Probing the end of the reionization epoch with deep spectroscopy

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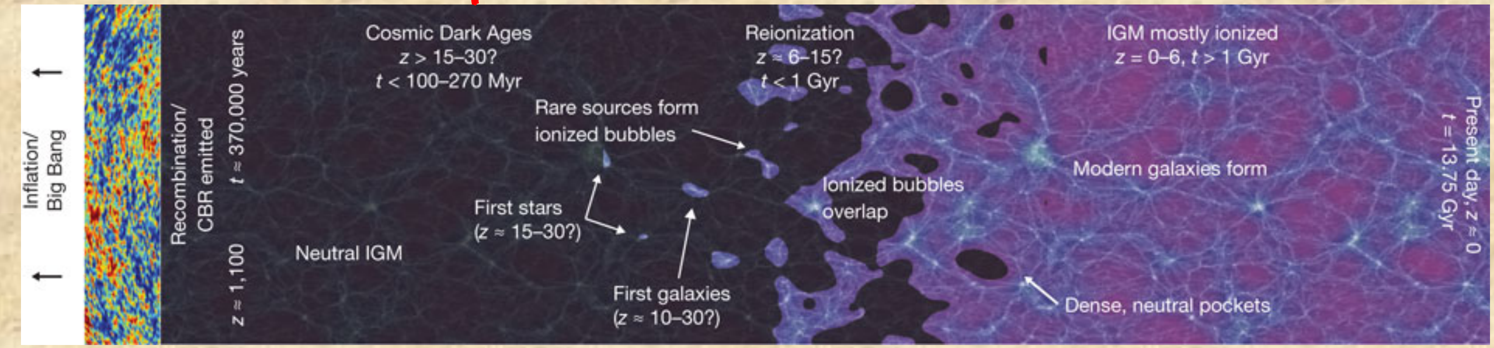
in collaboration with

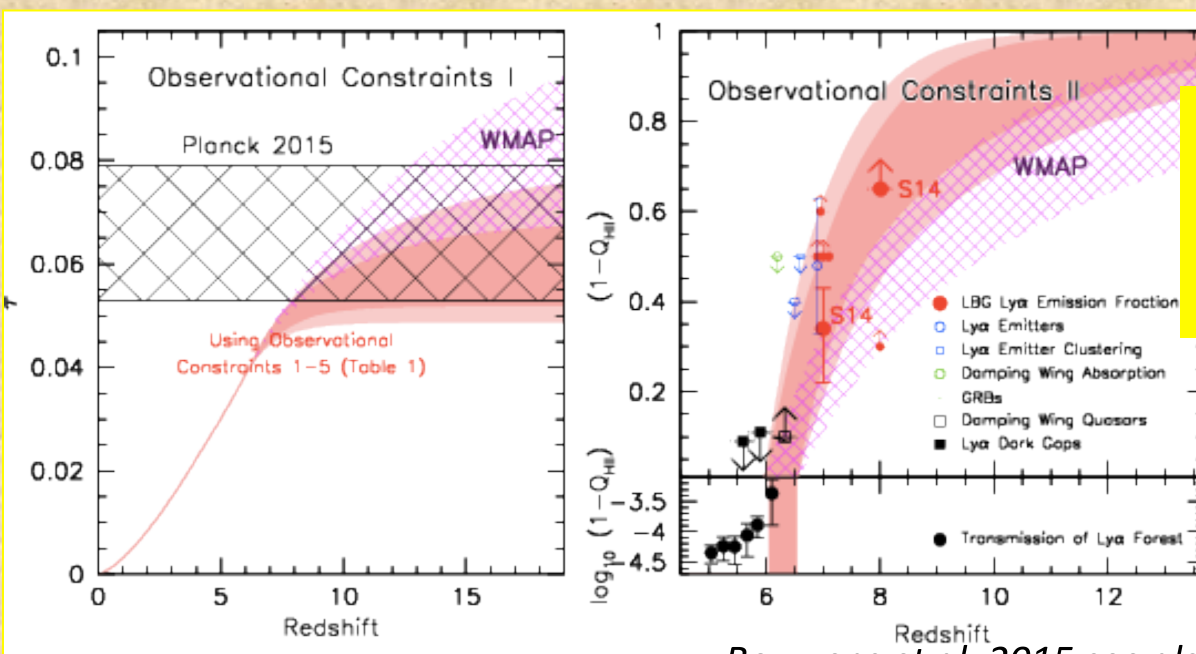
E. Vanzella, A. Fontana , M. Castellano, S. De Barros, A. Grazian M., R. Maiolino, et al.

Iluminating the Dark Ages: Quasars and Galaxies in the Reionization Epoch, Heidelberg 28th June 2016

The reionization epoch: where do we stand?



Star forming galaxies & AGN form bubbles of ionized hydrogen that grow and eventually overlap. At the end of this process the Universe is completely ionized again.



Open questions:

When? Δz ??

How? $d[Q_{HII}]/dt$??

Who? Ionizing sources?

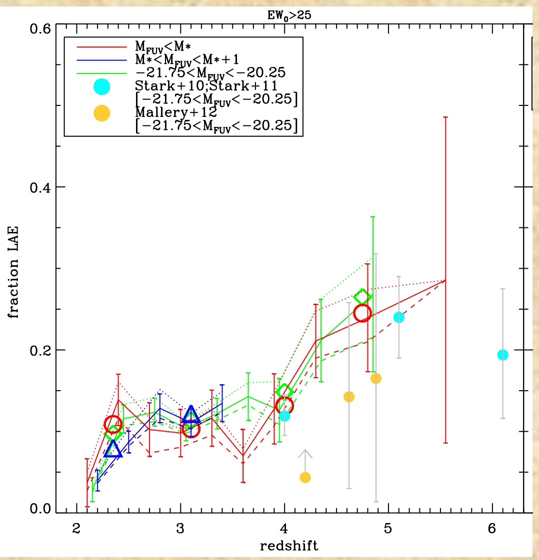
Bouwens et al. 2015 see also Robertson et al. 2015

Latest constraints coming from Planck results compared to observational inferences from : Lyα emission fraction, LAE clustering, LAE LF, Damping Wing QSOs, GRBs, Lyα Dark Gaps etc

Probing the reionization epoch with Lyman Break galaxies and Lyα emission

The Lyα emission should be present in all young star forming galaxies: it is quenched mainly by dust within the galaxies (although the final transmission is due also to the escape fraction, outflows etc)

As we go to higher redshift we observe a steady increase of the fraction of Lyα emission amongst LBGs (from z≈2 to z≈6): this is an indication that galaxies become on average younger and less dusty hence they have stronger Lyα (*Cassata et al. 2014, Stark et al. 2010, Vanzella et al. 2009; Stanway et al. 2009*)



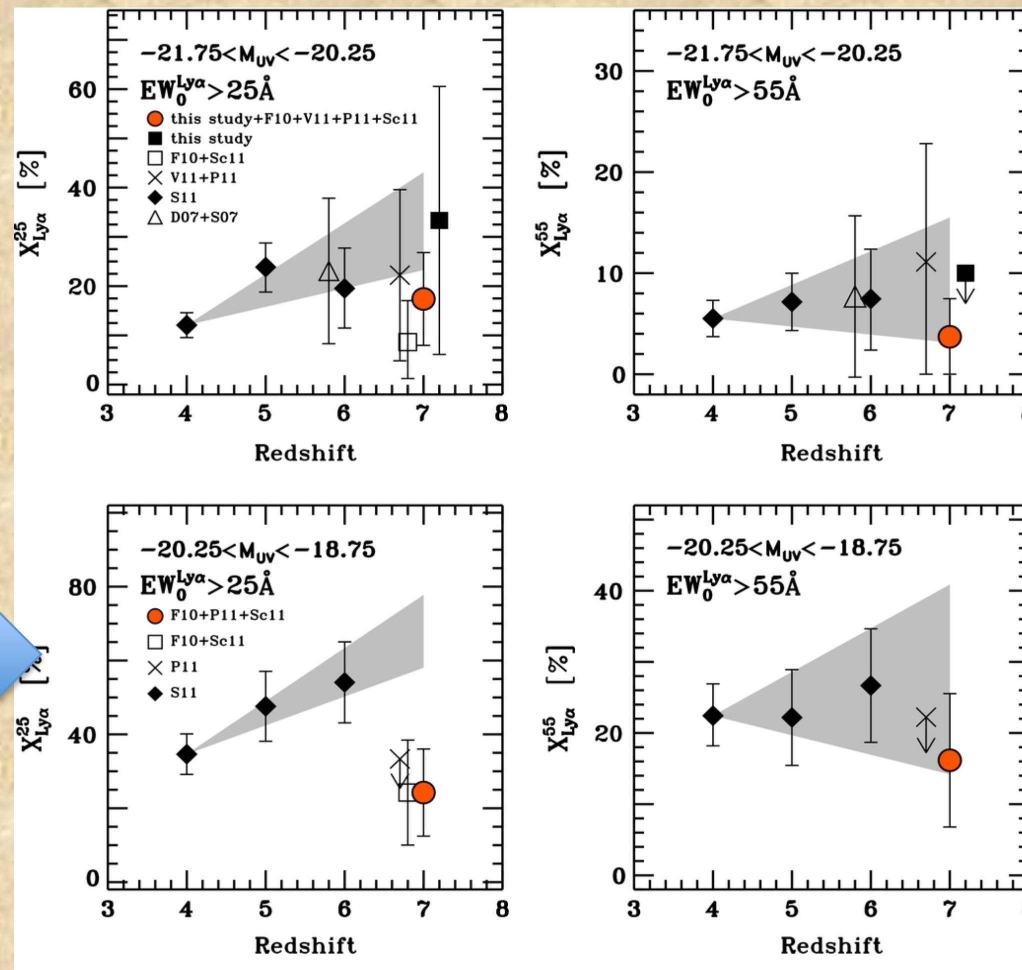
Cassata et al. 2014 (VUDS data)

As we probe earlier epochs, we should get to a point where the Universe becomes partly neutral: since the Lyα line is easily suppressed by even a small amount of neutral hydrogen *we expect to detect a lack of Lyα emission is star forming galaxies* provided that the galaxies properties do not change significantly over the same time interval

When does the Ly α decline?

Early results (Fontana et al. 2010, Stark et al. 2010, LP et al.2011, Ono et al. 2012) by several independent groups indicated that at z≈7 the fraction of Lyα emission in LBGs is considerably lower than at ≈ z 6

The rise and fall of Ly α is particularly pronounced for the faintest galaxies (but samples are smaller and observations more difficult)



Stark et al. 2010, Pentericci et al. 2011, Ono et al. 2012
Schenker et al. 2012, Pentericci et al. 2014, Caruana et al 2014

CANDELSz7 : an ESO Large Program to probe the reionization epoch

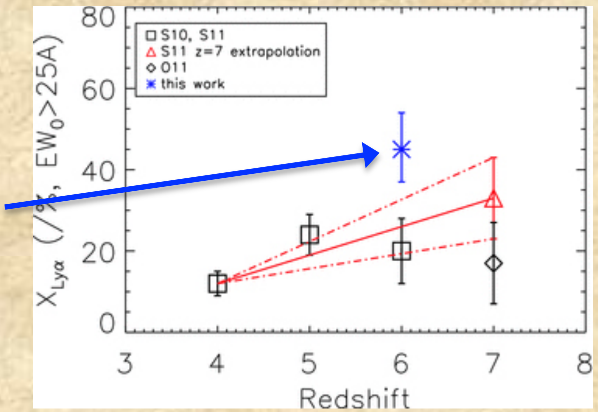
Motivation

A. The early samples were **still small** and **very heterogeneous** in terms of :

-selection (color vs zphot)

-observational set-up (i.e. redshift coverage)

-Lyα EW limit reached



B. The distribution of Lyα was still uncertain also at z≈6 (e.g. Curtis-Lake et al. 2012 claimed a much higher fraction of emitters) hence the real drop from z≈6 to z≈7 might change

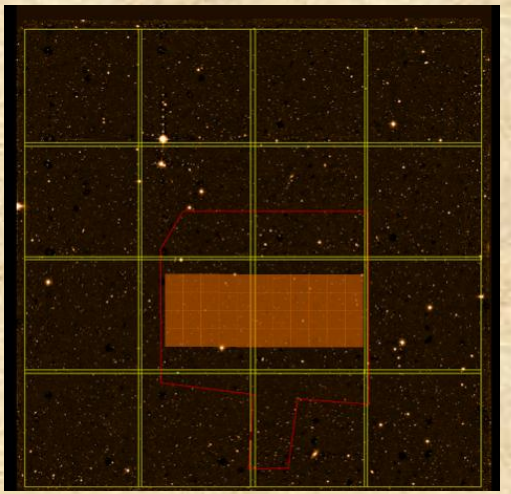
C. Potential bias could arise at z≈6 samples from the selection in z-band (which contains the Lyα line) as done in early surveys

D. Large field to field variation (e.g. Ono et al. 2012) were observed probably due to spatial fluctuations depending on the degree of homogeneity/inhomogeneity of the reionization process (e.g. Taylor & Lidz 2014)

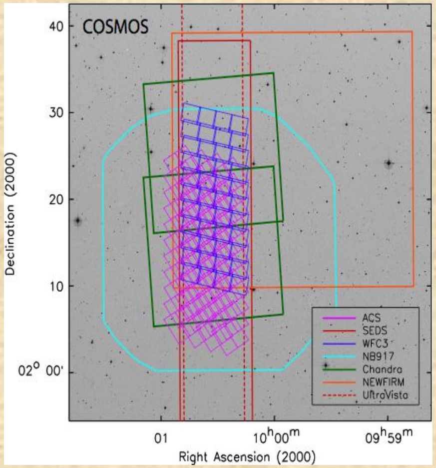
To overcome these problems we designed and carried out CANDELSz7 an ESO Large Program with FORS2 to observe 200 galaxies at 5.5 < z < 7.3 in COSMOS/UDS/GOODS-S selected from the CANDELS official catalogs to determine a solid and unbiased statistics of Lyα fractions in this redshift range.

GOODS-SOUTH

UDS



COSMOS

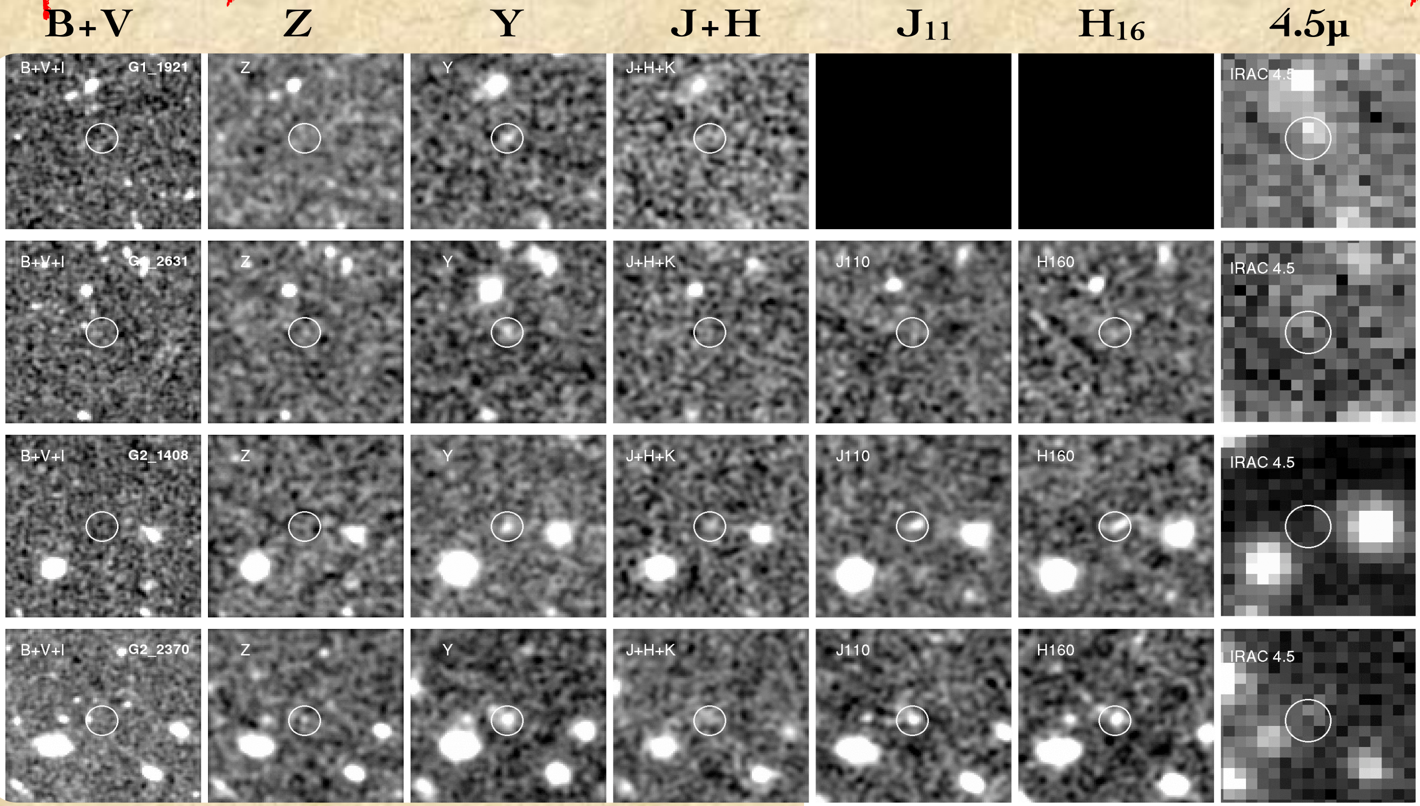


-Galaxies are selected with homogenous color-color criteria from the CANDELS data :

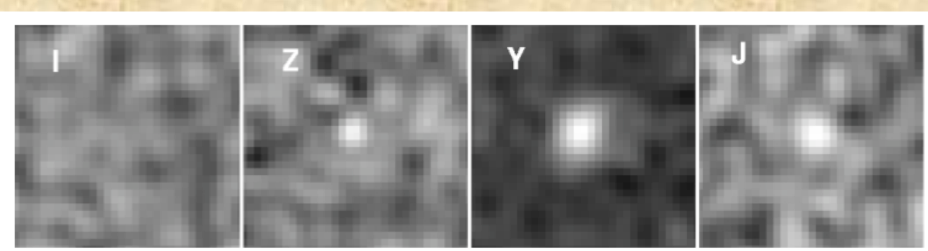
-The selection band (H-band) is independent of the presence of Lyα both at z=6 **&** z=7 unlike past surveys and minimizes any bias

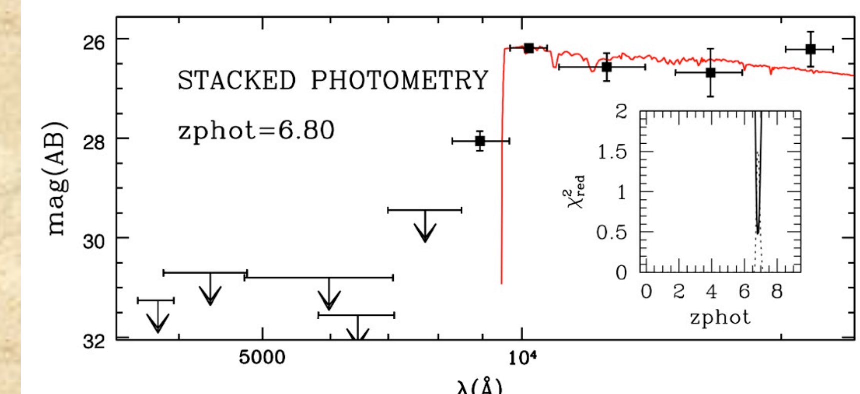
-We employ a unique spectroscopic set up and observational strategy: total integration time varies from 15 (for bright targets) to 25 hours (for faint targets) **to reach a uniform EW limit for all galaxies**.

Examples of z=7 candidates in the GOODS-SOUTH field



STACK OF ALL GOODS-S CANDIDATES



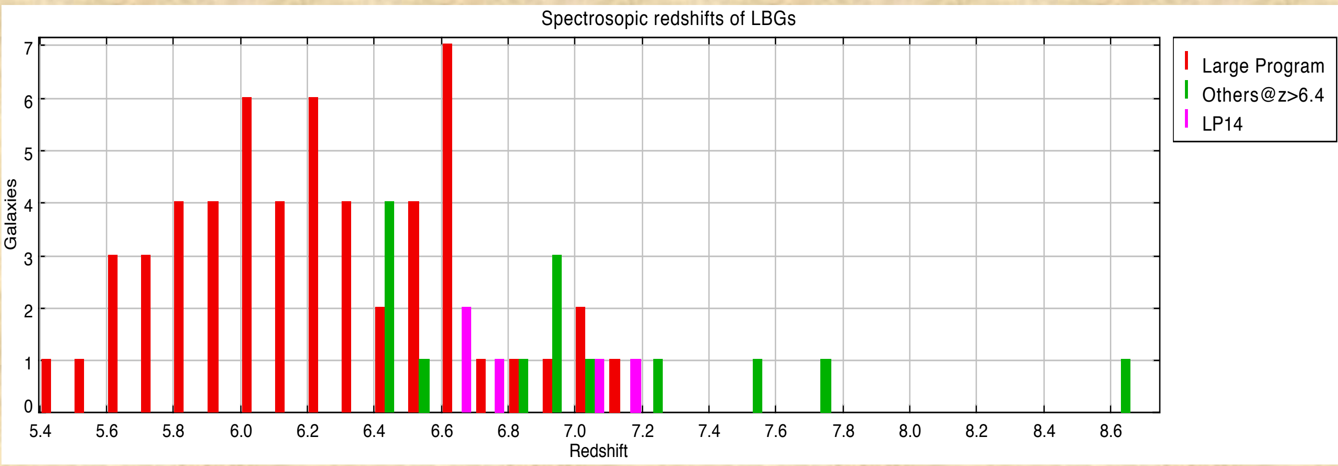


Very deep optical data are required to get rid of interlopers

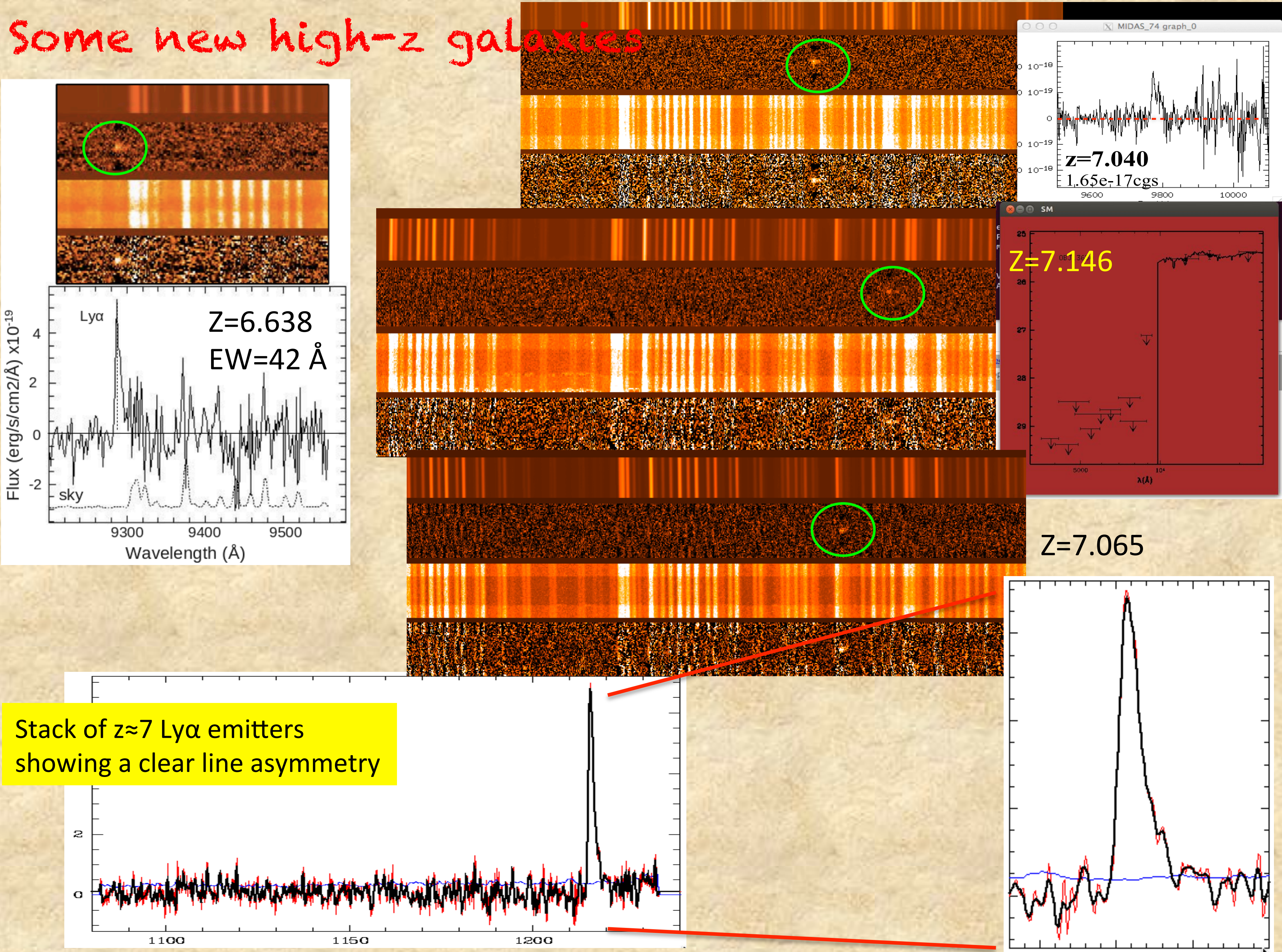
CANDELSz7 final observation log

FIELD	TOT TIME	OBSERVED	REDUCED	ANALYSED
GOODS1	25	25	YES	YES
GOODS2	25	25	YES	YES
UDS1	15	15	YES	YES
UDS2	15	15	YES	YES
UDS3	15	15	YES	YES
COSMOS1	15	15	YES	YES
COSMOS2	15	15	YES	YES
COSMOS3	15	15	YES	YES
TOTAL	140 hours	140hours		

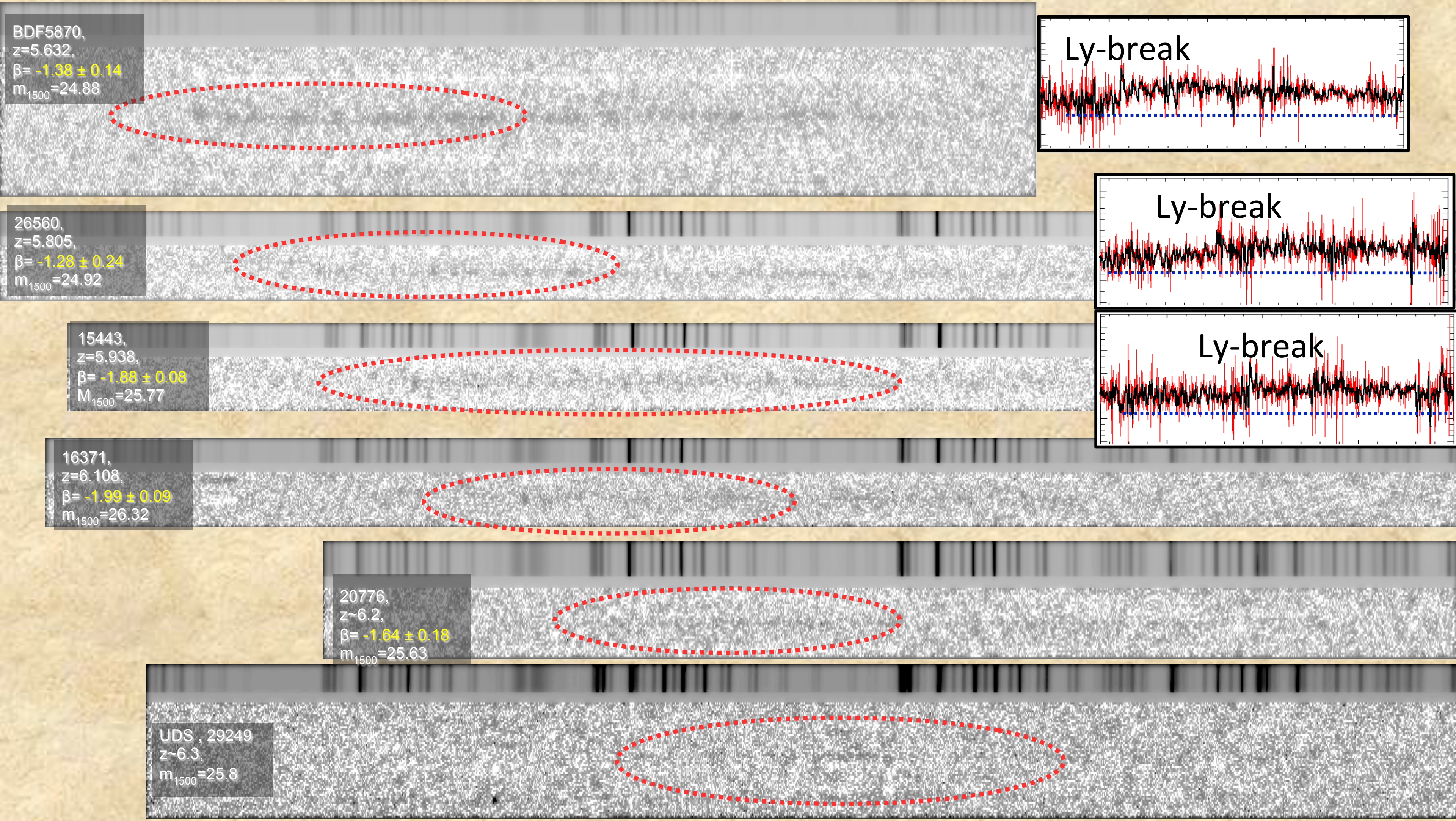
We have confirmed 15 new galaxies at $6.5 < z < 7.2$ all with Lyα emission, ≈ 40 new $5.5<z<6.5$ galaxies with Lyα plus several with no Lyα emission



Some new high-z galaxies



Deep spectroscopy starts to reveal faint z≈6 non-Lyα emitters

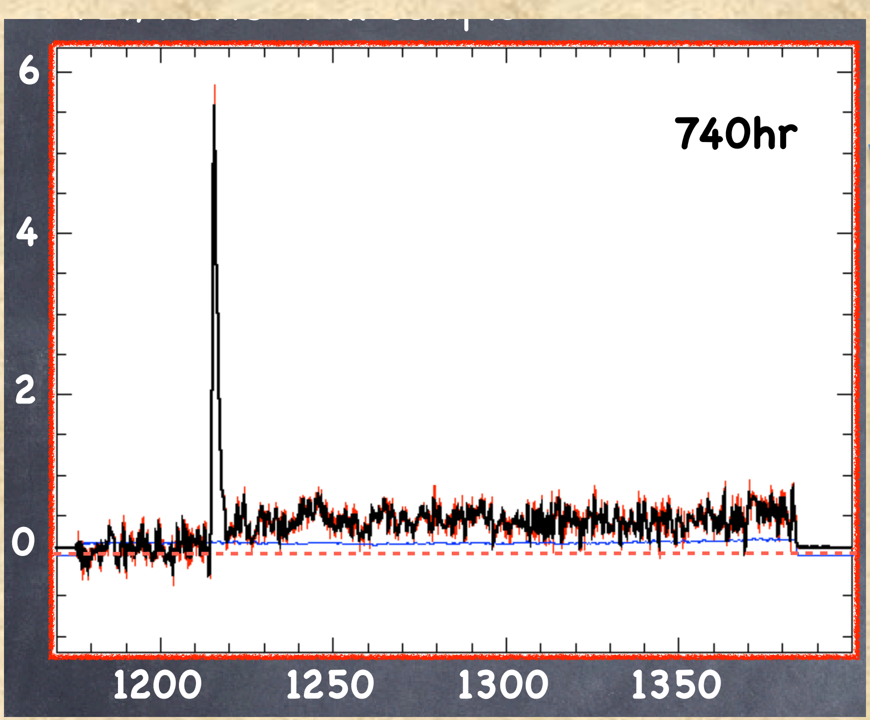


Measure redshift for faint (mag=25-26) galaxies with no Lyα emission. Non trivial

Half of the LBG population at z=6

Vanzella, Pentericci et al. in prep.

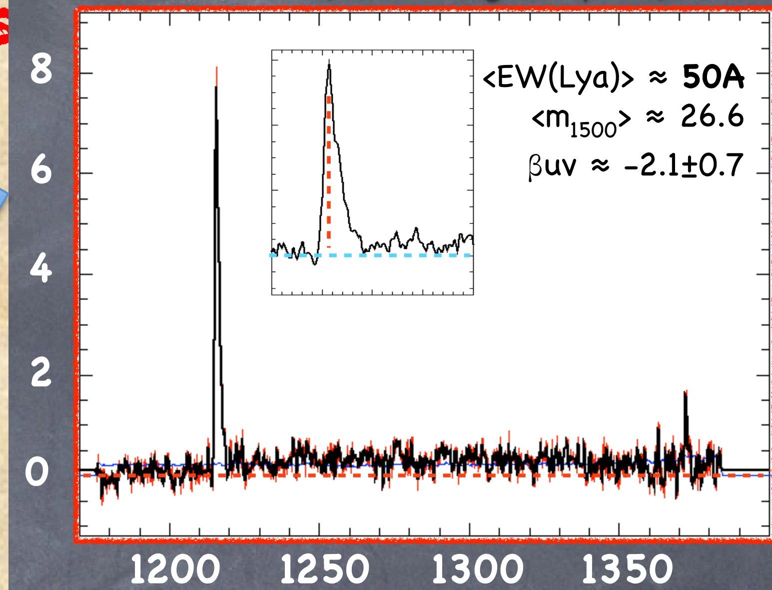
Deep stacking of z=6 galaxies



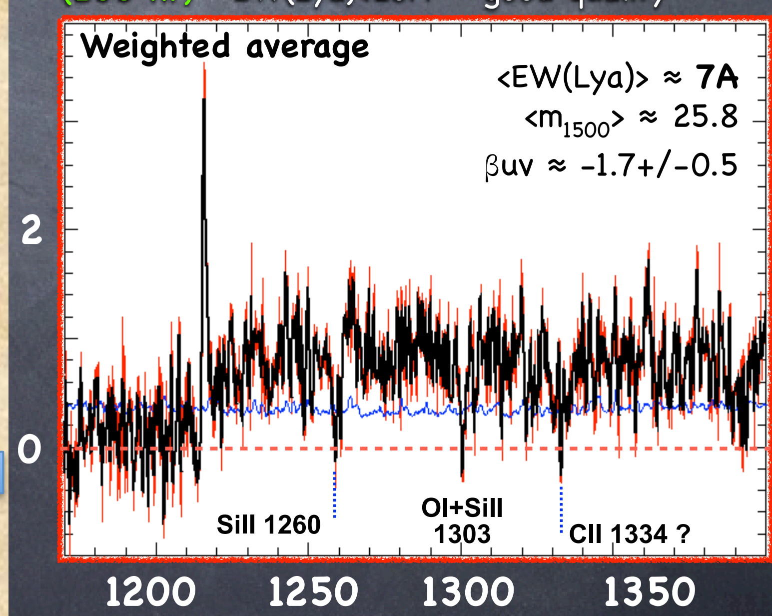
EW>20Å

EW<20Å

(400 hr) EW(Lya)>20A good-quality



(200 hr) EW(Lya)<20A good quality

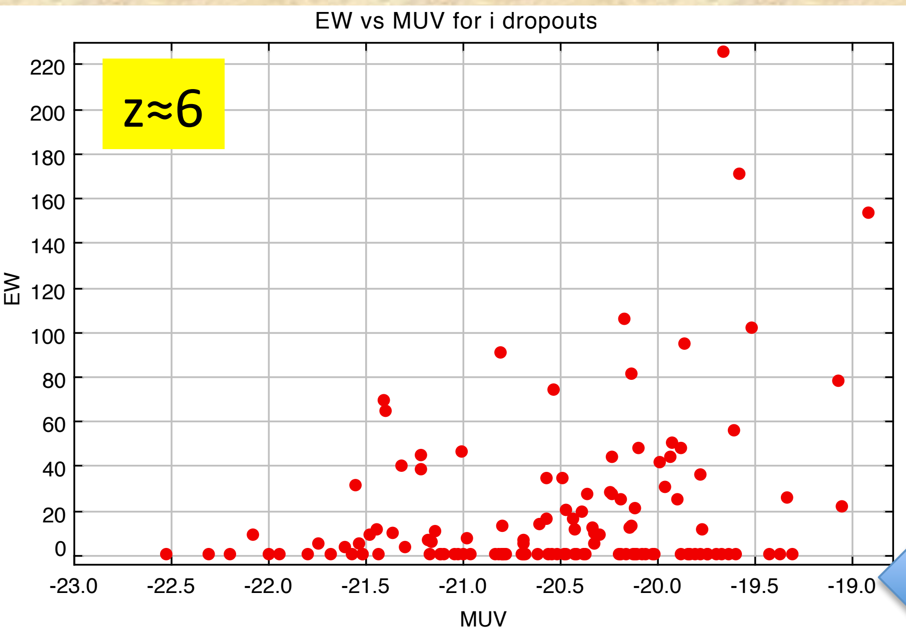


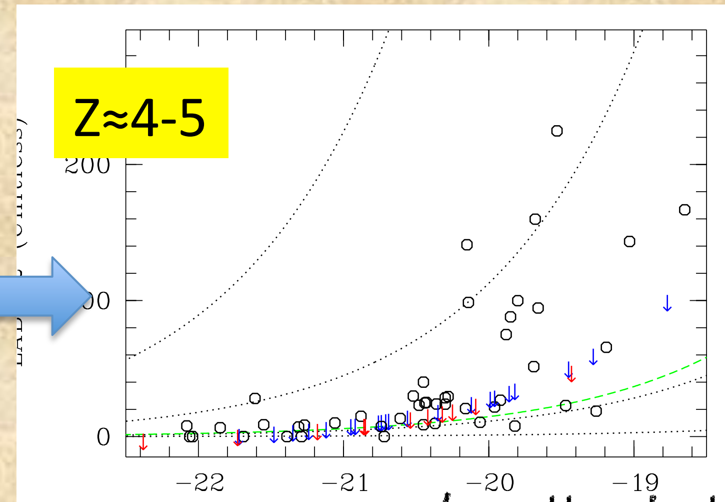
Compete sample: equivalent to 740 hours

Stacks allow us to study average properties: ISM abs lines , UV slopes, sizes and trends.

E.g. correlation between strength of UV absorption lines and Lyα emission at z=6

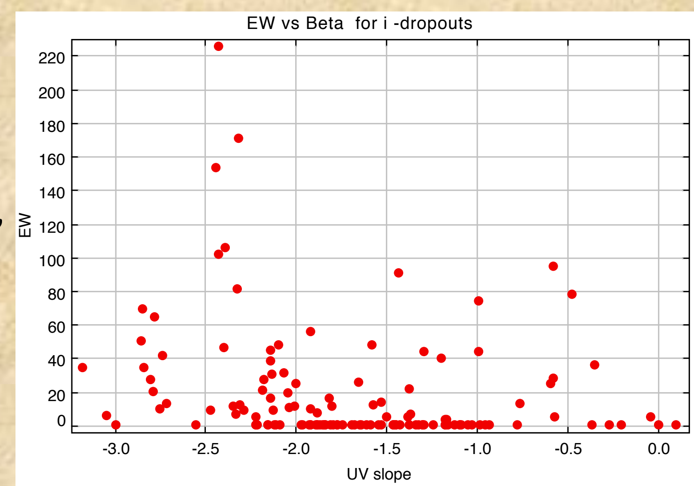
For the large sample of z=6 galaxies we can observe the clear trend that fainter galaxies have progressively brighter Lyα emission exactly as observed at lower redshift





Vanzella et al. 2009

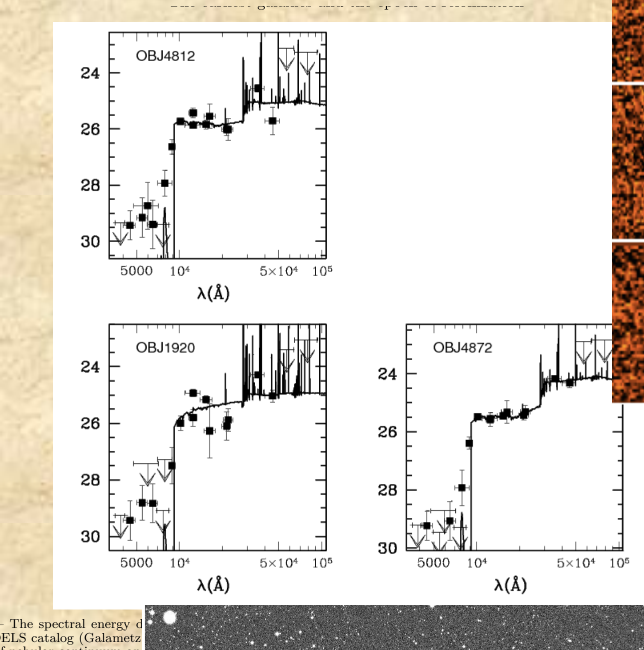
We observe a less strong correlation between the UV slope β and Lyα EW, which is observed at lower redshifts

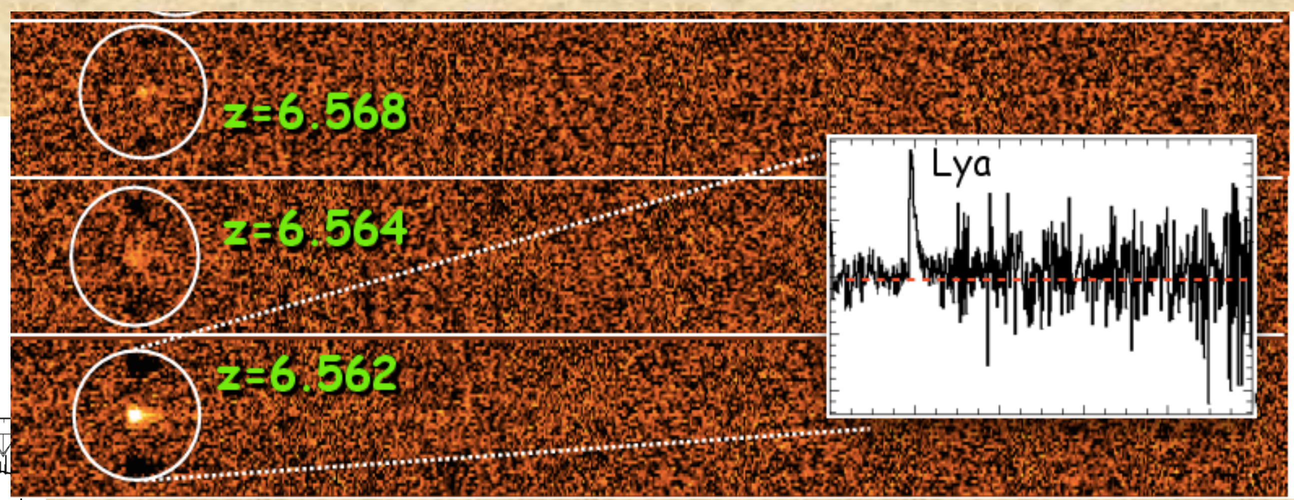


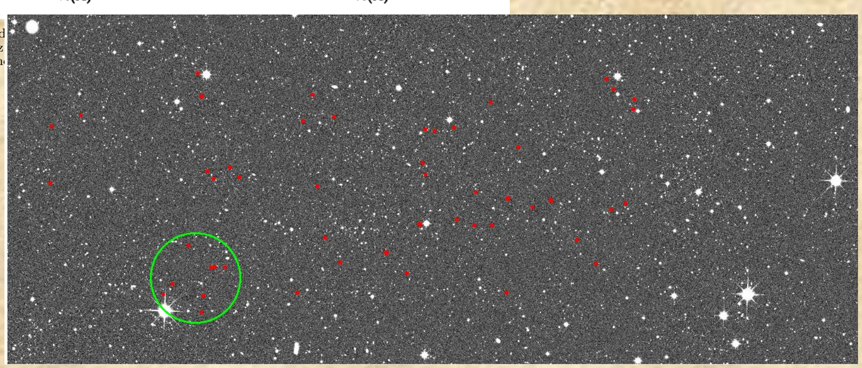
Early structures at the end of the reionization epoch: a triplet of galaxies at z=6.6 in the UDS field

We found 3 extremely bright galaxies (M_{UV}=-21-21.5) with Lyα emission.

Their redshifts are within 250 km/s of each other and the sky positions within 1 arcmin (≈340 kpc proper) at z=6.56

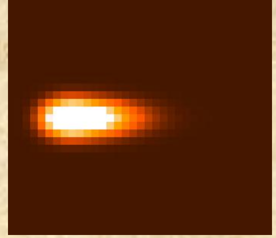


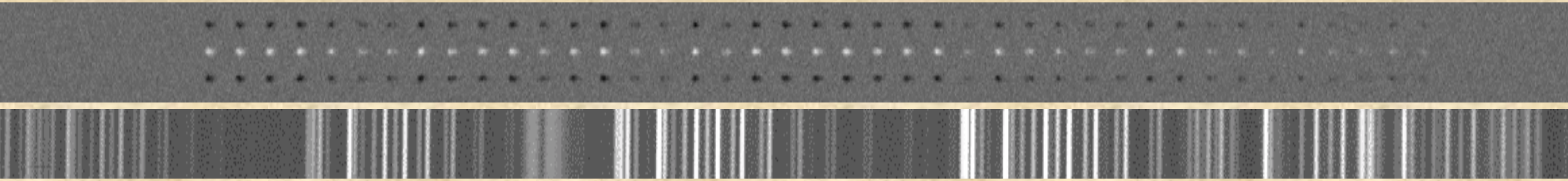


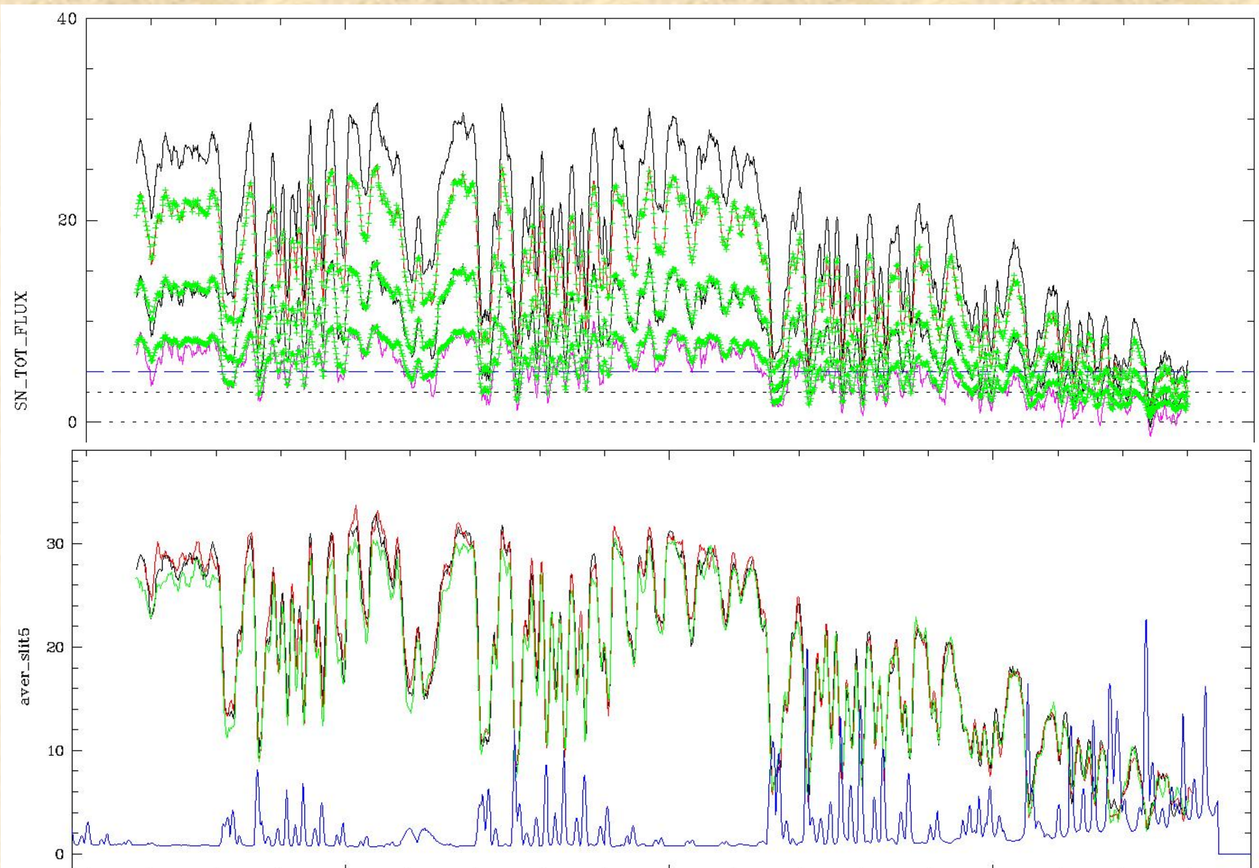


There is a >5σ over-density of photometric galaxies around the triplet

To evaluate the fraction of Lyα emitters at z≈6 and z≈7 we first perform accurate 2D simulations to assess the sensitivity of our spectroscopic observations (and hence the EW limit reached for each object). Fake Lyα lines with realistic shapes, are inserted in real raw frames at varying wavelength and then processed as real data by our own reduction pipeline

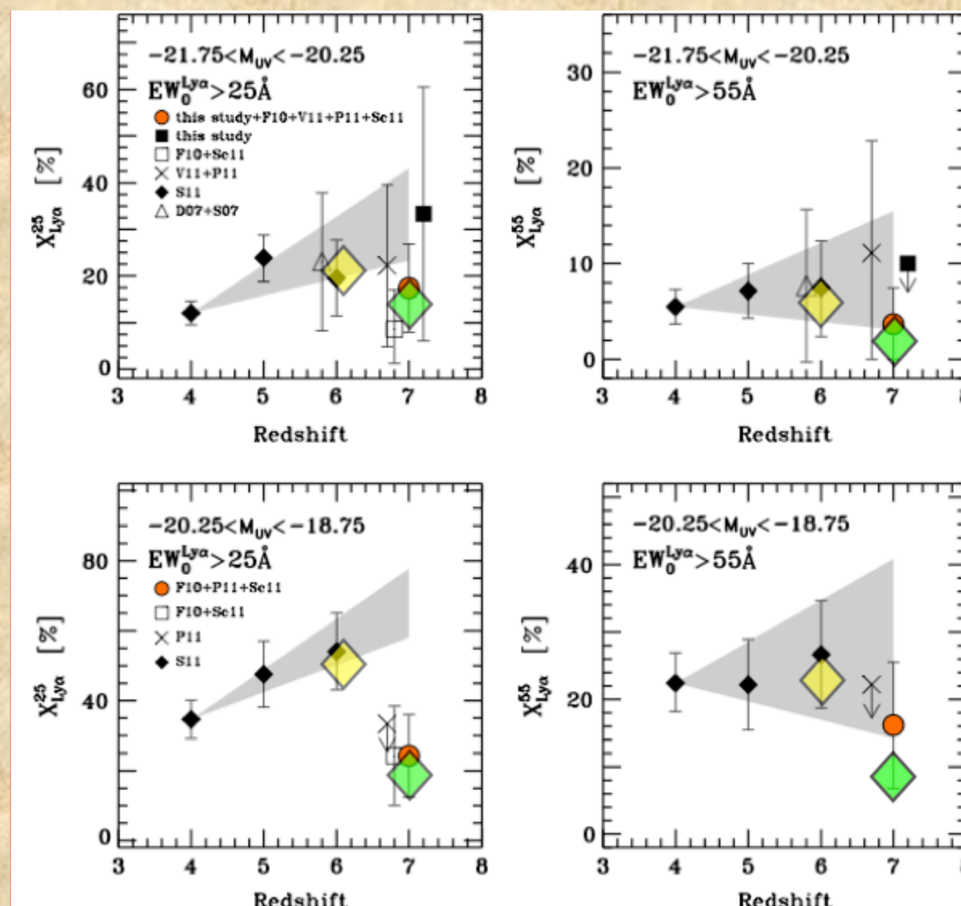






Simulations are repeated for different line fluxes, different slits in the masks, and different spatial positions along the slit to get all possible resulting S/N, which are then converted into EW limits depending on the magnitudes of the targets)

Including new Large Program data & earlier & archival observations we assembled a sample of ≈120 z-dropouts & 180 i-dropouts in 8 independent fields: this is the largest homogeneous sample of high-z galaxies observed spectroscopically. We can now measure the Lyα emission fraction at z=6 & z=7 with great accuracy



bright galaxies (M_{UV}<-20.25)

faint galaxies (M_{UV}>-20.25)

EW(Lyα) > 25 Å

EW(Lyα) > 55 Å

new z=7 limits

new z=6 limits

Ono et al. 2012

Is Lyα quenched by neutral hydrogen?

The challenge in using Lyα emitting galaxies as a probe of reionization lies in correctly interpreting observations

The Lyα transfer involves a wide range of scales including

-interstellar medium with dust and gas distribution and kinematics (e.g. Hutter et al. 2014)

-circum-galactic medium i.e. direct environment of the galaxies out to few hundreds kpc (e.g. Laursen et al. 2011)

-IGM which contains diffuse neutral gas surrounding large ionized bubbles which themselves contain dense self-shielding gas clouds

The reduced visibility of Lyα emission during the EoR is controlled by both diffuse HI patches in large-scale bubble morphology and small-scale absorbers. The possible approaches are:

1)The "bubble" models where small scale absorbers are neglected and the global HI fraction measures the content of HI in the diffuse neutral IGM outside the ionized bubbles(e.g. Dijkstra et al. 2011, Jensen et al. 2013)

2) The "Web" models where only small scale HI absorbers are considered (e.g. Bolton & Haenhelt 2013)

3) The "Web-bubble" models which contain both neutral phases (e.g. Mesinger et al. 2015, Choudhury et al. 2015, Kachiiki et al. 2016)

In addition the escape fraction of LyC photons adds another degeneracy parameter as explored e.g. in Mesinger et al. 2014

Setting constraints on the neutral hydrogen fraction

An example of **bubble model** is the one developed by **Dijkstra & Whyite (2011)** which couples large scale semi-numeric simulations of reionization with galaxies outflows, adapted to our redshift and mass range

Assumptions – the Universe is completely ionized by z=6

- the escape fraction of LyC photons remains unchanged
- the EW distribution at z=6 is modeled as an exponential function matching observations
- the halos of simulated LBGs have $5x\ 10^8\ M_\odot < m_{halo} < 10^{12}\ M_\odot$ SFR up to 1-20 $M_\odot$/yr
- the galaxies have no dust

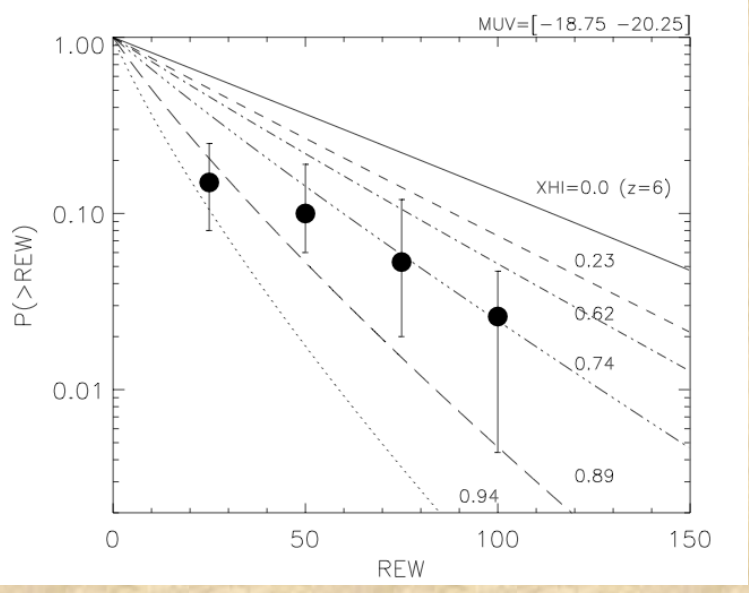
Variables:

--Outflowing wind velocity
FIDUCIAL MODEL 200 km/s

--Neutral hydrogen fraction

--Column density of HI

FIDUCIAL MODEL: $N_{HI}=10^{20}\ cm^2$

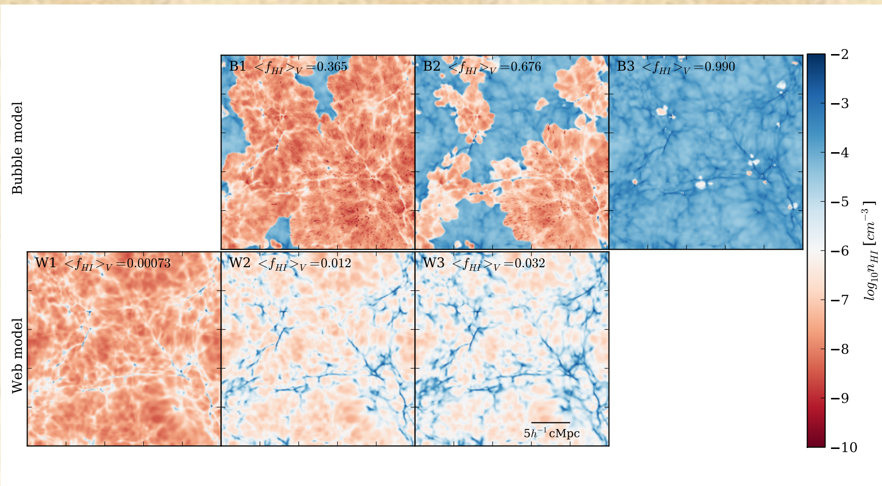


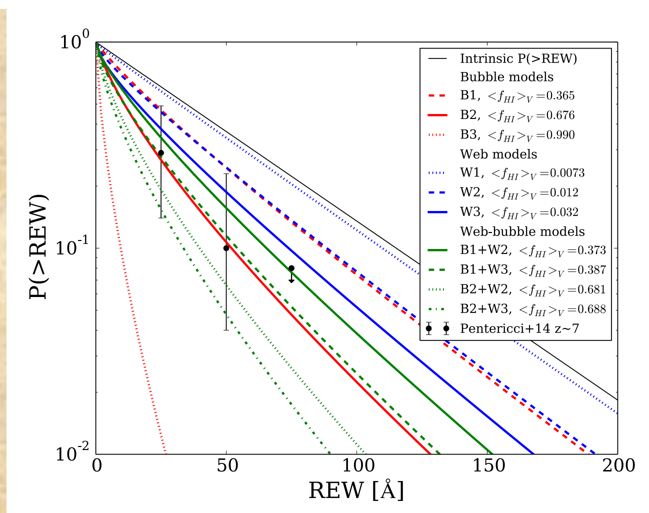
$X_{HI} \geq 0.62$ @z=7

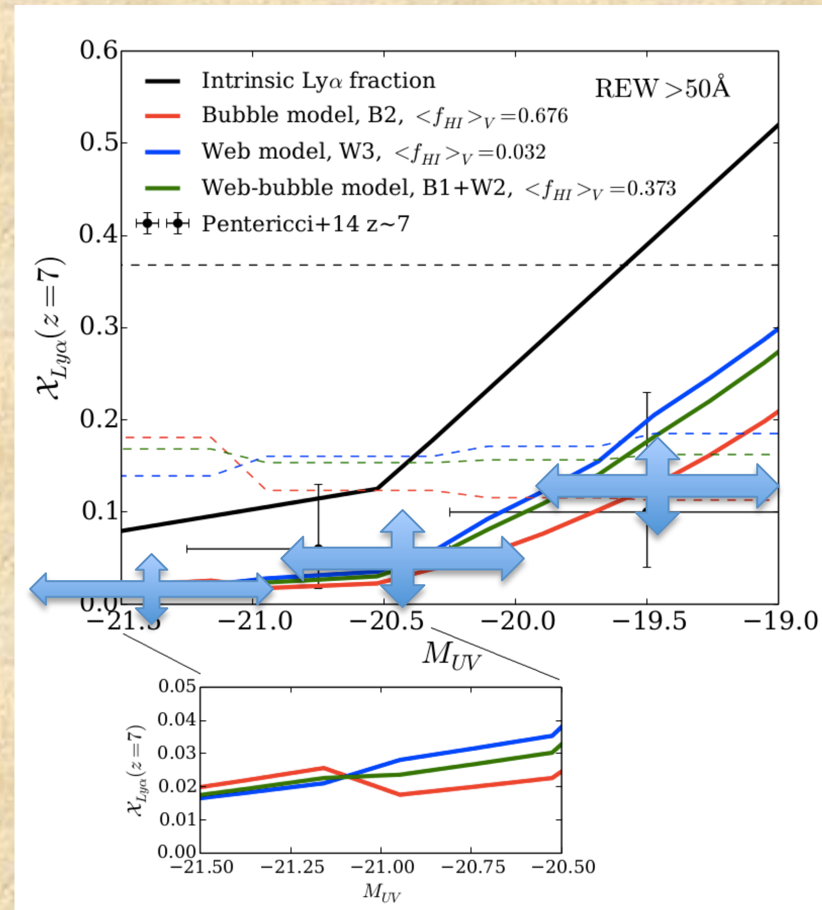
New limits from final sample

Setting constraints on the neutral hydrogen fraction

An example of **web-bubble model** is the one developed **by Kachiiki et al. 2016** together with purely web and purely bubble models: they show that a joint analysis of LAE LF and Ly emission fraction in LBGs can potentially discriminate between these models







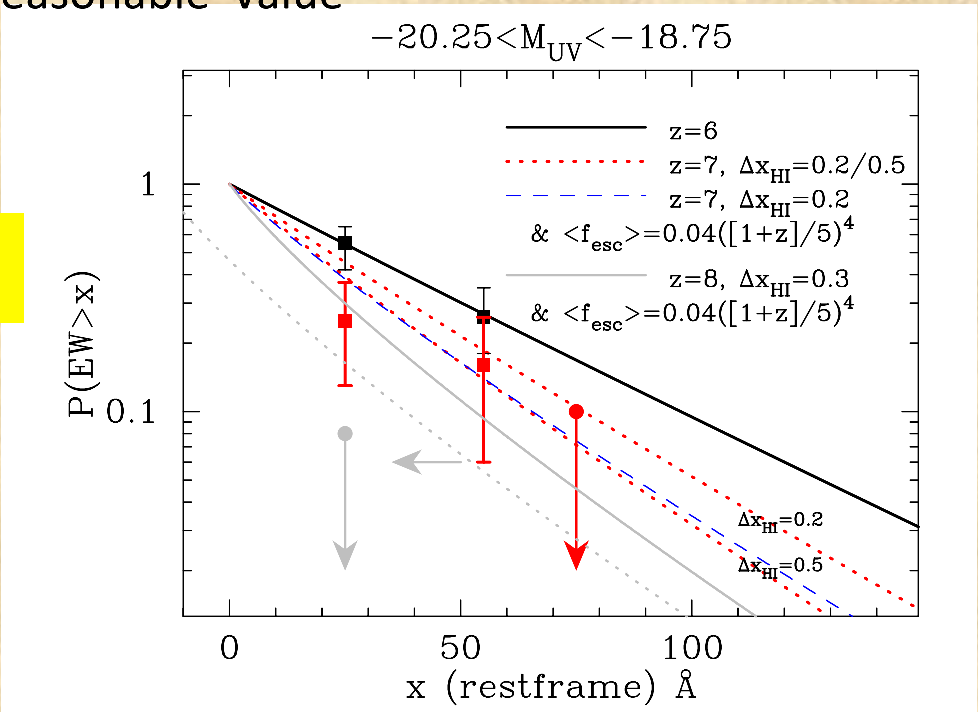
Setting constraints on the neutral hydrogen fraction

Alternatively the observed reduction in Lyα at z=7 could be explained by an evolution in the escape fraction of ionizing photons, f_{esc} as in **Mesinger et al. 2014**

To match the observed data with a pure evolution in f_{esc} and no change in HI, requires f_{esc} values that are far too large (f_{esc}=0.65 at z=6 and 0.75 at z=7) compared to low redshift

However assuming $f_{esc}=0.04[(1+z)/5]^4$ (as in Becker & Bolton 2013) coupled with change in HI can do the job with a more reasonable value

$X_{HI} \geq 0.2$ & f_{esc}=0.26 @z=7

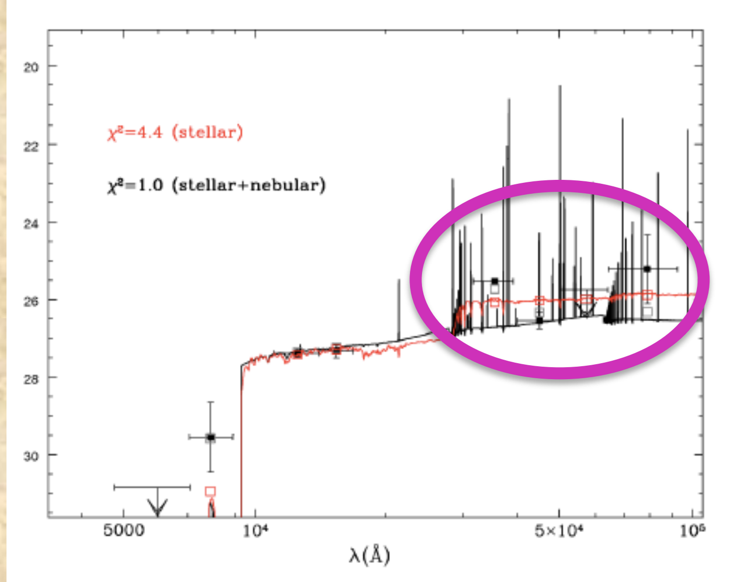


Can we set any (indirect) constraint on fesc at high z?

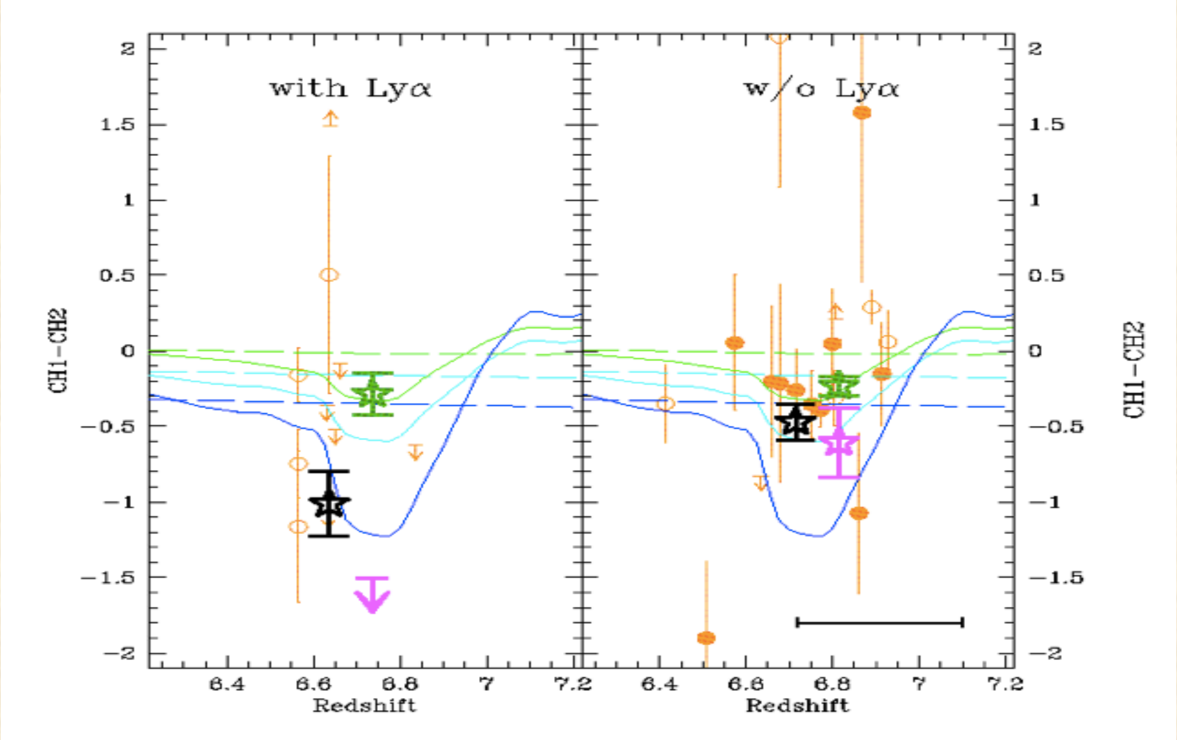
While increasing f_{esc} and increasing neutral hydrogen have similar (degenerate) effect on the visibility of the Lyα line, the optical emission lines [OIII] and Hβ are only affected by f_{esc}

Although the direct detection of these lines will be possible only with JWST, they can be already studied from the IRAC bands.

Accurate SED fitting of high redshift galaxies requires almost always strong contribution by nebular lines (e.g. De Barros et al 2014)



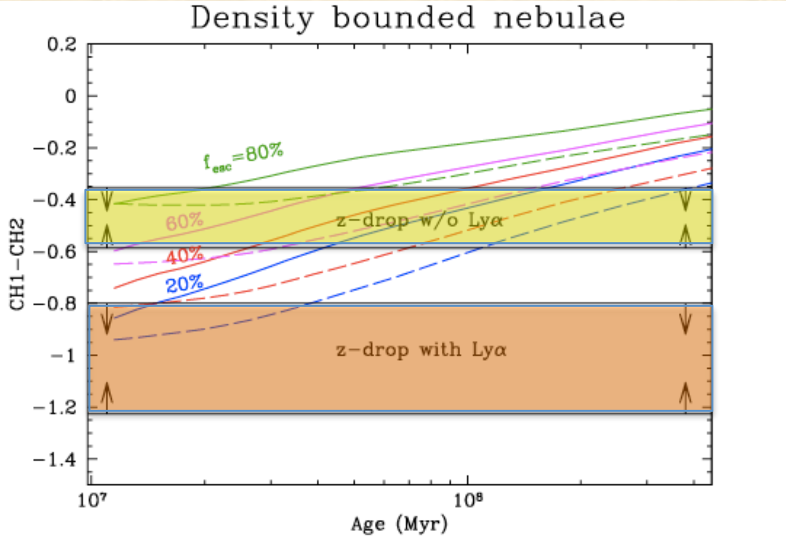
We selected galaxies with z=6.5 - 7 and derived IRAC CH1-CH2 colors of those in UDS and GOODS fields where the deepest IRAC imaging is available.
We divide our sample in galaxies with and without Lyα emission line

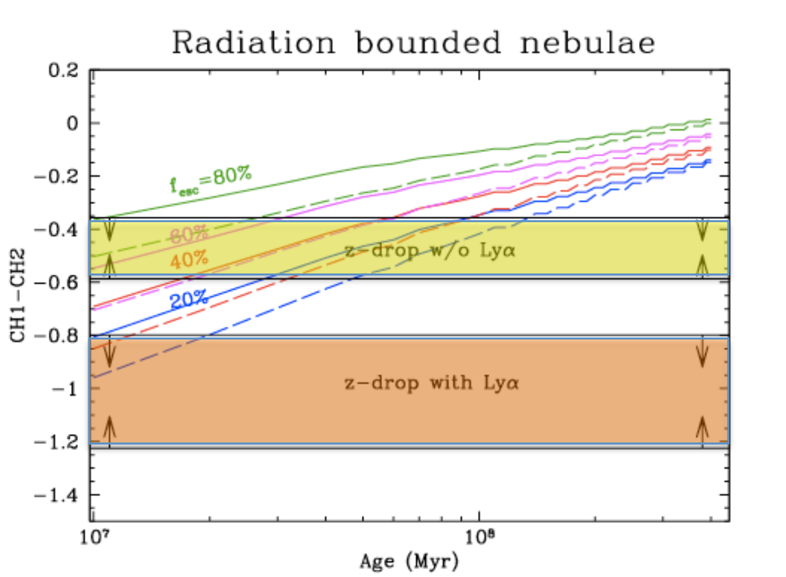



Stacked color

Although a large scatter is present in both samples, the galaxies with Lyα in emission have a much larger color term (Ch1-Ch2=-1.0±0.21) than galaxies without Lyα (Ch1-Ch2=-0.47±0.11)

Castellano, Pentericci et al A&A to be subm.





We compute the expected IRAC colour for different f_{esc} values as a function of galaxy age for:

1) stellar + nebular templates (Schaerer & de Barros 2009), assuming caseB recombination and He and metals lines from Anders et al. (2003) as in a radiation bounded nebula.

2) a density bounded nebula modelled with CLOUDY with stellar templates from BC03

In both scenarios, Lyα emitters are reproduced only if f_{esc}< 20%. At variance the colours of non-emitters are consistent with higher f_{esc} if age <300 Myrs (density bounded model) or <100 Mys (radiation bounded)

If the trend of decreasing Lyα is confirmed → galaxies at z > 7.5 might mostly have extremely faint Lyα emission lines (EW < 10 Å flux < 10^{-18} erg/s/cm) or Lyα may be absent → it will be hard to secure the redshifts of *statistical samples* of z=7.5-8.5 galaxies with current near-IR facilities (MOSFIRE, KMOS, LUCIFER..)

We have to seek new methods to confirm the redshift of sizeable samples of galaxies during the first 600 Mys

**Alternative selection e.g. indication of strong [OIII]+Hβ in IRAC 4.5μ channel. (Roberts-Borsani et al 2016, Stark et al 2016)

Alternative emission lines shifted in the near-IR e.g. **CIV 1548, OIII]1664 & CIII]1909 which are not affected by neutral hydrogen (Oesch et al. 2015)

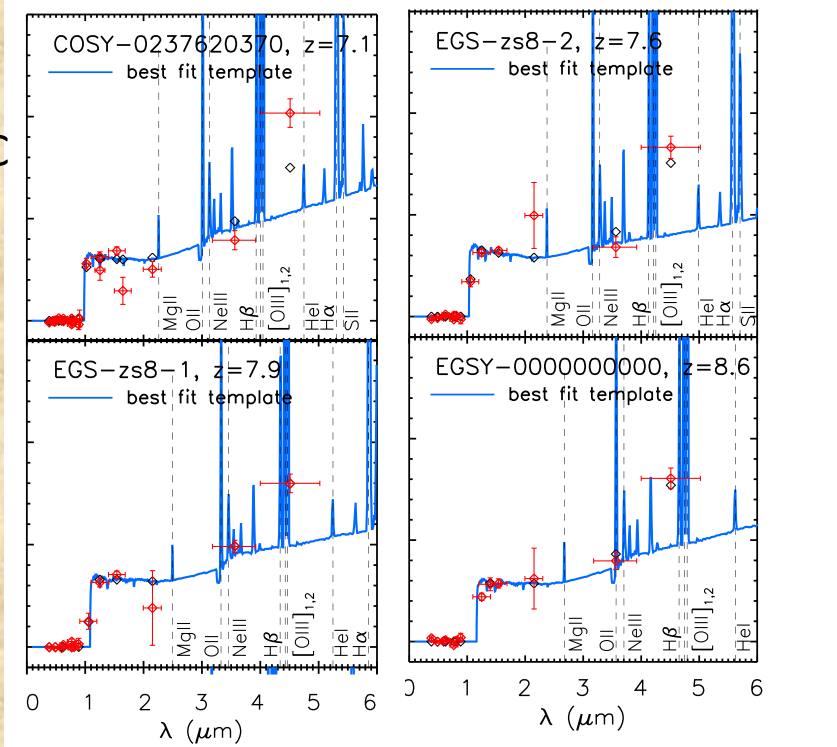
**Lensed galaxies where Lyα should be stronger

**ALMA observations of [CII]158μm

A new recent development

At 7<z<9 the [OIII]-Hβ lines pollutes the 4.5 IRAC channel. Selecting sources with a strong 4.5μ excess targets galaxies with intense line emission

In the CANDELS fields 4 such sources were identified and spectroscopy confirmed the presence of Lyα in all of them (Stark et al. 2016, Oesch et al. 2015) including most distant galaxy at z=8.68 (Zitrin et al. 2015)



Roberts-Borsani et al (2015)

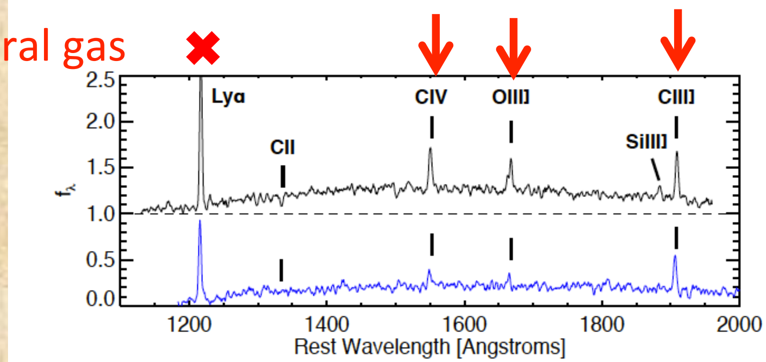
But at these redshifts the IGM should be almost completely neutral…so what's happening?

Photoionization models require large ξ_{ion} suggesting efficient LyC production: the intense radiation could have carved large bubbles of ionized hydrogen in an otherwise neutral IGM already at earlier times, boosting the transmission of Lyα (Stark et al. 2016)

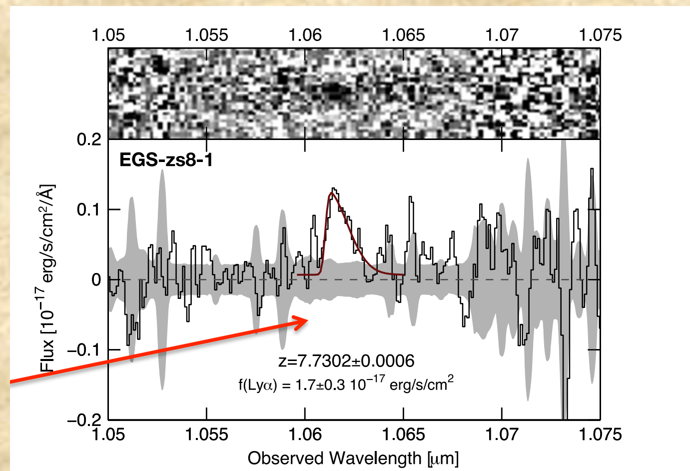
In addition clustering around very bright sources (the 4 galaxies have M_{UV} ≈-22) could contribute In forming bubbles of ionized gas (e.g. Castellano et al. 2015 overdensity of z=7 candidates around two confirmed galaxies)

Alternative emission lines

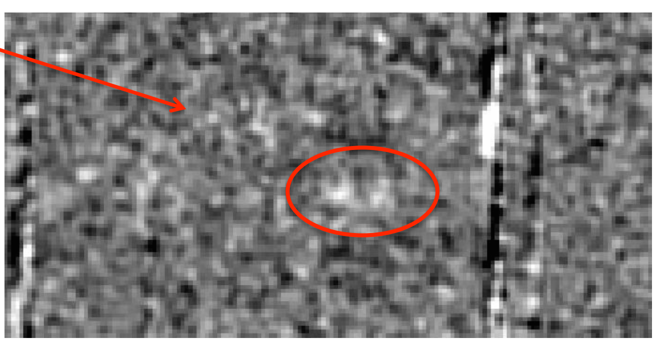
Neutral gas

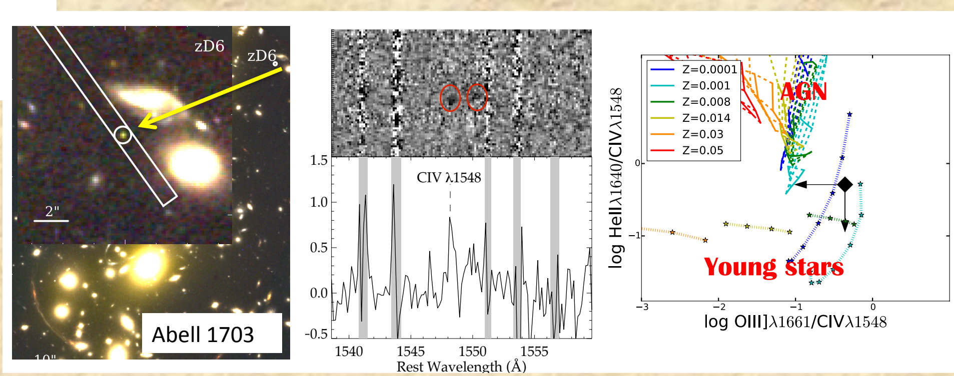


1) Some UV emission lines could be particularly strong in faint, metal poor galaxies: e.g. CIV 1548, OIII]1664 & CIII]1909 , which are not affected by neutral gas absorption



e 2015





CIV doublet in a z=7.04 lensed galaxy:
CIV/Lyα >> than in normal galaxiess
High ionization ξ_{ion}/ low metallicity ≈0.01 solar

Lyα (top) and CIII](bottom) emission lines in the z=7.73 galaxy identified by Oesch et al. (2015)

Lensed galaxies

Lyα should be very strong in very faint galaxies given the M_{uv} vs EW relation observed at lower redshift

So far few spectroscopic confirmations (Bradac et al. 2012, Schenker et al. 2012, Vanzella et al. 2014, Huang et al. 2015)

Systematic searches:
CLASH VLT follow up (Rosati et al.): probed not deep enough for z≈7 galaxies

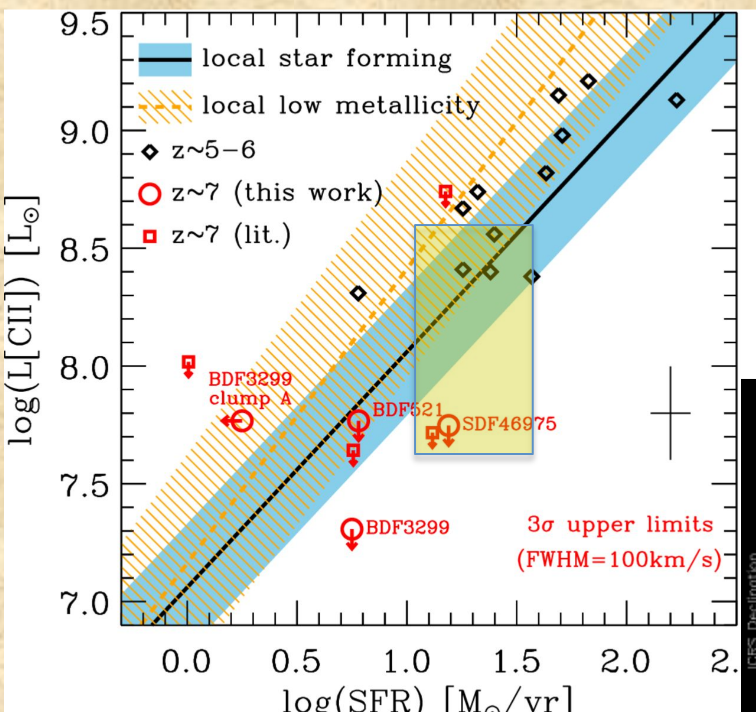
GLASS (The Grism Lens-Amplified Survey from Space, PI T. Treu) In 24/159 candidate high-z galaxies we detect emission lines consistent with Lyα @ 6.2 < z< 10.2 (Schmidt et al. 2015). However purity < 100% and some of the lines are ambiguous and/or low S/N

KMOS follow up of GLASS (ESO Large Program, PI A. Fontana)
Spectroscopic observations of 7 clusters with targets preselected to show signature of Lyα in the HST low resolution spectra
– 20 hours per cluster, > 25 candidates emitters at z>7

ALMA observations

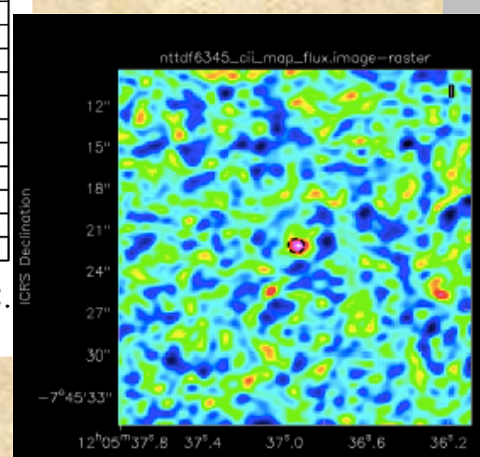
[CII]158μm line is not effected by neutral hydrogen & dust. Up to z=5-6 the CII-SFR relation is similar to the one for local star forming galaxies (Capak et al. 2015, Willott et al. 2015)

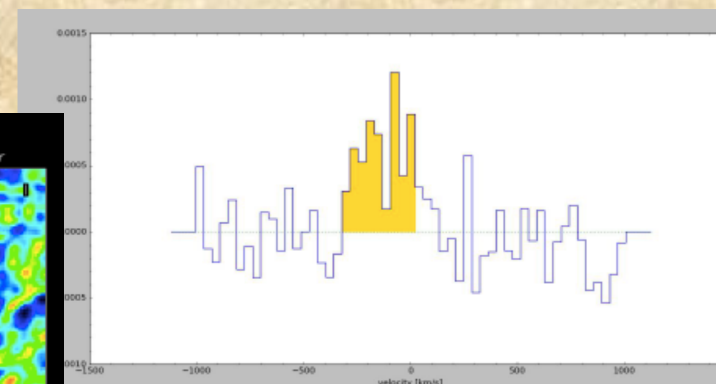
At z≈7 galaxies observations were initially disappointing with several non detections (Ota et al. 2014, Gonzalez-Lopez et al. 2014, Ouchi et al. 2013) but we are starting to get some results (Maiolino et al. 2015, Watson et al. 2015)



We obtained time in ALMA Cycle 3 to observe the 7 brightest galaxies from the ESO Large Program with Lyα emission at 6.6<z<7.2 and SFR > 15 $M_\odot$/yr

…………………results are very promising!!!





A clear detection of CII ,

the rest under analysis now

STAY TUNED!!!