Exploring the reionization epoch with deep spectroscopy

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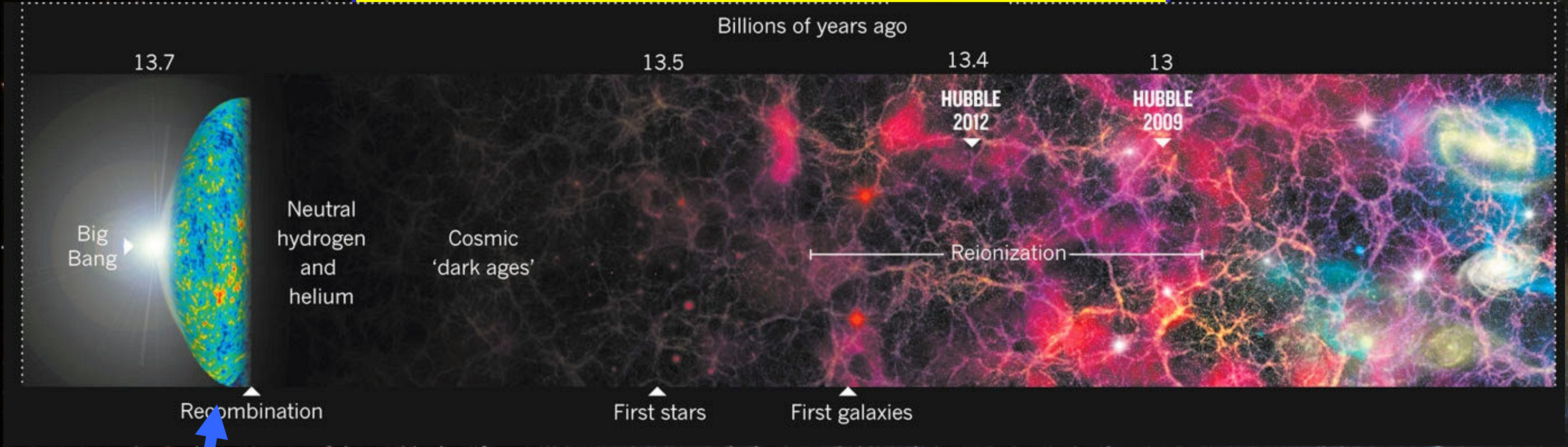
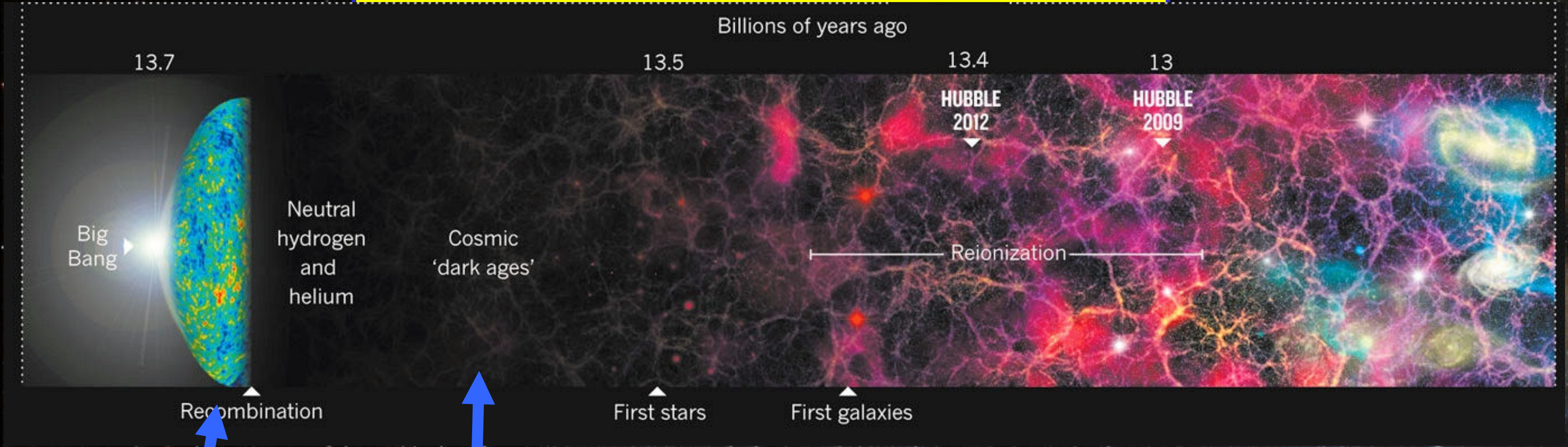
OAR

Cosmic reionization in brief



Constraints from cosmic microwave background

Cosmic reionization in brief



Dark ages the universe is mostly neutral but the first stars and galaxies start to ionizie their surroundings

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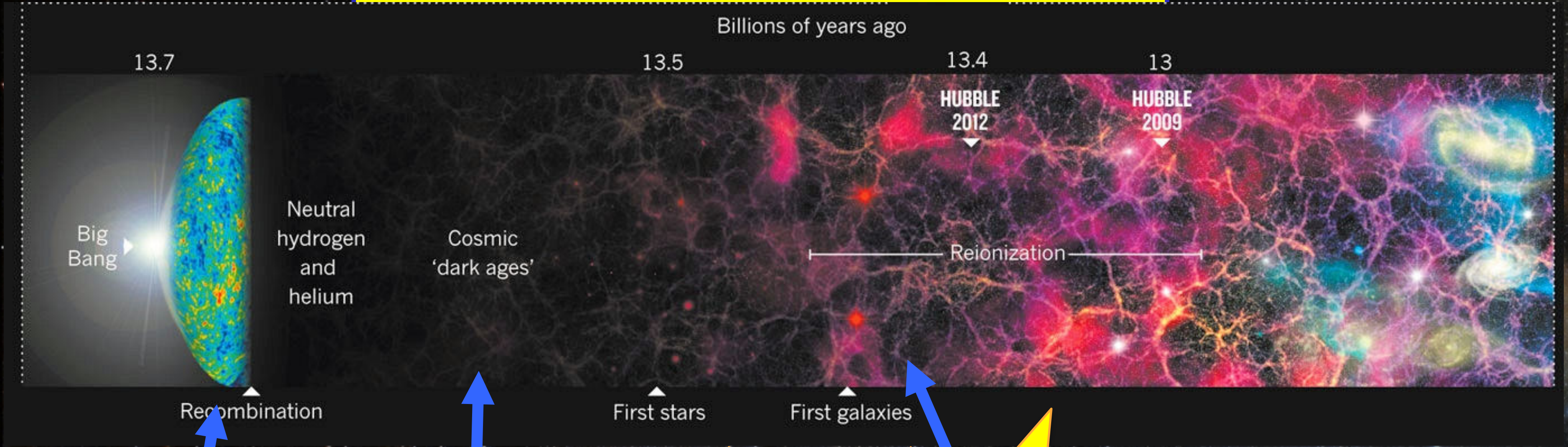

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GP trough in QSO spectra
LAE clustering/ LAE LFunction
Fraction of Lyα emission in LBGs
GRBs - Lyα Dark Gaps
QSO damping wing

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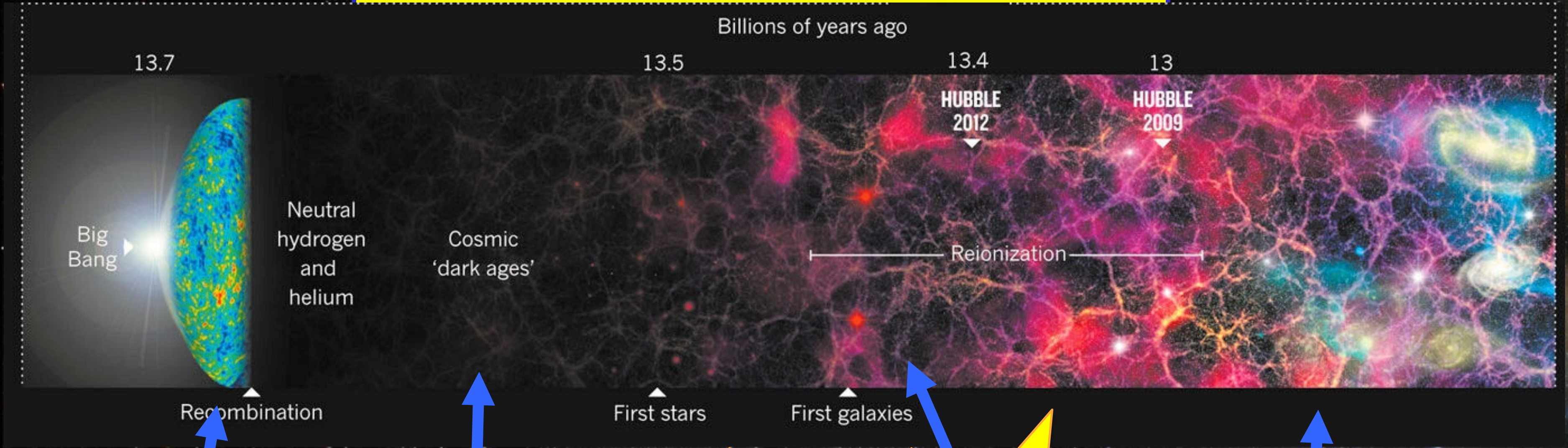

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Galaxies and structures emerge after reioization

Galaxies and reionization

☆ **Key questions**

-When did Cosmic reionization occur?

-How did it proceed in space and time?

- Which were the main sources responsible?

☆ Techniques and results with current facilities

-the unique role of Multi Object Spectrographs

☆ Can FORS2 be still competitive in the future?

Key question

When did reionization occur ? how did it proceed in time?

Our current knowledge comes from 2 classes of probes

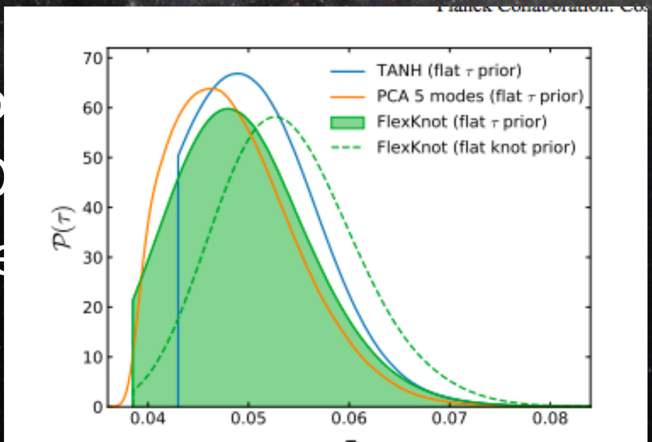
1) <u>Integral contraints</u> from cosmic microwave background observations in the form of Thompson scattering optical depth. The latest result is τ_e=0.054±0.007 (Plank collaboration 2018) , suggesting a mid-point reionization redshift of z_{re} = 7.7 ± 0.7 i.e. reionization happened relatively fast and late

<u>2)**astrophysical observations**</u> that allow to

hydrogen content at a given redshift and LO

observations of Lyα galaxies, QSOs (GP effe

GRBs



Key question

When did reionization occur ? how did it

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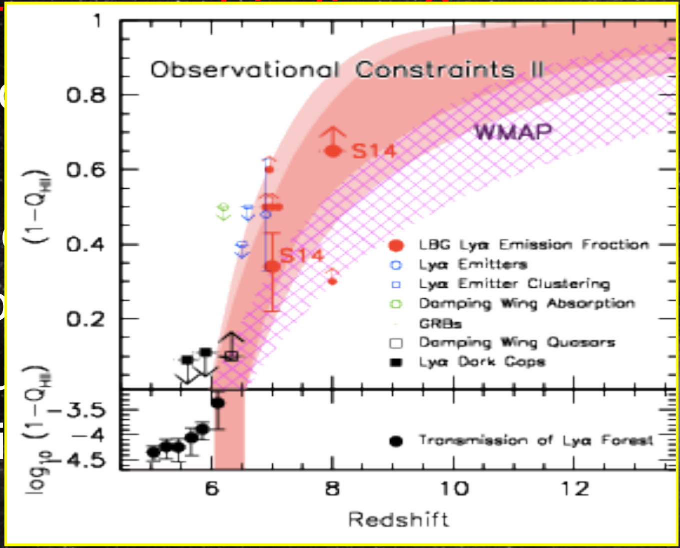
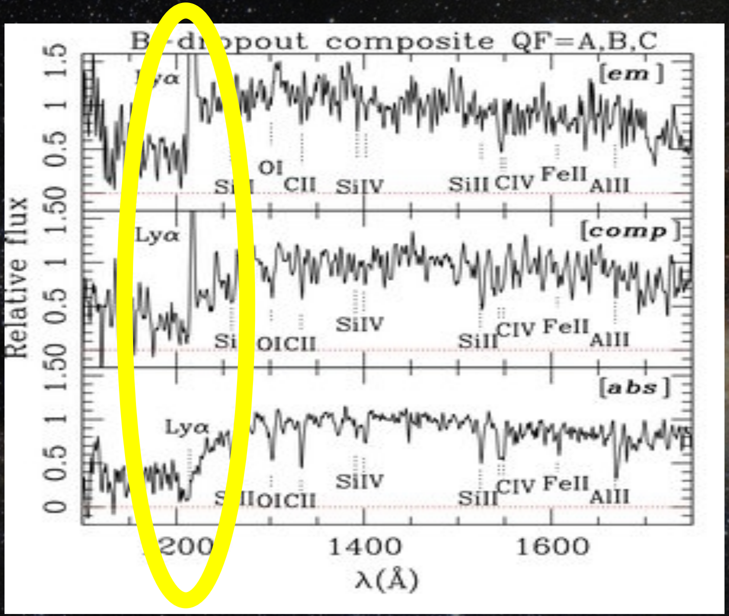
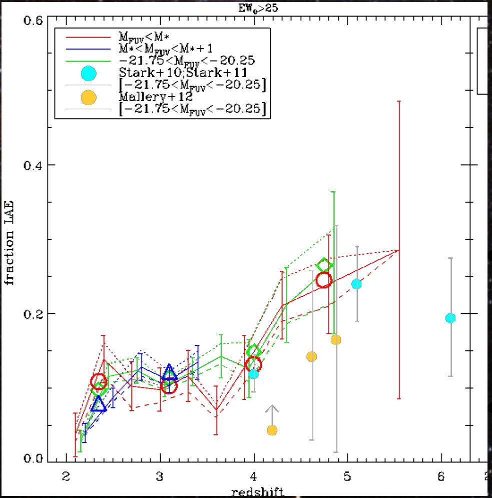


2)**<u>astrophysical observations</u>** that allow to measure the neutral hydrogen content at a given redshift and LOS e.g. spectroscopic observations of Lyα galaxies, QSOs (GP effect, damping wing), GRBs

***The Lyα emission** has become one of the main probes of neutral hydrogen content and reionization timeline*

The Ly α line is emitted by a young dust free population: up to 6-7% of the light from galaxies could emerge as Lyα. The presence of Ly α in the spectrum of a SF galaxy depends on many factors e.g. the dust content and distribution the presence of outflows and so on….

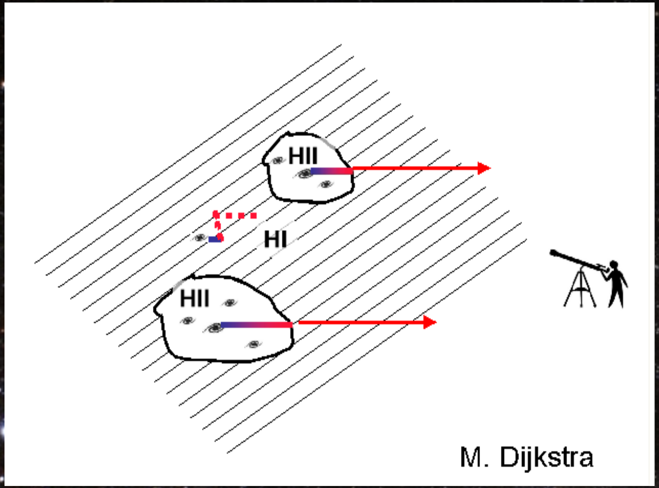




As we move to higher redshift the Ly α line is increasingly frequent in star forming galaxies (Vanzella+09,Stark+10, Cassata+14)

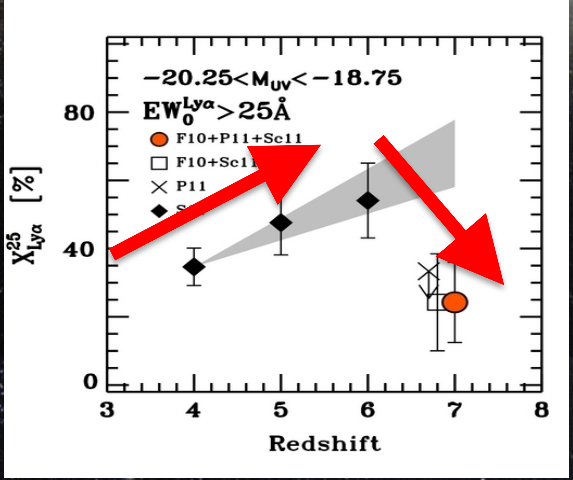
→this can easily been explained as galaxies are younger and have less dust ✔

***The Lyα emission** has become one of the main probes of neutral hydrogen content and reionization timeline*



- However being a resonant line it is easily suppressed by neutral hydrogen
→In a partially neutral IGM, Ly α is suppressed and we only see it escaping from galaxies that reside in ionized bubbles

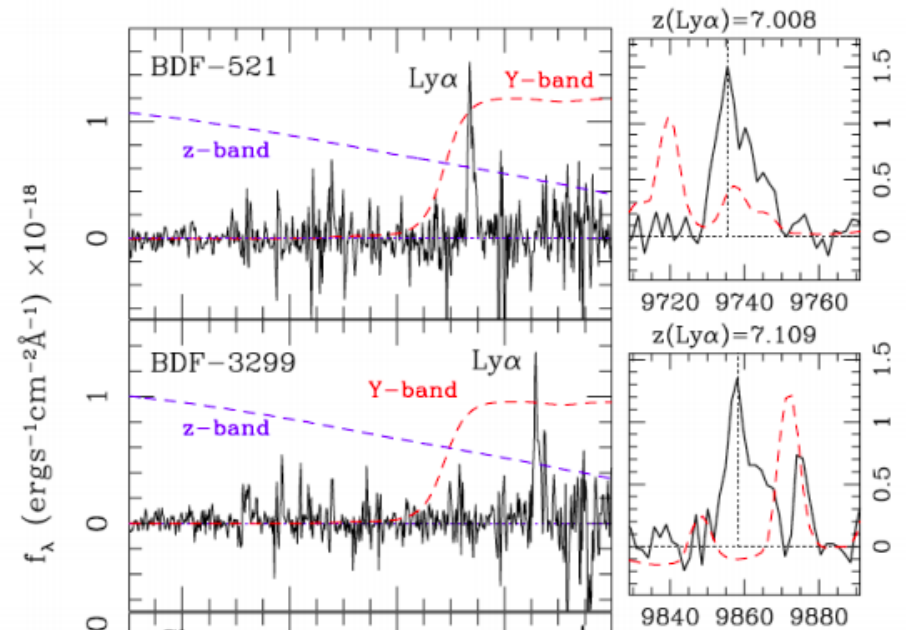
- At z> 6 we start to observe a decline of the line → a change of galaxy properties is unlikely on such a short timescale!
→ increasing neutral IGM? → **smoking gun of reionization?**



Pentericci+11,14, Stark+11,Ono+12, Schenker+12,14,Treu+13

In the past decade we have exploited the capabilities of FORS2 to push our knowledge of the reionization sources

First spectroscopically confirmed galaxies at z>7 with the emission line showing the classical asymmetric profile . Observations were obtained with FORS2 and 15 hours of integration

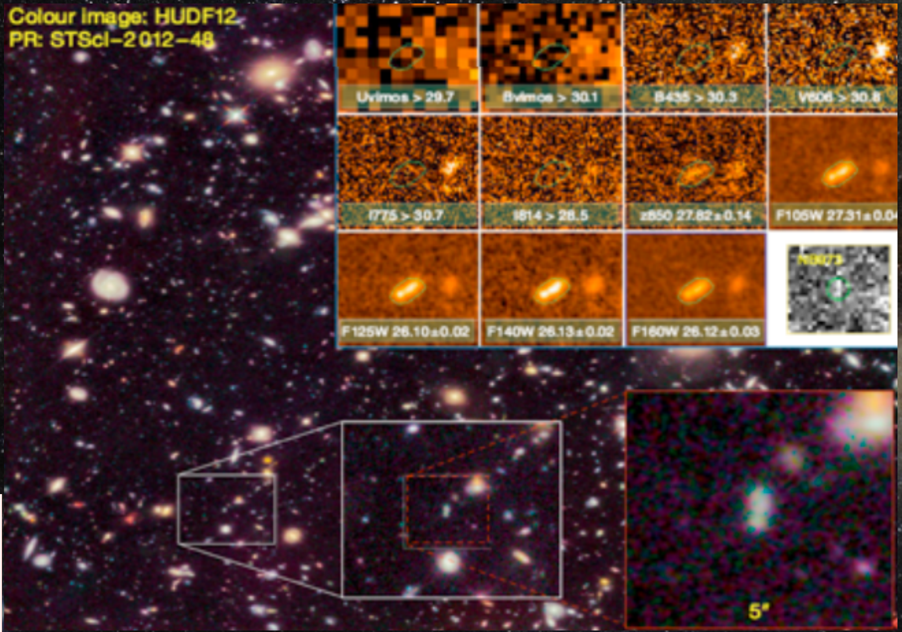


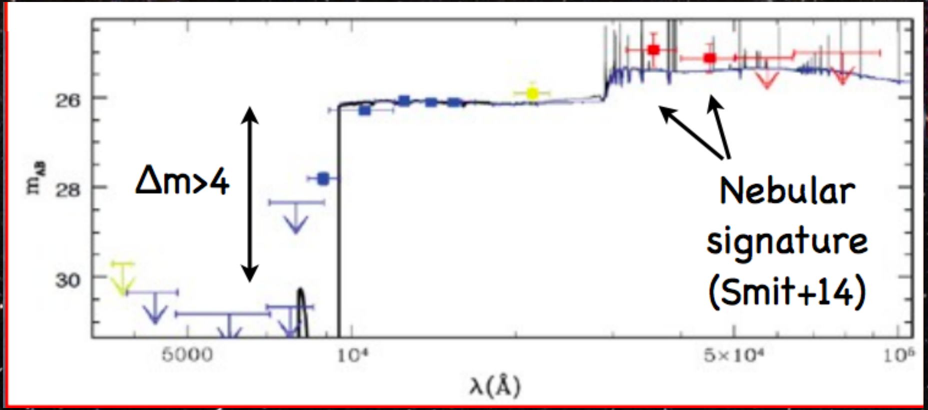
SPECTROSCOPIC CONFIRMATION OF TWO LYMAN BREAK GALAXIES AT REDSHIFT BEYOND 7

E. VANZELLA[1], L. PENTERICCI[2], A. FONTANA[2], A. GRAZIAN[2], M. CASTELLANO[2], K. BOUTSIA[2], S. CRISTIANI[1], M. DICKINSON[3], S. GALLOZZI[2], E. GIALLONGO[2], M. GIAVALISCO[4], R. MAIOLINO[2], A. MOORWOOD[5], D. PARIS[2], AND P. SANTINI[2]

Actually not all observations were so successful…….

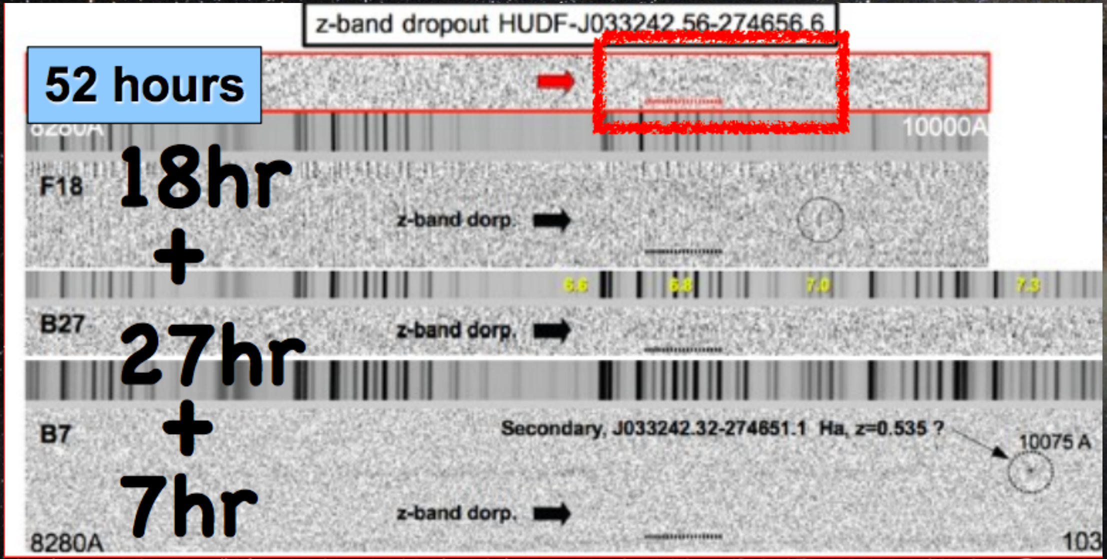
The galaxy GDS1408 is the brightest candidate identified in the Hubble Ultradeep Field (HUDF) area.It is oneof the most solid z=7 candidates, it was first detected by Bouwens +04 in the NICMOS HUDF data, and subsequently identified also by Castellano+10 and in the HUDF WFC3 data (Bouwens +10; Oesch+10; McLure +10; Bunker+09)





Actually not all observations were so successful…….

No Lyα is observed down to a flux limit of $f(Ly\alpha) < 1x10^{-18} erg/s/cm^2$ in skyline free regions



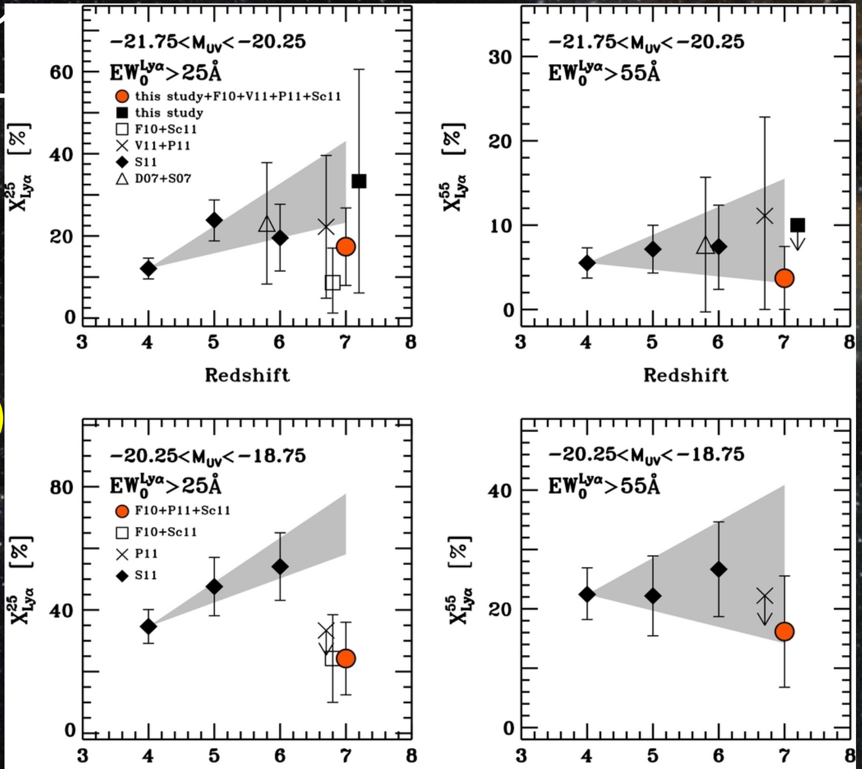
Deepest spectrum of 52 hours FORS2/VLT ever obtained in the reionization epoch by combining the data taken by 3 independent groups (PI Bunker 27 hours, PI Fontana 12 hours, PI Bouwens 7 hours) also obtained from archival research.

When exactly does the Lyα decline?

Early results by several independent groups indicated that the fraction is rising up to z=6 and then sharply declining (Stark+2010, Fontana+2010, Pentericci +2011, +2014, Ono + 201
Treu+2013, Caruana-

The rise and fall of Lyα is particularly pronounced for the faintest galaxies (but at these magnitudes samples are smaller and observations more difficult)

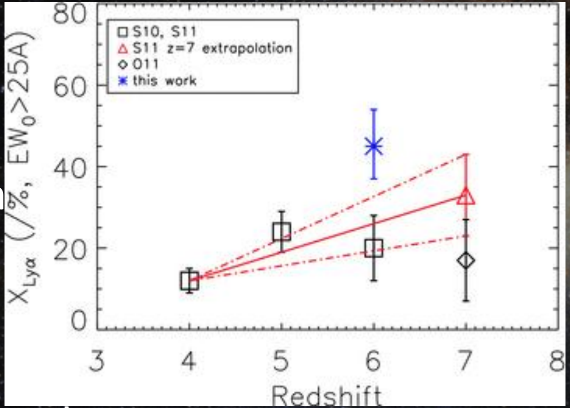
Field to field variation are large (patchy reionization LP+2014)



Early results by several groups were somewhat contradictory

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)



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)

CANDELSz7 - probing the reionization epoch with deep spectroscopy (ESO Large Programme 2013-2016)

A deep survey of galaxies at z~6-7 with VLT-FORS2 (LP 190.A-0685, PI L. Pentericci) 140 hours

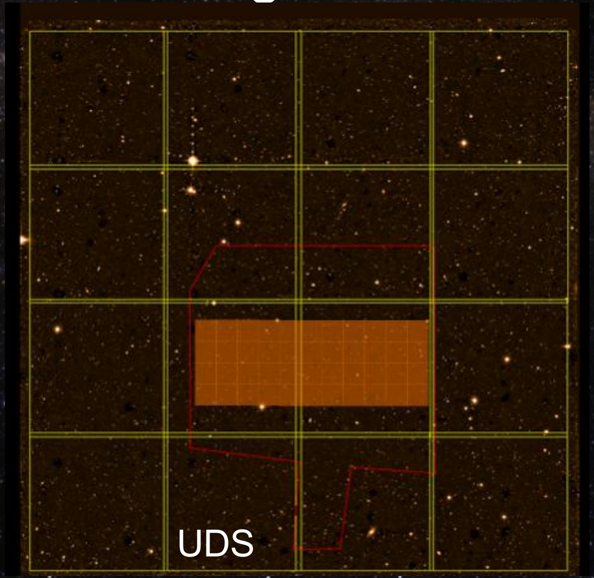
- t_{int}=10-20 hours
- CANDELS fields (GOODS-S COSMOS UDS)
- FORS2 observations cover the Lya visibility in the range 5.8<z<7.3
- Target selection based on LBG color diagrams and CANDELS accurate photometric redshifts
- **Including ancillary programs (PI Fontana, Bunker) we analysed a total of 230 hours of FORS2@VLT observations**

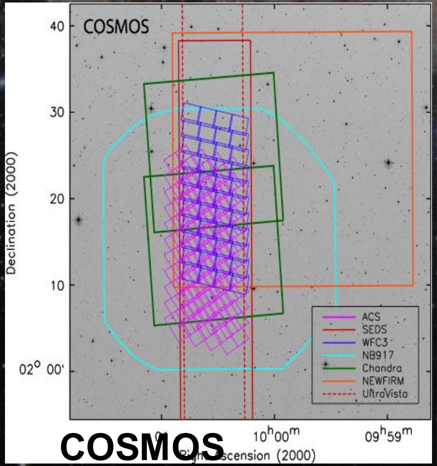
Aims

- Evolutions of the Lyα visibility over the epoch of the reionization -> constrain neutral hydrogen fraction as a function of redshift and luminosity
- Evolution of Lyα properties of galaxies vs other physical parameters
- Provide targets for ALMA

Results can be found in Pentericci +2018, De Barros LP+2017, Castellano, LP+ 2017

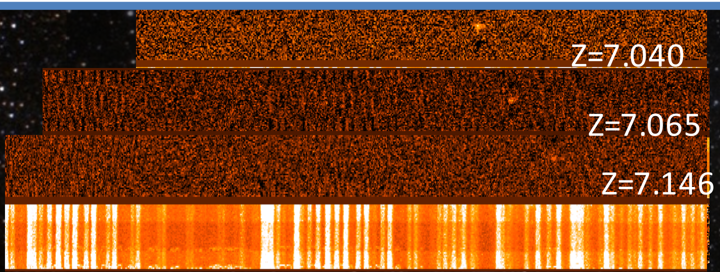
Galaxies are selected with homogenous color-color criteria from the CANDELS fields (GOODS South, UDS and COSMOS) which boast ultradeep HST data :
-The selection band (H-band) is independent of the presence of Lyα both at z=6 **&** z=7 unlike past surveys and minimizes any bias
-We employ a unique spectroscopic 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**.

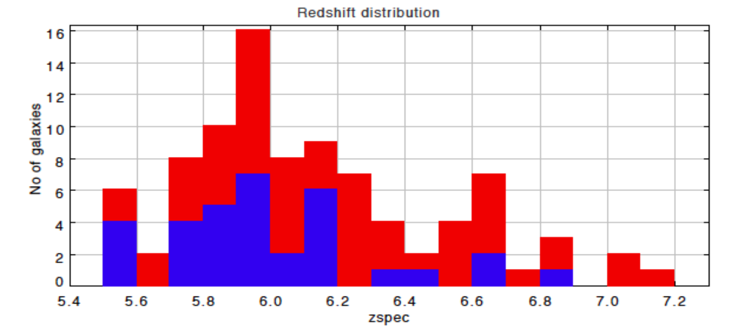


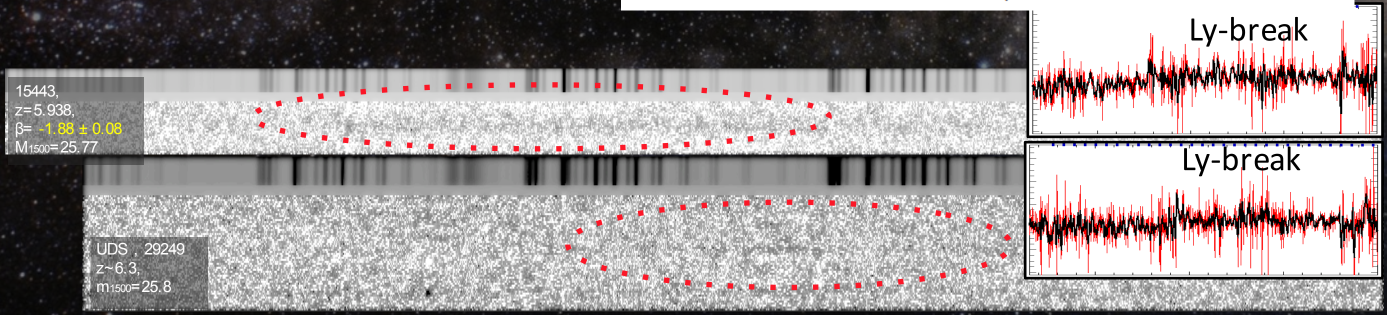


Results from Large program

We have have observed >160 galaxies with photometric z between 6 and 7.3 in the CANDELS fields GOODS-S, COSMOS and UDS, confirming the reshifts of >55 new objects mainly through Lyα emission



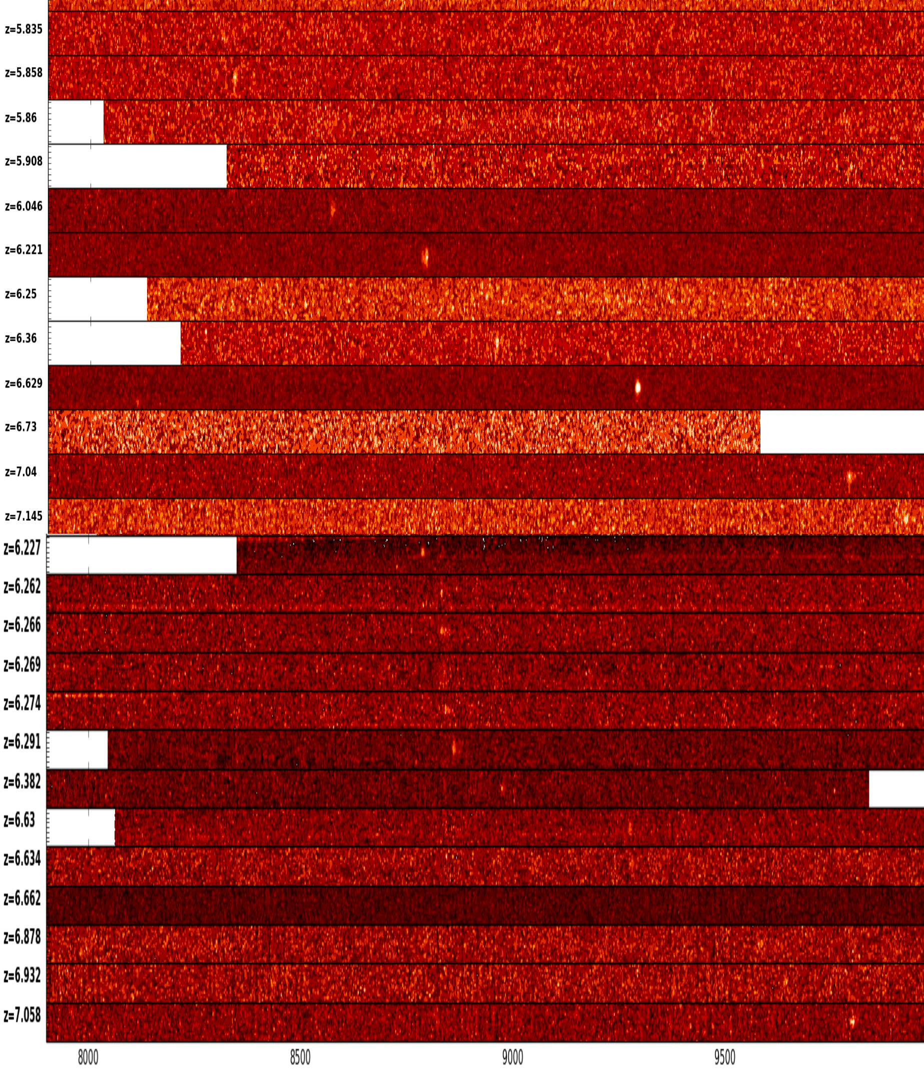




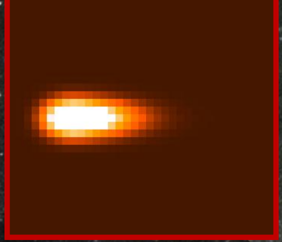
We measure redshift for faint (mag=25-26) galaxies with no Lya emission up t z=6.3-6.4. Non trivial. <u>Half of the LBG population at z=6</u>

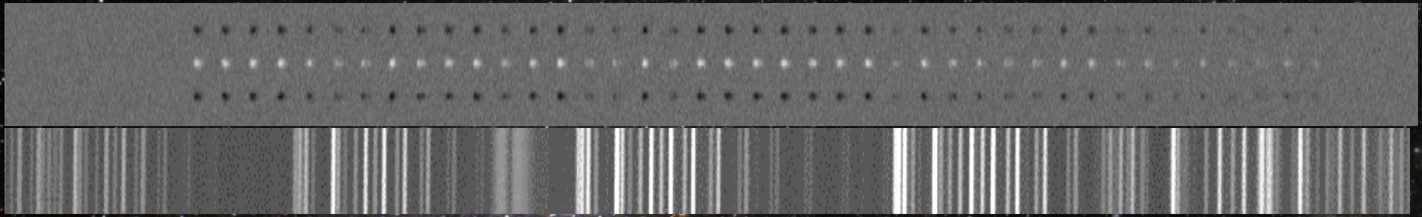
Pentericci+2018 A&A in press
De Barros, LP+ 2017
All data are being release through the ESO archive

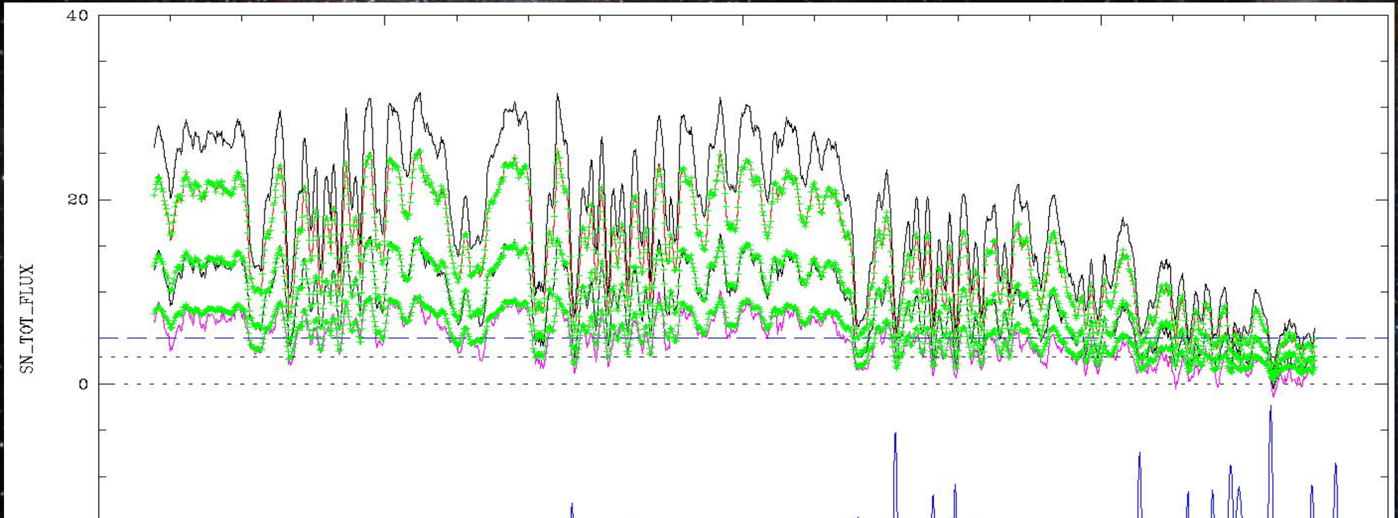
Including the new Large program data + earlier & archival observations (LP+2014,LP+2011,Vanzella+2011,2009, Caruana+2012,2014) we have assembled observations for a sample of >260 galaxies with 110 having a robust spectroscopic redshift in 8 independent fields (including 4 of the CANDELS fields), mostly observed with the same instrumental set-up and with similar limiting flux. For the undetected objects we set firm limits on the Lyα EW using very accurate simulations (see Vanzella+14, LP+14 and next slide)



To evaluate the fraction of Lyα emitters at z≈6 and z≈7 we 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



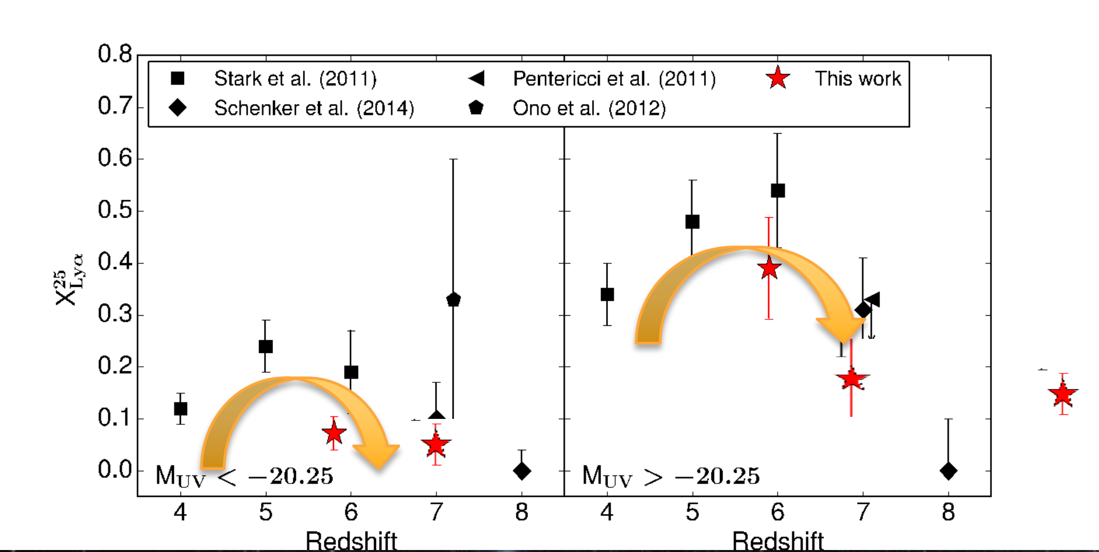




Simulations are repeated for different line fluxes, different slits in the masks, and different spatial positions along the slit to get all possible resulting S/N, which are then converted into EW limits depending on the magnitudes of the targets)

CANDELSz7: fractions of Lya emitters

Using the new data from our large program as well as all previous observations available we have re-evaluated **with greater accuracy** the fraction of Lya emitters at z=6 and z=7 separately for faint and bright sources

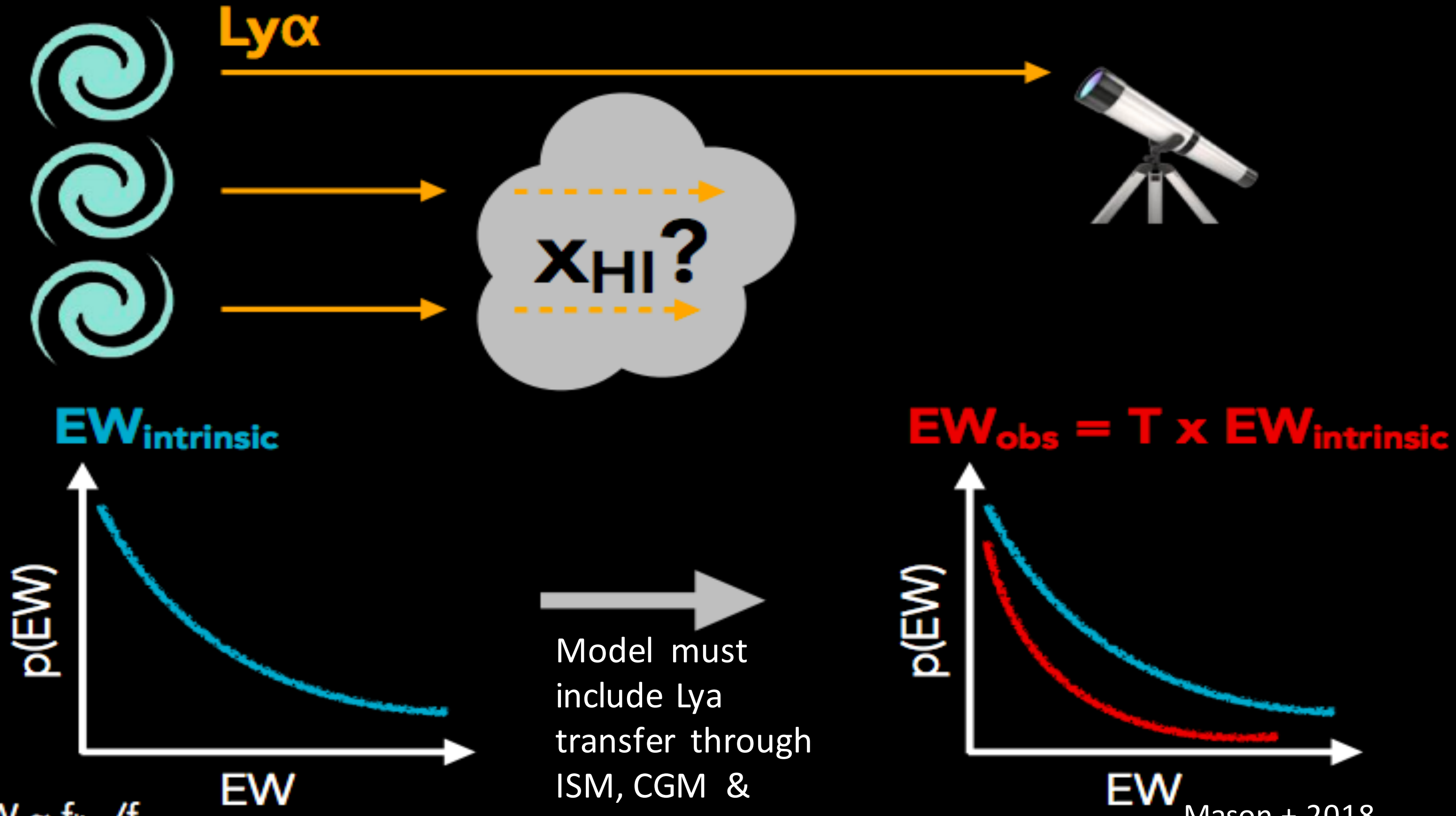


New points

We still see considerable differences between studies due to e.g. F2F variations, pre-selection criteria. Our results point to a a scenario where the down-turn of Lyα appears already at z<6 and is less drastic than previously believed

→ Reionization might be a more extended process and not yet completed by z=6 in agreement with some recent observations of QSO proximity zones (Eilers+2017)

How to we interpret the drop of Lya in terms of neutral hydrogen content at a given redshift?



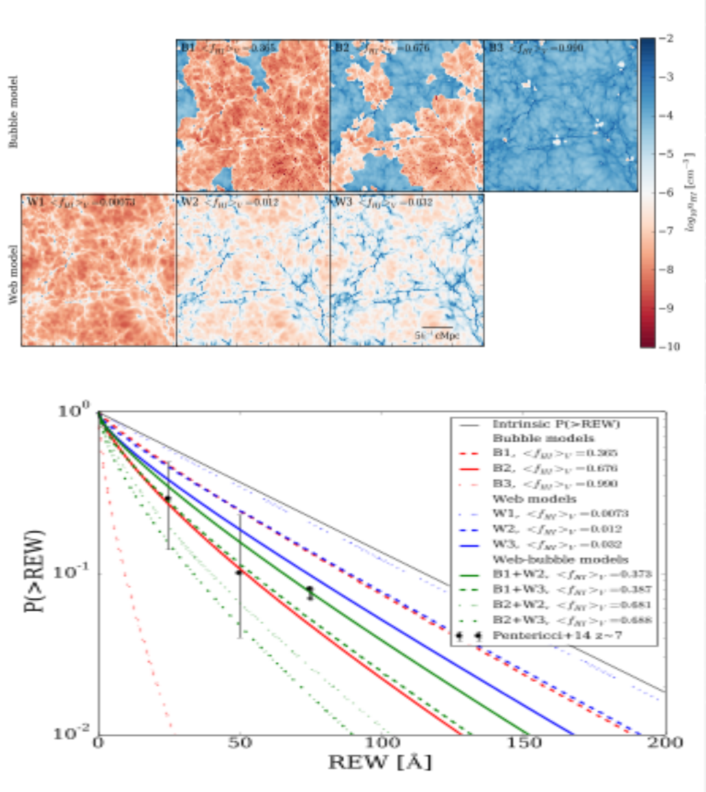
EW ~ f_{line}/f_{cont}

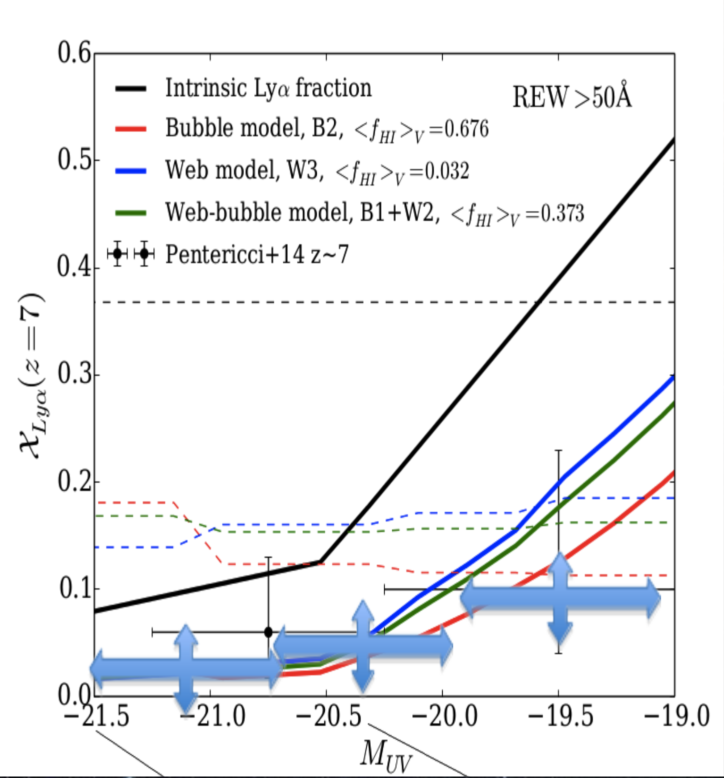
Model must include Lya transfer through ISM, CGM & IGM

Mason + 2018

Implications on the neutral hydrogen fraction

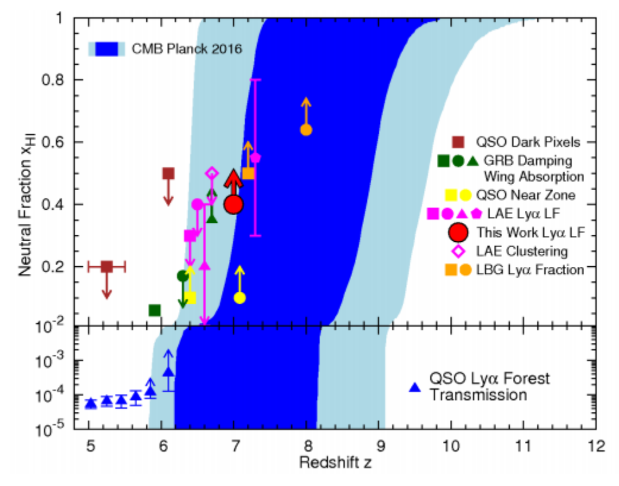
There are intrinsic degeneracies between the effects of small scales HI absorbers and diffuse neutral IGM. Kachiiki+2017 show that a joint anaysis of LAE LF and Lya fraction i LBGs can potentially discriminate between models.





The new z=7 measurements favour slightly a bubble model with XHI=0.67

The reionization timeline: current results



Kazuaki+2017

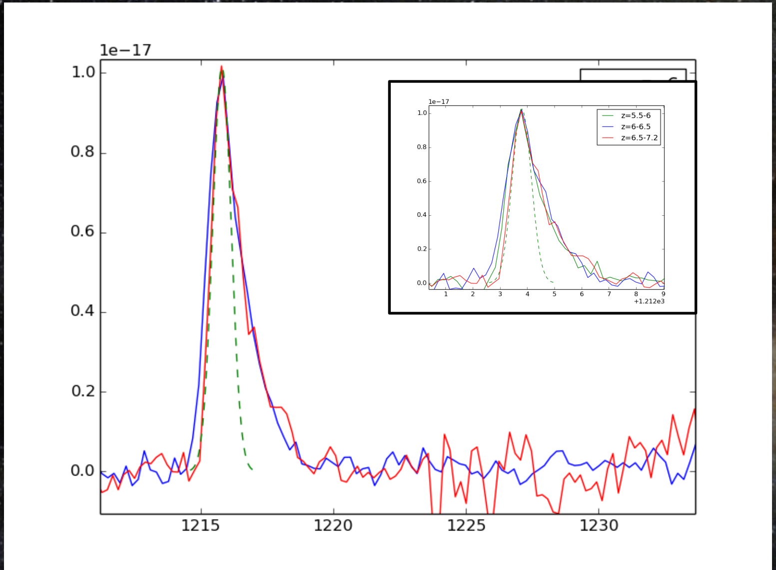
Still some tension between Plank data and LBGs and LAEs surveys data (to be updated after full analysys of latest results)

Cosmic reionization history (neutral fraction x_{HI} as a function of redshift) constrained by LBGs and LAE surveys using the various probes described before The blue and light-blue shaded regions show the 68% and 95% allowed intervals of reionization history, respectively, constrained by the redshift-symmetric reionization model and the analysis of the Planck 2016 CMB observations data by Planck Collaboration

Lyα fraction in LBGs $X_{HI} > 0.4\text{-}0.6$ @z=7
LAEs LF $X_{HI} \leq 0.2$ @z=6.5
LAEs clustering LF $X_{HI} \leq 0.5\text{-}0.4$ @z=6.5

First constraints on the effect of reionization on Ly α shape

Including previous data with FORS2 observations **taken with the same 600z grism** and using only high quality spectra we produced spectral stacks at z=7 (~20 galaxies) and z=6 (~50 galaxies)

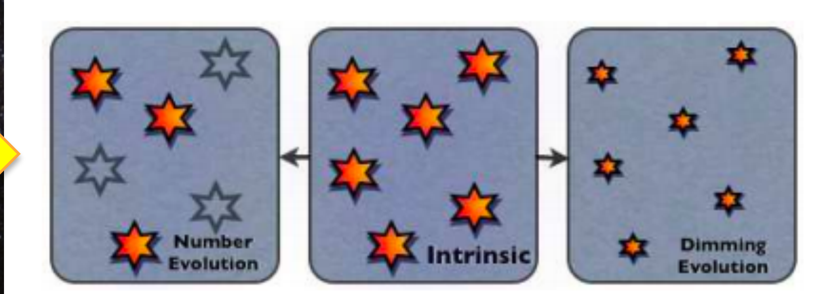


The blue side of the Lyα emission line is completely erased at z=7, where it is consistent with the instrument profile, while in the lower redshift stack some emission is still present at a significant level. Both stacks have a similar red extended tail.

Since the galaxies in the two samples span the same range of M_{UV} and SFR,
the difference in the observed shape of the Ly α profile might be due to the impact of the IGM (e.g. Laursen+2011).
First time we see a change in the shape of Lyα!

Constraints on the topology of reionization and sizes of HII regions will come from the spatial distribution of Lyα emitters and the evolution of bright and faint sources

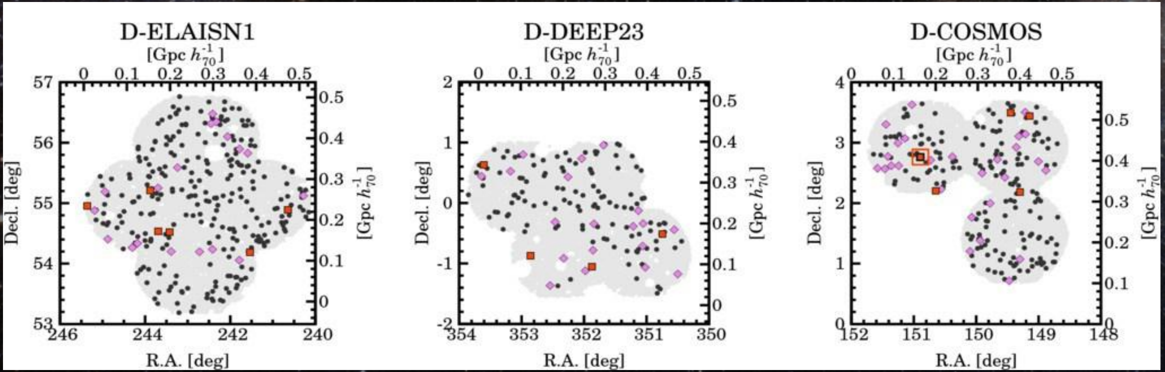
Patchy reionization (number evolution)



Smooth reionization (homogeneous dimming)

Constraints on the topology of reionization and sizes of HII regions will come from the spatial distribution of Lyα emitters and the evolution of bright and faint source

e.g.SILVERRUSH the Hyper Suprime-Cam (HSC) Subaru Strategic Program is mapping the distribution of LAE on scales of degrees.



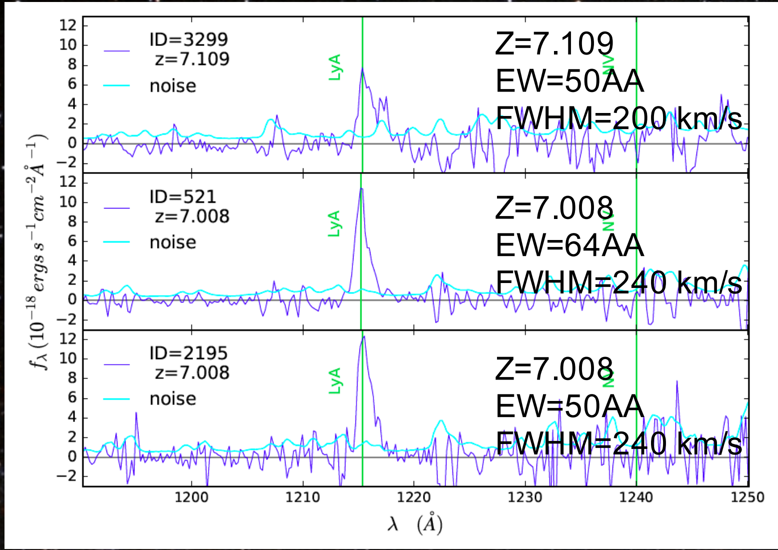
(Ouchi + 2017)

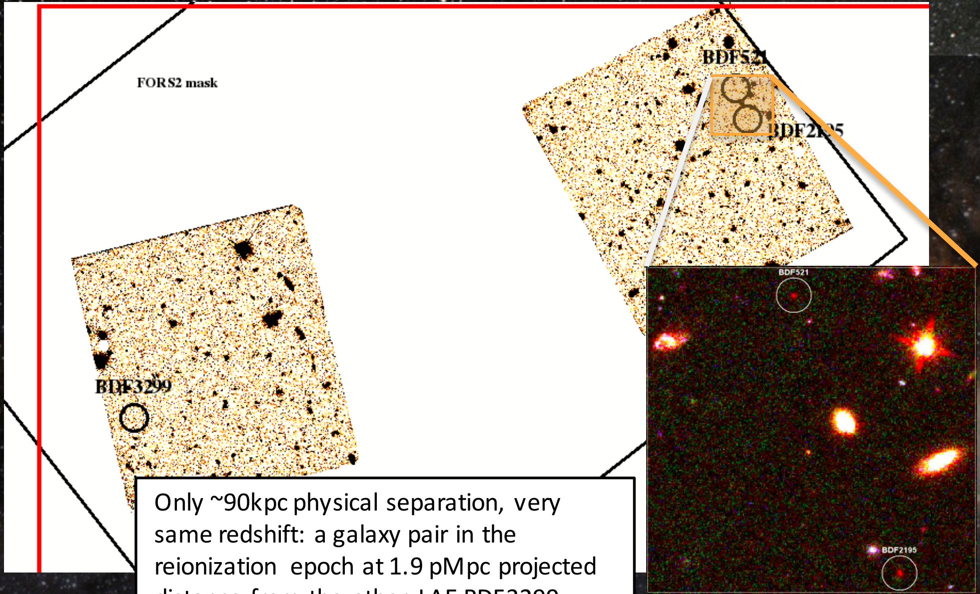
In the future SKA/LAE synergies will provide constraints on the neutral hydrogen fraction from the cross-correlation of the 21cm signal and LAEs density maps (e.g. Hutter + 2018)

Constraints on the topology of reionization and sizes of HII regions will come from the spatial distribution of Lyα emitters and the evolution of bright and faint source

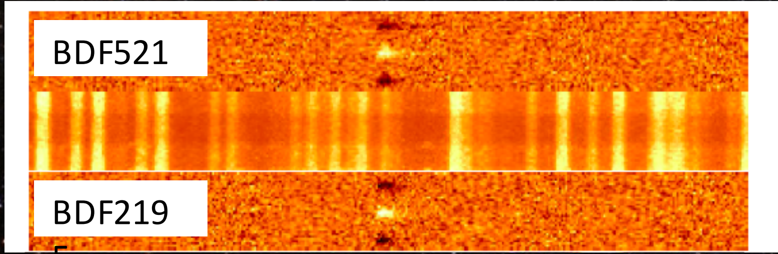
An alternative way are targeted studies of overdense regions: in the our large dataset including previous programs we have identified one such very peculiar region which we followed up with HST imaging and further ***FORS2 observations***

Evidence of a reionized bubble with high Lyα visibility





Only ~90kpc physical separation, very same redshift: a galaxy pair in the reionization epoch at 1.9 pMpc projected distance from the other LAE BDF3299

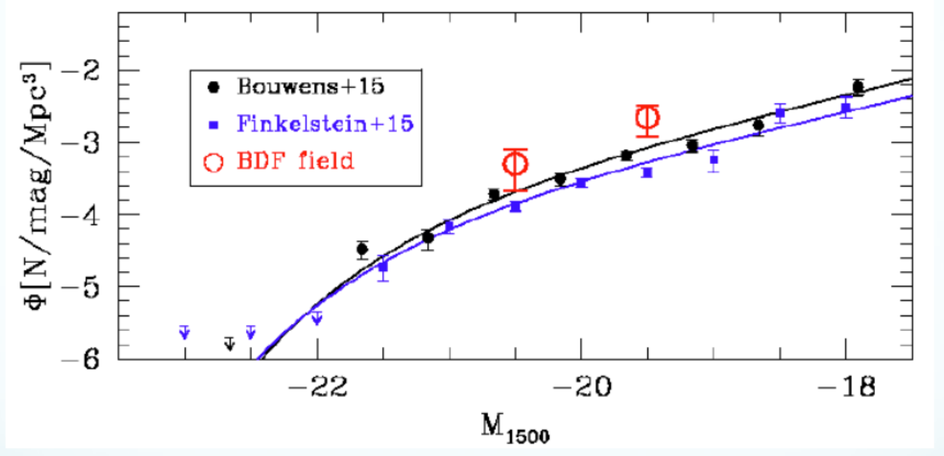


✧ We have discovered and confirmed 3 bright Lyα emitters at z=7.008, 7.008, 7.109 within a region of just 2 Mpc.

Castellano LP + 2018 ApJL

MC+

Evidence of a reionized bubble with high Lyα visibility



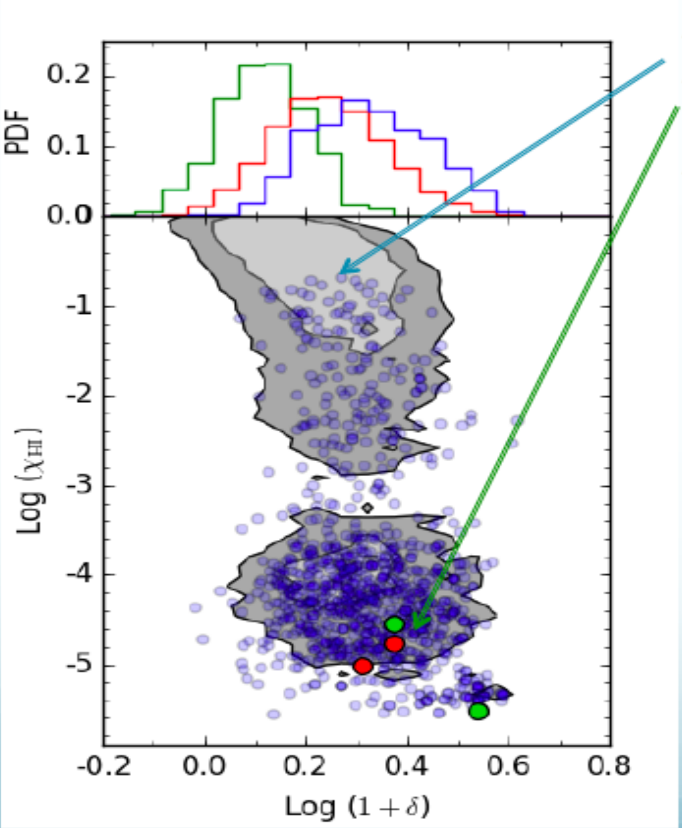
FWHM=240 km/s

- The three emitters sit in an overdensity of galaxies (14 additional galaxies with a photometric redshift consistent with z=7) with 3-4 x average LF at z~7.
- This is consitent with a positive relation between ionization state and density → INSIDE OUT REIONIZATION SCENARIO (McQuinn+07, Dayal+09).

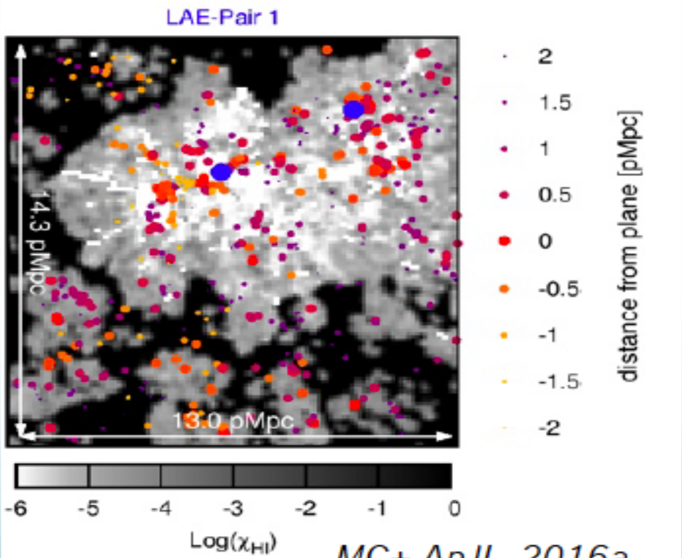
- The 14 fainter galaxies must have contributed in reionizing the bibble although they don't show Lyα emission (puzzling!!!)

Connection between reionization and overdensities

Comparison with SPH model (Hutter+14,+15).



- ✓ Relation between density and HI fraction
- ✓ LAE pairs live in overdense regions with low HI
- ✓ BDF analogs are reionized, overdense bubbles



MC+ ApJL, 2016a

Key question: did galaxies reionize the Universe?

Ionization rate	$\dot{n}_{\rm ion} = f_{\rm esc}\xi_{\rm ion}\rho_{\rm UV}$
Recombination time	$t_{\rm rec} = [C_{\rm H\,II}\alpha_{\rm B}(T)(1 + Y_{\rm p}/4X_{\rm p})\langle n_{\rm H}\rangle(1+z)^3]^{-1}$

Three key observables

ρ_{UV} Integrated UV flux density of high redshift star forming galaxies, especially sensitive to the contribution of fainter galaxies (this is computed by integrating the LF down to M_{UV}=some value)

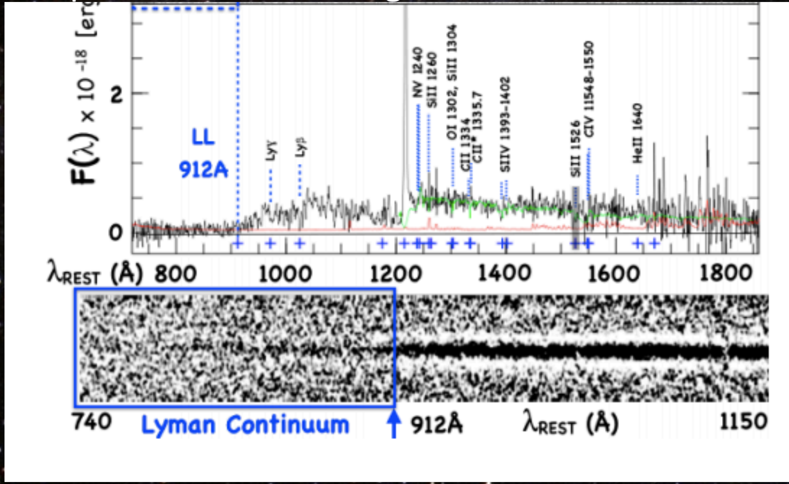
ξ_{ion} is the rate of ionizing photons produced by galaxies which is determined by the nature of the stellar populations

f_{esc} is the fraction of LyC ionizing photos that escape (on average) from galaxies

The elusive f_{esc} parameter

We need to know the average value of fesc at z=7-10 (the reionization epoch) but we can only measure it up to z=4-4.5. Beyond this redshift , the attenuation of the intergalactic medium is too high (Inoue et al. 21014)

Ion 3 at z=4.0 is one of the few galaxies at z>3 with a convincing spectroscopic detection of LyContinuum (Vanzella+18). The spectrum was obtained with the FORS2 blue optimised chip and 14 hours integration



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ian+2017

The escape fraction of this galaxy is 0.6 bur most of the few confirmed LyC leakers have mainly very low values of ~ 0.06- 0.20

Is this enough for ionization? Or a substantial increase with redshift is needed?

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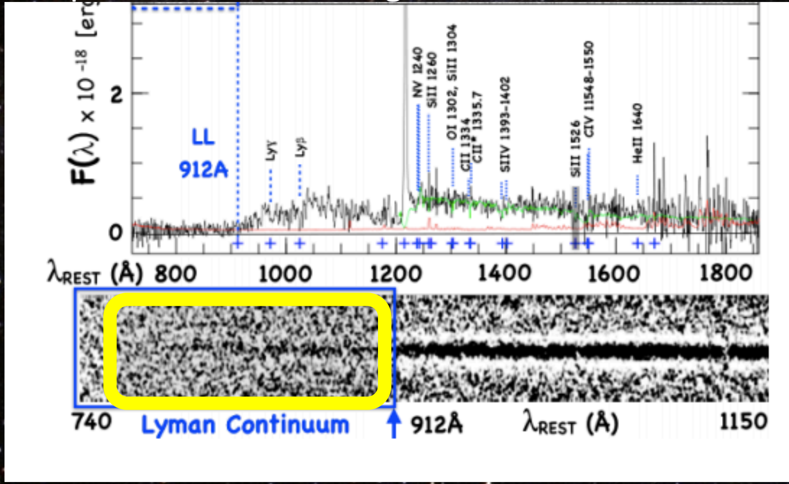

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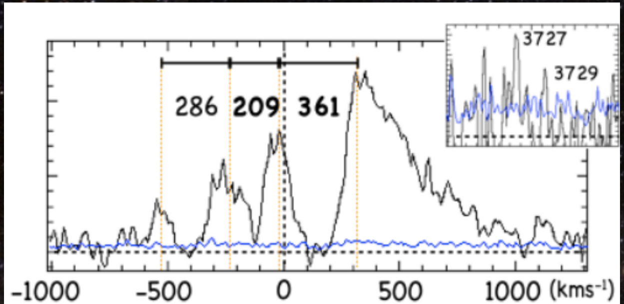
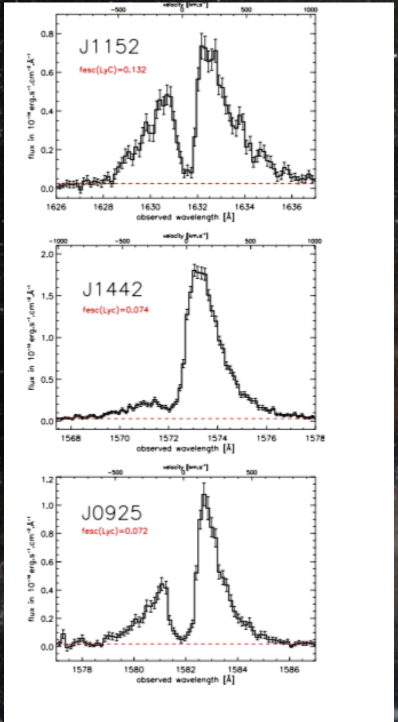
Even for LyC emitters with high escape fraction, the signal is extremly faint, ultradeep integrations are needed and the best sensitivity in the region 3500-4500 Ang

The elusive f_{esc} parameter:

The observations of the few solid known LyContinuum emitters have shown that they tend to have a very bright Lyα emission. with a peculian double peaked profile (Verhamme+17, 15, Jaskot&Oey14, Vanzella+18)



XSHOOTER spectrum of Ion3



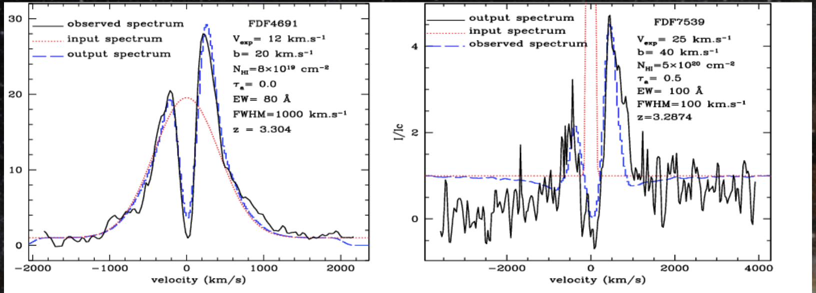
COS spectra of 3 known local LyC emitters (fesc7-13%) with bright double peaked Lyα (Verhamme+17)

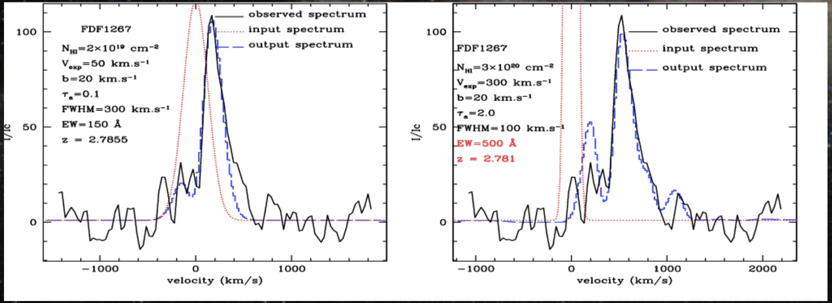
This is are also supported by theoretical models which predict a tight relation between mechanism that allow the escape of Lyα photons and LyC photons (Dijkstra+16)

The elusive f_{esc} parameter: what can we do with FORS2

Since it is much easier to detect Lyα than LyContinuum (and it can be done at any redshift) the profiles of Lyα emitters can become an empirical indirect diagnostics to search more efficiently for LyContinuum emission

The Lyα profiles can be studied in all the range from z=2.5 to z=7.2





Spme example of FORS2 spectra of double peaked Lyα emitters at z=3 (with yet unmeasured LyC emission) obtained with the Medium resolution grism e (R=2000) Tapken +07

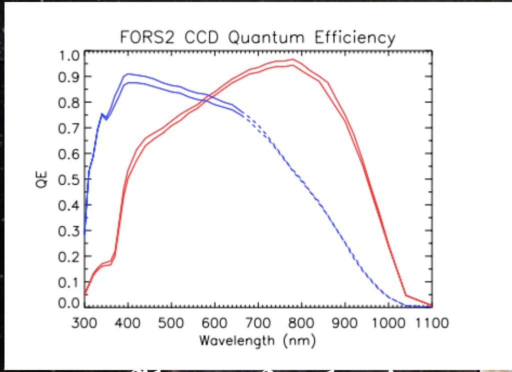
Can FORS2 still play a relevant role in the next few years to study reionization??

- ✧We still need to enlarge samples and confirm new sources in the reionizatio to better constrain models --- MUSE is a great instrument but the detectability of Lyα stops at z=6.5….just before the key epoch of interest ☹

- ✧FORS2 has large enough FOV to explore peculiar over-dense regions where Lyα visibility might be enhanced. The aim is to determine the link between galaxy density and reionization status -- NO other largish facility available @VLT since the VIMOS decommissioning

- ✧From the analysis of the Lyα profile change during the reionizaion we can also set contraints on the netrual hydrogen variations– medium resolution observations (R=2000-2200) are already suitable to perform this

Can FORS2 still play a relevant role in the next few years to study reionization??



✧Direct detection of LyC emission in galaxies at z=3-4 -- blue optimised CCD that is currently available only in visitor mode is particularly valuable for this

✧In the medium resolution mode (R2000) we can study the Lyα profiles of galaxies to set indirect constraint on the LyC escape fraction --- clearly XSHOOTER resulution would be ideal but the MOS capability still makes FORS2 competitive to characterise large samples

✧FORS2 spectra will still be very valuable even after the advent of MOONS and JWST which will only cover the 6500 Ang and above range.

Summary and conclusions

✧ Current knowledge of the reionization epoch has improved greatly but still there are uncertainties both on the observational and theoretical side

✧ Best constrain we have is a > 60% neutral IGM at $z\sim7$ partially in constrast with Planck results.

✧ First evidence of evolution in Lyα shape: blue side erased from $z\sim6$ to $z\sim7$.

✧ First evidence of a reionized bubble: enhanced Lyα visibility in a overdense region → galaxy density drives reionization

✧ We believe galaxies were the main drivers of reionization (i.e. they produced the photons needed) but measuring the escape fraction of these ionizing photons is still hard. The Lya line is the most promising indirect indicator for LyC escape.