Galaxies in the reionization epoch: the first science case for MOSAIC

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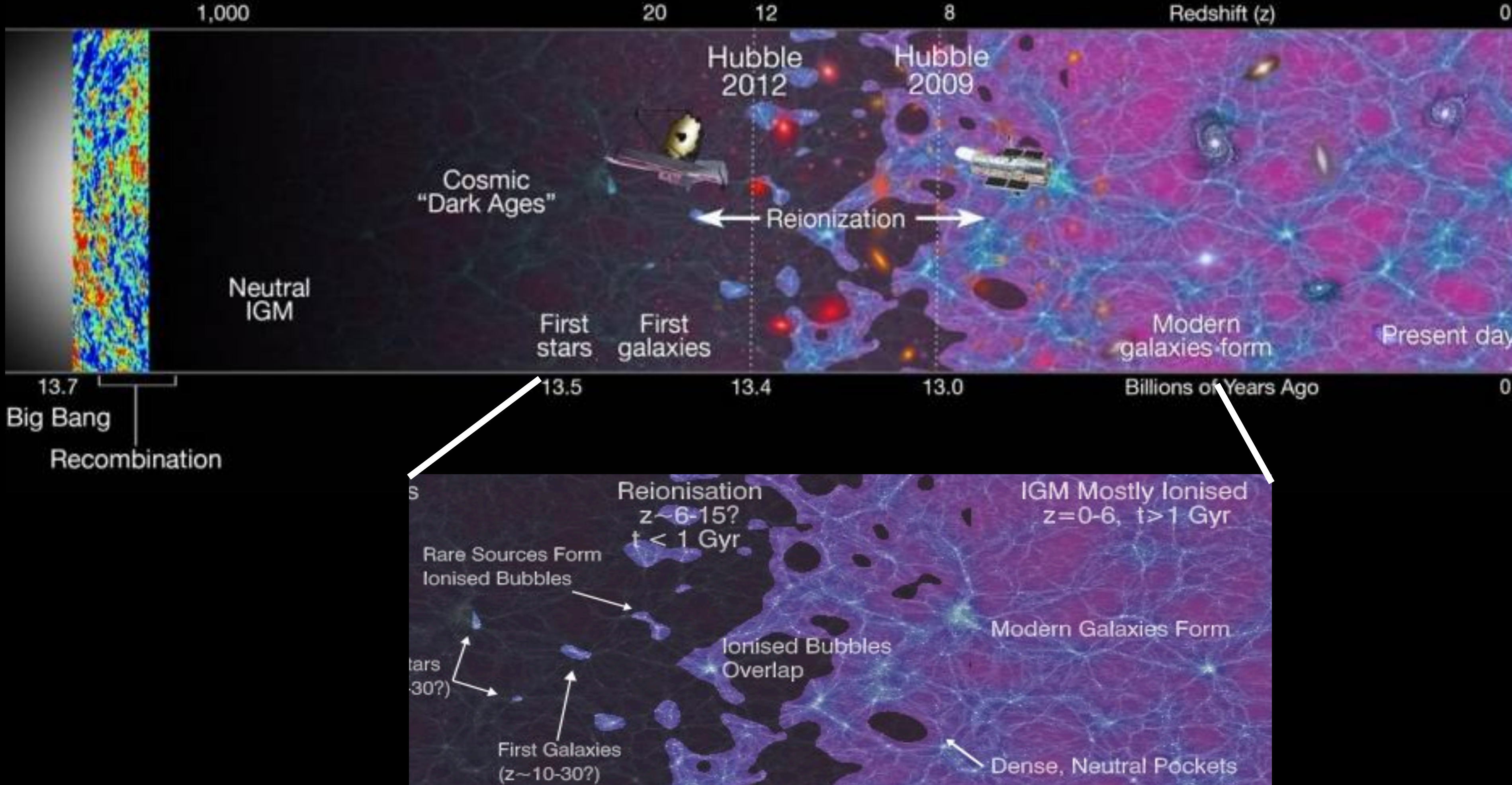
Outline

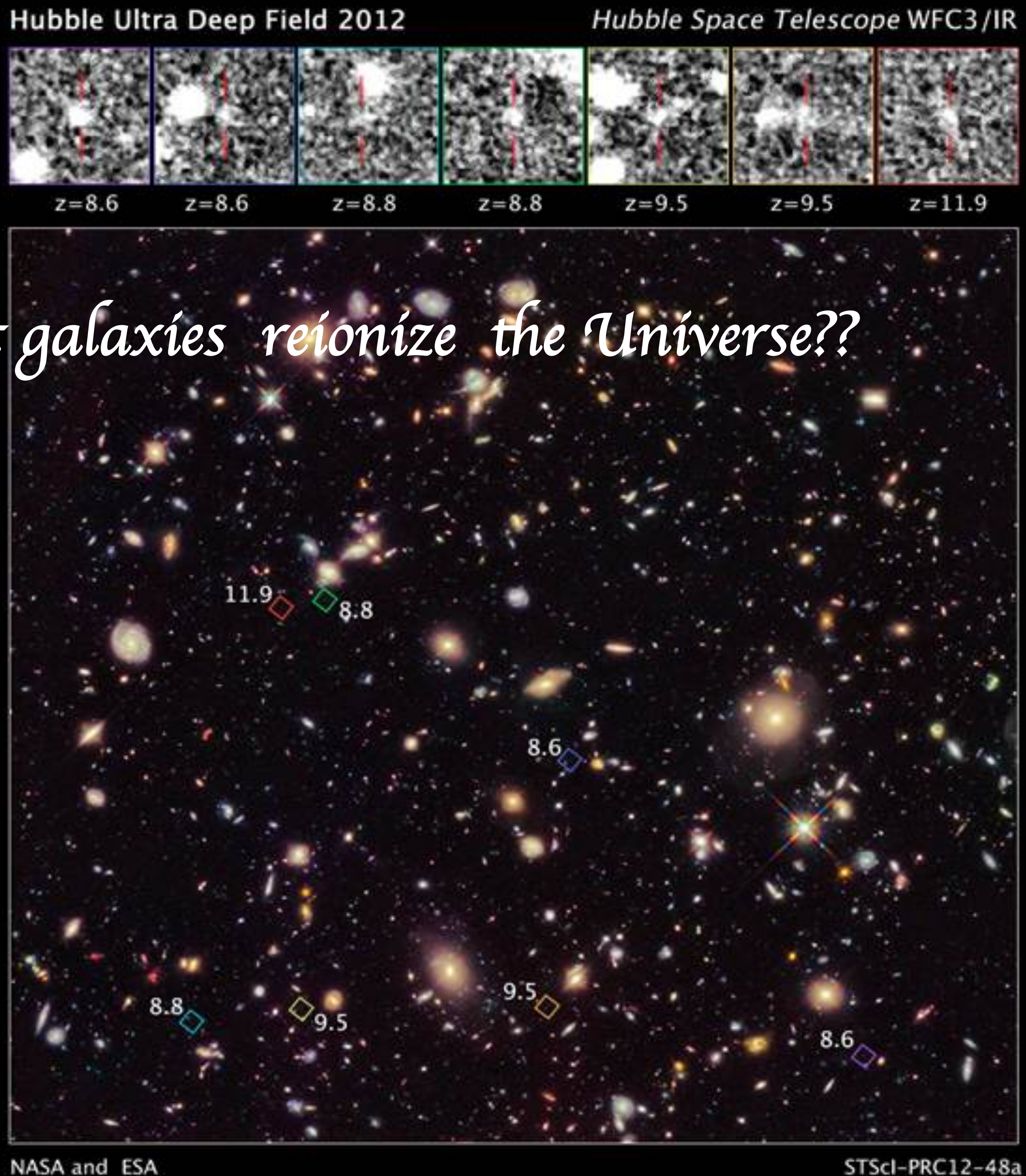
- The first galaxies and the reionization epoch
- Lyα fading in LBGs as a powerful probe of reionization
- MOSAIC: a high multiplexing MOS to observe the first galaxies
- Simulations of MOSAIC observations of Lyα emission and UV absorption lines in faint LBGs at z=9

1. When did cosmic reionisation start ???



The transition from the neutral IGM left after the Universe recombined, at $z \approx 1,100$, to the fully ionized IGM observed today is termed cosmic reionization. Hydrogen in the IGM remained neutral until the first stars and galaxies, formed, at $z \approx 15–30$: these primordial systems released energetic UV photons capable of ionizing local bubbles of hydrogen gas.As the abundance of these early galaxies increased, the bubbles increasingly overlapped and progressively larger volumes became ionized. The process ended at $z \approx 6–8$.

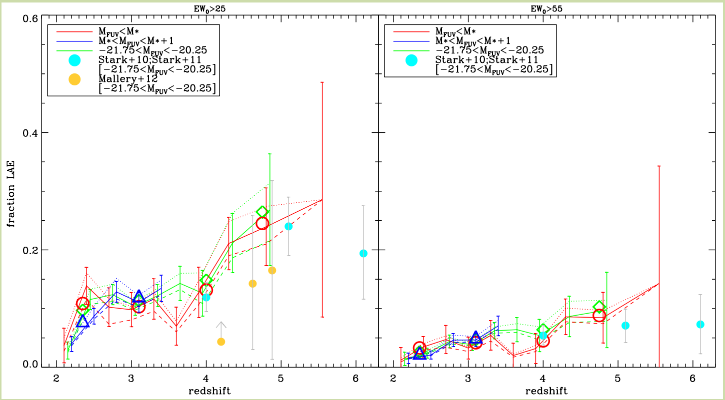
2. Did faint galaxies reionize the Universe??



*Ly*α *emission in Lyman Break Galaxies as probe of the reionization epoch*

RATIONALE - The Lyα emission is 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, dust distribution 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*)



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 <u>*we expect to detect a lack of Lyα emission is star forming galaxies*</u> provided that the galaxies properties do not change significantly over the same time interval

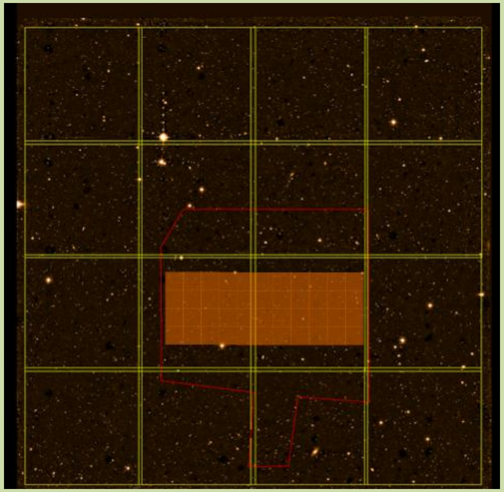
When exactly does the Lyα starts to disappear from the spectra of LBGs?

Early results (Fontana et al. 2010, Pentericci et al. 2011, Ono et al. 2012) indicated that this might be at z=7

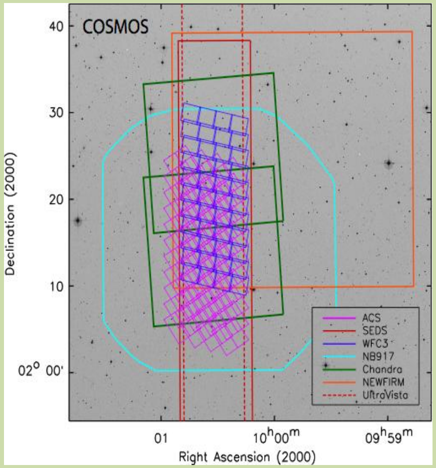
To give a solid answer to this question we designed the **ESO Large Program CANDELSz7: looking for the CANDELS that reionized the Universe (PI. LP)** which obtained 140 hours of FORS2@VLT to observe 200 galaxies at $5.8 < z < 7.4$ in COSMOS/UDS/GOODS-S and determine a solid and unbiased statistics of the evolution of Lyα fractions in this redshift range.

GOODS-SOUTH

UDS

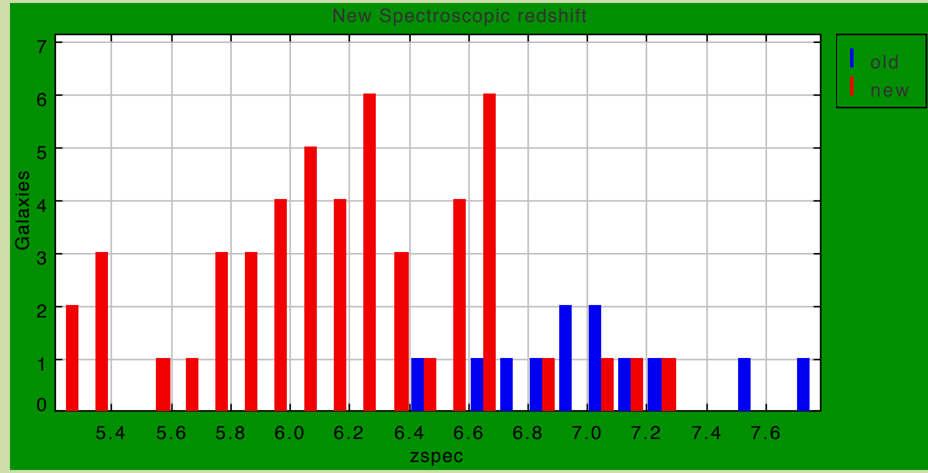


COSMOS

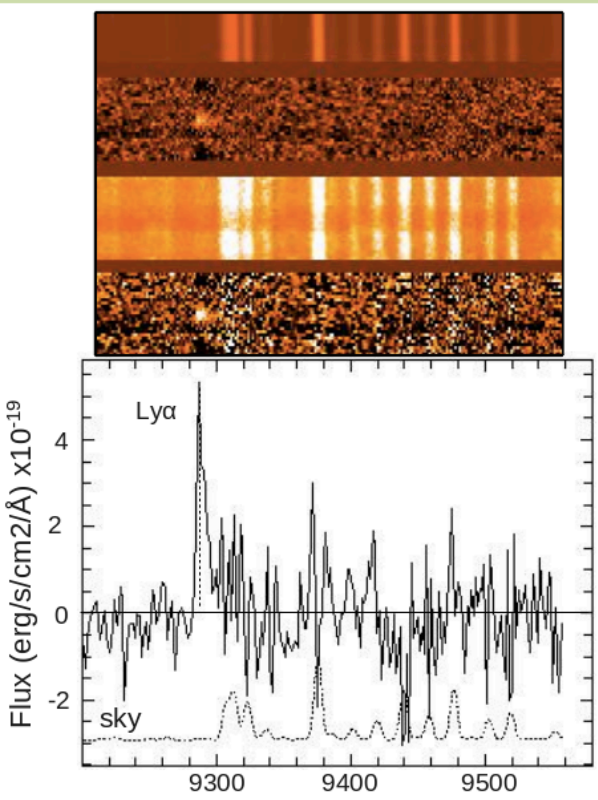


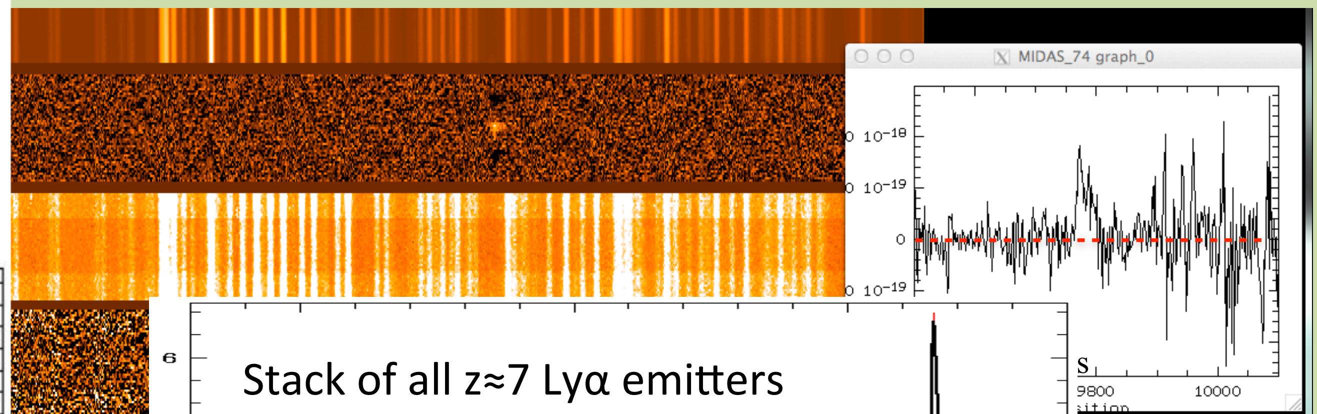
So far we analized ≈60 new candidate z=7 galaxies:
In addition a large number of i-dropouts observed (to re-evaluate EW distribution at z=6) and some high-z AGN and massive galaxies

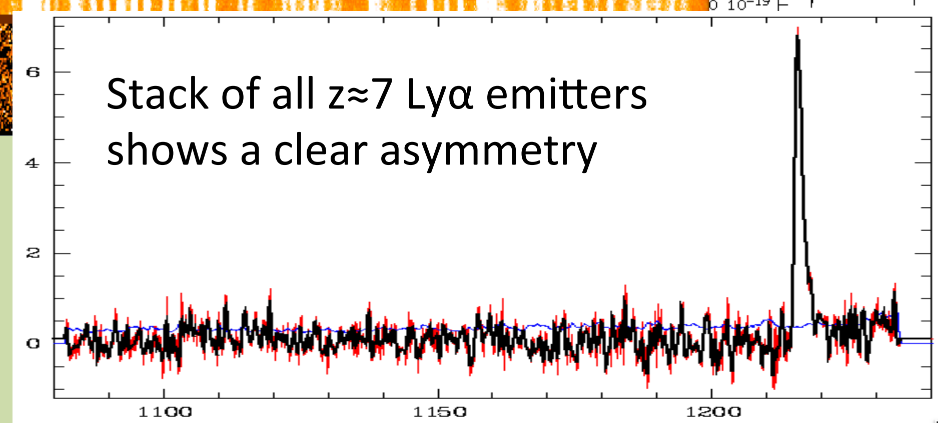
We have confirmed already > 50 new high redshift galaxies including 14 at t 6.5< z < 7.2 all with Lyα emission



Some new high redshift galaxies in COSMOS...





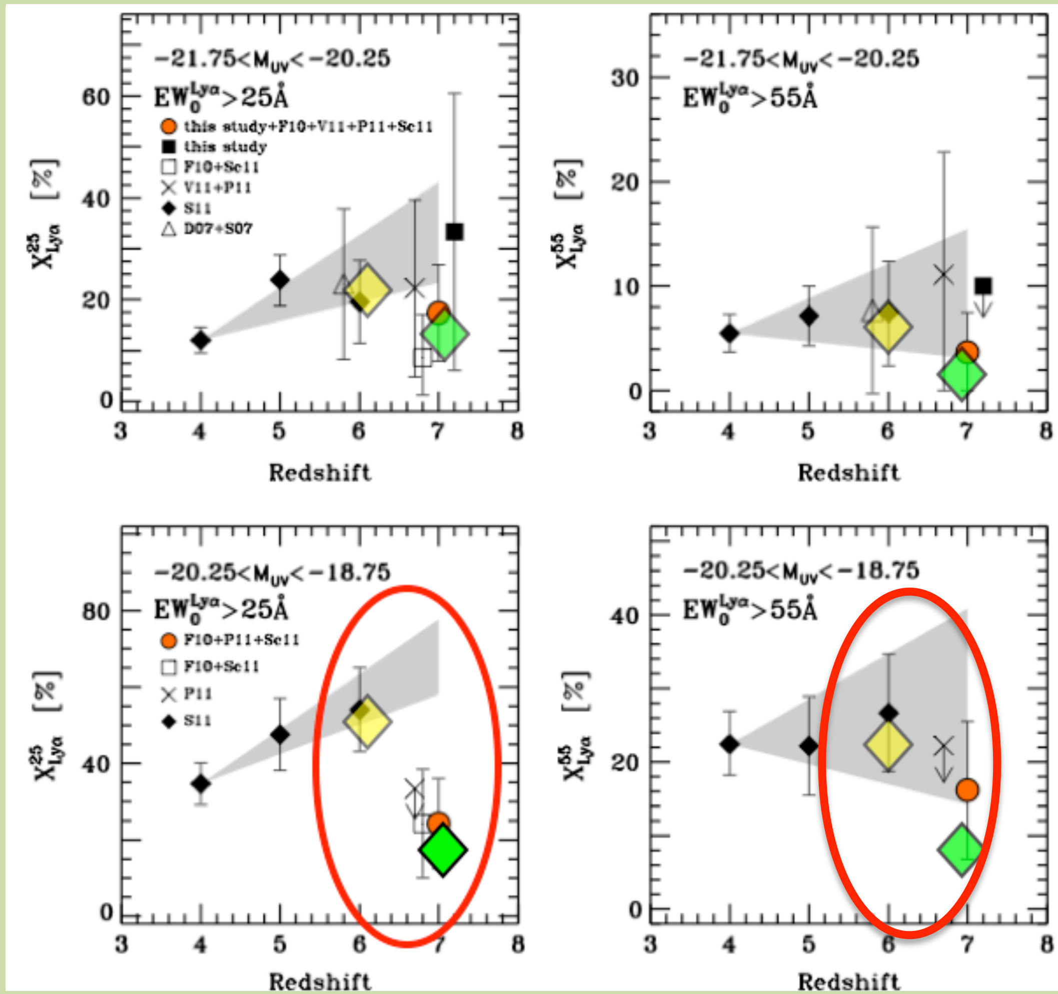


Including Large Program, earlier literature and archival spectra we have assembled a sample of ≈110 solid z-dropouts (z=7 candidates) and 140 i-dropouts (z=6 candidates) with deep observation.

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
- (LP et al. 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

The Lyα fraction drops significantly from z=6 to z=7 : what does it mean ?

☒ A significant fraction (> 60-70%) of selected galaxies is not at z≈7; however we do not detect any other line/feature in almost all cases & 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

☑ There is an increase in the amount of neutral hydrogen in the surrounding IGM that quenches the Lyα emission : we are probing the end of the reionization epoch

(or a combination of these last two items e.g. Mesinger et al. 2014)

If Lyα is quenched by neutral hydrogen we can set constraints on the neutral hydrogen fraction with the help of models

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

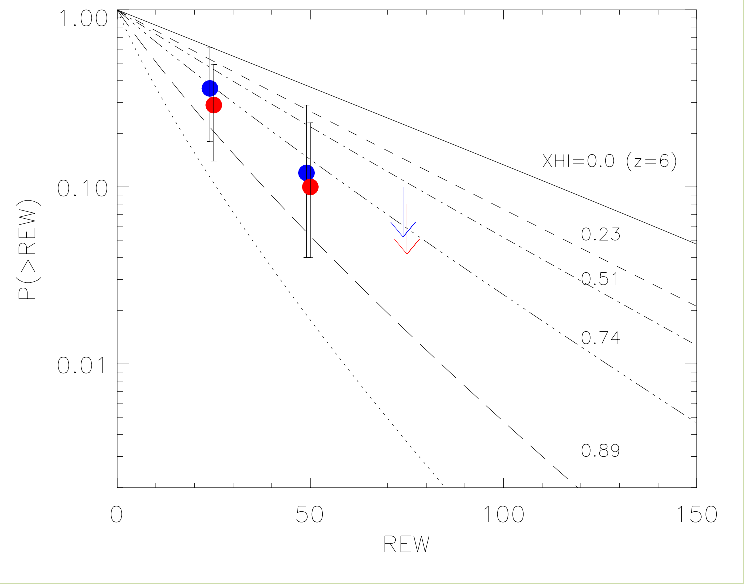
--Neutral hydrogen fraction

--Column density of HI

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

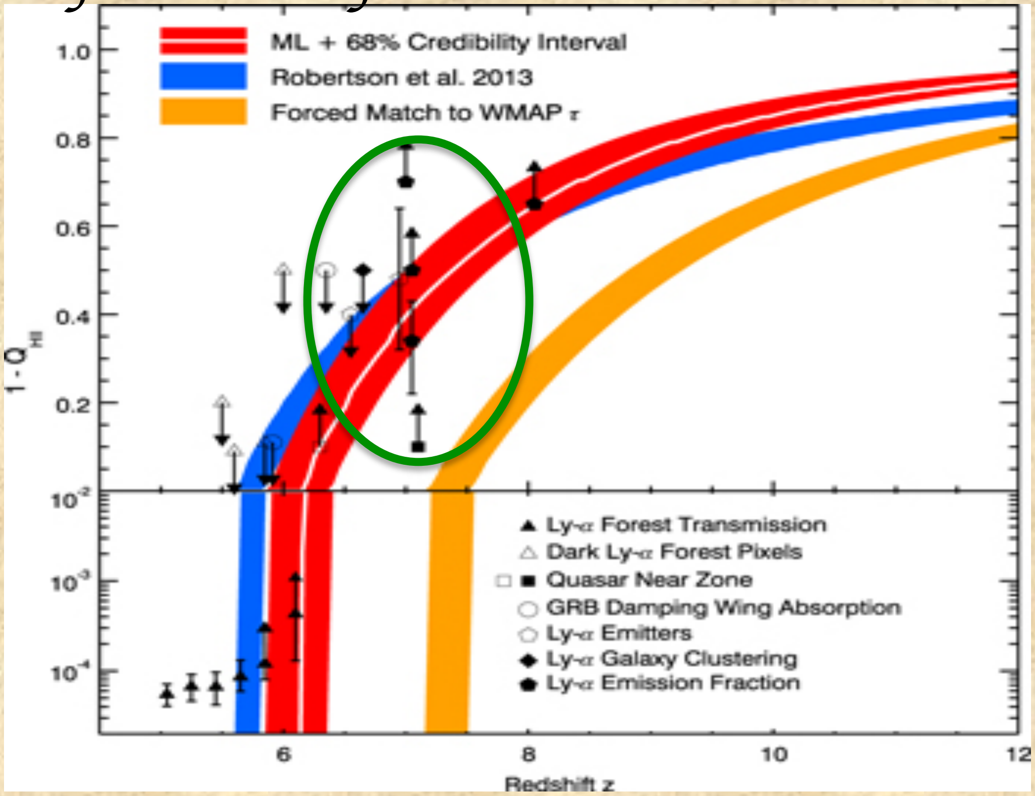
● ● fractions assuming that 0-20% of the candidates are lower redshift interlopers

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



Pentericci et al. in prep

The evolution of the neutral fraction

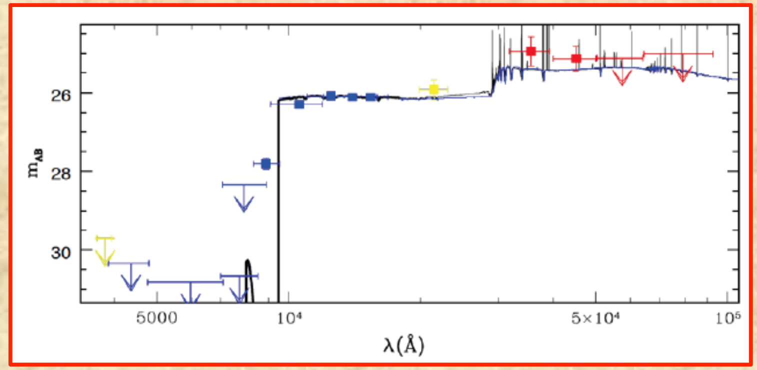


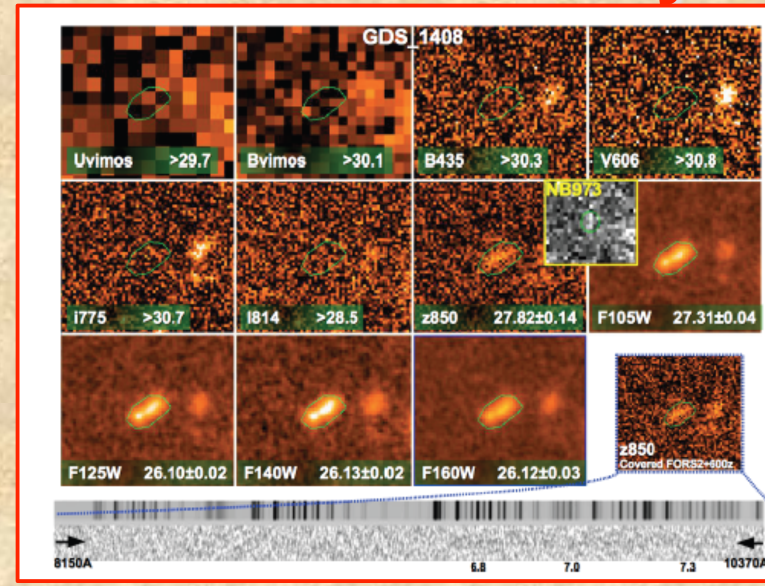
Upper panel Neutrality of the intergalactic medium as a function of redshift. Observational constraints by Robertson et al. (2013), updated to include recent IGM neutrality estimates from the observed fraction of Ly*α* emitting galaxies (Pentericci et al. 2014; Schenker et al. 2014), constraints from the Ly*α* of GRB host galaxies (Chornock et al. 2013), inferences from dark pixels in Ly*α* forest measurements (McGreer et al. 2015). The evolving IGM neutral fraction computed by the model is also shown (red region is the 68% credibility interval; white line is the ML model). Data and models are remarkably consistent. **Bottom panel:** the IGM *neutral fraction* near the end of the reionization epoch, where the model fails to capture the complexity of the reionization process. The model forced to reproduce the *WMAP τ* is in orange.

Observationally: galaxies at z > 7 mostly have extremely faint Lyα emission lines (EW < 10 Å flux < 10^{-18} erg/s/cm) <u>or Lyα may be absent</u>

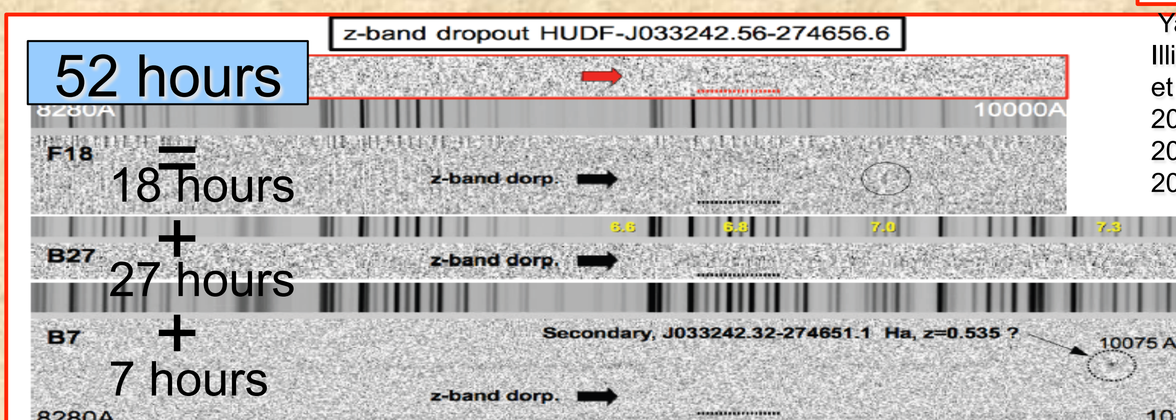
A **52 hours** FORS2 spectrum of a z~7 candidate: **NO Lyα!**

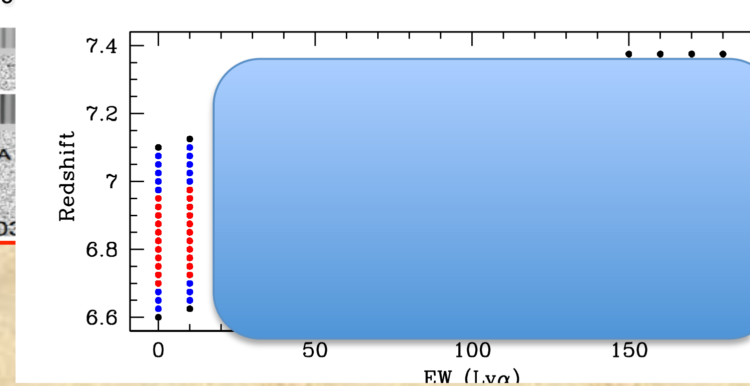
One of the most robust z~7 candidate in HUDF





Yan & Windhorst 2004; Bouwens et al. 2004; Bouwens & Illingworth 2006; Labbé et al. 2006; Bouwens et al. 2008; Oesch et al. 2010; Fontana et al. 2010; McLure et al. 2010; Bunker et al. 2010; Yan et al. 2010; Finkelstein et al. 2010; Castellano et al. 2010; Wilkins et al. 2011; Bouwens et al. 2011; Grazian et al. 20

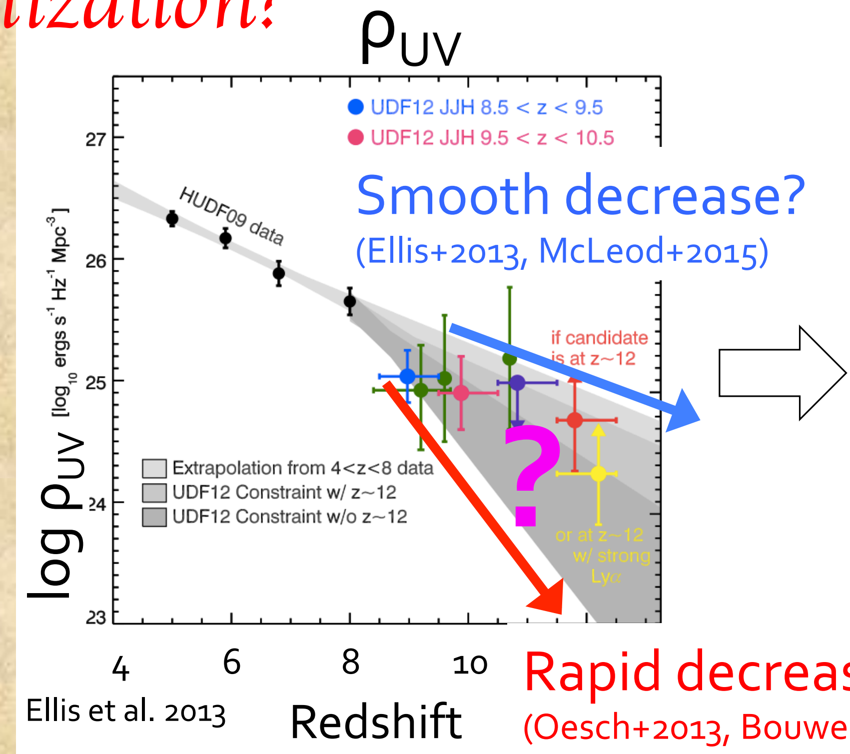


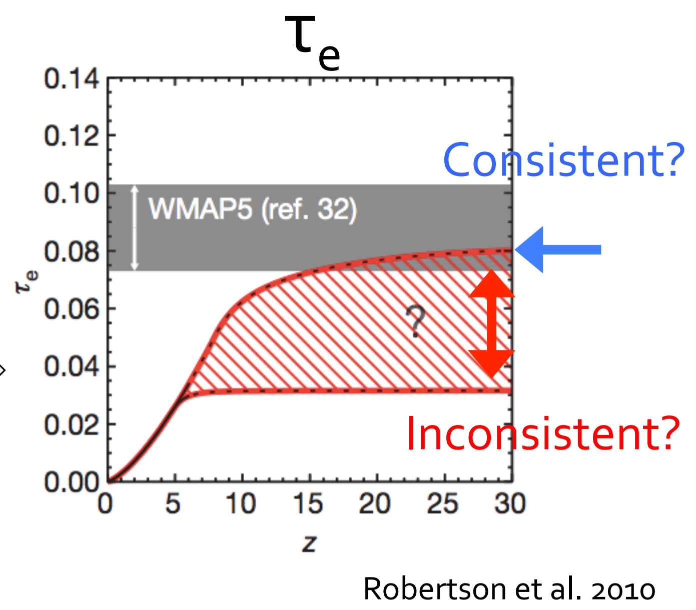


f(Lyα)<3e^{-18} erg/s/cm^2 EW(Lyα)<9A rest-frame

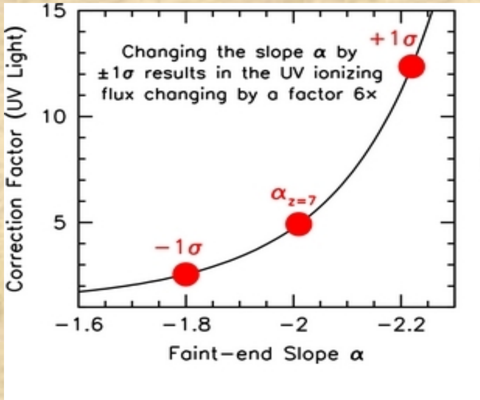
Vanzella et al. 2014

Are z>7 LBGs the sources responsible for reionization?





Large uncertainty on ρ_{UV} due also to the unknown faint end slope of UV luminosity function at z>7 : if the slope is steep (i.e. there are many very faint objects) then galaxies can do the job!!!



Bouwens et al. 2011, Grazian et al. 2012, Atek et al. 2015

The trend of decreasing Lyα is solid

<u>It continues at $z \gg 7$</u>

→ 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 attempts <u>on many tens of galaxies</u>

Implications for observations:

It will be impossible to secure the redshifts of *statistical samples* of faint $z=7.5-9$ galaxies even with current near-IR facilities (MOSFIRE, KMOS, LUCIFER)

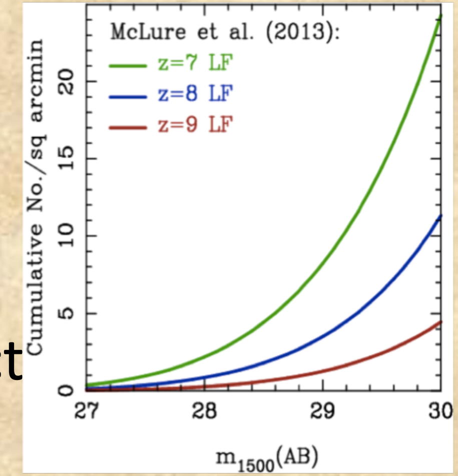
Use of alternative emission lines as efficient redshift indicators (e.g. CIII]@1909Å in the near-IR of [CII]@158μm with ALMA) so far have failed

<u>To gather statistical samples , explore the reionization epoch and find the galaxies responsible for reionization during the first 500 Myrs we will need E-ELR (and JWST)</u>

………… MOSAIC!!!

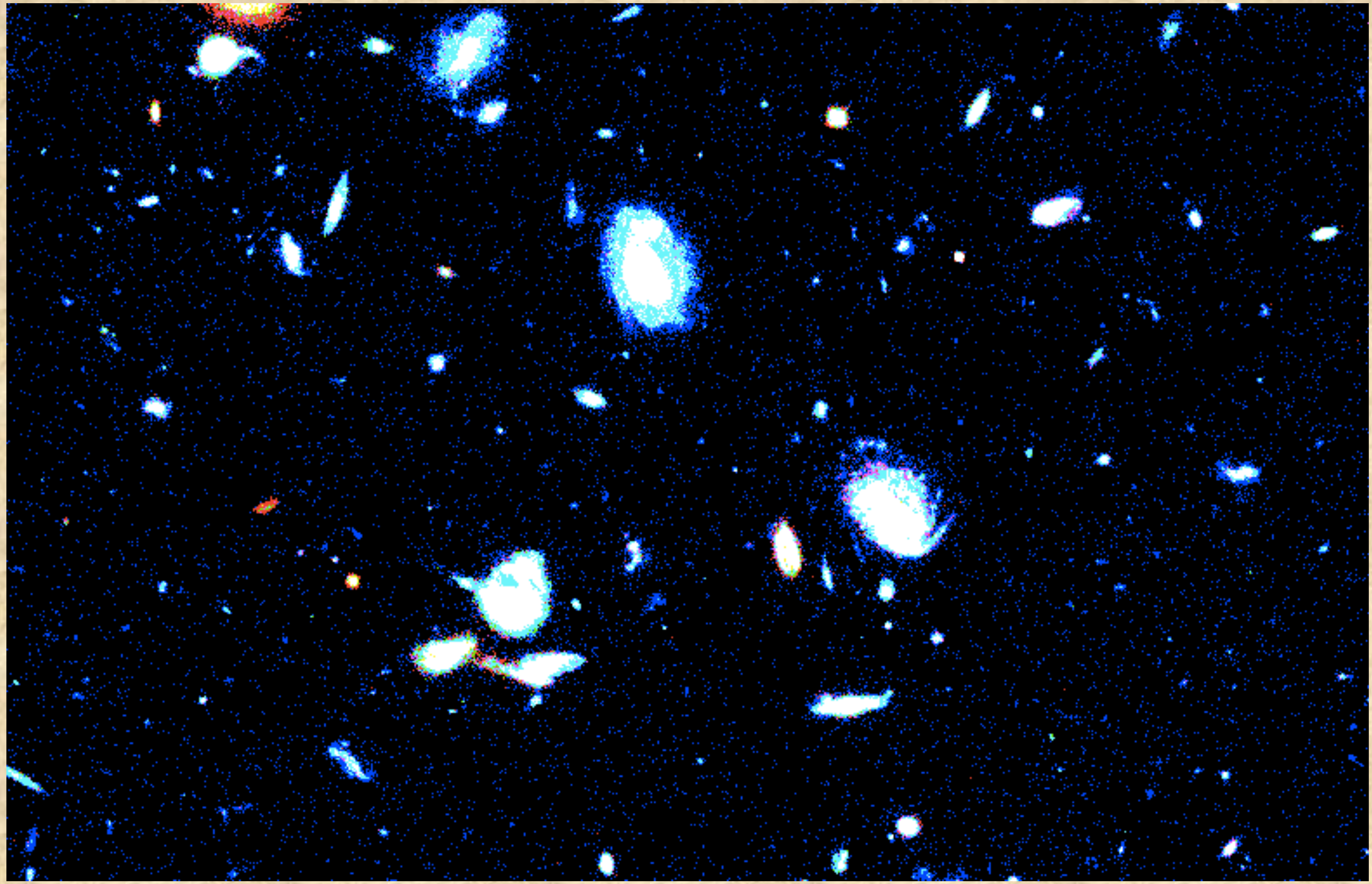
WHY MOSAIC?

- We want to extend the Lyα search to z=10 and above to find the sources responsible for reionization and determine the timeline of this process
- We need to measure Lyα lines with fluxes 10-20times fainter than current samples (down to 10^{-19} erg s^{-1} cm^{-2} and even deeper for lensed objects)
- We need a multi-object instrument to match density of M_{uv}=30 galaxies, presumably the main responsible of reionization – also MOS capability can mitigate the long integration needed to detect continuum and absorption lines for redshift determination when Lyα is absent



- Good image quality because the z> 7 sources are com light radii < 0.15 arcsec Grazian et al. 2012)
- An IFU capability to resolve their clumpy structure

ELT-MOS/MOSAIC



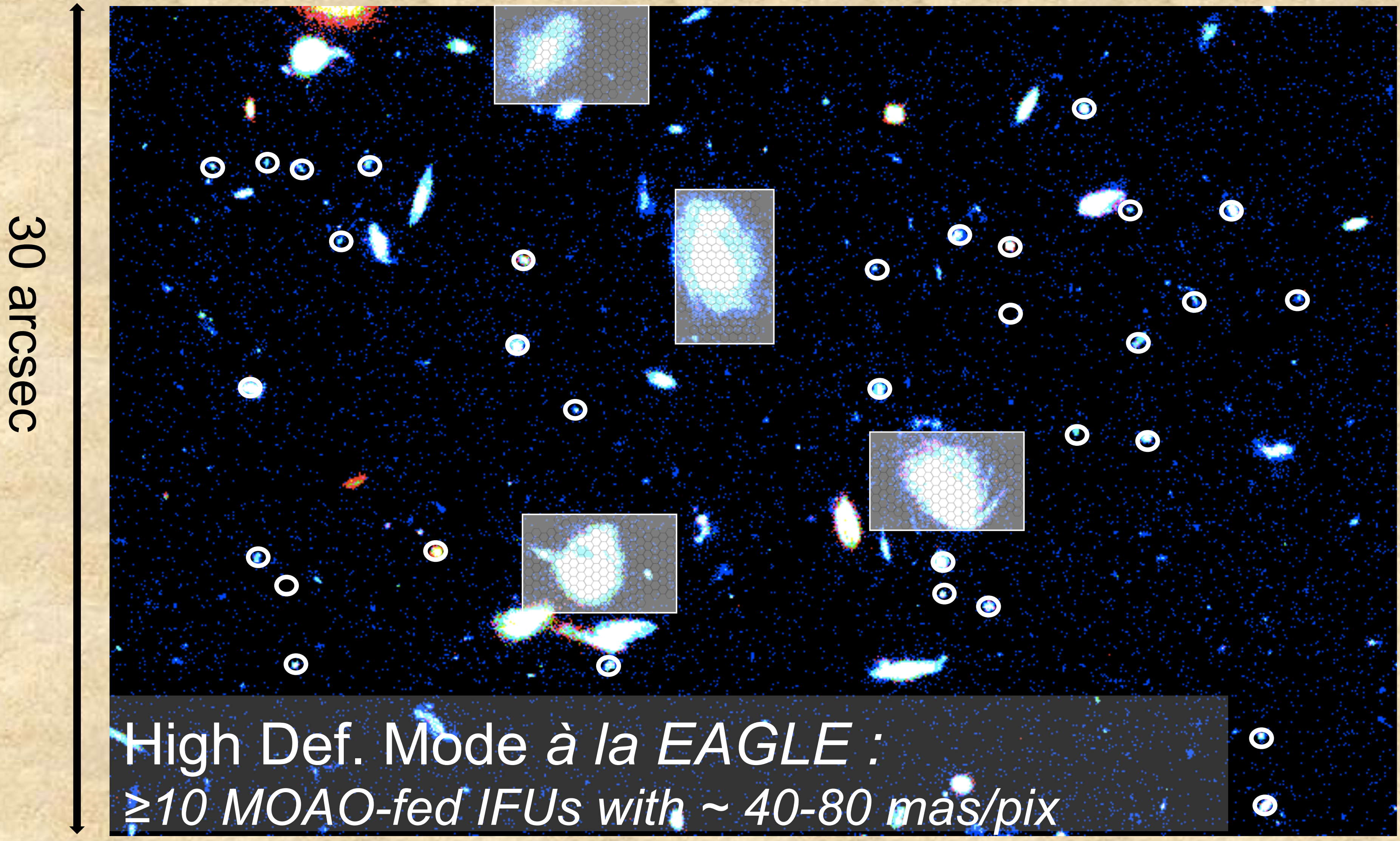
30 arcsec

ELT-MOS/MOSAIC

High Multiplex Mode *à la OPTIMOS-EVE* :

100-250 Fibers with GLAO/seeing resolution

ELT-MOS/MOSAIC



ELT-MOS White Paper

MOSAIC

- SC1: First light - spectroscopy of the most distant galaxies
- SC2: Spatially-resolved spectroscopy of high-z galaxies
- SC3: Role of high-z dwarf galaxies in galaxy evolution
- SC4: Tomography of the IGM
- SC5: Resolved stellar populations beyond the Local Group
- SC6: Galaxy archaeology with metal-poor

& more…

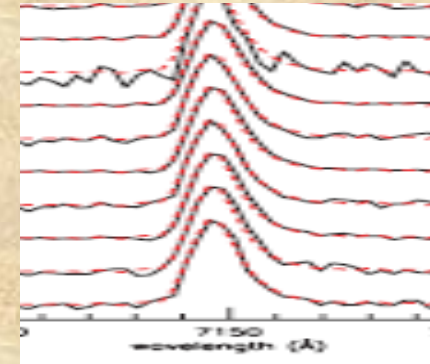
Next step is to prioritise TLR and iterate with technical & operational feasibility

SIMULATIONS

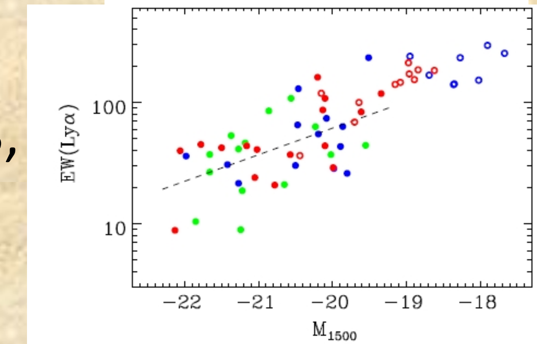
Table 3: Summary of top-level requirements from each Science Case

Case	Target densities	FoV/target	Spatial resolution	λ-coverage (μm)	*R*
SC1	1-2 arcmin^{-2}	2" × 2"[3]	40-90 mas	1.0-1.8 *1.0-2.45*	5,000
	10s arcmin^{-2}	–	(GLAO)	1.0-1.8 *1.0-2.45*	>3,000
SC2	1-2 arcmin^{-2}	2" × 2"	50-80 mas	1.0-1.8 *1.0-2.45*	5,000
	10s arcmin^{-2}	–	(GLAO)	1.0-1.8 *1.0-2.45*	> 3,000
SC3	≥ ~20 arcmin^{-2}	–	(GLAO)	0.8-1.7	≥5,000 *~10,000*
SC4	0.5-1 arcmin^{-2}	2" × 2"	(GLAO)	0.4-1.0 *0.37-1.0*	5,000 *10,000*
SC5	Dense	1" × 1" *1.5" × 1.5"*	≤75 mas *20-40 mas*	1.0-1.8 *0.8-1.8*	5,000
	10s arcmin^{-2}	–	(GLAO)	0.4-1.0	≥5,000 *≥10,000*
SC6	10s arcmin^{-2}	–	(GLAO)	0.41-0.46 & 0.60-0.68 *0.38-0.46 & 0.60-0.68*	≥15,000 *≥20,000*

Simulations of LBGs and LAEs at z=9



- Lyα emission is assumed to be co-spatial with the UV emission and modelled as a truncated Gaussian with 200 km/s blue shift compared to systemic redshift (e.g. Shapley et 2003) ad width of 270 Km/s (Vanzella et al. 2010, Hu et al. 2010)
- EW of emission line changes with L_{UV} according to the correlation observed at z=6-7 (Jiang et al. 2013, LP et al in prep)

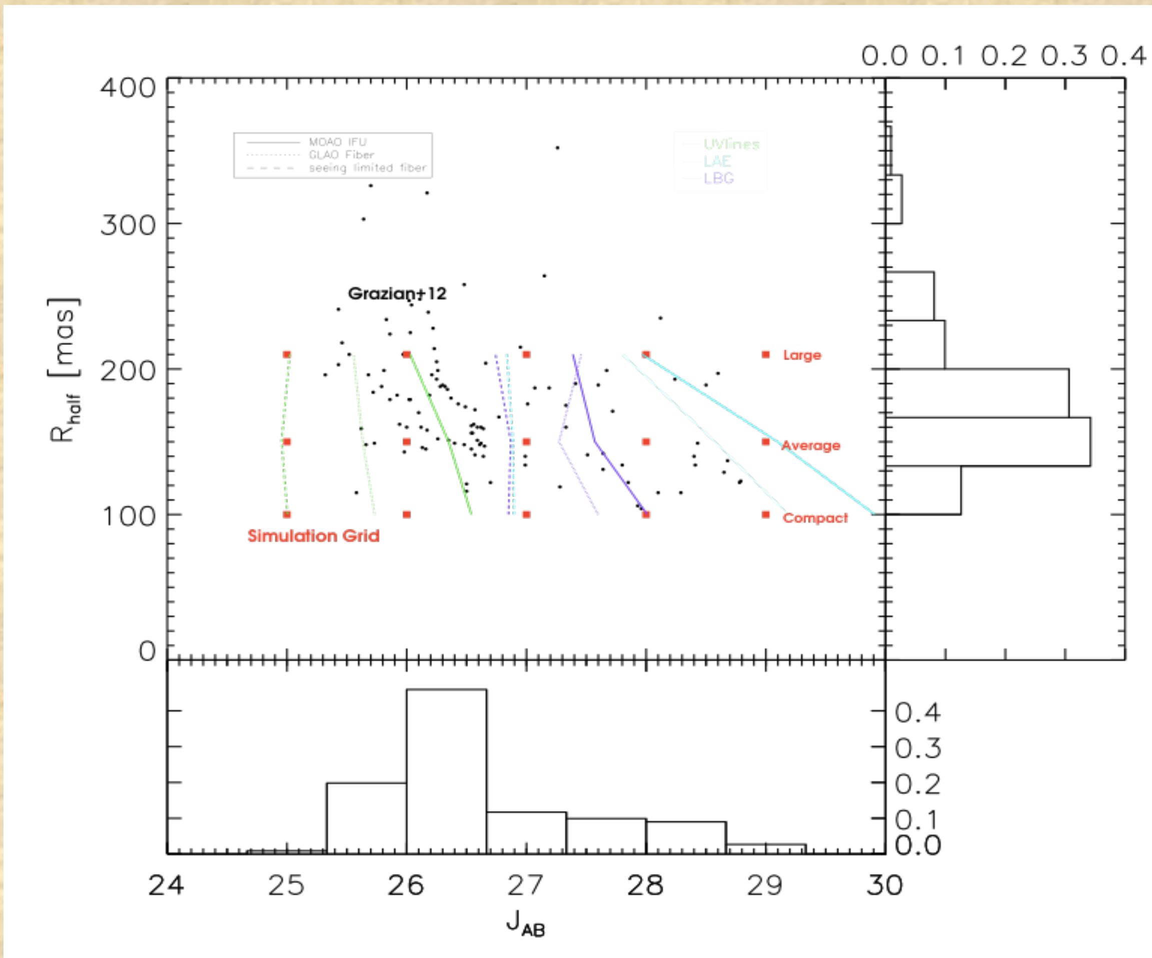


- Several PSFs are simulated (seeing limited, GLAO etc) (kept constant during the exposure time)
- Atmospheric absorption is modelled following Paranal-like site
- Sky emission (zodiacal emission, thermal emission, mo
- Sky subtraction is simulated in each spaxel (in the HDM mode)

MOSAIC

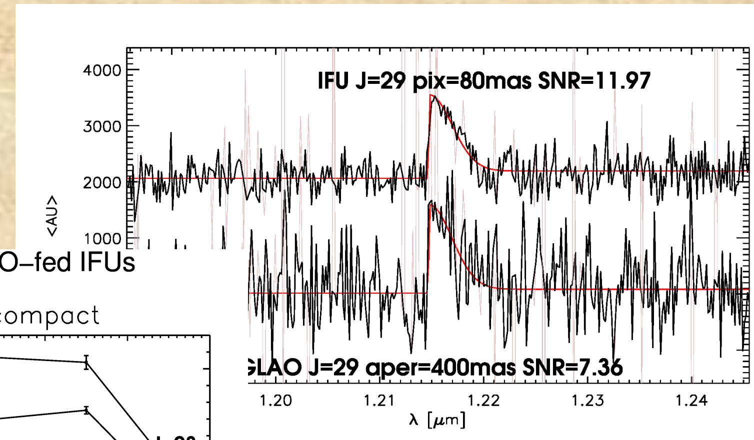
WEBSIM http://websim.obspm.fr

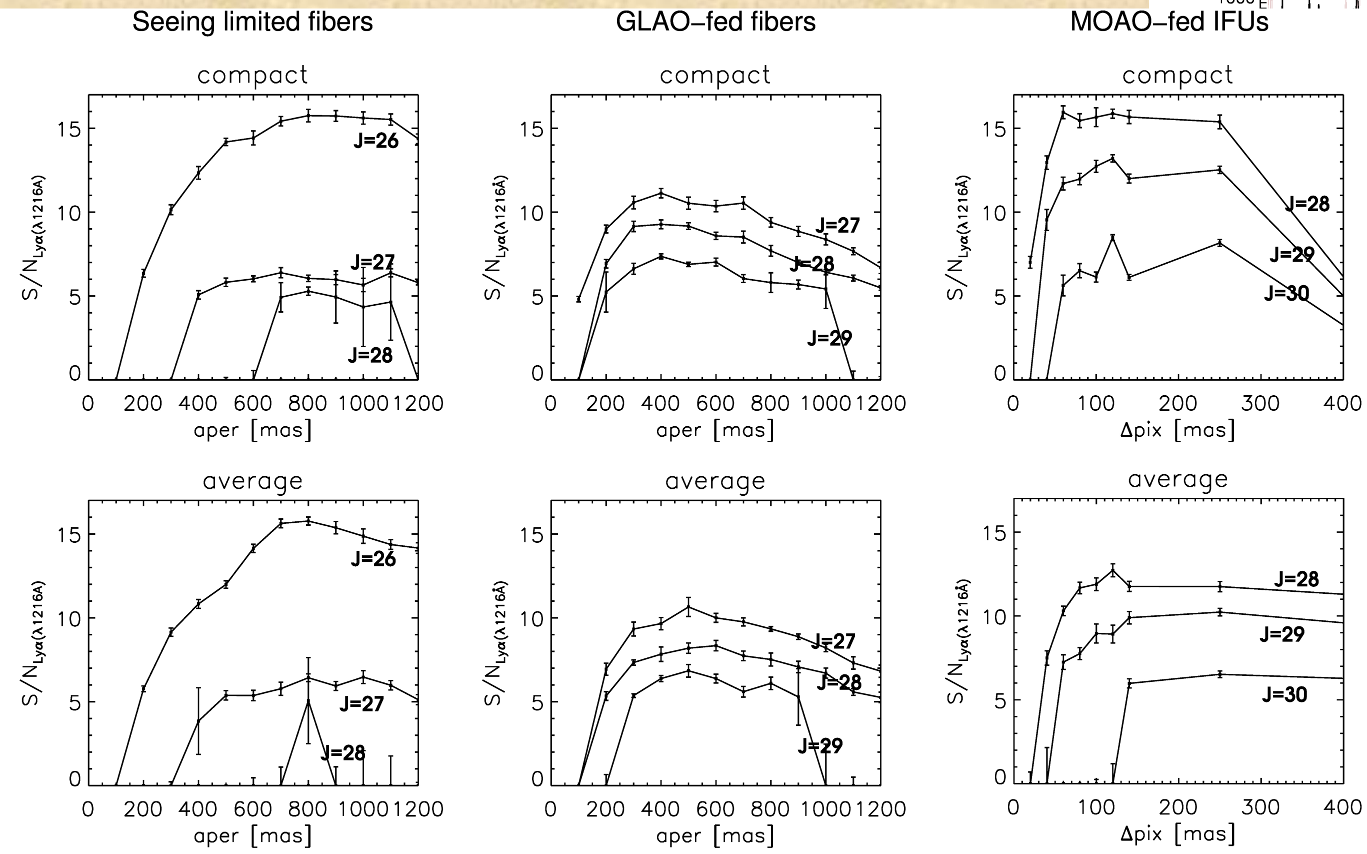
An important input of the simulations is the **size of the high redshift galaxies**
We start from the observed magnitude- size relation determined for z=7 LBGs from CANDELS data (small dots Grazian et al. 2012).
The grid of simulated observations is shown by the red squares (Large Average and Compact galaxies respectively with hl radius of 200-150-100 mas)



MOSAIC

Detecting Lyα in a z=9 galaxy

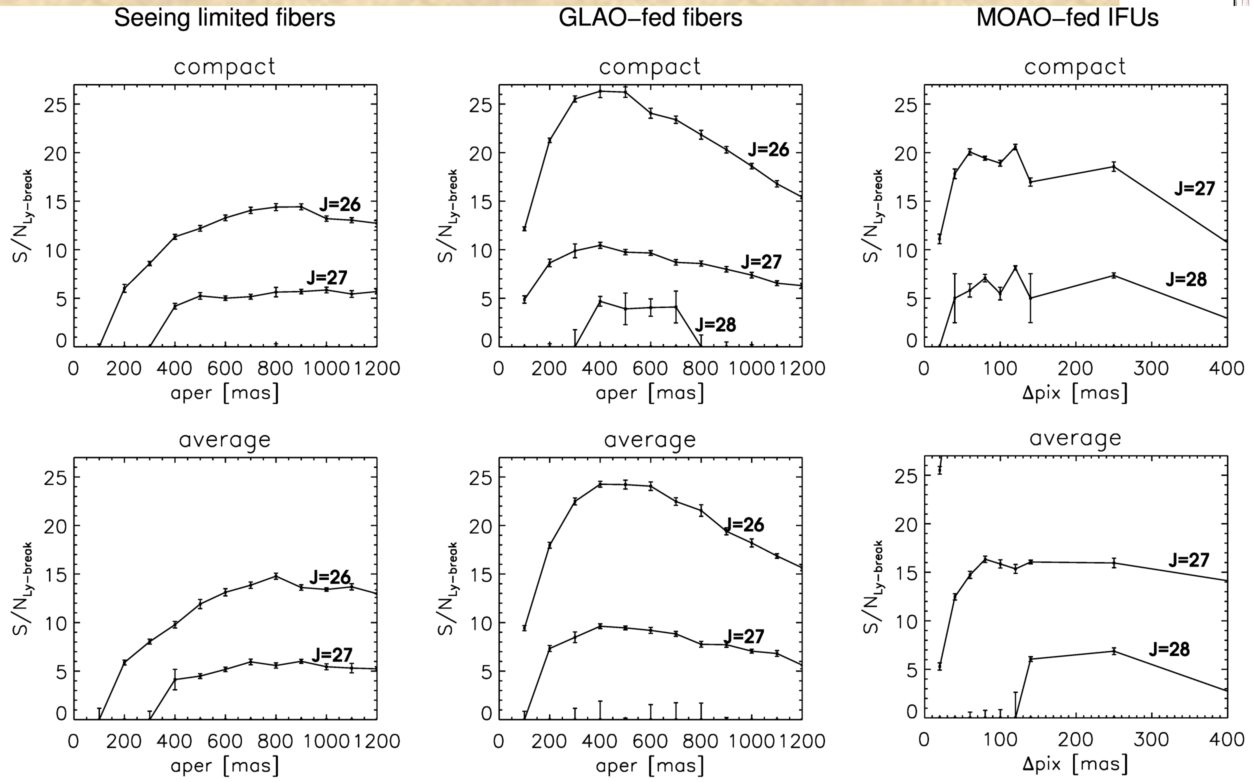


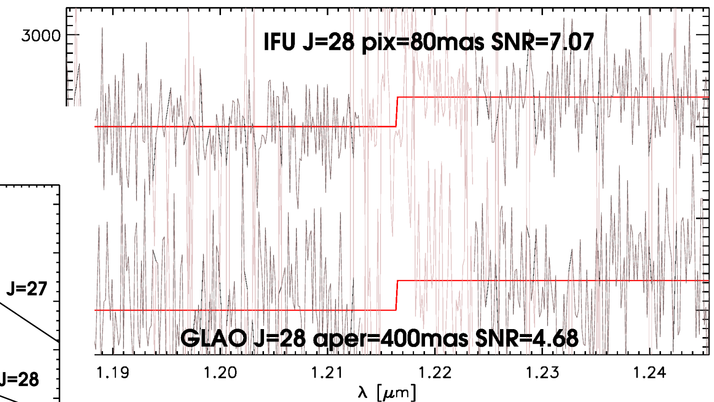


The SNR on the integrated Lyα flux from a galaxy at z=9 observed for 10 hours as a function of aperture size, results are shown for compact (100 mas) and average (150 mas) galaxies. The EW of the emission line varies from 10Å for J=27 to 70Å for J=30 as observed at lower redshift

MOSAIC

Detecting the Lyman break and continuum in a z=9 LBG



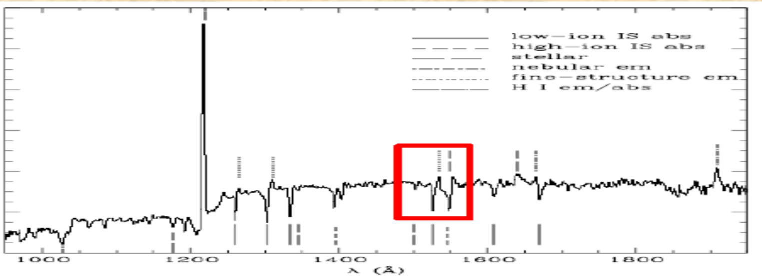


Integrated spectra of a J=28 source

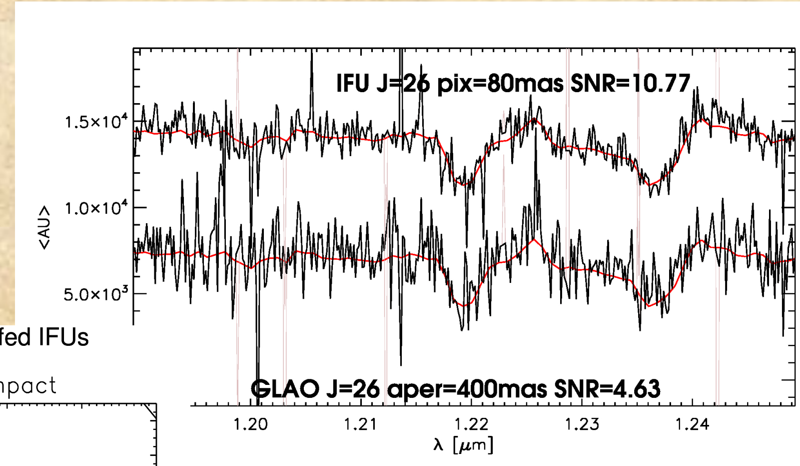
The Lyman break feature in a z=9 LBG as seen by MOSAIC in 10 hours integration. The top panel shows the SNR on the Lyman break from a compact (100 mas) and average (150 mas) sources with total magnitude J=26 and 27 respectively.

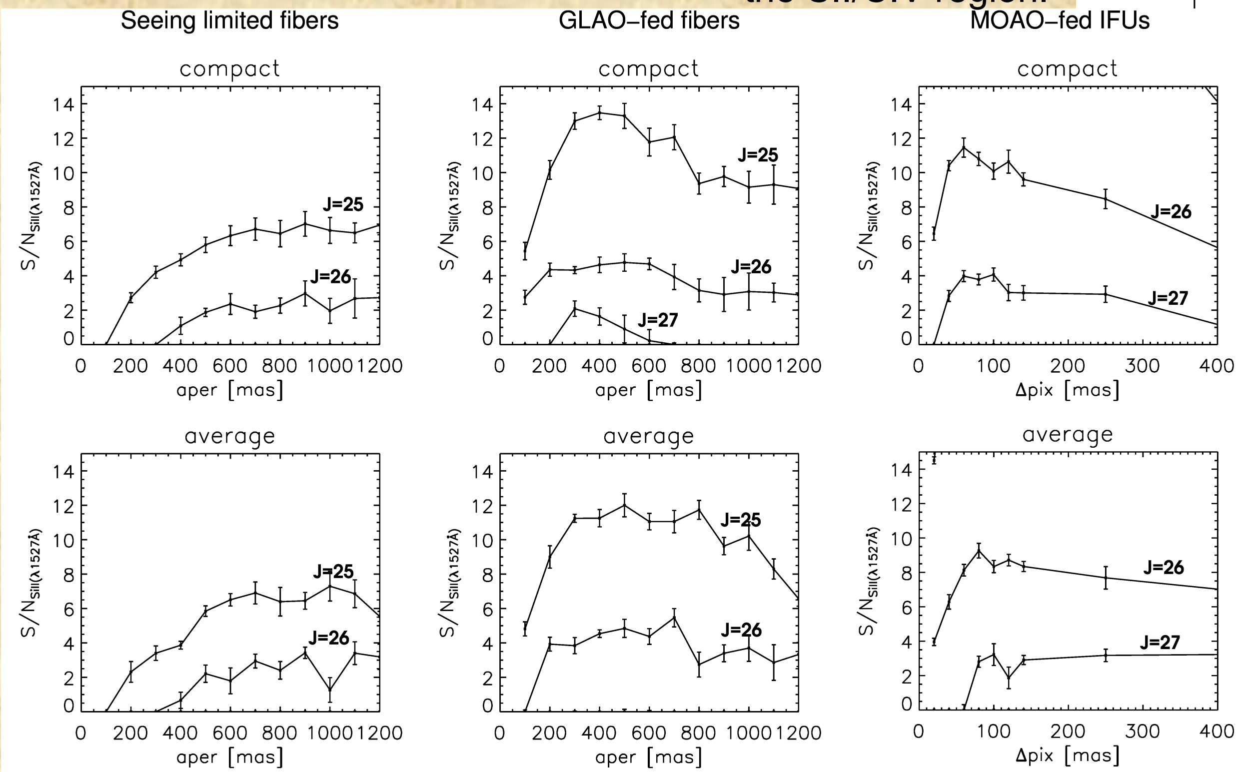
MOSAIC

Detecting UV interstellar absorption lines at z=7



Spectral template
Stacked z~3 LBG spectrum (Shapley +03) rescaled in flux & resampled at R=5000. Focus on the SII/CIV region.





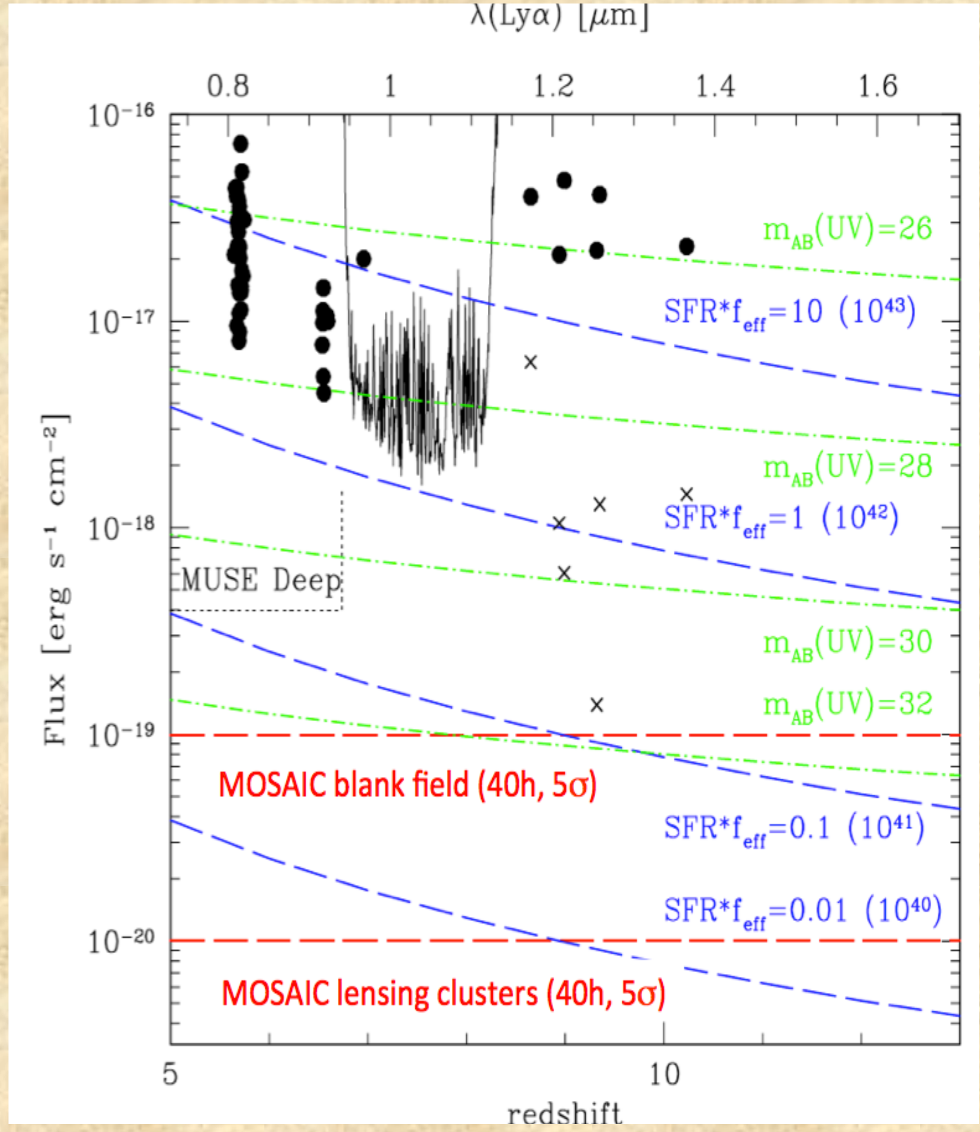
The SNR on the UV interstellar absorption lines as seen by MOSAIC in 40 hours integration from z=7 objects with J=25 and J=26: this type of observations will be feasible only with "Large Program"

MOSAIC

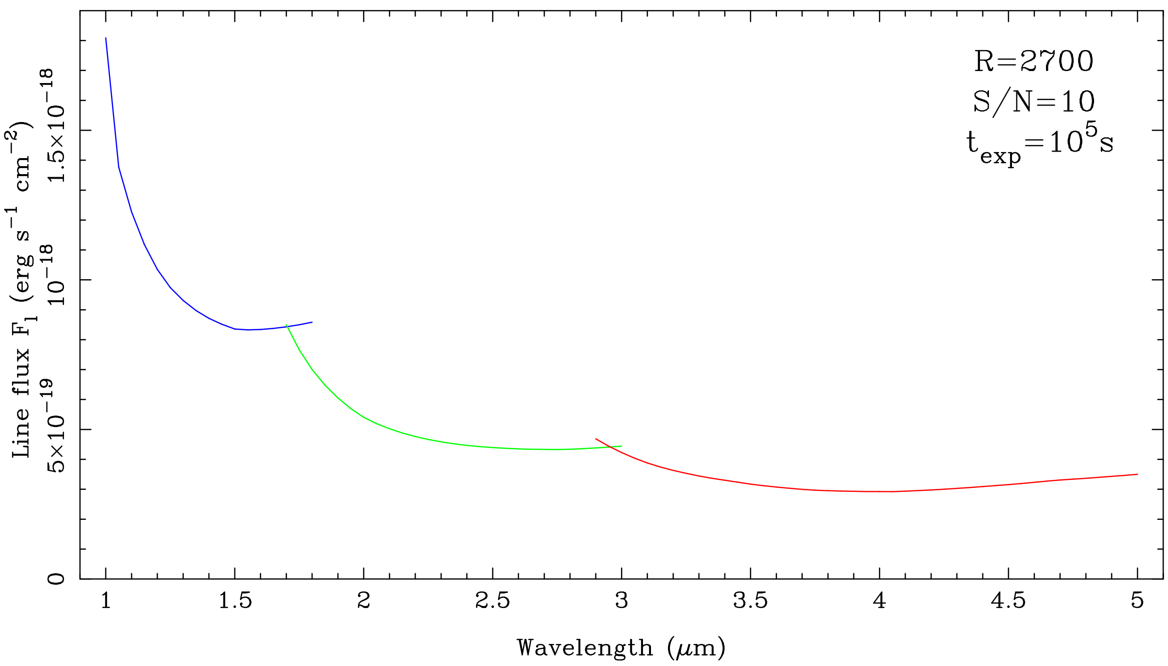
- To be continued….
- For more details see Disseau et al. 2014 (SPIE 9147) and the MOSAIC white paper (Evans et al. 2015 arXiv:1501.04726)

Science with MOS: towards the E-ELT Era

- 7 - 11 Sept 2015
- Cefalu, Sicily, ITALY



λ(Lyα) [μm]
0.8
1
1.2
1.4
1.6
10^−16
10^−17
10^−18
10^−19
10^−20
Flux [erg s^−1 cm^−2]
m_AB(UV)=26
SFR*f_eff=10 (10^43)
m_AB(UV)=28
SFR*f_eff=1 (10^42)
MUSE Deep
m_AB(UV)=30
m_AB(UV)=32
MOSAIC blank field (40h, 5σ)
SFR*f_eff=0.1 (10^41)
SFR*f_eff=0.01 (10^40)
MOSAIC lensing clusters (40h, 5σ)
5
10
redshift



R=2700
S/N=10
$t_{exp}=10^5$s
Line flux F_l (erg s^{-1} cm^{-2})
0
5×10^{-19}
10^{-18}
1.5×10^{-18}
1
1.5
2
2.5
3
3.5
4
4.5
5
Wavelength (μm)