PROBING THE END OF THE REIONIZATION EPOCH WITH THE MOST DISTANT GALAXIES

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in collaboration with
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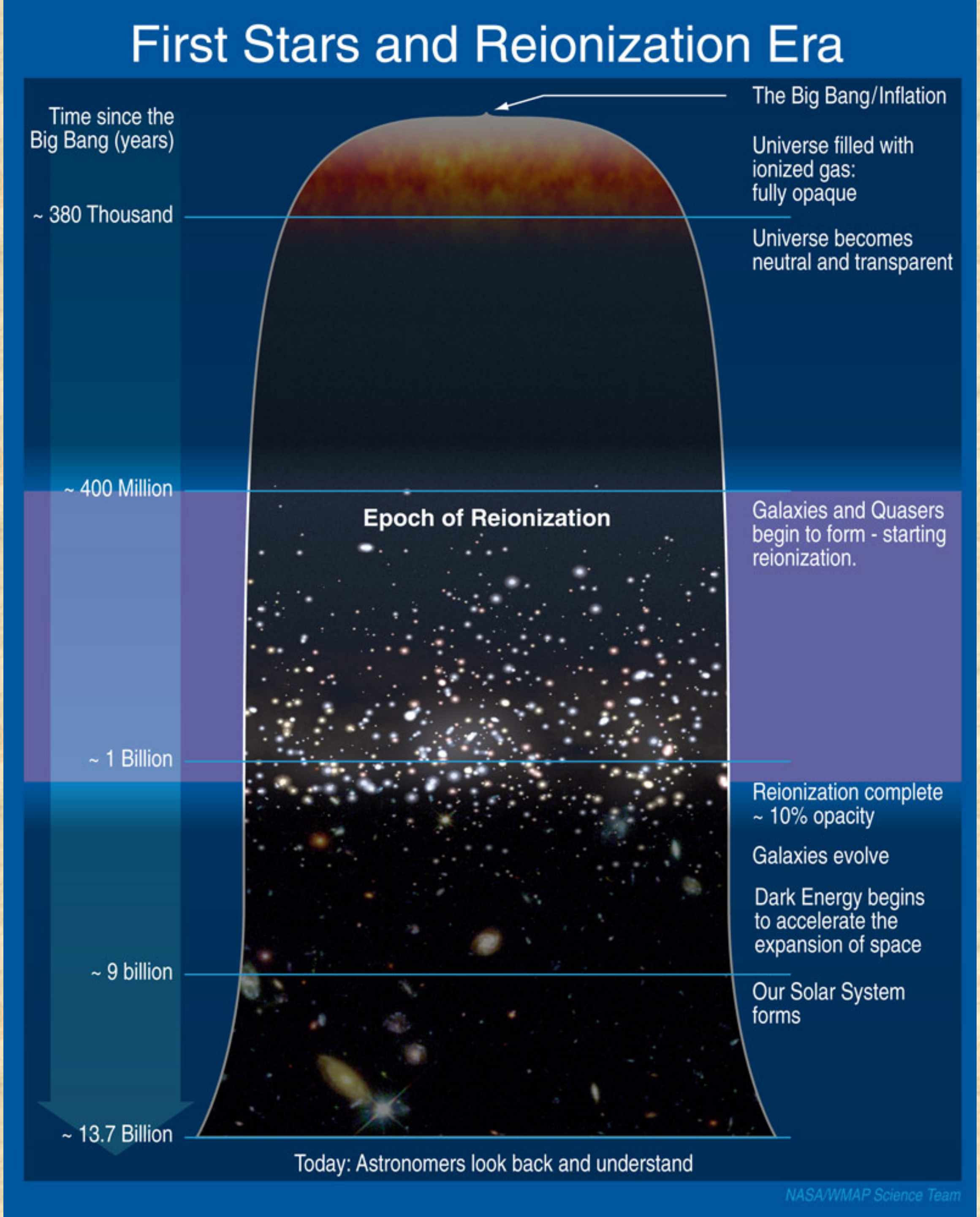
Back to the edge of the Universe, Sintra 15-19th March 2015



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.

Observational probes of reionization

1 Gunn Peterson trough in bright QSOs. QSOs at z ≥7 are extremely rare (Mortlock et al. 2011): only 1 such object was found so far (UKIDSS/VISTA-VIKING surveys). Moreover bright QSO probably lie in very biased region of the Universe (being the most massive objects observed at each epoch) hence they might not represent the general ionization conditions but only peculiar over-dense environments.

2 GRB hosts detectable even in dwarf galaxies/ no proximity effect (Tanvir et al. 2012) – Simple power law spectra : damping wing analysis to precisely measure X_{HII} However they are also VERY rare

3 High z LBGs and LAEs Use high redshift star forming galaxies (i.e. Lyα emitters and Lyman break galaxies as) as potential probes of neutral fraction in the IGM

These objects are 1. much more numerous

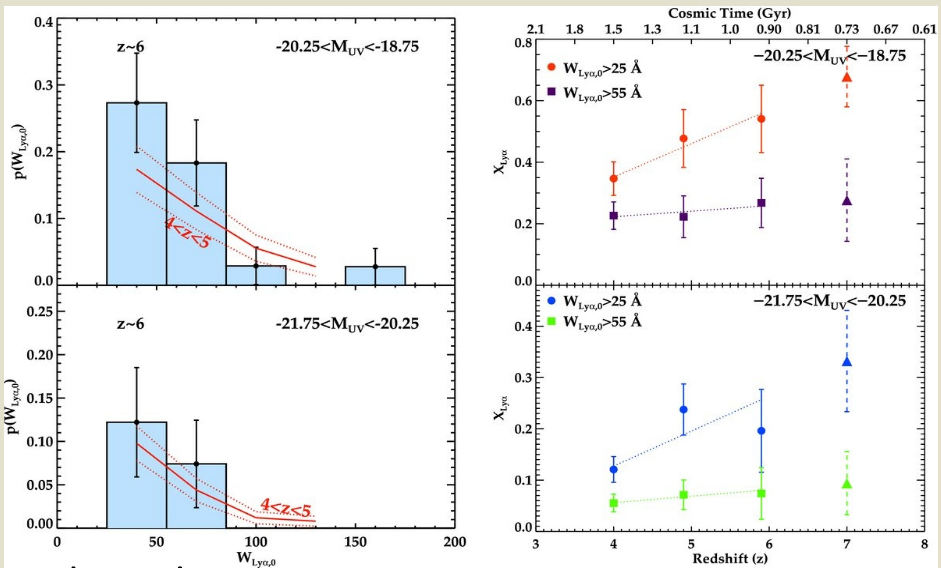
2. probe "normal" galaxy population

3. probe common conditions in the early Universe

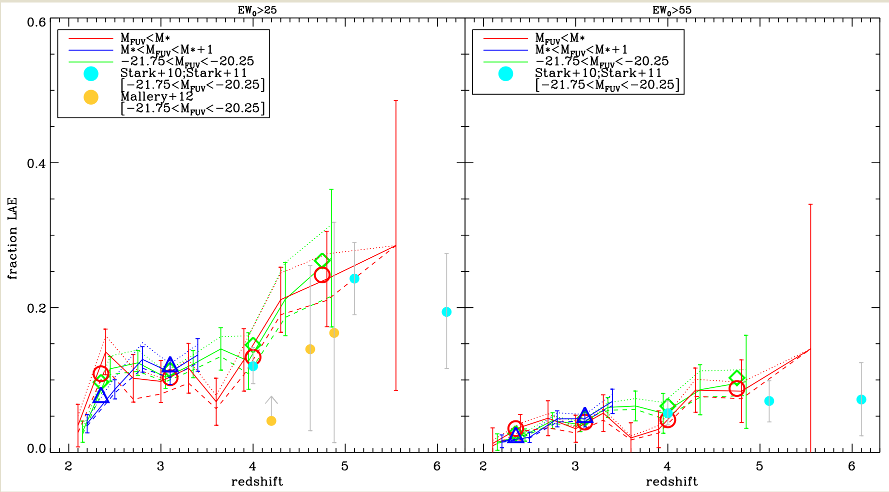
Evolution of the fraction of strong Lyα emission in samples of Lyman Break Galaxies

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)

<u>**As we go to higher redshift we observe a steady and marked increase of the fraction of Lyα emission amongst LBGs**</u> (from z≈3 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. 2010,2011, Vanzella et al. 2009; Stanway et al. 2009*)



Stark et al. 2010



Cassata et al. 2014 (VUDS data)

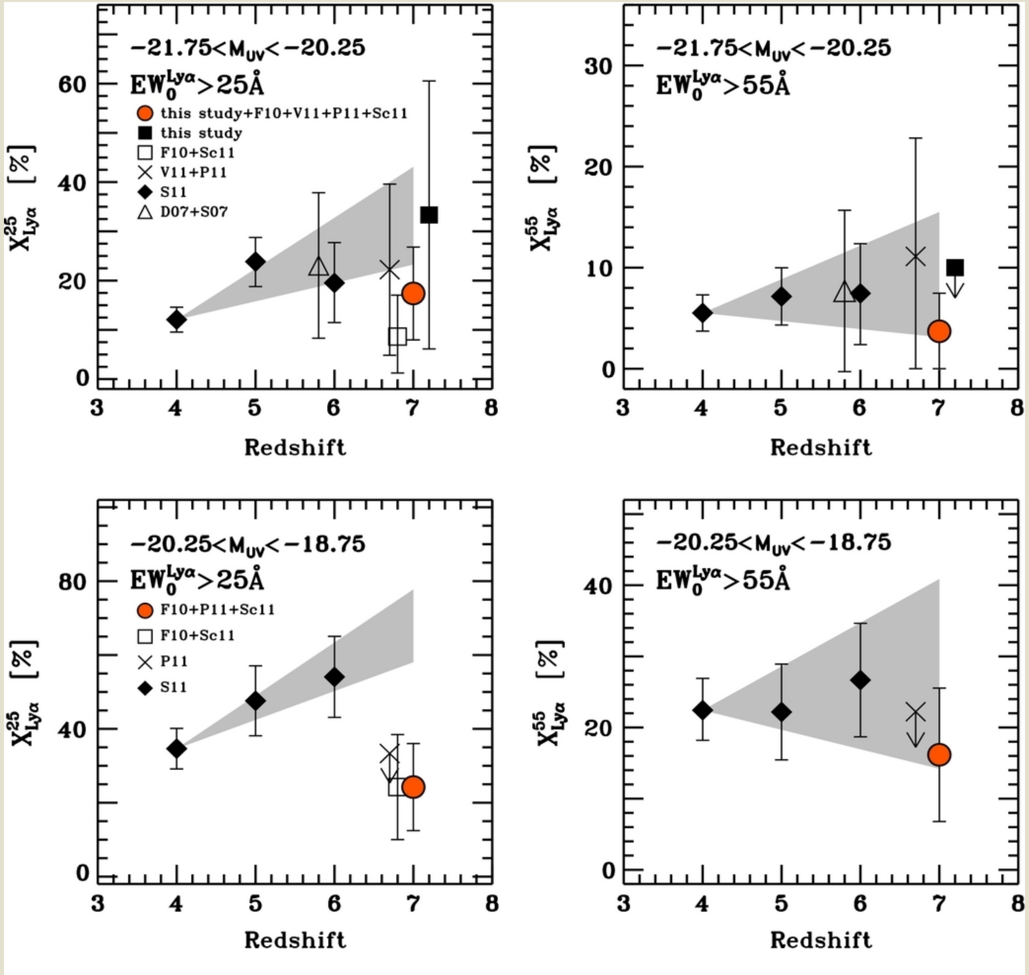
As we probe earlier epochs, we should get to a point where the Universe becomes partly neutral: since the Lyα line is easily suppressed by even a small amount of neutral hydrogen *we expect to detect a lack of Lyα emission is star forming galaxies* provided that the galaxies properties do not change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

Main advantages of using the fraction of Lyα emission in Lyman Break Galaxies as reionization probe over other statistical tools

✓ Being a fraction it is not subject to intrinsic number density evolution

✓ LBGs have measurable continuum colours (contrary to the majority of LAEs) therefore the galaxies' physical properties e.g. dust obscuration, stellar age, stellar mass can be measured individual objects and their evolution can be tracked independently

Early results (Fontana et a. 2010, LP et al.2011, Schenker et al. 2012 Ono et al. 2012) by several independent groups indicated that at z=7 the fraction of Lyα emitters in LBGs is considerably decreased compared to lower redshift



Pentericci et al. 2011-2014
Ono et al. 2012
Schenker et al. 2012

LIMITATIONS

*The samples are **still small** and **very heterogeneous** in terms of

1. selection (color vs zphot)
2. observational set-up (redshift coverage)
3. Lyα EW limit reached (not all spectroscopic data are deep enough)

*The EW distribution at z≈6 also uncertain (e.g. Curtis-Lake et al. 2012 claimed an even higher fraction of emitters) hence of the real drop from z≈6 to z≈7 might be smaller/larger

To overcome these problems we designed an ESO Large Program with FORS2 to observe 200 galaxies at $5.8 < z < 7.4$ in COSMOS/UDS/GOODS-S and determine a solid and unbiased statistics of Lyα fractions.

**Galaxies are selected with homogenous criteria from the CANDELS data : deep multi-wavelength optical, near-IR &mid-IR photometry helps disentangle changes in physical properties from changes due to IGM evolution.

** we employ a unique spectroscopic set up and observational strategy

** the selection band (CANDELS H-band) is independent of the presence of Lyα at z =6&7 unlike past surveys (see Eros's talk) and minimizes the bias

ESO FORS2 LARGE PROGRAM: Selection of z～7 candidates :

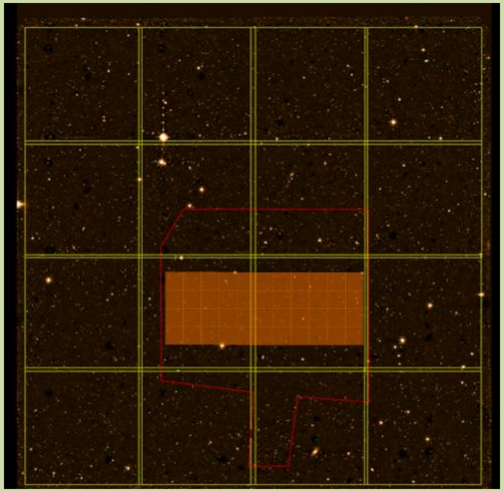
CANDELS: Cosmic Assembly Near-IR Deep Extragalactic Legacy Survey

PI S. Faber/H. Ferguson

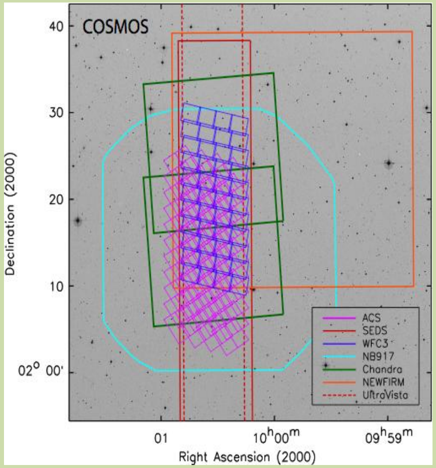
902 prime orbits using WFC3 and ACS + parallel orbits
5 fields: GOODS-N/GOODS-S/UDS/COSMOS/EGS
WIDE (700 sq arcmin)
DEEP (120 sq arcmin)
Ultra DEEP (10 sq arcmic)

GOODS-SOUTH

UDS

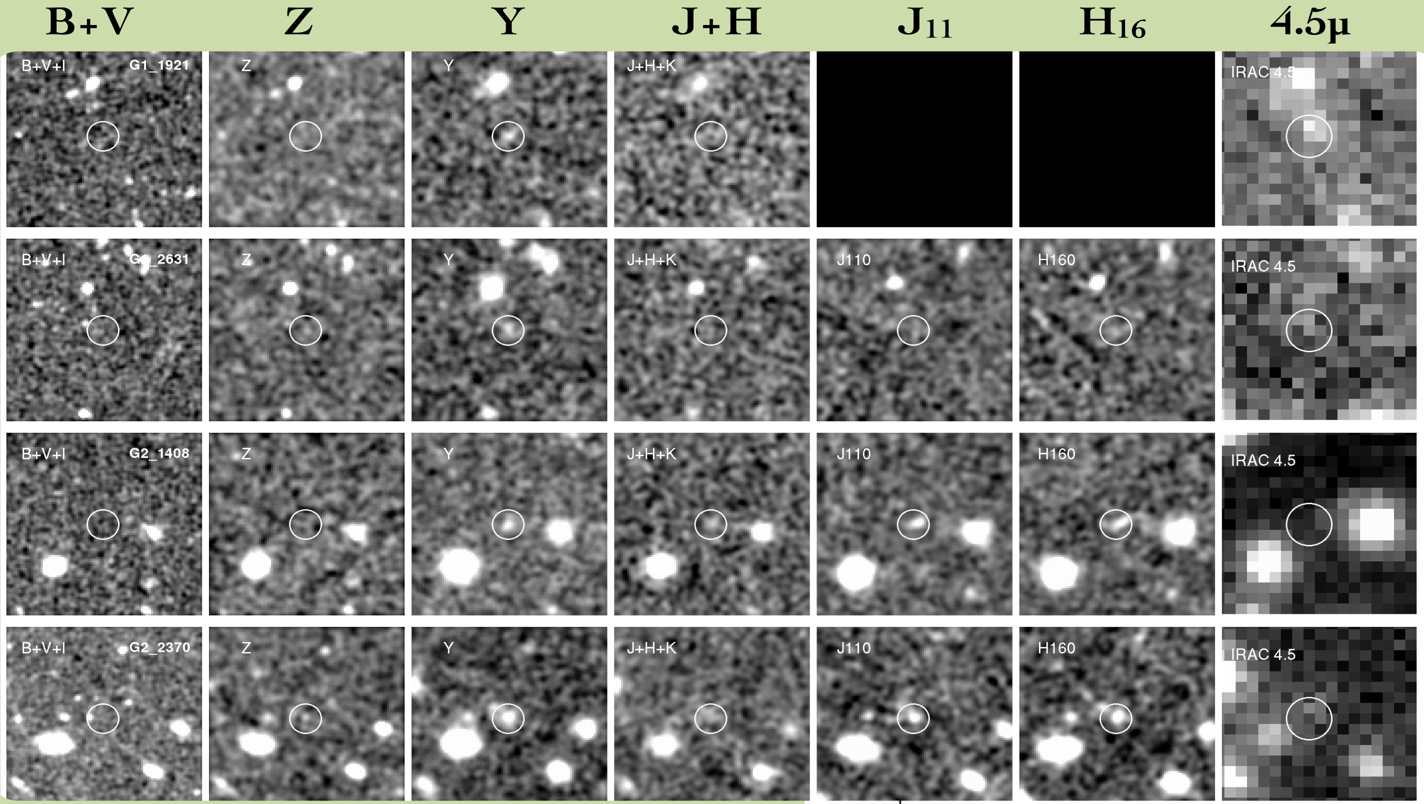


COSMOS

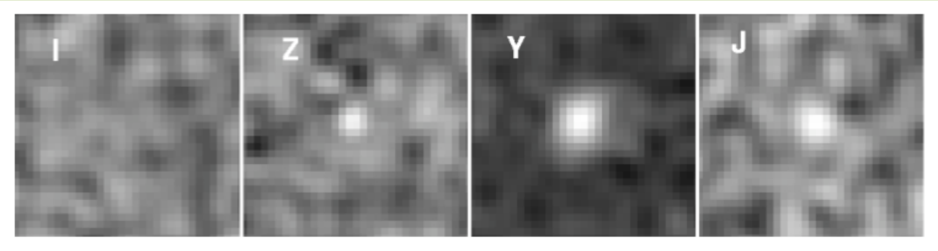


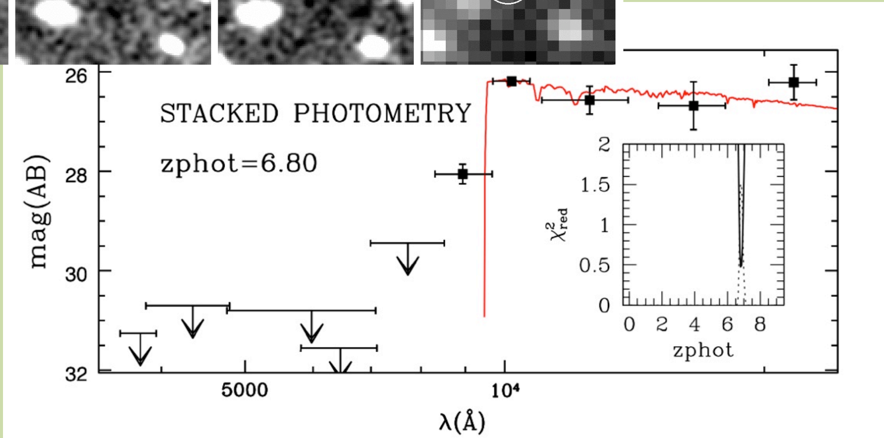
Objects are H-band selected (CANDELS official catalogs) and then a color color selection is applied : total integration time varies from 15 (for bright) to 25 hours (for faint) **to reach a uniform EW limit for all galaxies**

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

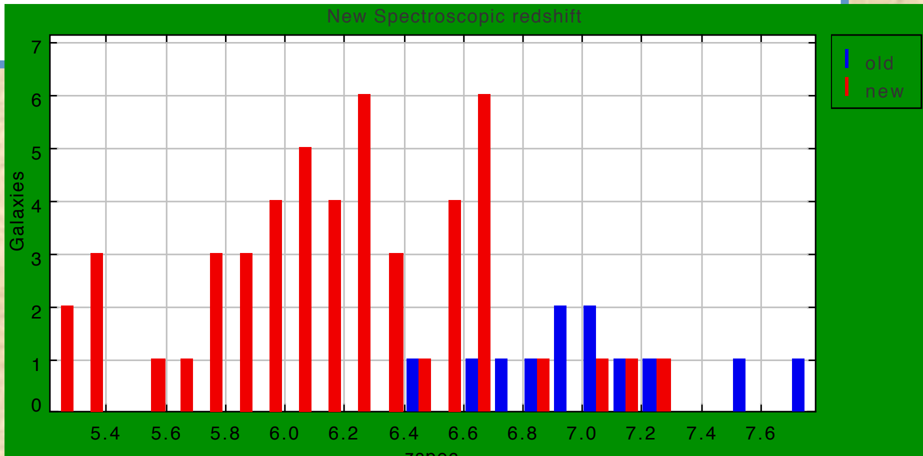
Castellano et al. 2010

STATUS OF ESO FORS2 LARGE PROGRAM AS OF 10/03/2015

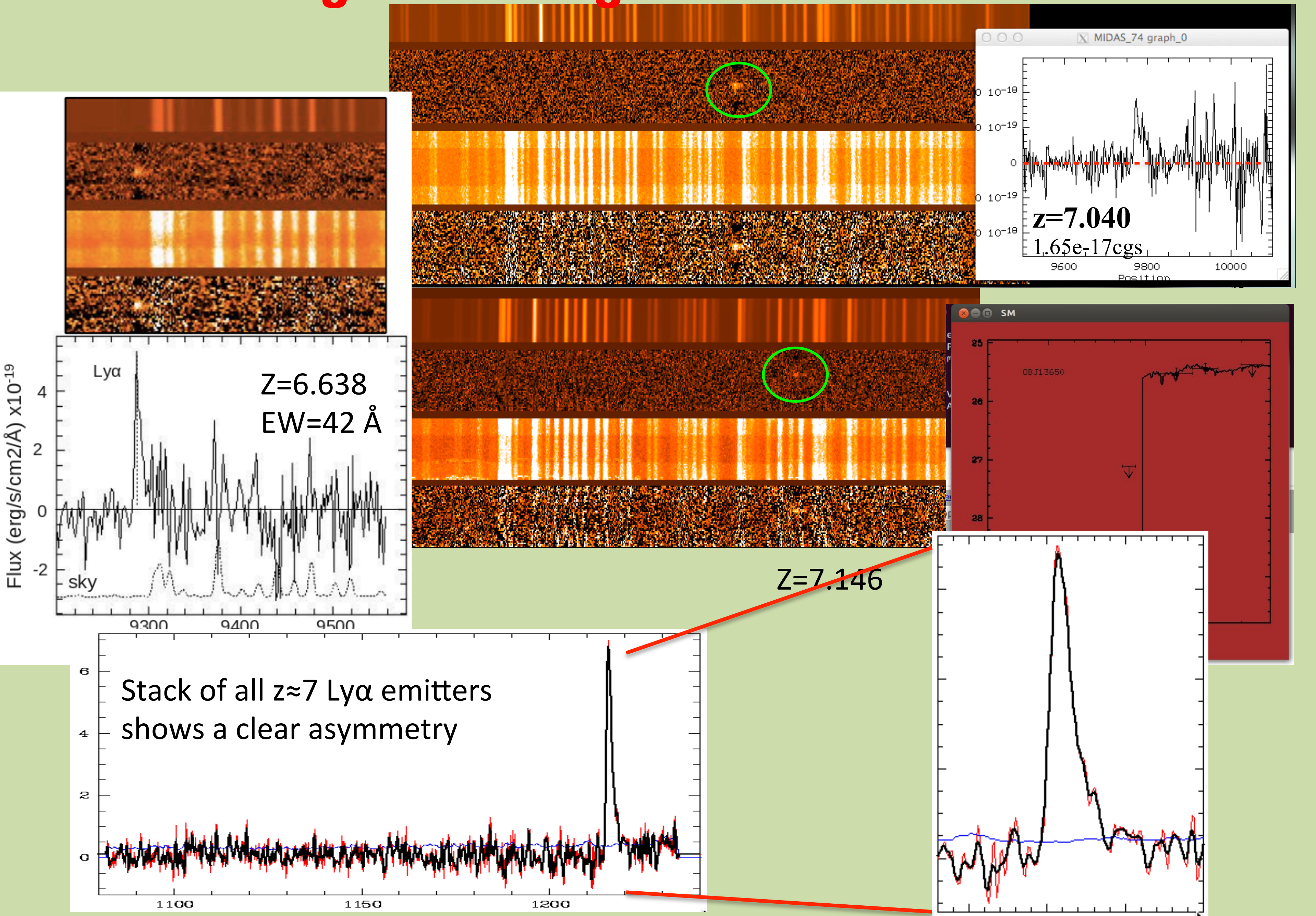
FIELD	TOT TIME	OBSREVED	REDUCED	ANALYSED
GOODS1	25	25	YES	YES
GOODS2	25	2	NO	
UDS1	15	15	YES	YES
UDS2	15	15	YES	YES
UDS3	15	0	NO	
COSMOS1	15	15	YES	YES
COSMOS2	15	15	YES	YES
COSMOS3	15	14	YES	PRELIM.
TOTAL	140 hours	101 hours		

So far we analised ≈55 new candidate z=7 galaxies observed in 3 independent fields (GOODS-S/UDS/COSMOS).
In addition a large number of i-dropouts observed (see Eros' talk for early results) , and some high-z AGN and massive galaxies

We have confirmed already 14 galaxies at 6.5< z < 7.2 all with Lyα emission and ≈ 35 i-dropouts including several with no Lyα emission (see Eros' talk)



Some new high redshift galaxies in COSMOS…

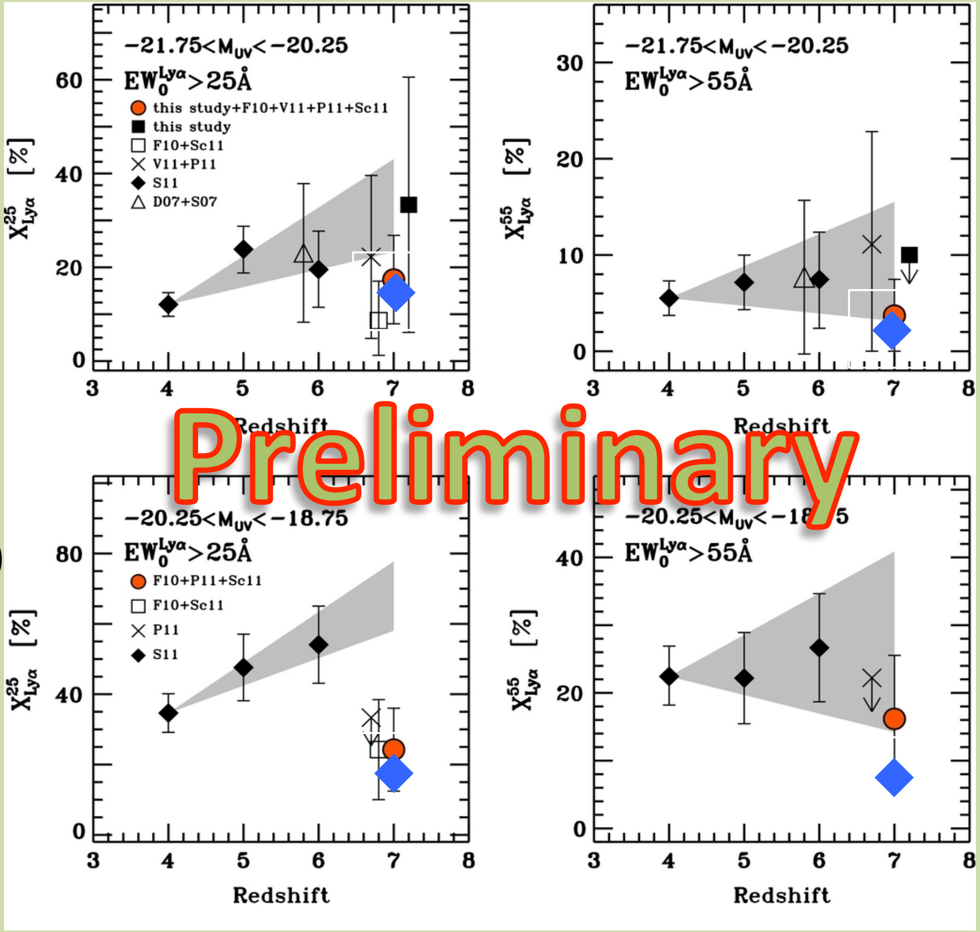


Including new Large Program data plus earlier literature plus some archival spectra we have assembled a sample of ≈120 solid z-dropouts.

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 (LP et al. 2015 in prep)

● limits Ono et al. 2012



bright galaxies (M_{UV}<-20.25)

faint galaxies (M_{UV}>-20.25)

EW > 25 Å

EW > 55 Å

What does it mean ?

☒ A significant fraction (> 60-70%) of selected galaxies is not at $z \approx 7$;
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

☒ There is a sudden (< 200 Myrs) change in some of the galaxies physical properties (unlikely from theoretical predictions and observations e.g. of UV continuum slopes Finkelstein et al. 2011)

☑ There is an increase in the Lyman Continuum escape fraction
(see talk by Marco Castellano this afternoon)

☑ There is an increase in the amount of neutral hydrogen in the surrounding IGM that quenches the Lyα emission

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

We employ the models developed by **Dijkstra & Whyite (2011)** which couple large scale semi-numeric simulations of reionization with galaxies outflows, adpated 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 that matches the observations **TO BE UPDATED with new z≈6 results!!!!**
- the halos of simulated LBGs have $5\times 10^{8}\,M_\odot < m_{halo} < 10^{12}\,M_\odot$ (this corresponds to SFR up to 1-20 $M_\odot$/yr as in Tren & Cen 2007)
- the galaxies have no dust both at z=6 and at z=7

Variables:

--Outflowing wind velocity

FIDUCIAL MODEL 200 km/s

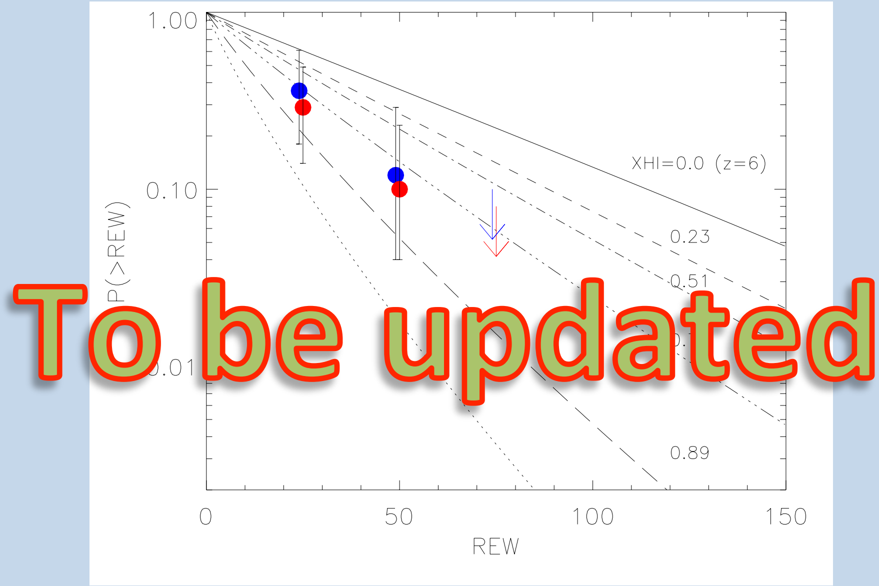
--Neutral hydrogen fraction

--Column density of HI

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

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

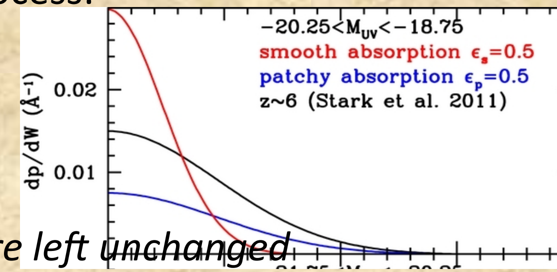
$X_{HI} \geq 0.5$ @z=7



Pentericci et al. 2014

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 <u>both</u> 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*

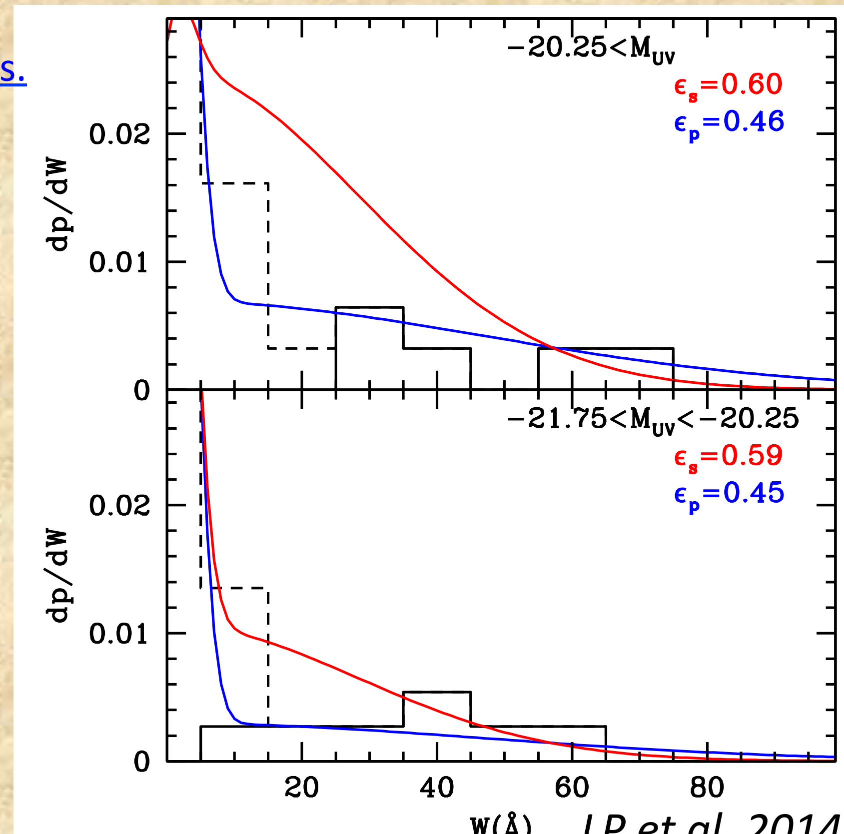
<u>Observing samples at different fluxes allow us to break the degeneracy between ε and the patchiness and hence measure the topology of the reionization process.</u>

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

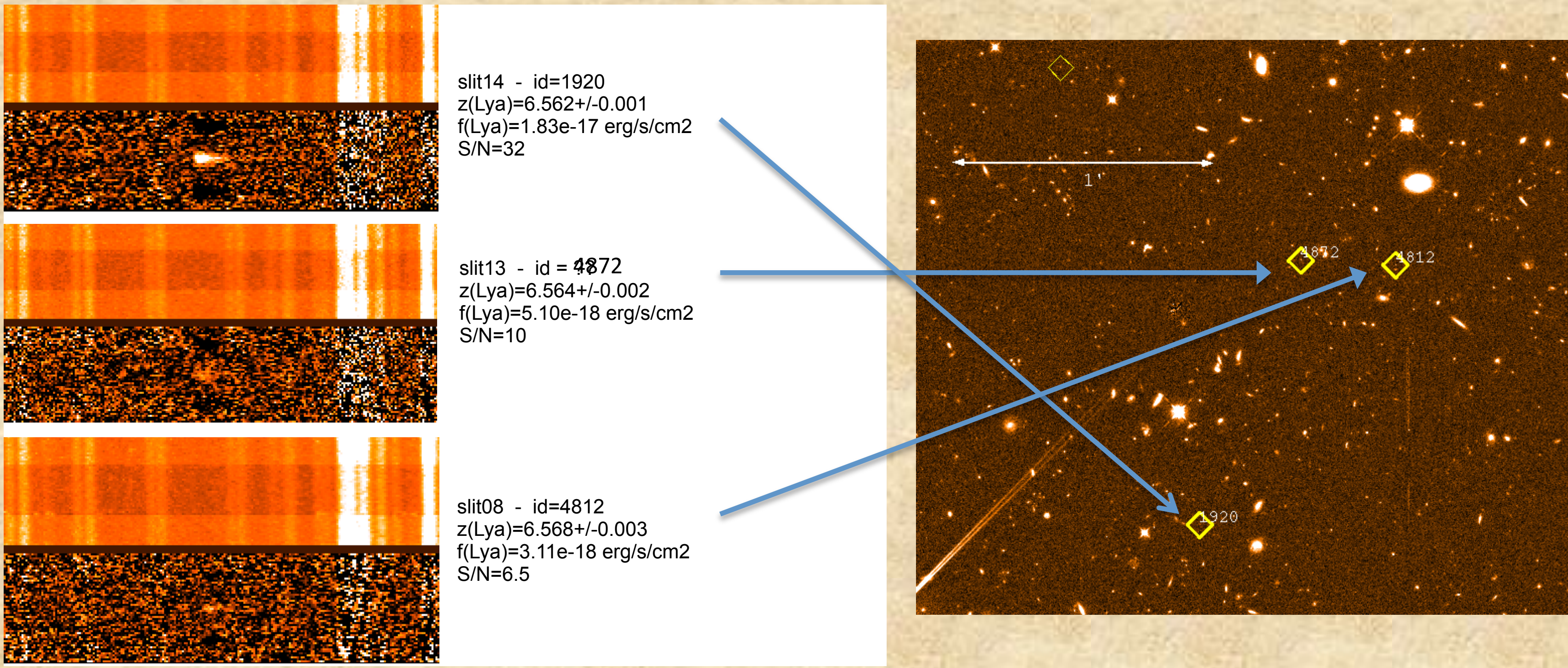
These results are from a pre-Large Program sample…new results to come soon!!



LP et al. 2014

Evidence for patchy reionization in the observations?
A triplet of z=6.6 galaxies!!

We found three extremely bright galaxies (M_{UV}=-21-21.5) with redshifts within 250 km/s and sky positions within 1 arcmin (≈340 kpc) at z=6.56 in the UDS field.



The inhomogeneous distribution of neutral hydrogen during the reionization process results in significant fluctuations of Lyα transmissivity (e.g. Choudhury et al. 2014)

Spatial distribution of triplet in the UDS CANDELS field (LP et al. 2015 in preparation)

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 z=7.5-7.7 galaxies confirmed (Finkelstein et al. 2013, Oesch et al. 2015, Watson et al. 2015) despite the many attempts.

To gather statistical samples and explore galaxy evolution during the first 600 Myr could be a task for ALMA: [CII]158μm is not effected by neutral hydrogen & dust….in z≈7 galaxies observations have proved hard so far (Ota et al. 2014, Gonzalez-Lopez et al. 2014 Ouchi et al. 2013) but maybe we are starting to get some results (Maiolino et al. 2015, Watson et al. 2015)

Otherwise…we'll have to wait for JWST & E-ELT!