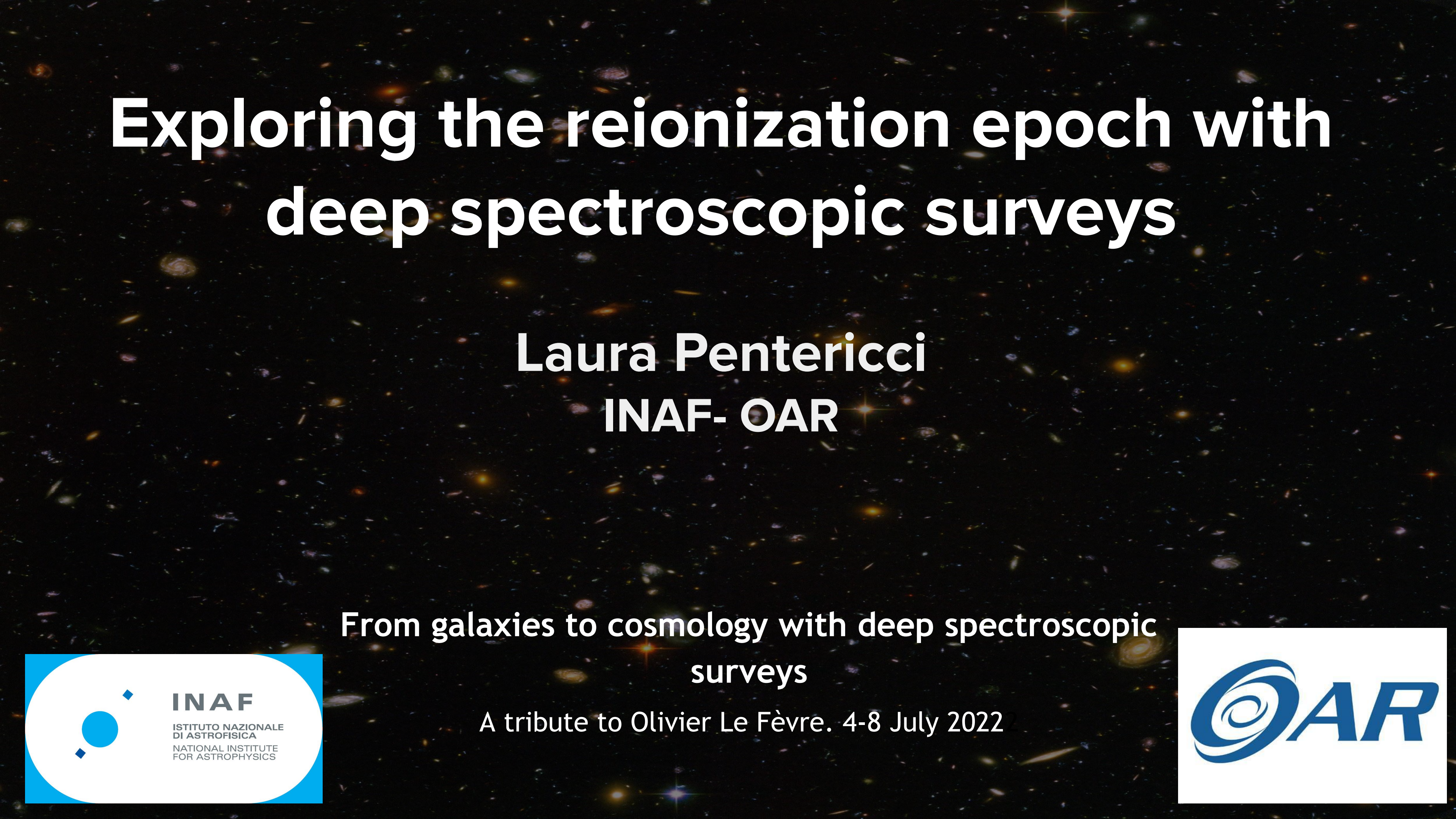


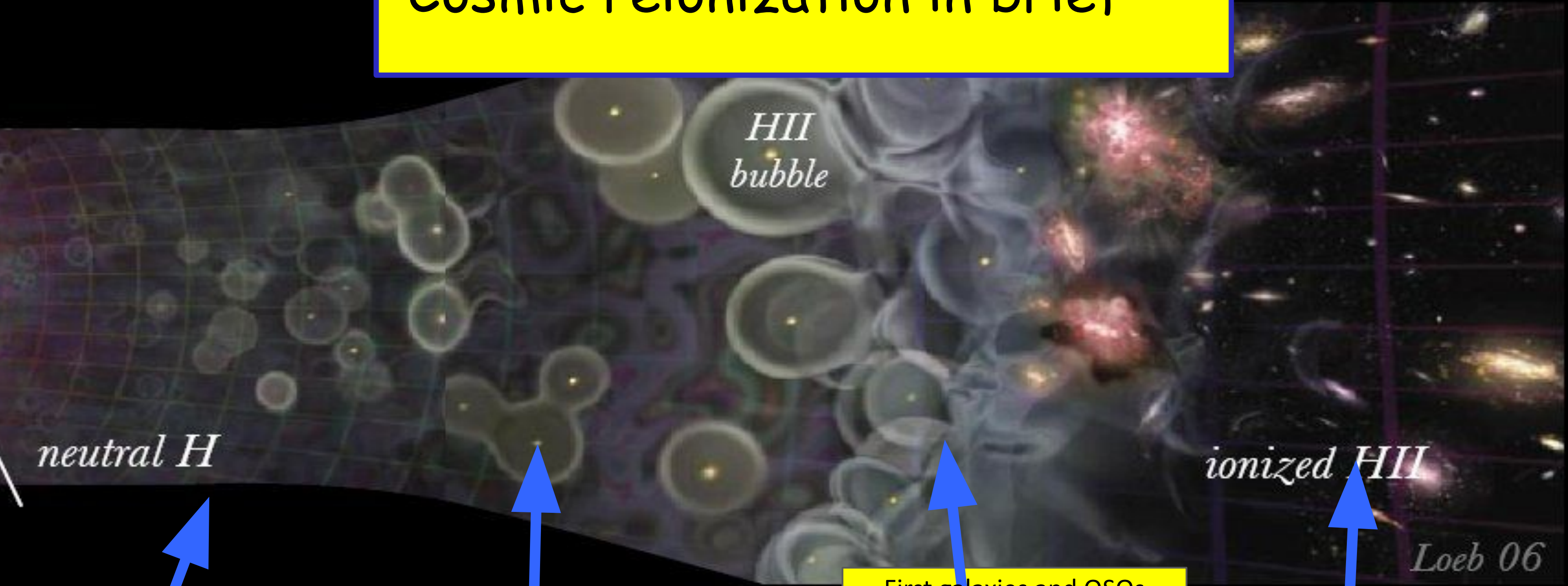
Exploring the reionization epoch with deep spectroscopic surveys

Laura Pentericci
INAF- OAR

From galaxies to cosmology with deep spectroscopic surveys

A tribute to Olivier Le Fèvre. 4-8 July 2022

Cosmic reionization in brief



After recombination the universe is completely neutral

In the so-called Dark Ages the first stars start to form and ionize their surroundings

First galaxies and QSOs form and produce increasingly larger ionized bubbles around them
The bubbles eventually over-lap

The IGM is completely ionized
t≃1Gyr

Galaxies and reionization

✫ **Key questions**

When did Cosmic reionization occur?

How did it proceed in space and time?

Which were the sources responsible?

✫ Results from deep spectroscopic observations of early galaxies

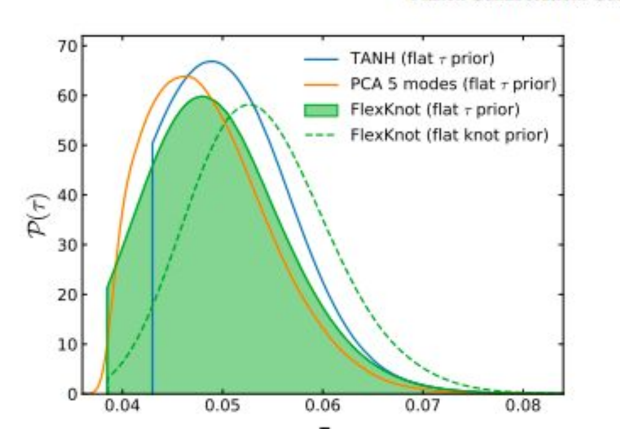
✫ What's next: JWST, MOONS, PFS, MOSAIC

Key question

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

Our current knowledge comes from 2 classes of probes

1) **Constraints** from cosmic microwave background observations in the form of Thomson scattering optical depth. Results from Planck τ_e=0.054±0.007 (Planck collaboration 2018) , suggesting a mid-point reionization redshift of z_{re} = 7.7 ± 0.7 i.e. reionization happened relatively fast and late

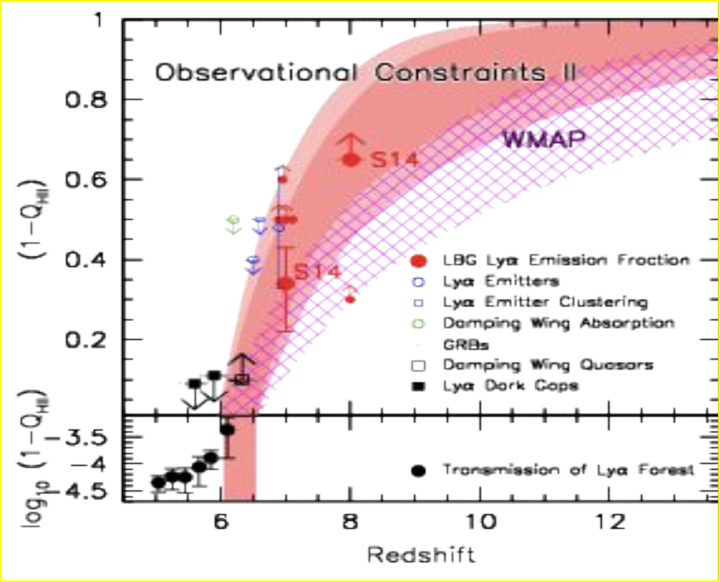


Key question

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

Our current knowledge comes from 2 classes of probes

2) observations of early galaxies, QSOs and GRBs that allow us to measure the IGM neutral hydrogen content *at a given redshift and for a given line-of-sight*

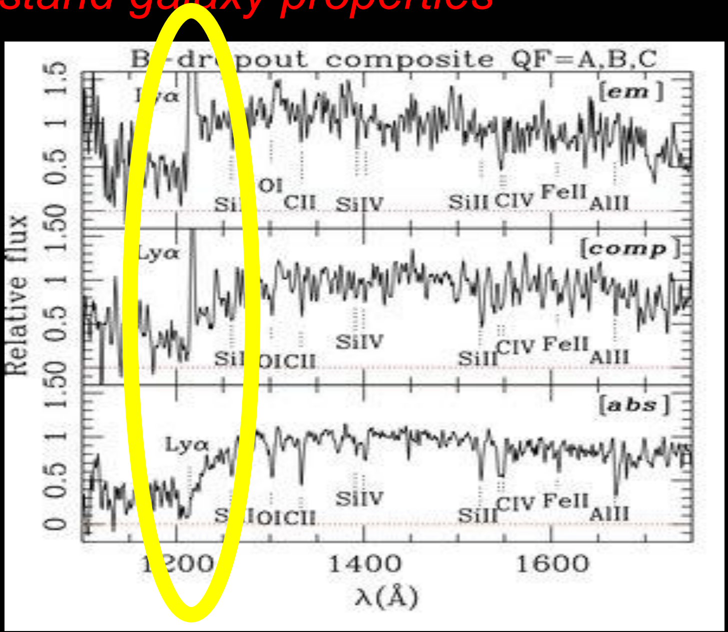


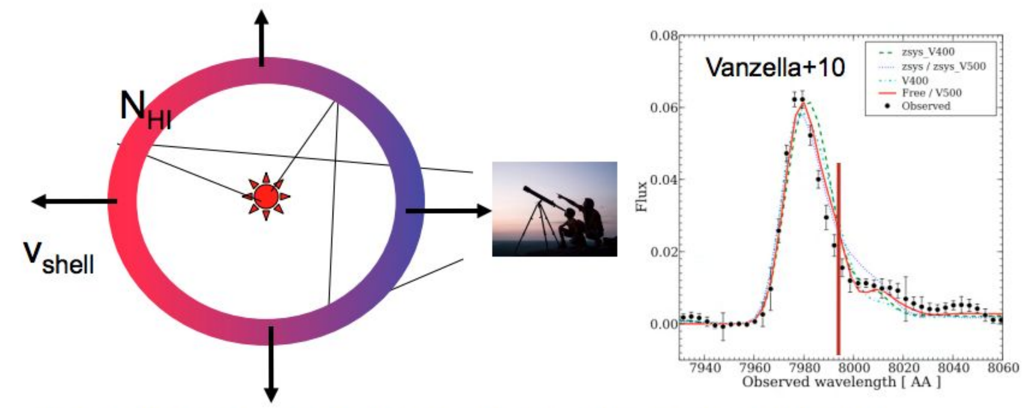
The Lyα emission *is one of the main probes of early galaxies*

It is both a tool to secure the redshifts and understand galaxy properties

The Lyα line is primarily emitted by young massive stars (SF galaxies) and AGN. Shock heating and cold accretion can also contribute.

In a young dust free stellar population up to 6-7% of the light from galaxies could emerge as Lyα.





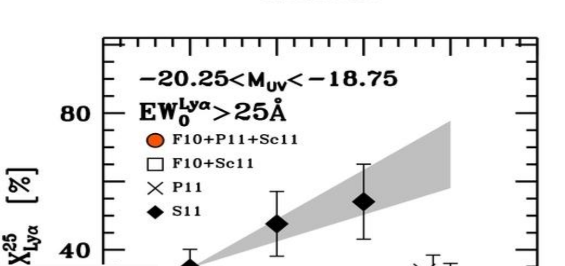
Observed Lya line shape (z<6) can be reproduced using spherical shells of outflowing HI gas, with column density N_{HI} and outflow speed v_{shell} .(e.g. Verhamme+08)

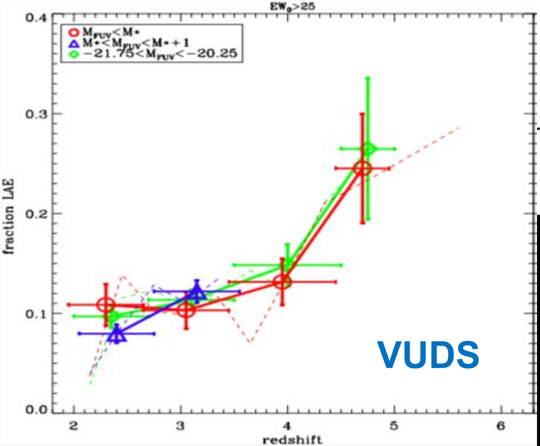
figure by M. Dijkstra

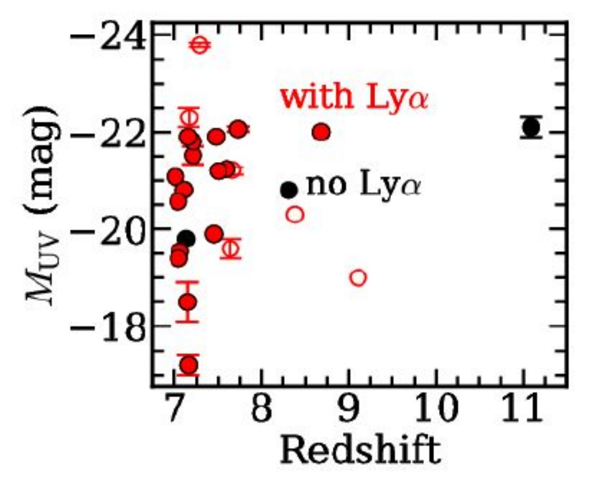
Lyα photos can be resonantly scattered and absorbed → the presence and shape of the line in the final spectrum depends on many factor e.g. dust content and distribution, gas kinematics, neutral hydrogen column density etc

In the last 10 years Lyα has been used as the main tool to confirm the redshifts of the most distant galaxies

As we move to higher redshift the fraction of Lyα emission in star forming galaxies <u>gets much higher</u> (Vanzella+09,Stark+10, Cassata+14)
→this can easily been explained as galaxies at earlier epoch are on average younger and less dusty





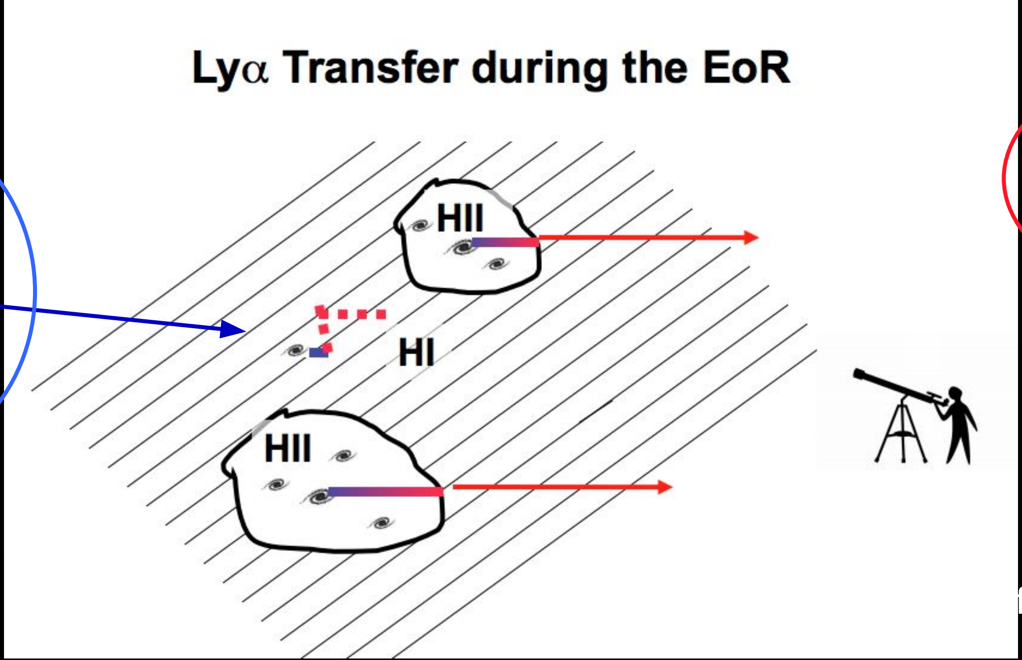


Ouchi+20
ARAA

Many of the most distant galaxies known to date have been confirmed through Lyα emission Vanzella+11, Ono+12 Finkelstein+13,Zitrin+15, Song+16, Stark+17, Larson+18, Hoag+18, Jung+19...

***The Lyα emission** is a powerful tool to probe the end of reionizaton (EoR)*

As we enter the epoch when the IGM is not completely ionized the Lyα photons escaping the galaxies can be further suppressed by the neutral hydrogen gas

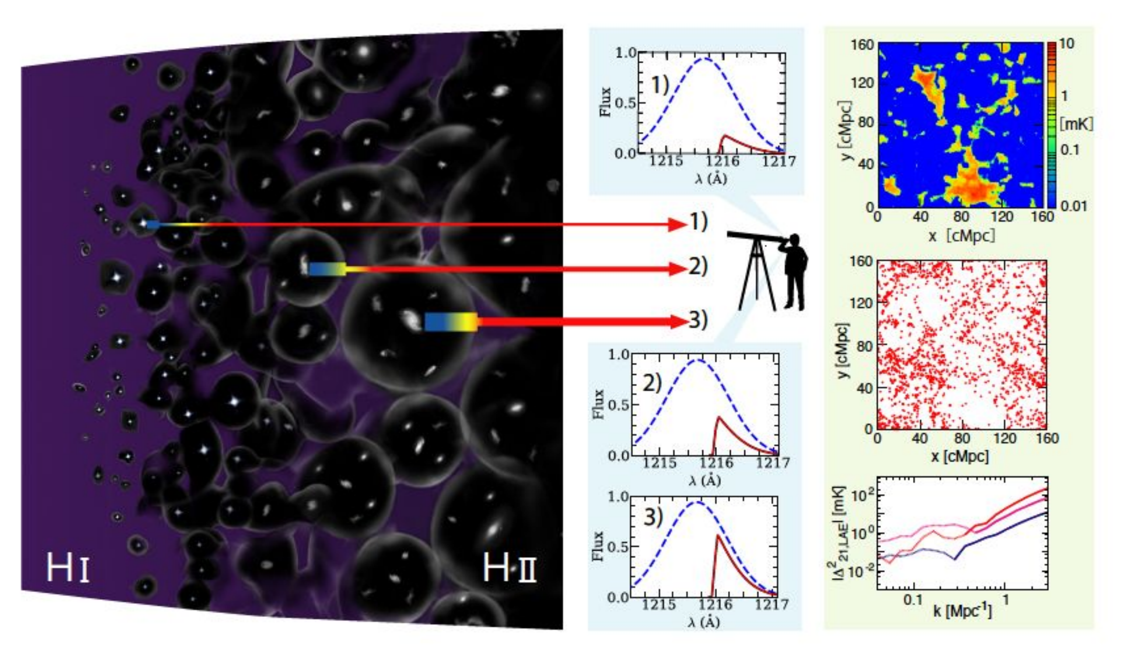


Lyα from a galaxy surrounded by neutral IGM is not transmitted

The Lyα from galaxies residing in ionized regions is transmitted to us

figure by M. Dijkstra

The Lyα emission is a powerful tool to probe the end of reionizaton (EoR)

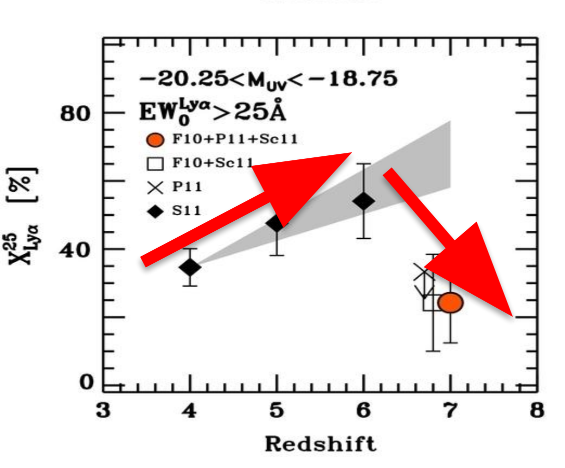


1)The Lyα visibility,
2) the Lyα line profile and
3) the clustering of Lyα emitting galaxies

1) 2) and 3) all depend on the amount and distribution of neutral hydrogen in the intervening IGM

Ouchi+20

The effects of neutral IGM content on the Lyα visibility are essentially measurable in two different ways:

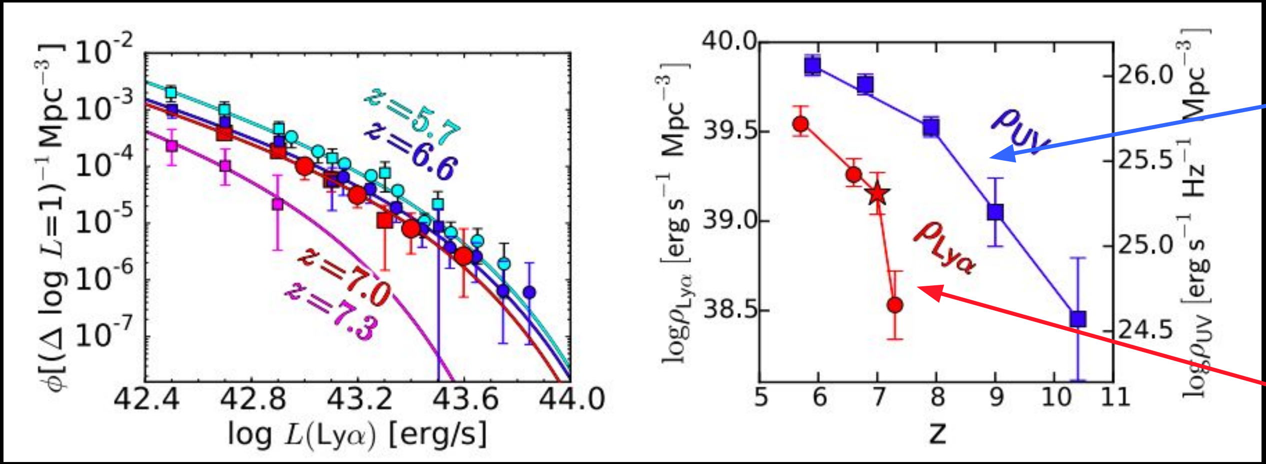


1) By measuring the fraction of UV selected star forming galaxies showing Lyα in emission above a certain EW threshold

In this case the rapid fall of Lyα fraction indicates reionization

The effects of neutral IGM content on the Lyα visibility are essentially measurable in two different ways:

2) By measuring the differential evolution of Lyα LF compared to the UV LF



the evolution of ρ_{UV} depends on SFR & galaxy evolution

evolution of $\rho_{Ly\alpha}$ depends on SFR & galaxy evolution <u>& IGM neutral fraction</u>

In this case, the redshift at which the $\rho_{Ly\alpha}$ decouples from ρ_{UV} indicates reionization (e.g. Itoh+18)

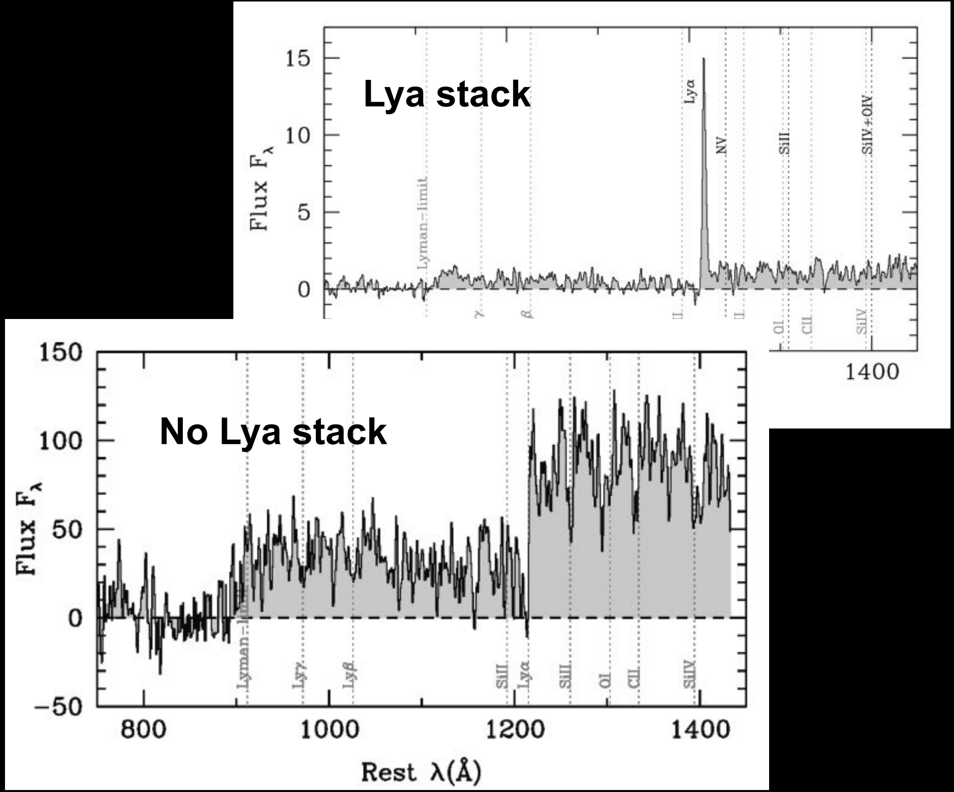
Spectroscopy of high redshift galaxies

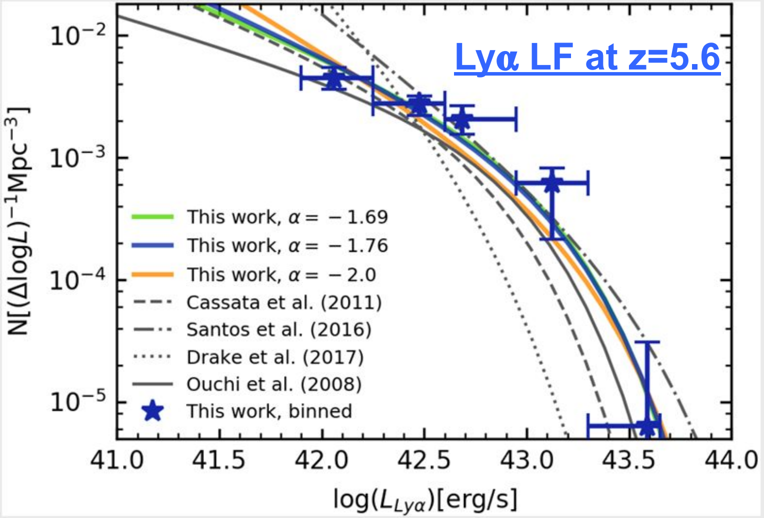
Multi object spectroscopy is the key tool to explore the end of reionization: giving precise redshift & Lyα emission measurements to

1. derive the Lyα fraction
2. validate the Luminosity Function based on narrow band data
3. probe neutral IGM
4. Probe the properties of cosmic reionizers

In the last 10 years many programs have involved large investment of times (many 100s of hours) on the best MOS @ biggest telescopes

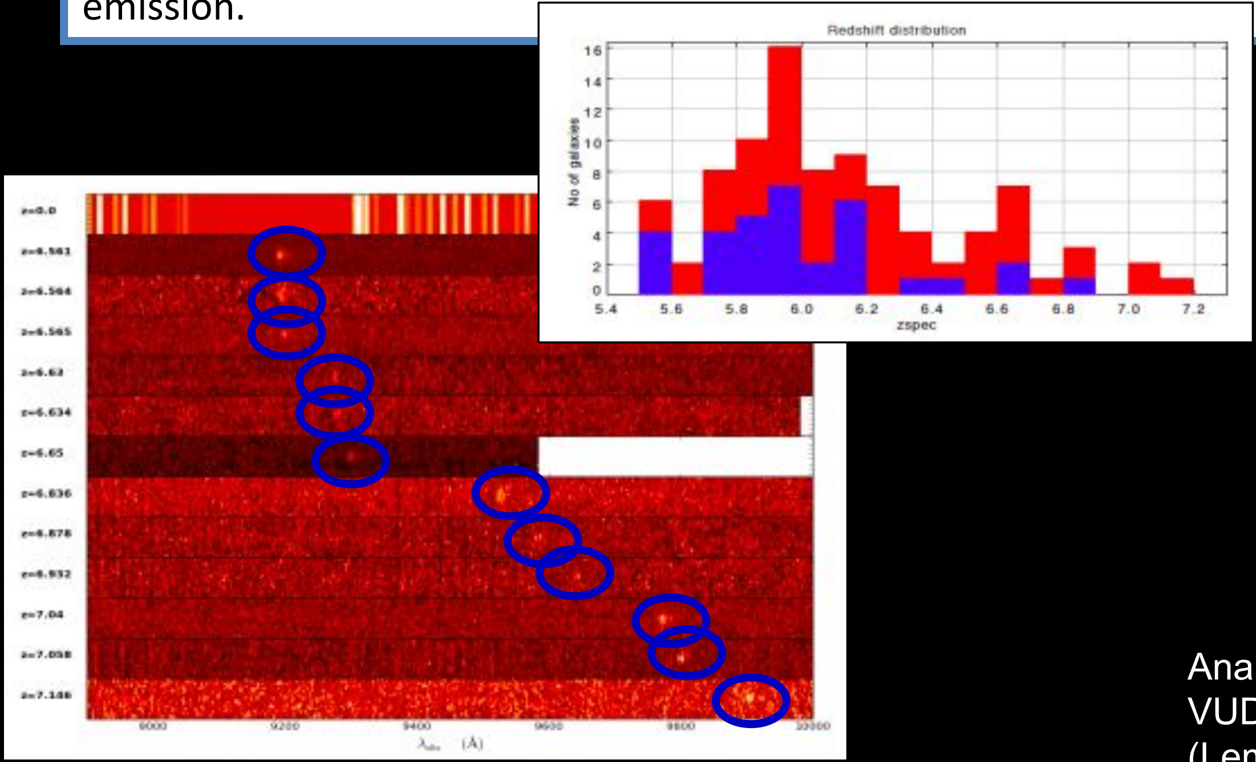
The VUDS survey: by observing many 10s of galaxies at $5<z<6.5$ VUDS contributed greatly to the solid characterization of the Universe at the end of reionization (Cassata+14, Khusanova+20)

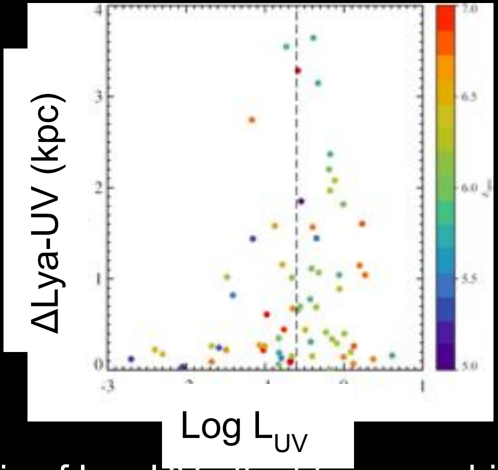




CANDELSz7: a large FORS2@VLT spectroscopic survey of CANDELS fields in the reionization epoch – Pentericci+18, De Barros+17, Castellano+18,Lemaux+21

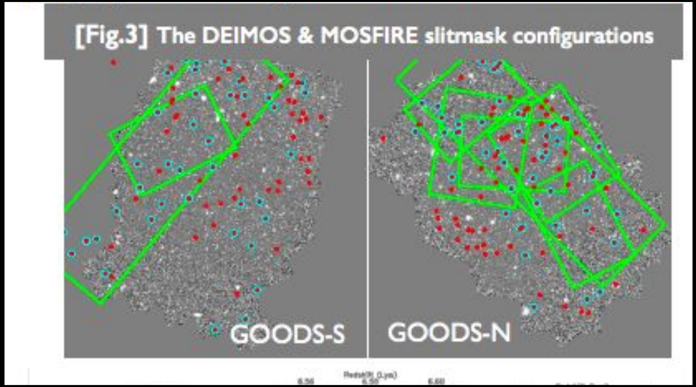
We have have observed >160 galaxies with photometric z between 6 and 7.3 in the HST-CANDELS fields GOODS-S, COSMOS and UDS, confirming the reshifts of >55 new objects mainly through Lyα emission.



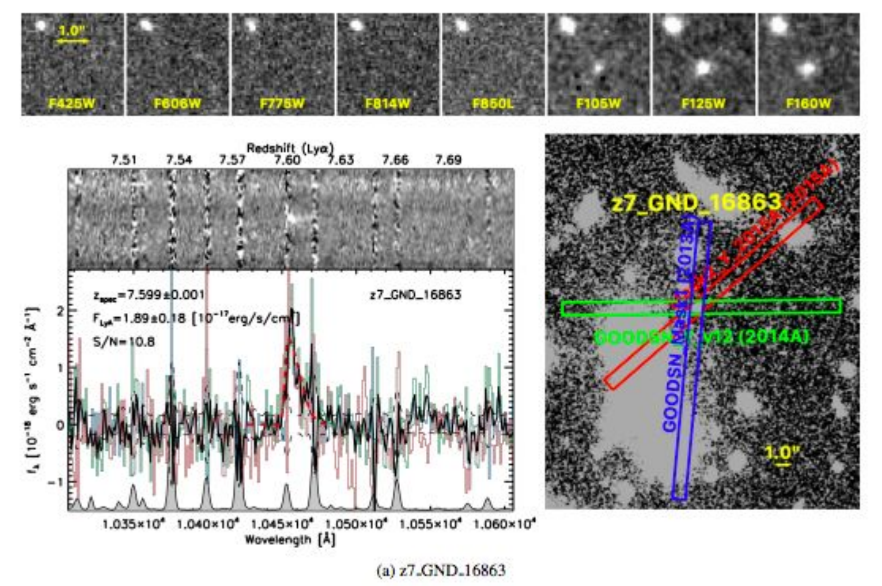


Analysis of Lya-UV offset from combined VUDS, CANDELz7 and Lensed survey (Lemaux+21)

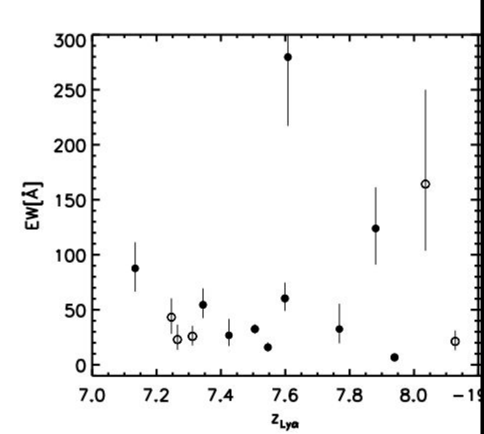
Texas Spectroscopic Search for Lyα Emission at the End of Reionization   Jung+20,Jung+21, PI S.Finkelstein


[Fig.3] The DEIMOS & MOSFIRE slitmask configurations

Spectroscopic observation of ~ 200 z = 5.5 – 8.2 candidate galaxies with Keck/DEIMOS & MOSFIRE



(a) z7_GND_16863

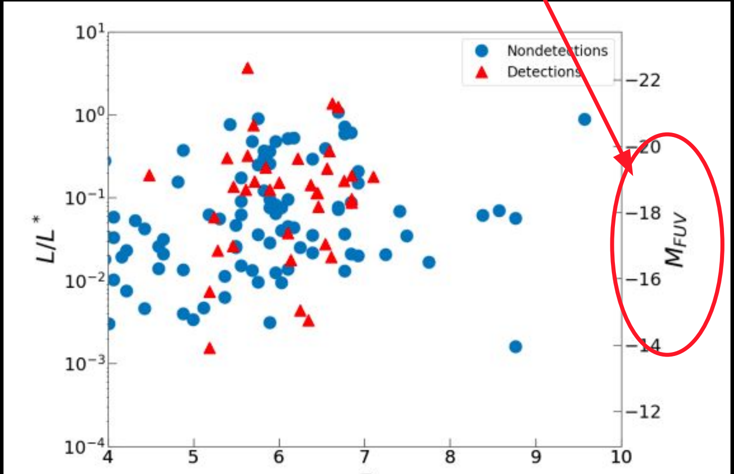


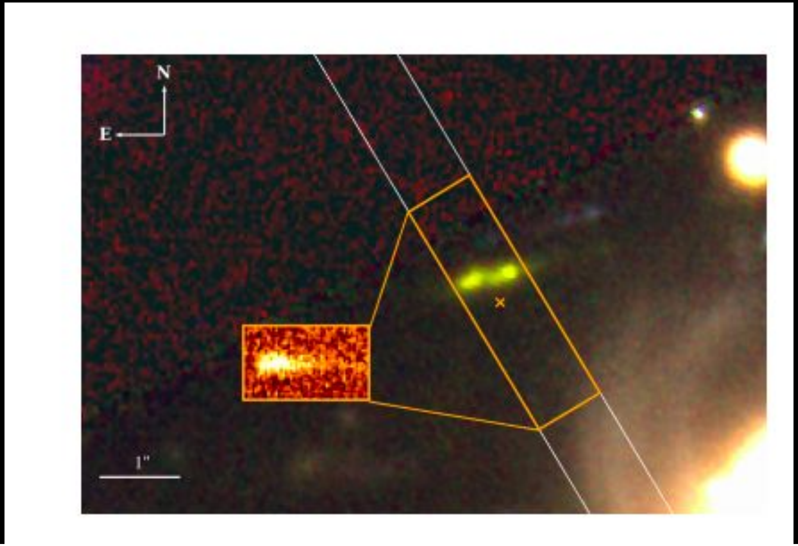
10 new solid detections of galaxies at 7<z<8 and many at 6<z<7

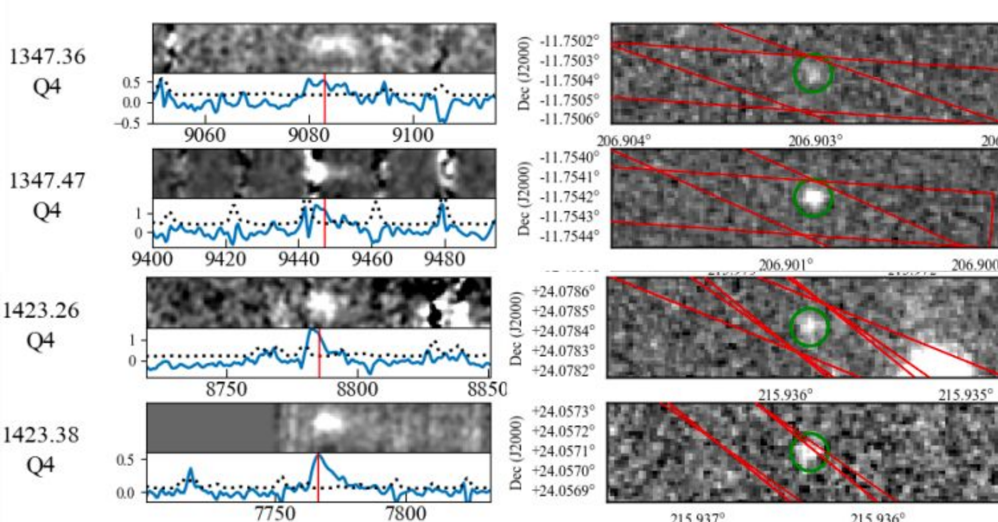
Spectroscopic survey of intrinsically faint emitters behind lensing clusters

Hoag+18, Fuller+20, Lemaux+20, Bolan+21 PI Bradac

This program exploits the magnification power of lensing clusters to reach galaxies with much fainter intrinsic M_{UV}



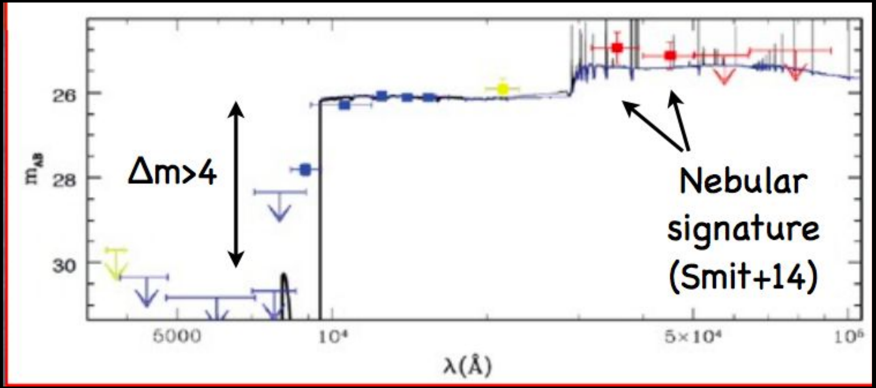


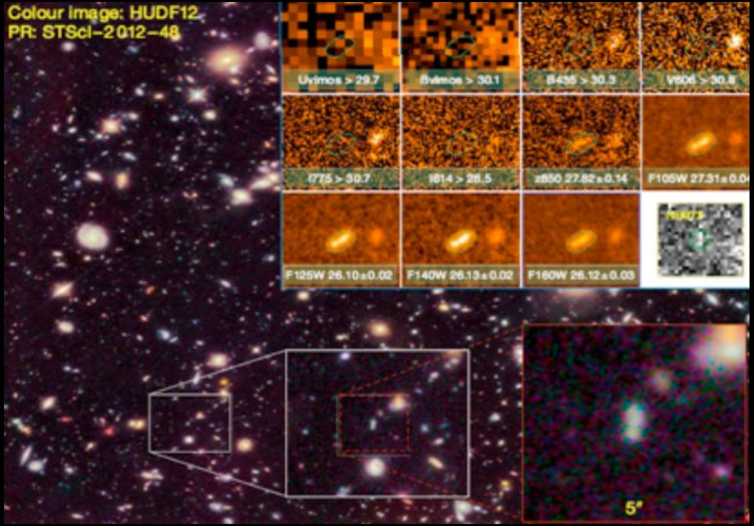


Almost 200 candidates observed at 5<z<7 with DEIMOS with 36 new confirmations of LAEs

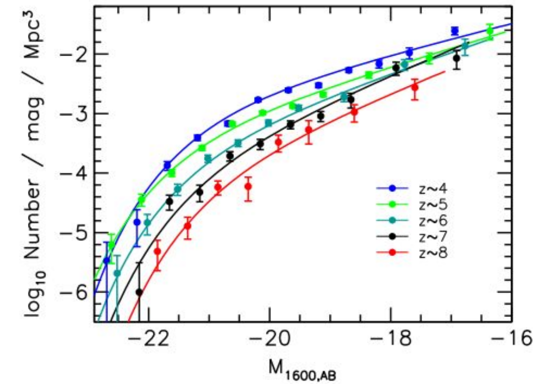
Just to show how hard are these observations....

The galaxy GDS_1408 (J=26) in the HUDF was selected by many different groups as one of the most solid z_{phot}=7 candidate from ultradeep HST imaging



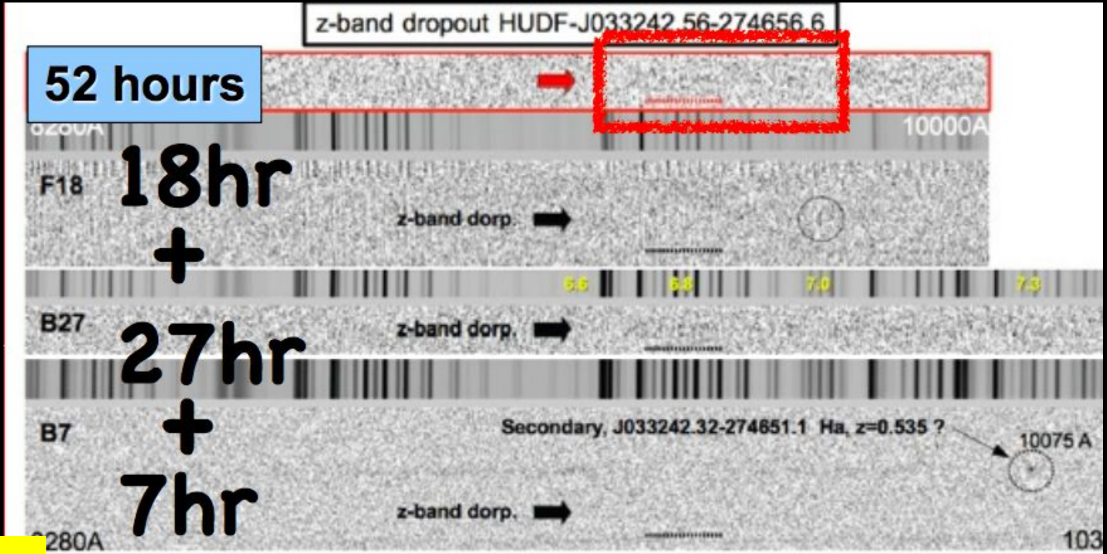


This galaxy appears in all Luminosity Function at z=7 (e.g. Bouwens+16 Castellano+12 etc)



This galaxy has no detectable Lyα!!

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

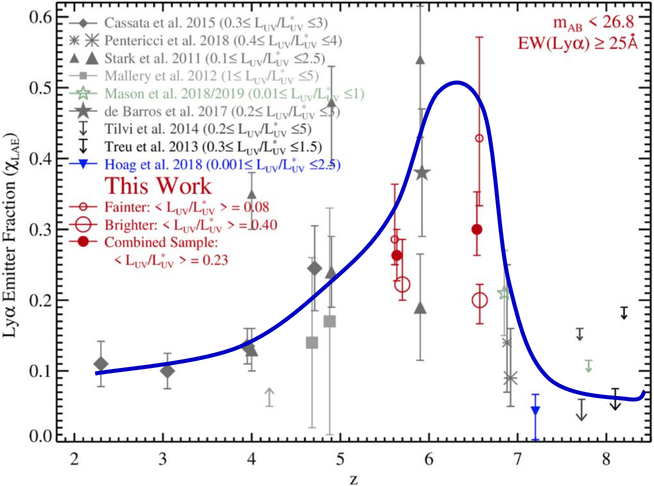


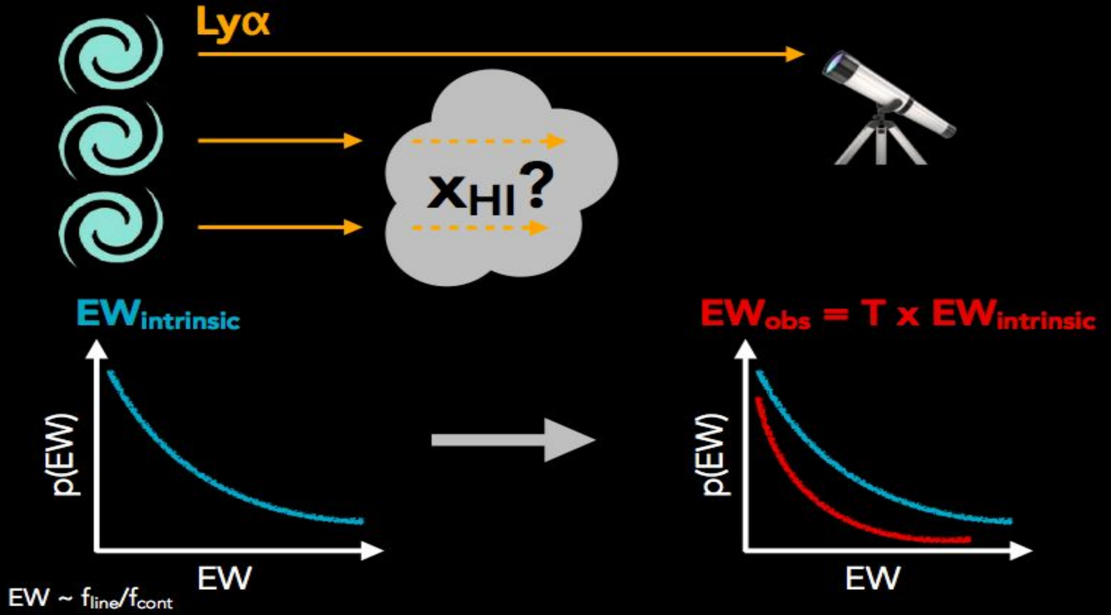
No Lyα is observed down to a flux limit of $f(\mathrm{Lya}) < 1\mathrm{x}10^{-18}\mathrm{erg/s/cm}^2$ in skyline free regions

that's hard also for JWST!! → **use other UV lines?**

The conversion from the measured transmission of Lyα emission to a constraint on the IGM neutral hydrogen fraction is a non-trivial exercise and requires extensive modelling the physics from pc to Gpc scales

Results show a rapid fall after z=7 (Fuller+20)

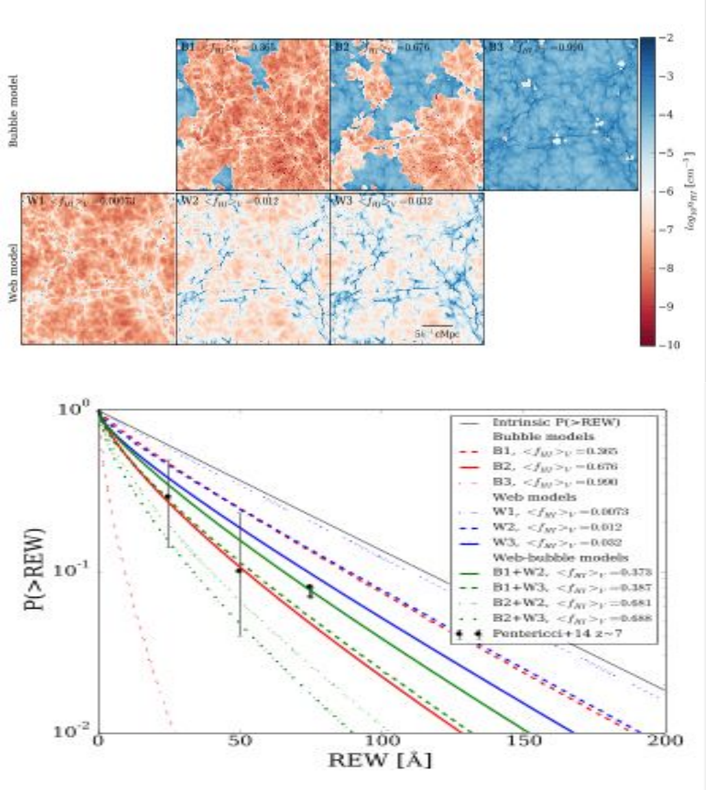


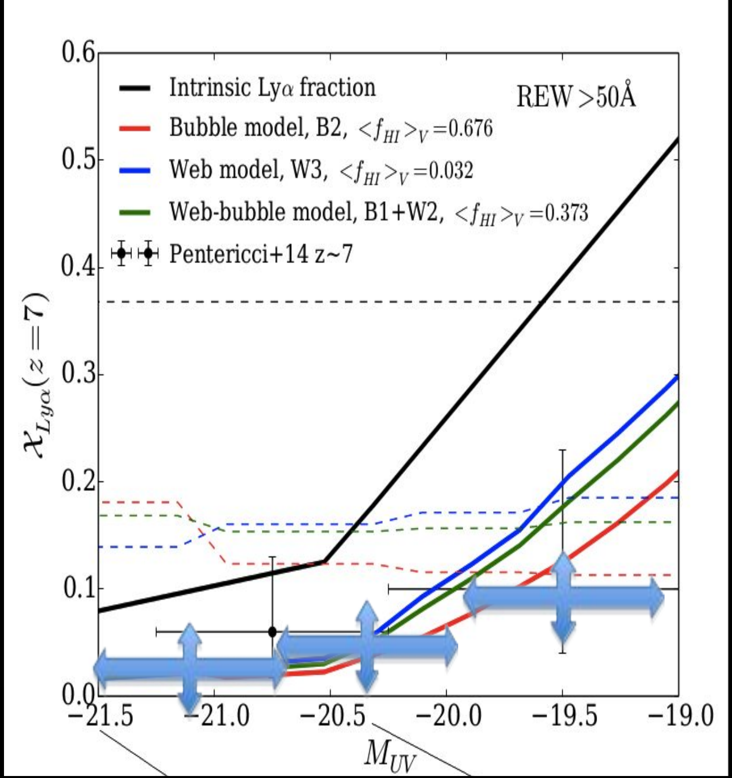


Mason + 2018

Implications on the neutral hydrogen fraction

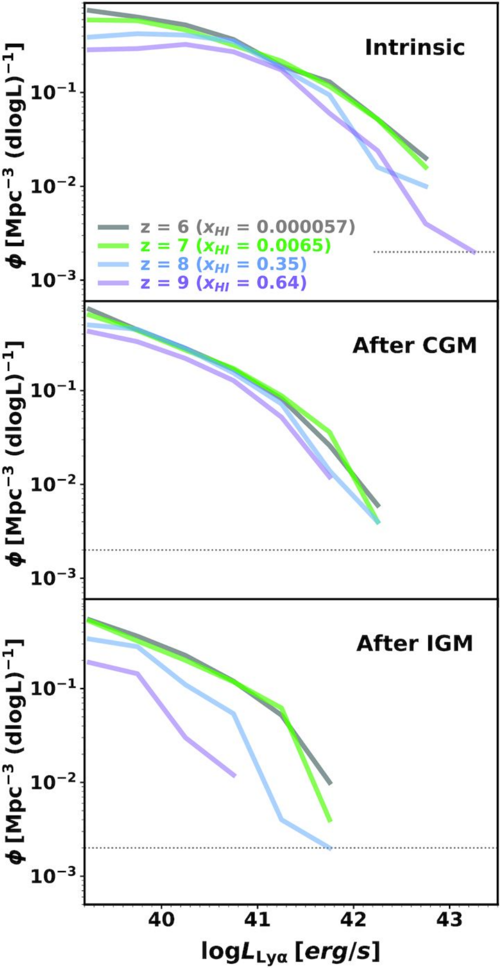
There are intrinsic degeneracies between the effects of small scales HI absorbers and diffuse neutral IGM. Kakiichi+2017 use cosmological hydrodynamical + RT simulations to show that a joint analysis of LAE LF and Lya fraction can potentially discriminate between models.





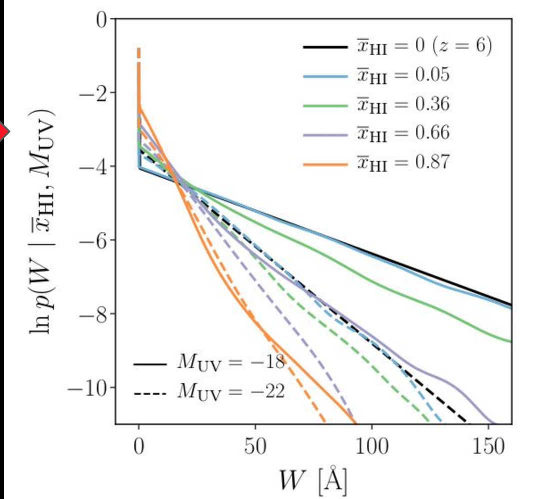
The new z=7 measurements favour slightly a bubble model with XHI=0.67

Examples of models output



Redshift evolution of the Ly α luminosity functions
- intrinsic emission is shown in the first panel and the the effects of internal absorption, and IGM transmission are shown for different neutral hydrogen fractions (SPHINX simulations Garel+21)

The predicted EW distribution of Ly α emission for bright (M_{UV}=-22) and faint galaxies (M_{UV}=-18) for various values of neutral hydrogen fraction (reionization simulations+empirical models Mason+18)



The reionization timeline: current results

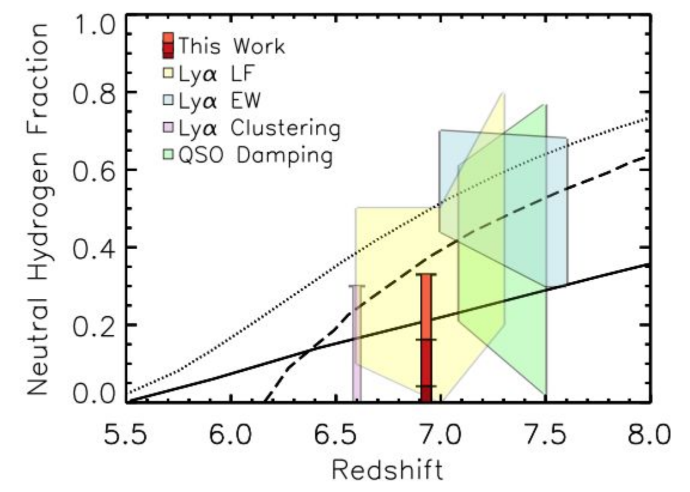


Figure from Wold+21

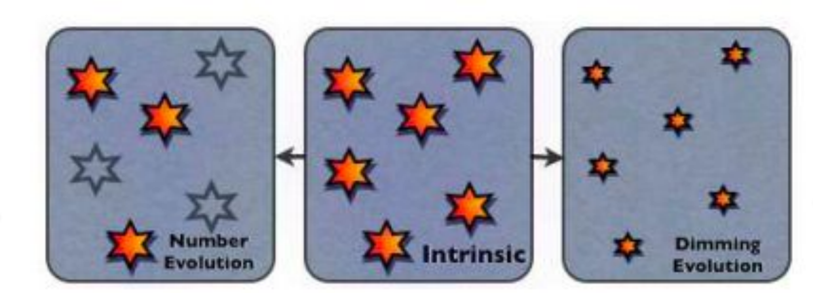
Results from
-Lyα LF evolution (Itoh+18, Konno+18,Wold+21,
-LAE clustering analysis (Ouchi+18).
-GRBs Lyα damping wing absorption (z=5.9 Totani+16, z = 6.3 Totani+06, z = 6.7 Greiner+09),
- QSOs damping wing (Greig+19; Ba˜nados+19).
- Lyα emitting fraction in LBGs (combined from Jung+20, Mason+18 and more)

Lyα fraction in LBGs $X_{HI} > 0.4$ @z=7-7.5
LAEs LF $X_{HI} \lesssim 0.3$ @z=7
LAEs clustering LF $X_{HI} \lesssim 0.3$ @z=6.6

Cosmic reionization history (neutral fraction x_{HI} as a function of redshift).
The solid line represents a gradual reionization scenario (Finkelstein+19) while the dashed curve is the late and rapid reionization scenario by Robertson+15 and the dotted line by Kulkarni+19

Uncertainties are still too large to constrain scenarios ☹

What about the topology of reionization?
can we say something about it with present data?

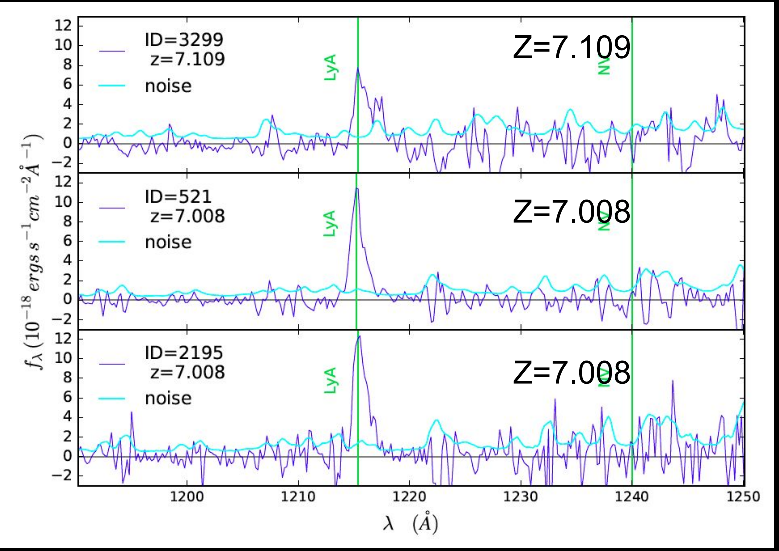


Patchy reionization
Some regions have much higher transmission than others

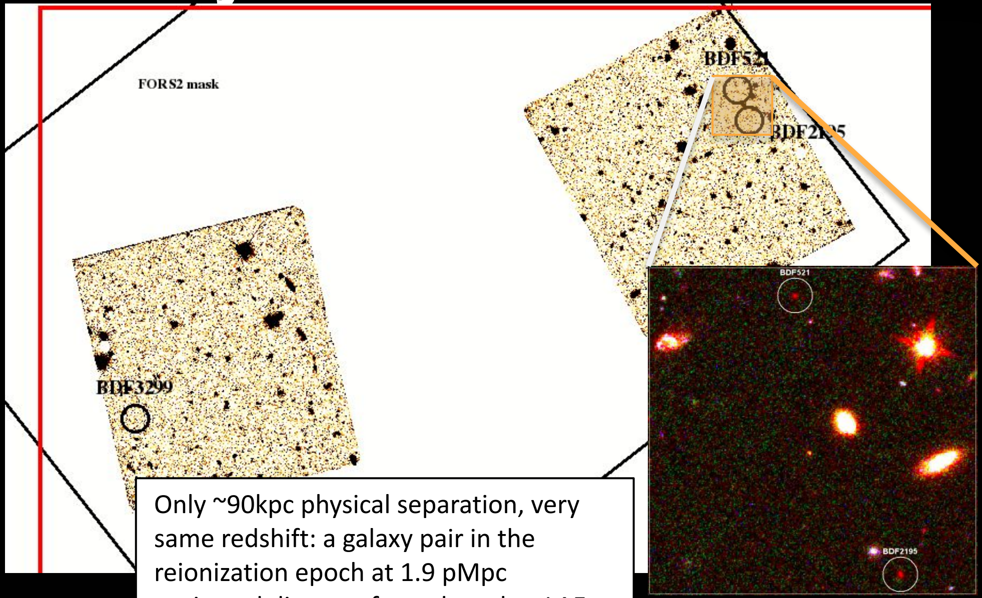
Smooth reionization (homogeneous dimming)
All regions have the same transmission
Clustering is unaltered

What we can do for the moment is study the first indication of reionized bubbles that we are finding in the data

Evidence of reionized bubbles: regions with high Lyα visibility



Castellano+18,+22

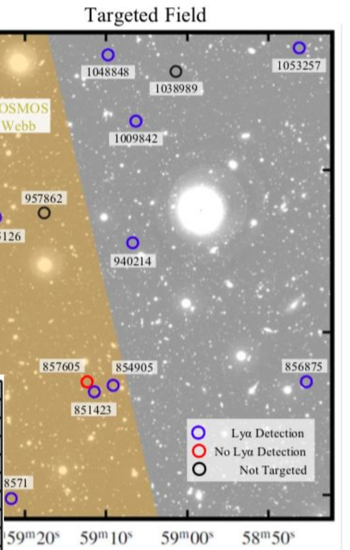


Only ~90kpc physical separation, very same redshift: a galaxy pair in the reionization epoch at 1.9 pMpc projected distance from the other LAE BDF3299

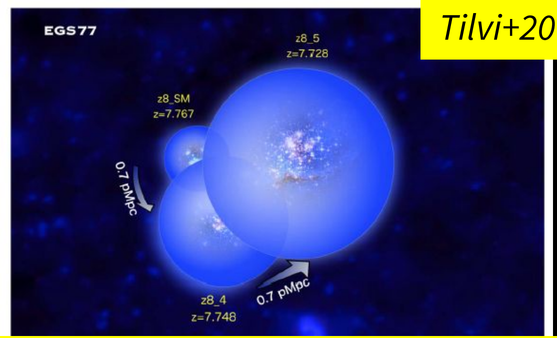
We have discovered and confirmed 3 bright Lyα emitters at z=7.008, 7.008, 7.109 within a region of just 2 Mpc in the BDF field.

Evidence of reionized bubbles: regions with high Lyα visibility

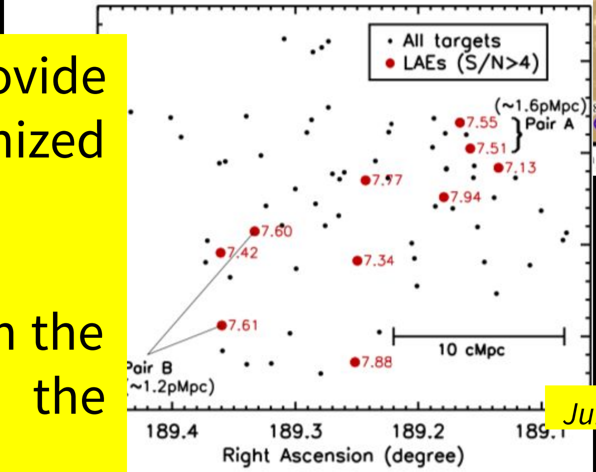
Endsley+22 z=6.8, COSMOS



Tilvi+20 z=7.7, EGS



- Do the sources we see provide enough photons to form the ionized bubbles?
- Are these sources AGNs?
- Are there other fainter sources in the vicinity that contribute to the ionizing budget?



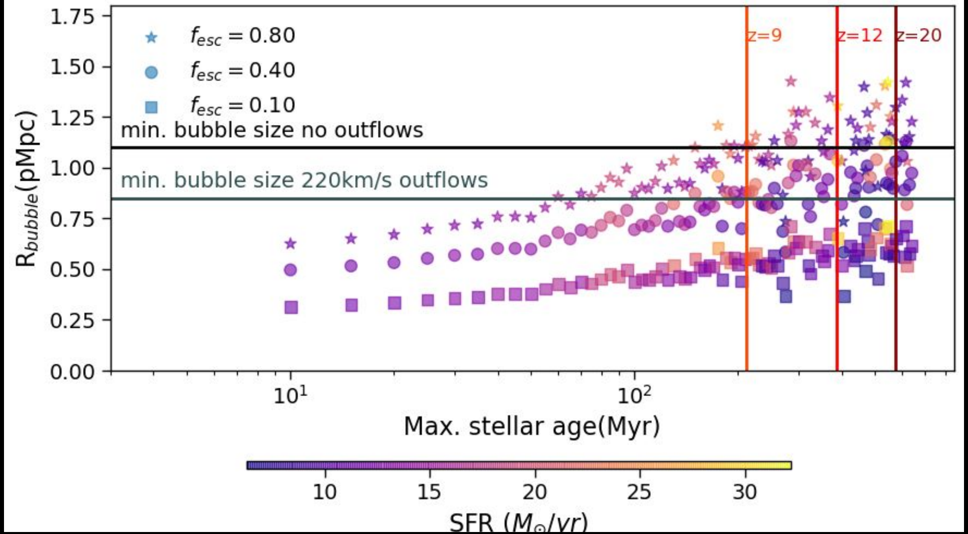
Jung+20 z=7.6, GOODS-N

Connecting galaxy physics and reionization in the ”reionized bubbles”

$$R \approx \left(\frac{3\,\dot{N}_{\rm ion}\, f_{\rm esc}\, t}{4\pi\, \bar{n}_{\rm H\,I}(z)} \right)^{1/3}$$

Each galaxy can carve an ionized bubble whose size depends on:

1. the lifetime of the activity
2. the number of ionizing photons produced
3. the number of ionizing photons that escape
4. the local neutral content of the IGM



The three BDF emitters cannot carve a large ionized bubble to allow us to see the Lyα under realistic assumptions i.e. f_{esc}=10%

→ need some other source of photons

Connecting galaxy physics and reionization in the ”reionized bubbles”

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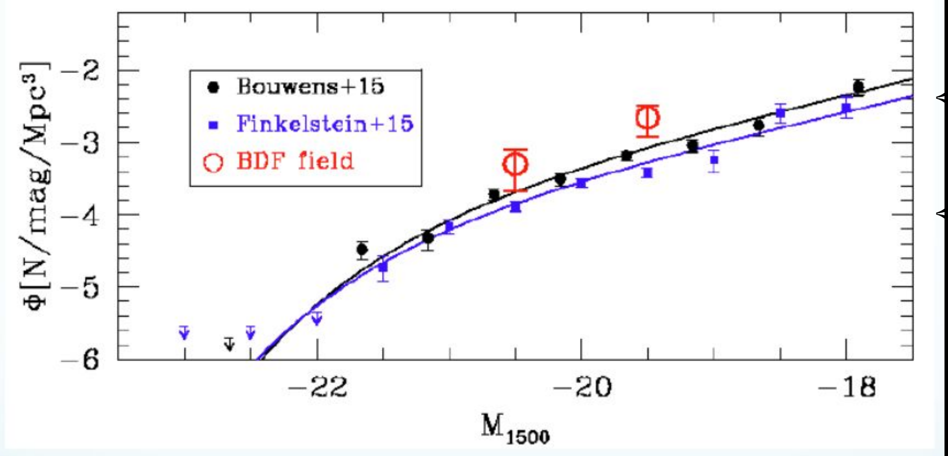


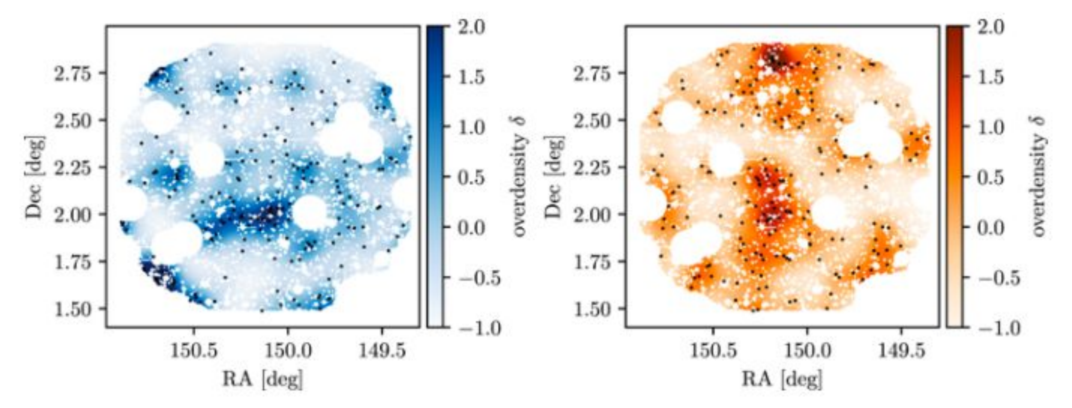
However they sit in an overdensity of galaxies with with 3-4x average LF at z~7.

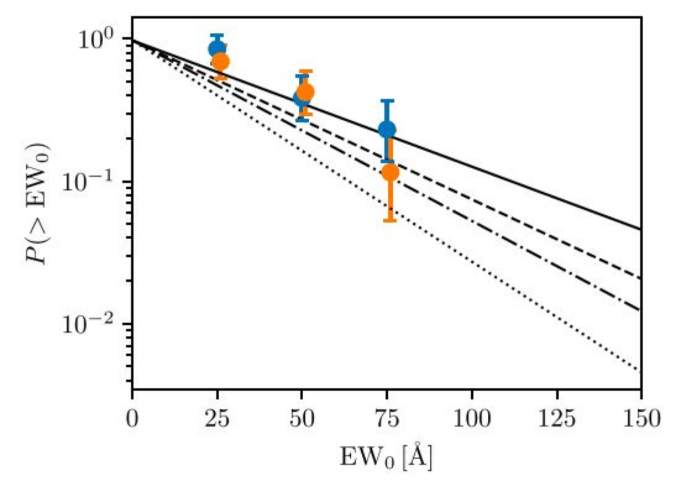
These companion galaxies must have helped in forming the ionized bubble

Mapping the Spatially Inhomogeneous Cosmi Reionization with Subaru HSC

Yoshioka+22

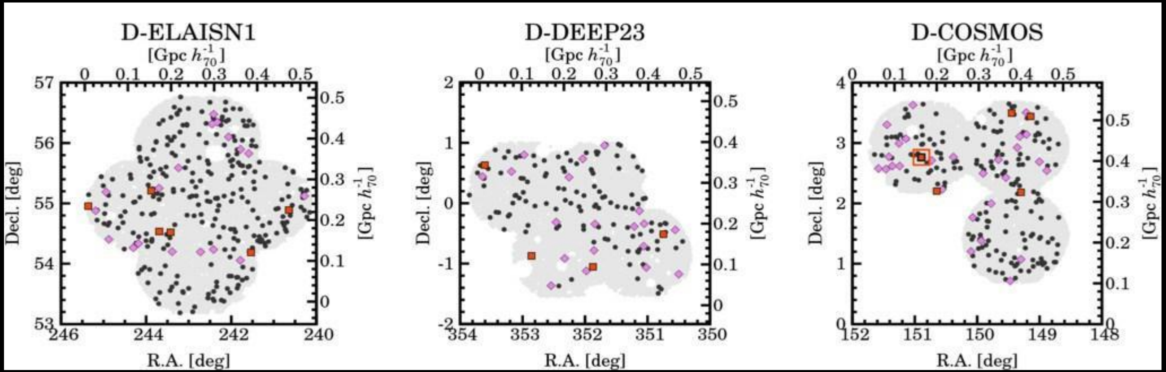
Spatial density of LAEs@z=6.6 Spatial density of LBGs@z=6.6





the variation of n(LAE)/n(LBG) within the field of view for every 140 pMpc^2 area is found to be as large as a factor of 3.

Constraints on the topology of reionization will come from the clustering evolution of Lyα emitters

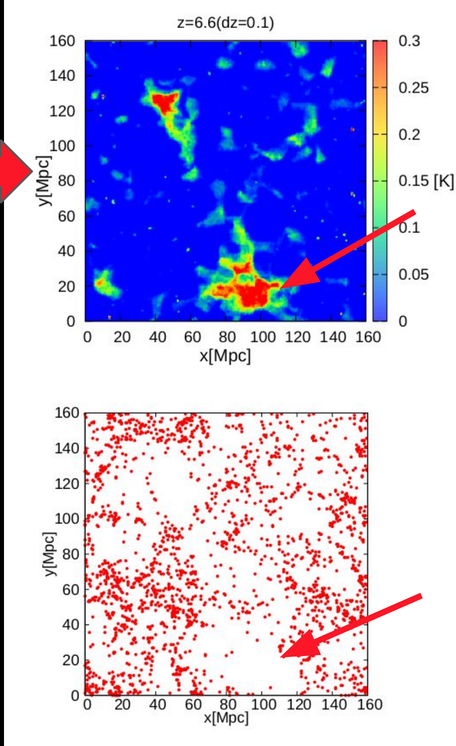


Ouchi + 2017

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

Constraints on the topology of reionization will come from the cross-correlation of 21 cm signal and Lyα emitters

In the future SKA/LAE synergies will provide constraints on the neutral hydrogen fraction from the cross-correlation of the 21 cm signal and LAEs density maps (e.g. Hutter + 2018, Heneka+20, Zackrisson+20. Pagano+21 etc)

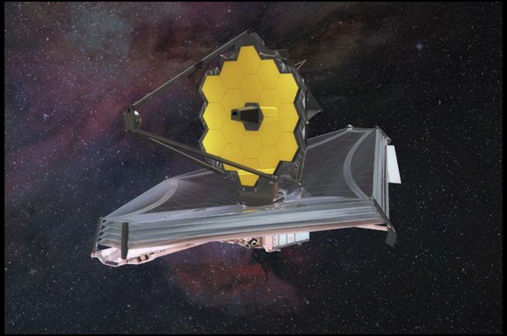


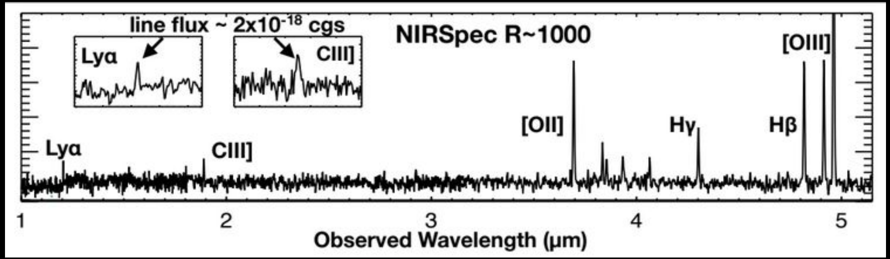
21 cm brightness temperature maps (fully ionized regions in blue)

LAE distribution map

Kubota+18

We are on the verge of a huge jump in our ability to study the epoch of reionization





A simulated NIRSpec spectrum of z=8.9 galaxy of the ERS program CEERS (PI Finkelstein)

NIRSPEC@JWST will open an entirely new parameter space
→ we will be able to routinely observe extremely faint Lyα
→ in the absence of Lyα , other UV and/or optical lines (not affected by neutral IGM) will be detectable at z>10, to give an unbiased census of galaxies and allow a precise measurement of the Lyα fractions

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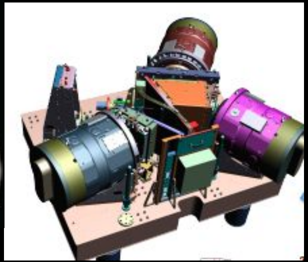
MOONS
Multi Object Optical and Near-infrared Spectrograph

Prime Focus Spectrograph
SuMIRe



Largest areas

The upcoming optical-to near-IR spectrographs MOONS@VLT and PFS@Subaru with their very large field of view will allow us to study the large scale distribution of bright LAEs up to z>10.

→ we will study the relative clustering of LAEs and LBGs and their evolution

→ we will identify overdense regions as the possible site of early reionization

...and of course we still do not know the culprit: did galaxies reionized the Universe?

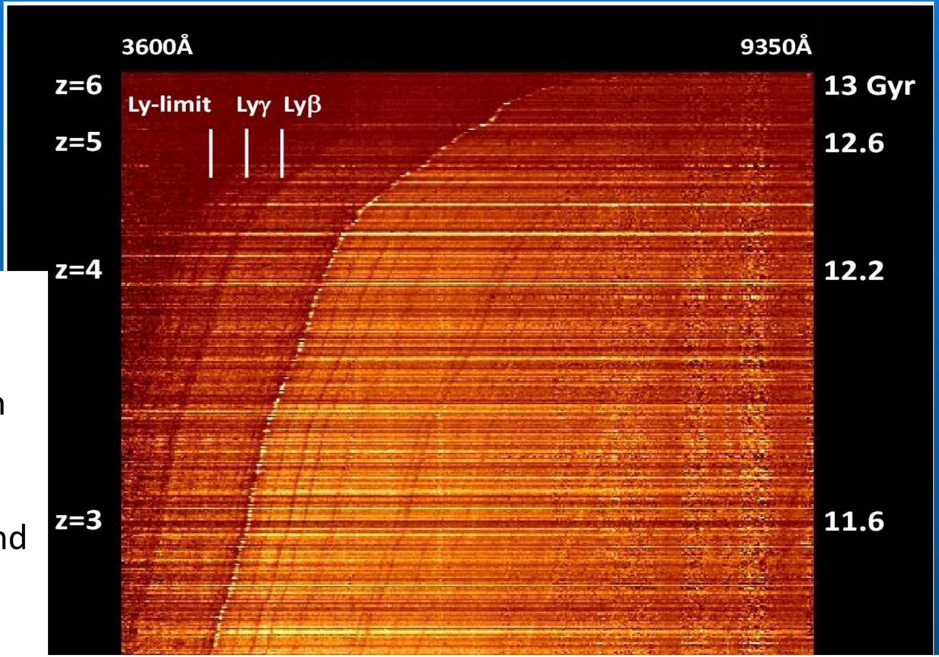
Ionization rate	$\dot{n}_{\rm ion} = \boxed{\overset{???}{f_{\rm esc}}\,\overset{?}{\xi_{\rm ion}}\,\overset{\rm Ok?}{\rho_{\rm UV}}}$
Recombination time	$t_{\rm rec} = [C_{\rm H\,II}\alpha_{\rm B}(T)(1+Y_{\rm p}/4X_{\rm p})\langle n_{\rm H}\rangle(1+z)^3]^{-1}$

...but this would require another talk!!

Oliver’s legacy

Oliver has been one of the pioneers of spectroscopic extragalactic surveys.
Besides being a great scientist, a world leader in the study early galaxy evolution and on their large scale distribution, he was a great inspiration for many of us for his enthusiasm and determination.

He was also one of the first to realize that team work and collaboration are essential for exploiting the great amount of data provided by large scale observational surveys, and only working together we can achieve our goals



...from the building of VIMOS (his “baby”) to the key role he played in the development of NIRSpec@JWST, the Subaru PFS -Prime Focus Spectrograph, the Euclid mission and last but not least the initial design of MOSAIC@ELT, he has led the transformation of our field

The impact of his legacy will accompany us for many years to come

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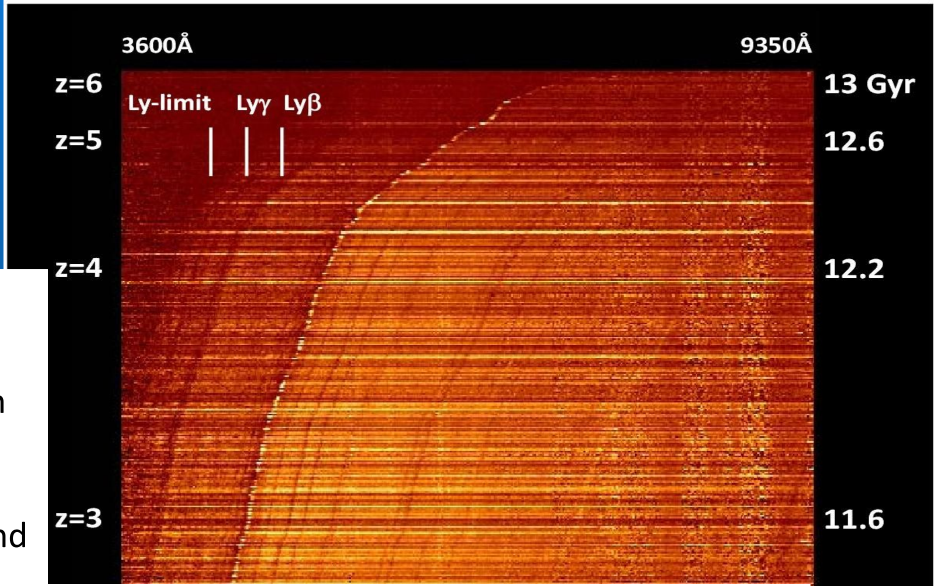

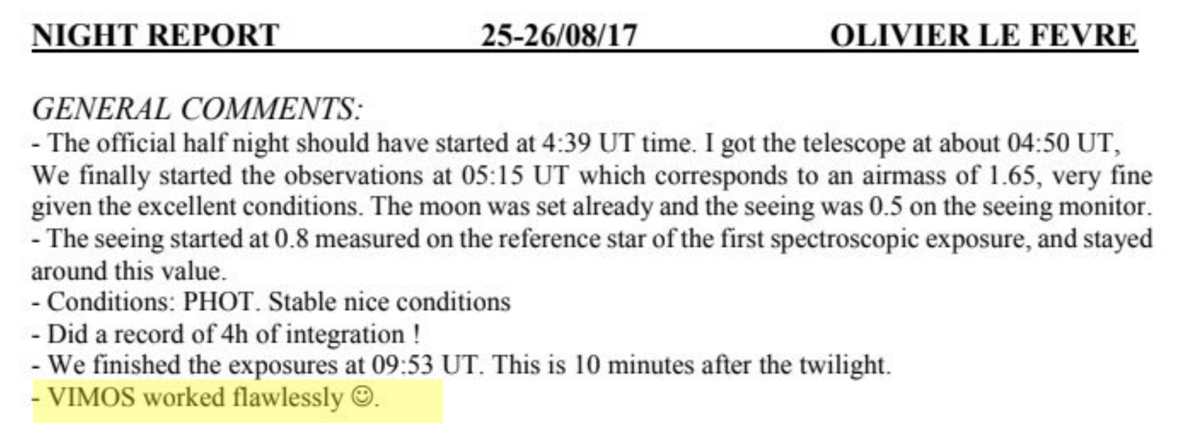

NIGHT REPORT 25-26/08/17 OLIVIER LE FEVRE

GENERAL COMMENTS:

- The official half night should have started at 4:39 UT time. I got the telescope at about 04:50 UT, We finally started the observations at 05:15 UT which corresponds to an airmass of 1.65, very fine given the excellent conditions. The moon was set already and the seeing was 0.5 on the seeing monitor.
- The seeing started at 0.8 measured on the reference star of the first spectroscopic exposure, and stayed around this value.
- Conditions: PHOT. Stable nice conditions
- Did a record of 4h of integration !
- We finished the exposures at 09:53 UT. This is 10 minutes after the twilight.
- VIMOS worked flawlessly ☺.