Probing the reionization epoch with the most distant galaxies… ….and possibly with millimeter spectroscopy

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in collaboration with
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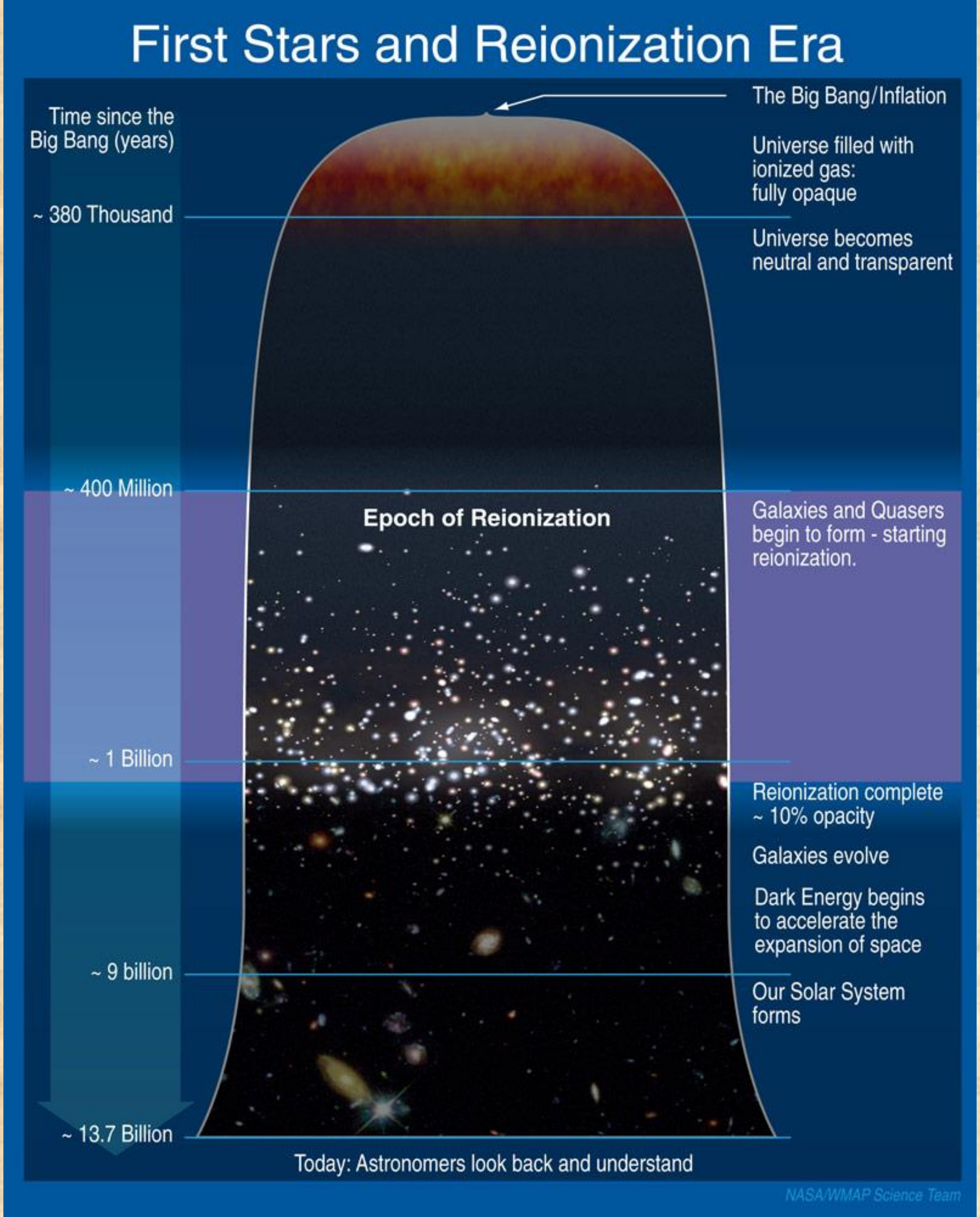
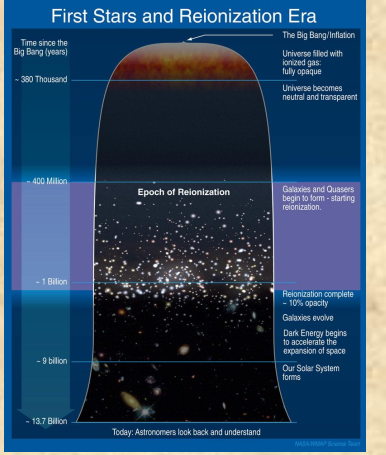
A. Grazian, E. Vanzella et al.

ALMA workshop, Bologna 20 gennaio 2015



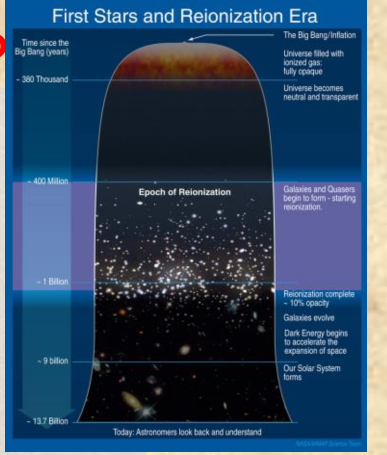
Reionization Epoch:
Star forming galaxies & AGN form bubbles of ionized hydrogen that grow and eventually overlap. At the end of this process the Universe is completely ionized again.

KEY QUESTIONS :

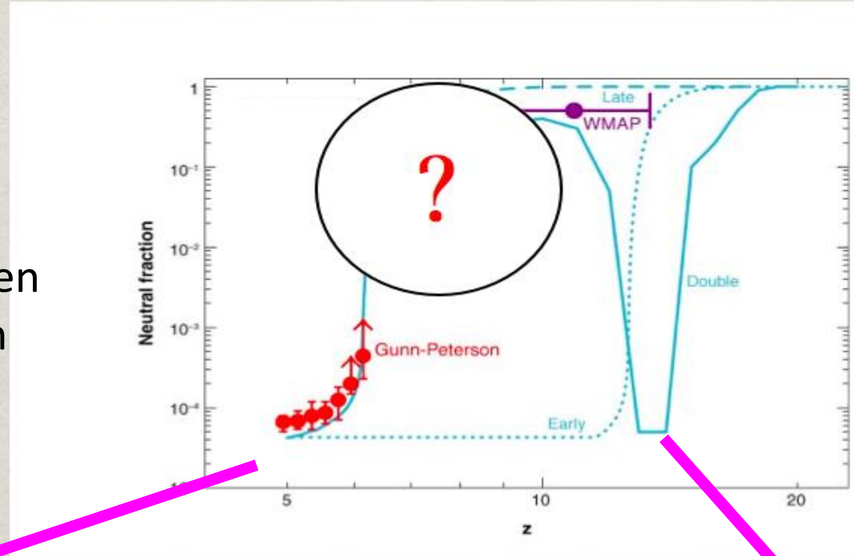


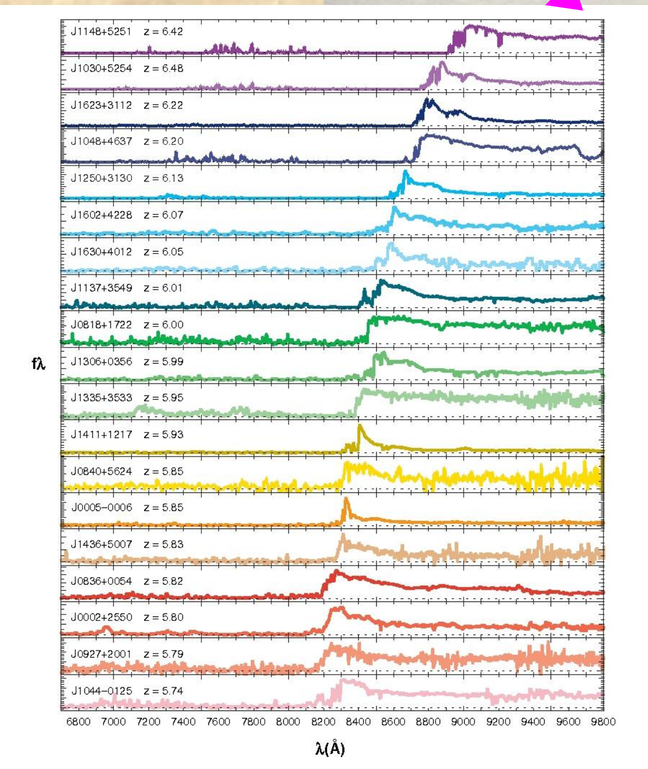
- **When did reionization start ?**
- **How did it proceed in time ? Sharp vs Extended**
- **How did it proceed spatially? Homogeneous vs inhomogeneous**
- **What were the main sources responsible for the ionizing photons? Faint star forming galaxies/ AGN/ exotic objects?**
- **How can we investigate star & galaxy formation during the first billion year?**

Time-line of HI reionization: where do we stand?



Neutral hydrogen fraction

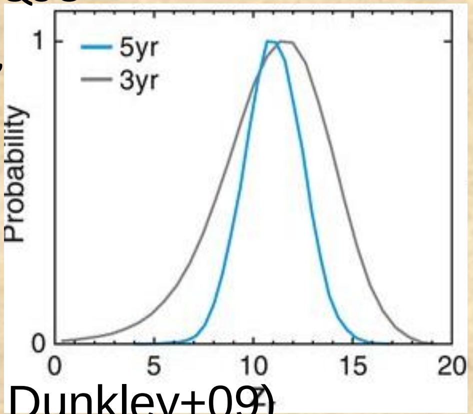




QSO Gunn Peterson trough :

--> IGM ionized by z~6 (e.g. Fan+06)

--> HI neutral fraction >0.1 at z~7 from QSO ULAS J1120+0641 (Mortlock et al. 2012, Bolton et al. 2012)



WMAP τ_{es} :

→ Reionization at z≈10 (Komatsu+09)

(z>6.7 if instantaneous, Dunkley+09)

Also recent results from Planck collaboration

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-CFHRQ, 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_{HI}. However they are also VERY rare

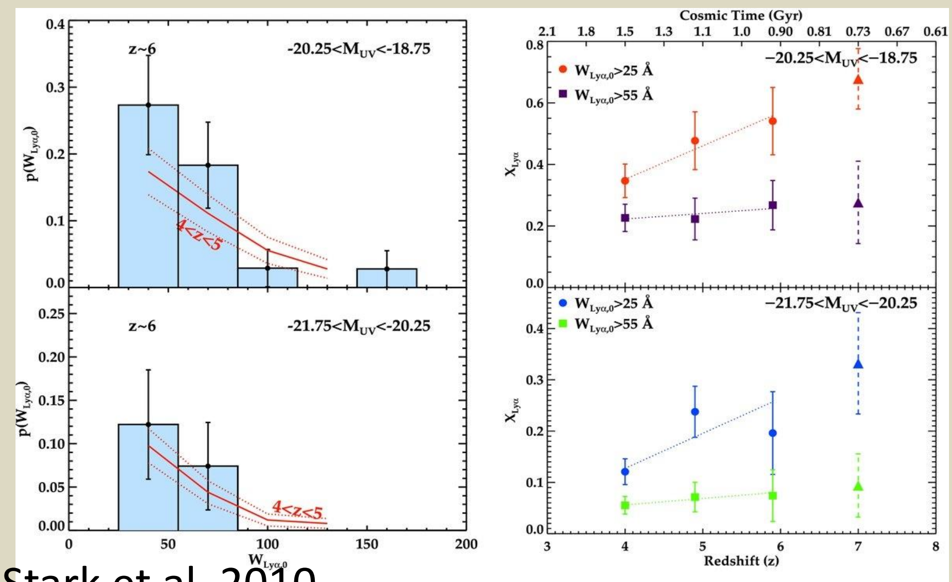
3 High z LBGs and LAEs Use high redshift star forming galaxies (i.e. Lyα emitters and Lyman break galaxies as) as potential probes of neutral fraction in the IGM

These objects are 1. much more numerous
2. probe "normal" galaxy population
3. probe common conditions in the early Universe

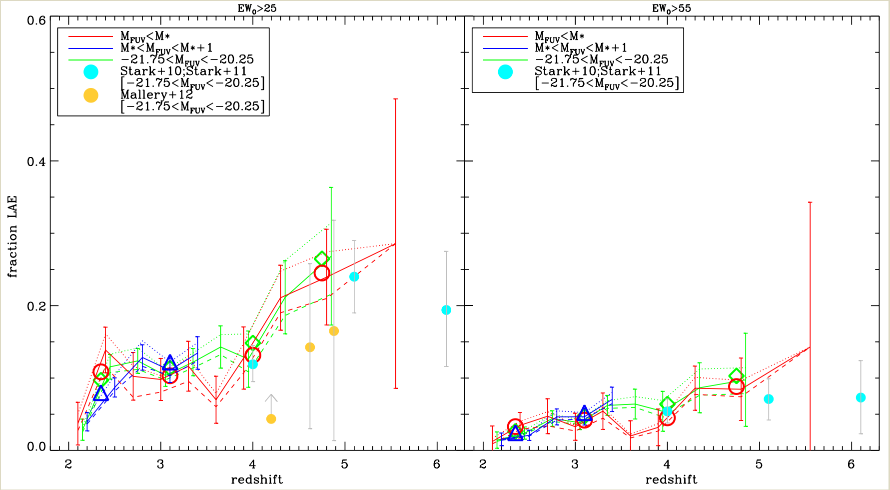
Evolution of the fraction of strong Lyα emission in samples of Lyman Break Galaxies

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

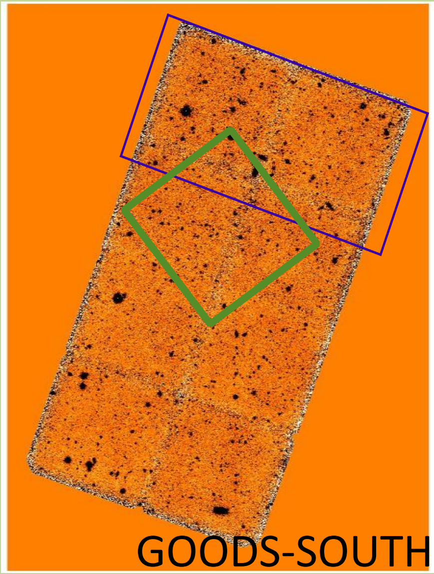
Main advantages of using the fraction of Lyα emission in Lyman Break Galaxies as reionization probe over other statistical tools

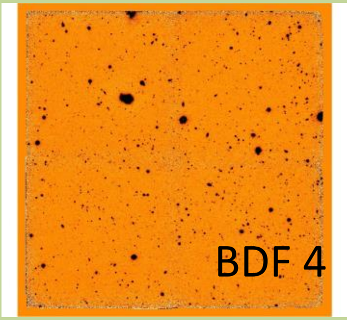
✓ Being a fraction it is not subject to intrinsic number density evolution

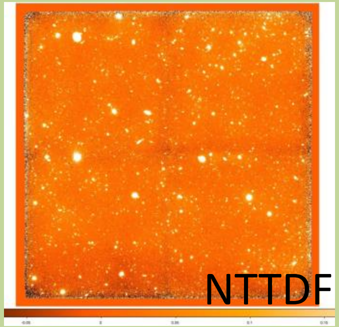
✓ LBGs have measurable continuum colours (contrary to the majority of LAEs) therefore the galaxies' physical properties e.g. dust obscuration, stellar age, stellar mass can be measured individual objects and their evolution can be tracked independently

Searching for z～7 galaxies:

HAWKI ESO Large Program (PI A. Fontana)~160 Hours







Fields with excellent complementary multi-wavelength coverage. Three independent fields to beat cosmic variance

Total area surveyed = 200 arcmin sq

CANDELS: Cosmic Assembly Near-IR Deep Extragalactic Legacy Survey (PI S. Faber/H. Ferguson)

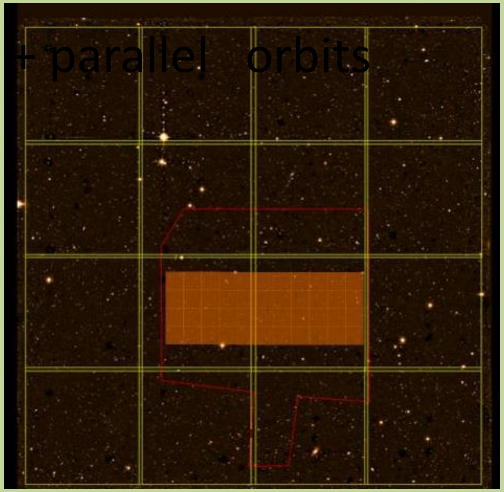
902 prime orbits using WFC3 and ACS + parallel orbits

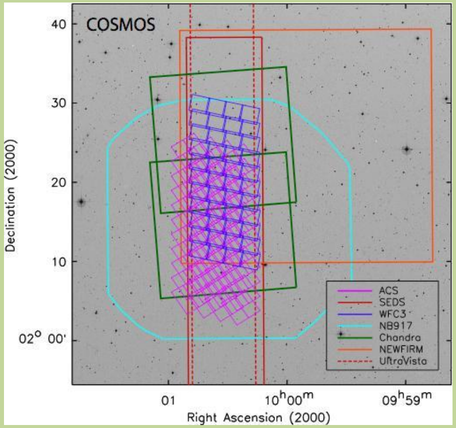
5 fields: GOODS-N/GOODS-S/UDS/ COSMOS/EGS

WIDE (700 sq arcmin)

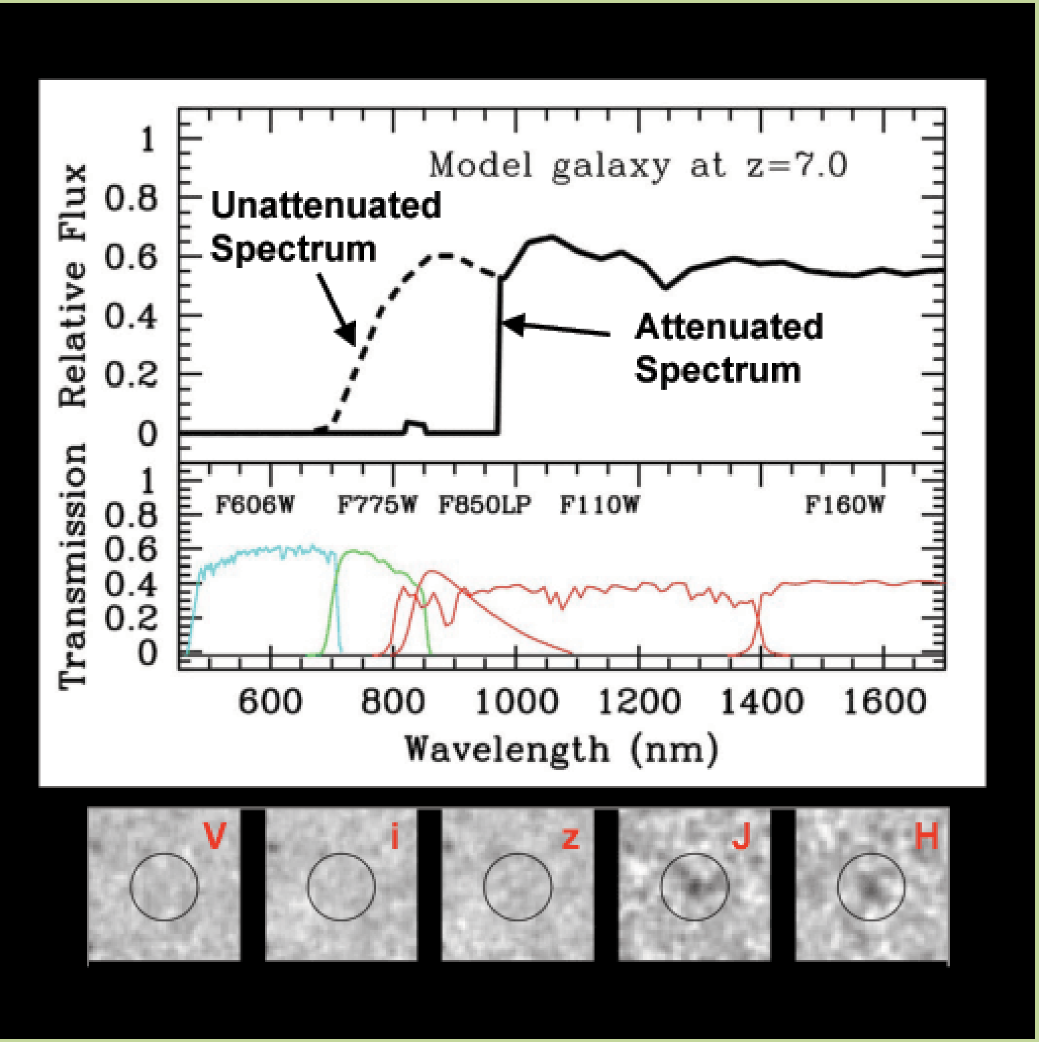
DEEP (120 sq arcmin)

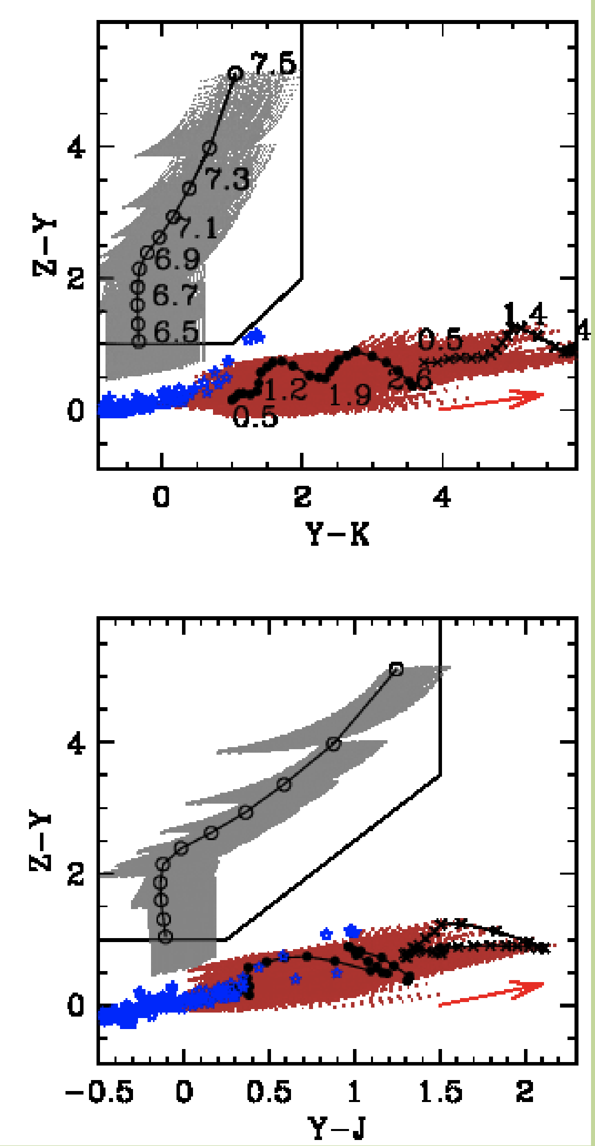
Ultra DEEP (10 sq arcmic)





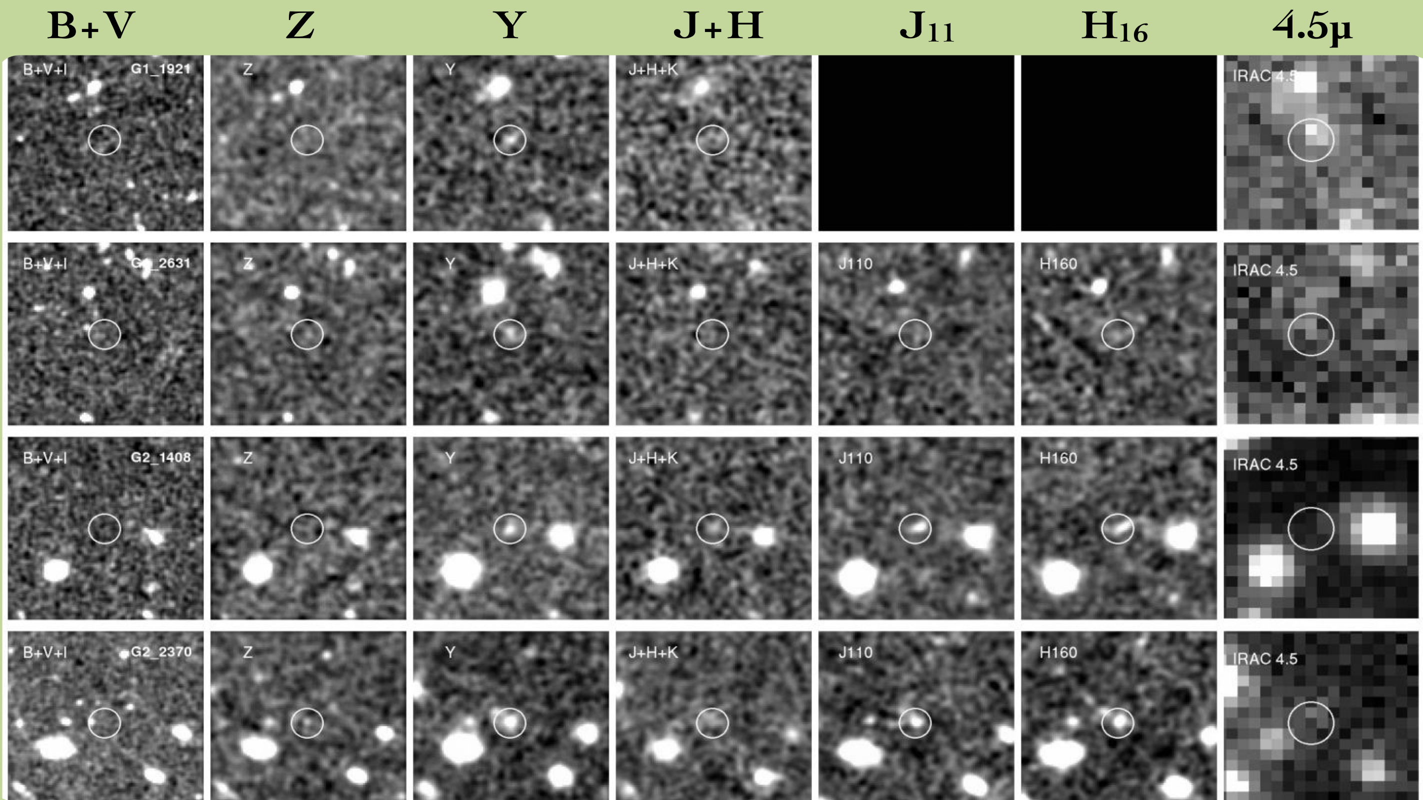
lyman break galaxies at z=7 (z dropouts)



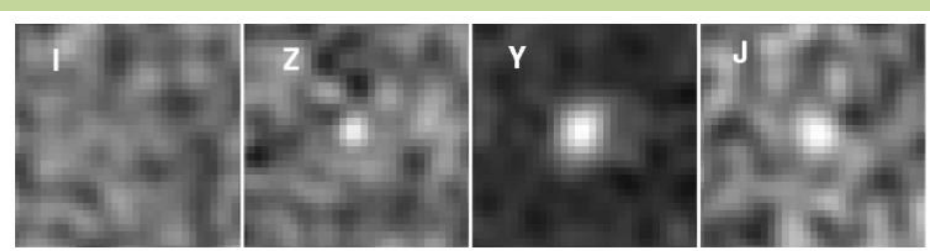


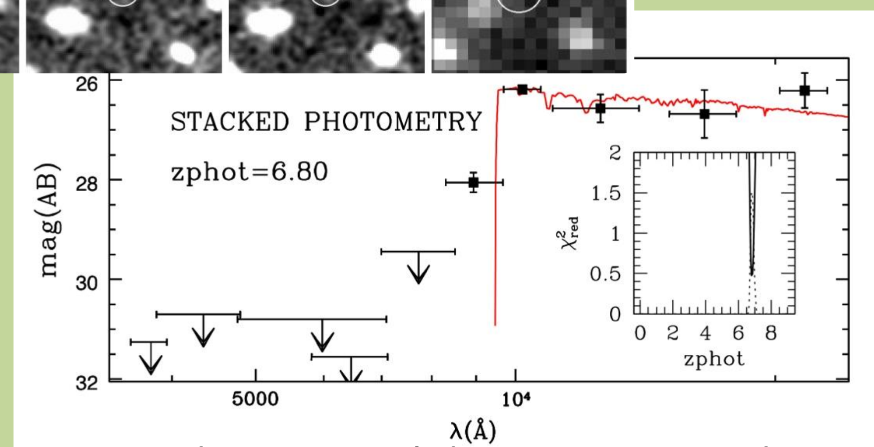
WITH A RECASTING OF THE LYMAN BREAK TECHNIQUE:
A CANDIDATE GALAXY AT Z ~7 WILL HAVE A SHARP DROP IN COLOR BETWEEN THE Z AND J BAND (**ALSO CALLED Z-DROPOUTS**): IF WE PLOT ITS COLORS IN A Z-J VS J-K DIAGRAM (OR Y instead of J) IT WILL OCCUPY A VERY DISTINC REGION AND WILL BE EASILY DISTINGUISHED FROM ALL OTHER LOWER-Z GALAXIES AND STARS

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



STACK OF ALL CANDIDATES





Castellano et al. 2010

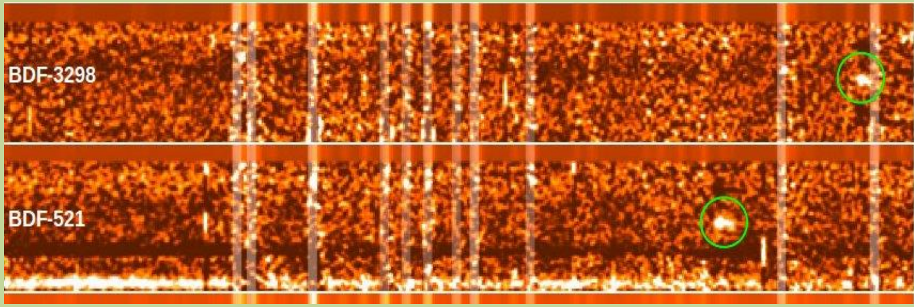
Very deep optical data are required to get rid of interlopers

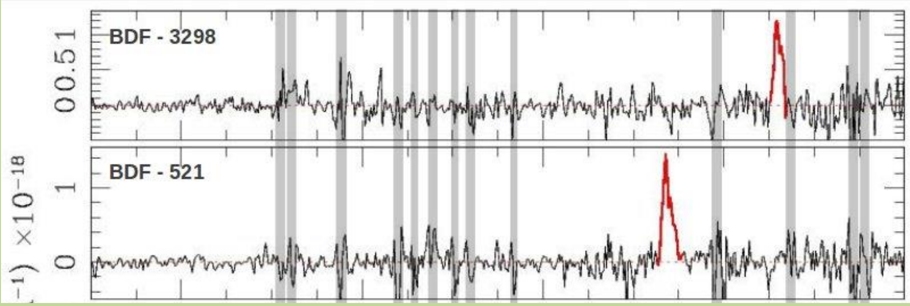
Spectroscopy for redshift confirmation is probing very hard.

So far >60 candidate z=7 galaxies observed in 5 independent fields (GOODS-S/COSMOS/UDS/BDF4/NTTDF) with integration times = 15 hours/target with red-enhanced FORS2@VLT

Part of these results come from an on-going ESO Large program (PI L.Pentericci) with FORS2 aimed at observing 200 candidate galaxies at photometric redshift 5.8 < z < 7.3 (with 140 hours)

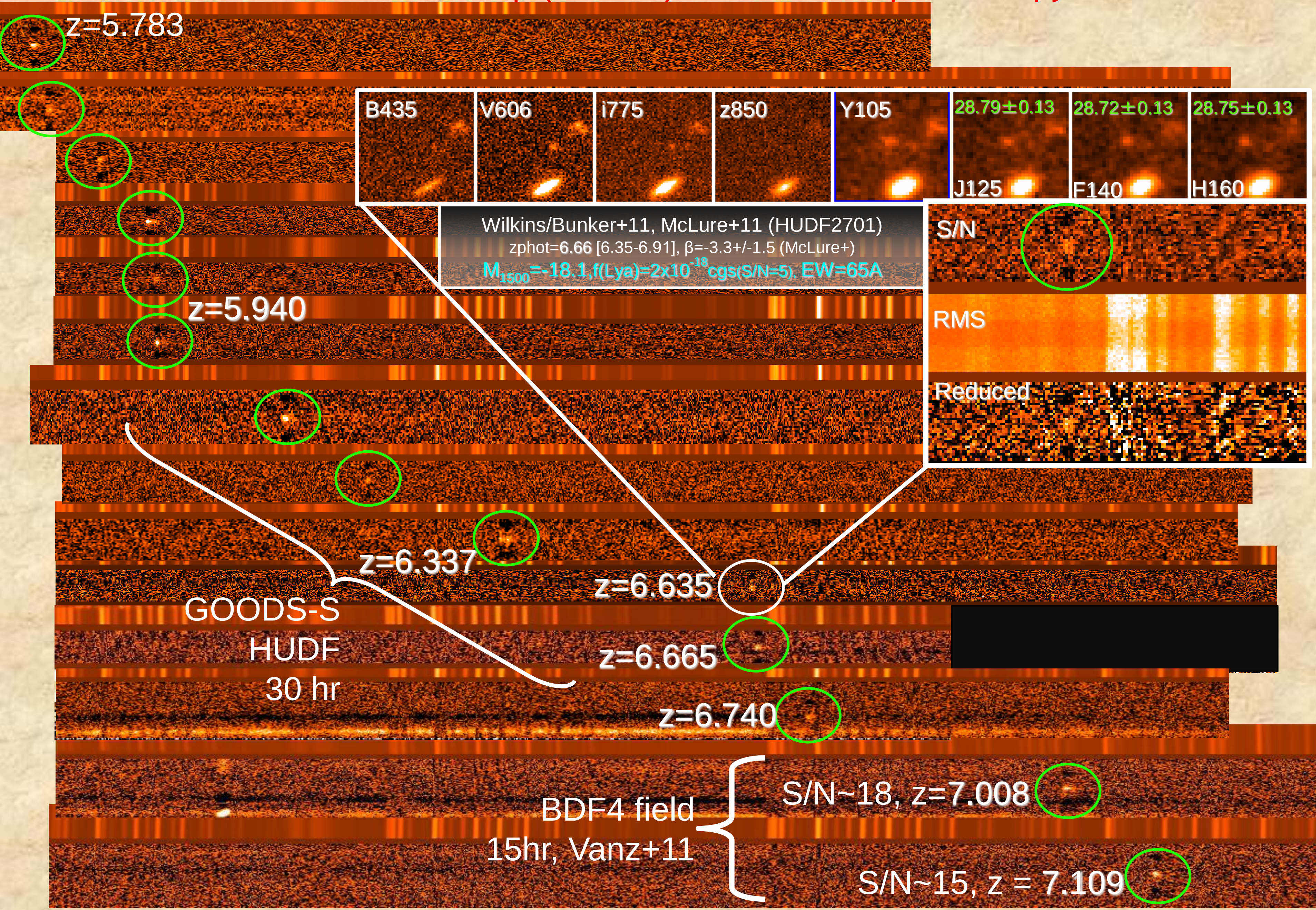
In addition data for 4 z-dropouts retrieved from archival programs (30 hours FORS2)





RESULTS: Overall only 10 confirmed redshifts out of 65.
9 with Lyα line emission@ 6.7 < z < 7.1.
Only 4 galaxies with EW>50Å

Deep (15-30hr) VLT/FORS2 spectroscopy at redshift >5.7



Vanzella - Sesto - July 2014

Many additional results from the literature

Schenker et al. 2012 +2014

Observed 38 candidates: mixture of z and Y-dropouts (6.3 < z < 9)

Spectroscopic observations with Keck/DEIMOS NIRSPEC or MOSFIRE

3 candidates confirmed at z=7 with Lyα EW ≈ 25-30 Å

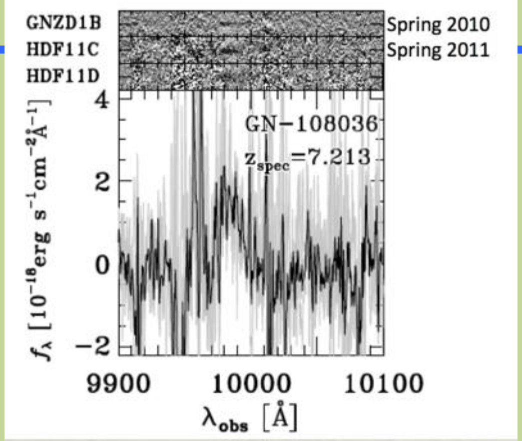
1 tentative detection at z=7.62

Ono et al. 2012

Observed 11 z-dropouts selected from ultra-deep SUBARU Y-band imaging of GOODS-N/SDF fields+ Keck spectroscopy

3 candidates confirmed at z=7 with bright Lyα emission (EW ≈ 30-55 Å

8 undetections

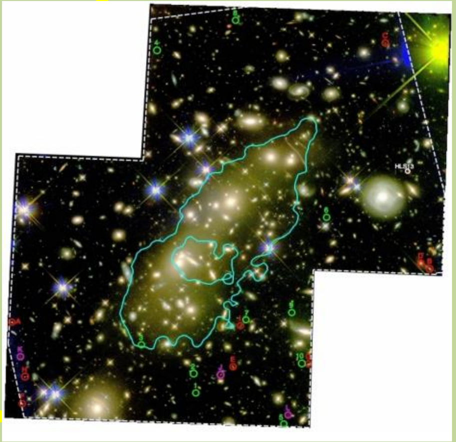


Bradac et al. 2012

Observed 10 candidates lensed galaxies behind the Bullet cluster (lensed by a factor of 3) FORS2@VLT observations 16.5hours

1 candidate confirmed at z=6.74 with Lyα emission

Constrain the faint end (M_{UV}=-19)



Caruana et al. 2013+2014

Observed a mixture of i-z-Y droputs in the GOODS-south field observed. Up to 27 hours integration with FORS2

No confirmations at z=7

Tilvi et al. 2014

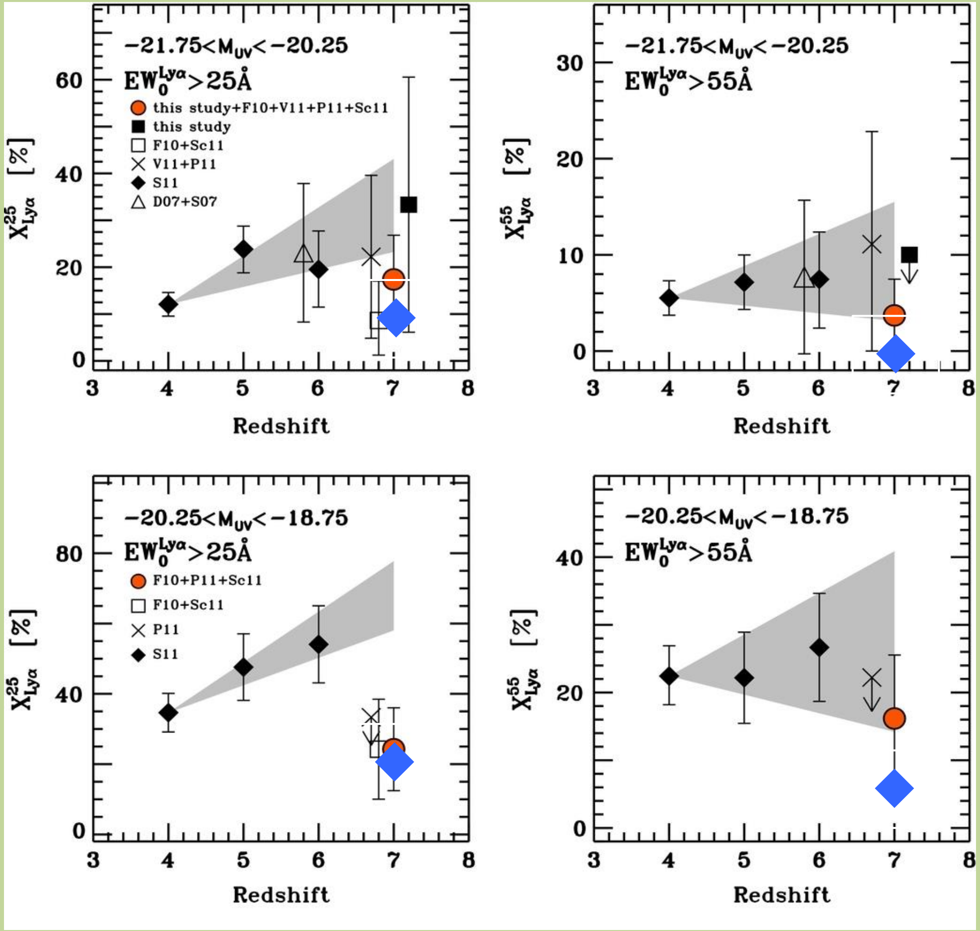
Finkelstein et al 2013

Observed a mixture of 43 z-Y dropouts in the CANDELS fields with MOSFIRE

1 galaxy at z=7.51

With the new samples we find solid evidence for a decline in the fraction of Lyα emission in LBGs at redshift above 6

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.



bright galaxies

faint galaxies

new z=7 limits (Pentericci +14)

limits Ono et al. 2012

EW > 25 Å

EW > 55 Å

WHAT DOES IT MEAN?

☒ A significant fraction (> 60-70%) of selected galaxies is not at z≈7; however 1. we do not detect any other line/feature

2.The LBG technique works very well up to z=6 with <20% interlopers

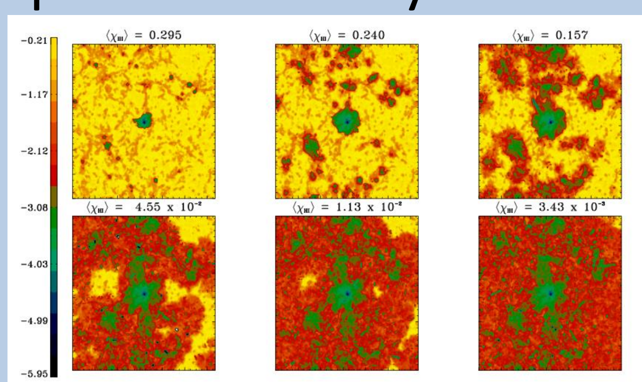
→ would be v-faint low-z galaxies showing extreme line emission that can mimic the Lyman break (e.g. Hayes et al.2012)

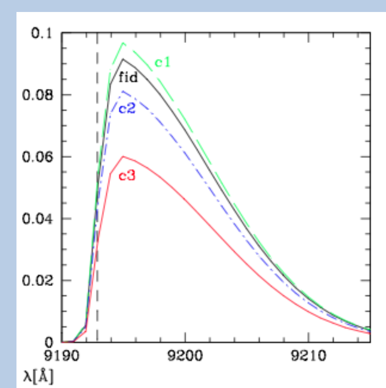
☒ There is a sudden (< 200 Myrs) change in some of the galaxies physical properties (unlikely from theoretical predictions and observations e.g. of UV continuum slopes Finkelstein et al. 2011)

☑ 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

The amplitude of the drop seems to be more pronounced for fainter galaxies that for brighter ones (although samples of fainter galaxies is somewhat considerably smaller) --> this might suggests that reionization proceeded inside-out





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.
- 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

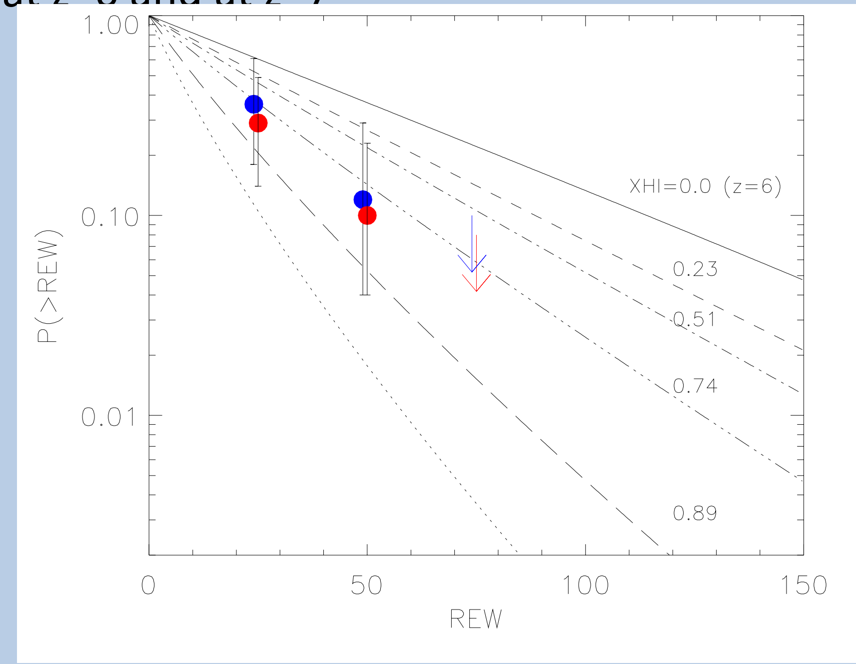
--Neutral hydrogen fraction

--Column density of HI

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

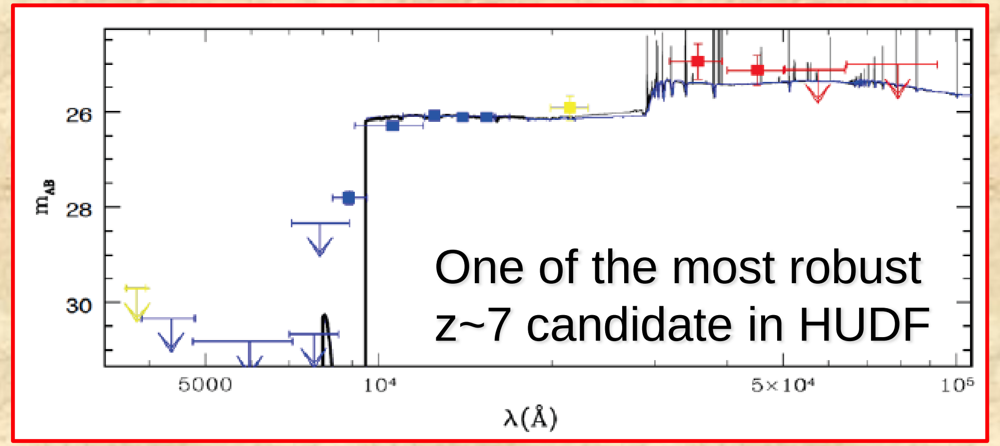
● ● fractions assuming that 0-20% of the Candidates are lower redshift interlopers

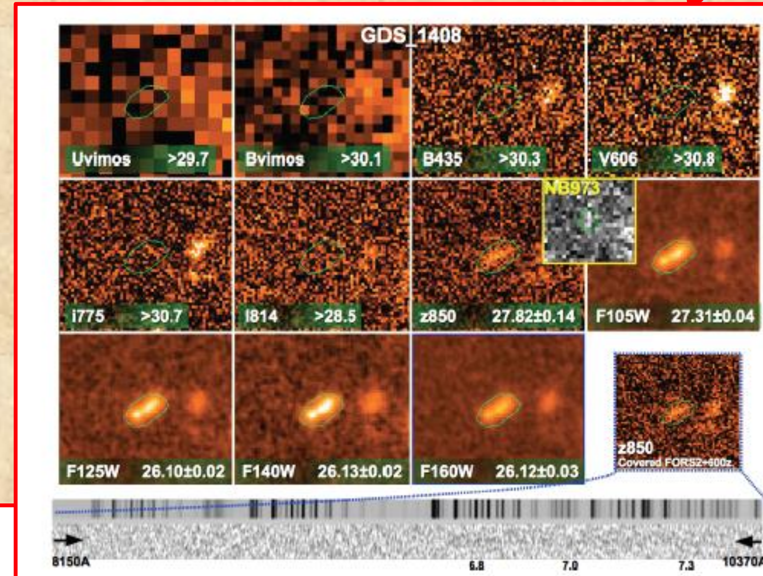
$X_{HI} \geq 0.5$ @z=7



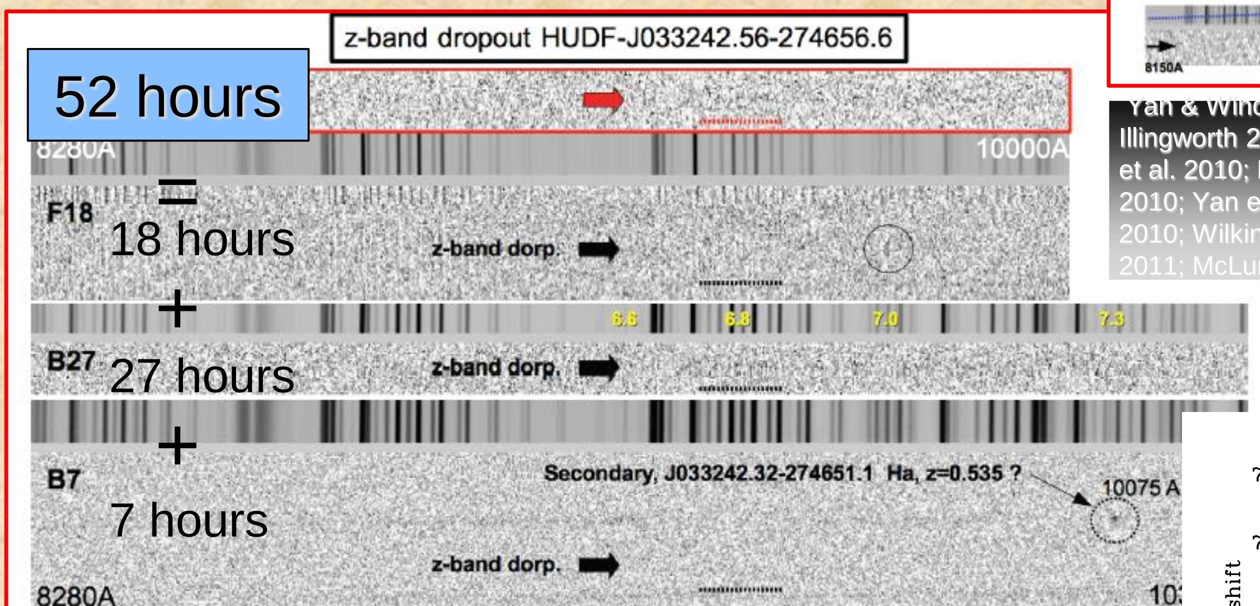
Pentericci et al. 2014

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

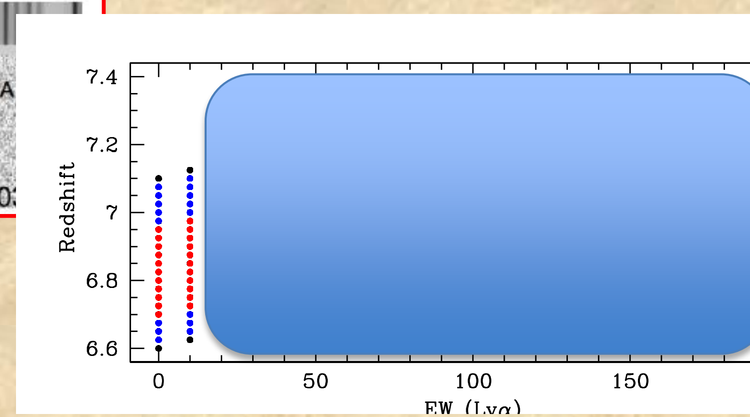




Yan & Windhorst 2004; Bouwens et al. 2004; Bouwens & Illingworth 2006; Labbé et al. 2006; Bouwens et al. 2008; Oesch et al. 2010; Fontana et al. 2010; McLure et al. 2010; Bunker et al. 2010; Yan et al. 2010; Finkelstein et al. 2010; Castellano et al. 2010; Wilkins et al. 2011; Bouwens et al. 2011; Grazian et al. 2011; McLure et al. 2013; Bouwens etal. 2014

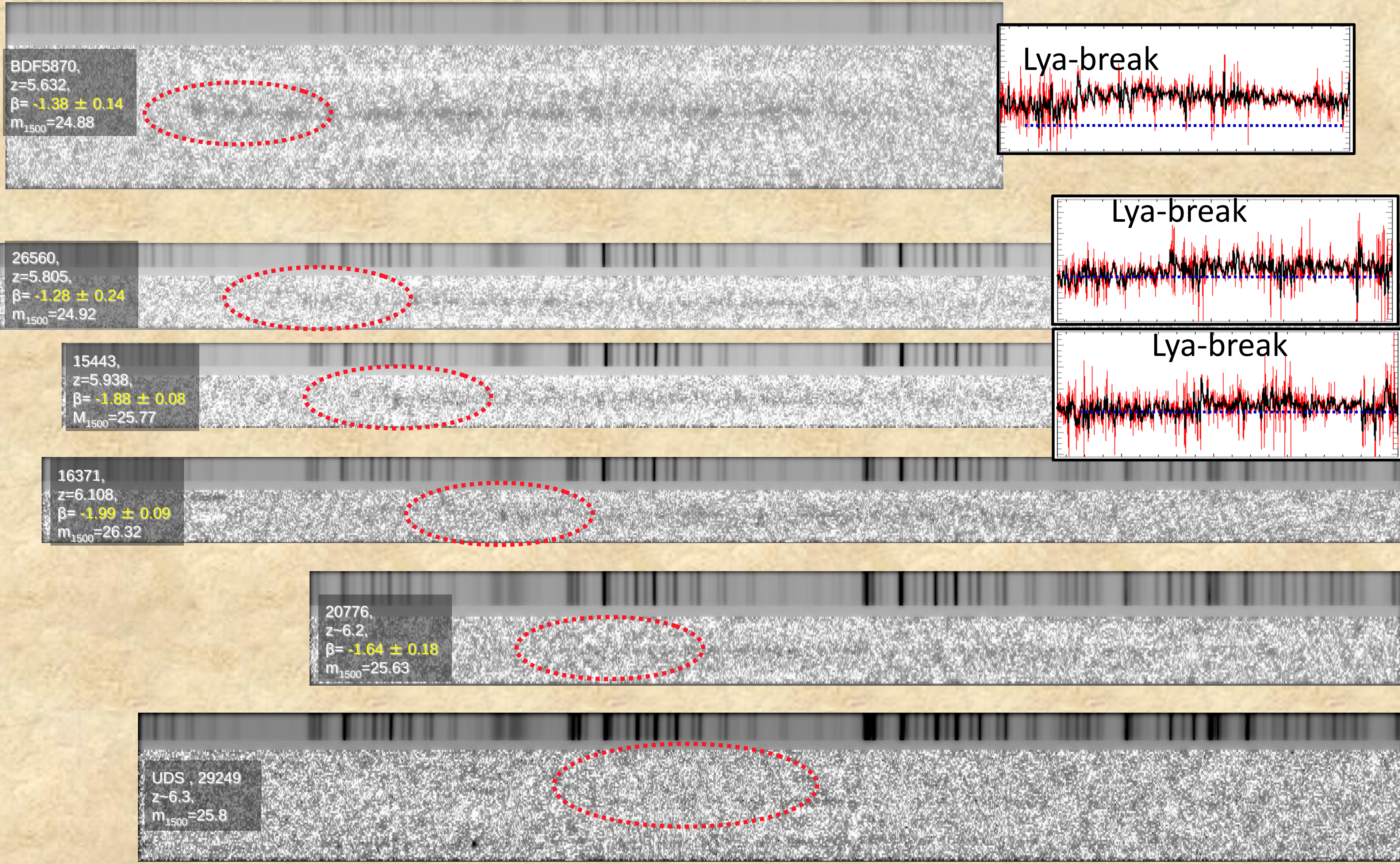


f(Lyα)<3e^{-18} erg/s/cm^2
EW(Lyα)<9A restframe
6.7<z<7.0



Vanzella et al. 2014

Deep spectroscopy starts to reveal faint z~6-6.5 non-Lyα emitters



Vanzella, Pentericci et al. in prep.

If the trend of decreasing Lyα is confirmed ….

→ galaxies at $z \geq 7$ might mostly have extremely faint Lyα emission lines (EW < 10 Å flux < 10^{-18} erg/s/cm) <u>or Lyα may be absent so most galaxies willl remain without a spectroscopic redshift</u>

→ it will be harder to secure the redshifts of statistical samples of z=7.5-9 galaxies with current near-IR facilities (MOSFIRE, KMOS, LUCIFER..)

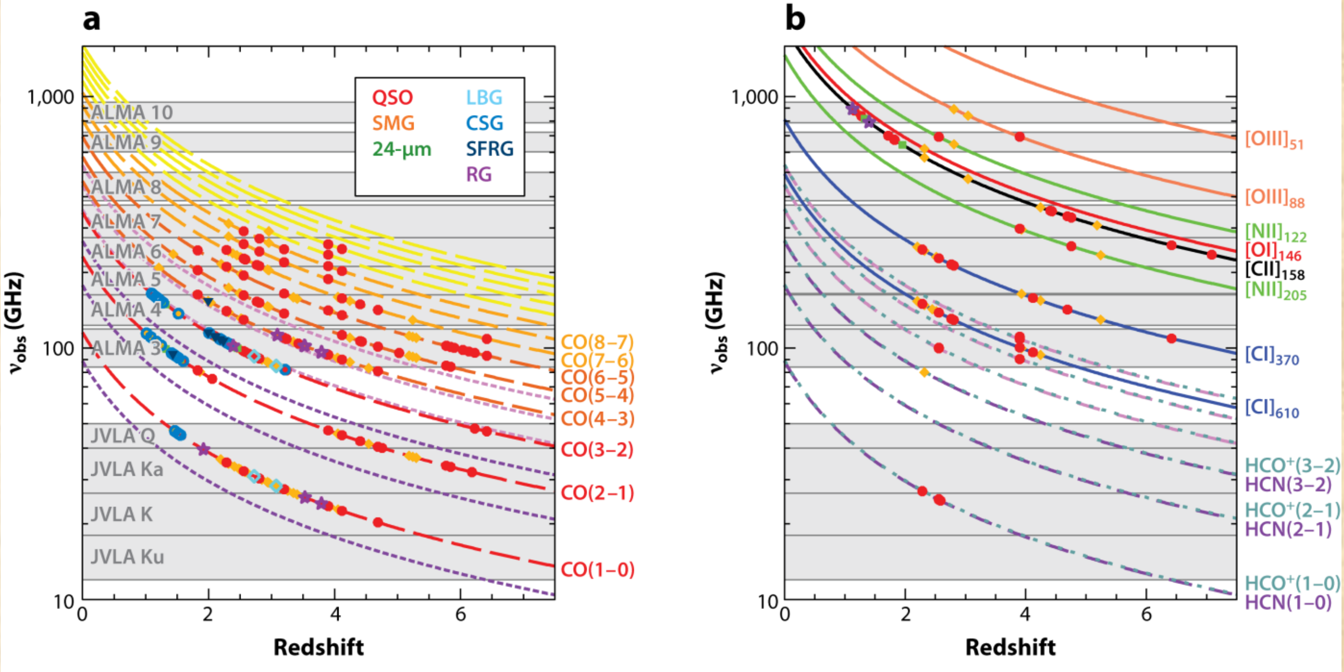
→ Indeed a single z=7.51 galaxy was confirmed out of 43 observed by Finkelstein et al. (2013). A further tentative z=7.6 galaxy in Schenker et al. (2014).

We need alternative methods to determine the redshifts of sizeable samples of galaxies which are needed to explore galaxy evolution during the first 600 Myr, validate the Luminosity Function, the SFRD evolution and so on…..

….can this be a task for ALMA?

…can this be a task for ALMA? YES!!!

The most promising valid alternative is [CII]158µmwhich is has been shown to be the strongest cooling line of ISM in many galaxies (e.g. >100 times stronger than CO(1-0=, CO(2-1) etc in z=1-2 star forming galaxies Stacey et al. 2010), has a luminosity as high as 1% of total FIR luminosity (Maiolino et al 2009) is and it is observable in ALMA band 6 at redshift up to 8



Carilli CL, Walter F. 2013.
Annu. Rev. Astron. Astrophys. 51:105–61

Advantages:
[CII]158μm is not effected by neutral hydrogen → it can be detected also in galaxies without appreciable Lyα

[CII]158μm can give us a dust-free estimate of SFR in a galaxy

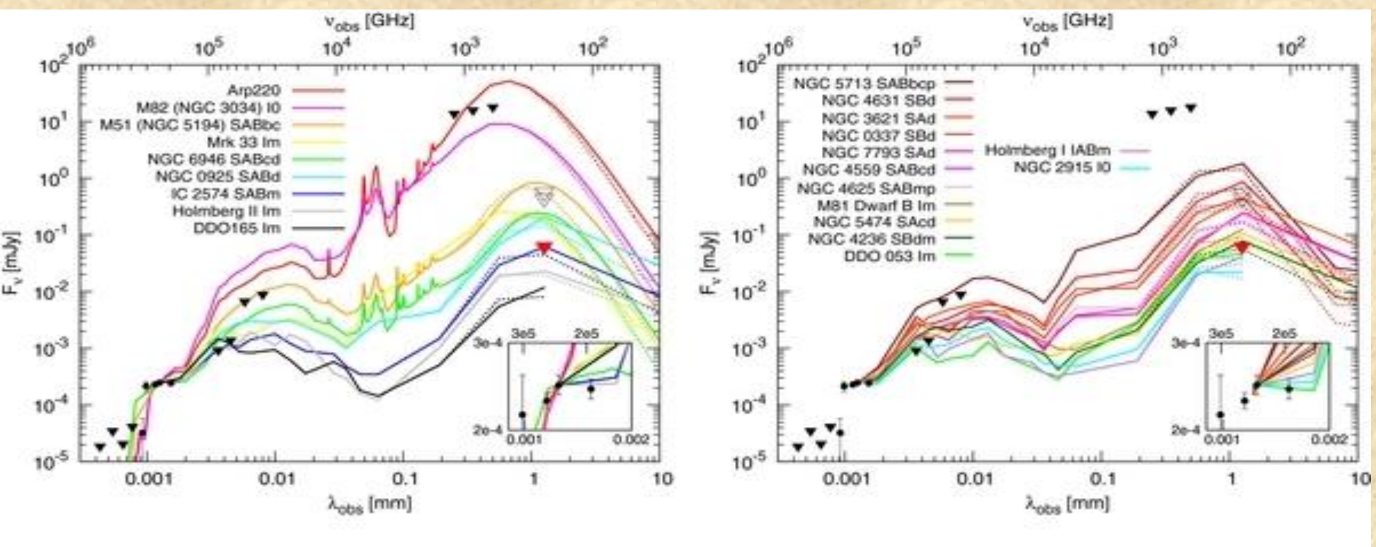
[CII]158μm coupled with continuum emission is a potential tracer of metallicity (e.g. de Breuck et al. 2011)

[CII]158μm probes the systemic redshift of a galaxy, with an accuracy of $\Delta z=0.0005$→ in galaxies with visible Lyα, the systemic redshift allows us to precisely model the asymmetric profile of Lyα hence constrain the neutral hydrogen that is effecting this line.

So ALMA is potentially both a redshift machine for high redshift galaxies and can probe the reionization epoch.

Unfortunately…..so far there are no detections of [CII]158μm in normal star forming galaxies (LAEs and LBGs) within the reionization epoch either with ALMA and/or PdBI (e.g. Ota et al. 2014, Schaerer et al. 2014, Gonzalez-Lopez et al. 2014, Ouchi et al. 2013, Kanekar et al. 2013, Walter et al. 2012.)

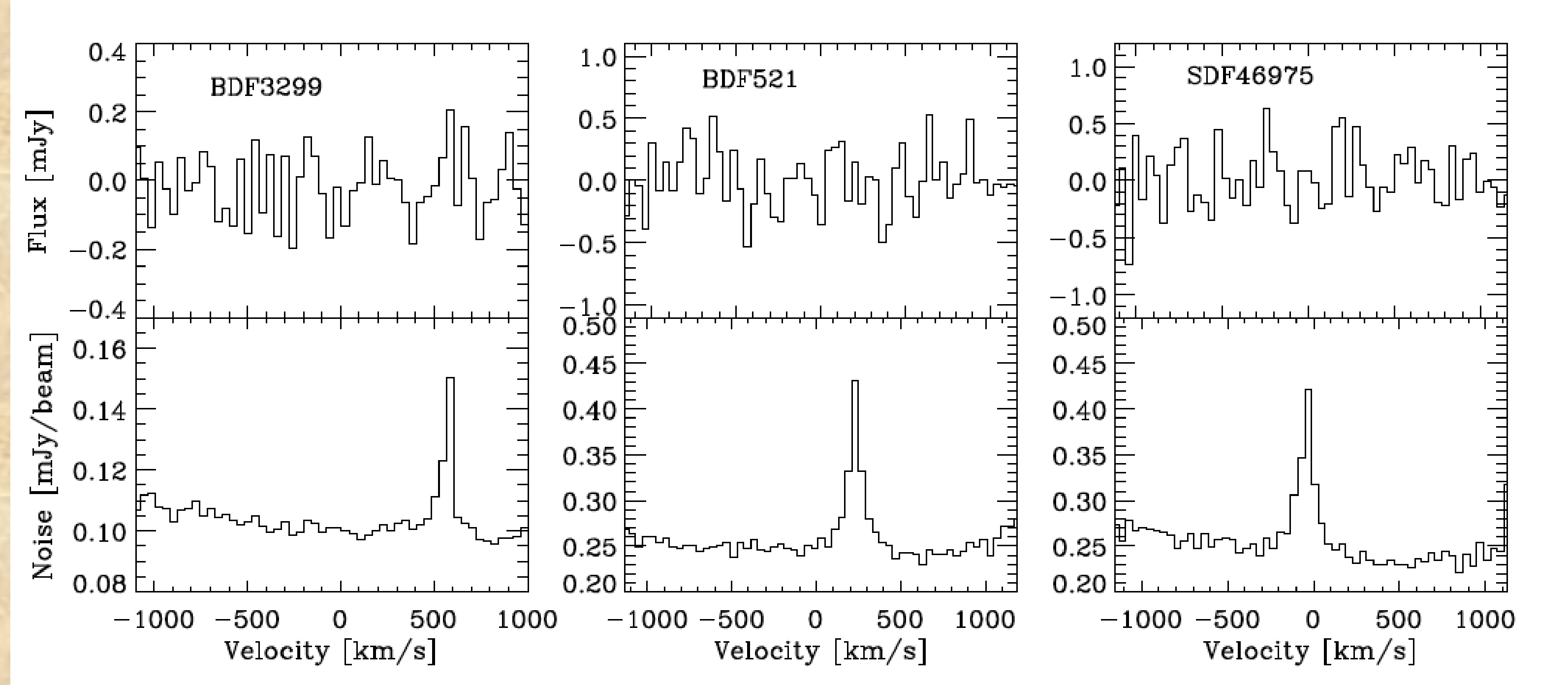
Iok1 z=6.96 (Iye et al. 2006)
An LBG with strong Lya emission and SFR_{UV}≈24 $M_{\odot}yr^{-1}$ (allowed range 23.9-33.8$M_{\odot}yr^{-1}$)
Observations reaching a sensitivity of σ_{line}=240μJy $beam^{-1}$ and σ_{cont}=21μJy $beam^{-1}$ at a resolution 1".5x1".2
Undetected both [CII]158μm and in the thermal continuum emission



SED of IOK-1: ALMA upper limits (red triangles) at 1.3mm; previous IRAM/PdBI and CARMA observations are also shown (lower and upper open triangles) from Ota et al 2014, Walter et al. 2012 Gonzalez-Lopez et al. 2014

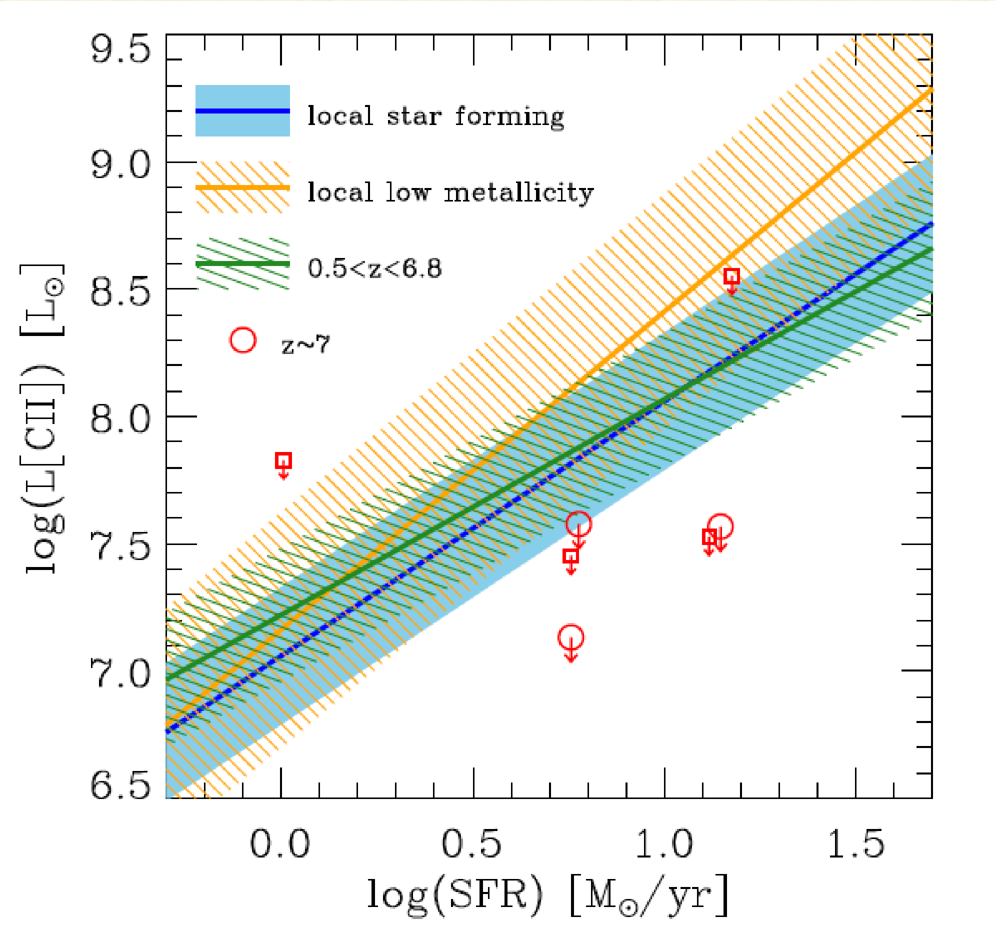
Our more recent observations of three $z \approx 7$ galaxies in the reionization epoch were also not lucky: they are undetected both in line and thermal continuum emission (Maiolino et al. in preparation see also Stefano's talk)

name	redshift	SFR_{UV} $M_{\odot} yr^{-1}$	rms_{line} μJy	rms_{line} mJy	L[CII] $10^7 L_{\odot}$
BDF-3299	7.109	5.7	7.8	0.095	<1.3
BDF-512	7.008	6.0	17.4	0.267	<3.8
SDF-46975	6.844	15.4	19.2	0.271	<3.6



Spectra of the three sources (upper plots) with rms noise (lower plot) centered at the Lyα redshift in each case.

No clear detections of [CII]158μm in z≈7 galaxies so far



The [CII] 158μm luminosity vs SFR of all high redshift normal star forming galaxies at z=7 that have been observed with ALMA: the red circles are our new sources, red squares are sources from Ota et al.2014 Schaerer et al. 2014; Gonzalez Lopez et al.2014.
The green line and hatched region show the relation found at z< 6.5; the orange line and region are the relation for local low metallicity dwarf; the blue line is the relation for local star forming galaxies (De Looze et al. 2014)

Our limits (circles) are well below the expectations for lower redshift galaxies with similar SFR.

- Most likely explanation for low [CII and weak dust emission is a very low metallicity gas and little dust in near-primordial systems (e.g. Vallini et al. 2013, see also Livia's talk) so the low redshift relation between [CII]158μm luminosity and SFR cannot be applicable at z>6.5

WHAT NOW??

….does this mean that ALMA cannot be used as a redshift machine??
Hopefully not!!

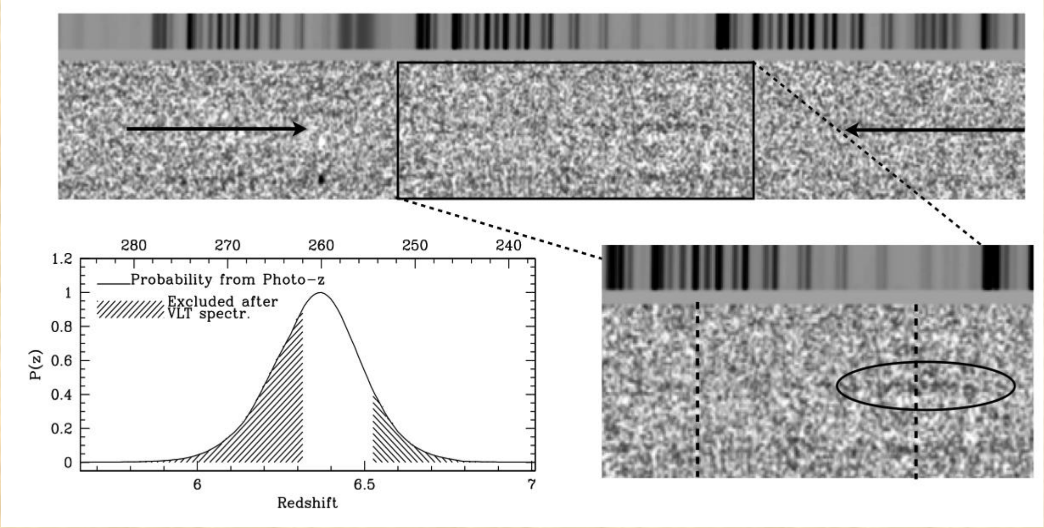
→ Observed galaxies are still only a handful, some of the limits are not very significant yet and the scatter in the low redshift SFR-[CII] relation is a large factor
Maybe just slightly deeper integration and/or larger samples are needed.

→ We are waiting for few more sources at z=7 to be observed : proposal accepted (as filler) for NTT6345 (SFR=20 $M_{\odot} yr^{-1}$) and NTTFDF-474 (SFR=10$M_{\odot} yr^{-1}$), sensitivity to be achieved on the line is 0.015 mJy (PI L.Pentericci)
Other similar proposal accepted in Cycle 2 (PIs Egami, Watson, Knudsen)

Several more potential targets with confirmed redshifts are coming up from the FORS2 VLT Large Program and will be subject to future time requests.

WHAT NOW??

→ So far we have observed LBGs/LAEs with redshift known from the Lyα line …these galaxies tend to be the faintest in continuum emission (e.g. Stark et al. 2010) maybe an alternative would be to observe high z LBGs with no Lyα but with a continuum and Lyman break detection so that we have a good constrain on the redshift



UDS22555 One of the brightest galaxies shows continuum emission plus a drop but no emission line in 15 hours of FORS2 integration z=6.42±0.11 (Pentericci etc al. 2014) Several more examples like this from VLT Large Program.

The redshift uncertainty from a full spectro-photometric analysis is 1/3 of the photometric redshift uncertainty alone (CANDELS photometry): this object can be observed with only 2 spectral scans of ALMA ..unfortunately our proposal was rejected ☹

→ In alternative other lines observable with ALMA could be explored e.g. [OIII]88μm that traces ionized gas like Lyα but is not effected by neutral gas, or UV emission lines redshifted to the near-IR e.g. CIII] 1909A (e.g. Stark et al. 2014)