Probing the earliest galaxies and reionization

Eros Vanzella

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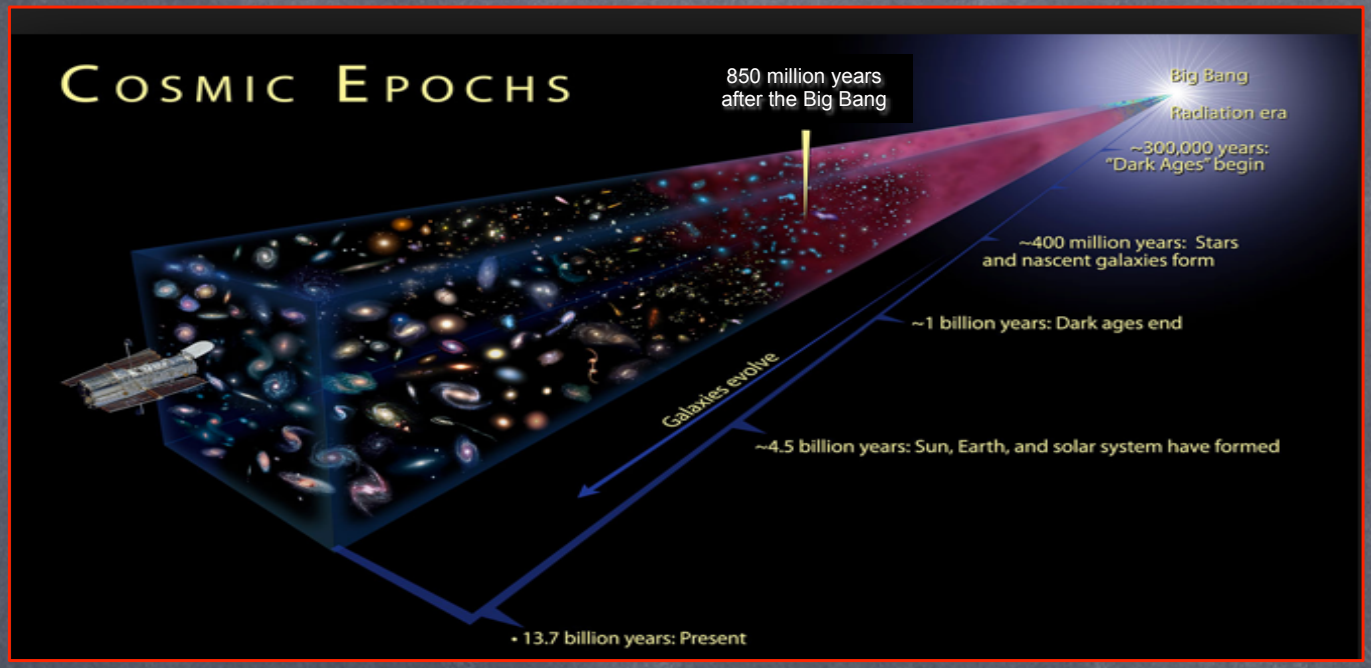
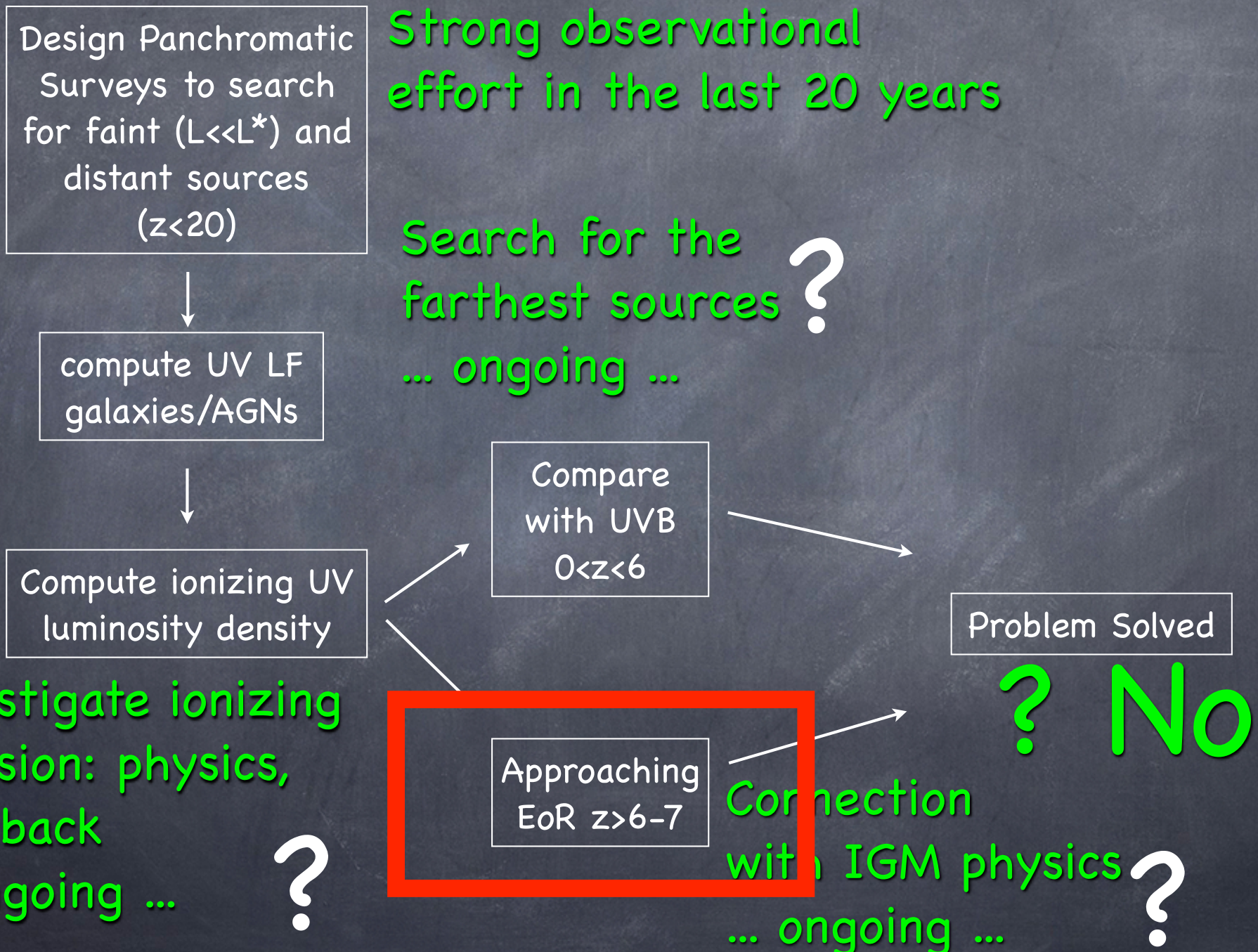


Lecture #4

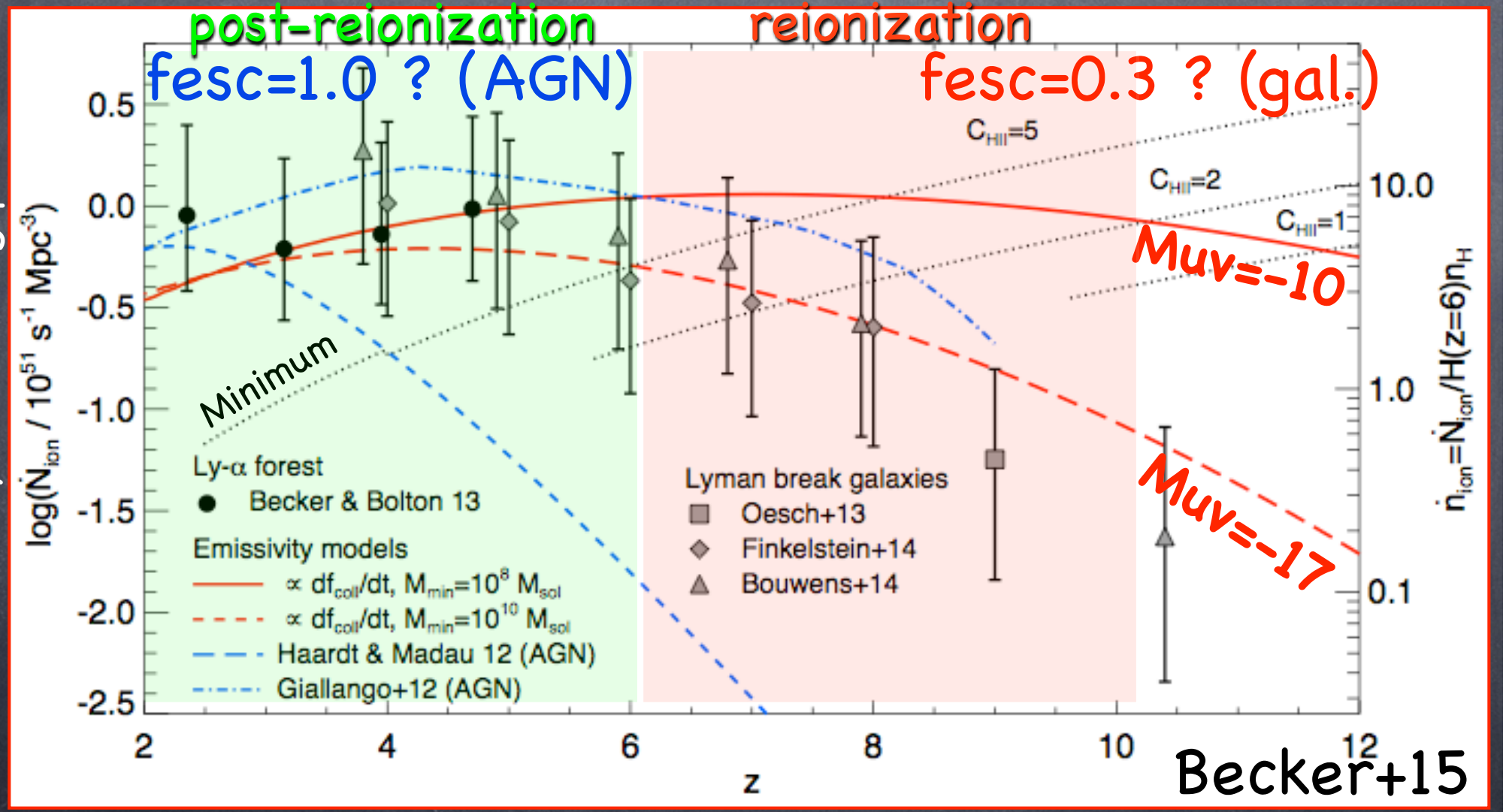
Cosmic hydrogen reionization: who, when, how ...



Who is responsible for the ionization ?

$$\phi(M_{1400}) \xrightarrow[\text{integrate; assume } M_{lim}]{} \rho_{L_{1400}} \xrightarrow[\langle N_{\gamma<912}/N_{\gamma 1400}\rangle]{} \dot{N}_{ion}^{int} \xrightarrow{f_{esc,rel}} \dot{N}_{ion}$$

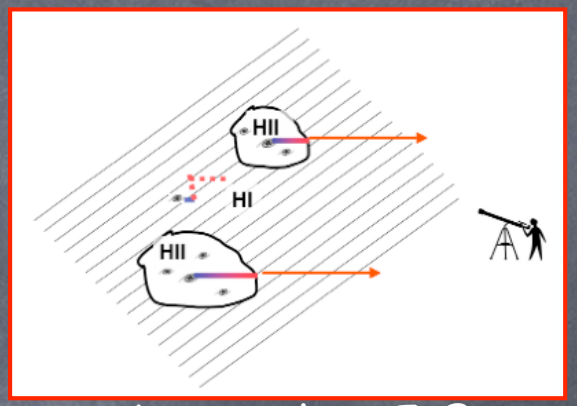
$$\frac{dQ_{H\,II}}{dt} = \dot{n}_{ion} - \frac{Q_{H\,II}}{\bar{t}_{rec}}$$



... the faint domain L<L* is relevant in this game... redshift 6-7 is also a critical epoch

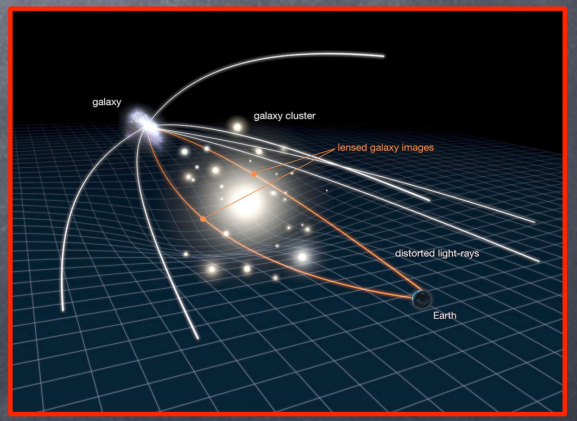
1) **Probing EoR with Lyα-emitters**
(e.g., Miralda-Escude (1998)

Neutral intergalactic gas is opaque to background Lyα emitting sources



Lya probes EoR

2) **Search for sub-L* z≈3-7 SF galaxies, the faint population**



"Cosmic telescopes"

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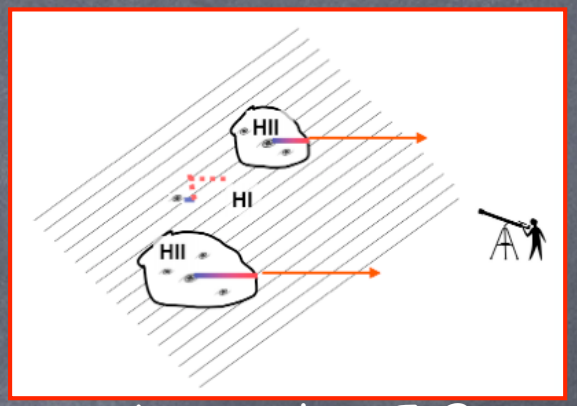
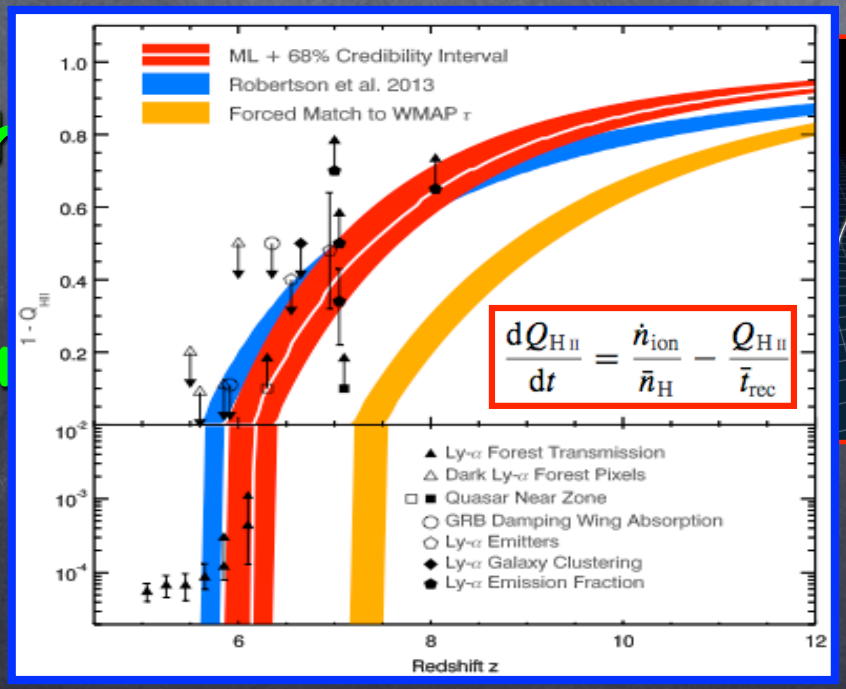


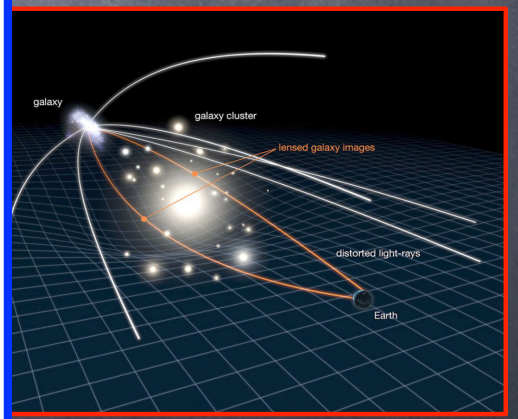
Lya probes EoR

1) **Probing EoR with Lya-emitters**

(e.g., Miralda-Escude (1998)

2) **Search**
z≈3-7
the fai

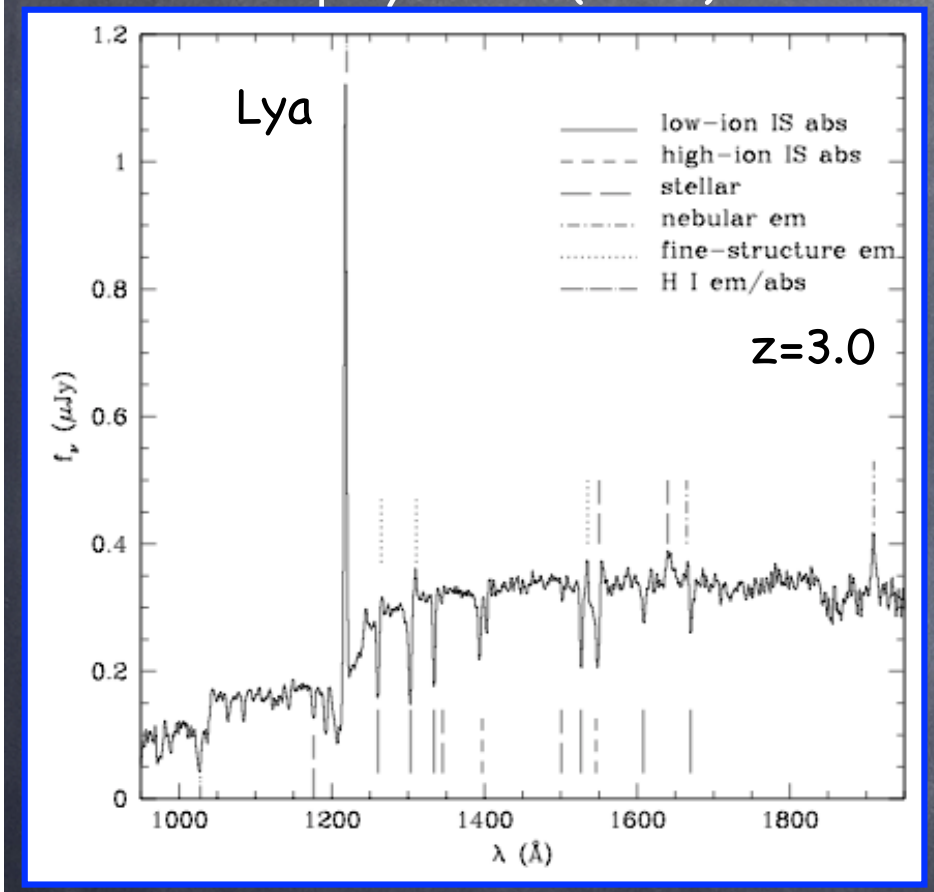




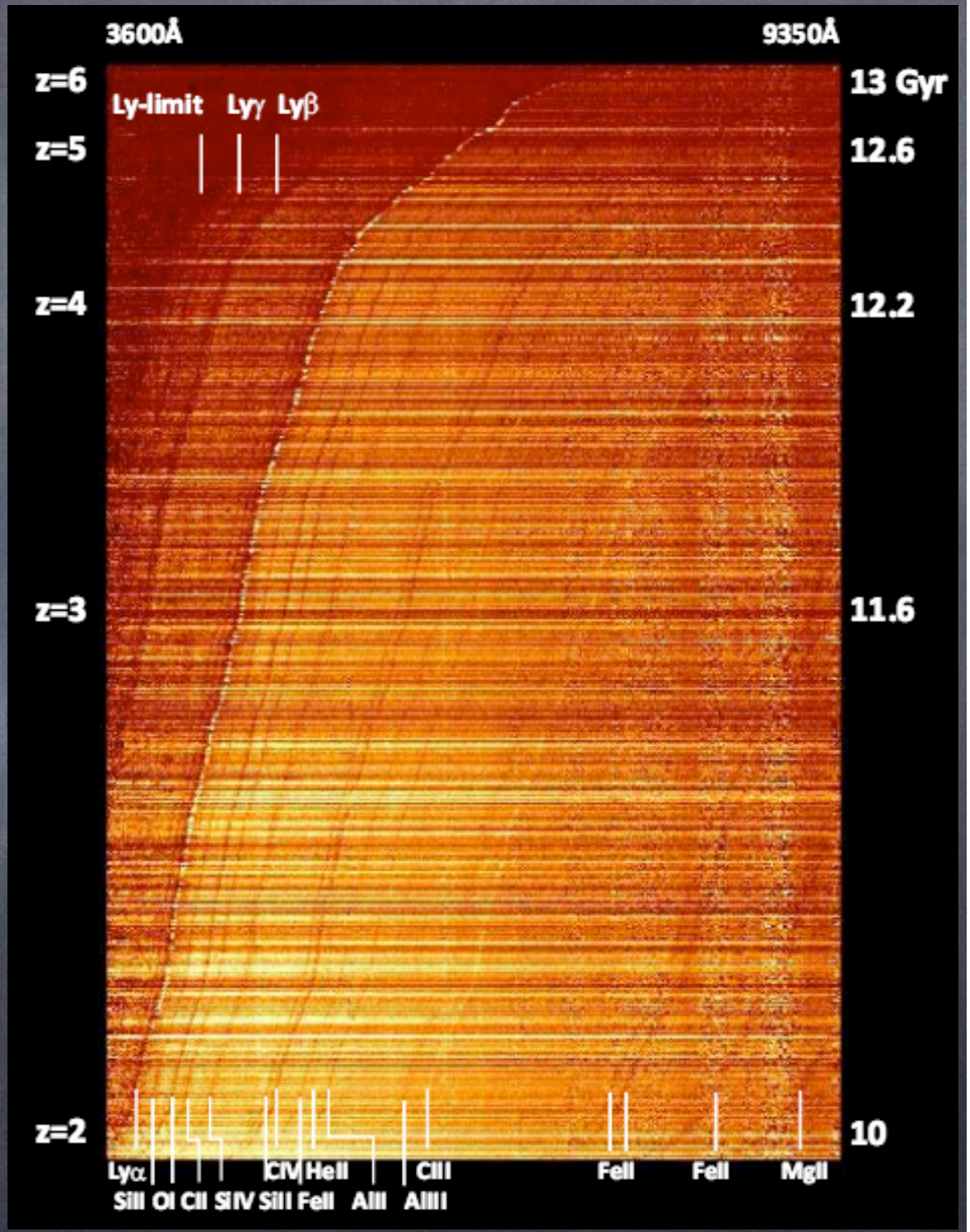
"Cosmic telescopes"

First, what do we know at 2<z<6 ?

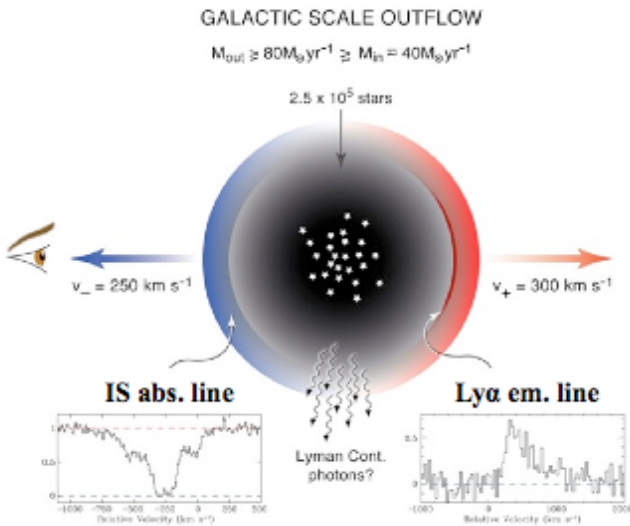
Shapley et al. (2003)



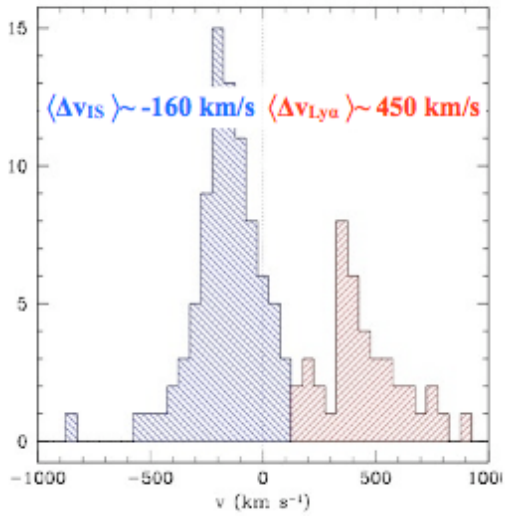
From the VUDS survey
Le Fevre et al. 2015



… remember the RT equation (Lect. #1) for Lya photons…

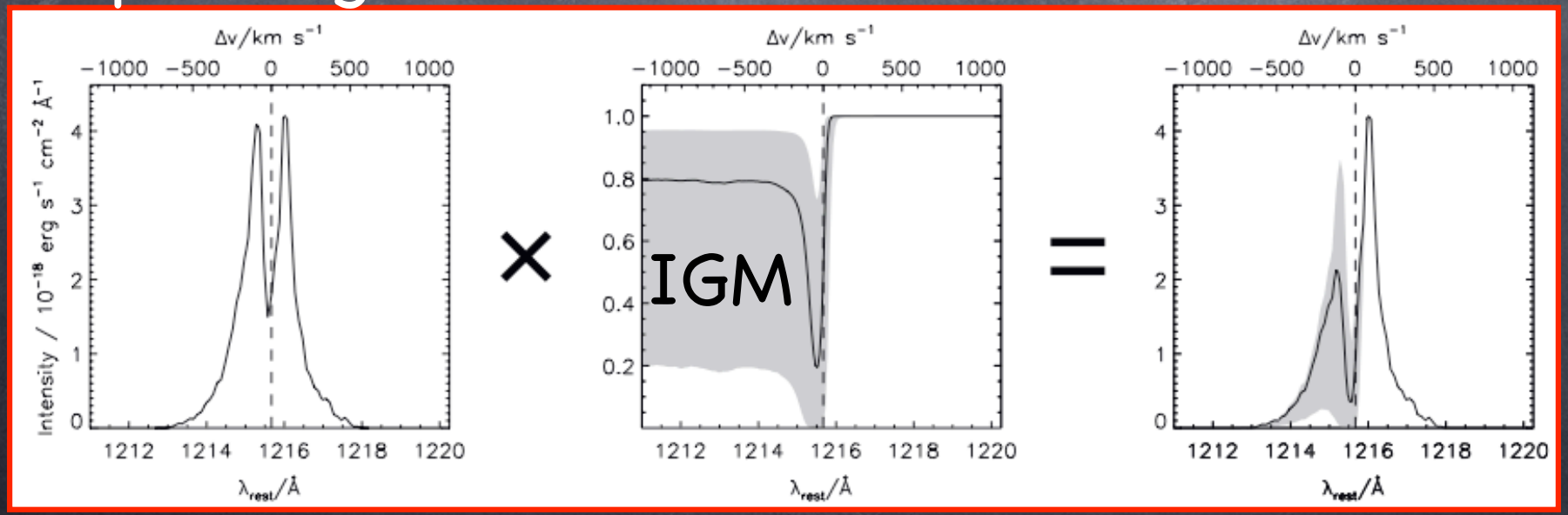


Dijkstra's review



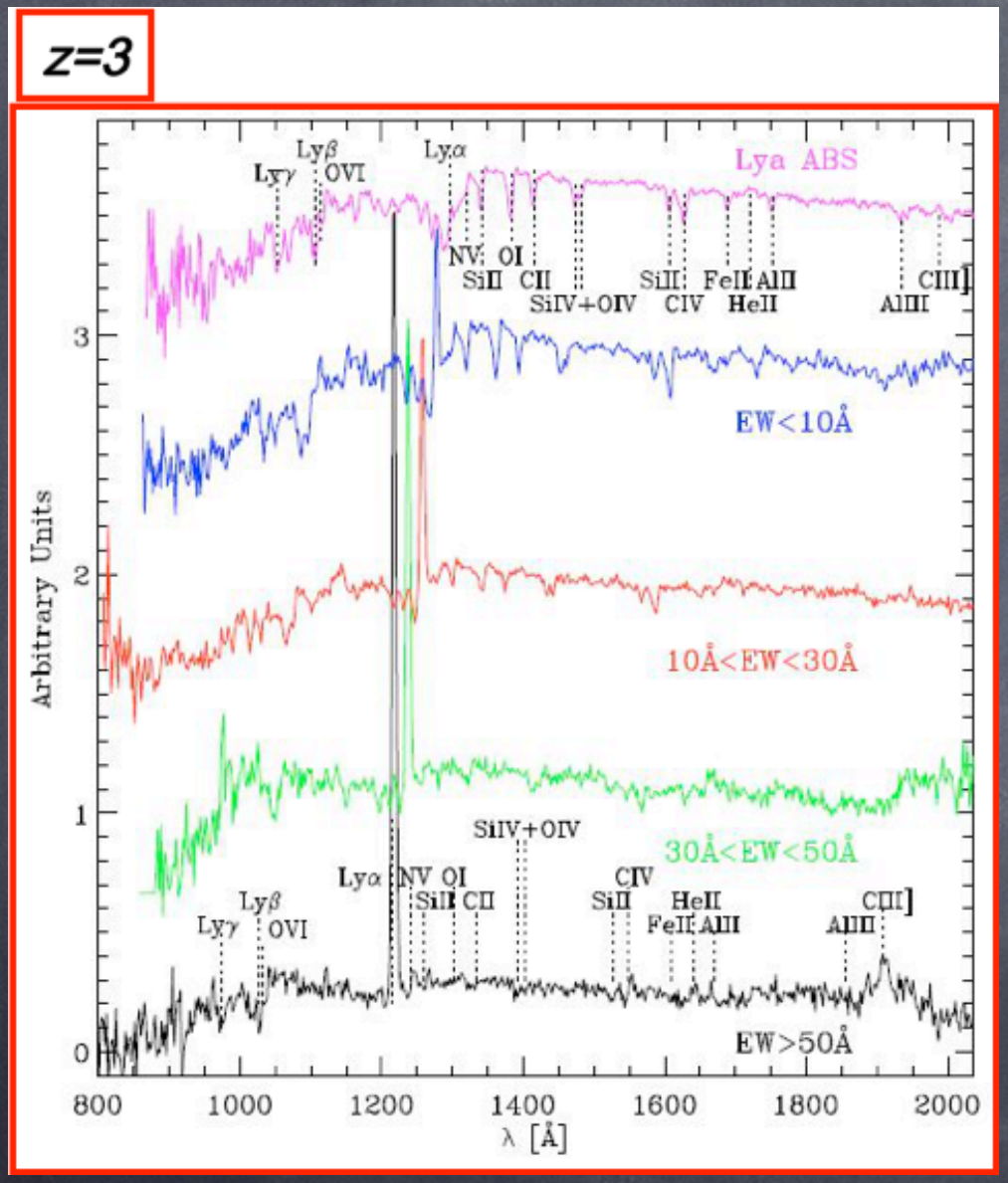
Lya photons are:
- destroyed by dust
- scattered by HI
- diffused in space and frequency

Expanding shell models + IGM:



Laursen et al. (2011)

General trends observed at z<6: Lya photons escape from "clean" ISM, i.e. low dust, not too much HI => low mass galaxies



Anti-correlation between Lya - abs. lines

Anti-correlation between Lya - UV slope

On average, Lya emission increases in young low-mass, low UV-luminous galaxies

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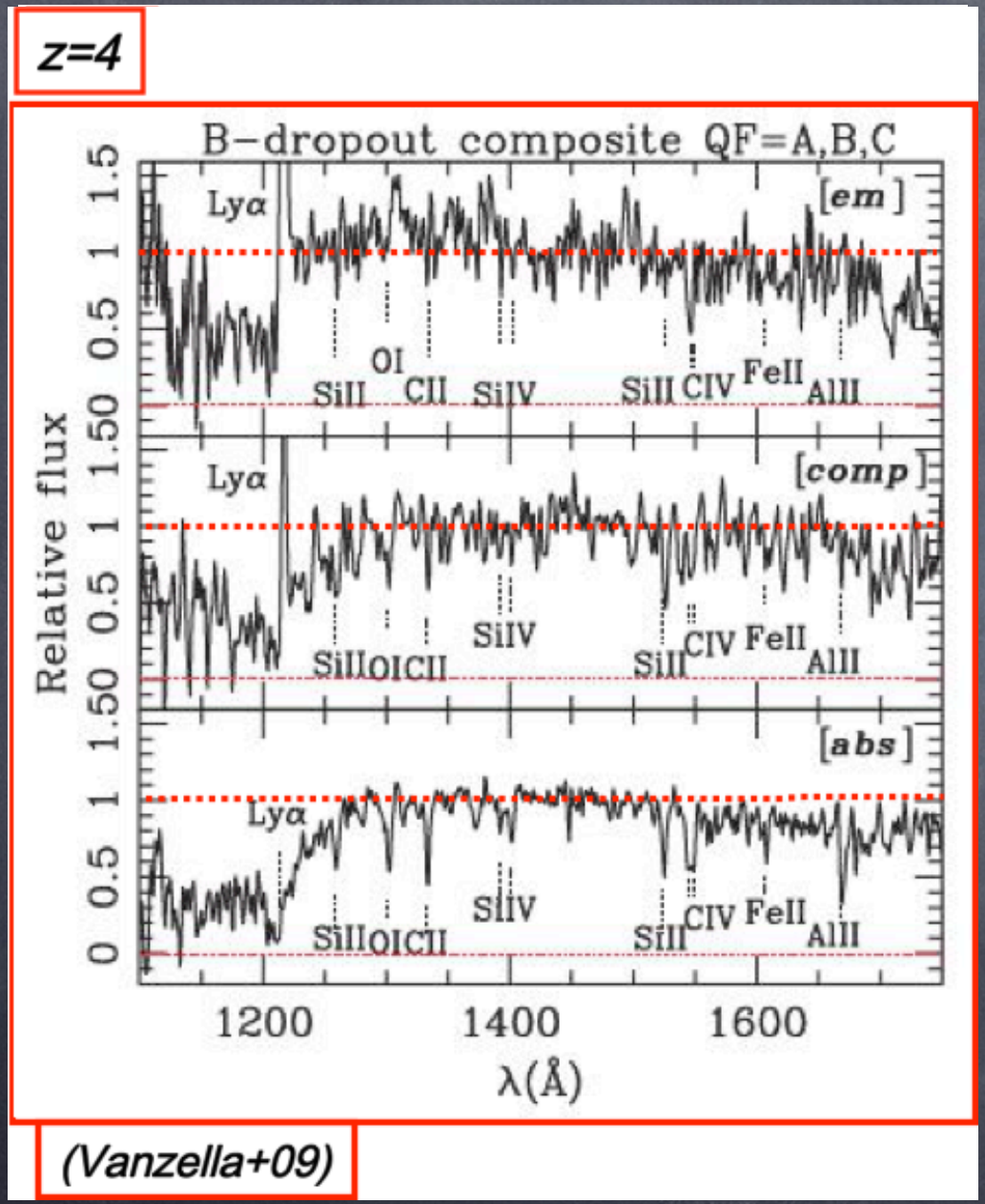

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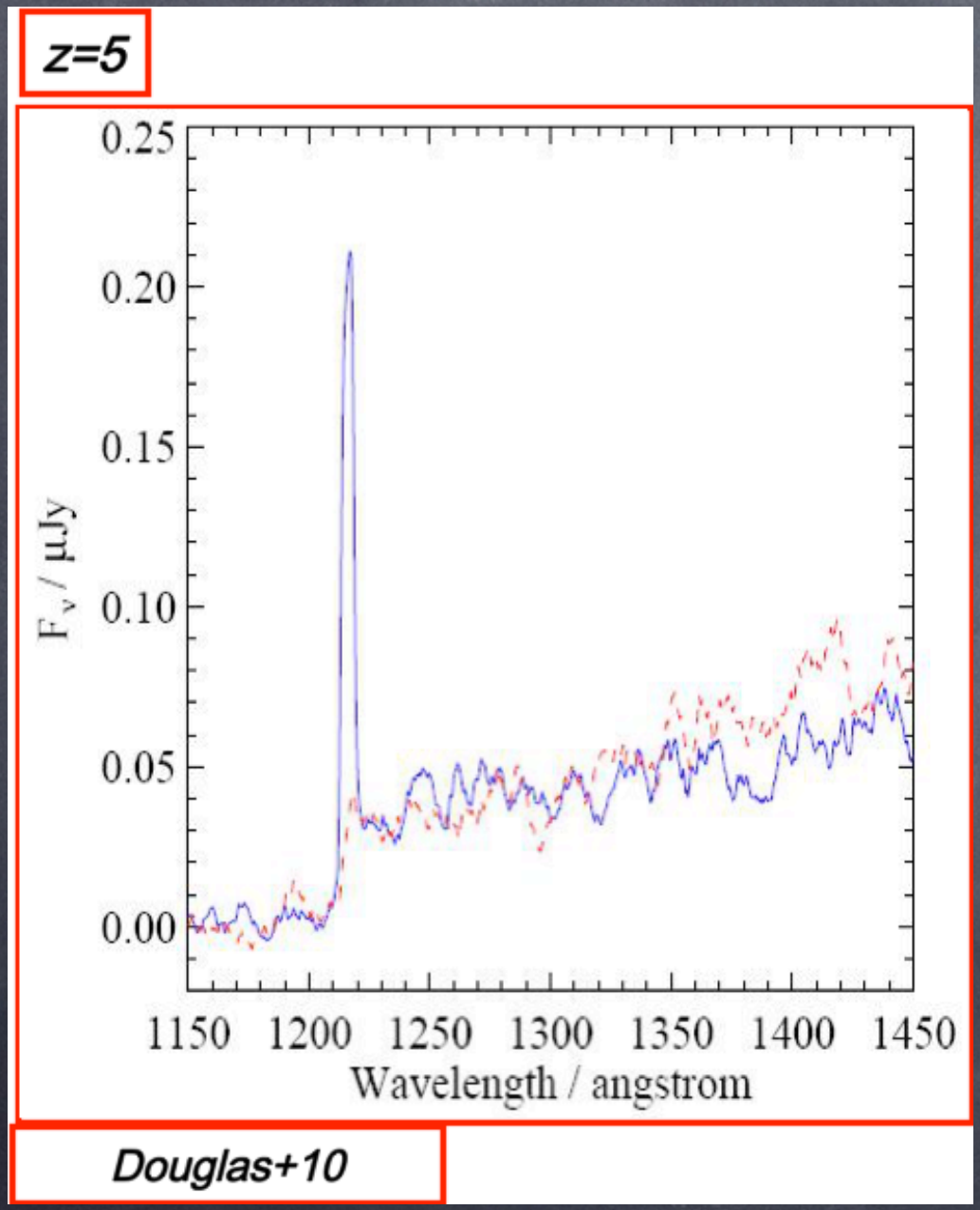

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z=6

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Anti-correlation between Lya - UV slope

On average, Lya emission increases in young low-mass, low UV-luminous galaxies

Spectroscopic search of z≃6 and 7 galaxies

VLT/FORS2 Large programme on CANDELS fields (ongoing) + data from literature

Run	Field	Total (hr)
190.A-0685(A)	UDS	15.0
190.A-0685(B)	GOODS	25.0
190.A-0685(C)	COSMOS	15.0
190.A-0685(D)	UDS	15.0
190.A-0685(E)	UDS	15.0
190.A-0685(F)	GOODS	25.0
190.A-0685(G)	COSMOS	30.0 (2x15)
		140hr

VLT/FORS2 Programme (PI Fontana)

Run	Field	Total (hr)
085.A-0844(A)	NTT	15.0 h
084.A-0951(A)	GOODS	18.0 h
085.A-0844(C)	BDF	15.0 h
088.A-0192(D)	UDS	15.0 h
		63hr

VLT/FORS2 Programme (PI Bunker) (Archive)

Run	Field	Total (hr)
088.A-0968(A)+ 088.A-1013(A)	HUDF	27.0
		27hr

The final sample

a) ≳ 200 spectra of z≃6 galaxies

b) ∿ 100 spectra of z≃7 galaxies

6-30hr integration time each object (up to **50hr**)

z=6 selection:

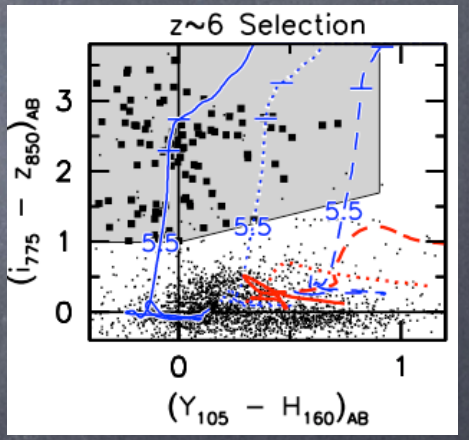
Homogeneously selected,

H-band based (H < 27.5)

[i-z > 1.0 & Y-H < 0.5]

+ non-detection optical

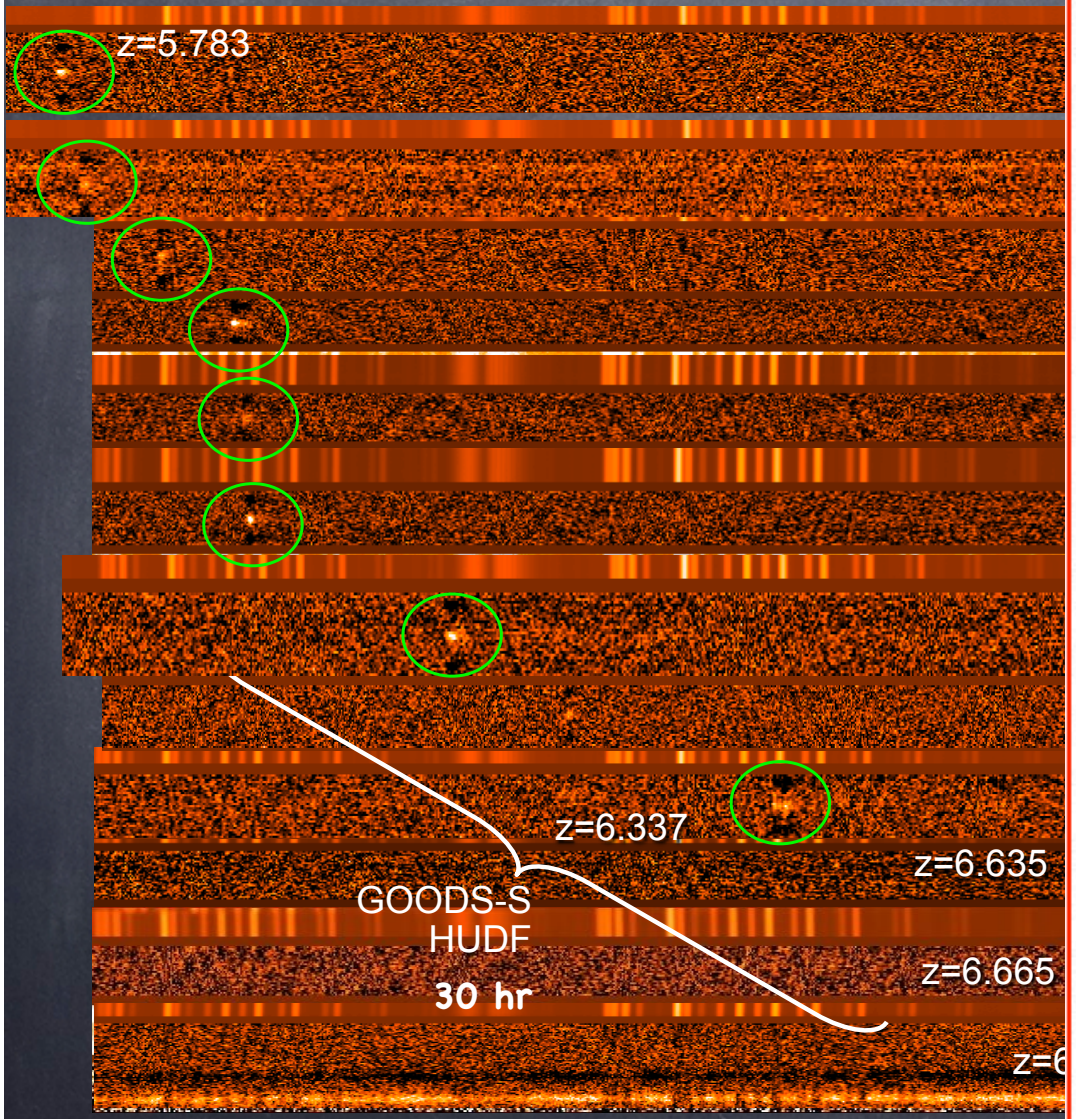
(e.g. Bouwens et al. 2014)

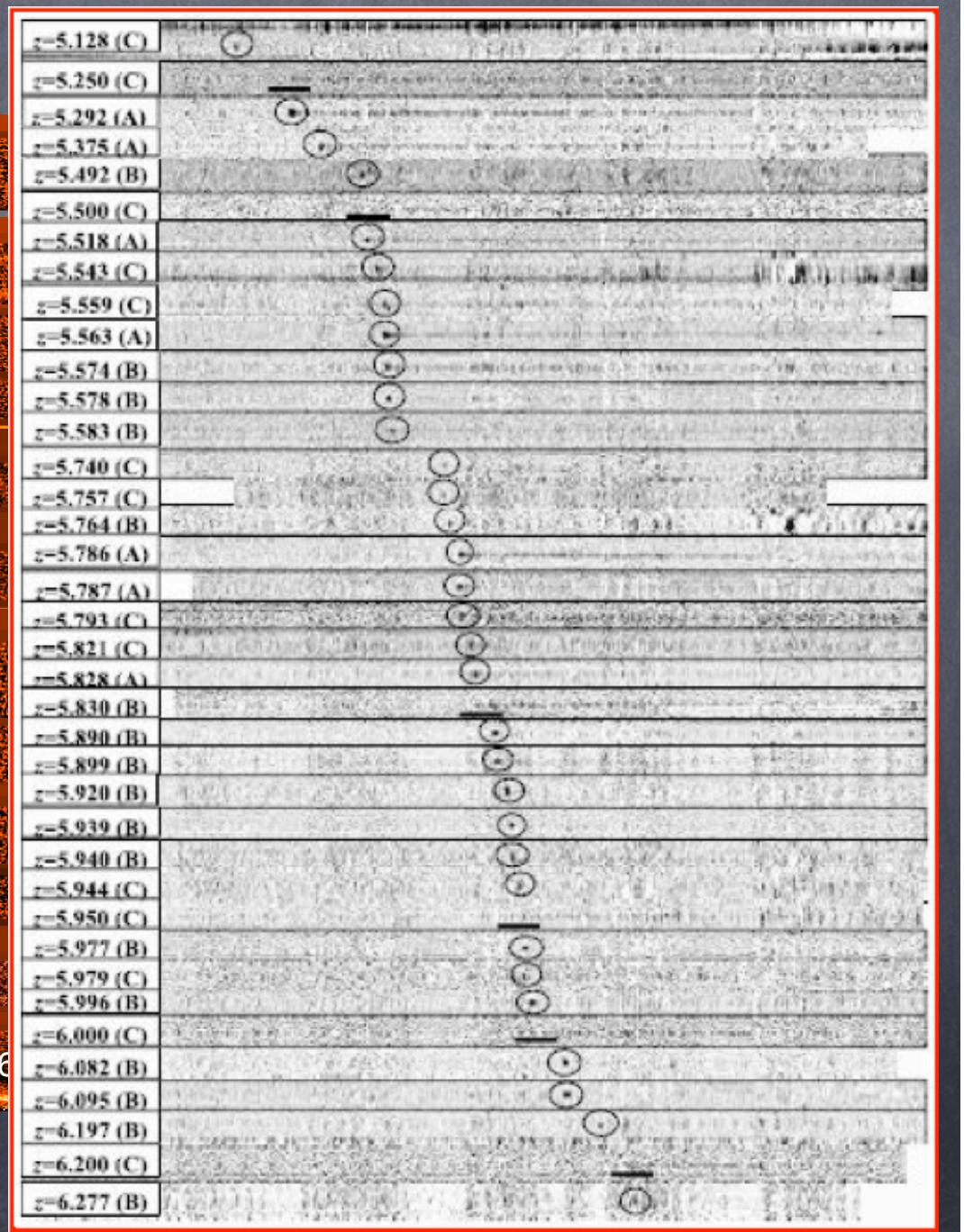


Current **z=6** sample: **150 deep spectra! Ongoing...**

Example: spectra of redshift 6 galaxies

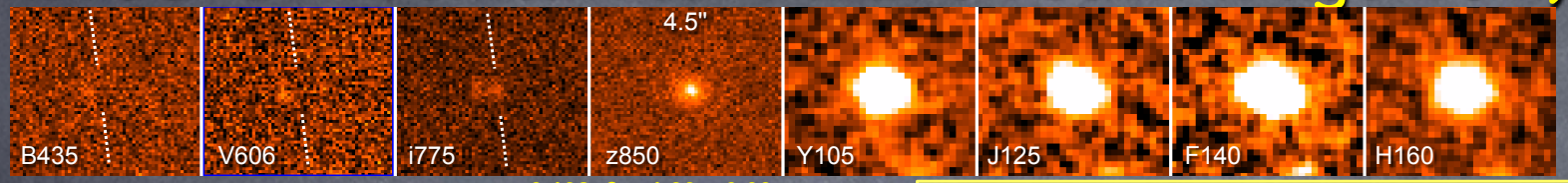
Despite the long integration time only Lya line is detected ...





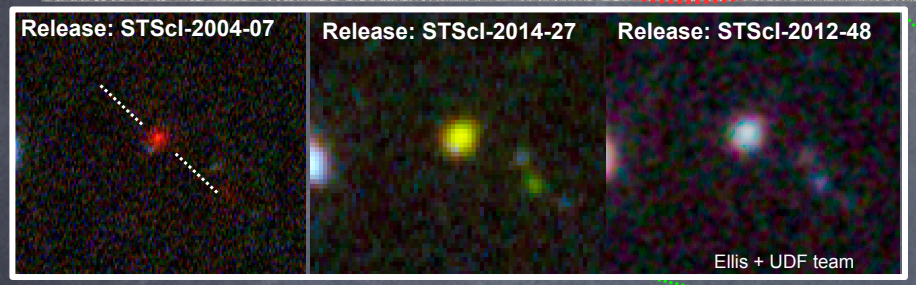
Deep spectroscopy reveals faint z≃6 **non**-Lya emitters (I)

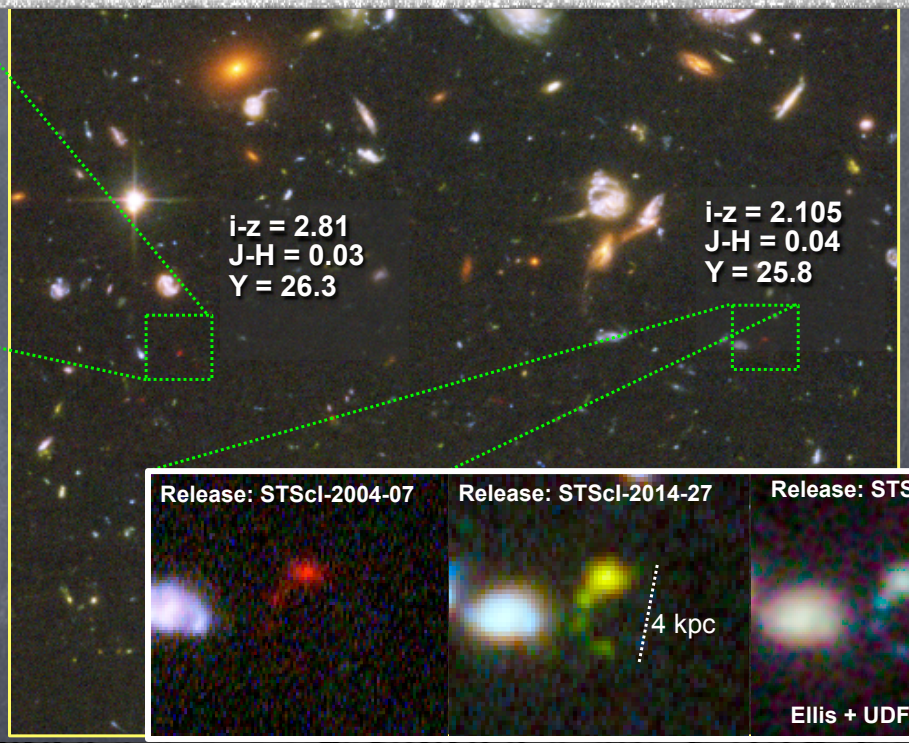
(m1500≃26 remember UV LFs reach mags 30...)

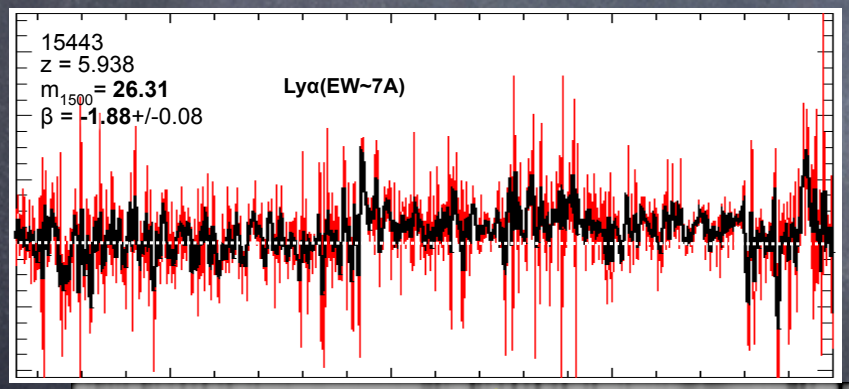


z =6.108, β= -1.99 ± 0.09

(30hr VLT/FORS2)
EW(Lya)=9A



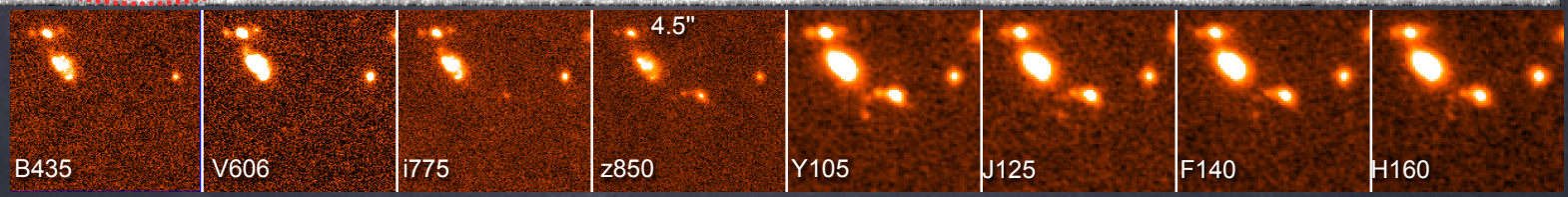




z =5.938, β=-1.88 ± 0.08

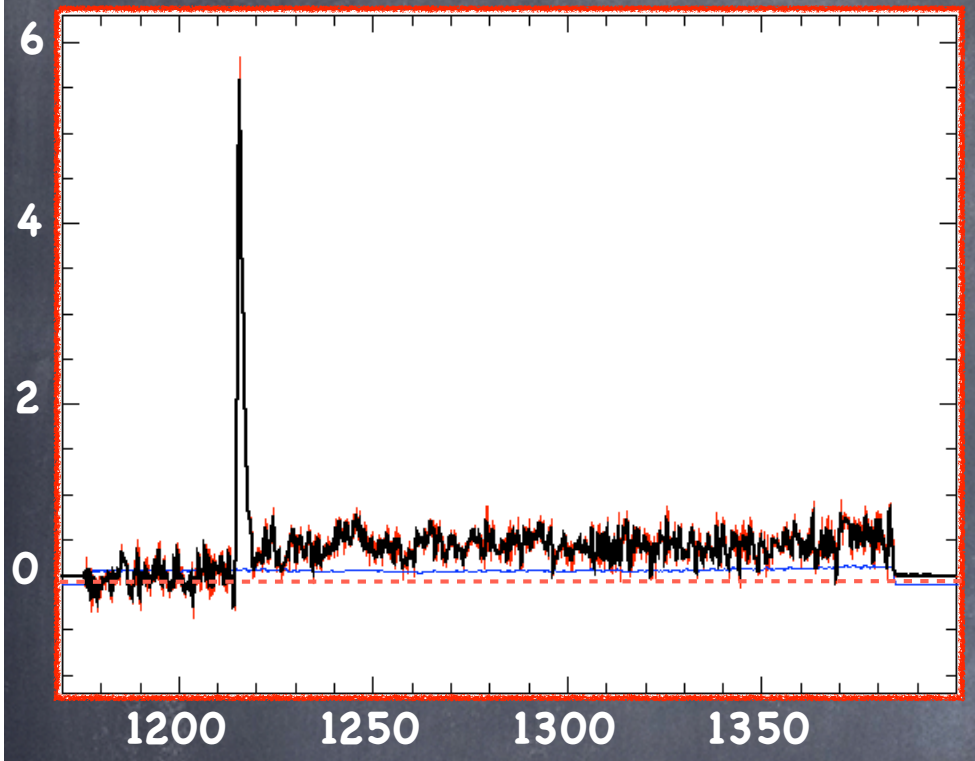
EW(Lya)=7A

(30hr VLT/FORS2)



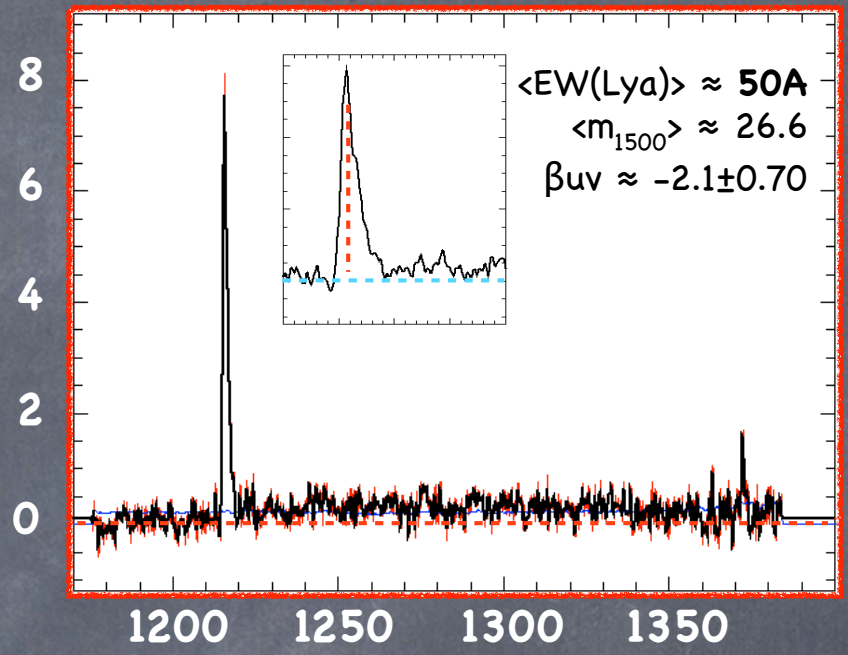
As for z~3-4 we are trying to stack and look at spectral shape...

740hr VLT/FORS full sample (good z)



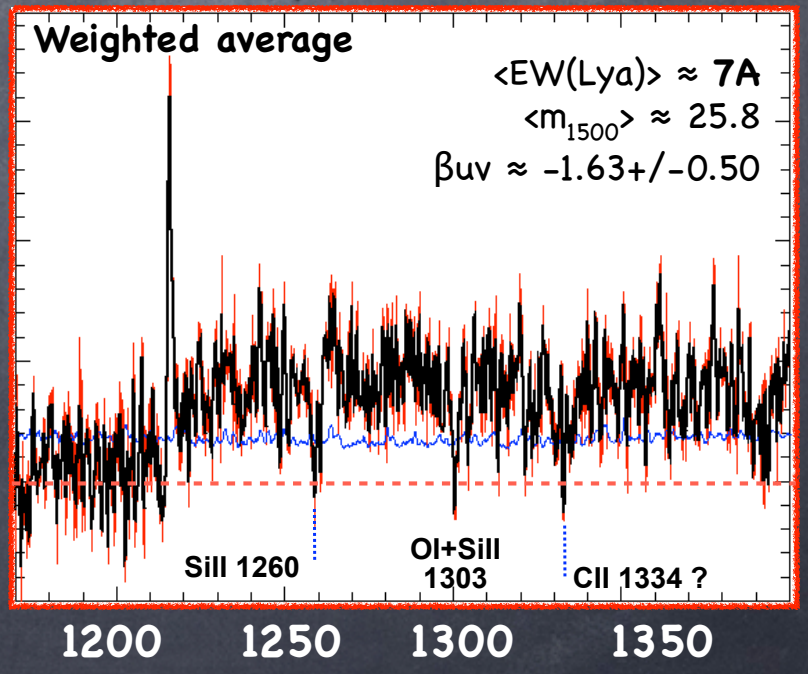
EW(Lya)>20A

(400 hr) EW(Lya)>20A



EW(Lya)<20A

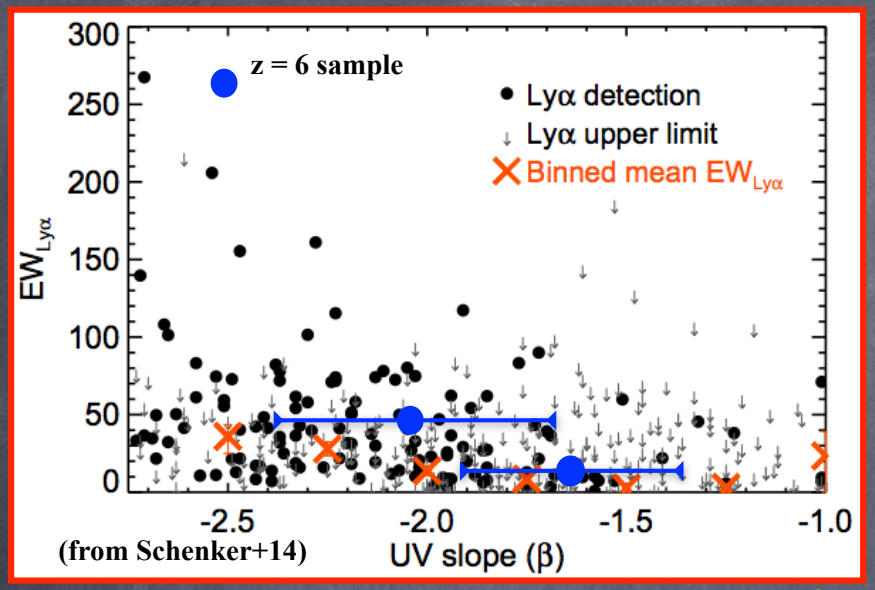
(200 hr) EW(Lya)<20A



Measure redshift for faint (mag≈26) z≈6 non-LAEs:

1) first time, not trivial,
   ~ half of the LBG population
2) perform stacking, study properties:
   → UV slope, ISM lines, size ...
   similar to lower-z (Shapley+03; Vanzella+09)
3) better characterization of the Lya demography,
   comparison with the occurrence at z>6.5 → EoR

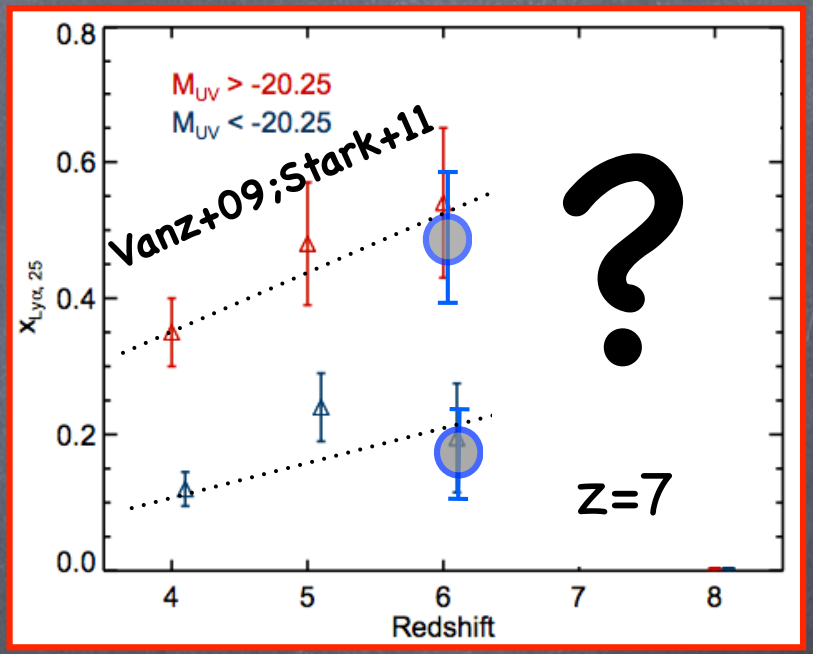
Fraction of Lya lines at z≃6 and UV slope dependency

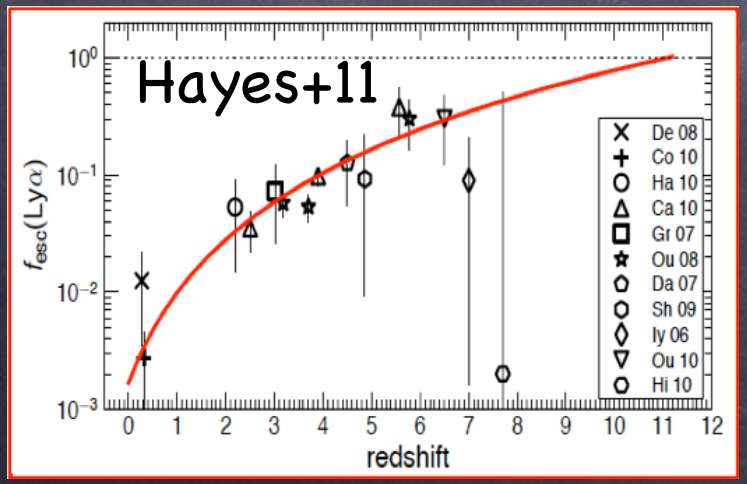


UV slope derived from multi-band fitting, best quality spec., possible separation between emitters and non-emitters, as already observed at lower-z (z~3-5)

$(F_\lambda = \lambda^\beta)$

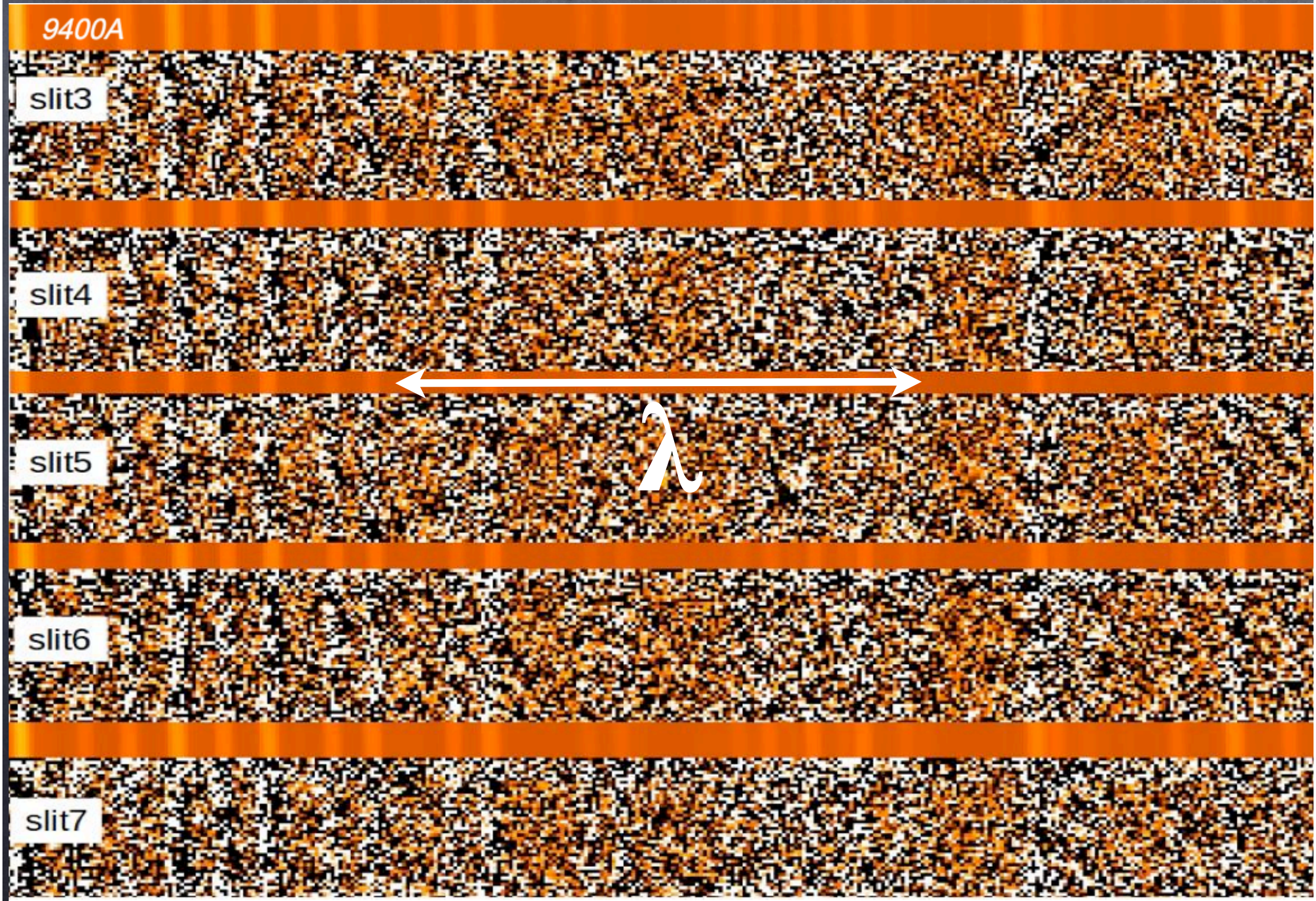
EW(Lya)>25A (EWlim<25A)



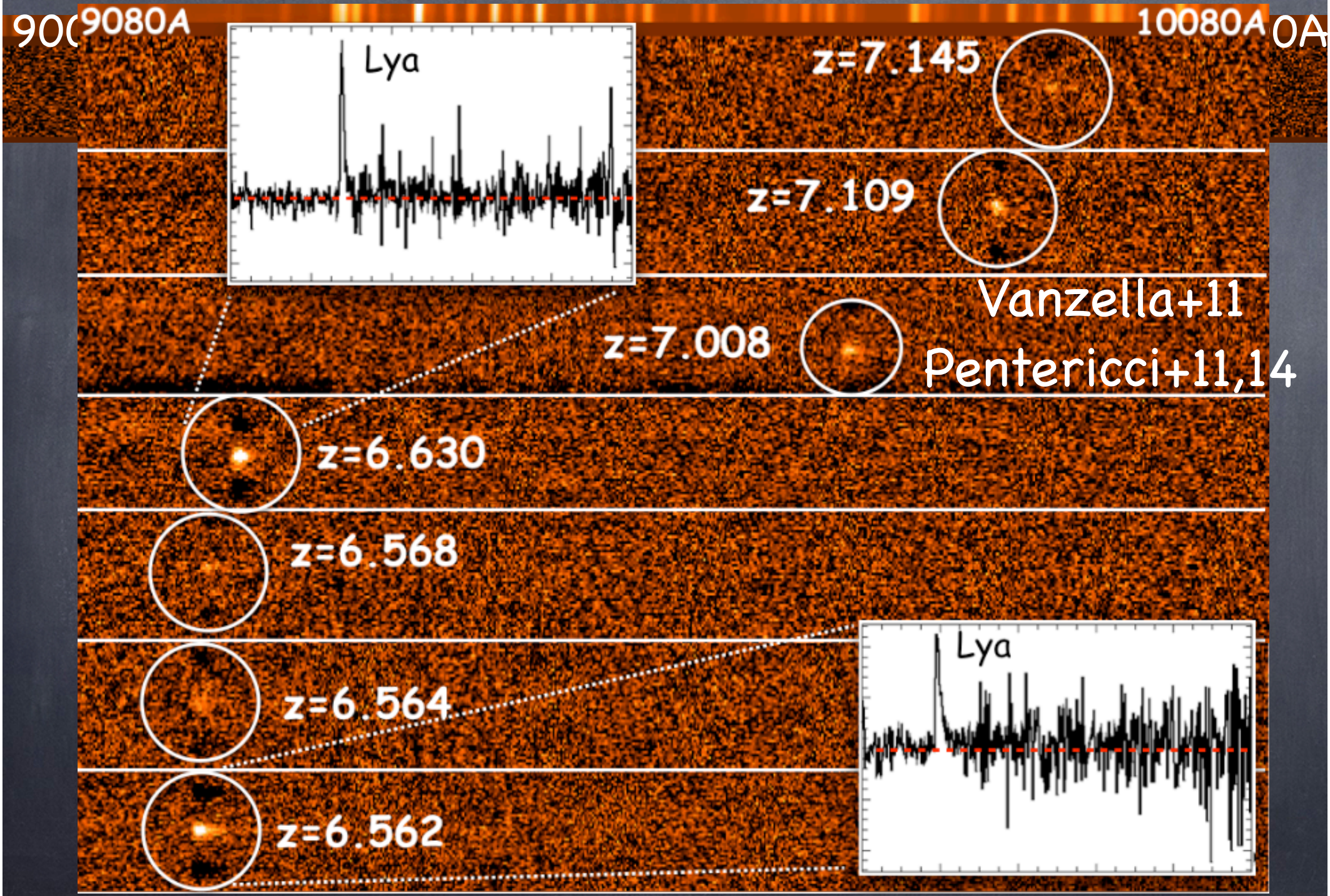


146 with spectrum: z>5.5 or no-z (current+previous surveys)
130 H-band detected, match color criterium (i-z>1 & J-H<0.5)
95 have observed EW limit <25A (3-sigma)
➜ 37 Muv>-20.25 49% with EW(Lya)>25A
➜ 58 Muv<-20.25 15% with EW(Lya)>25A

It was difficult !! Require careful redution..

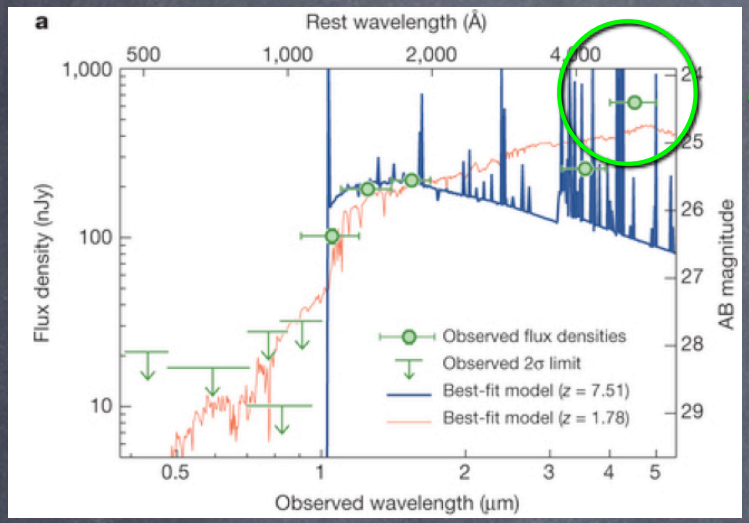


... z>6.5, if Lya is present ... (15 - 20 hr integration)



The most distant spectroscopically confirmed galaxies detected through Lya, but faint line...

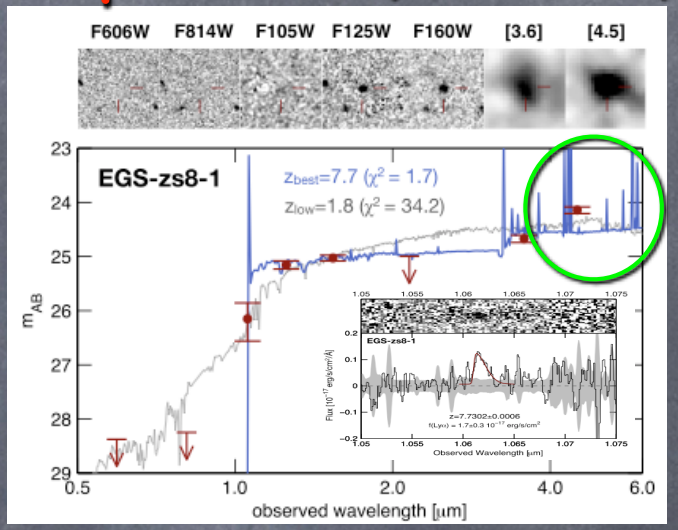
zspec=7.51 (Finkelstein+13)



1 out of 40 observed

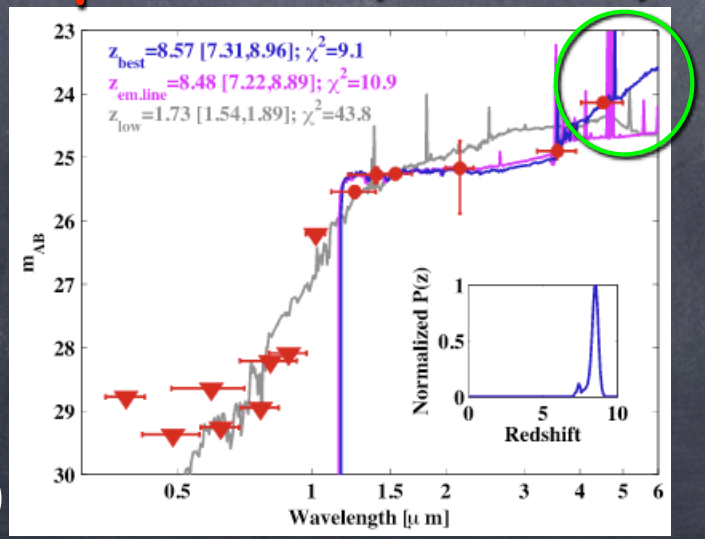
EW([OIII]+Hb) ~ 600A

zspec=7.73 (Oesch+15)



EW([OIII]+Hb) ~ 720A

zspec=8.68 (Zitrin+15)



large EW([OIII]+Hb)

there are also many unsuccessful observations (no z) ...

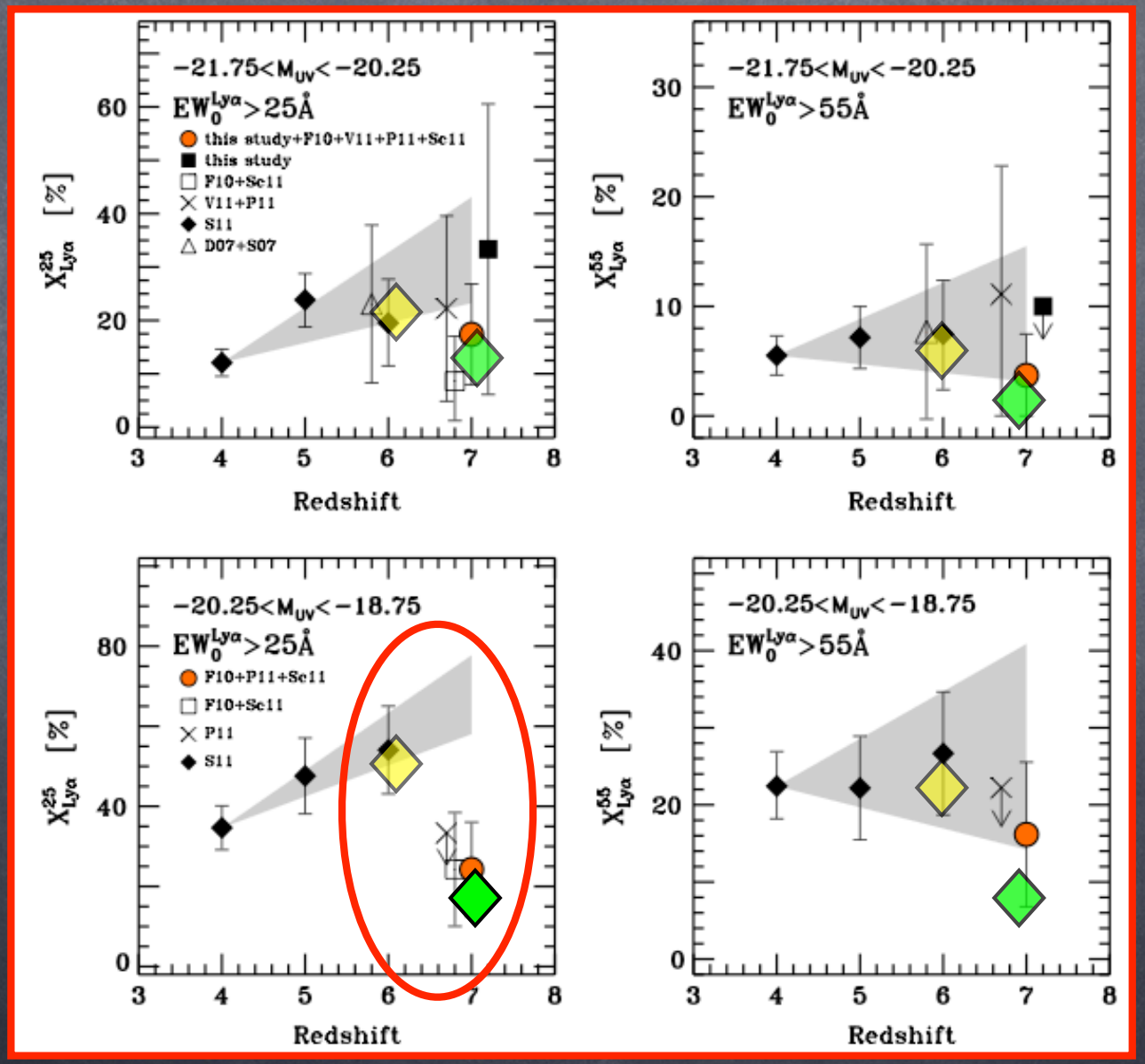
… Suppressed Lyα Flux from Galaxies at z>6 : Lyα Fraction

120 z-band and 180 i-band dropout analyzed in 5 independent fields (BDF, NTT, COSMOS, UDS, GOODS) + data from other groups

- New z~7 limit Pentericci 2015 in prep.
- New z~6 fract. Vanzella 2015 in prep.

See also:
Ono+12; Shenker+14
Finkelstein+14,
Caruana+14 …

Same signature found in LAEs:
Ouchi+10
Kashikawa+11
Ota+11



EW(Lya)>25A EW(Lya)>55A

Muv bright

Muv faint

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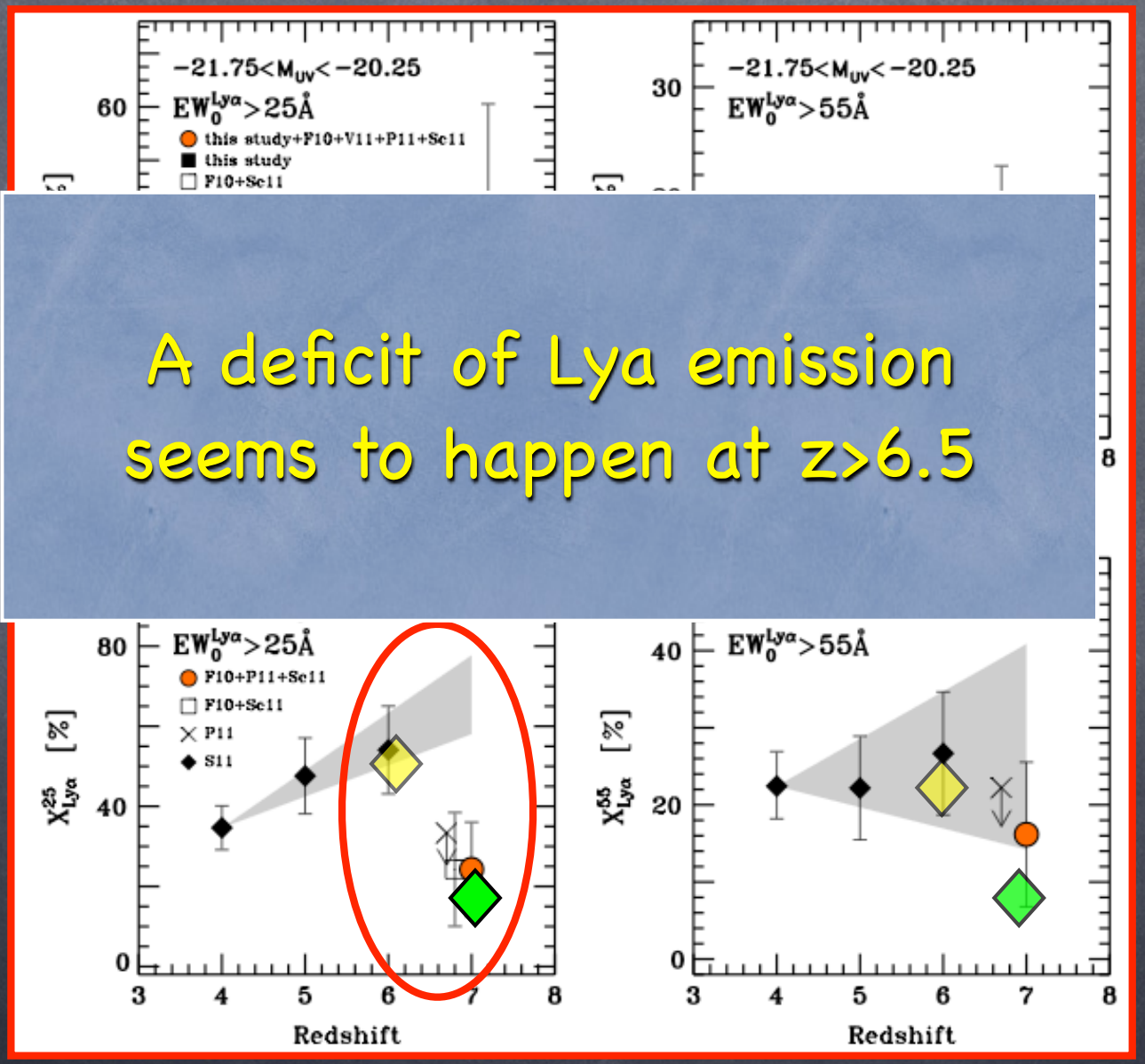


A deficit of Lya emission seems to happen at z>6.5

Muv bright

Muv faint

EW(Lya)>25A

EW(Lya)>55A

What does it mean ... ?

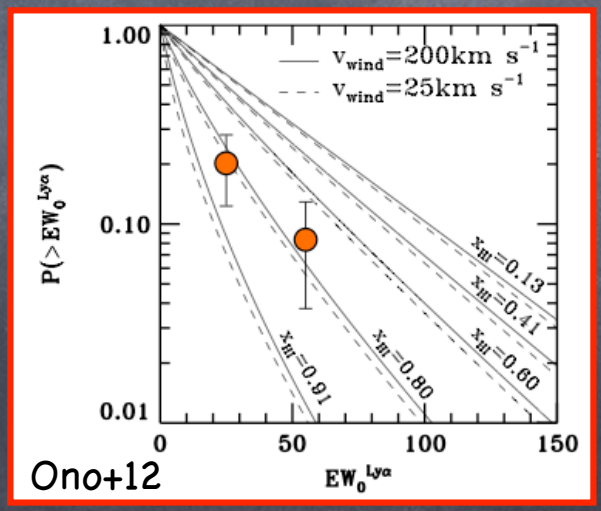
- A significant fraction (> 60-70%) of selected galaxies is not at z≈7; however,
  1. other line/feature are not detected in almost all cases
  2. The LBG technique works very well at z=6 with <20% interlopers

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

- There is an increase in the Lyman Continuum escape fraction (Dijkstra+14)

$$L_{\alpha,\mathrm{obs}} \propto \dot{N}_{\mathrm{ion}}(1 - f_{\mathrm{esc}}) f_{\mathrm{esc}}^{\mathrm{Ly}\alpha} \mathcal{T}_{\mathrm{IGM}}$$

- There is an increase in the amount of neutral Hydrogen in the surrounding IGM that quenches => EoR



X_{HI} = 0.5 @ z=7 IF X_{HI} = 0.0 @ z=6

Theoretically (very) difficult to achieve:

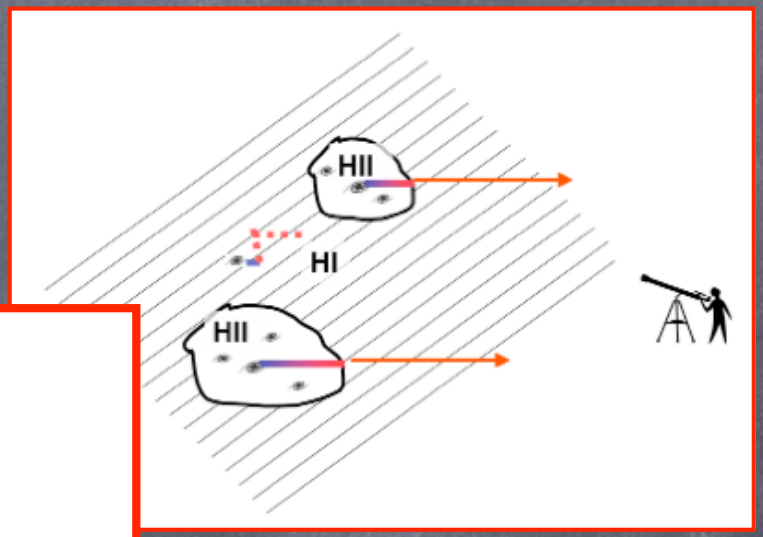
- still observational uncertainties
- evolving fesc (Dijkstra, X_{HI} = 0.2 @ z=7)
- self-shielding absorbers inside ionized bubbles (Bolton & Haehnelt 2013)

... are we entering the EoR ?

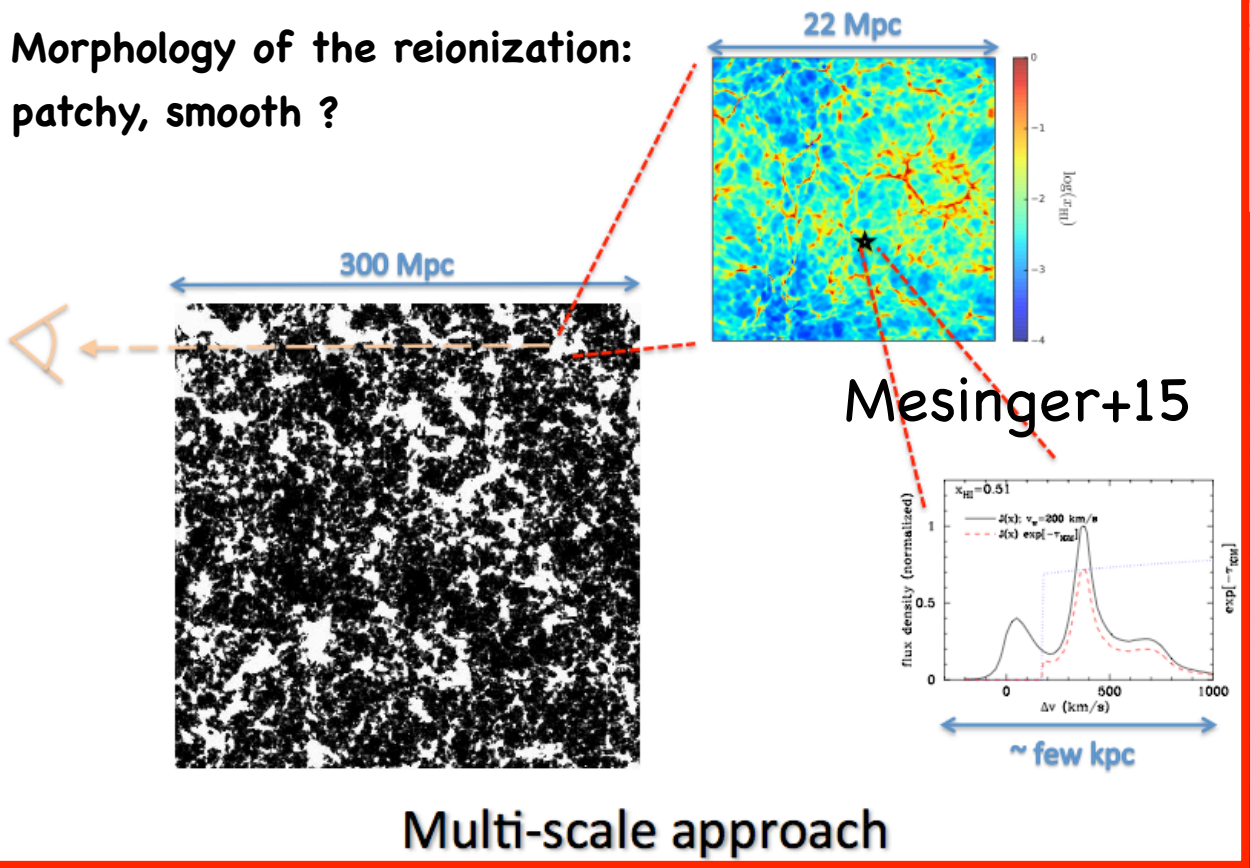
Lya demography suggests EoR > 6-7

This is consistent with the GP through (IGM), EoR > 6.5 (Lecture #1)

Deficit of Lya lines seems fully consistent, though we need (too?) rapid decreases of Q_{HII}



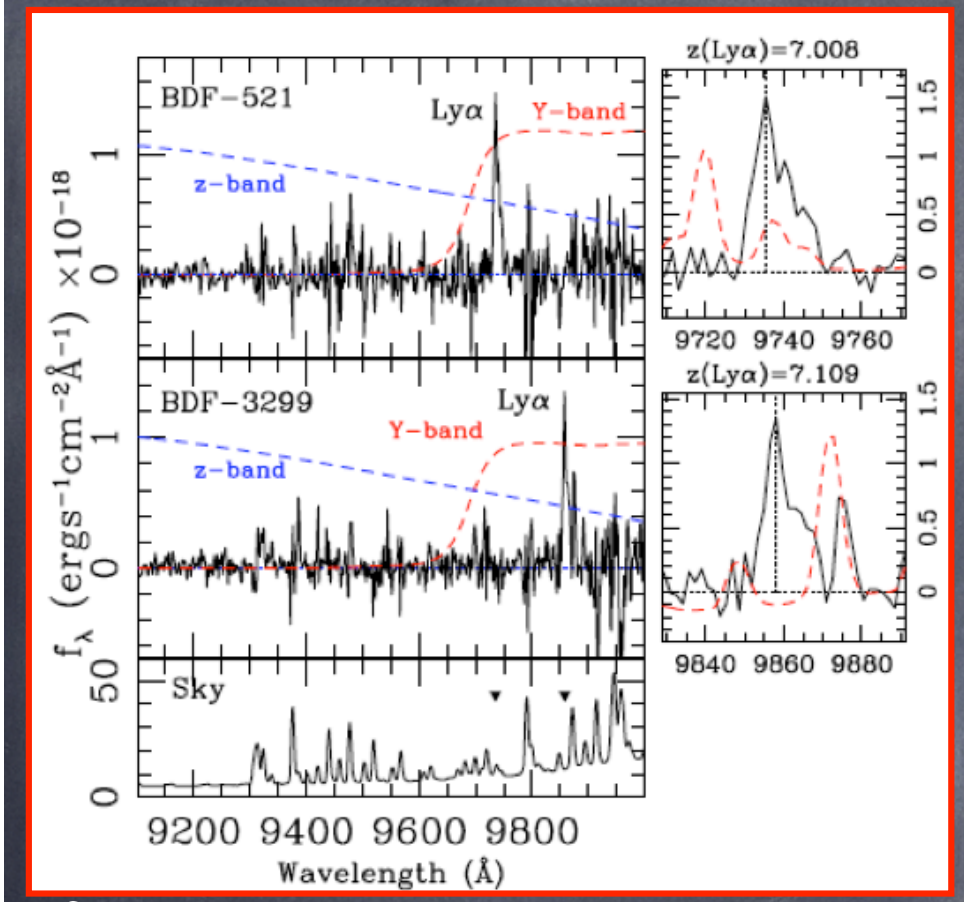
Morphology of the reionization: patchy, smooth ?

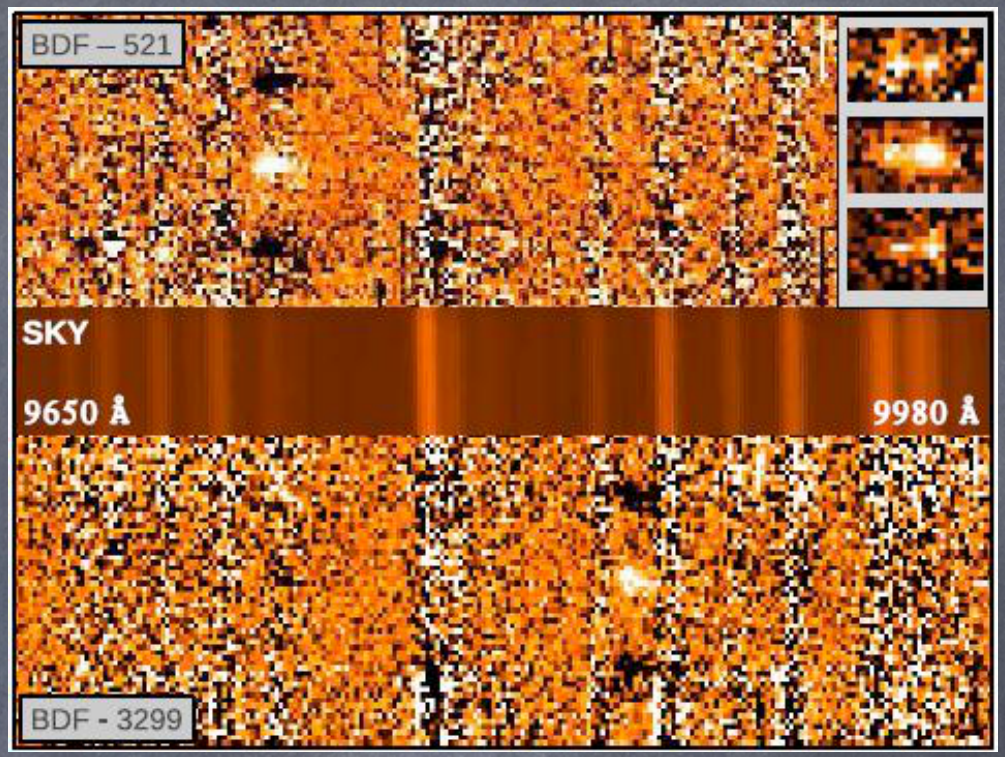


Occurrence and spatial distribution of Lya emitters can tell us something about topology of reionization
Inside-out / Outside-in
smooth/pathcy
(Choudhury+08)

An overdensity at redshift 7 ?? Pathcy reionization ?

The highest-z galaxies with the highest EW(Lya)





Separated by 4.4 Mpc only

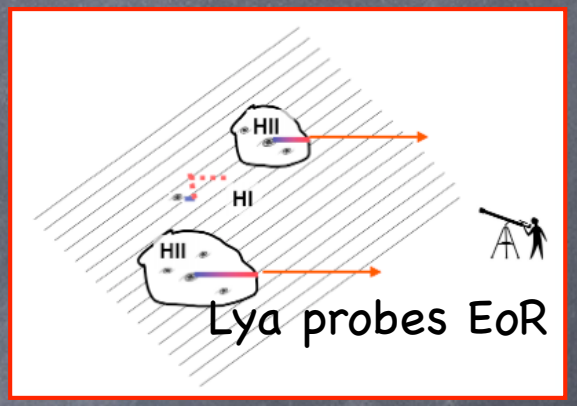
If we assume they are surrounded by a neutral IGM, the visibility of the Lya cannot be explained even assuming **fesc=1** for both...

Are there faint galaxies clustered around that are boosting the HII zone and the Lya visibility ? (=> fesc > 0)

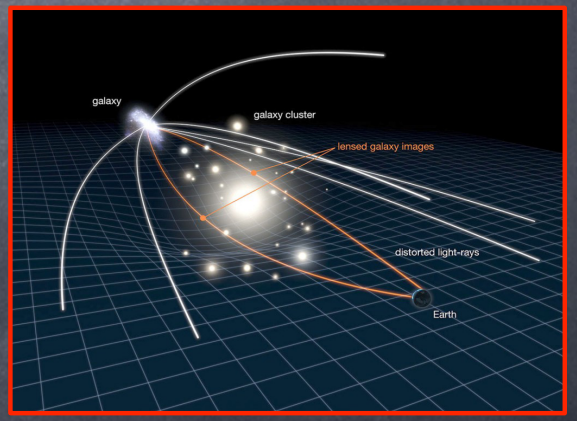
The farthest and faintest sources (outline)

1) **Probing EoR with Lyα-emitters**
(e.g., Miralda-Escude (1998)

Neutral intergalactic gas is opaque to background Lyα emitting sources



2) **Search for faint (L<0.1L*)**
z≈6-7 SF galaxies, ionizers ?

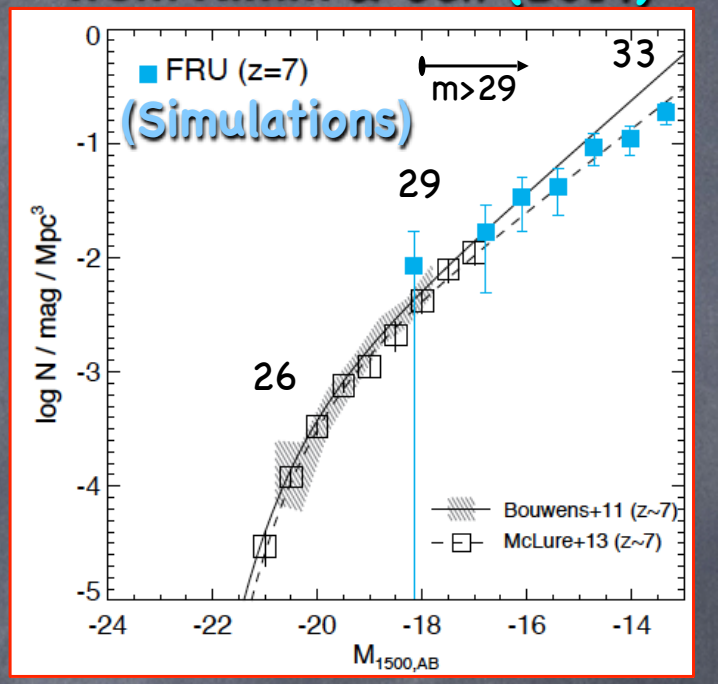


(Re)Ionizing sources may live in a fainter luminosity regime

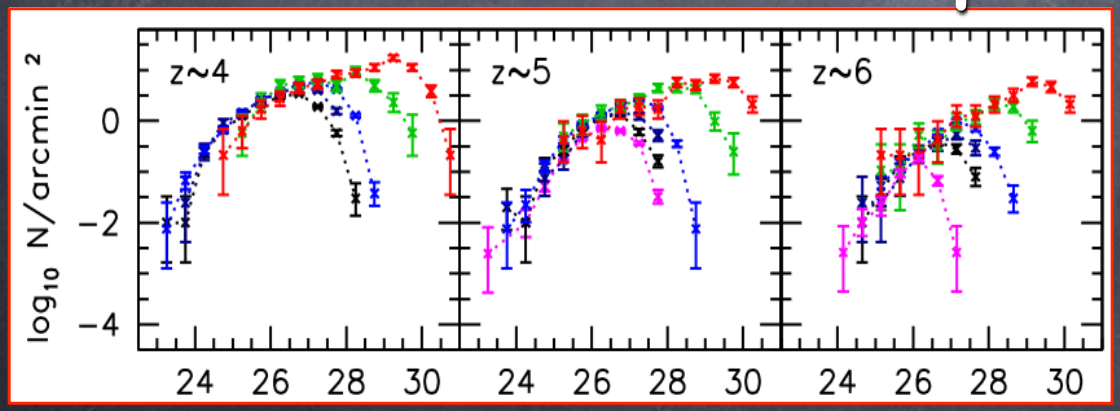
Simulations

Faint star-forming galaxies (L<<L*, Mh<10^9 $M_\odot$) could play a major role in the reionization:
(Muv ~ -18 ... -10) → m1500 ~ 28 - 36) fesc >10-50%
[e.g., Wise+14; Kimm&Cen+14]

from Kimm & Cen (2014)



Observations in the deepest fields - HUDF

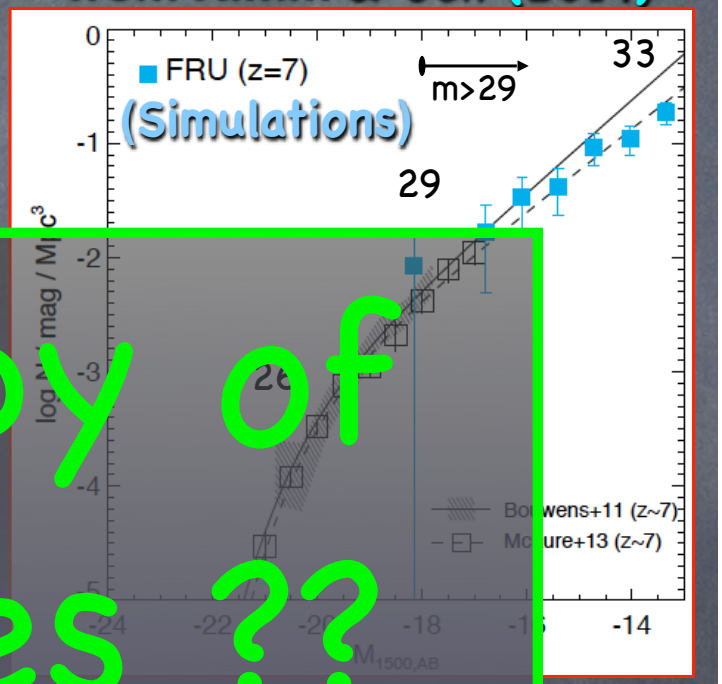


Bouwens et al. (2015)

(Re)Ionizing sources may live in a fainter luminosity regime

Simulations

from Kimm & Cen (2014)



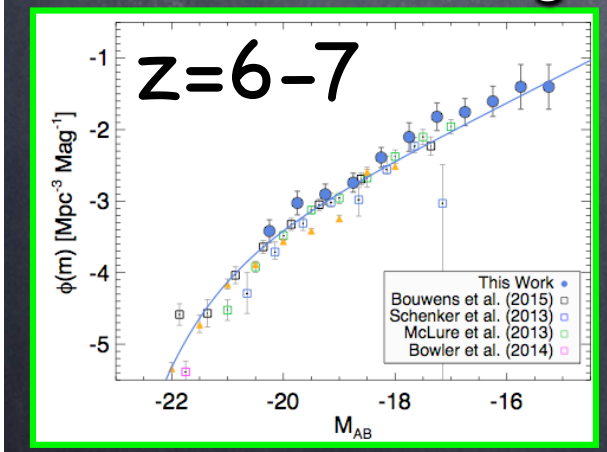
Faint star-forming galaxies (L<<L*, Mh<10^9 $M_\odot$) are probably playing a major role in the reionization:

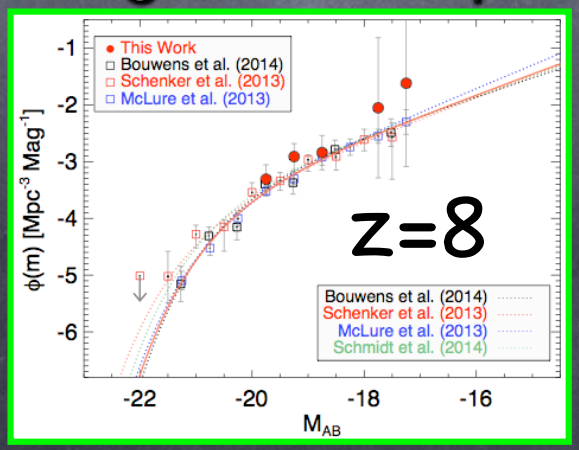
(Muv ~ -18 ... -10 → Mh~10^8 ~ 28 - 36) es >10-50%

[e.g., Wise+14; Kimm&Cen+14]

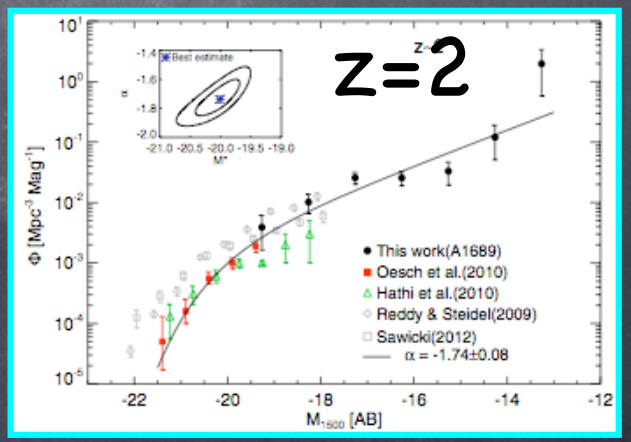
Spectroscopy of faint sources ??

Gain from strong lensing (M*) ... Epoch





Atek et al. (2015)



Alavi et al. 2014 (A1689)

… spectroscopically confirmed faint z>6 galaxies… the deepest spectroscopic observations

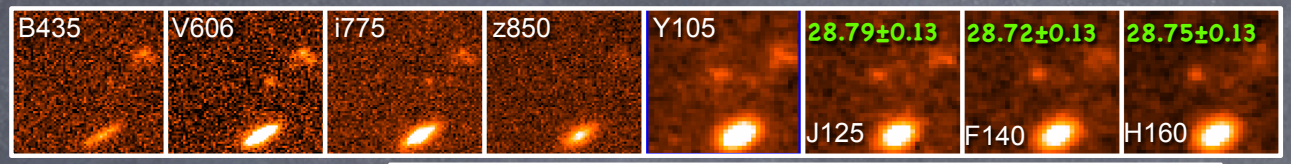
Brute force: VLT/FORS 30hr

HUDF

z=6.635

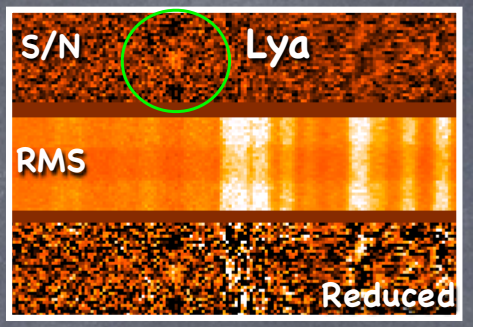
Mabs = -18

m(Y,J,H) S/N≈7



Wilkins/Bunker+11, McLure+11 (HUDF2701) zphot=6.66 [6.35-6.91], β=-3.3+/-1.5 (McLure+)

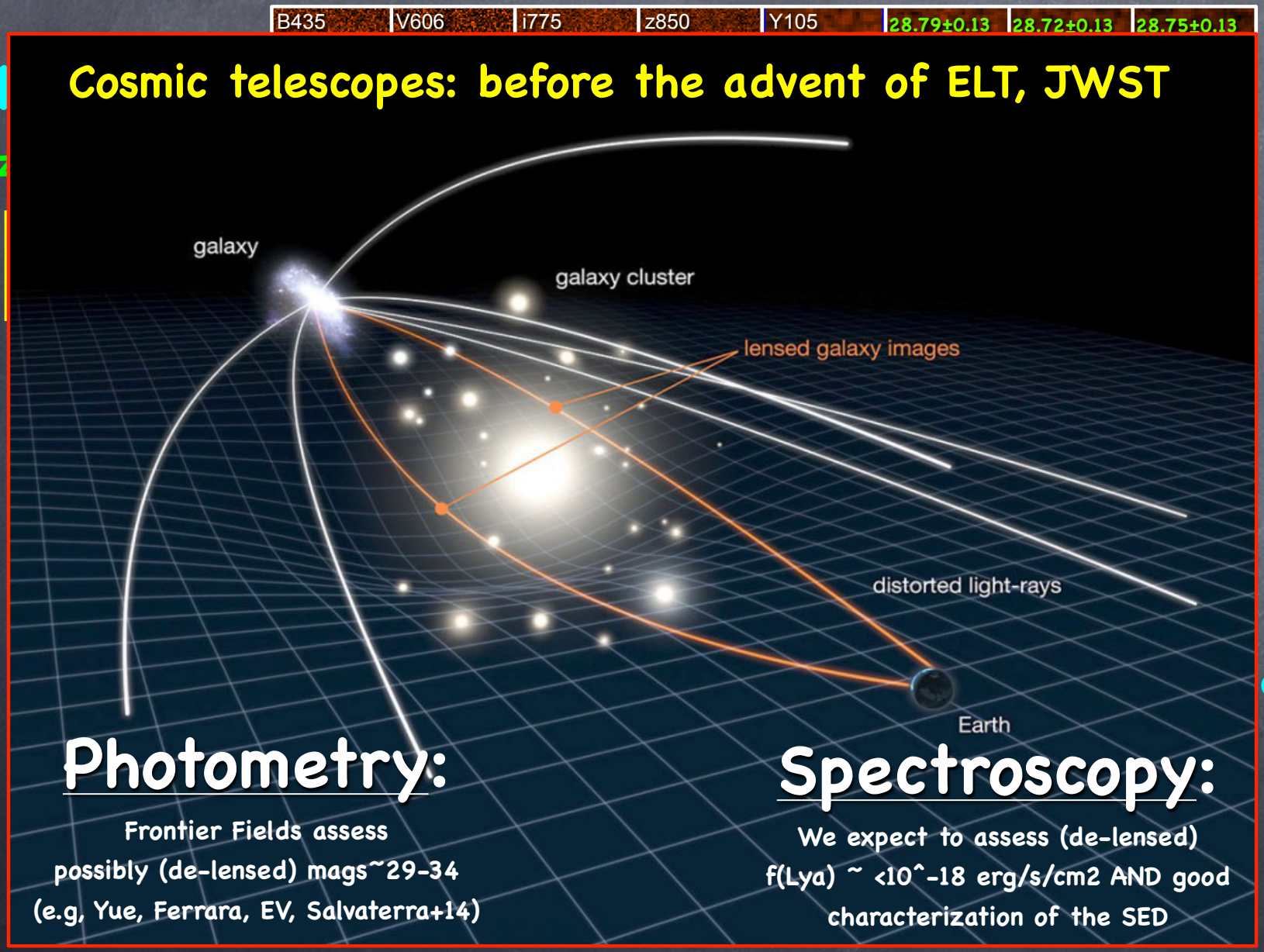
f(Lya)=2x10^{-18}erg/s/cm2 (S/N=7), EW=65A

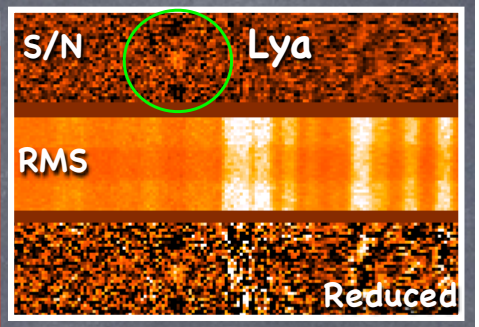


OR …

... spectroscopically confirmed faint z>6 galaxies... the deepest spectroscopic observations

Brute force: VLT/FORS 30hr



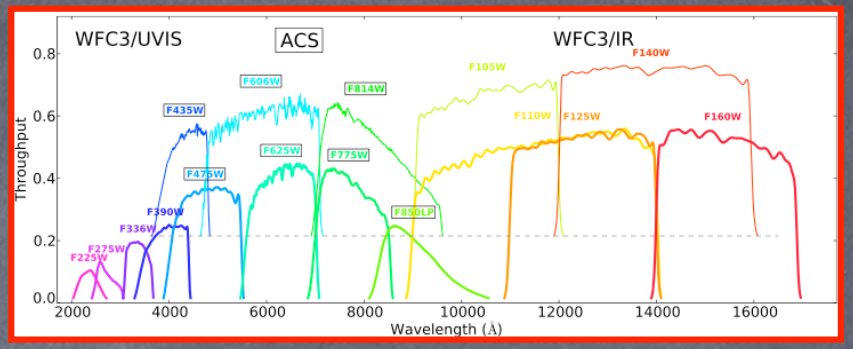


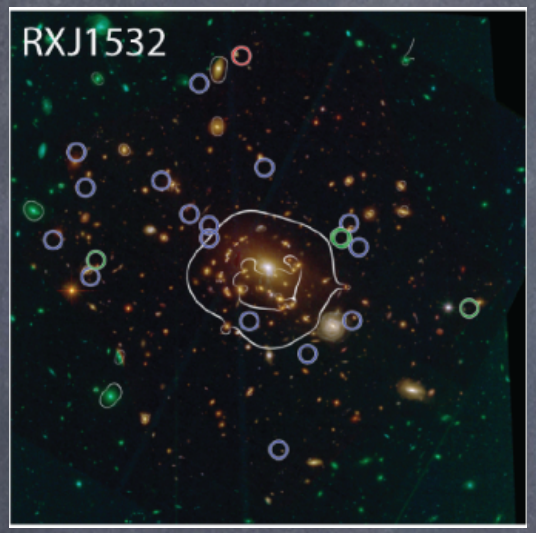
Hubble Frontier Fields
DD (observing time) initiative, 140 orbits
cluster/blank fields
m≈28.7-29 5-sigma
+ magnification

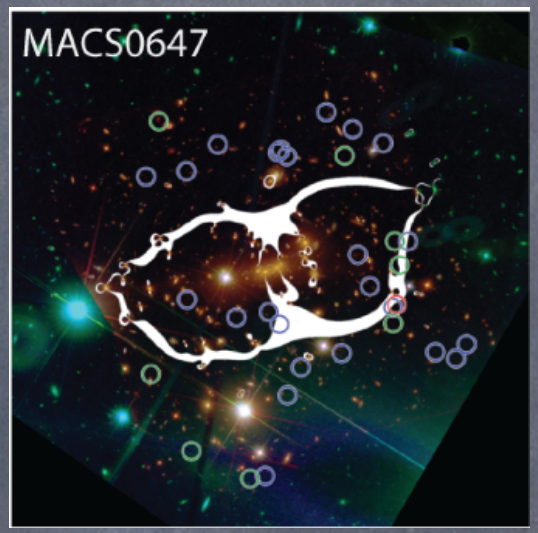
CLASH: 500 HST orbits
(P.I Postman, M.)
25 galaxy clusters
m~27.5 5-sigma
(16-band filters)
+ magnification

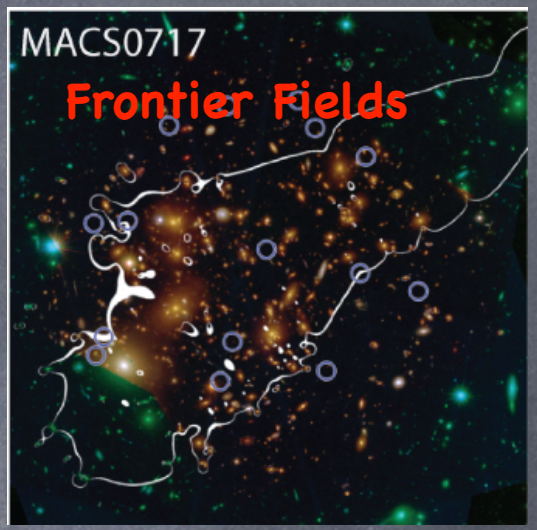
LBT/MODS spectroscopic program :

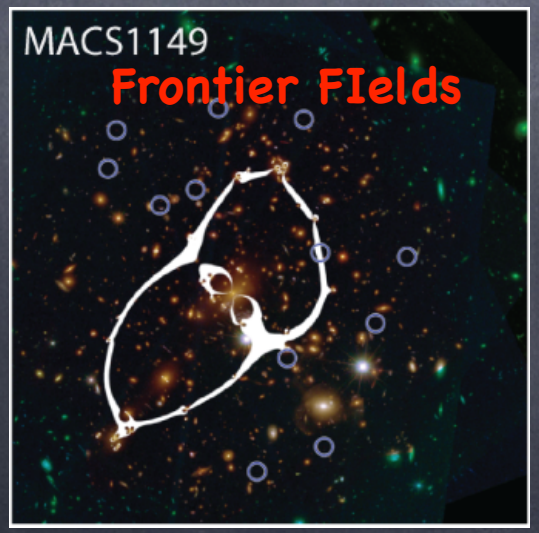
Targets: magnified 5.5<z<7.5 galaxy candidates from CLASH (Bradley et al. 2014) in 5 clusters, 6 hours per cluster, two Frontier Fields

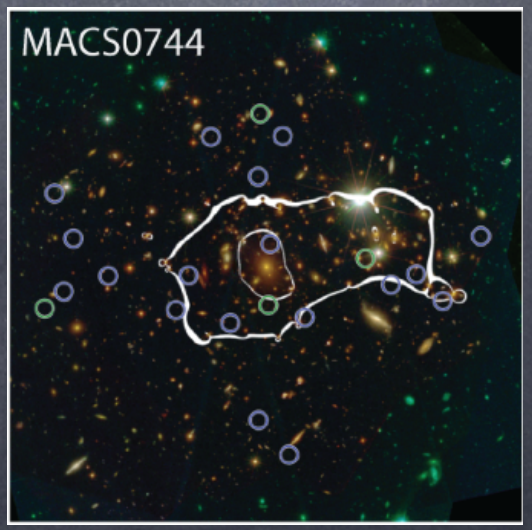












The faintest spectroscopically confirmed z>6 galaxies

Two sources have been confirmed at **zspec=6.4**

2014, ApJL, 783,12

Magnification:

Frontier Fields LENS models:
http://archive.stsci./prepds/frontier/lensmodels/
publicly available, 7 different groups
provide magnifications (D. Coe, STScI)

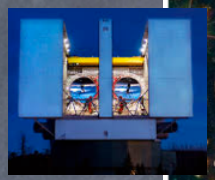
$$\mu = 17.4^{+25}_{-13}(^{+50}_{-12})$$

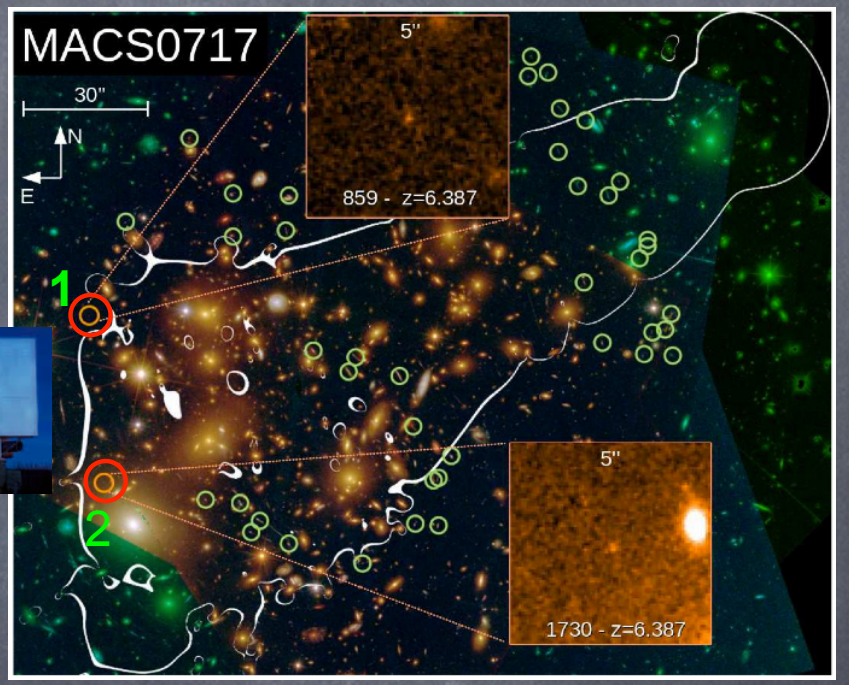
$$\mu = 6.9^{+1}_{-1}(^{+30}_{-2})$$

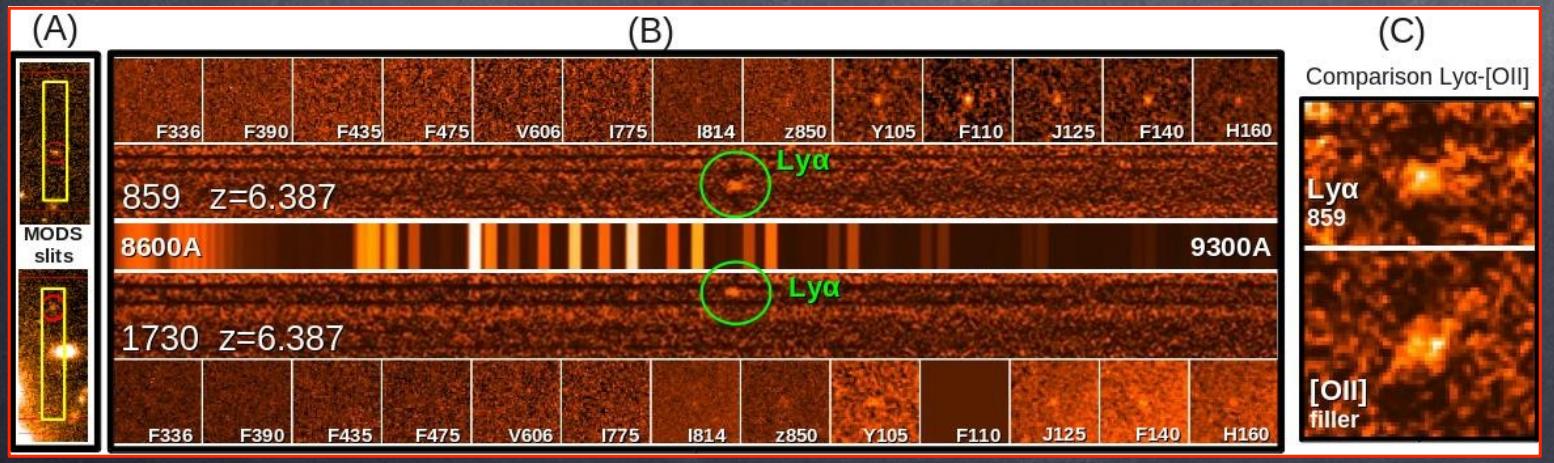
Intrinsic

m_{1500} ~ 29-30

M1500 ~ -17.2





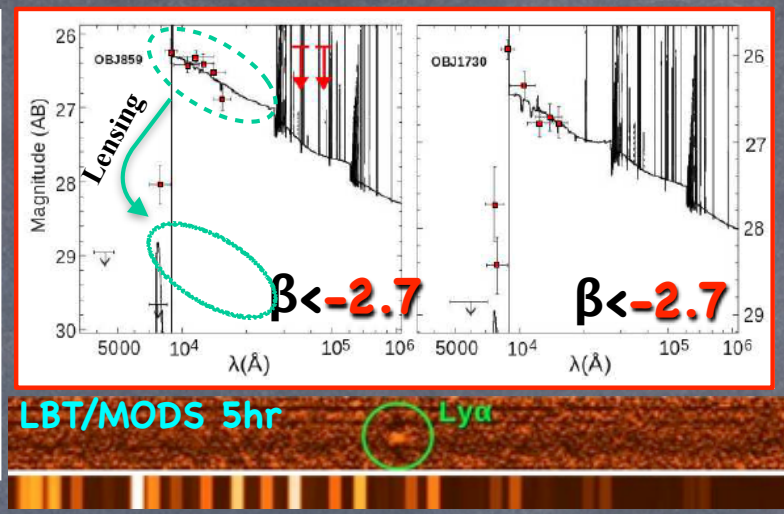


LBT/MODS

The faintest z>6 galaxy spectroscopically confirmed extremely blue source

Newborn galaxy?
z=6.4
Vanz(2014a)

Mabs = -17,
SFR<2 $M_\odot$/yr
size< 0.5 sq.kpc
$M^* \approx 10^7 M_\odot$
E(B-V) ≈ 0
age ≈ 20Myr
$Z < 0.02 Z_\odot$



NIR(CLASH)$_{OLD}$ S/N≈8

Have we found a "ionizer" ?

NIR(HFF)$_{NEW}$ S/N≈50
... in progress

λ <912A

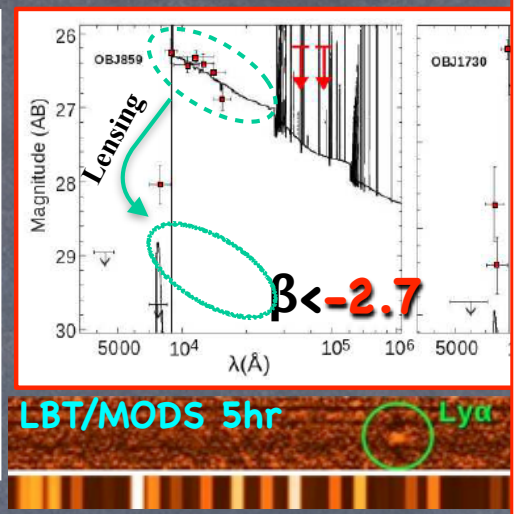
$$f_{esc} = \exp[-\tau_{H\,I,ISM}(LyC)] \times 10^{-0.4(A_{LyC})}$$

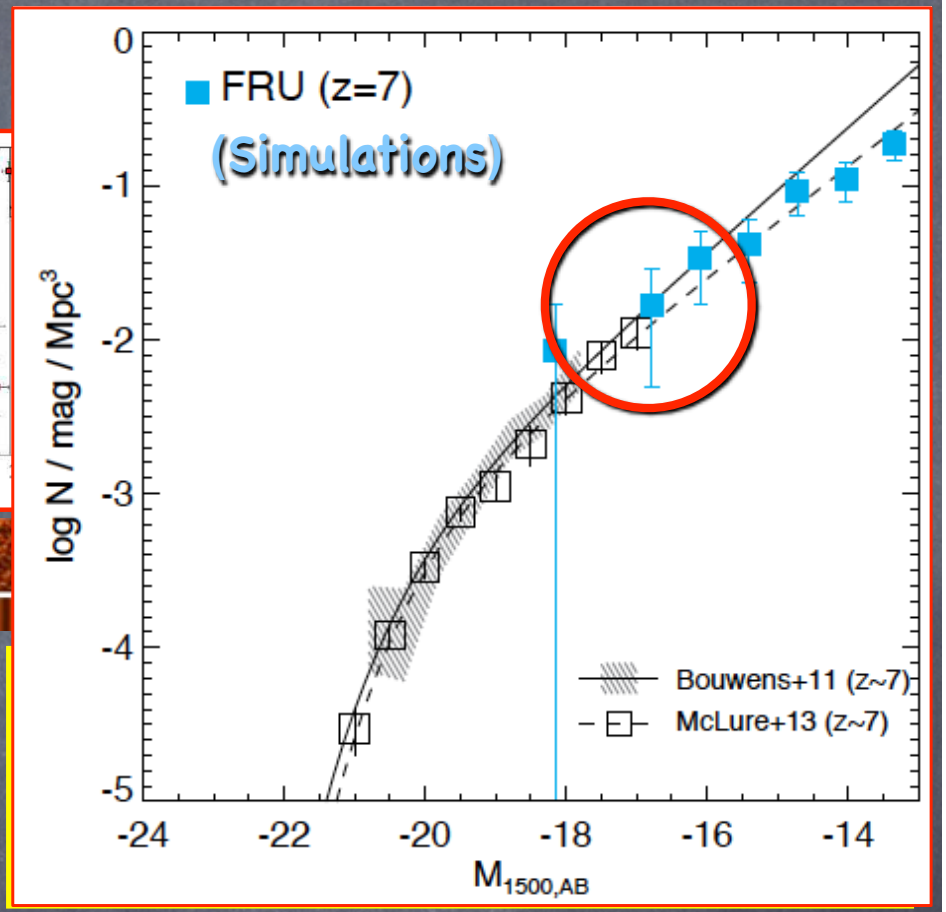
fesc <-> UV slope
Inoue +11
Zackrisson+13
Schaerer+11

The faintest z>6 galaxy spectroscopically confirmed extremely blue source

Newborn galaxy?
z=6.4
Vanz(2014a)

Mabs = -17,
SFR<2 $M_\odot$/yr
size< 0.5 sq.kpc
$M^* \approx 10^7 M_\odot$
E(B-V) ≈ 0
age ≈ 20Myr
$Z < 0.02 Z_\odot$





NIR(CLASH)$_{OLD}$ S/N≈8

Have we found a "ionizer" ?

gas abs. dust. abs

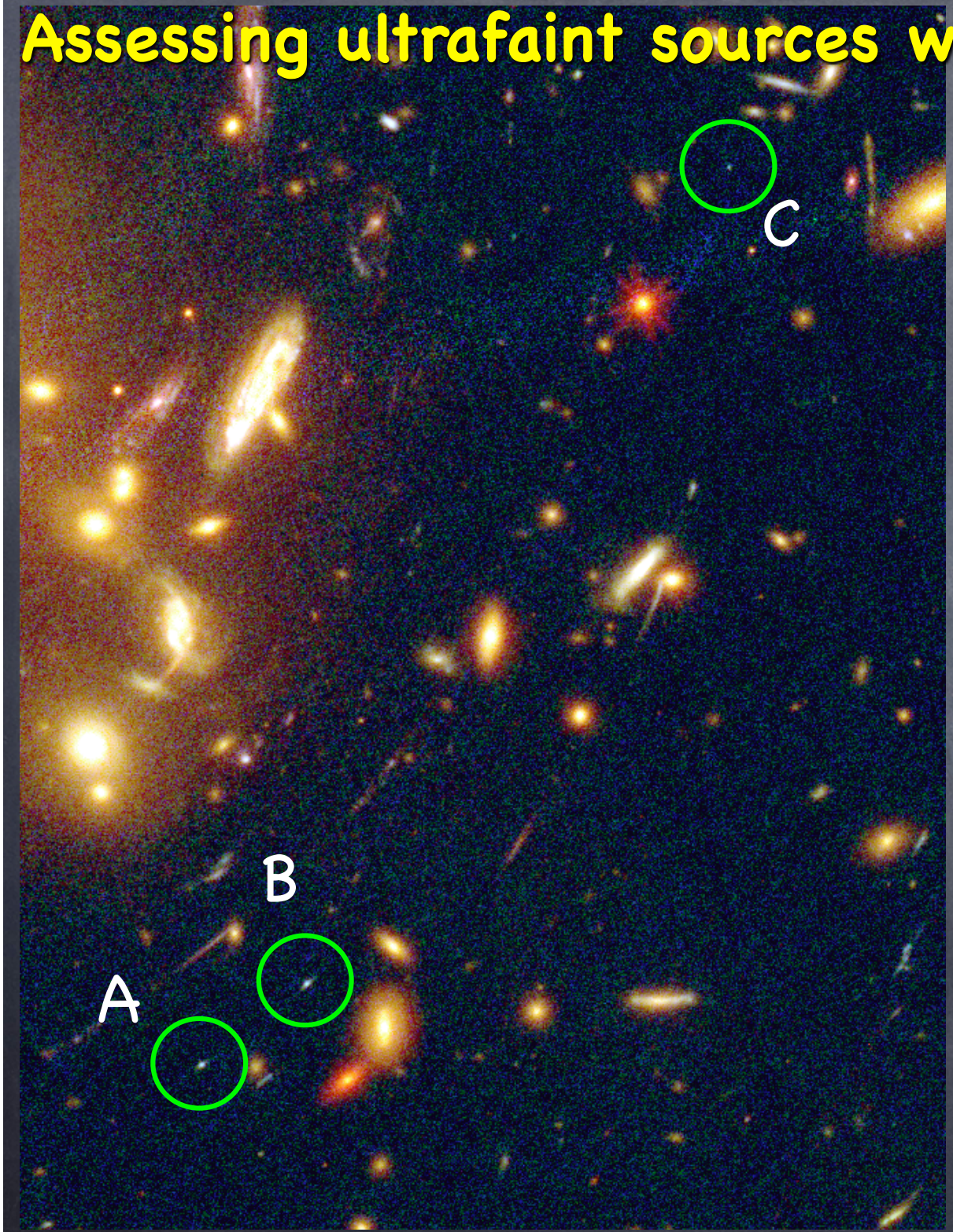
λ <912A $f_{esc} = \exp[-\tau_{H\,I,ISM}(LyC)] \times 10^{-0.4(A_{LyC})}$ > 0 (possibly)

> 0 ? ≈1

fesc <-> UV slope
Inoue +11
Zackrisson+13
Schaerer+11

... how can we infer the escaping ionzing radiation from z>6 sources ?
(LyC not visible directly at z>6)

Assessing ultrafaint sources with spectroscopy



Again, strong lensing

z=3.11

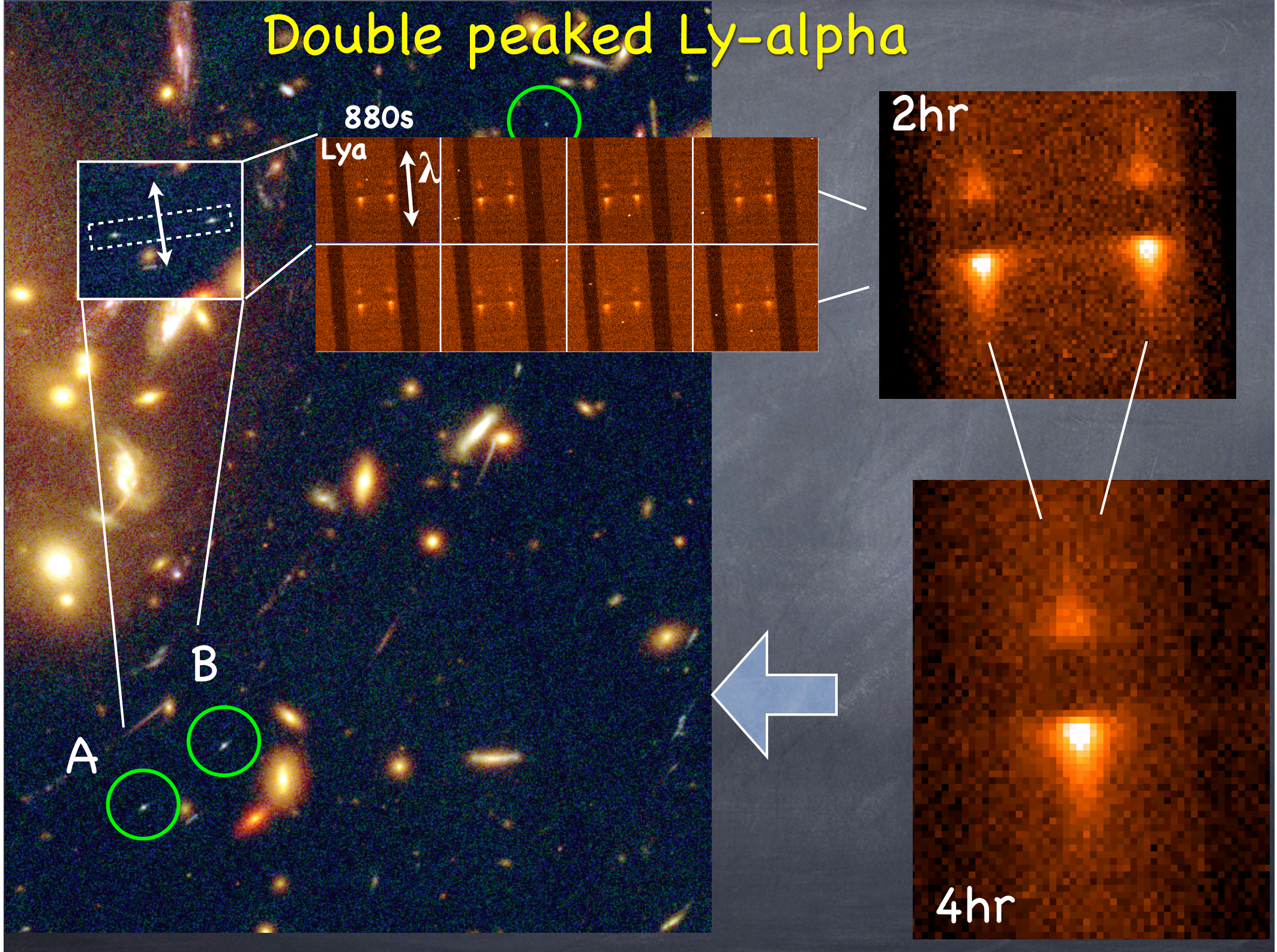
m(1500)~29.30

Muv = -16

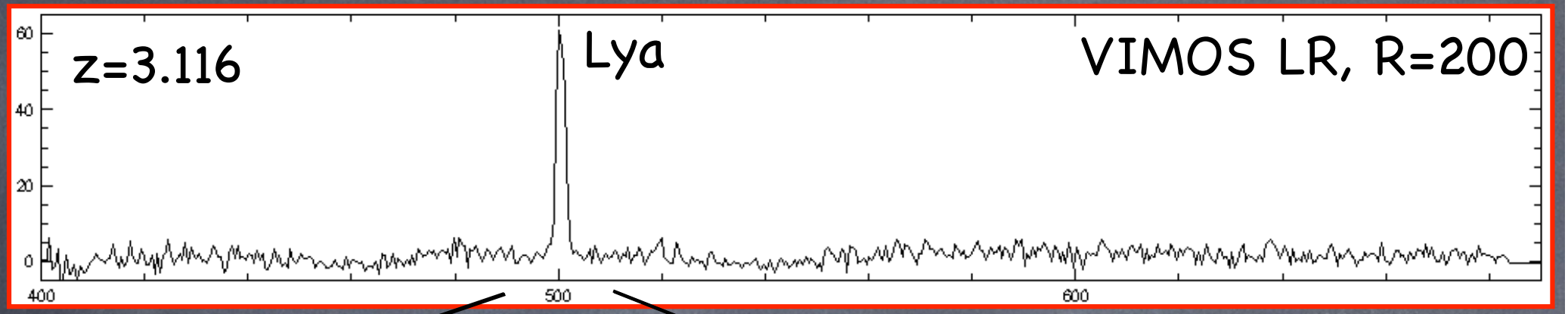
L = 0.015L*

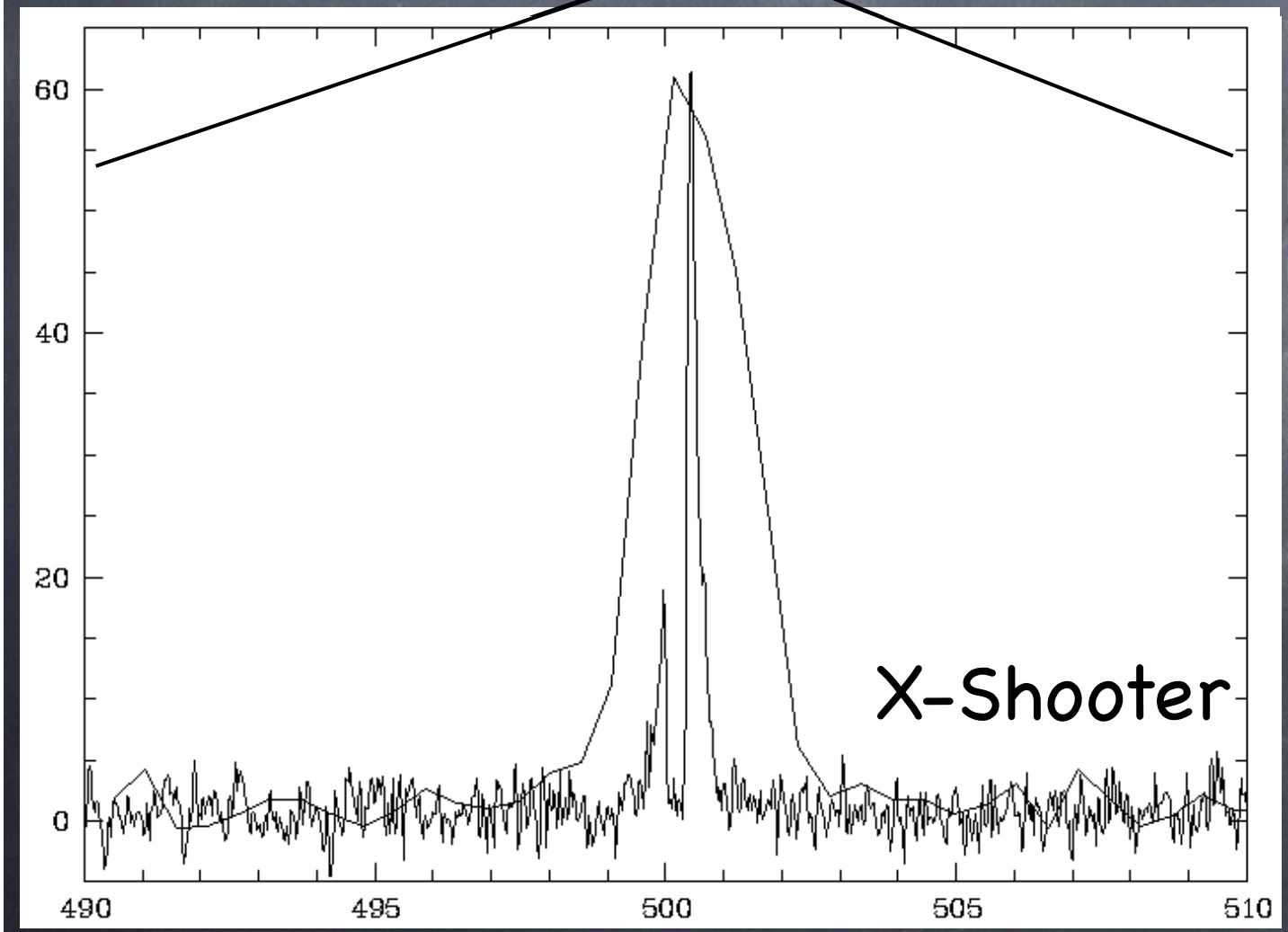
Reff ~ 200 pc

Double peaked Ly-alpha



Initially discovered by CLASH-VLT





VLT/X-Shooter, R=4350

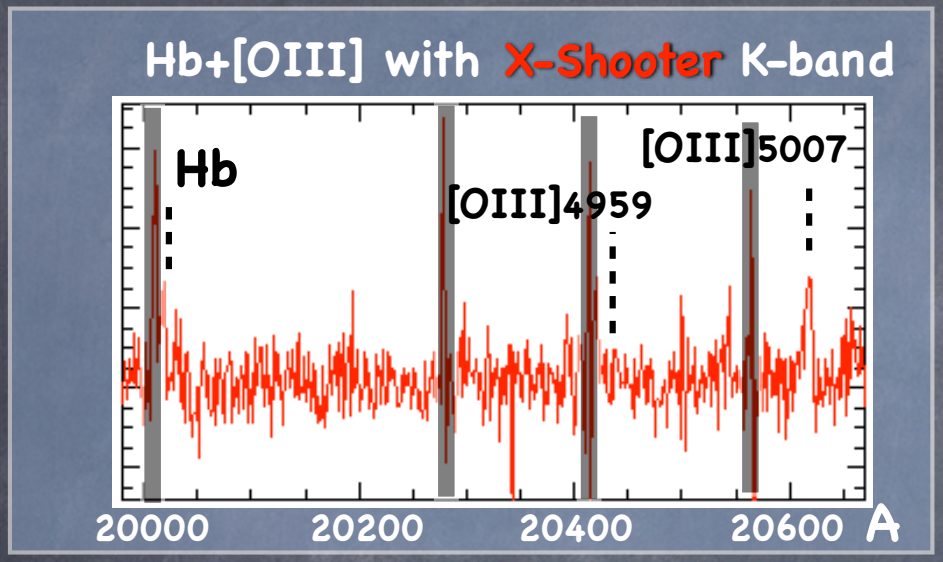
8.2m ⌀, in lensed fields

Lya(blue)=8.0e-19 cgs S/N=30

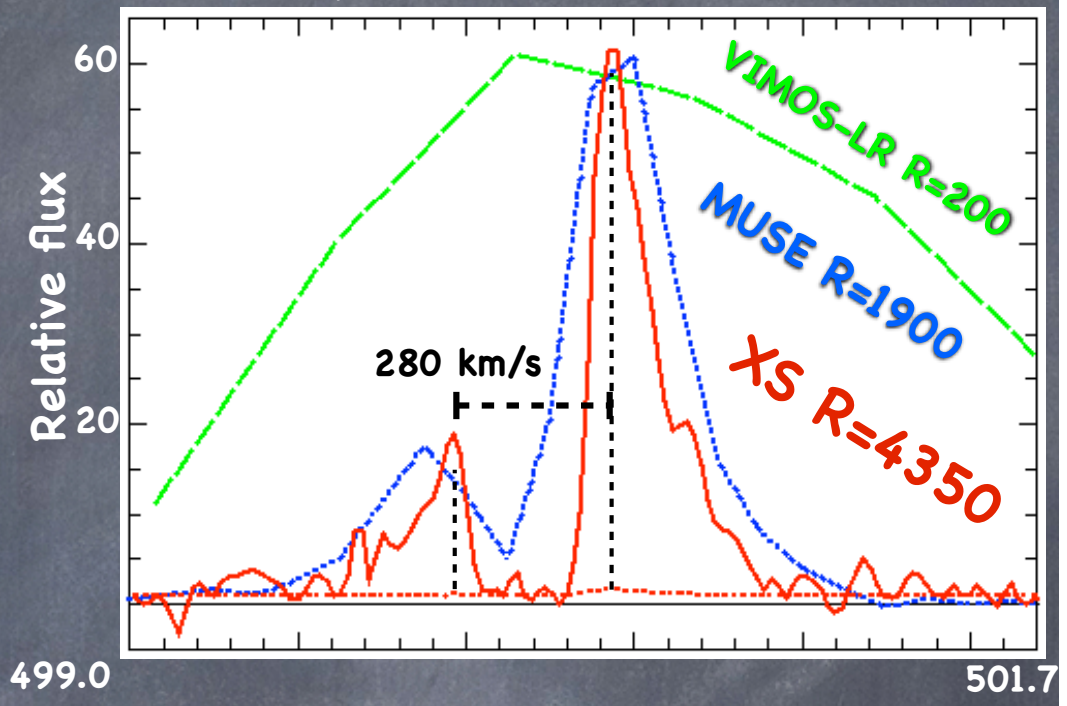
Lya(red)=3.0e-18 cgs S/N=60

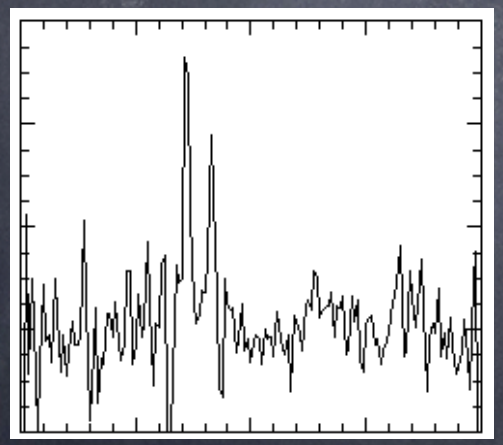
1 OB -> 2hr

Optically thin medium (modeling): narrow feature(s)



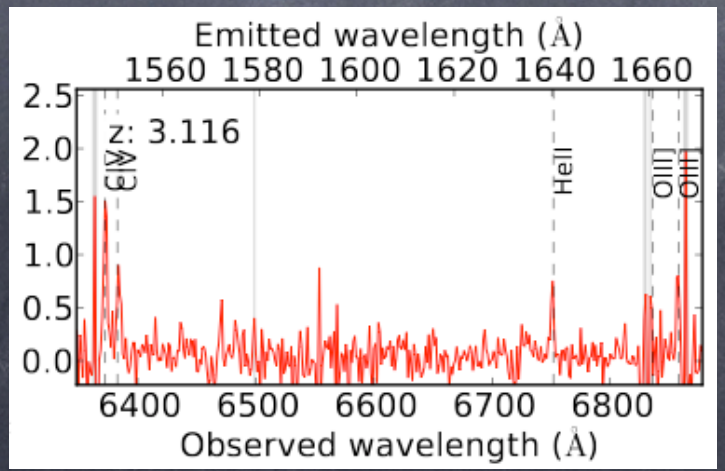
zoom in the K-band





CIV 1548-1550

hot stars or AGN ?



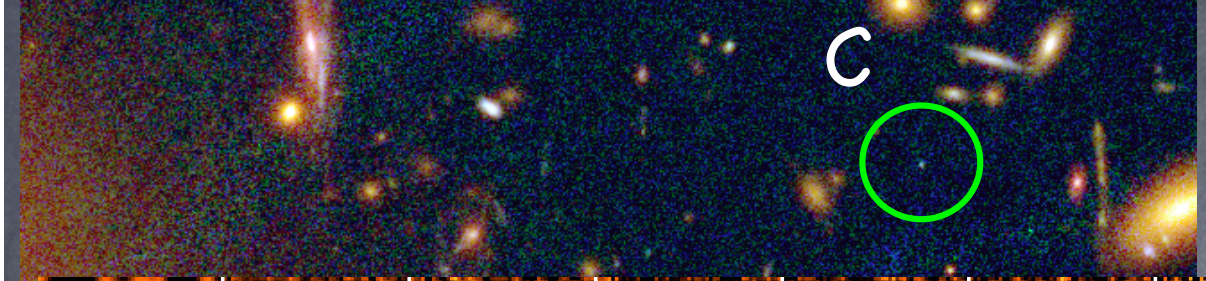
MUSE

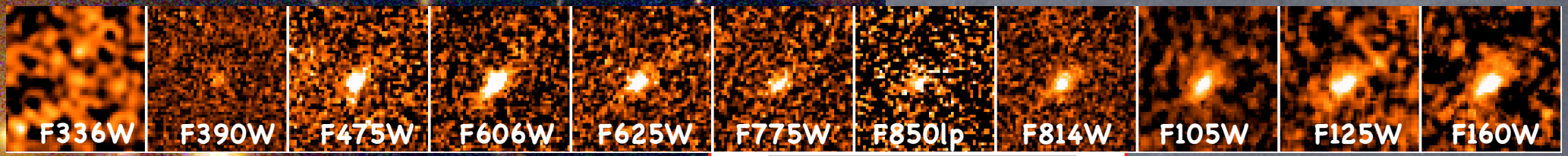
From RT modeling

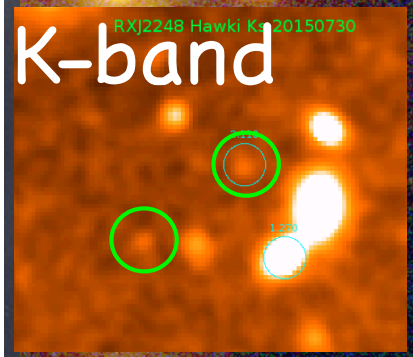
Log(NHI)<18 ?

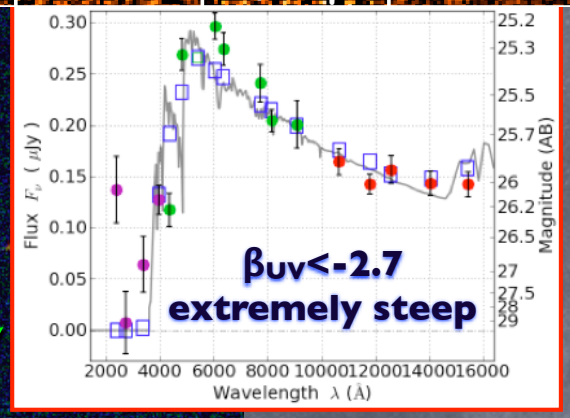
possibly fesc>0

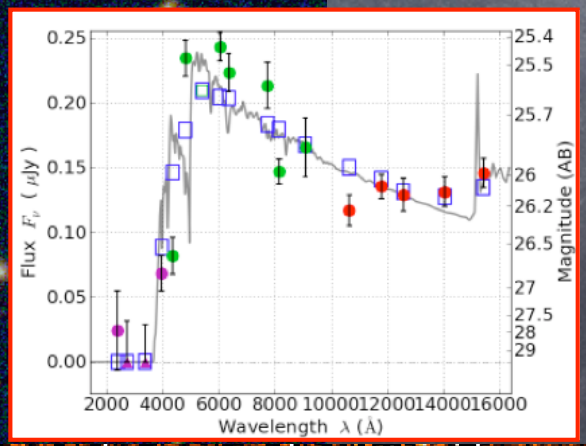
vexp=50km/s











B

A

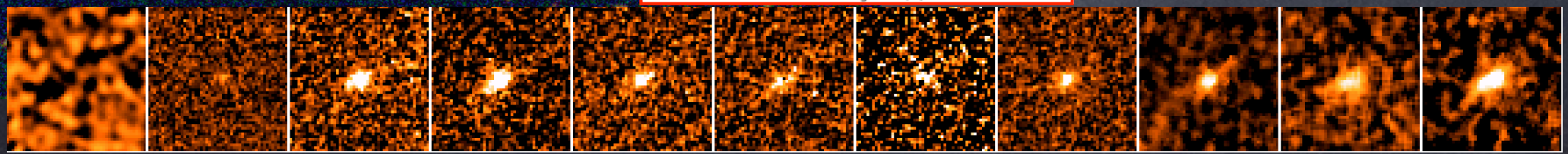
z=3.11

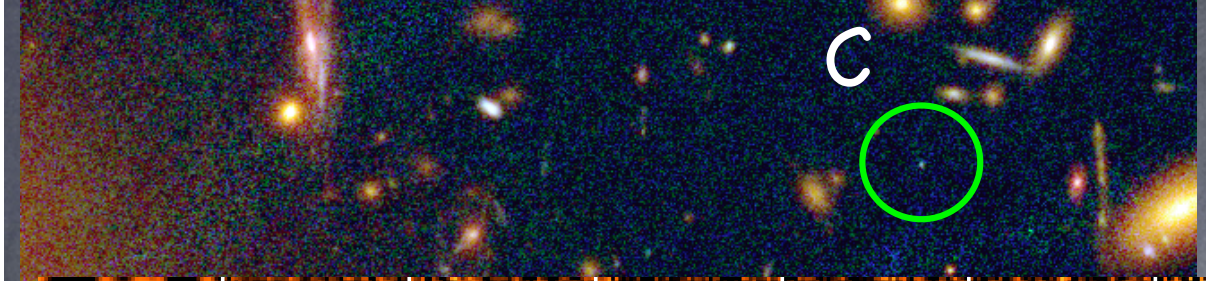
m1500 = 29.30

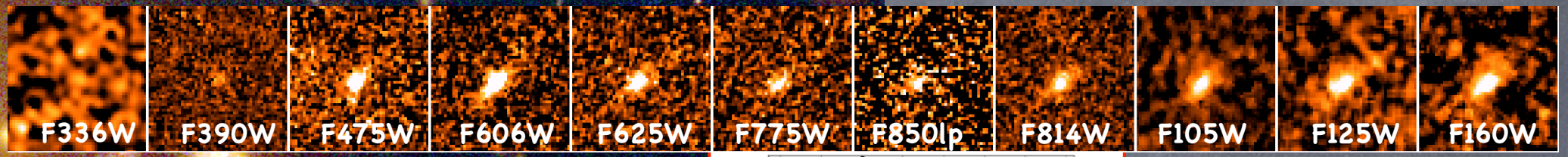
V625-I814 = -0.45!!

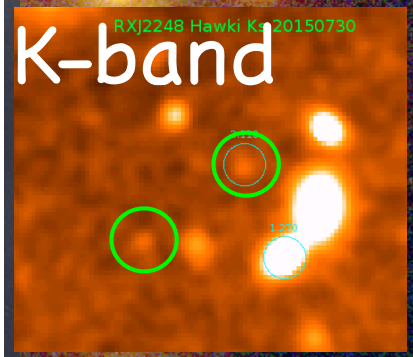
extremely blue

dust-free

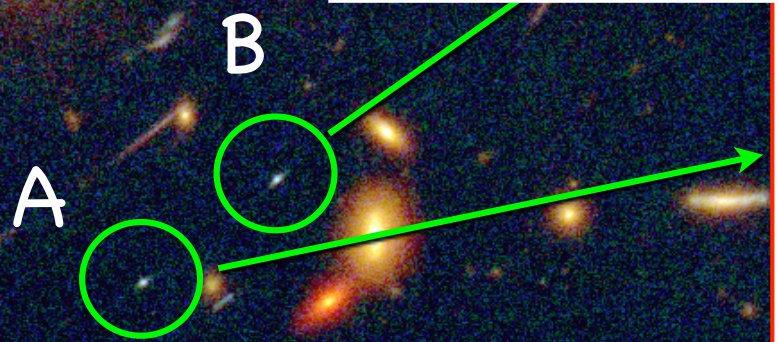


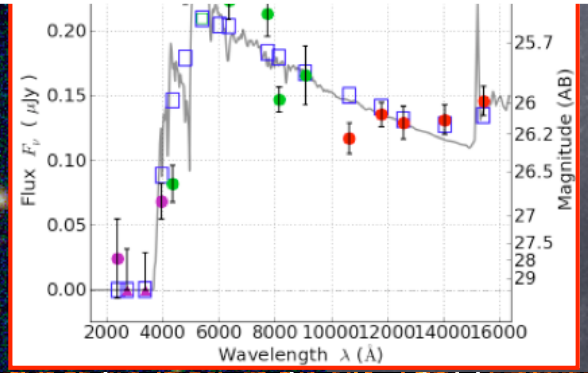




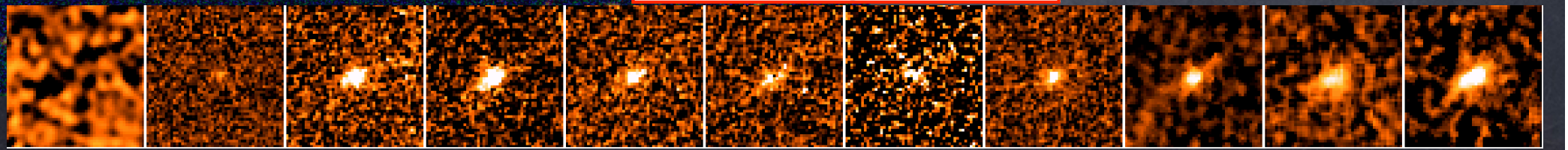


Is this an example of a faint ionizer ??
We will see in 6 months (HST observations)





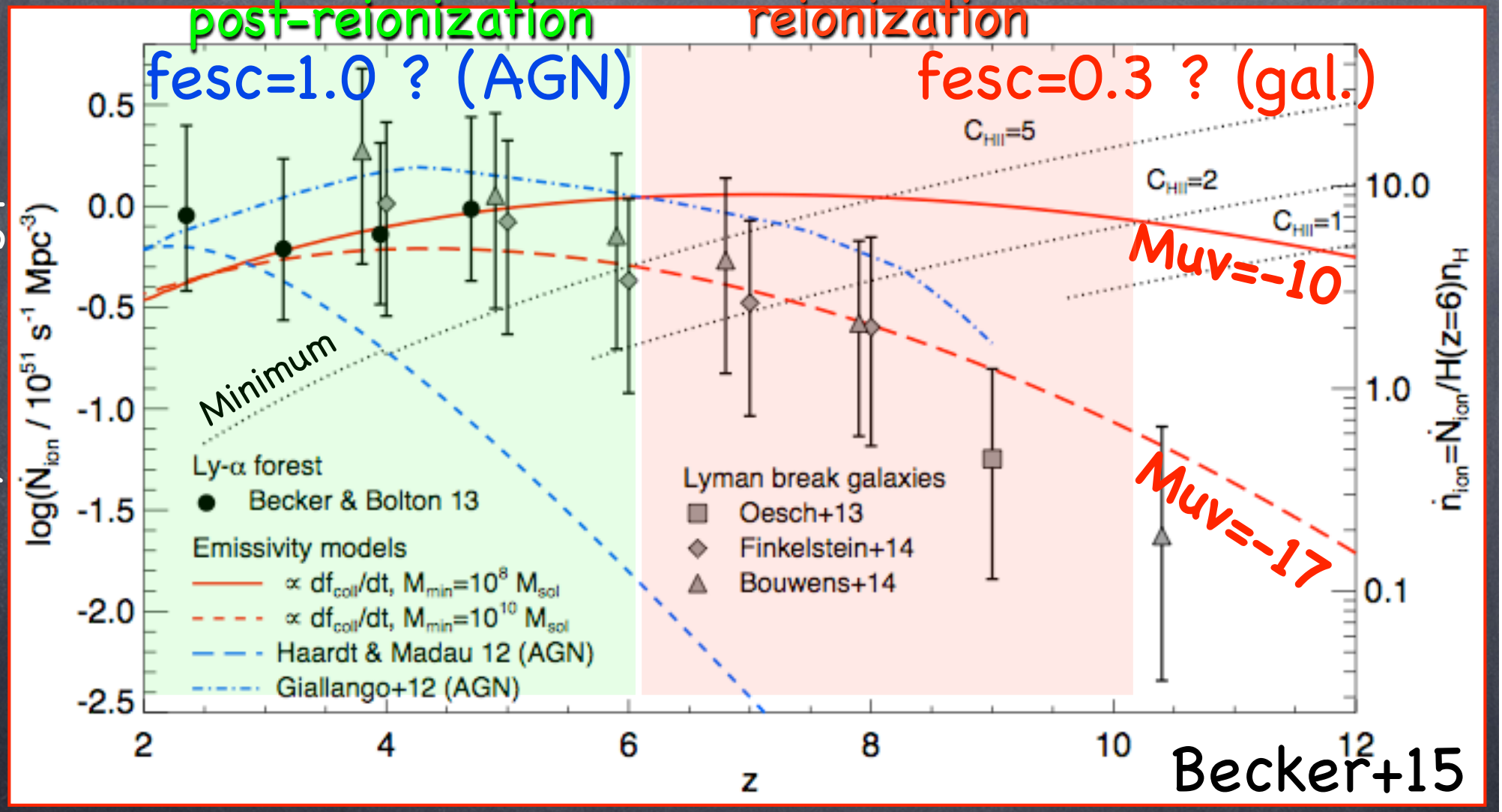
11
00 = 29.30
I814 = -0.45!!
extremely blue
dust-free



Who is responsible for the ionization ?

$$\phi(M_{1400}) \xrightarrow[\text{integrate; assume } M_{lim}]{} \rho_{L_{1400}} \xrightarrow[\langle N_{\gamma<912}/N_{\gamma 1400}\rangle]{} \dot{N}_{ion}^{int} \xrightarrow{f_{esc,rel}} \dot{N}_{ion}$$

$$\frac{dQ_{H\,II}}{dt} = \dot{n}_{ion} - \frac{Q_{H\,II}}{\bar{t}_{rec}}$$



AGNs - select AGNs from X, challenging
- faint-end LFs ? Uncertain (zspec)
- fesc ? Helium reionization ?

SF-galaxies - faint-end LFs ? Ok, there are many!
Some with zspec (Alavi 2014)
-fesc ? (low for bright...)

Open issues

$$\phi(M_{1400}) \xrightarrow[\text{integrate; assume } M_{lim}]{} \rho_{L_{1400}} \xrightarrow[\langle N_{\gamma<912}/N_{\gamma 1400}\rangle]{} \dot{N}_{ion}^{int} \xrightarrow[f_{esc,rel}]{} \dot{N}_{ion}$$

What we would like to know:

(1) LFs vs. redshifts at all luminosities Count objects

(2) fesc vs. redshift at all luminosities LyC leakage

Galaxies:

point (1) is addressed up to z~8

point (2) is partially addressed

(bright galaxies shows low fesc)

AGNs:

point (1) is partially addressed

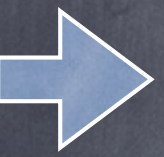
(the faint-end still uncertain, especially at high-z)

point (2) is partially addressed

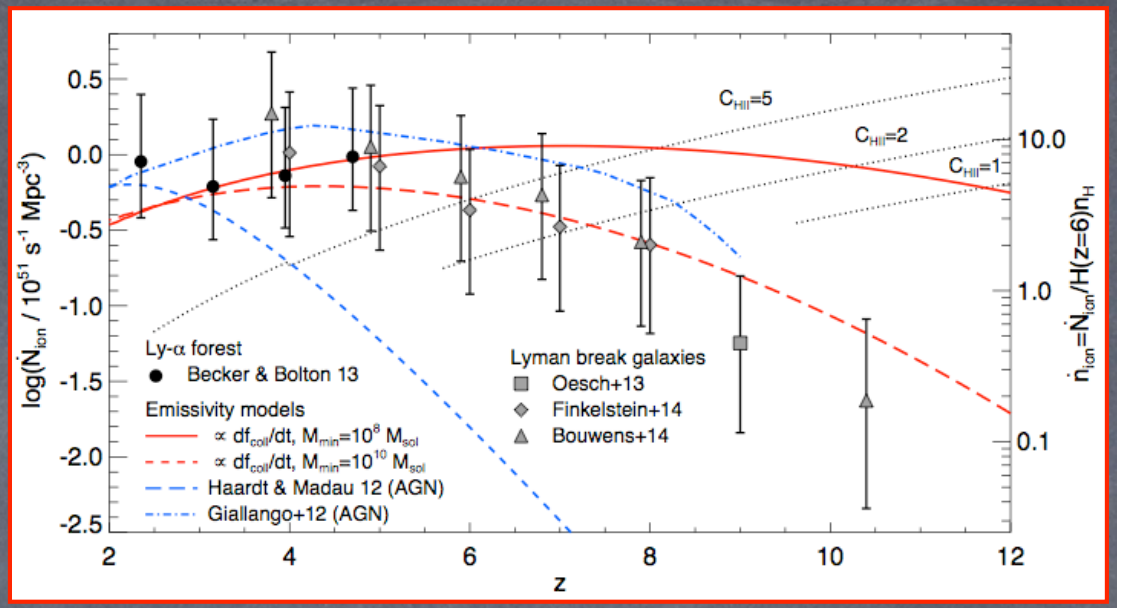
Are we mixing things in the selections ?

Open issues:

At z<3.5 the ionization from **known** AGN can explain the UVB (e.g., Fontanot+14)



No need for galaxies at z<4 ?
Consistently with fesc~0-0.05



If at z>3.5 the QSO emissivity decreases rapidly, and given the flat behavior of the photo-ionization rate (IGM):

We need an increase of fesc in galaxies in a short time scale (1.5Gyr), to sustain ionization up to some redshift

- How the AGN LFs evolve with redshift and in the faint regime ?
- Bright AGN have fesc>0. What is the fesc for faint AGNs (BH~10^6-10^7 M⊙) ?
- If AGNs are not sufficient at z>3.5, why fesc in galaxies should increase rapidly ?

Either the properties of galaxies **evolve rapidly (ISM)** to increases fesc or most of the low mass galaxies should **host massive BH** and sustain low level accretion over prolonged period of time...

Observations would be very informative to models.

Questions