The contribution of Quasars and Galaxies to the UV background

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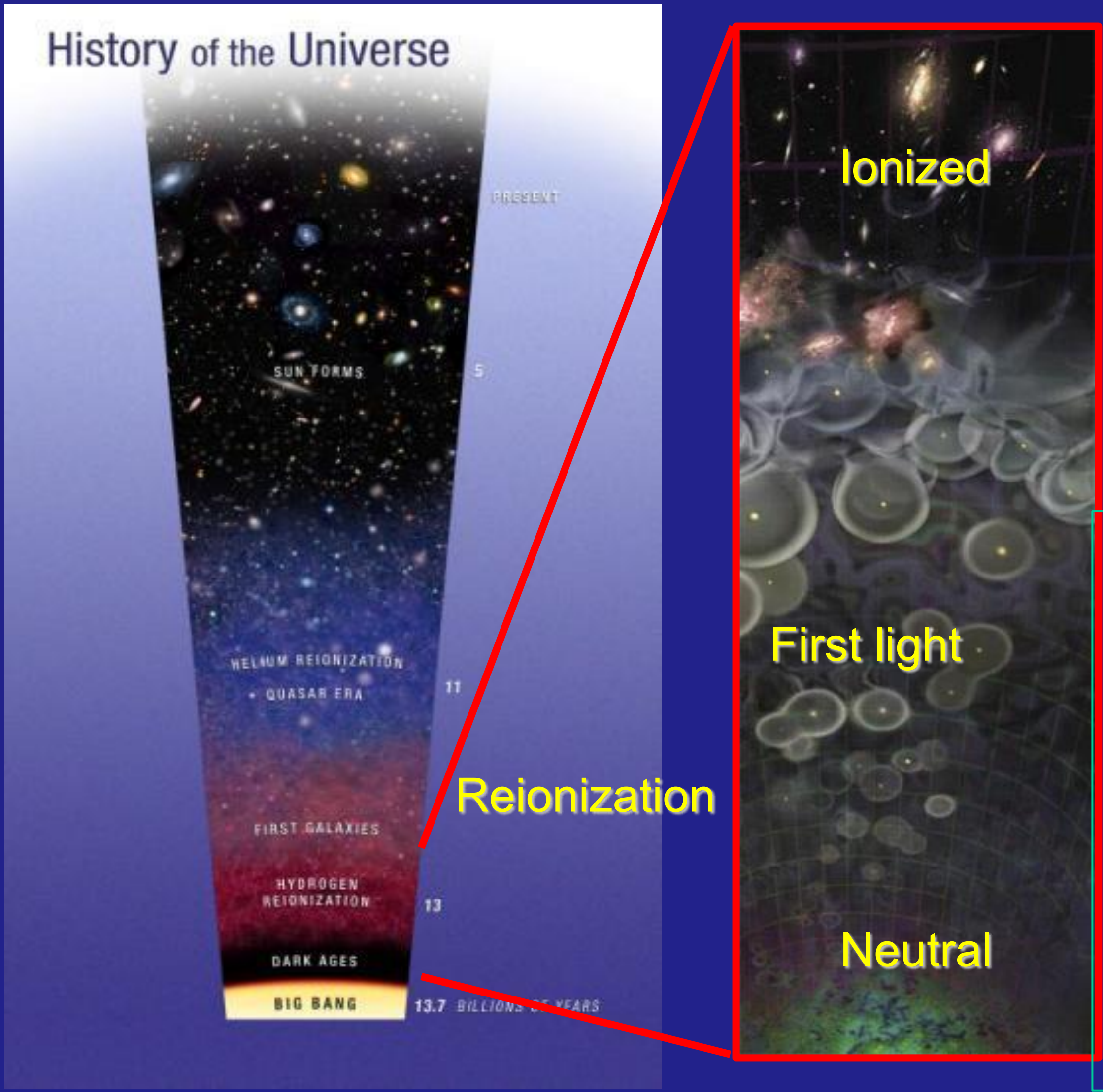
HI reionization: why is it important?



- first structures produce γs that end the Dark Ages
- γs affect gas cooling (consequently SF)
- and the collapse of (small) dark matter halos
- critical interplay

- What sources were responsible for reionization ? Were galaxies responsible of that ?

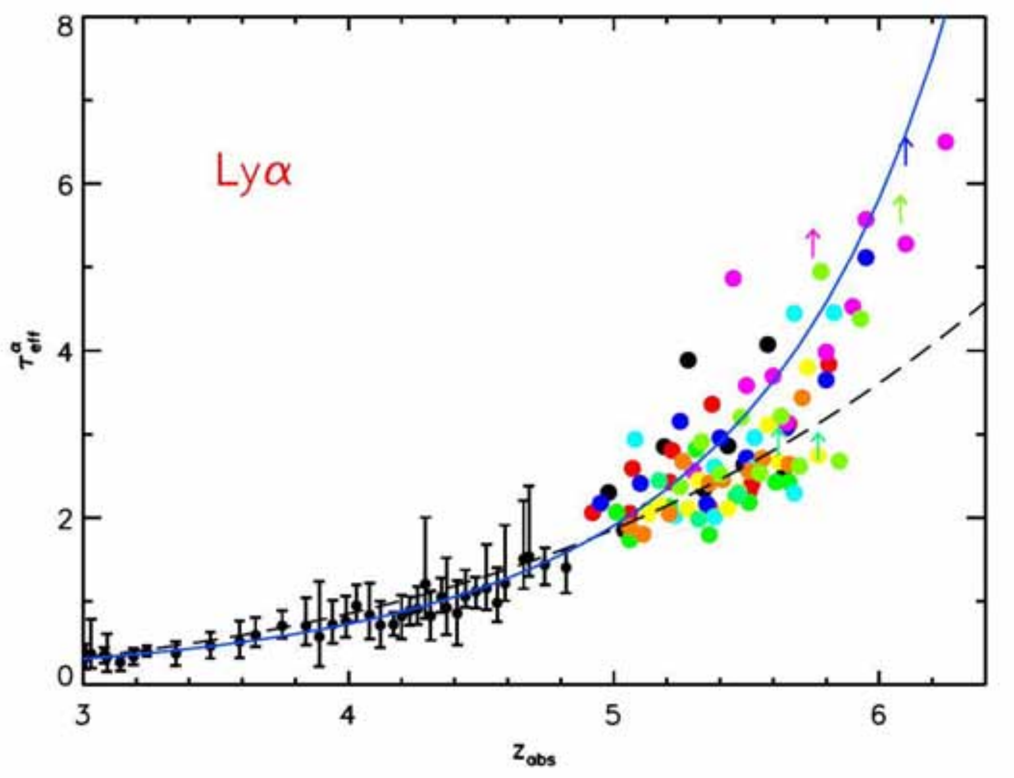
- When and how did reionization Occur ?

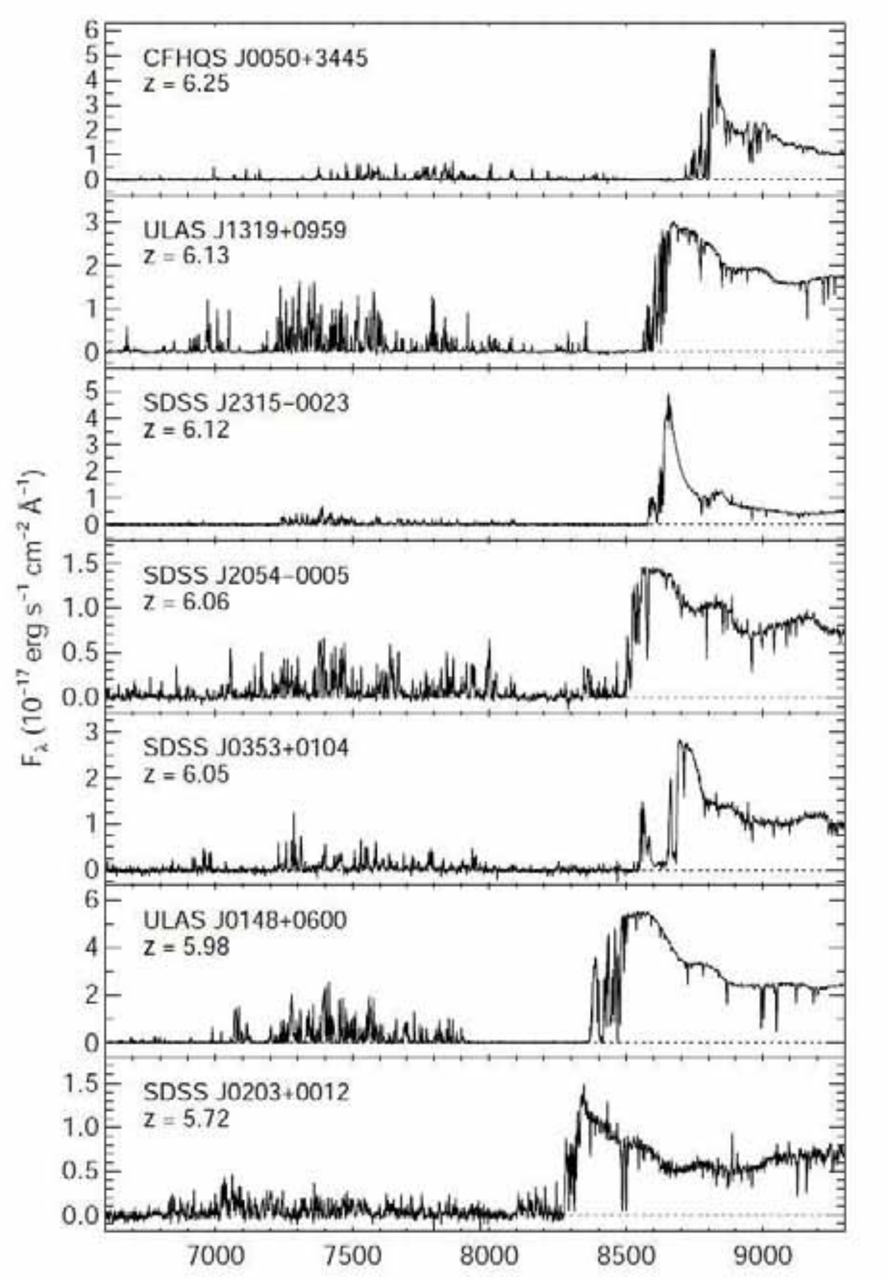
- What keeps the Universe ionized down to lower redshift?

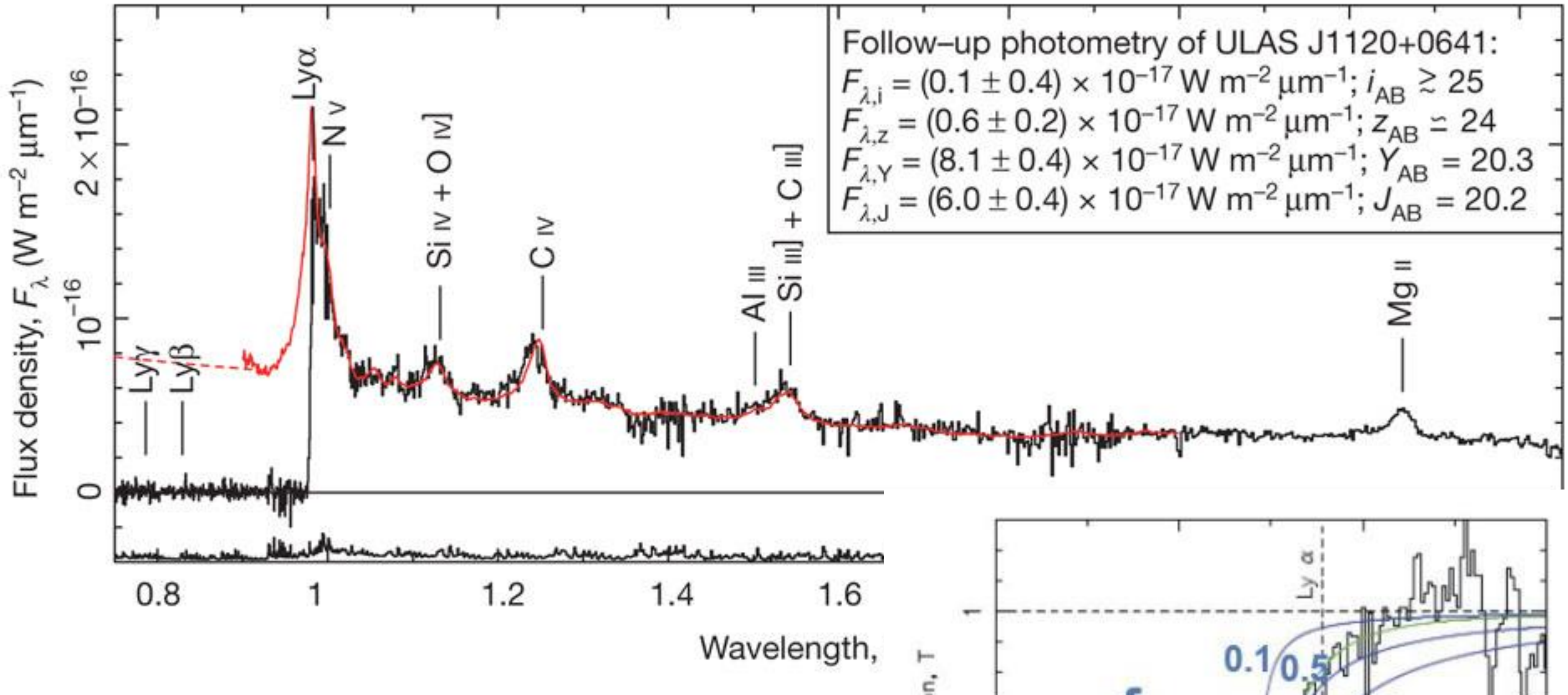
HI reionization: constraints (1) Ly forest

QSO Gunn-Peterson trough

→ IGM ionized by z~6 (Fan+06, see also McGreer 2011, Becker+, 2007, 2015)

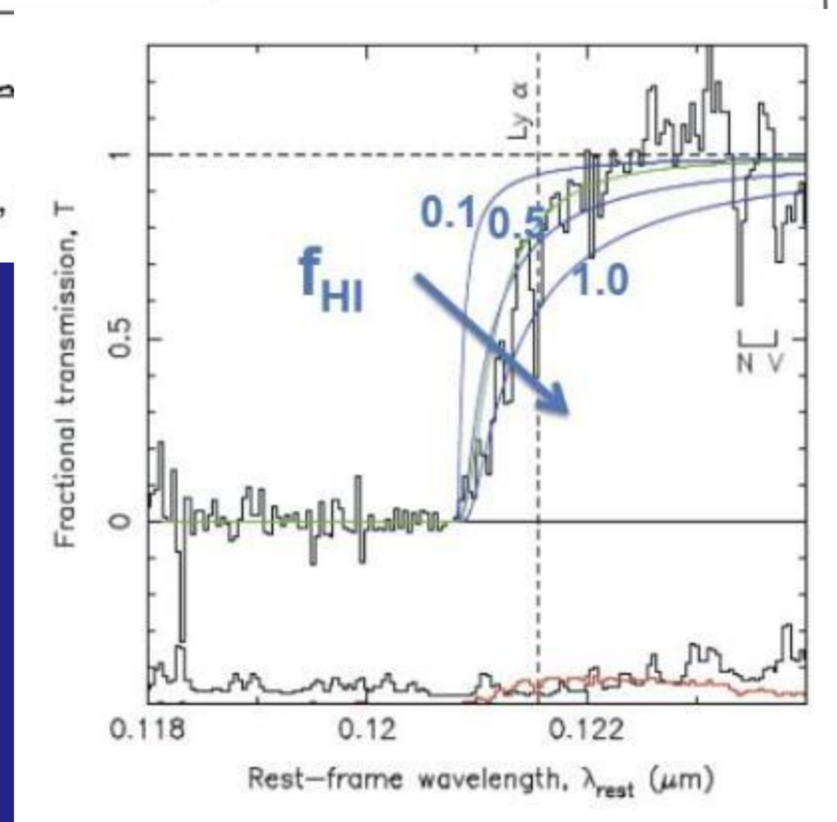






ULAS J1120+0641
Damping wing @
Z(systemic) = 7.085
$f_{HI} > 0.1$

(Mortlock+11, Bolton+11)

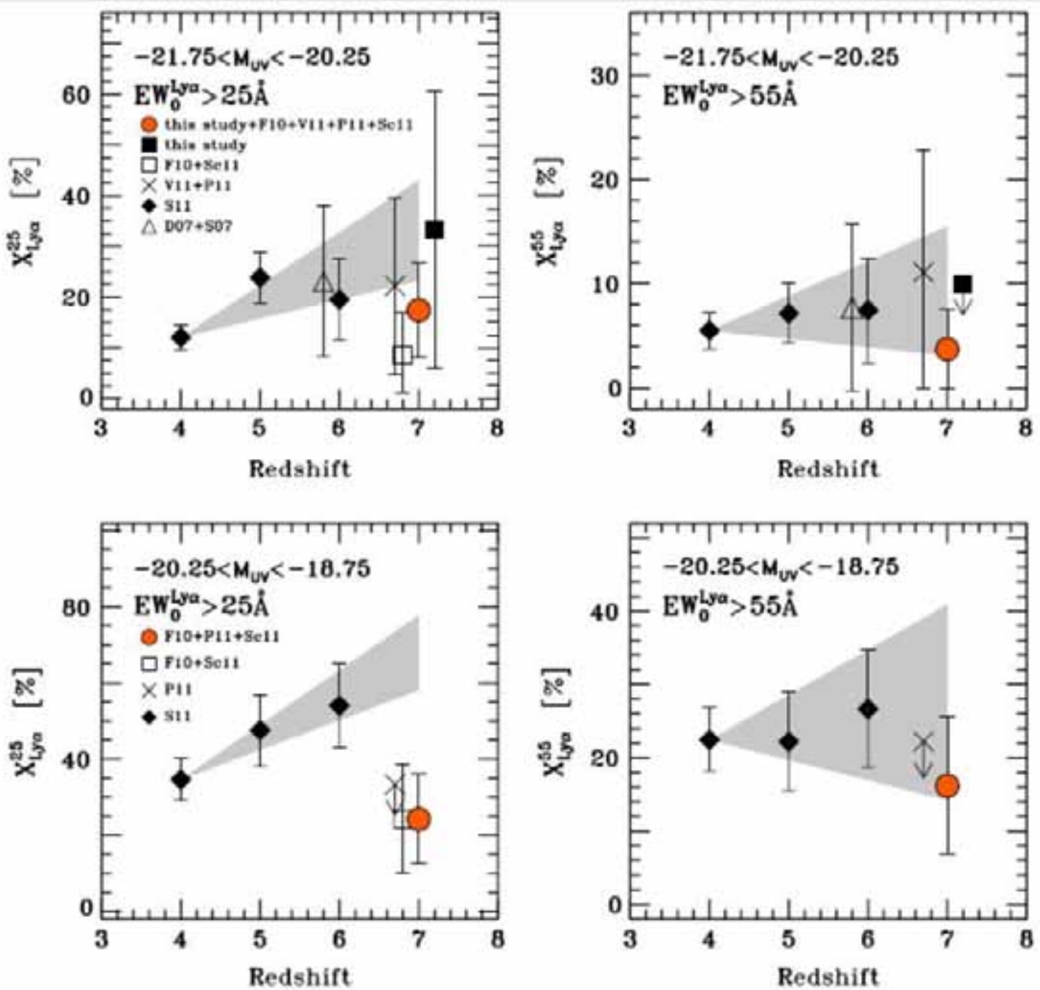


Lack of Lyα emission as a tracer of increasingly neutral IGM/CGM

Since the beginning interpreted as

increased IGM absorption -> onset of re-ionization!

(Stark+10, Fontana+10, Pentericci+11, Ono+12, Treu+12, 13 ,Schenker+12, 14)



Ono+12

Konno+14: 7 LAE observed, ~65 expected

ACCELERATED EVOLUTION OF LYα LUMINOSITY FUNCTION AT $z \gtrsim 7$

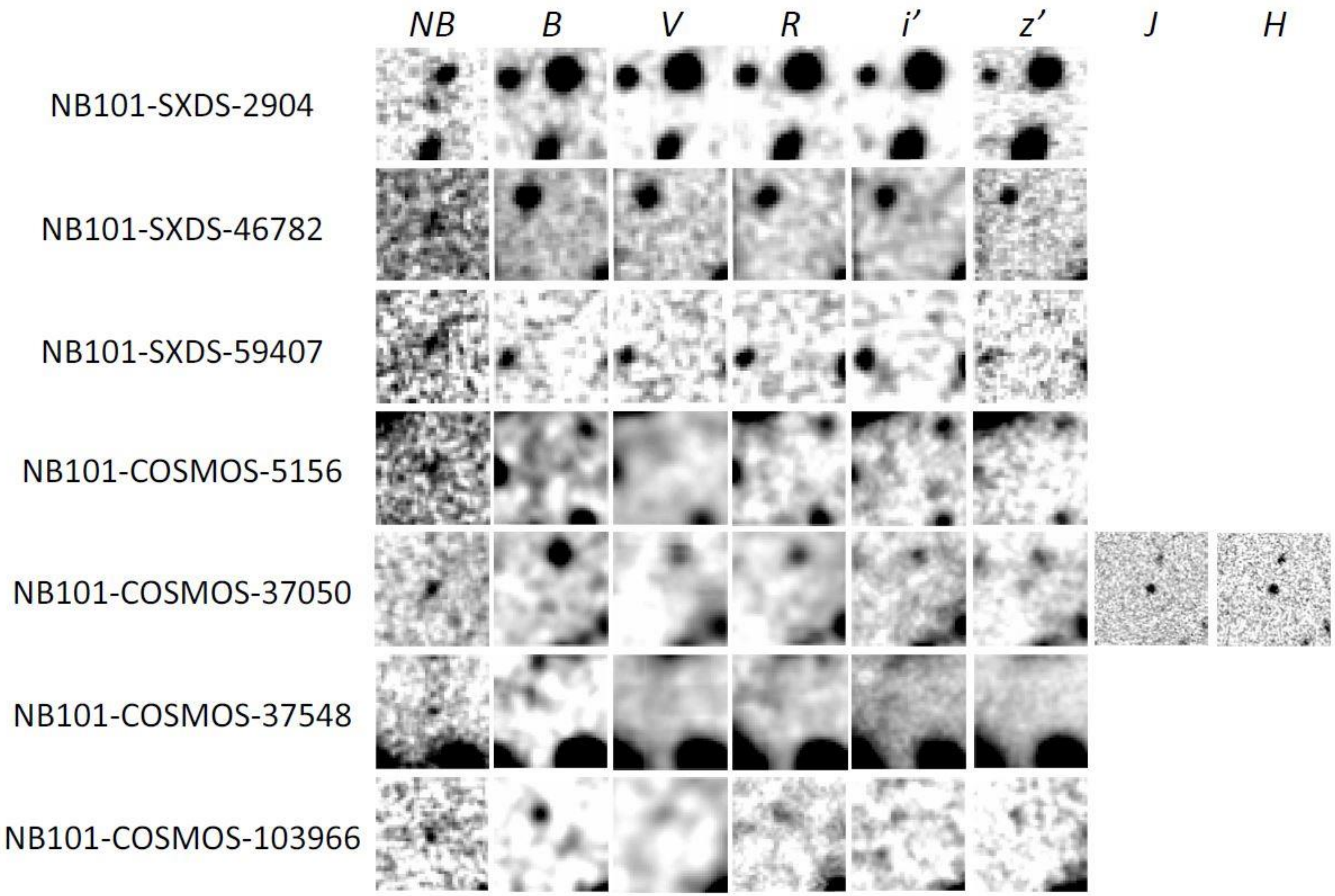
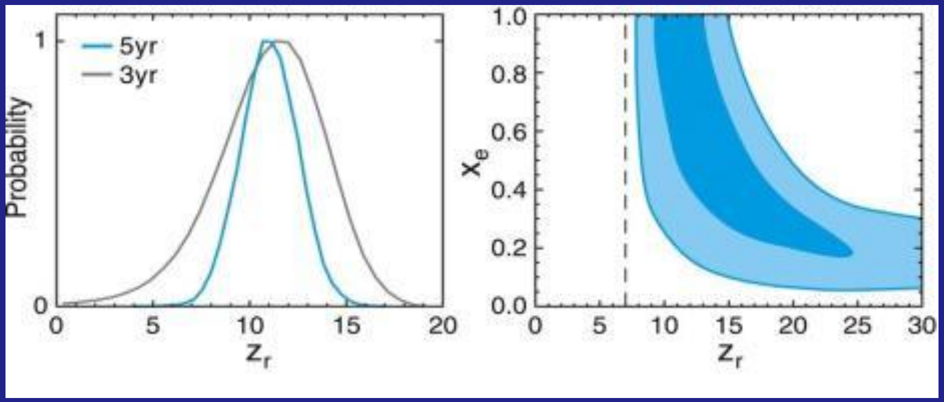


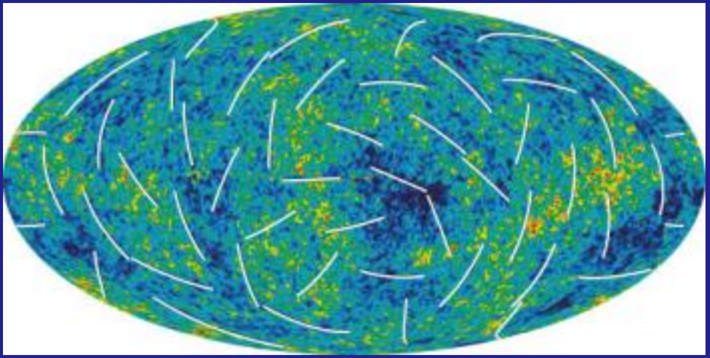
Figure 4. Snapshots of our $z = 7.3$ LAE candidates. The size of each image is $6'' \times 6''$. North is up and east is to the left.

HI reionization: constraints (2) CMB

Reionization



WMAP

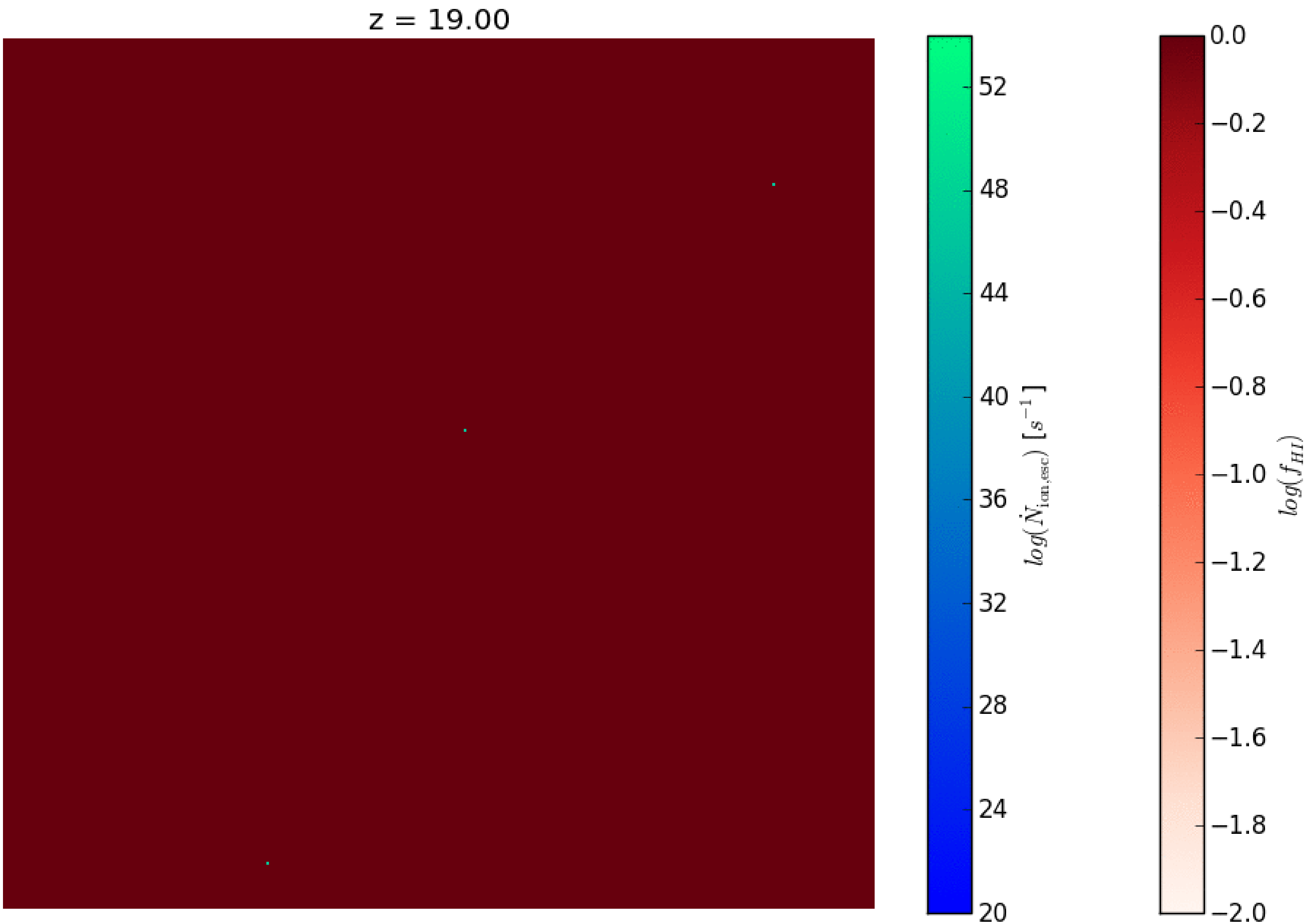


WMAP : Thomson optical depth of the IGM via the large scale polarization
→ Reion. began at z~10-15 (Dunkley+09)

***z(reion)* = 10.6 ± 1.2**
Komatsu+11
(instantaneous)

τ= 0.17 ± 0.08 (WMAP1, 2003) → z(ri) = 17 ± 3, 11<z(ri)<30
τ = 0.09 ± 0.03 (WMAP3, 2007)
τ = 0.087± 0.017 (WMAP5, 2009)
τ = 0.088± 0.015 (WMAP7, 2010)

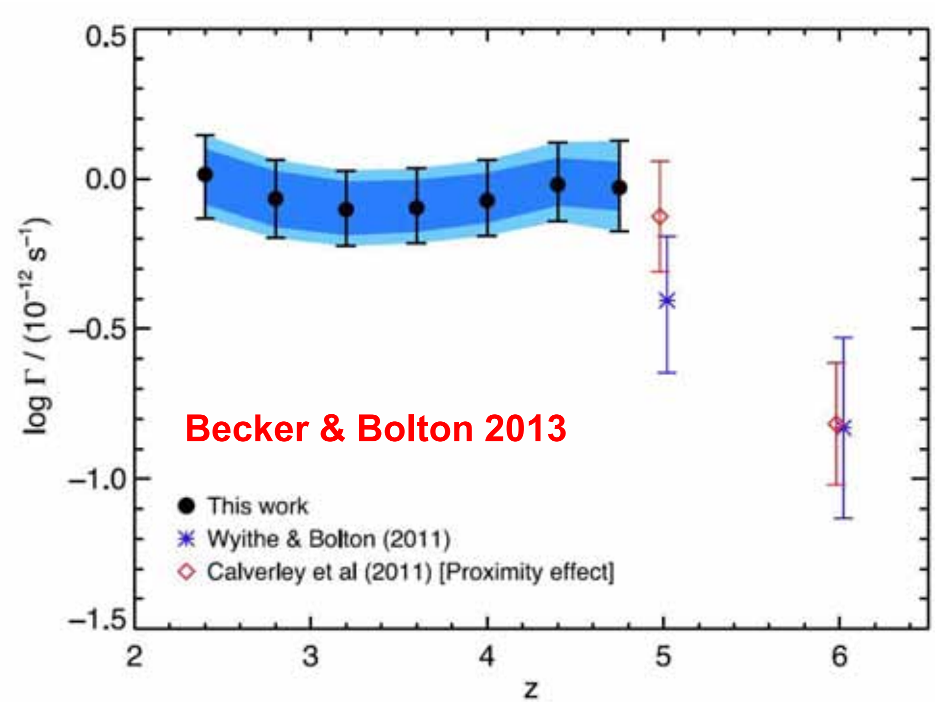
PLANCK Collab. 2014 z(re) = 11 **± 1**
τ=0.066±0.016 2015 z(re) = 8.8 +1.7 -1.4 ←

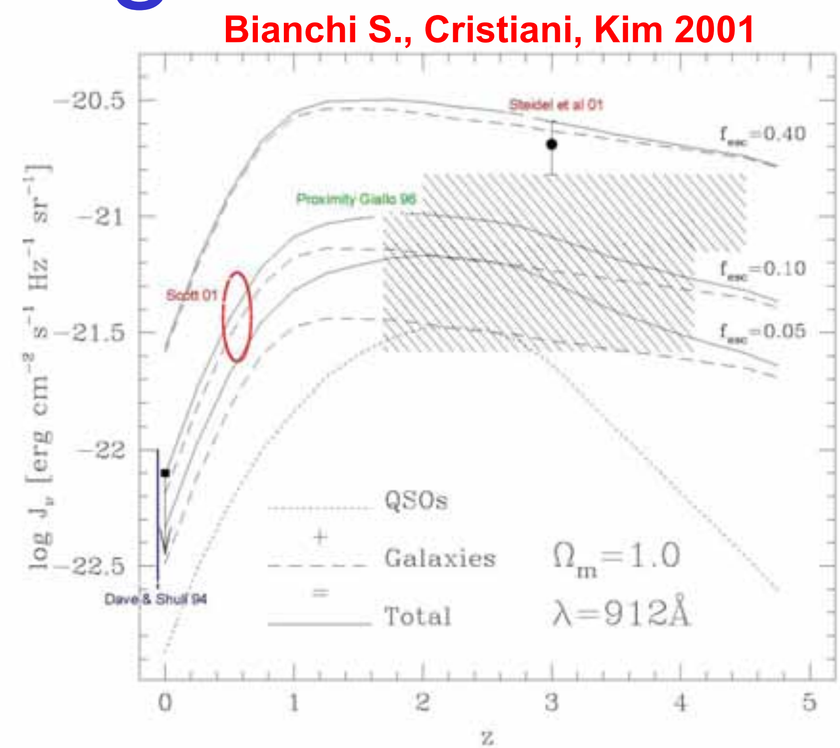


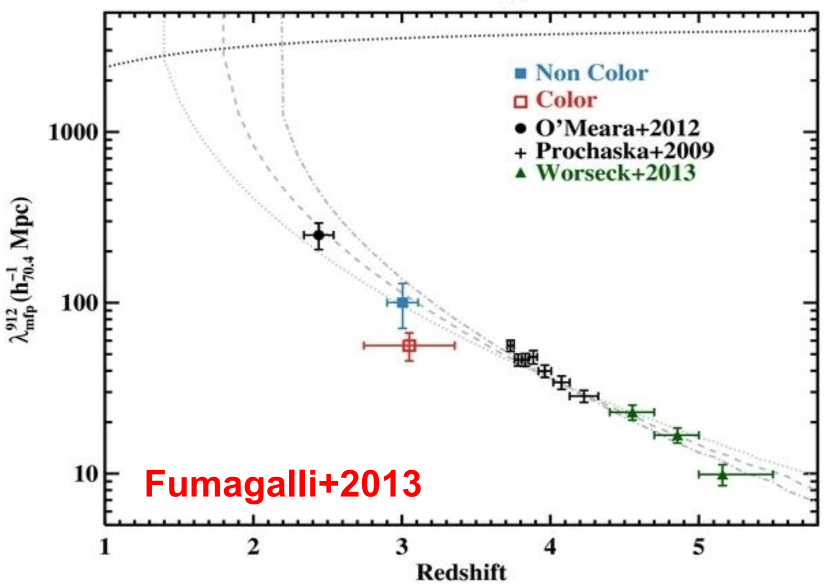
z = 19.00
52
48
44
40
36
32
28
24
20
$log(\dot{N}_{\rm ion,esc})$ $[s^{-1}]$
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
−1.4
−1.6
−1.8
−2.0
$log(f_{HI})$

Norman+ 2016

The UV Background







from IGM simulations/proximity

compare with emission from Galaxies/AGN and with IGM opacity (e.g. mfp @ 912 A)

LBG Contribution

- High-z LBG-LFs Bouwens+11a,b
- Rate of emitted ionizing photons

$$\rho_{\rm SFR}(z)\ ({\rm M_\odot\ yr^{-1}\,Mpc^{-3}}) = \frac{\rho_{\rm UV}(z)\ ({\rm erg\ s^{-1}\,Hz^{-1}\,Mpc^{-3}})}{1.05\times 10^{28}}$$

$$\Gamma_{\rm LBG}(z)\,({\rm s^{-1}\,Mpc^{-3}}) = \kappa\ f_{\rm esc}\,\rho_{\rm SFR}(z)$$

- Total required ionizing photon rate Madau+99

$$\Gamma_{\rm ion}(z)\,({\rm s^{-1}\,Mpc^{-3}}) = 0.027\,\kappa\left(\frac{C}{30}\right)\left(\frac{1+z}{7}\right)^3\left(\frac{\Omega_{\rm b}h_{70}^2}{0.0465}\right)^2$$

$$C(z) = 1 + 43\times z^{-1.71}$$

Haardt&Madau12

Observations: escape fraction of ionizing radiation (LyC) at z<4 gas transmission, dust extinction (+ geometry)

Intrinsic ionizing photons unknown: commonly adopted strategy is to compare the observed flux at LyC to the observed flux at a frequency where the intrinsic emissivity can be inferred

Ionizing photons UV (λ<912A) LyC

Attenuation by ISM (HI , dust)

Attenuation by the IGM (LAF, LLS, DLAs)

NON-ionizing photons UV (λ~1500A)

Attenuation by ISM (dust)

$$\left(\frac{f1500}{f_{LyC}}\right)_{OBS} = \left(\frac{L1500}{L_{LyC}}\right)_{INT} \times 10^{-0.4(A1500-A_{LyC})} \times \times e^{\tau_{HI,IGM}(LyC)} \times e^{\tau_{HI,ISM}(LyC)}, \quad (1)$$

Siana+07
Vanzella+12

$$f_{\rm esc,rel} \equiv \frac{(L1500/L_{LyC})_{\rm int}}{(F1500/F_{LyC})_{\rm obs}} \exp(\tau_{LyC}^{\rm IGM}), \quad (2)$$

Steidel+01

$$f_{\rm esc} = 10^{-0.4A_{1500}} f_{\rm esc,rel}$$

$$f_{\rm esc} = \exp\left[-\tau_{HI,ISM}(LyC)\right] \times 10^{-0.4(A_{LyC})}, \quad (3)$$

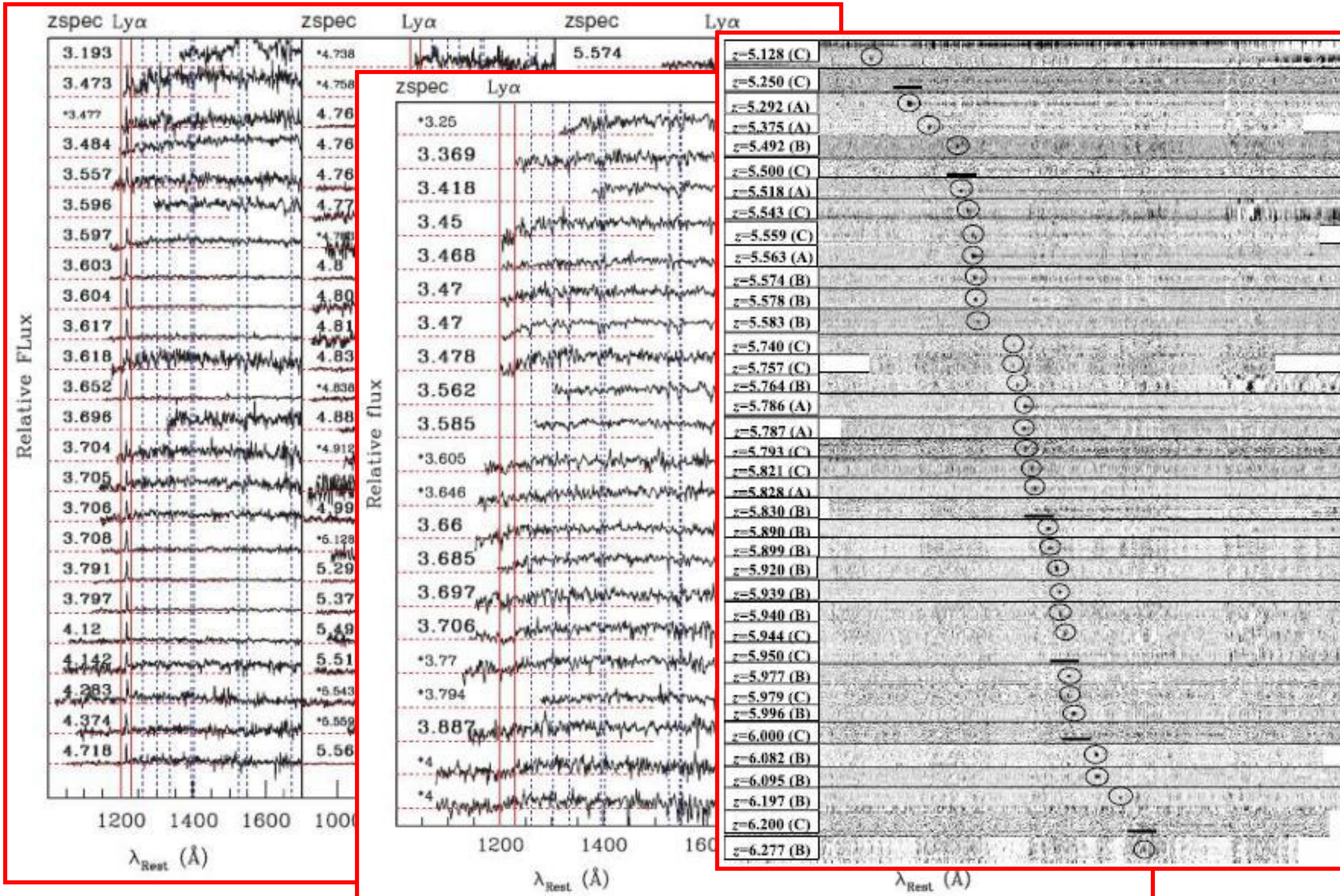
< 1   < 1

$$10^{-0.4(A_{1500}-A_{LyC})} \times f_{\rm esc,rel} = \exp\left[-\tau_{HI,ISM}(LyC)\right] \quad (4)$$

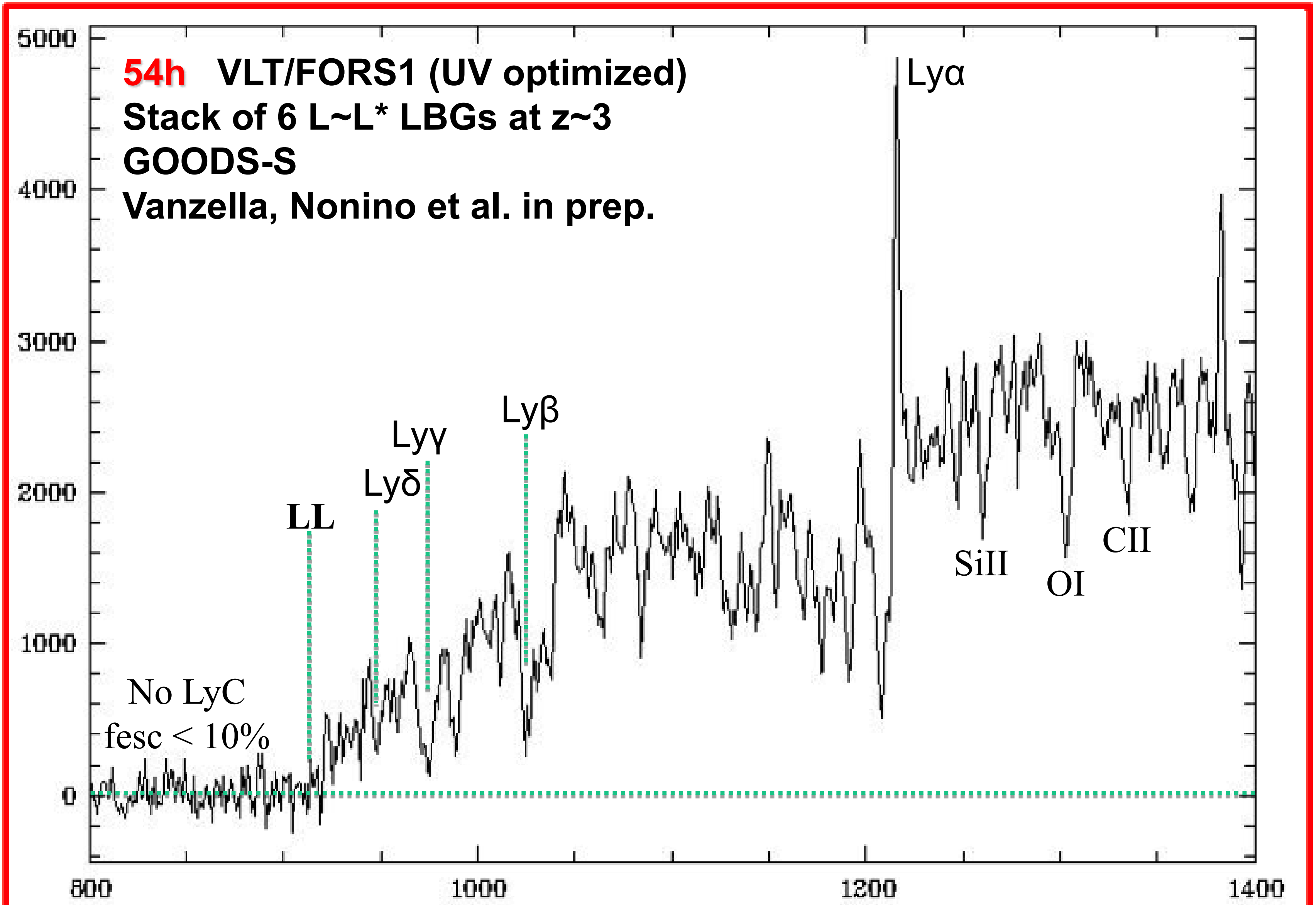
< 1

fesc : is smaller than 1 by definition,
fesc,rel : should be < 1, otherwise $A_{900} < A_{1500}$

1D FORS2 spectra in the GOODS-S survey (Vanzella et al. 2009)

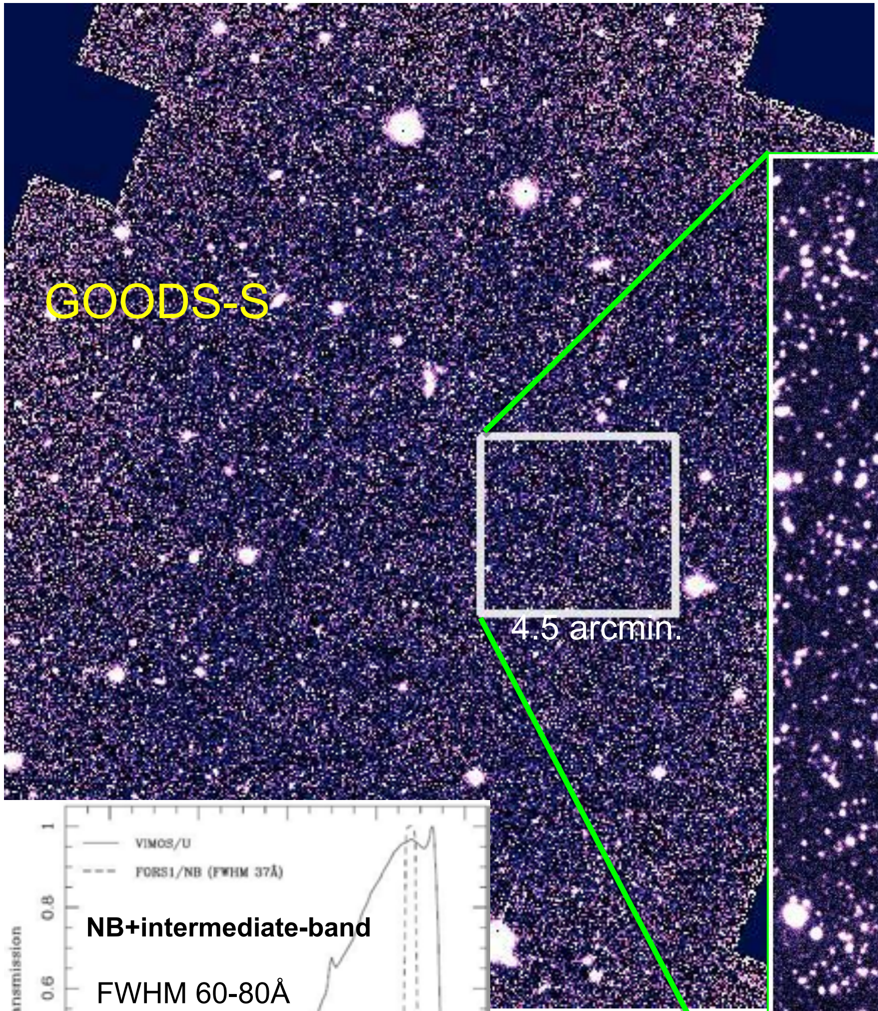


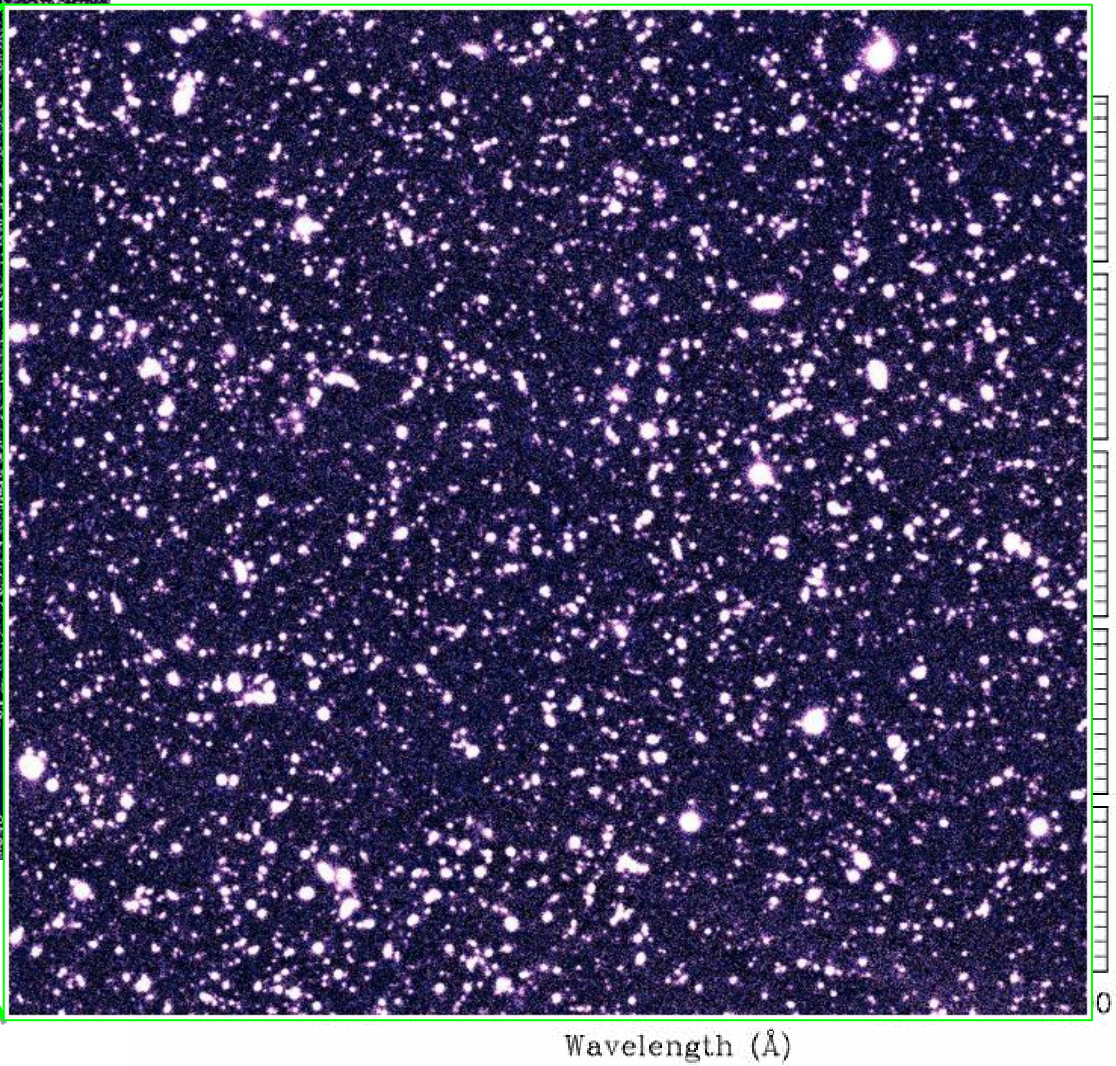
Spectroscopy: GOODS-S

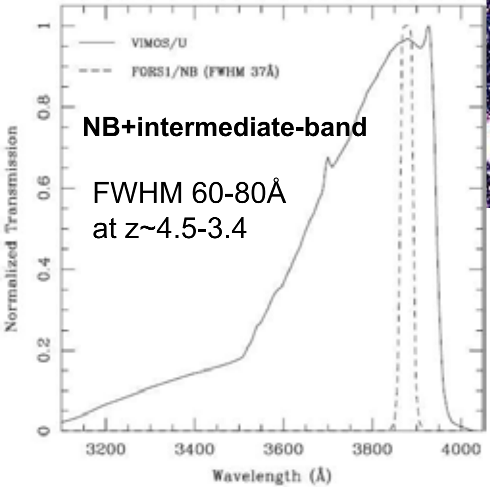


Ultra-deep VLT/VIMOS U-band survey (Nonino+09)

- Mag-U 30.4 (1-sigma) AB at 1σ (1.2'' diam.)
  It probes the LyC (910A-700A) for galaxies at z>3.4
- NB filter 28.9 (1-sigma) , HUDF, LyC at z>3.35 (Hayes+11)

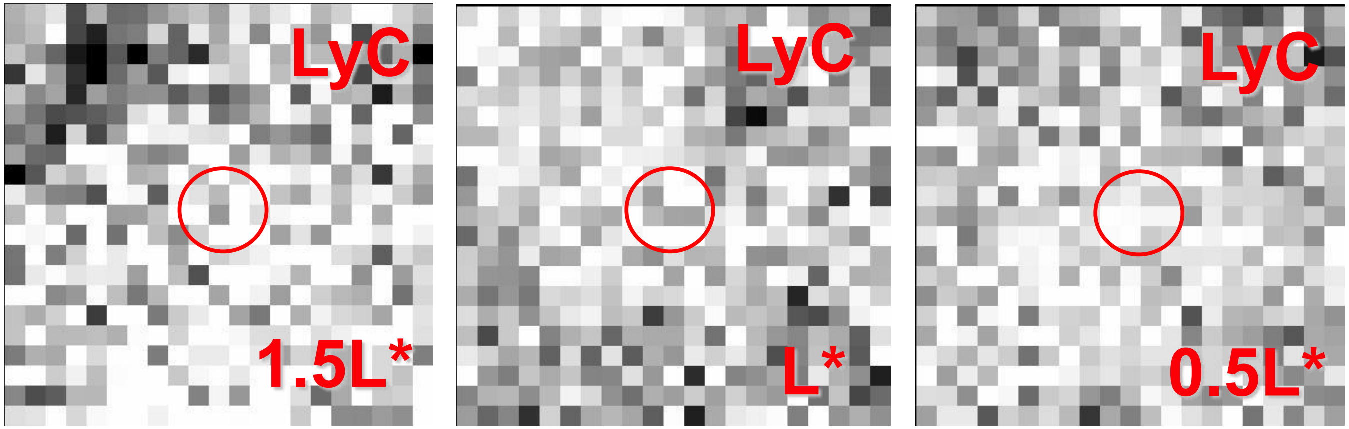






from Vanzella+10; Inoue11 pc

Stacking galaxies 3.4<z<3.7 LBGs (GOODS-S)



Upper limits on fesc
Vanz+10a (stacks + MC Simul.)
foreground statistics
Vanz+10b (MNRAS)

Caveats in the fesc measurements
Vanzella et al. (2012) ApJ

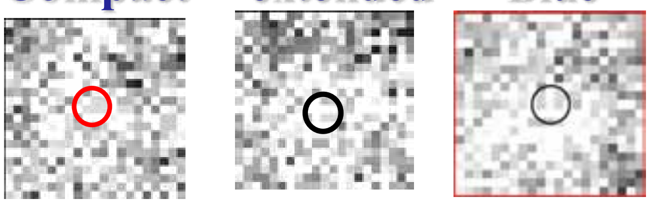
22 LBGs <Δm>=7.5 **fesc,rel < 3%**

20 LBGs <Δm>=6.6 **fesc,rel < 5%**

25 LBGs <Δm>=6.1 **fesc,rel < 9%**

U>32.7 (1σ) fesc,rel < 2.36%

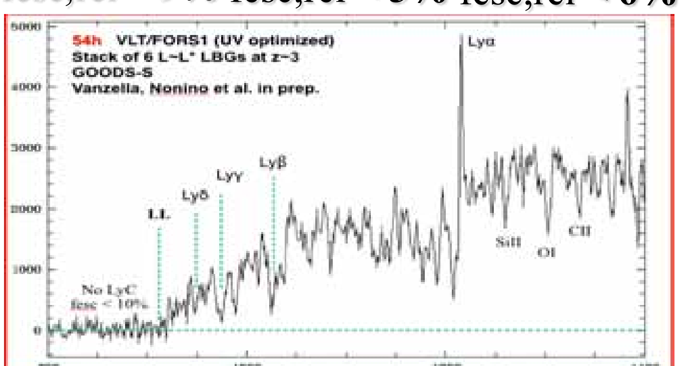
Compact **extended** **Blue**



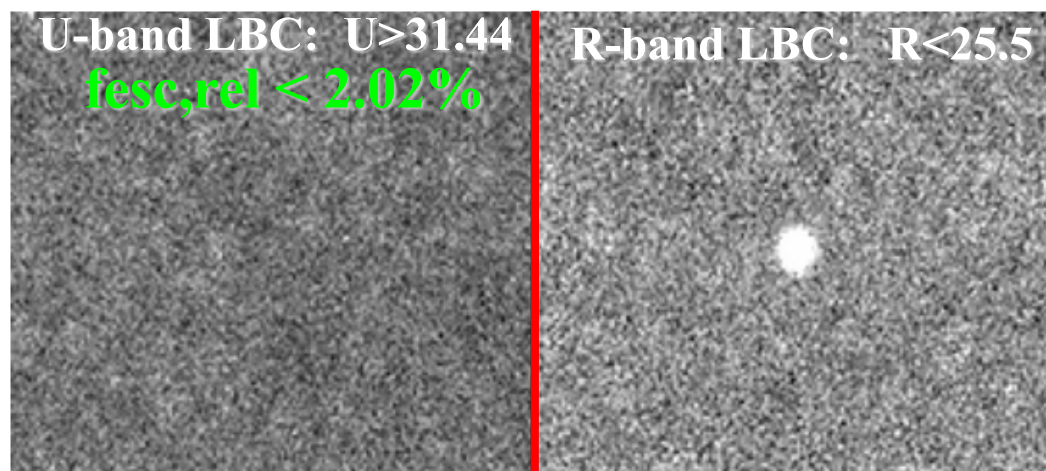
h.l.r. <1kpc fesc,rel < **9%**

h.l.r. >1kpc fesc,rel < **5%**

β [-2 ... -2.35] fesc,rel < **6%**

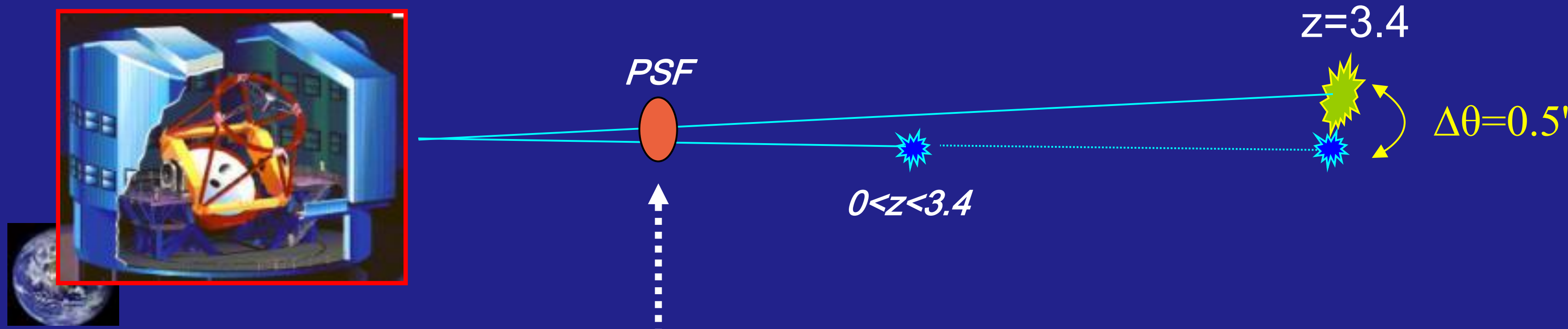


COSMOS field. Boutsia+11; Grazian et al. in prep.



48 galaxies, 3.27<z<3.4, <z>=3.3, fesc,rel < 2.02%
VUDS spec survey (Le Fevre et al. 2014, 10000 2<z<6)

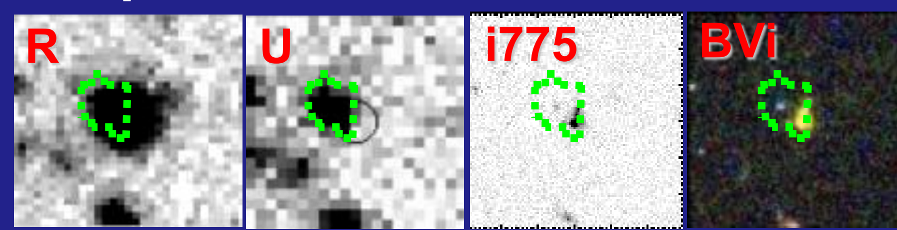
f_{esc} from z>~3 galaxies: contamination from low-z



Example in GOODS z=3.41

$$f_{\rm esc,rel} \equiv \frac{(L1500/L900)_{\rm int}}{(F1500/F900)_{\rm obs}} \exp\left(\tau_{900}^{\rm IGM}\right)$$

(L1500/L900)int=3, A1500=0.7, Tr(igm)=1



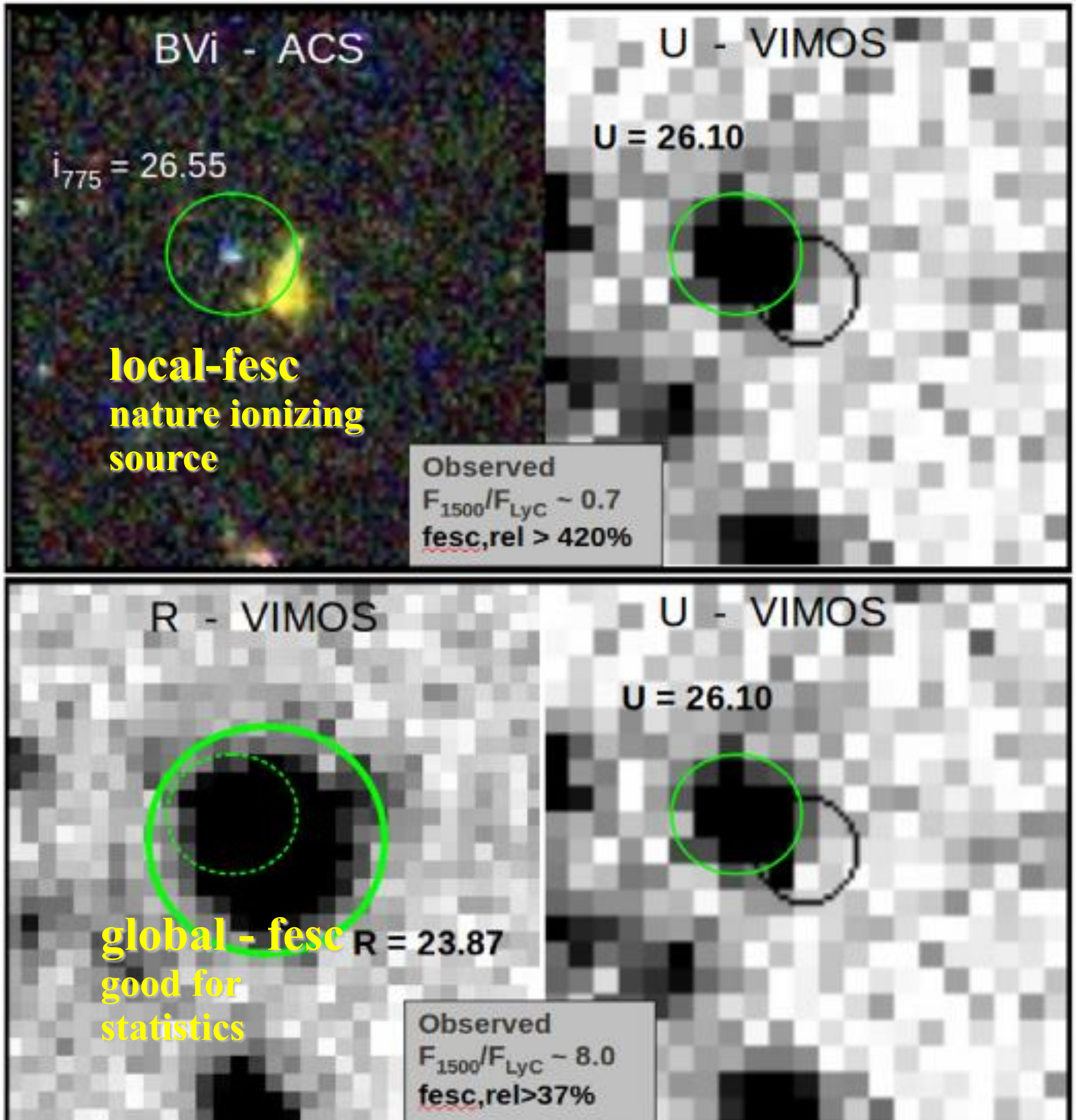
Ground based:
fesc > 17%
fesc,rel > 33%

From U and HST:
fesc > 230%
fesc,rel > 433%

Δ(B-V) = 1.71

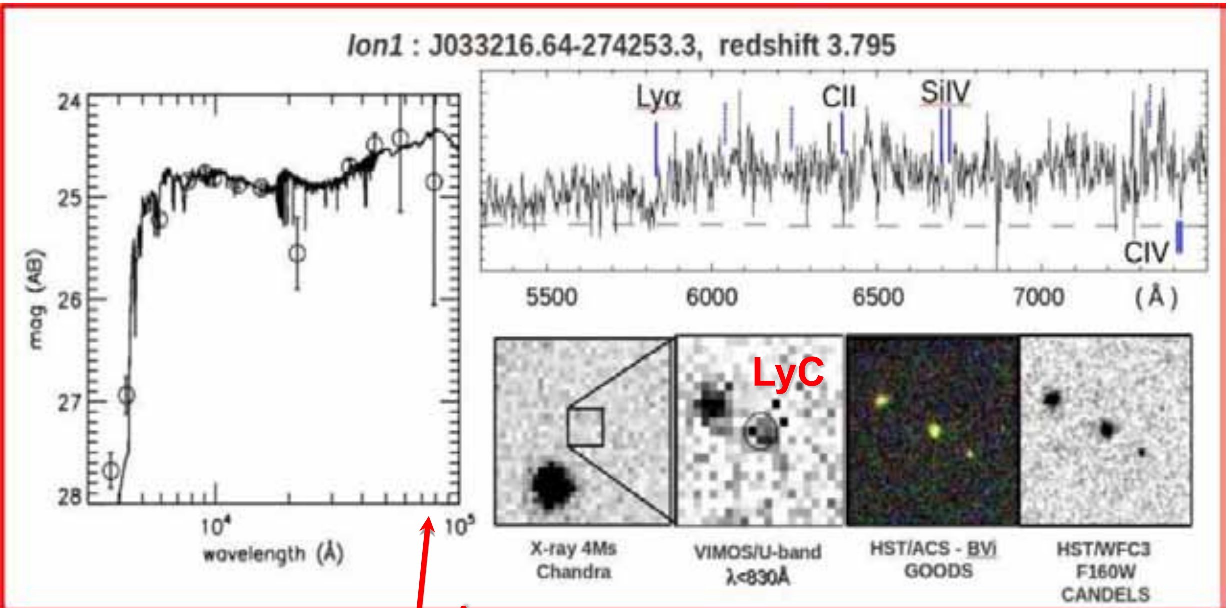
Prob. (zphot>3.4) < 1%

Foregrounds not always explain U-band detections (e.g., Nestor+12, Mostardi+13)


BVi - ACS
i_{775} = 26.55
local-fesc
nature ionizing
source
U - VIMOS
U = 26.10
Observed
F_{1500}/F_{LyC} ~ 0.7
fesc,rel > 420%
R - VIMOS
global - fesc
good for
statistics
R = 23.87
U - VIMOS
U = 26.10
Observed
F_{1500}/F_{LyC} ~ 8.0
fesc,rel>37%

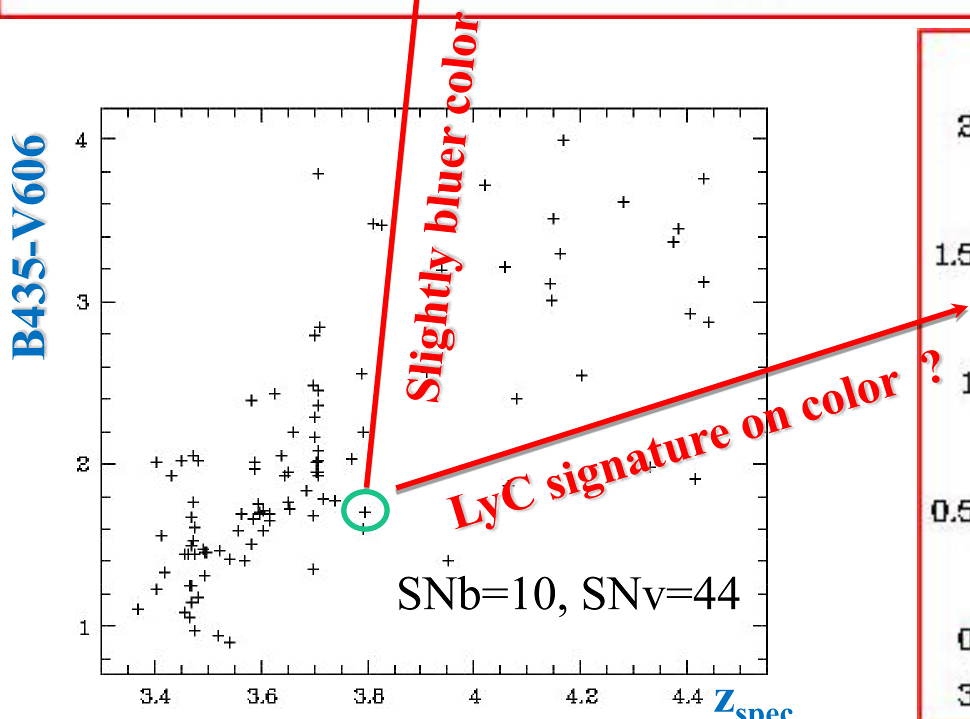
ONLY one LyC detected (1/100 LBGs)

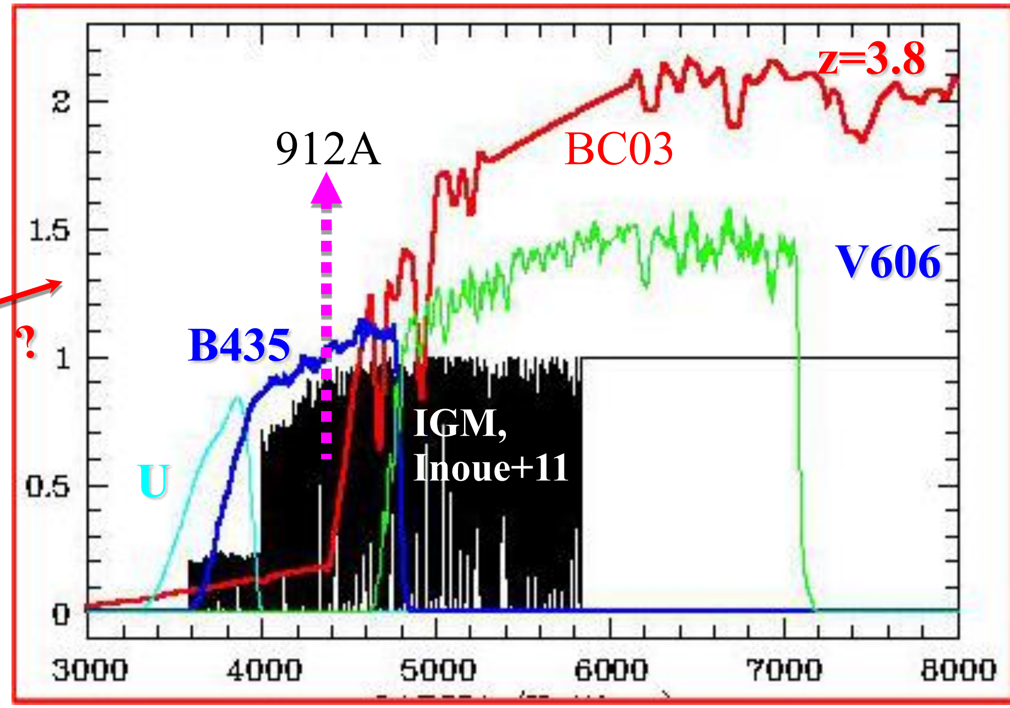
Ion1



zspec=3.795; zphot(CANDELS)=3.73
- **SFR~30 Msol/yr**
- **M*~2x10^9 Msol**
- **Re<0.8 Kpc (<300pc**, Giavalisco PC)
- **β = -2.1 +/- 0.2**
- **fesc>50% (L1500/L900=3, Tigm=1)**
- **No Lya line (fesc>80% ?,Nakajima & Ouchi+14)**
- **No X-ray, Lx[2-10kev] < 3x10^42 erg/s**

Linking LyC to Lya, ISM lines (CII, SiII):
Behrens+14; Verhamme+14;
Jaskot & Oey +14, Heckman+11 …





fesc from galaxies: current observations

Z~0 fesc ~ 0.01-0.02 MW (Bland-Hawthorn & Maloney 1999; BH et al. 2001)

fesc < 0.02-0.05 (spec. Leitherer+95; Deharveng+01)

fesc ~ 0.03 Haro11 (Leitet+11, but see Grimes+07, fesc<~2%)

Z~1 fesc < 0.02-0.05 (Siana+10; Malkan+03; Cowie+09; Bridge+11; Ferguson+01)

Z~2 <fesc> < 0.075 (c.l. 95%) (Chen+07) from GRBs

Z~3 fesc < 0.73 Inoue+05 (phot, 2 LBGs)

< 0.15 Fernandez-Soto+03 (phot, 27 LBGs)

< 0.16 Giallongo+02 (spec, 2 LBGs)

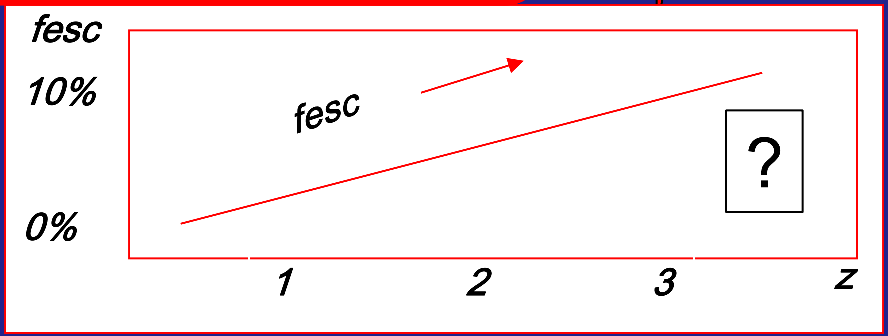
< 0.05 Boutsia+11 (phot, 11 LBGs) (LBT deep, ApJ)

fesc > 0.5 (spec. Stacking; ~30 LBGs, Steidel+01)

fesc > 0.1 (spec. Stacking; 14 LBGs, Shapley+06)

fesc > 0.2 (phot. NB, Iwata+09; Nestor+11) ~ 50 LyC

Many show spatially offset LyC

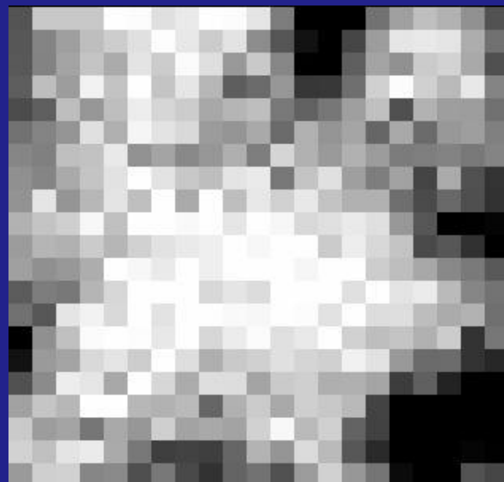


See Inoue+06, Haardt+11

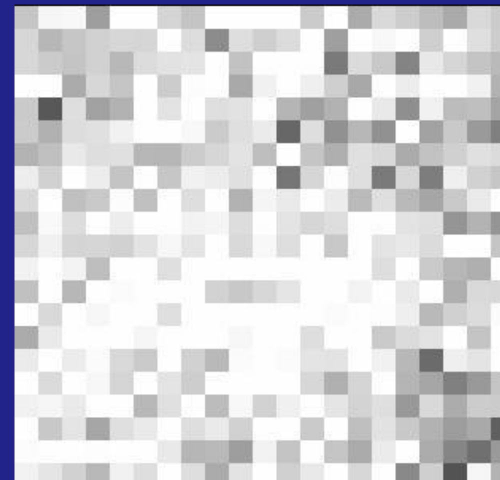
Stacking the 30 bluest LBGs ($F(\lambda) \sim \lambda^{\beta}$)

$\langle z \rangle = 3.60$, $\langle \beta \rangle = -2.10$ [-1.91,-2.40] , $\langle i_{775} \rangle = 25.17$

LBG



Average



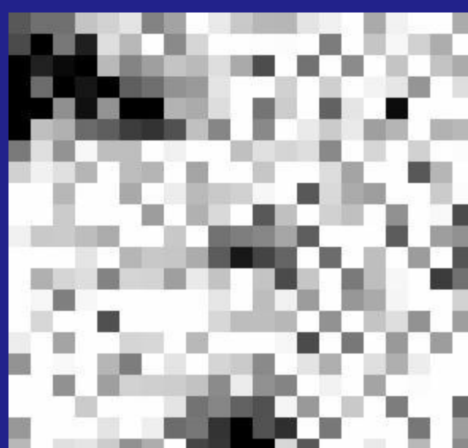
Median

β derived from Castellano+11 (arXiv-1109.1757)

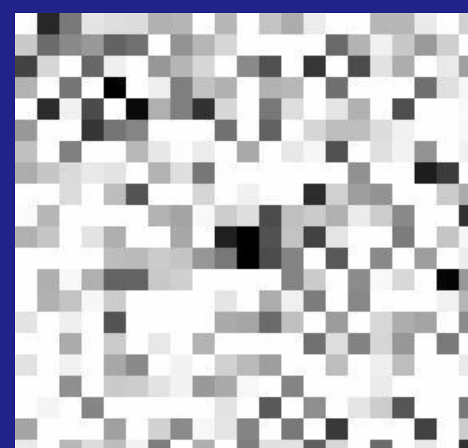
NO SIGNAL
fesc < 0.06
(fesc~fesc,rel)

Stacking the AGNs with z>3.4 (7 sources)

AGN



Average



Median

The IGM is not killing completely the ionizing photons

$\langle z \rangle = 3.634$, $\langle \beta \rangle = -2.04$, $\langle i_{775} \rangle = 24.12$

AGN Contribution

QSO LFs Hopkins; Fiore+12

- **Rate of emitted ionizing photons**

$$\Gamma_{\rm AGN}(z)\ ({\rm s^{-1}Mpc^{-3}}) = \int_{\nu_{\rm H}}^{\nu_{\rm up}} \sigma_\nu \frac{\rho_\nu(z)}{h_{\rm p}\nu}$$

$$\rho_\nu(z)\ ({\rm erg\ s^{-1}Hz^{-1}Mpc^{-3}}) = \int_{L_{\rm min}}^{\infty} \Phi(L,z)L_\nu(L)\,{\rm d}L$$

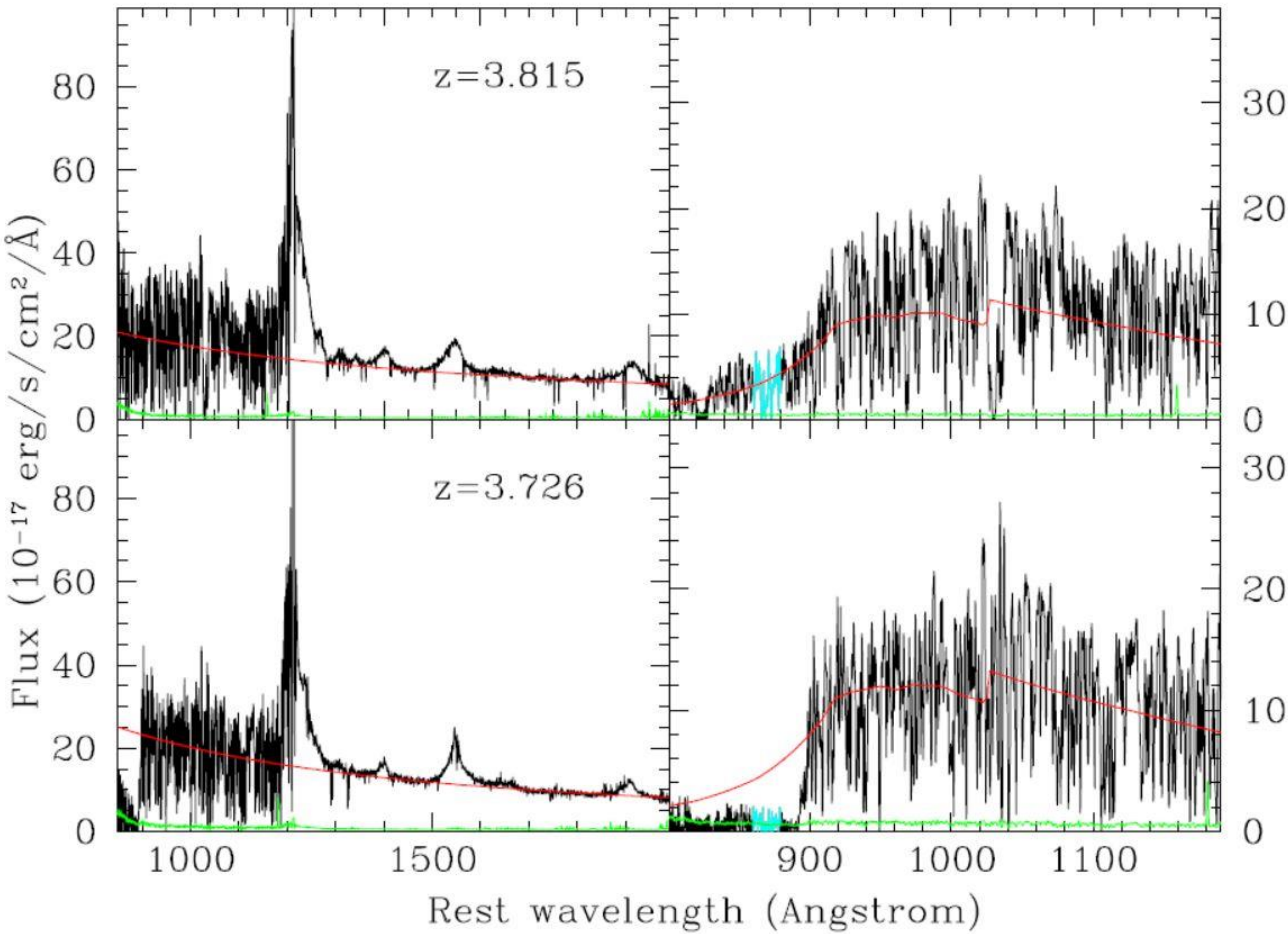
- **Total required ionizing photon rate** Madau+99

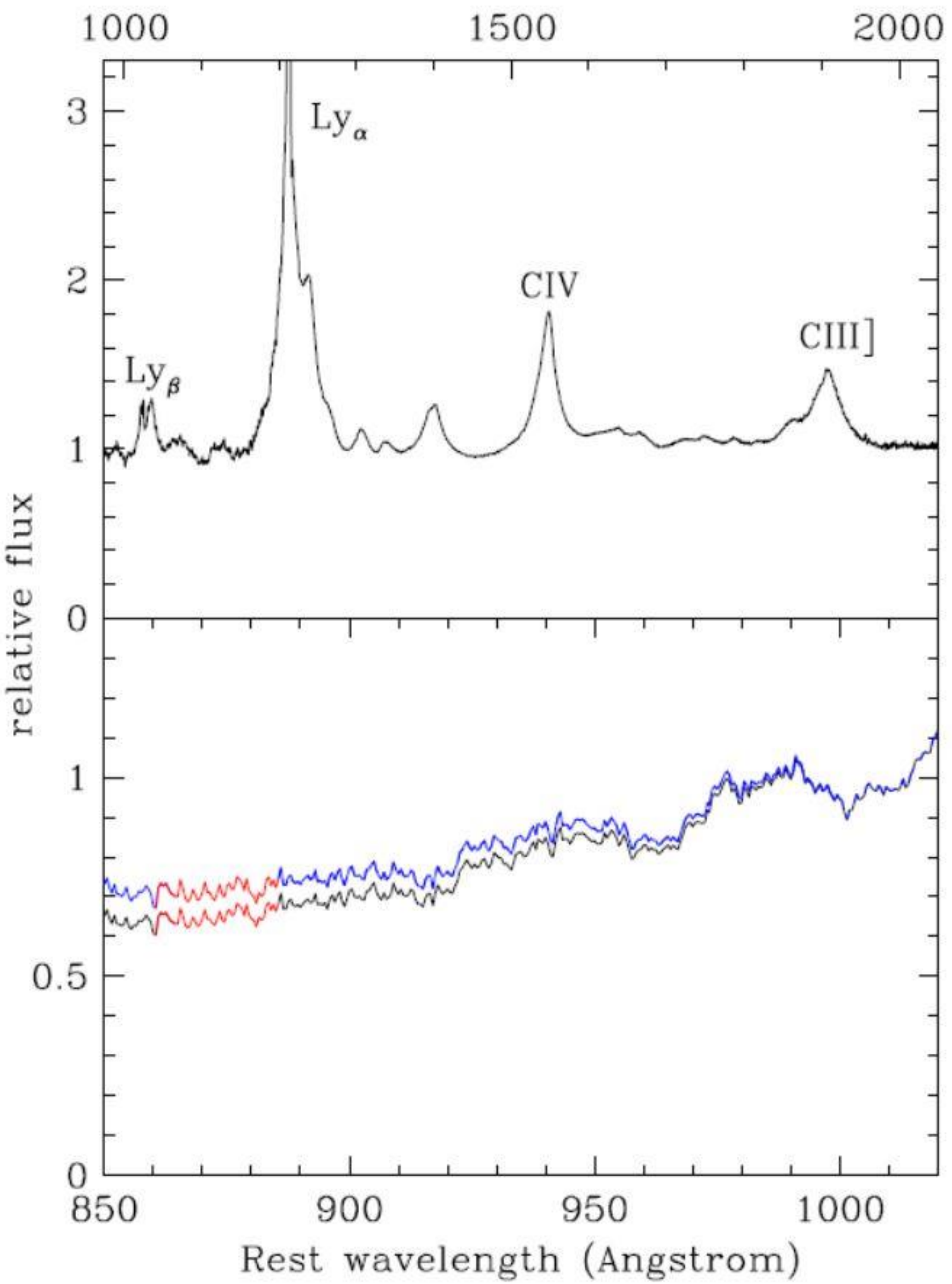
$$\Gamma_{\rm ion}(z)\,({\rm s^{-1}\,Mpc^{-3}}) = 0.027\,\kappa\left(\frac{C}{30}\right)\left(\frac{1+z}{7}\right)^3\left(\frac{\Omega_{\rm b}h_{70}^2}{0.0465}\right)^2$$

$$C(z) = 1 + 43\times z^{-1.71}$$

Haardt&Madau12

Cristiani+16 submitted





Cristiani+16 submitted

Spectral slope

$$F_\lambda \propto \lambda^{-\gamma}$$

<γ>=1.31 (disp.0.36)
cfr. Shull+12,
Stevans+14
Telfer+02 <γ>=1.31
@ <z>=1.17

Cristiani+16 submitted

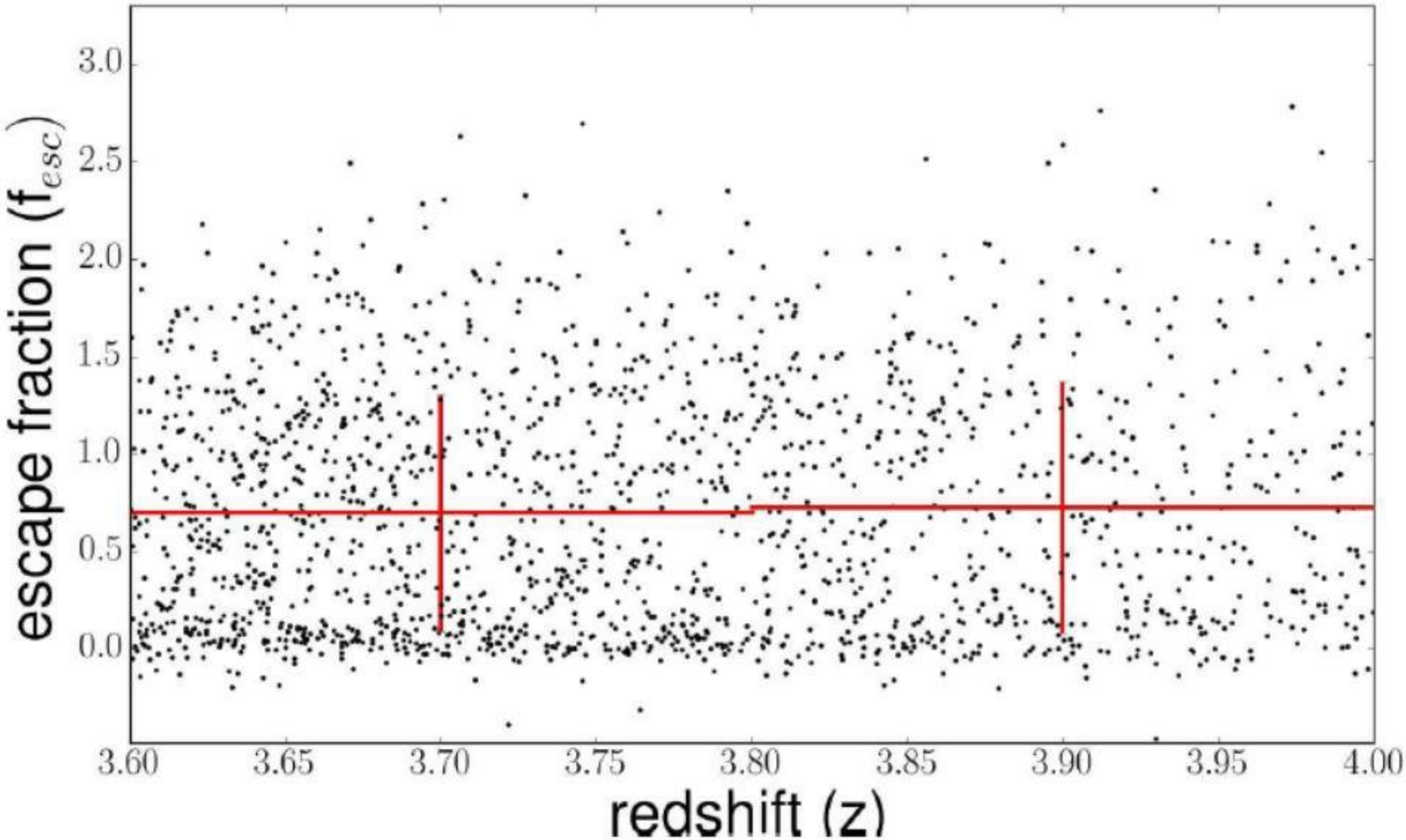


Figure 6. Escape fraction measured in the QSO spectra as a function of the redshift. The mean values in the intervals $3.6 < z \leqslant 3.8$ and $3.8 < z \leqslant 4.0$ are shown as continuous red segments, with the dispersion estimated as half of the difference between the 84.15 and 15.87 percentiles.

Cristiani+16 submitted

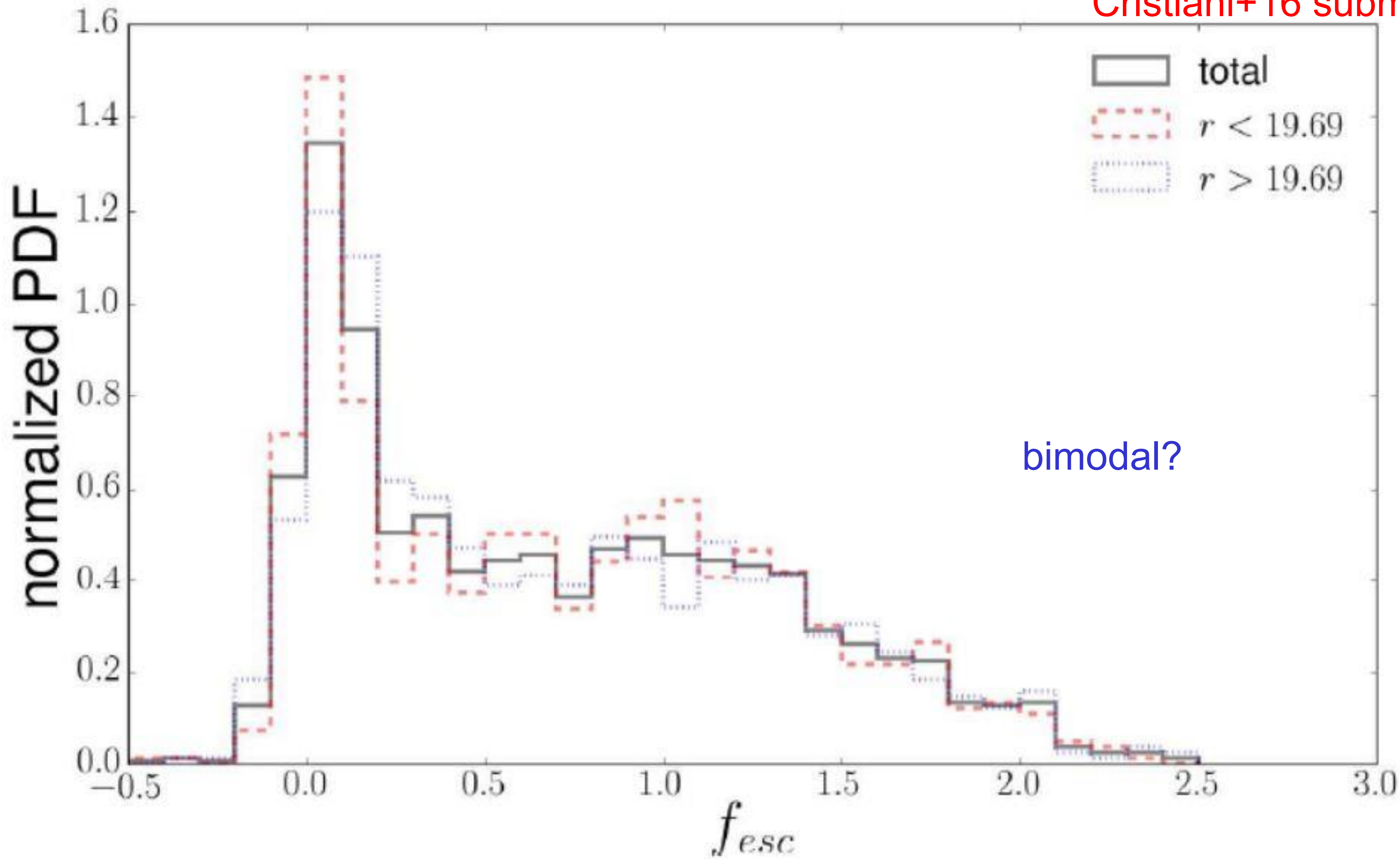
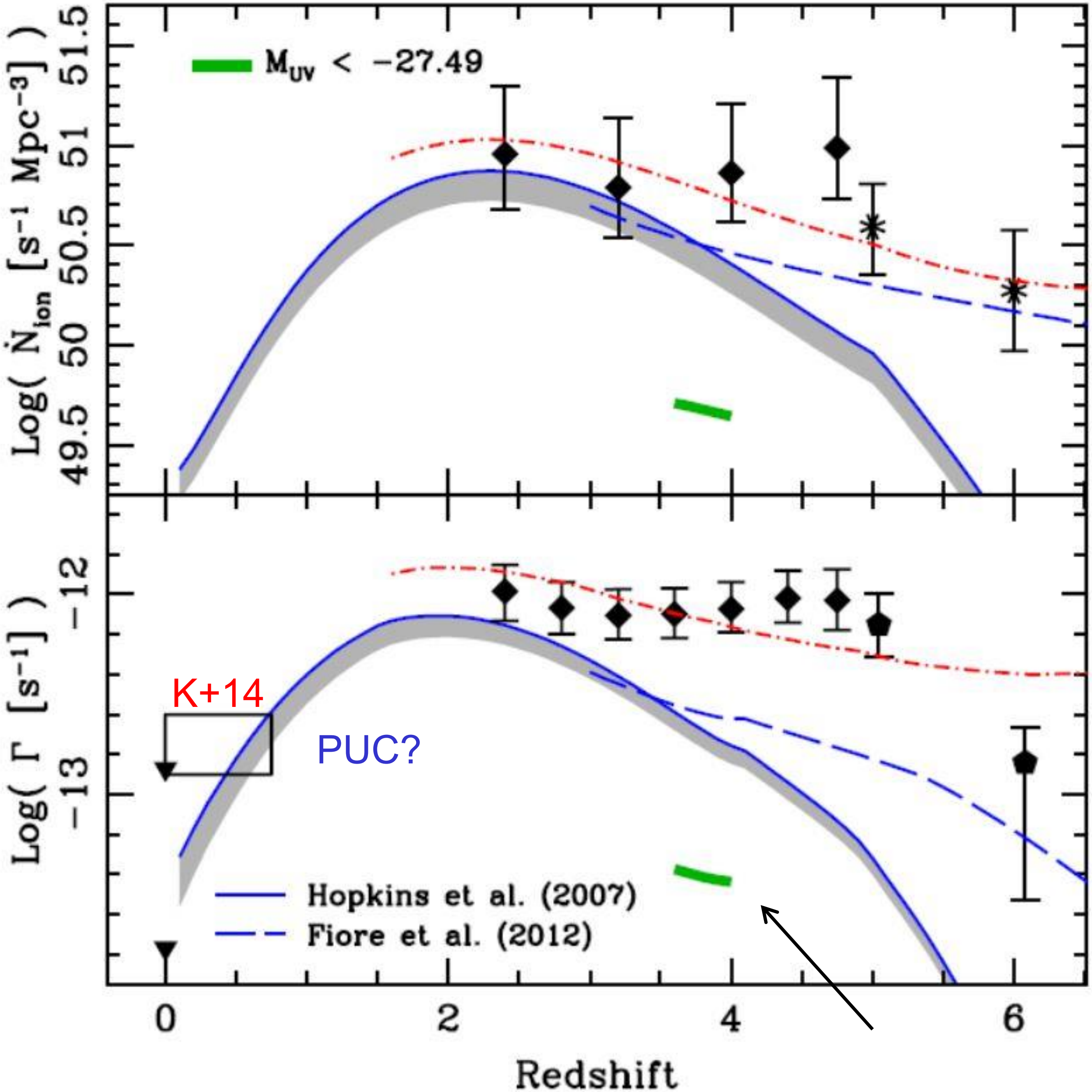
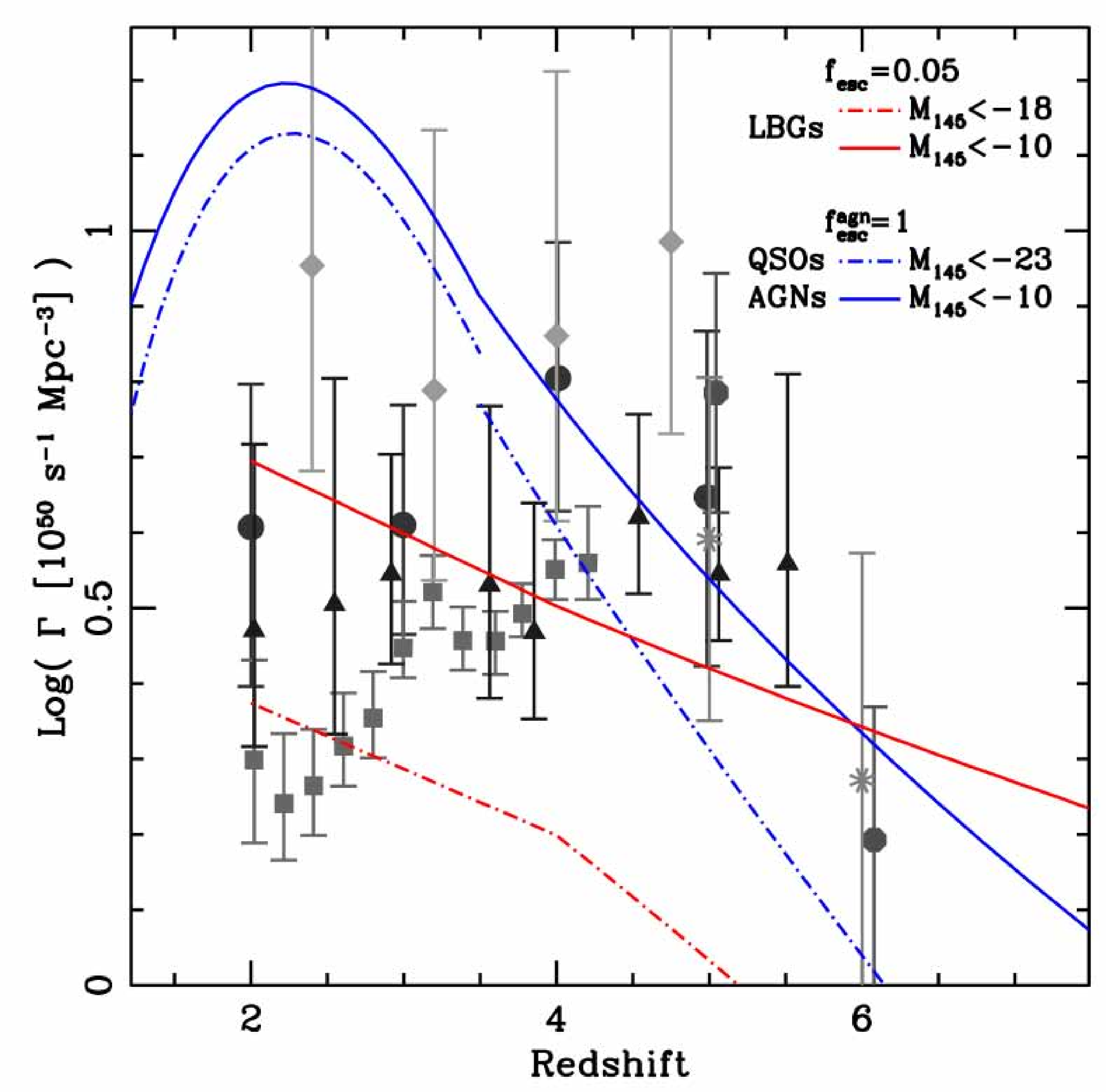


Figure 7. Normalized probability distributions of the escape fraction $f_{esc,q}$ for QSOs in the redshift interval $3.6 < z \leqslant 4.0$. The black continuous line shows the full sample. The red dashed line corresponds to objects with $r \leqslant 19.69$, while the blue dashed line refers to objects with $r > 19.69$.

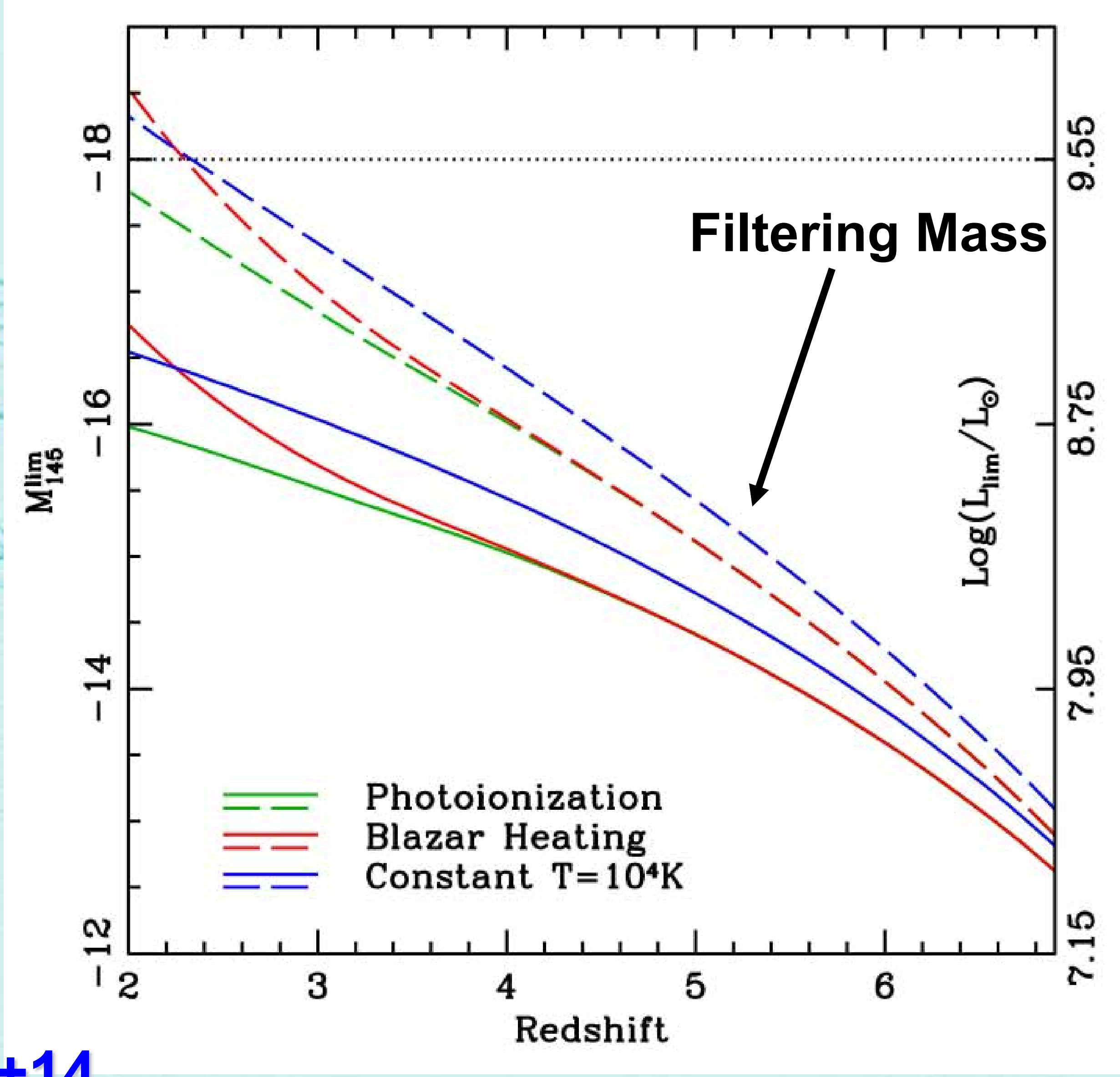


Cristiani+16 submitted
Fesc, QSO= 71-78%
Fesc, gal = 5.4-7.6%
characteristic mass!
M_UV < −27.49
Log(Ṅ_ion [s^-1 Mpc^-3])
Log(Γ [s^-1])
Redshift
K+14
PUC?
Hopkins et al. (2007)
Fiore et al. (2012)

Cosmic Ionizing Background



Limiting Magnitude

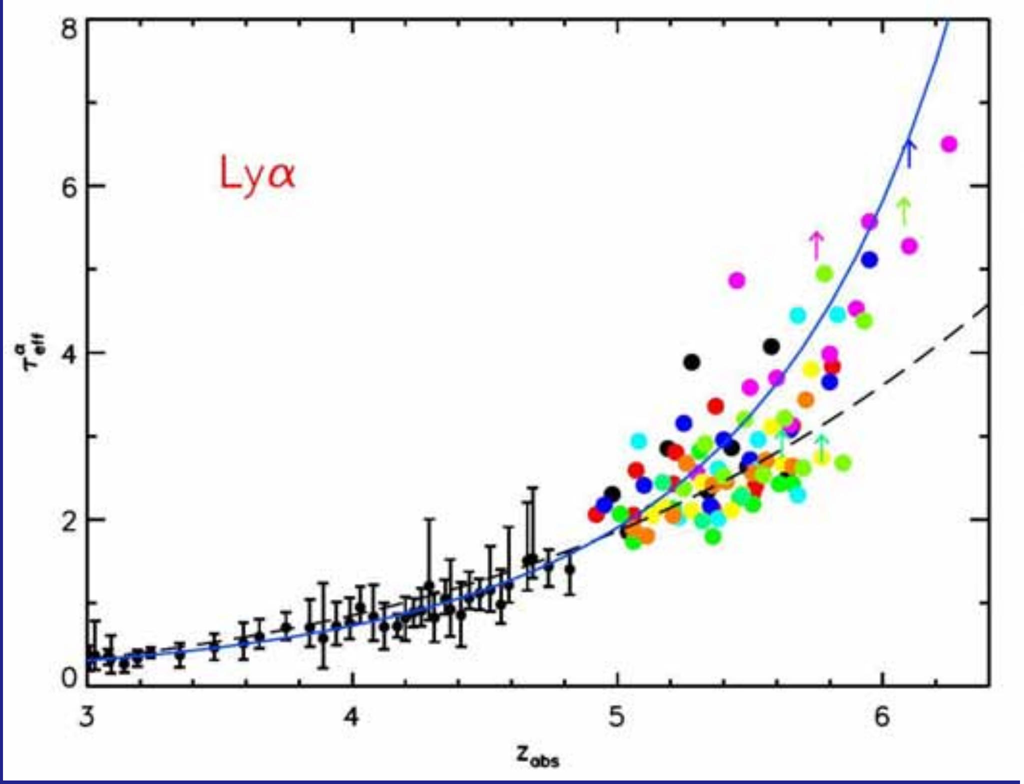


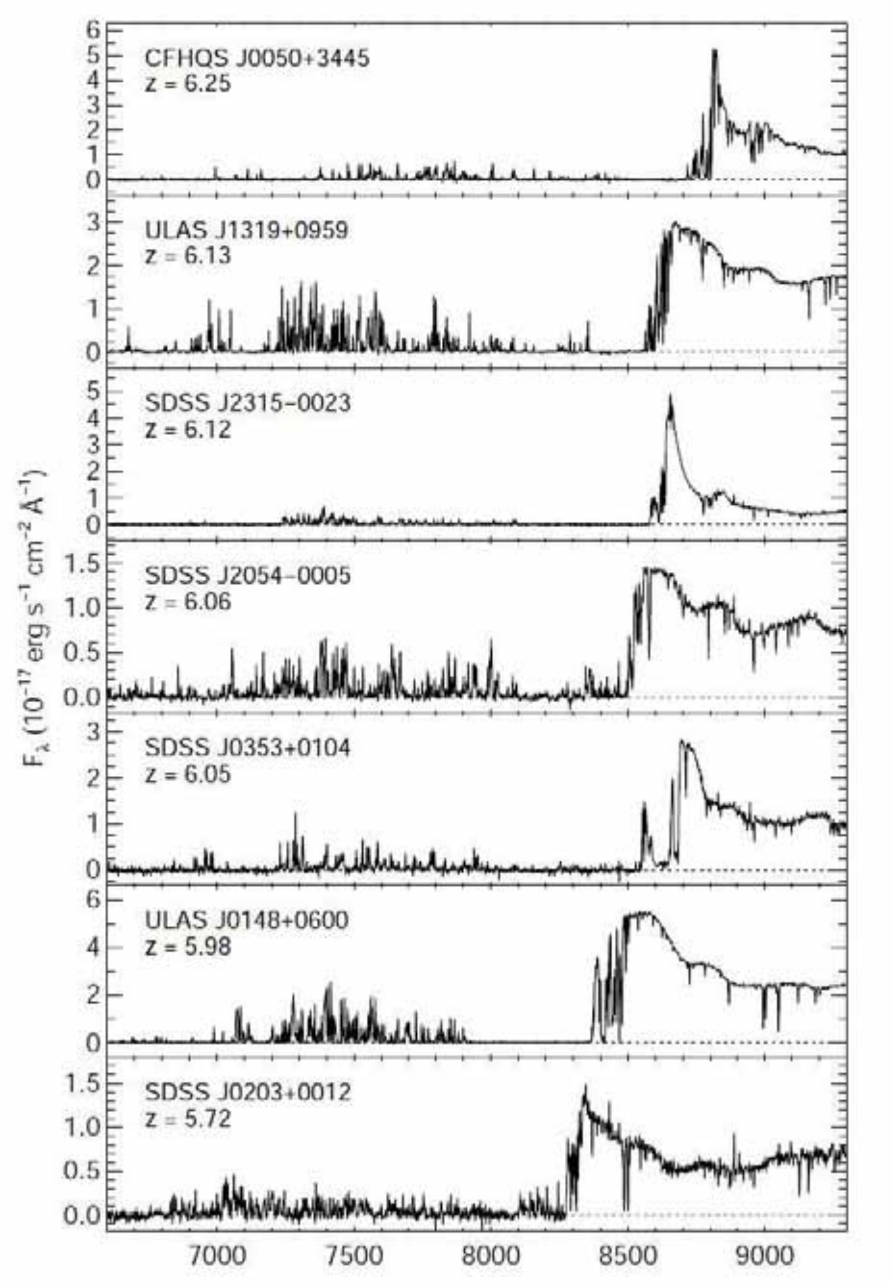
Fontanot+14

HI reionization: constraints (1) Ly forest

QSO Gunn-Peterson trough

→ IGM ionized by z~6 (Fan+06, see also McGreer 2011, Becker+, 2007, 2015)





Patchy reionization

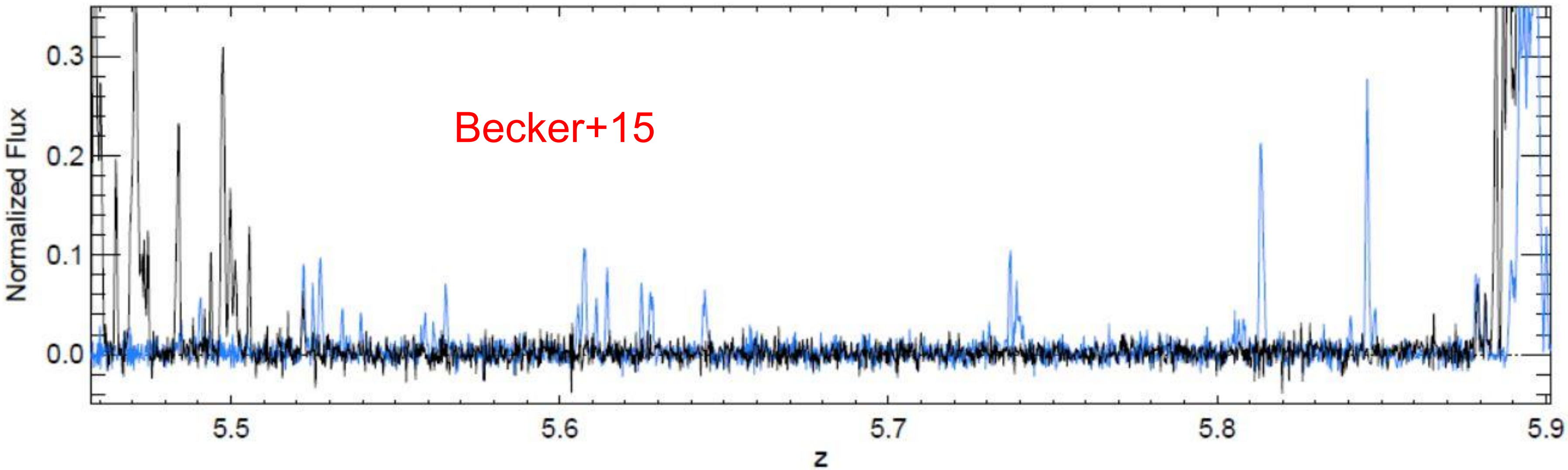


Figure 5. The Lyα trough (black) towards ULAS J0148+0600 overlaid with the Lyβ forest (blue) at the same redshifts. Lyγ absorption also occurs in the Lyβ forest at $z \leqslant 5.63$.

What are the sources? (overdensities of galaxies conncted to bubbles)
Density driven fluctuations? (temperature??)