CANDELSz7: Looking for the CANDELS that reionized the Universe

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in collaboration with
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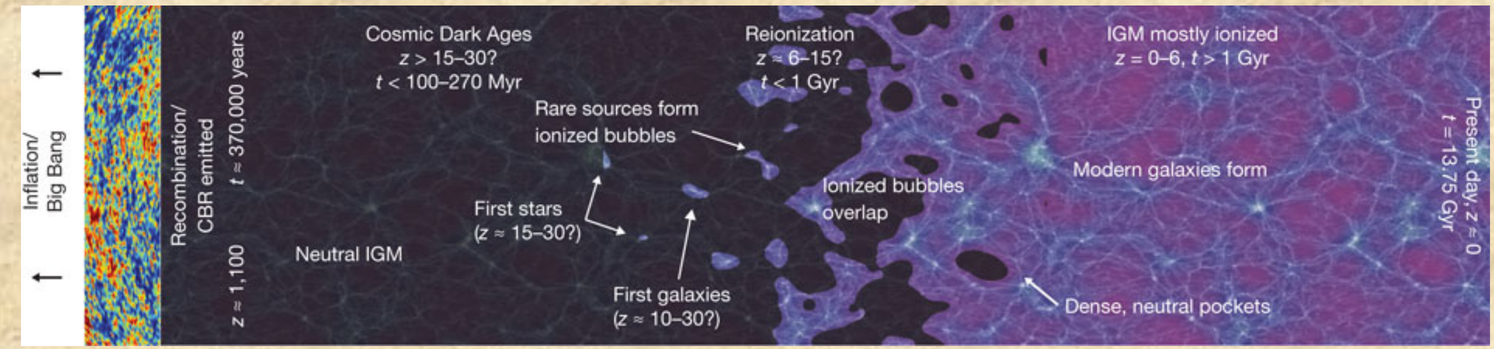
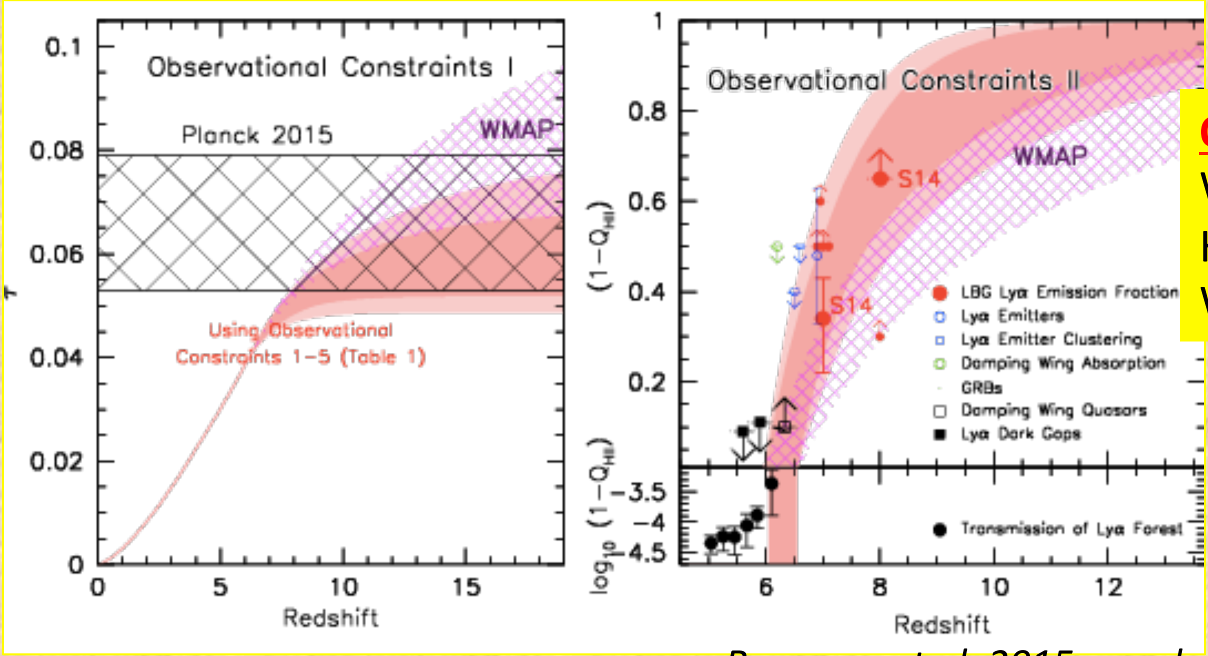
The early growth of galaxies, Sesto January 14th 2016

HI reionization epoch



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?

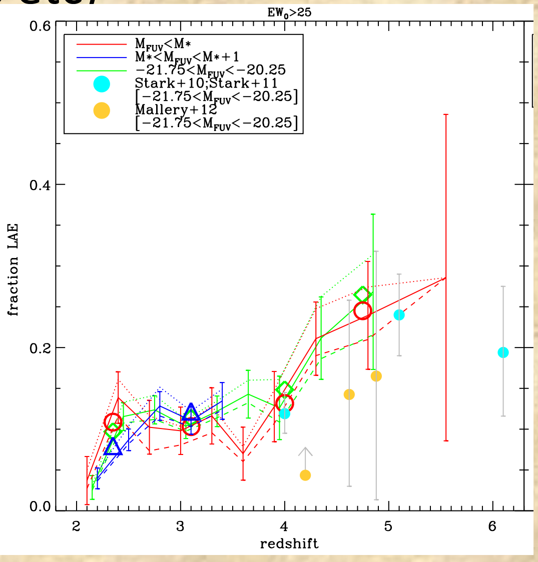
Bouwens et al. 2015 see also Robertson et al. 2015

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

RATIONALE - 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*)

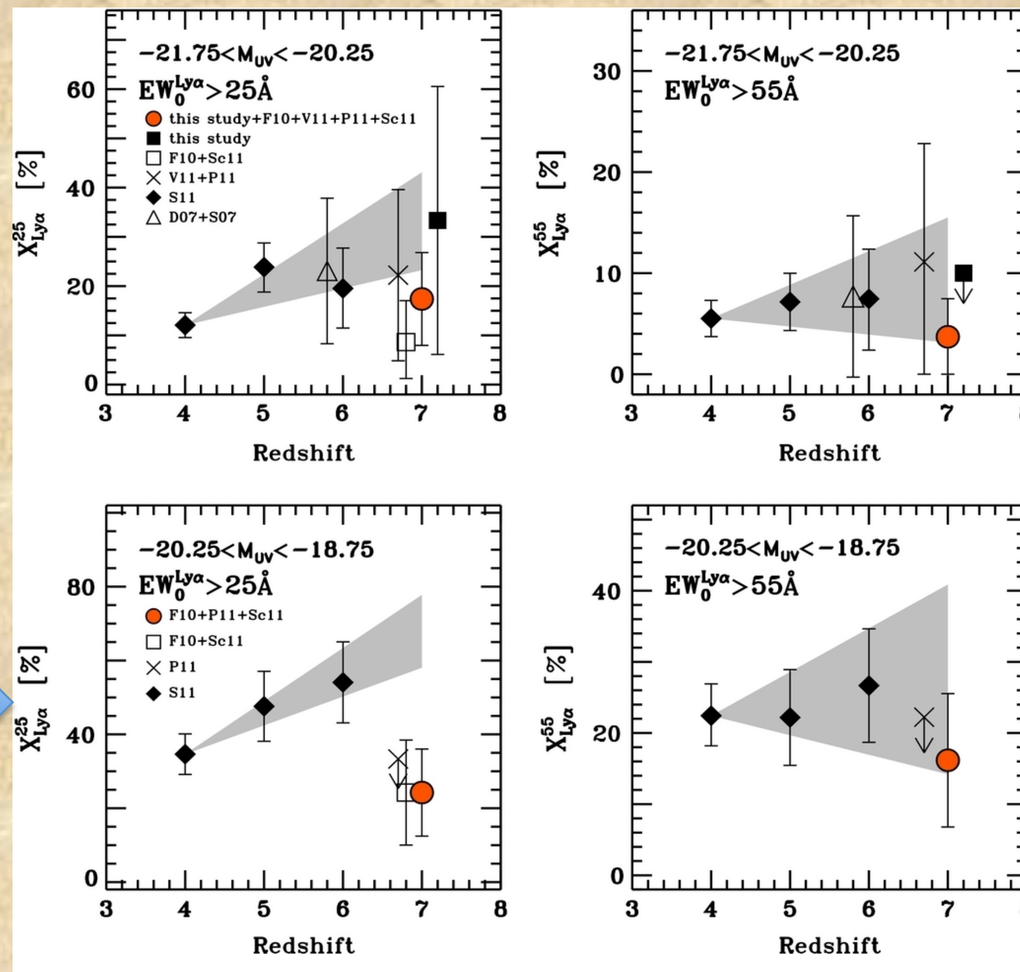


Cassata et al. 2014 (VUDS data)

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)

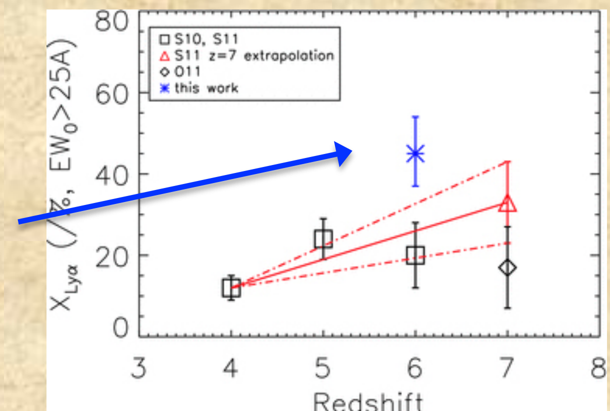


Stark et al. 2010, Pentericci et al. 2011, Ono et al. 2012 Schenker et al. 2012

CANDELSz7 : an ESO Large Program to probe the reionization epoch

Motivation

A.The early samples were **still small** and **very heterogeneous** in terms of :
1 selection (color vs zphot) 2. observational set-up (i.e. redshift coverage)
3. 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

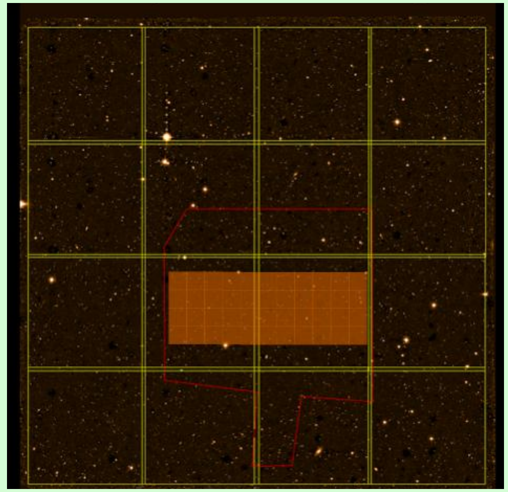
D. There were large field to field variation (e.g. Ono et al. 2012)probably due to spatial fluctuations depending on the degree of homogeneity/inhomogeneity of the reionization process (e.g. Taylor & Lidz 2014)

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.

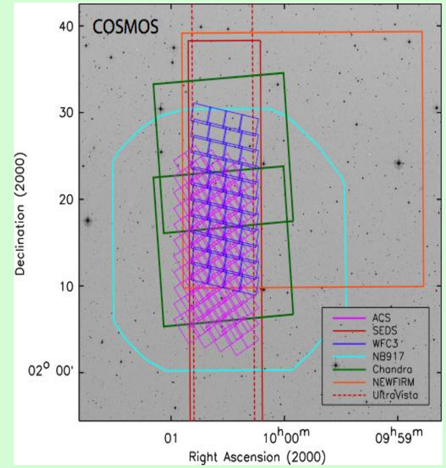
Selection of z ~ 6 & z ~ 7 candidates :

GOODS-SOUTH

UDS



COSMOS

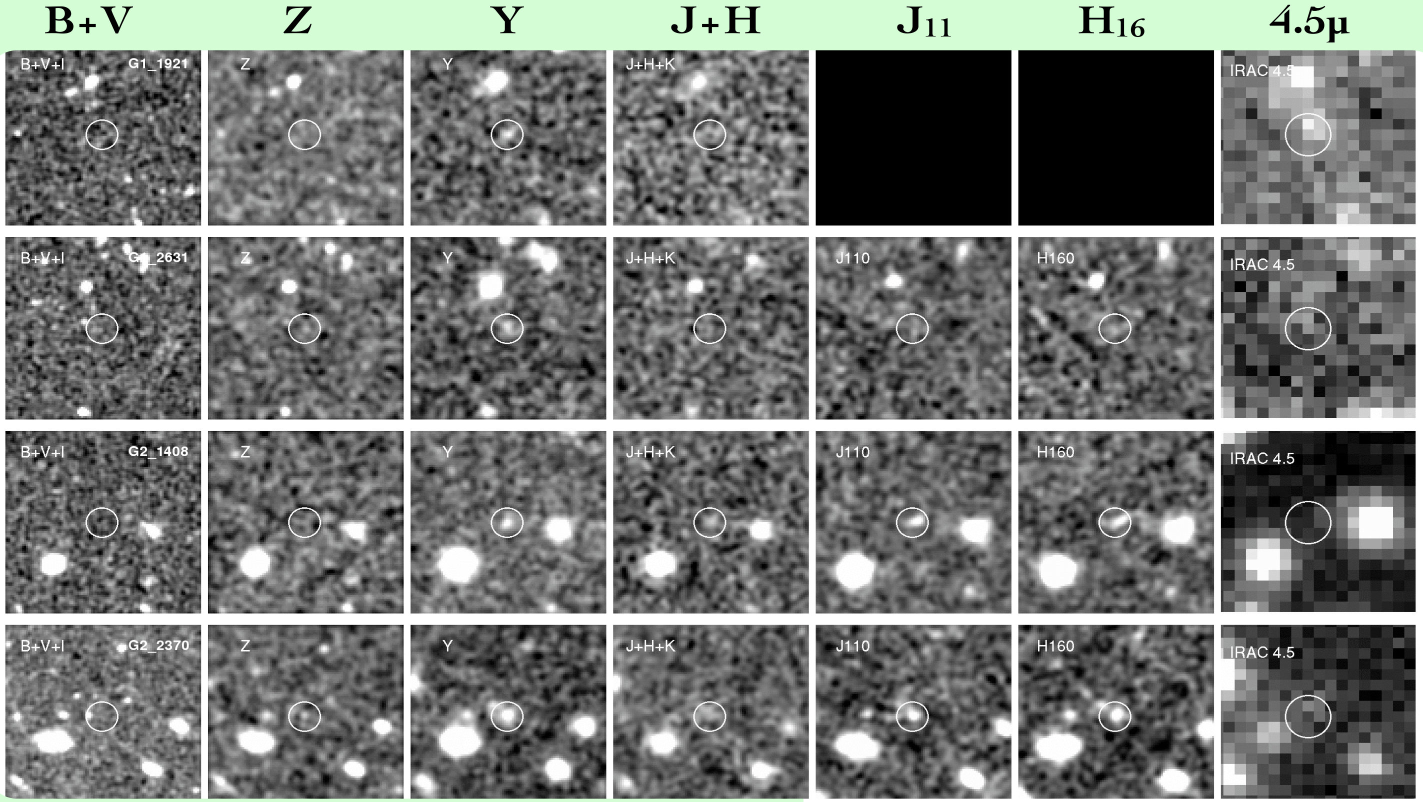


-Galaxies are selected with homogenous color-color criteria from the CANDELS data :

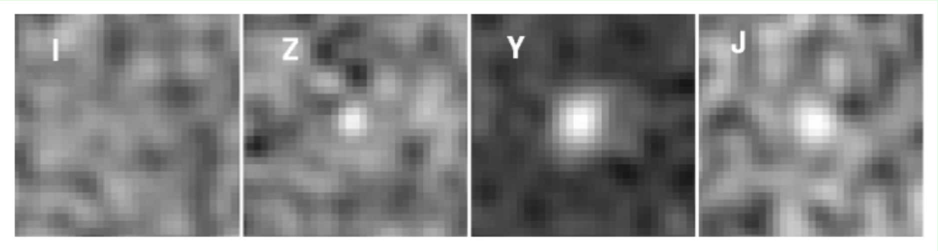
-The selection band (CANDELS H-band) is independent of the presence of Lyα both at z =6 AND z=7 unlike past surveys and minimizes the bias

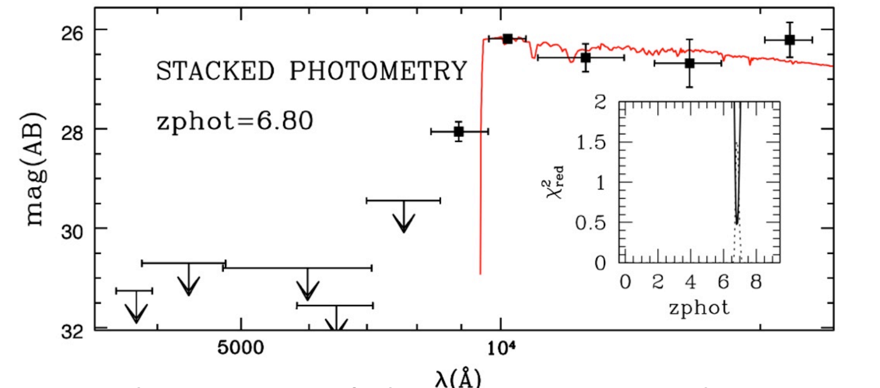
-We employ a unique spectroscopic set up and observational strategy: total integration time varies from 15 (for bright targets) to 25 hours (for faint targets) **to reach a uniform EW limit for all galaxies**.

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



STACK OF ALL CANDIDATES





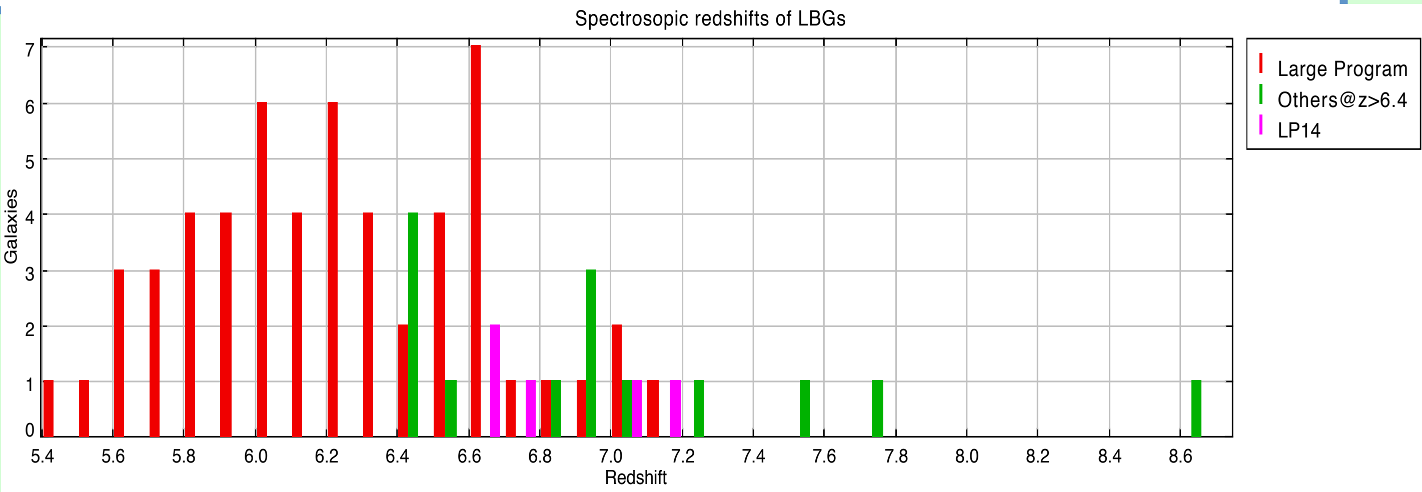
Very deep optical data are required to get rid of interlopers

CANDELSz7 OBSERVATIONS (just completed!!)

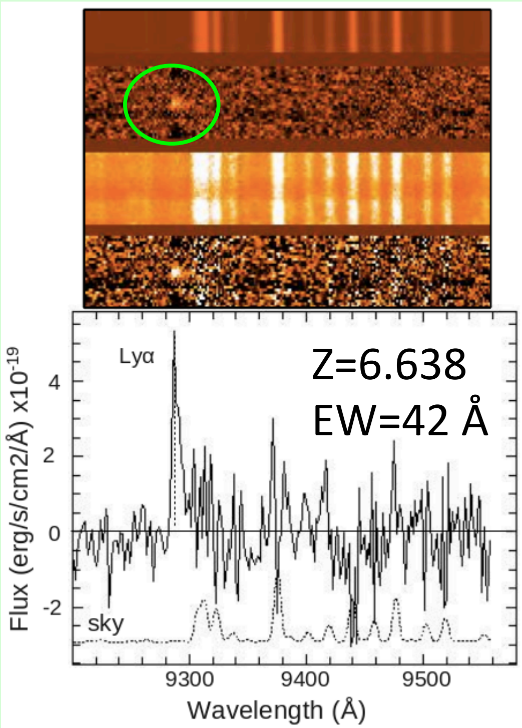
FIELD	TOT TIME	OBSERVED	REDUCED	ANALYSED
GOODS1	25	25	YES	YES
GOODS2	25	25	ONGOING	NO
UDS1	15	15	YES	YES
UDS2	15	15	YES	YES
UDS3	15	15	YES	ONGOING
COSMOS1	15	15	YES	YES
COSMOS2	15	15	YES	YES
COSMOS3	15	15	YES	YES
TOTAL	140 hours	140hours		

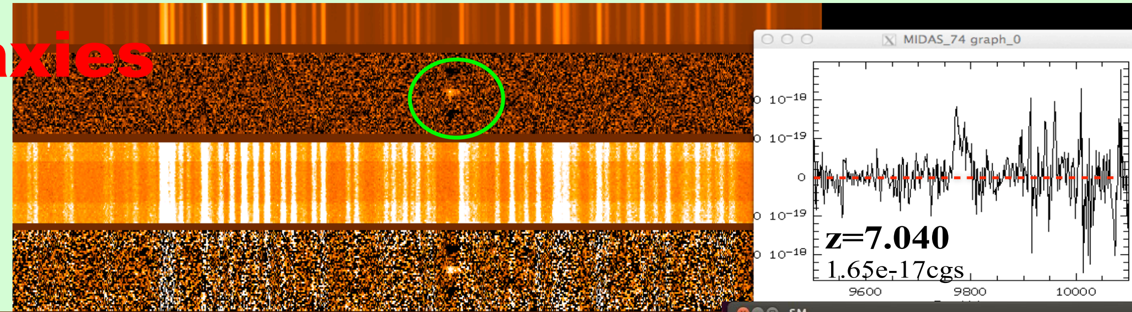
So far we analised ≈70 new candidate z dropouts (z≈7 candidate galaxies)
In addition a large number of i-dropouts observed and some high-z (z≈5) AGN candidates and several massive galaxies at low redshift.

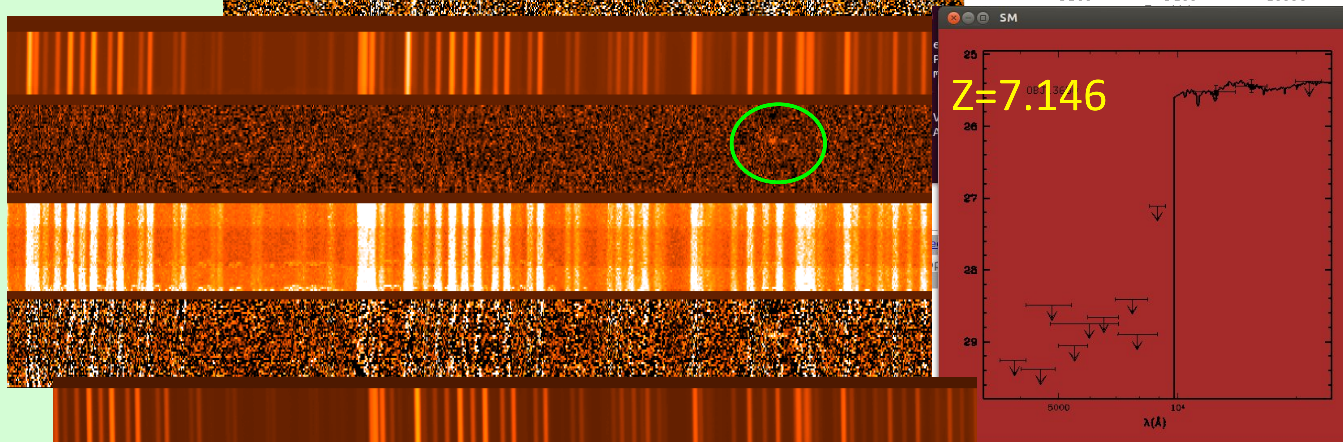
We have confirmed already 17 new galaxies at 6.5 < z < 7.2 all <u>with</u> Lyα emission and ≈ 40 new 5.5<z<6.5 galaxies with Lyα plus several with no Lyα emission

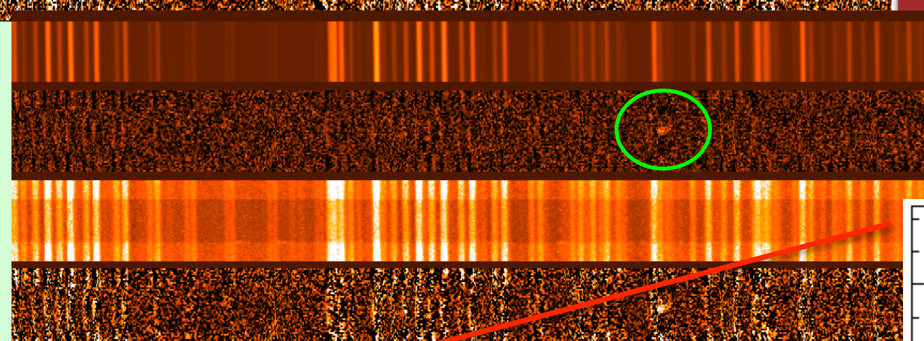


Some new high-z galaxies

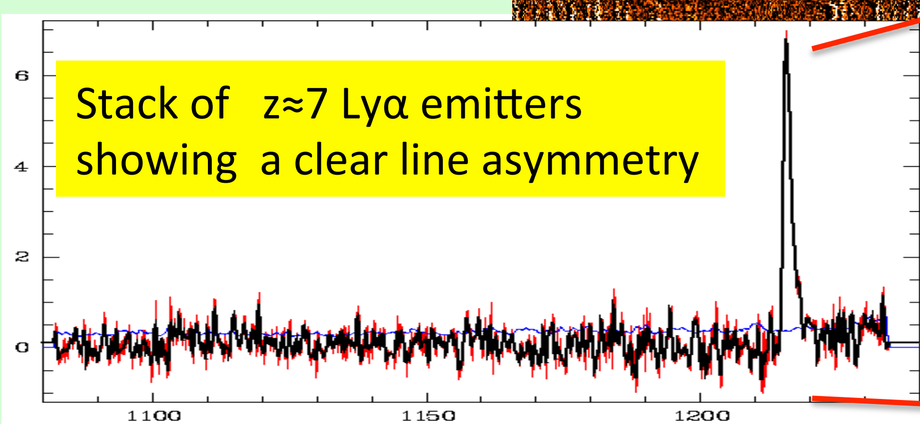


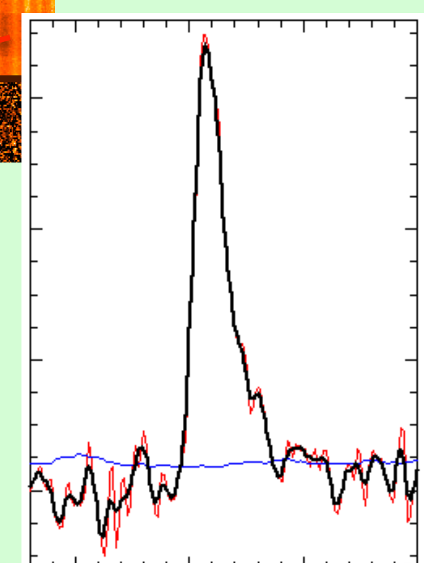




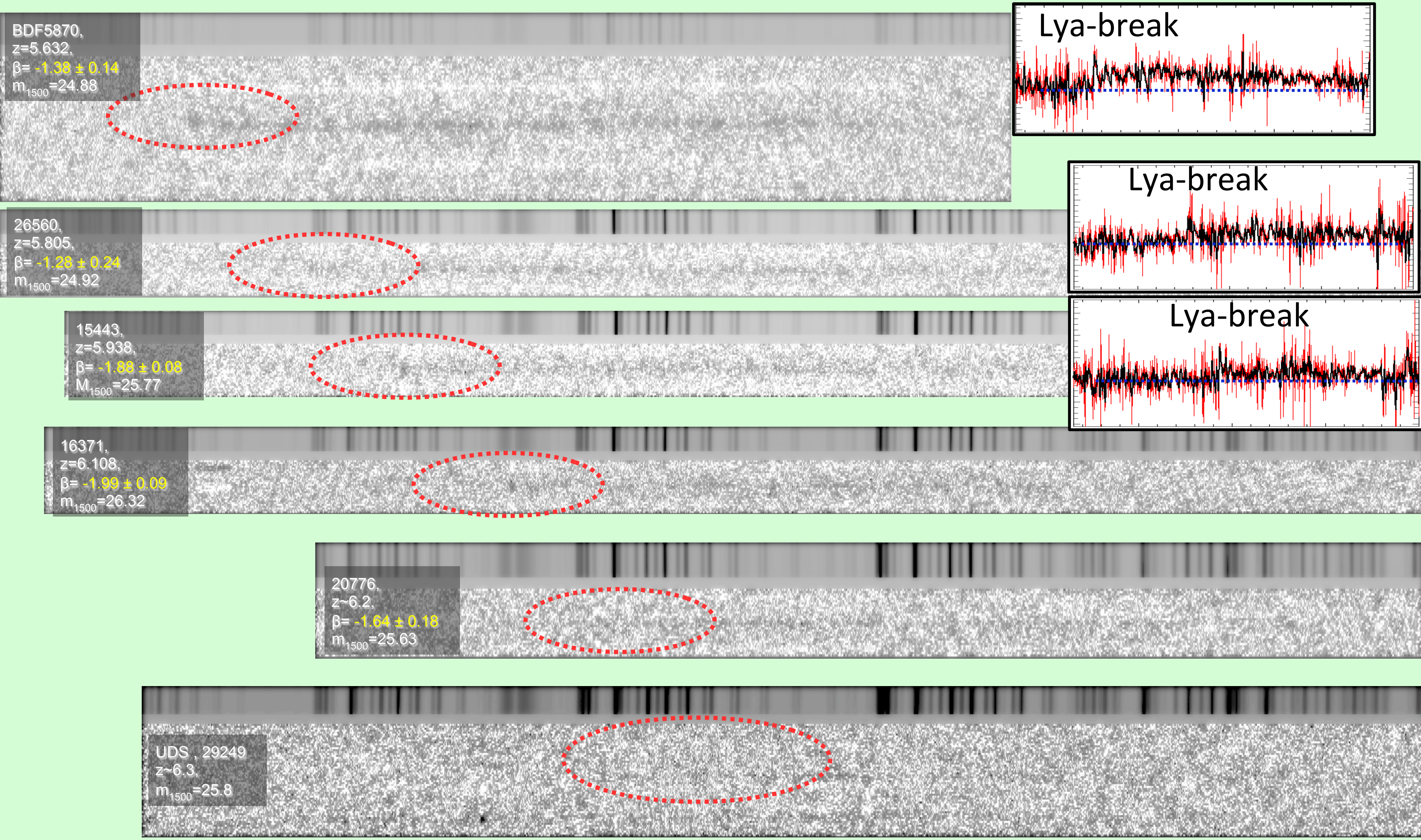


Z=7.065



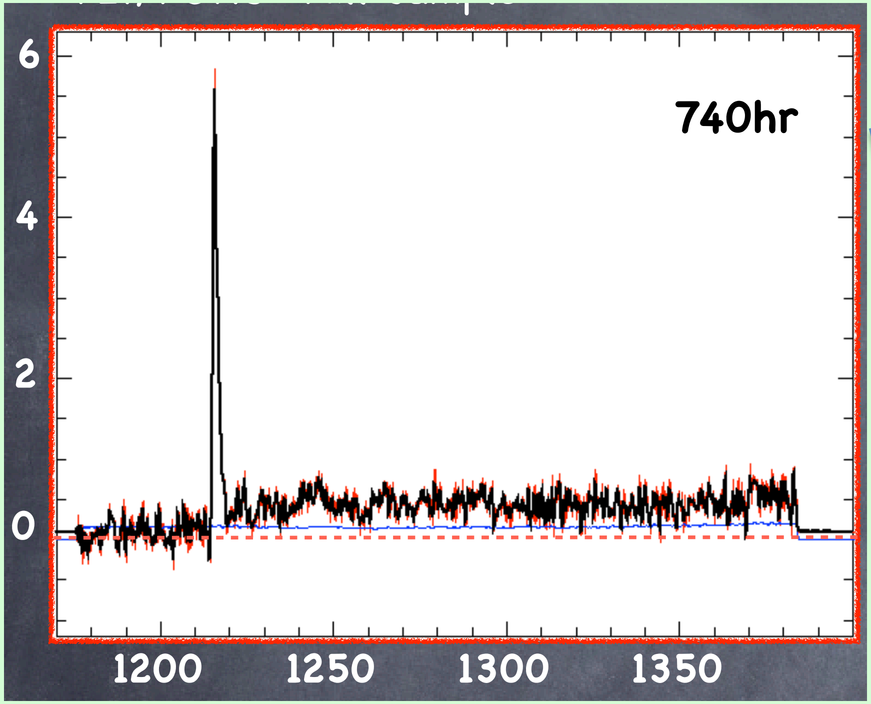


Deep spectroscopy starts to reveal faint z~6 non-Lyα emitters



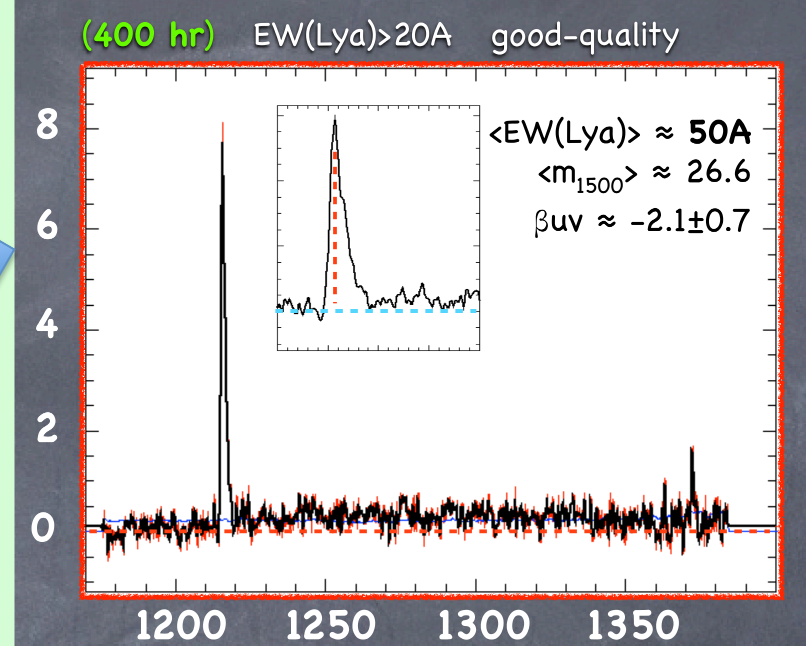
Vanzella, Pentericci et al. in prep.

Deep stacking of z=6 galaxies

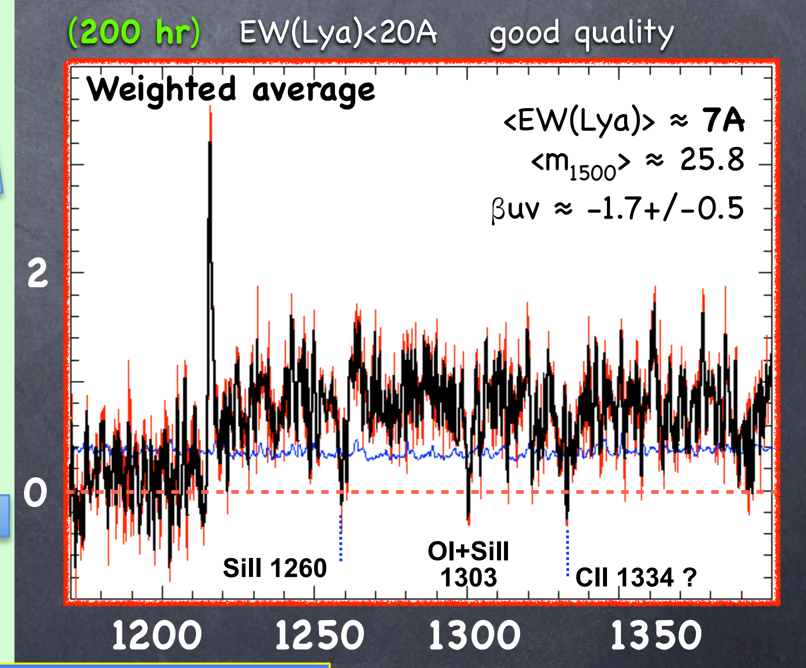


Compete sample: equivalent to 740 hours

EW>20Å



EW<20Å

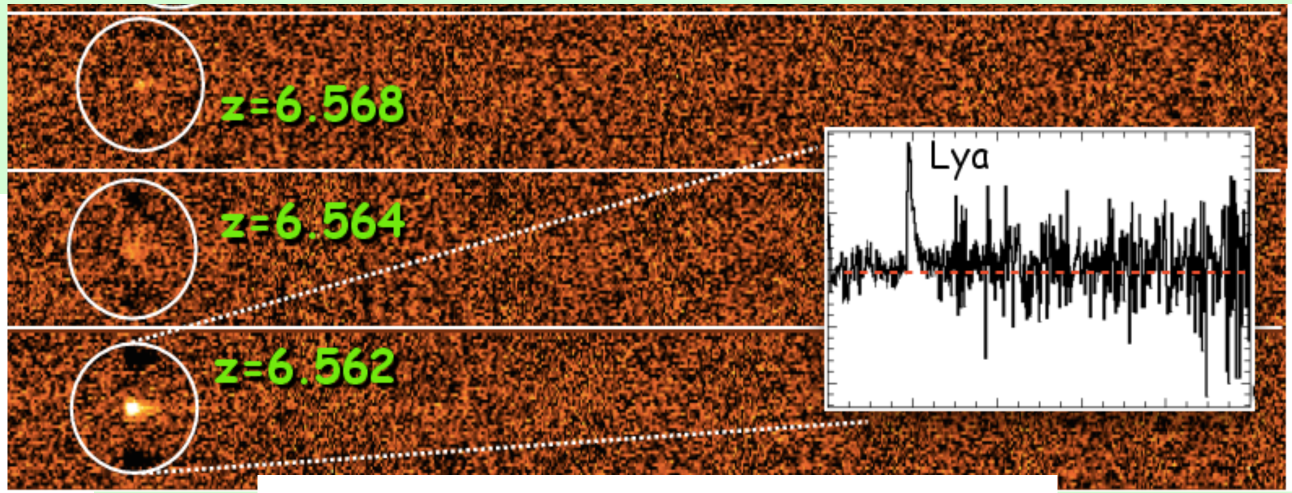


Measure redshift for faint (mag=26) non LAEs
First time, non trivial
Half of the LBG population at z=6
Stacks allow us s to study properties (ISM abs lines , UV slopes, sizes) and trends

See next talk by Stephane De Barros on properties of z=6 galaxies

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

We found three extremely bright galaxies (M_{UV}=-21-21.5) with Lyα emission line:
Their redshifts are within 250 km/s of each other and the sky positions within 1 arcmin (≈340 kpc proper) at z=6.56



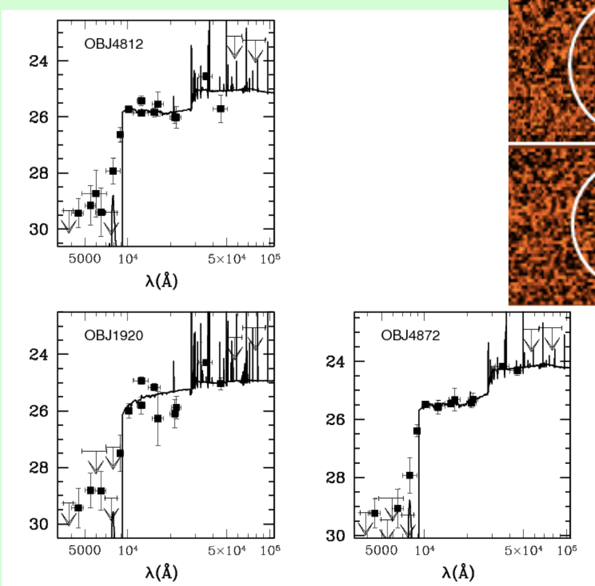
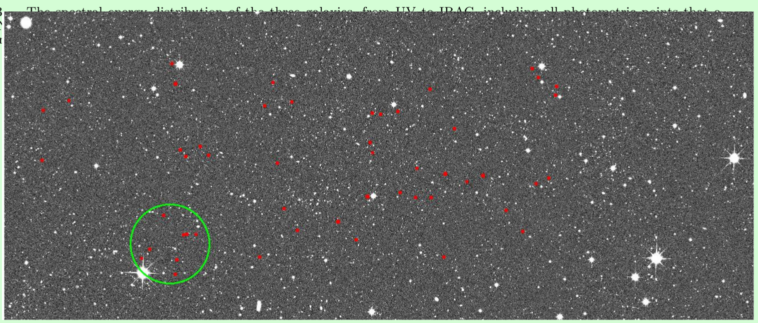


TABLE 2
PHYSICAL PROPERTIES OF THE TRIPLET

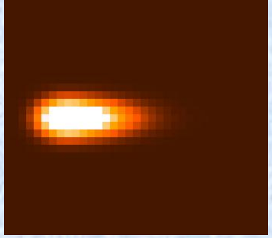
ID	Mass $10^9 M_\odot$	$SFR_{Ly\alpha}$ $M_\odot yr^{-1}$	SFR_{UV} $M_\odot yr^{-1}$	SFR_{SED} $M_\odot yr^{-1}$	Age Myrs	met	E(B-V)
UDS1920	4.7	1.5	15.0	46.7	100	0.2	0.1
UDS4812	7.1	8.9	15.8	7.1	250	0.2	0.0
UDS4872	19.8	2.4	20.0	7.0	355	0.2	0.0

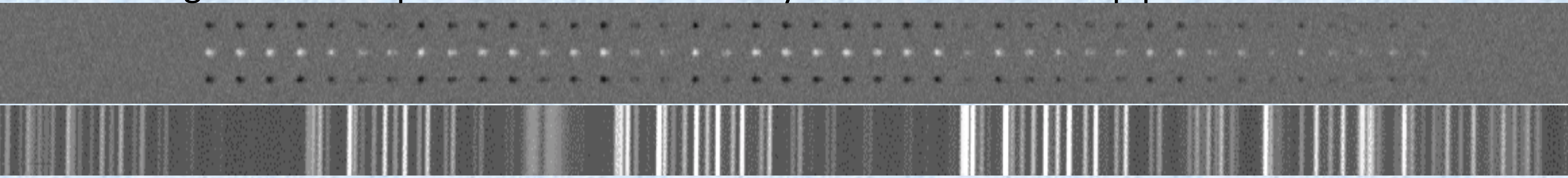
Galaxies have masses of 0.5-2 x10^{10} $M_\odot$
colors indicate the presence of strong nebular emission in IRAC Ch1 (see Marco's talk this afternoon)

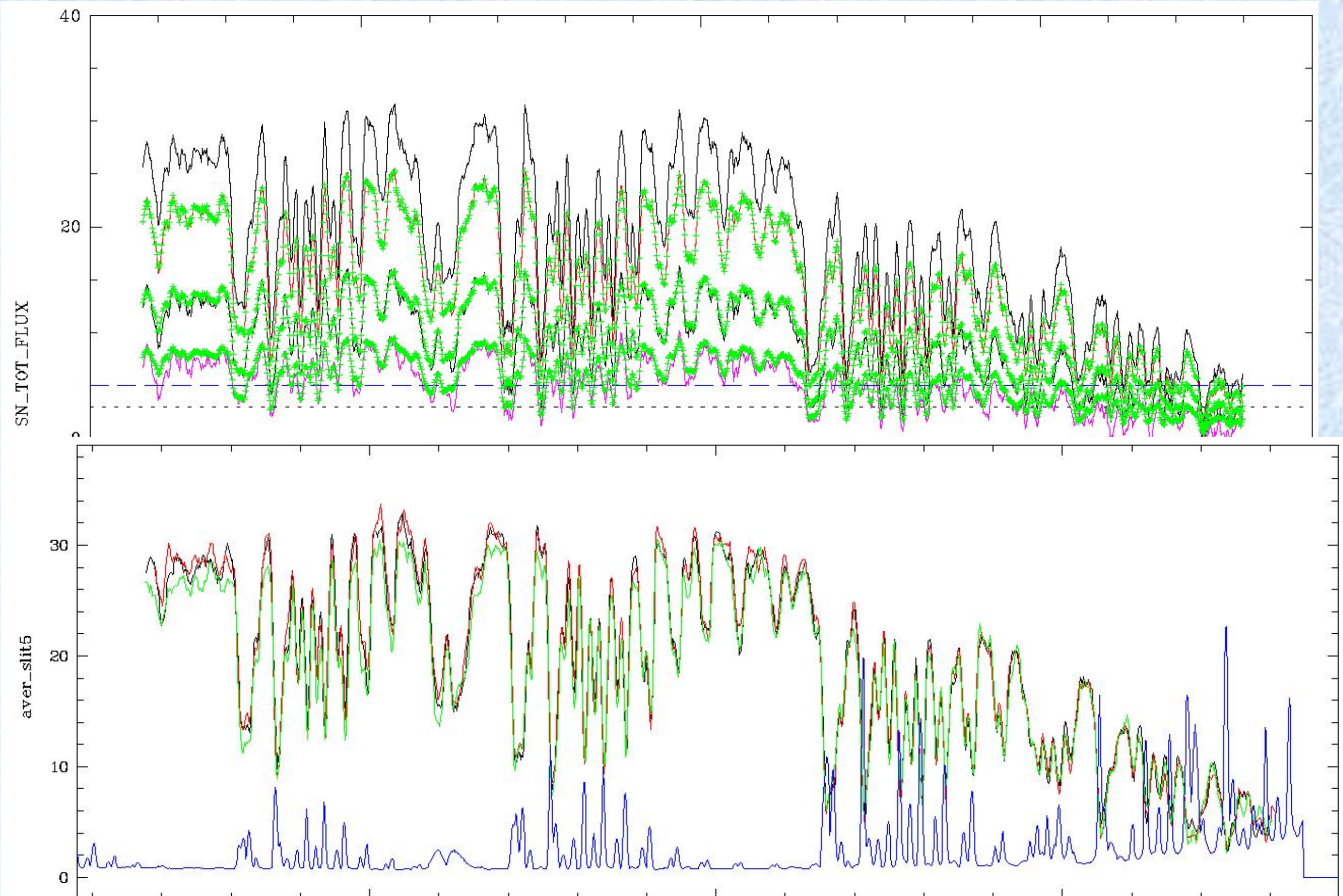


In red the position of all star forming galaxies in the UDS field with photometric redshifts=6.6±0.2. There is a >5σ over-density around the triplet. Compared to the most distant overdensity found @z=6.01 (Tashikawa et al 2014) , the redshift range of confirmed emitters is considerably narrower (Δz=0.006 vs 0.05)

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)

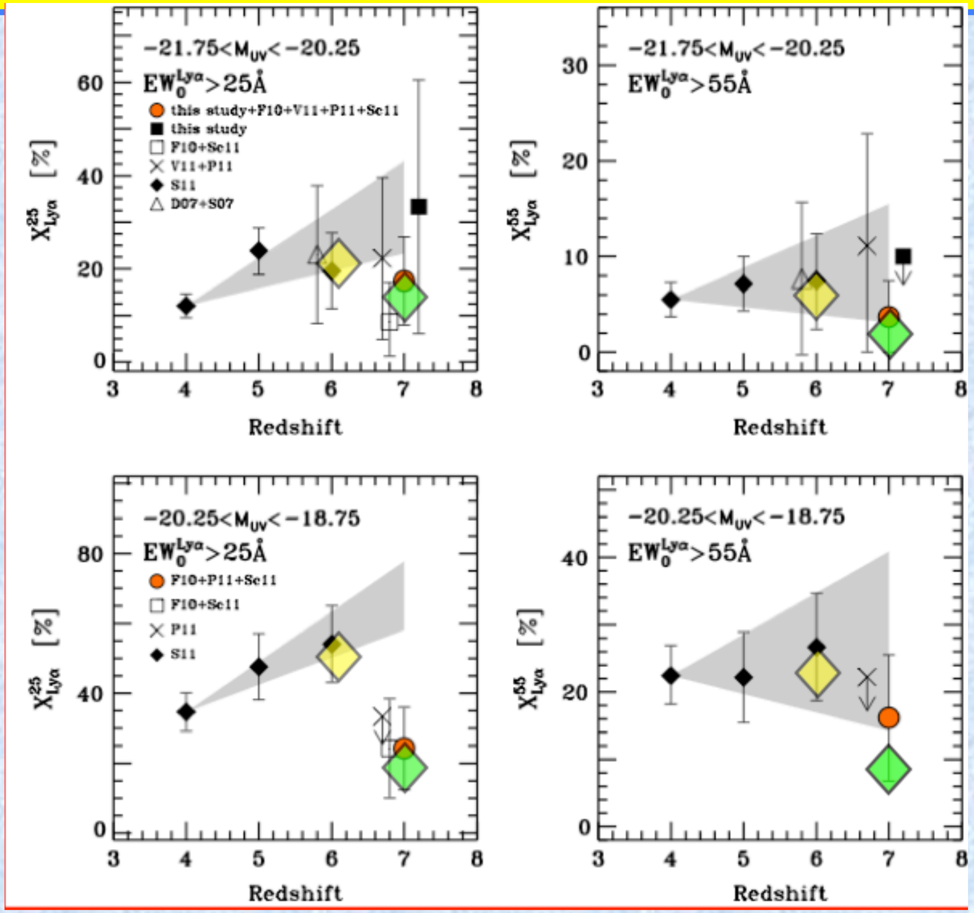
Including new Large Program data plus earlier and archival observations we have assembled a sample of ≈120 solid z-dropouts & 180 i-dropouts in 5 independent fields: this is the largest sample of high redshift galaxies observed spectroscopically. We can now measure the fraction of Lyα emission at z=6 and z=7 with great accuracy

Points at z=4,5,6 are derived from the large samples of Stark et al., Vanzella et al Stanway et al. Shaded areas are the uncertainties.

◆ new z=7 limits

◆ new z=6 limits

● limits Ono et al. 2012



bright galaxies (M_{UV}<-20.25)

faint galaxies (M_{UV}>-20.25)

EW(Lyα) > 25 Å EW(Lyα) > 55 Å

What does it mean ?

☒ A significant fraction (> 60-70%) of targeted galaxies is not at z≈7; however

1. we do not detect any other line/feature in almost all cases
2. The LBG technique works very well at z=6 with <20% interlopers
3. stacked optical bands yield to upper limits of > 30 mags on Lyα undetected objects

☒ There is a sudden (< 200 Myrs) change in some of the galaxies physical properties → unlikely from theoretical predictions and observations
e.g. UV continuum slopes which do not change sensibly in this redshift range (e.g. Bouwens et al. 2014)

☑ There is an increase in the Lyman Continuum escape fraction (Dijkstra et al. 2014)

$$L_{\alpha,obs} \propto N_{ion}(1-f_{esc})f_{esc}^{Ly\alpha}\, T_{IGM}$$

☑ There is an increase in the amount of neutral hydrogen in the surrounding IGM that quenches the Lyα emission e,g. Mesinger et al. 2014

Is Lyα quenched by neutral hydrogen? Setting constraints on the neutral hydrogen fraction through model comparison

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 (ISM) with dust and gas distribution and kinematics (e.g. Hutter et al. 2014)

-circum-galactic medium(CGM) 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 -emitting galaxies during the Epoch of Reionization (EoR) is controlled essentially 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 Lyman continuum photons adds another degeneracy parameter as explored in Mesinger et al. 2014

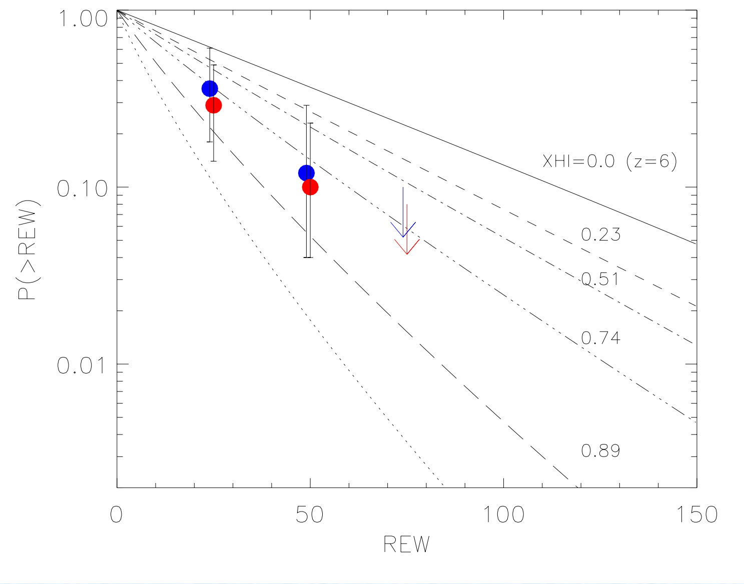
Is Lyα quenched by neutral hydrogen? Setting constraints on the neutral hydrogen fraction

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 $5\times 10^8 M_\odot < m_{halo} < 10^{12} M_\odot$ (SFR up to 1-20 $M_\odot$/yr as in Tren & Cen 2007)
- 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

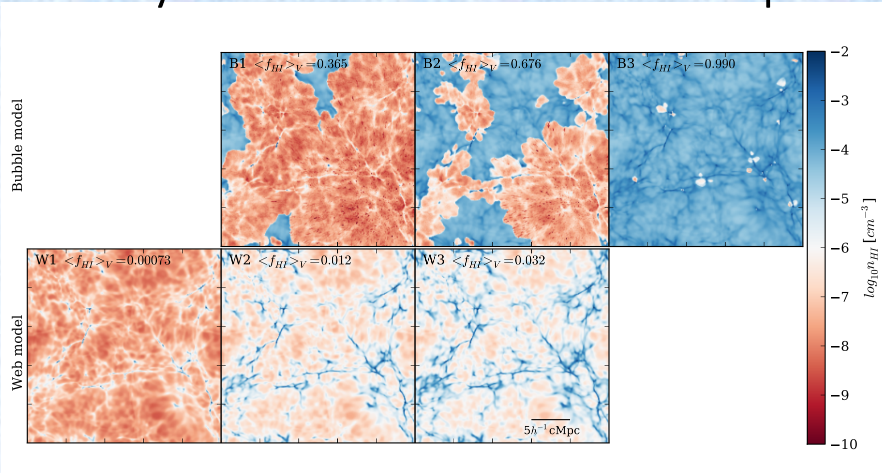
● ● fractions assuming that 0-20% of the candidates are lower redshift interlopers



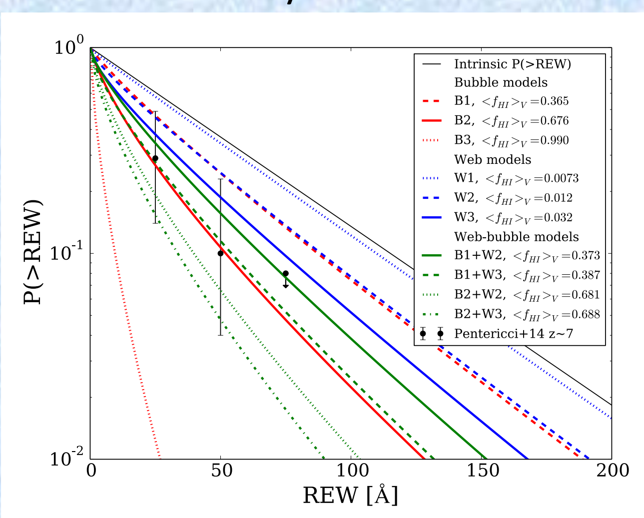
$X_{HI} \geq 0.5$ @z=7

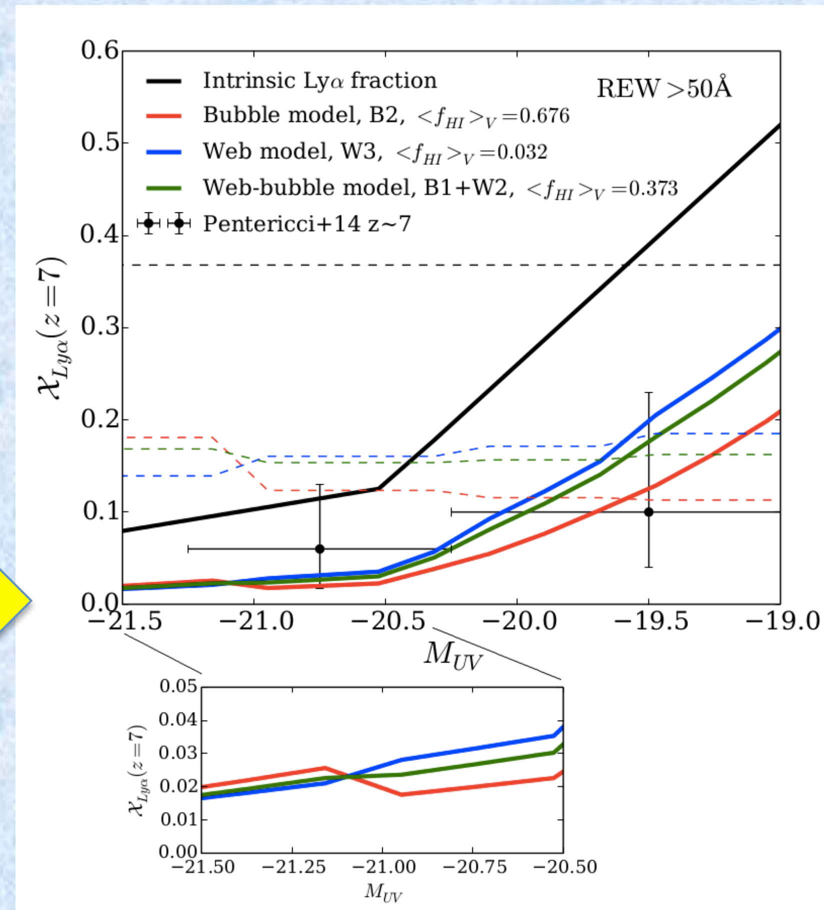
Is Lyα quenched by neutral hydrogen? Setting constraints on the neutral hydrogen fraction

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 three models



Bubble , Web, We-bubble models produce the same Lyα suppression with very different HI fraction



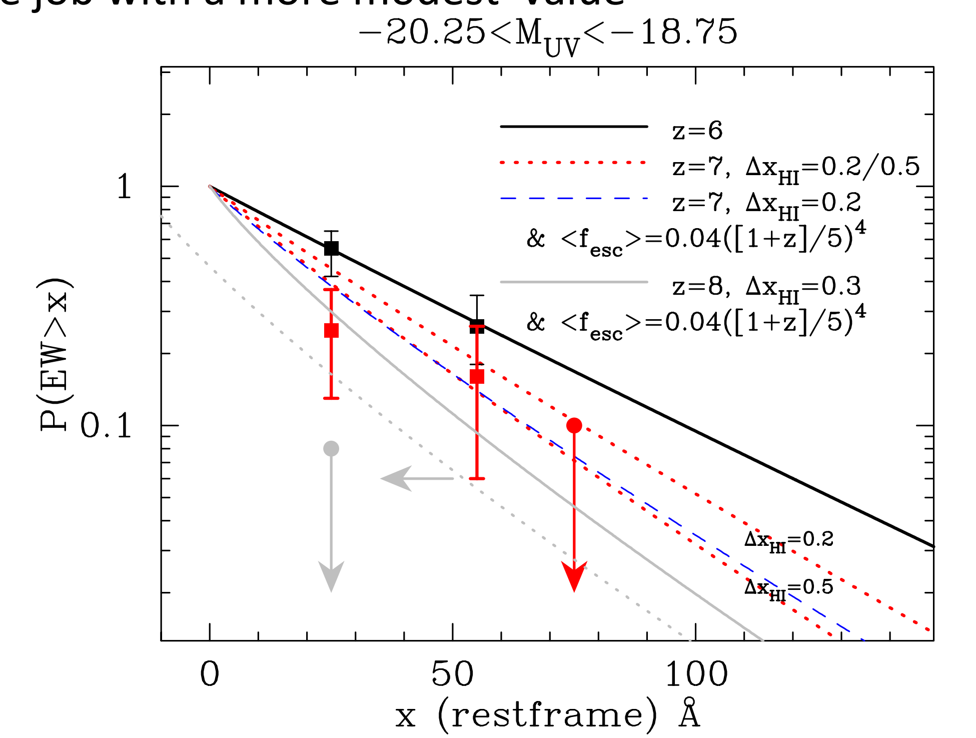


Is Lyα quenched by neutral hydrogen? Setting constraints on the neutral hydrogen fraction

Alternatively the observed reduction in Lyα flux from galaxies at z>6 can be explained by an evolution in the escape fraction of ionizing photons, f_{esc} as in **Mesinger et al. 2014**

To match the Lyα emitter fraction and the LAE LF both at z=6 & 7, models with a pure evolution in f_{esc} and no change in HI, require values that are at odds with the lower redshift observations (i.e. a small increase of Δf_{esc} =0.1 as long as f_{esc} =0.65 at z=6)

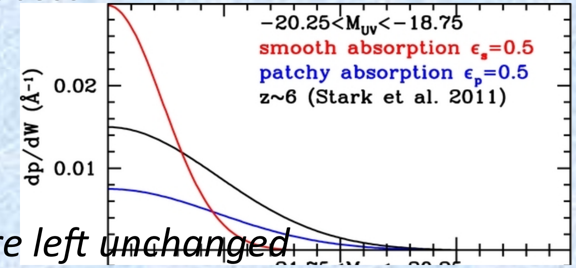
However assuming an increase in redshift of $f_{esc}=0.04[(1+z)/5]^4$ (as in Becker & Bolton 2013) coupled with change in HI can do the job with a more modest value



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

Measuring the topology of reionzation

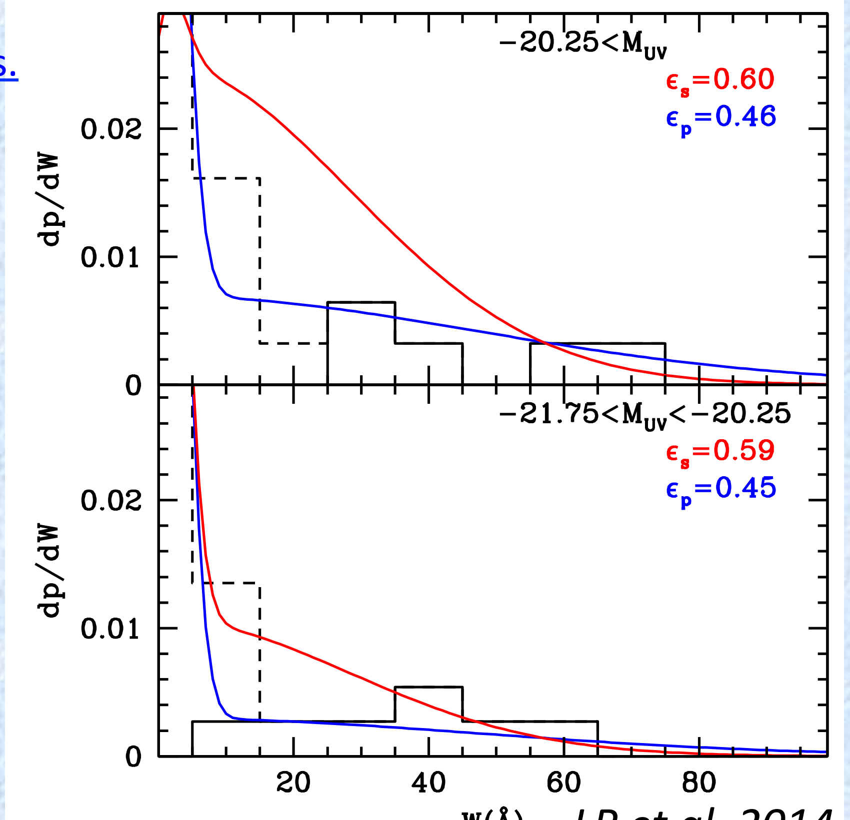
Treu et al. (2012) developed a simple model that can distinguish between a patchy and a homogenous reionization: the mean number of detections depend both on the average opacity of the IGM (the ε parameter) and on the patchiness of the reionization process:



(1) ***smooth reionization****: all emitters are quenched by the same average amount of neutral hydrogen , so the luminosity goes down homogeneously*

(2) ***patchy reionization*** *: some of the emitters are completely quenched by neutral hydrogen while others lie in ionized regions and are left unchanged*

Observing samples at different fluxes allow us to break the degeneracy between ε and the patchiness and hence measure the topology of the reionization process.



LP et al. 2014

Evidence ratio $\lg(Z_p/Z_s)$=1.26

↓

The patchy model is 18 times more favoured by the data compared to the smooth one; ϵ_p =0.45 ±0.11

Final results from Large Program Sample… coming soon!!

Clearly the next step is exploring the z>> 7 range and determine the re-ionization timeline up to earlier epochs.. ...not a easy task!!

If the trend of decreasing Lyα is confirmed → galaxies at z > 7 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..)

→ So far just 3-4 z> 7.5 galaxies confirmed (Finkelstein et al. 2013, Oesch et al. 2015, Zitrin et al. 2015...) despite the many attempts .

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

1. lensed galaxies (Lyα should be very strong in very faint galaxies given the M_{uv} vs EW relation observed at lower redshift)
2. other emission lines in the near-IR e.g., CIII], HeII, CIV (see Richard's talk)
3. ALMA observations of [CII]158µm

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

So far sparse results (Bradac et al. 2012, Schenker et al. 2012, Vanzella et al. 2014)

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 photometrically selected galaxies we detect emission lines consistent with Lyα @ 6.2 < z< 10.2 in the HST spectra (Schmidt et al. 2015)
However purity < 100% and some of the lines are ambiguous and/or low S/N

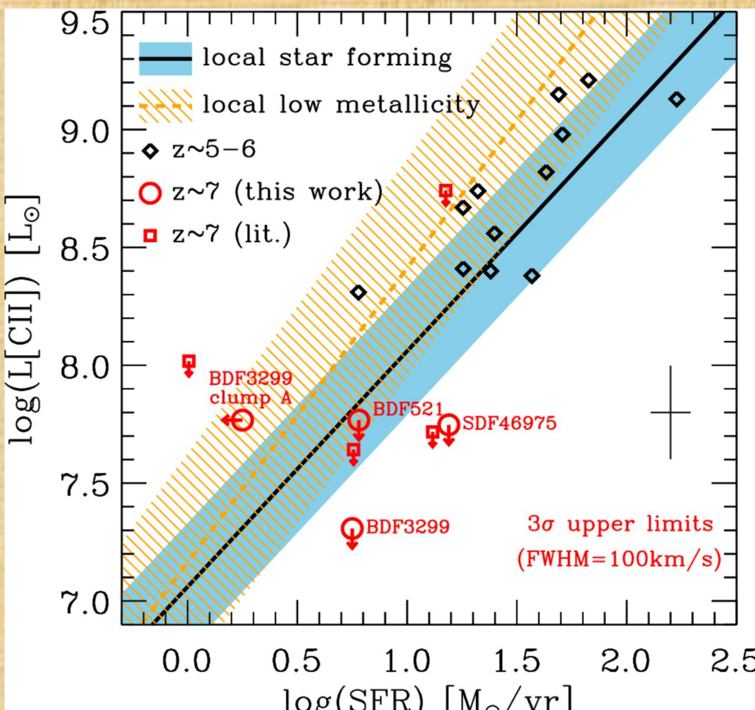
→ New systematic effort:
KMOS follow up of GLASS (ESO Large Program, PI A. Fontana)
Spectroscopic observations of 7 clusters with targets preselected to show signature of Lyα in the HST low resolution spectra
– 20 hours per cluster, > 25 candidates emitters at z>7 will be observed

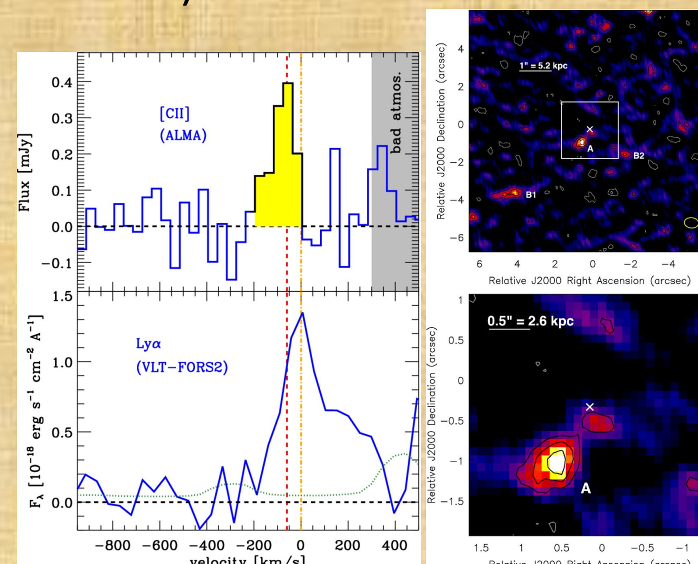
3 **ALMA observations**

[CII]158µm line is not effected by neutral hydrogen & dust.

At z=5-6 this line has been detected in many galaxies, and the CII SFR relation is similar to the one for local star forming galaxies (Capak et al. 205, 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)





[CII] in *BDF3299 z=7.108 (Maiolino et al. 2015)*

We have obtained time in ALMA Cycle 3 to observe the 7 brightest galaxies from the ESO Large Program with observed Lyα emission at redshift > 6.6 and SFR > 15 $M_\odot$/yr: the aim is to reach log (L[CII])≈7.5 …stay tuned!!