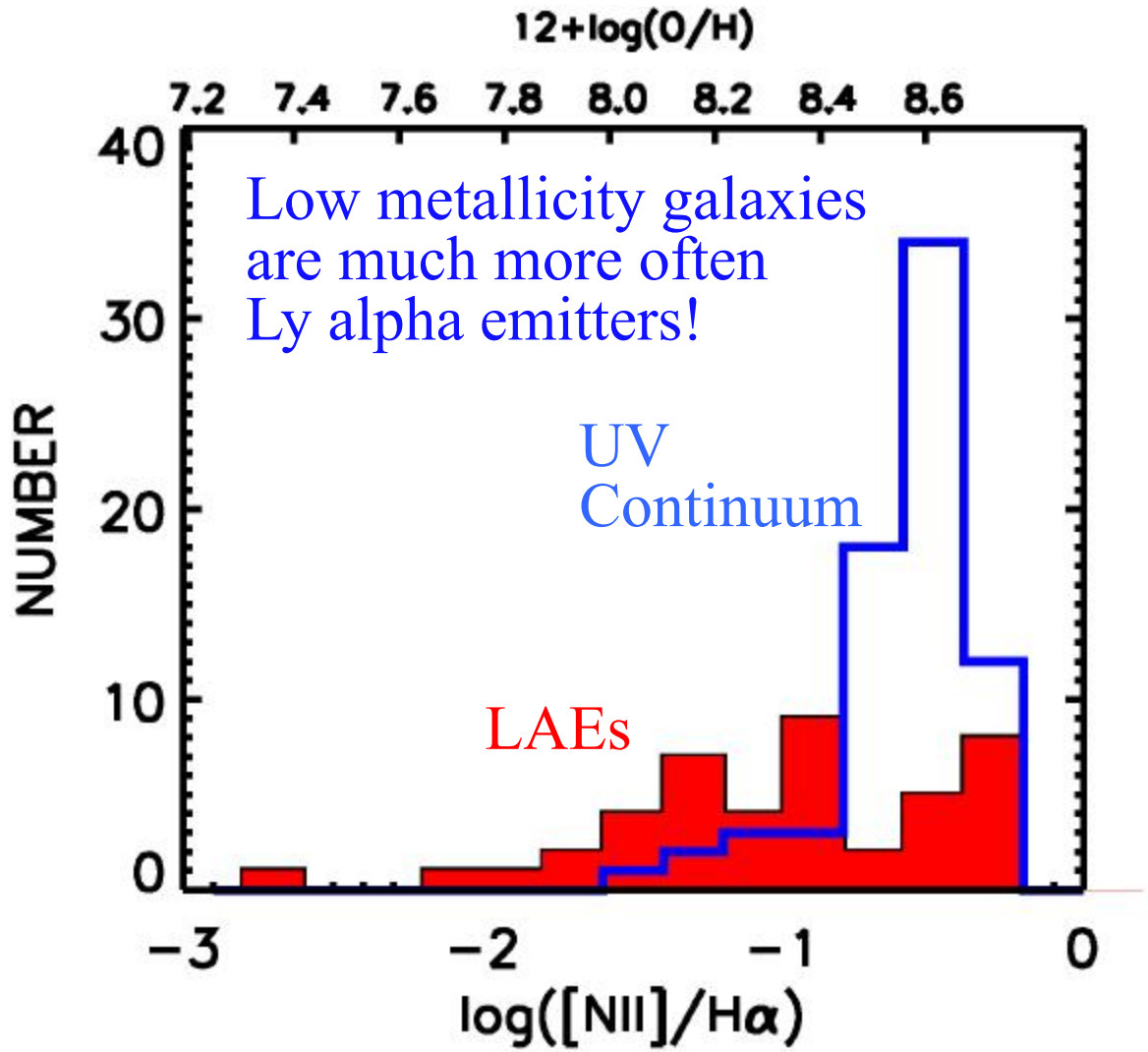


Local (Tremonti et al 2003)

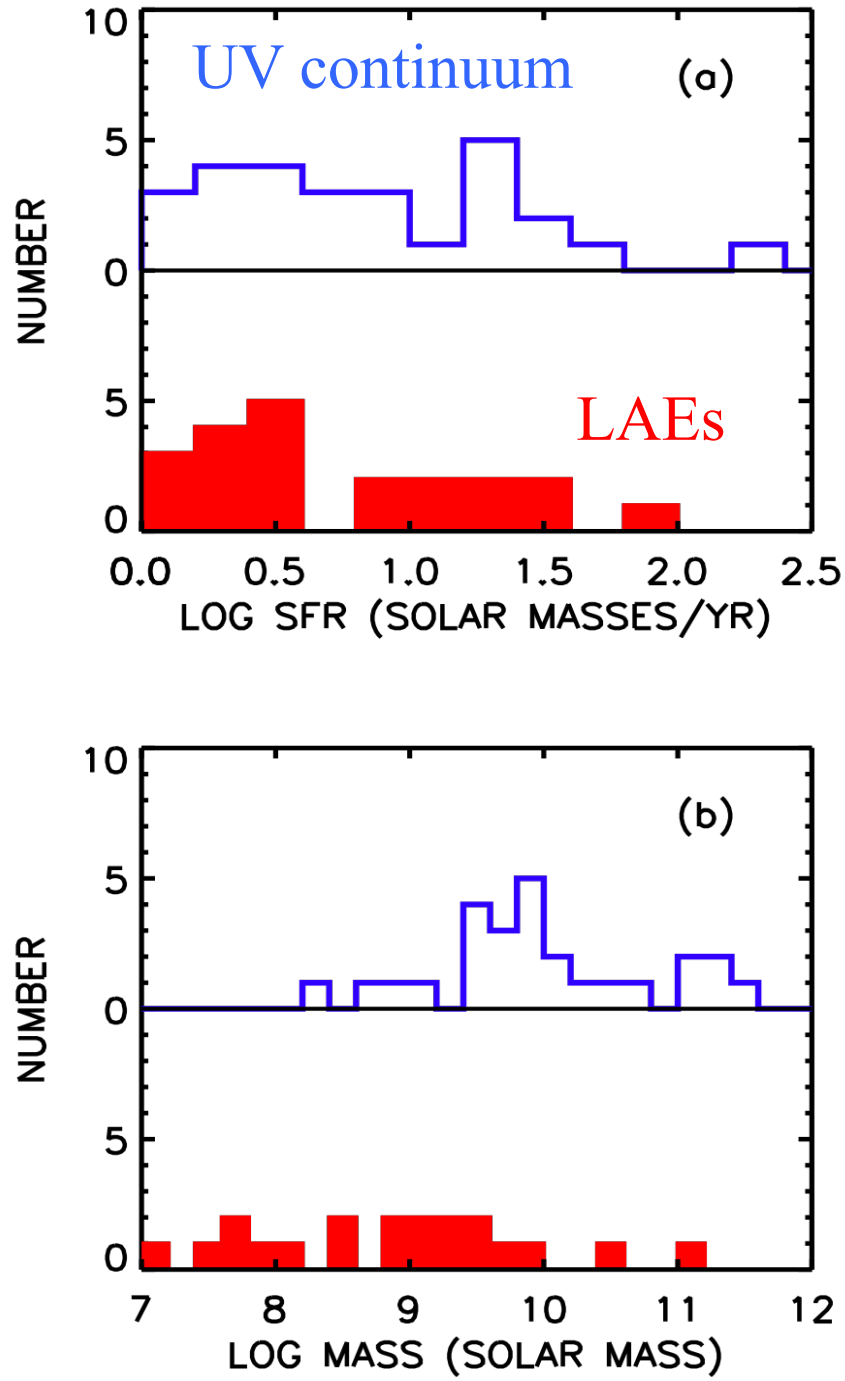
z=0.8 Cowie and Barger 2008

Based on direct method using the [OIII]4363 line

They are **much more luminous** than the blue compact galaxies but have just as low metallicity

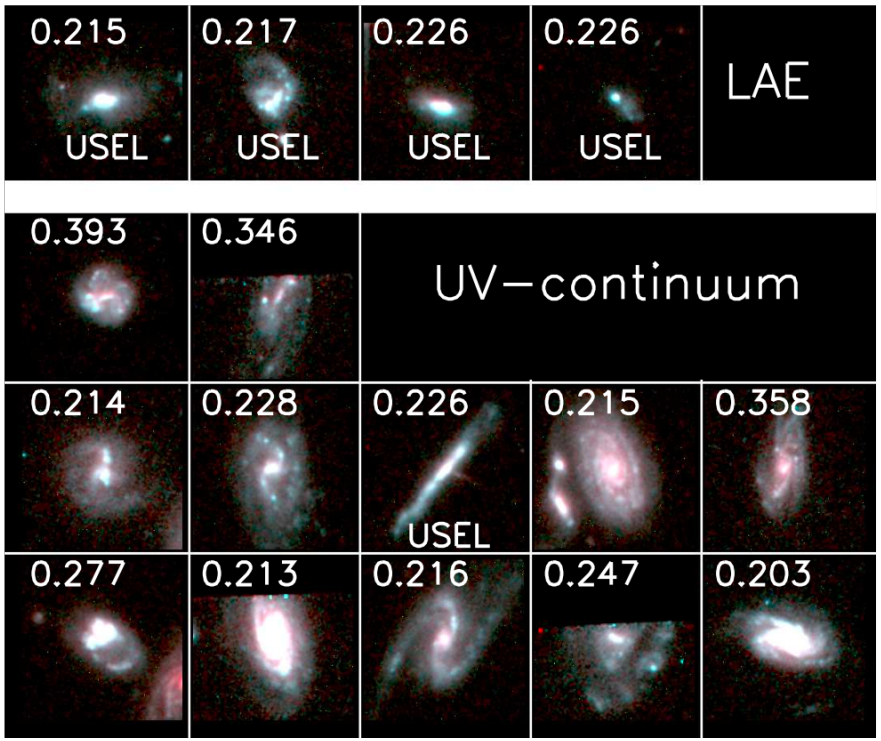


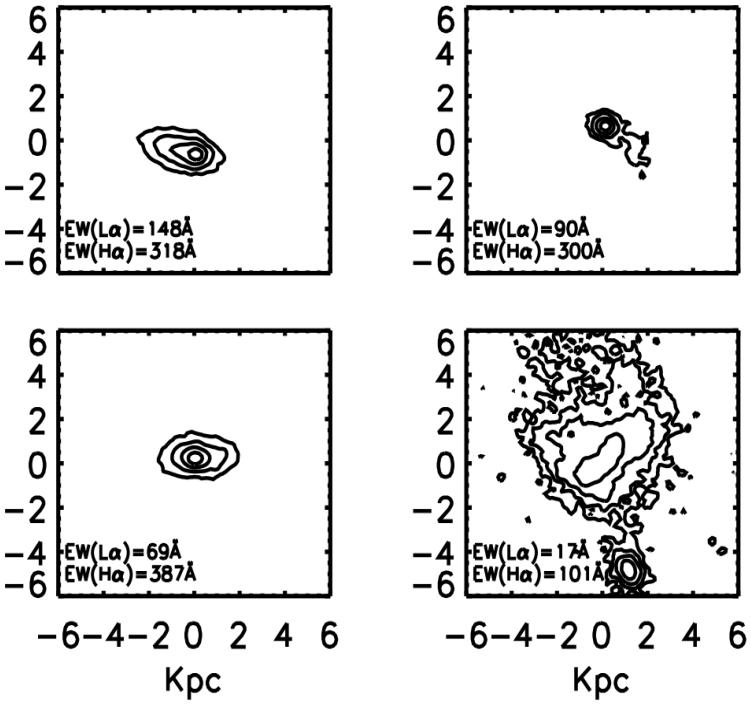
Lower mass but similar star formation rates



Morphologies (from GEMS)

1.6″.





LOW-z SUMMARY

- Lyman alpha emitters pick out young low-metallicity low-extinction galaxies which appear to represent the earliest stages in galaxy formation

- For young galaxies (age less than 100Myr and EW(H alpha) greater than 100A) about a third of all galaxies show EW(L alpha) greater than 20A

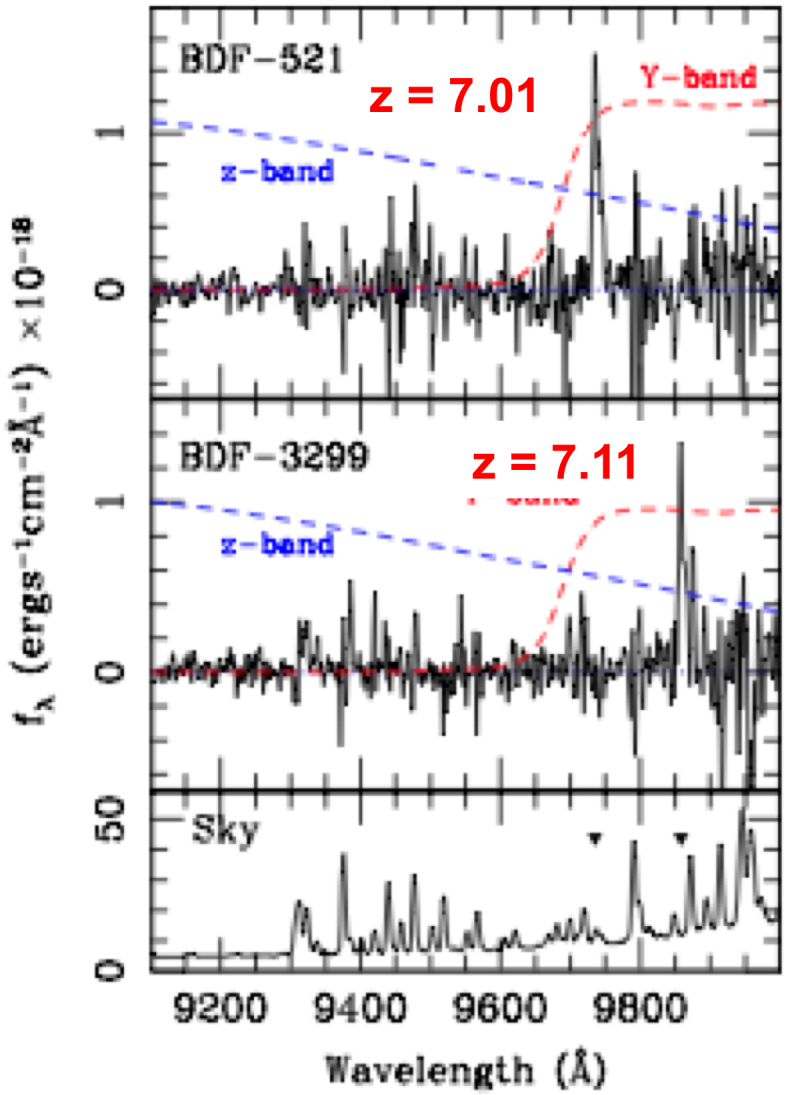
- There is a dramatic change in the properties of the LAEs over the z=0-1 range.

What can this tell us about the high redshift LAEs?

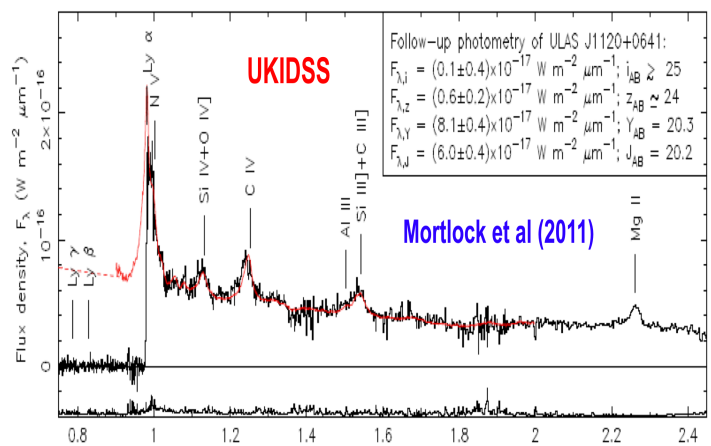
- Large samples of z=5.7 and 6.5 LAEs are now available selected with Suprime-cam narrow band imaging and followed up with Keck Deimos spectroscopy
- Hu et al. 2010 give spectra for 88 z=5.7 LAEs and 30 z=6.5 LAEs
- Ouchi et al. 2010 have comparable numbers

We are starting to probe z=7 but samples are still small so I'll concentrate on z=6.5

Vanzella et al. 2011 LAEs

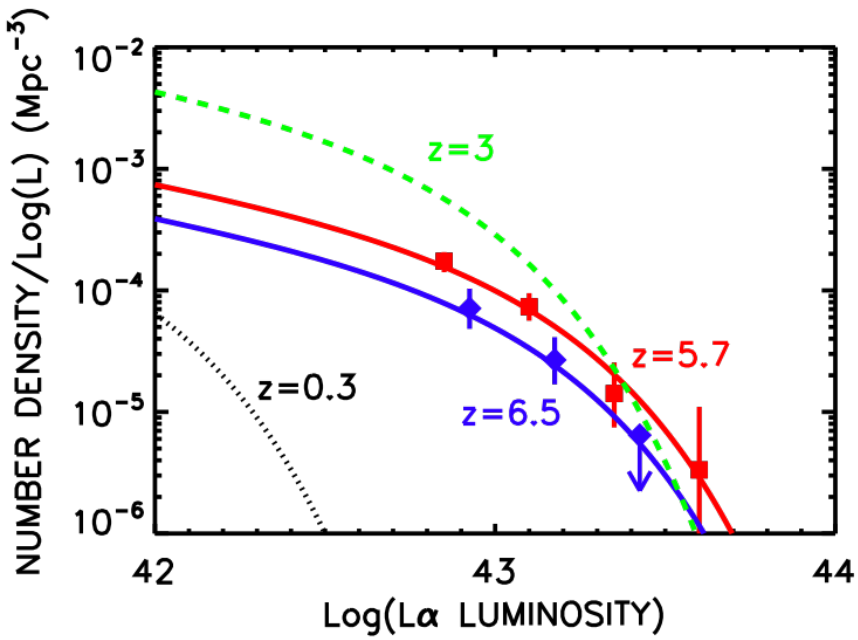


Mortlock quasar

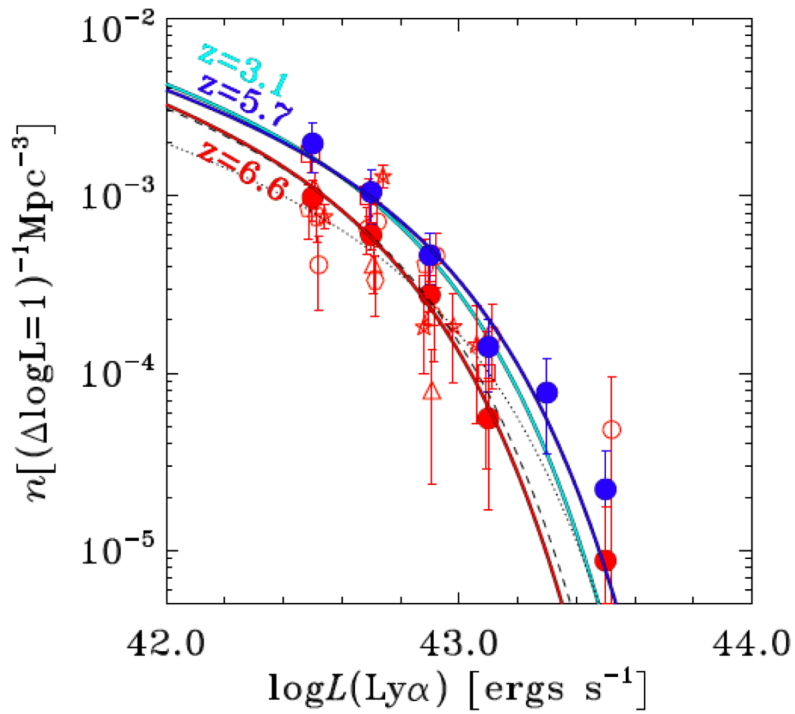


Recent measurements of high z LAE luminosity functions: show very similar drops between z=5.7 and z=6.5. Normalization differs by factor of ~2 (No clear explanation of discrepancy).

Such changes don't tell us much about reionization since the normalization depends on the SFR distribution, and also extinction and metallicity



Hu et al. 2010



Ouchi et al (2010)

However, we might see changes in the line widths and the equivalent widths as the neutral fraction increases

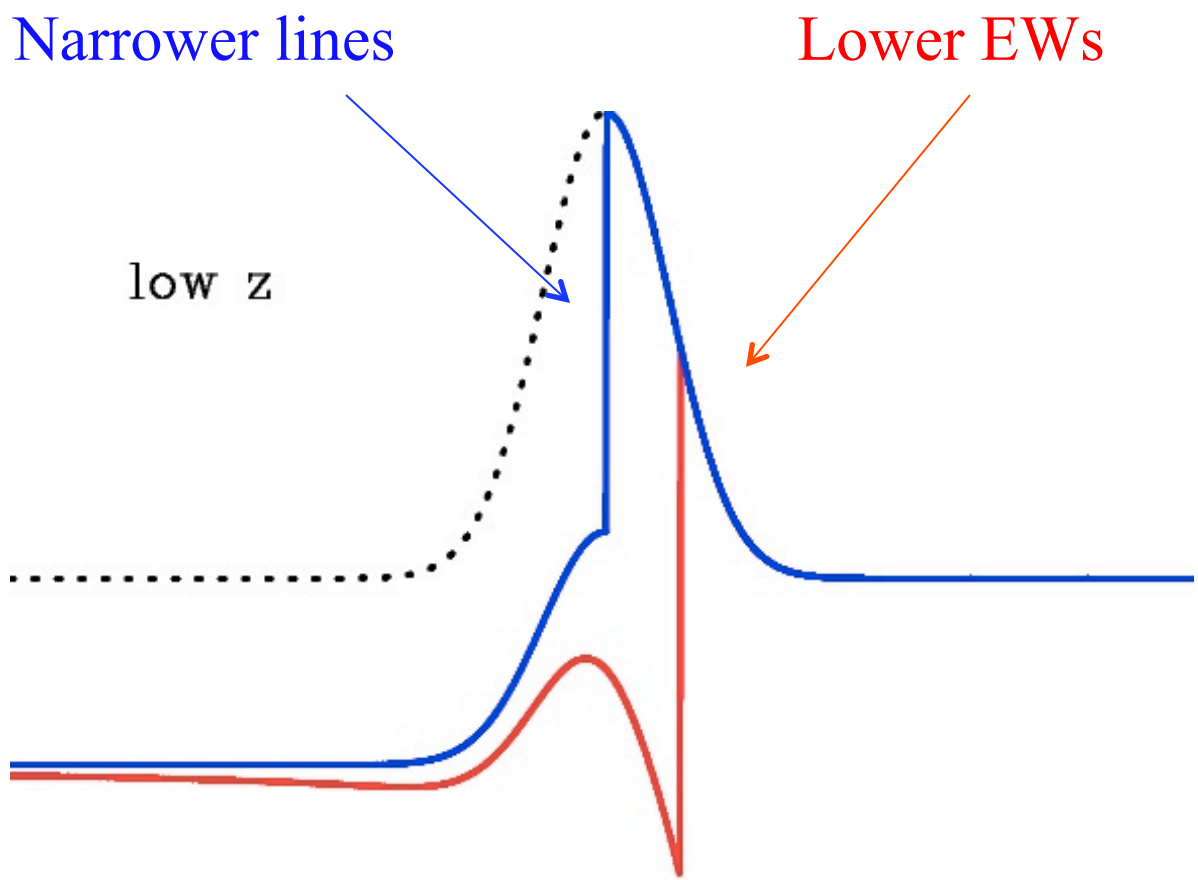


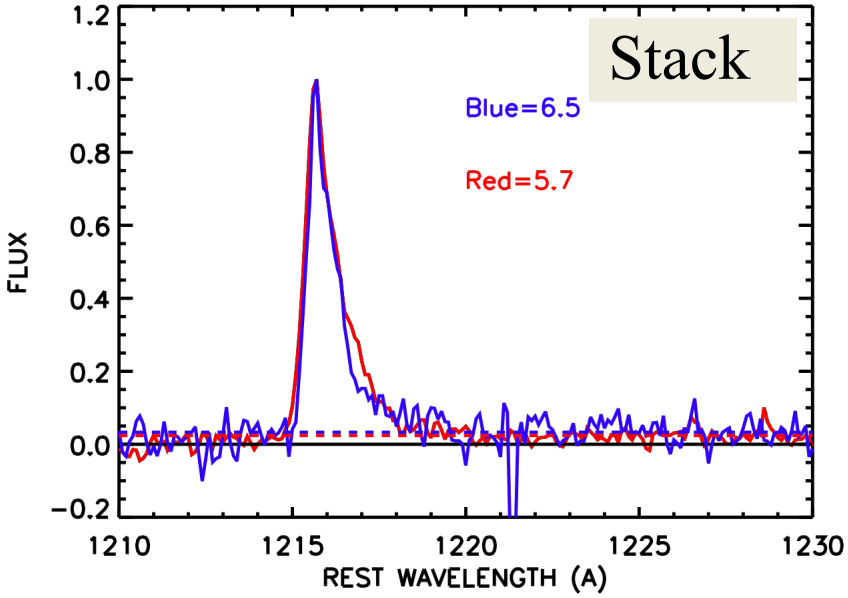
Figure from Dijkstra

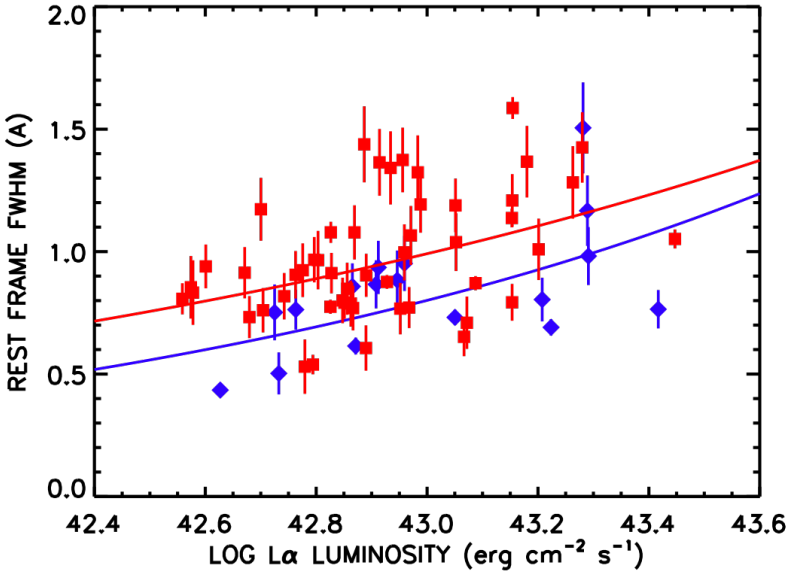
Are there changes in the line widths?

Velocity width in the range 150−360 km/s.

Lines are narrower at the higher redshift with a median value of 0.77 A at z=6.5 and 0.92 A at z=5.7. However, the difference is only marginally significant.

Higher luminosity sources are wider (opposite to Kashikawa et al. 2006 but in agreement with Ouchi et al. 2010)



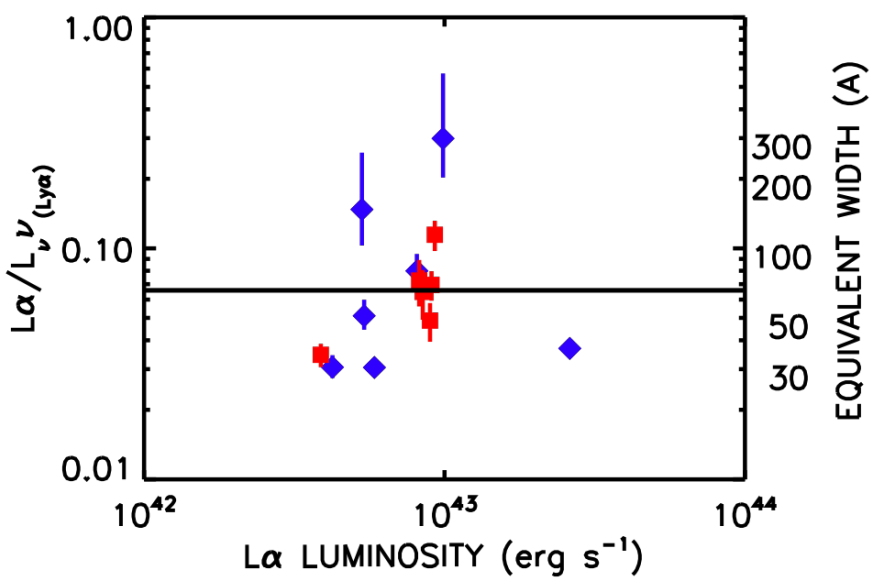


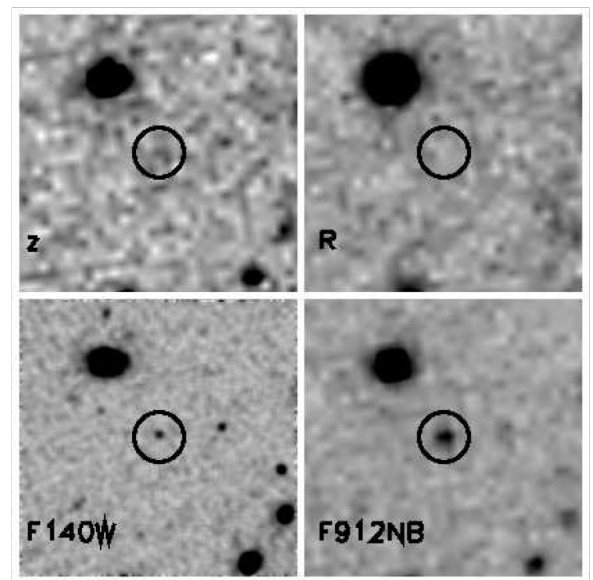
Hu et al. 2010

Or the equivalent widths ?

Precise measurements of EW range using WFC3 on HST: no change in distribution: L alpha lines have EWs very close to that expected from case B and very similar to values seen at lower redshift

Blue=6.5, Red=5.7



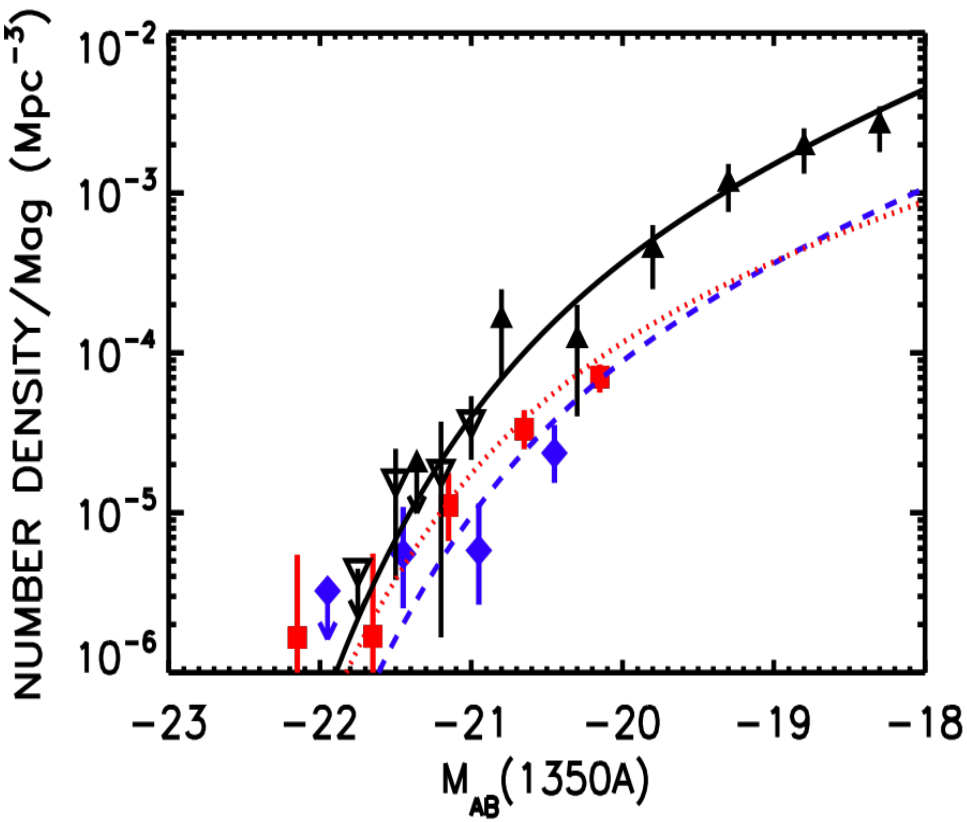


Cowie et al. 2011

How about the LAE fraction ?

Combine UV continuum measures in LAEs with LAE luminosity function to compare with break selected UV functions

For Hu et al. 2010 LAE luminosity function z=6.5 fraction is 24+/-6 % and z=5.7 fraction is 18+/-2%. Ouchi et al LAE function would raise this by a factor 2 at both redshifts.

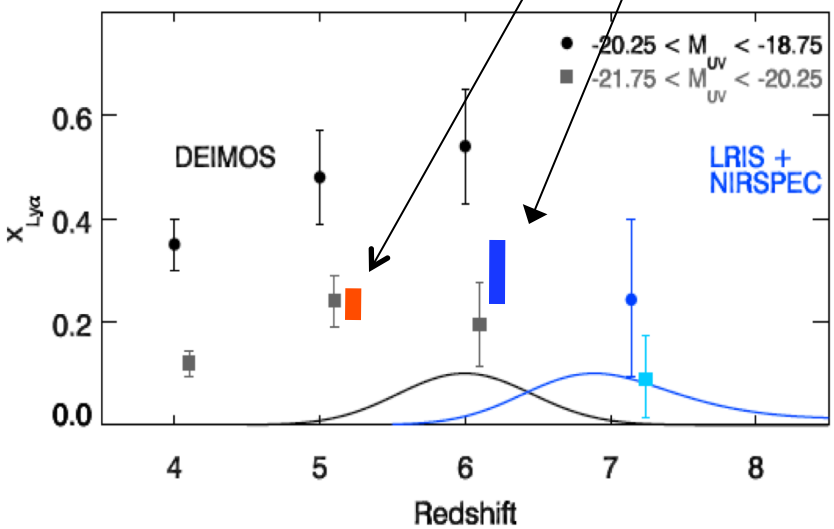


May be hints of drop in fraction at z~7: not very convincing as yet

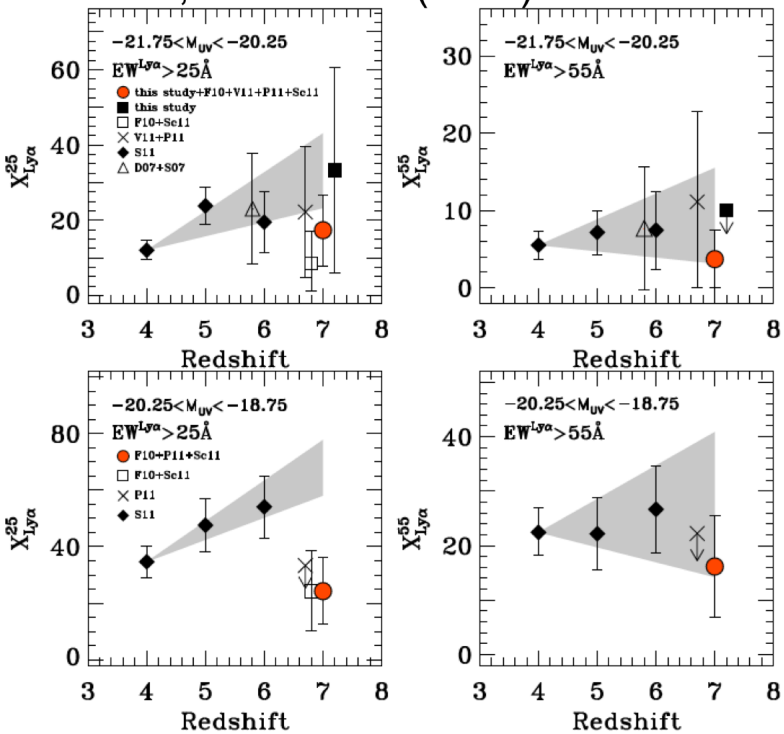
Cowie et al. 2011 values

Fraction of galaxies showing Lyα emission

Schenker, Stark, Ellis et al (2011)



Ono, Ouchi et al (2011)



Also see Fontana et al (2010) and Pentericci et al (2011).

High z SUMMARY

- In internally self consistent LAE samples there is very little change between z=5.7 and z=6.5
- There may be a hint that the lines are becoming narrower with higher redshift
- However, line width does depend on luminosity
- If there is strong evolution in the LAEs we are going to have to see it beyond 7

Conclusion

Galaxies grow along a well defined age-metallicity track with a smooth increase in mass and size. Extinction builds up as the size increases.

Ly alpha is primarily seen in the young high EW(H alpha) stages.

If galaxies are primarily young as at high z the L alpha fraction may be high but probably not much more than 50%. At low redshift the LAE fraction is much lower reflecting the low galaxy formation rate