Galaxies, Near and Far
Conference In honour of Bob Fosbury

Lyman break galaxies at z>3 and their contribution to the ionizing UV background

Eros Vanzella (INAF - Trieste)

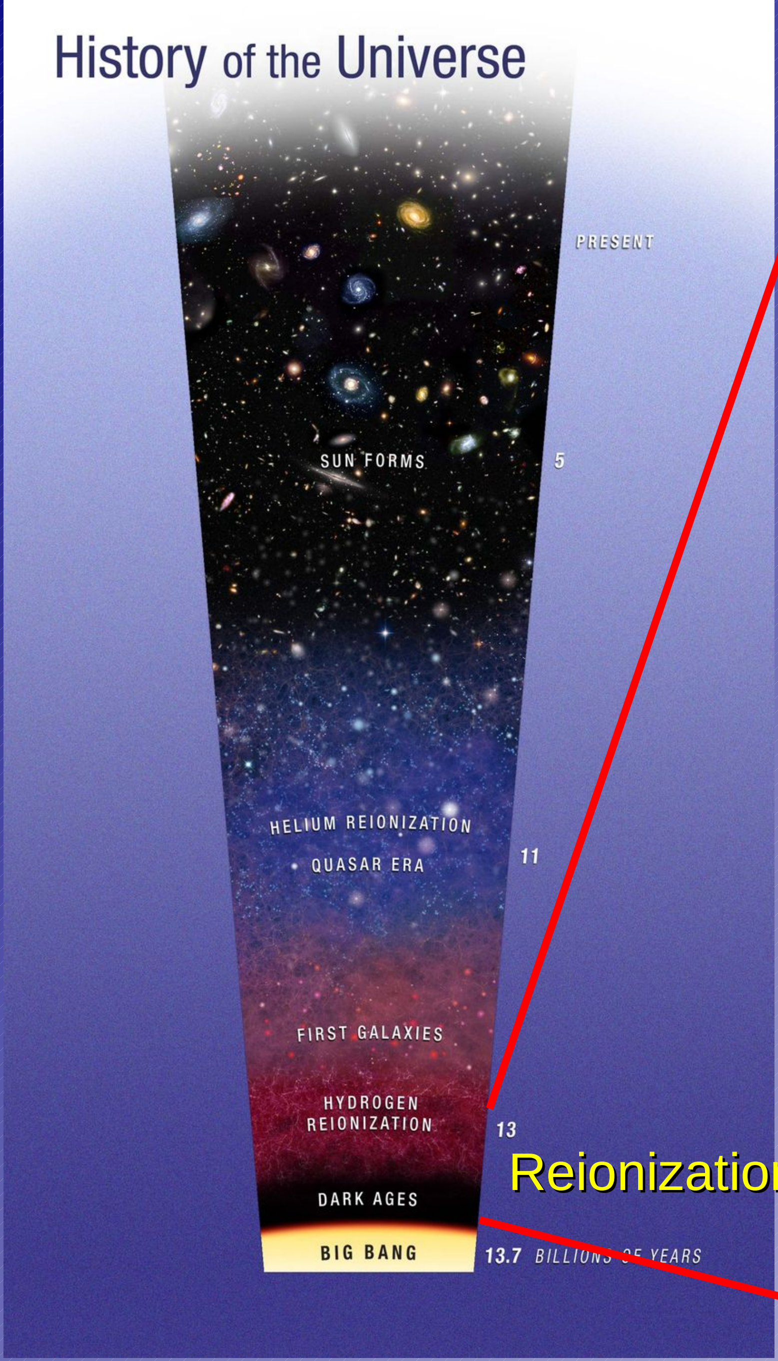
Collaboration
GOODS Team, ESO-GOODS (+ INAF-OAR)

Outline

HI Re-ionization, attack the problem from two sides, z~3-4 and z>7:

- ***What are we learning (observationally) from star-forming galaxies @ z~3-4 as "stellar ionizers" ?***
- ***New ultra-deep limits on escaping ionizing radiation from star-forming galaxies (GOODS) @ z~3.7***
- ***Approaching the re-ionization epoch, first galaxies confirmed at redshift beyond 7***

Motivation: HI reionization



Reionization

WMAP τ_{es}
→ Reion. began at z~10-15 (Dunkle+09)

QSO Gunn Peterson trough
→ IGM ionized by z~6 (Fan+06)

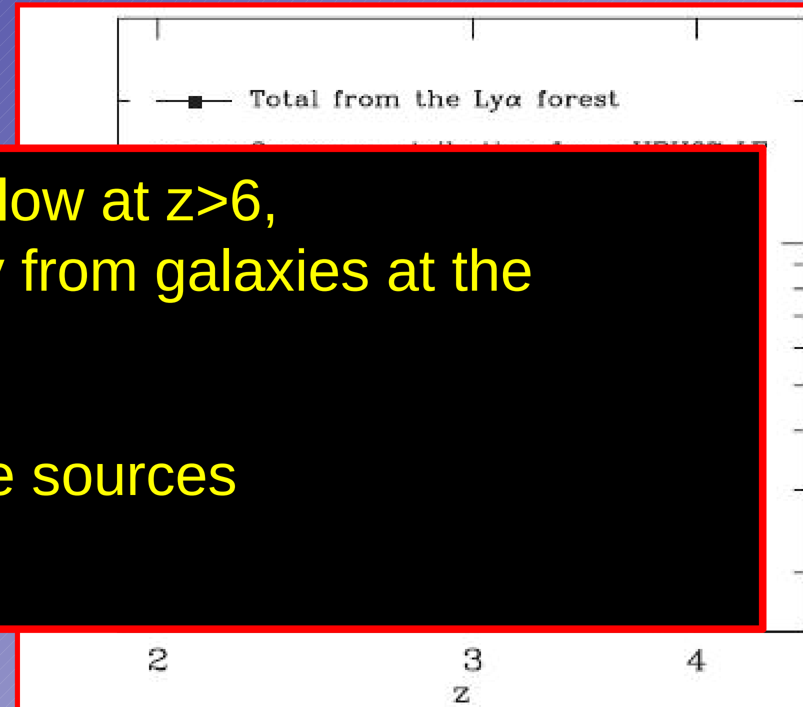
- What sources were responsible for reionization ?

- How reionization proceeds ?
(e.g. Multi-phases; Clustering; etc.)

- What keeps the Universe ionized down to lower redshift ?

- ...

What reionize (and keep ionized) the Universe ?



Faucher-Giguere+08

- the transmission of the IGM in extremely low at z>6,
it is impossible to estimate the *fesc* directly from galaxies at the epoch of reionization.

- measure *fesc* at z ~ 3 - 4 and relate these sources
to objects at z > 6

What is the ionizing photon production rate from galaxies and their contribution to the global ionization rate of hydrogen ?

$$\dot{\rho}_c(z) = \frac{0.027\, M_\odot}{\mathrm{Mpc}^3\,\mathrm{yr}} \frac{\mathcal{C}/f_{\rm esc}}{30} \left[\frac{1+z}{7}\right]^3 \left[\frac{\Omega_b}{0.0465}\right]^2$$

Pawlik+09

We must chart the abundance (LF) and SFR as a function of time (redshift) and estimate *fesc*, (escape fraction) of ionizing photons from star-forming galaxies

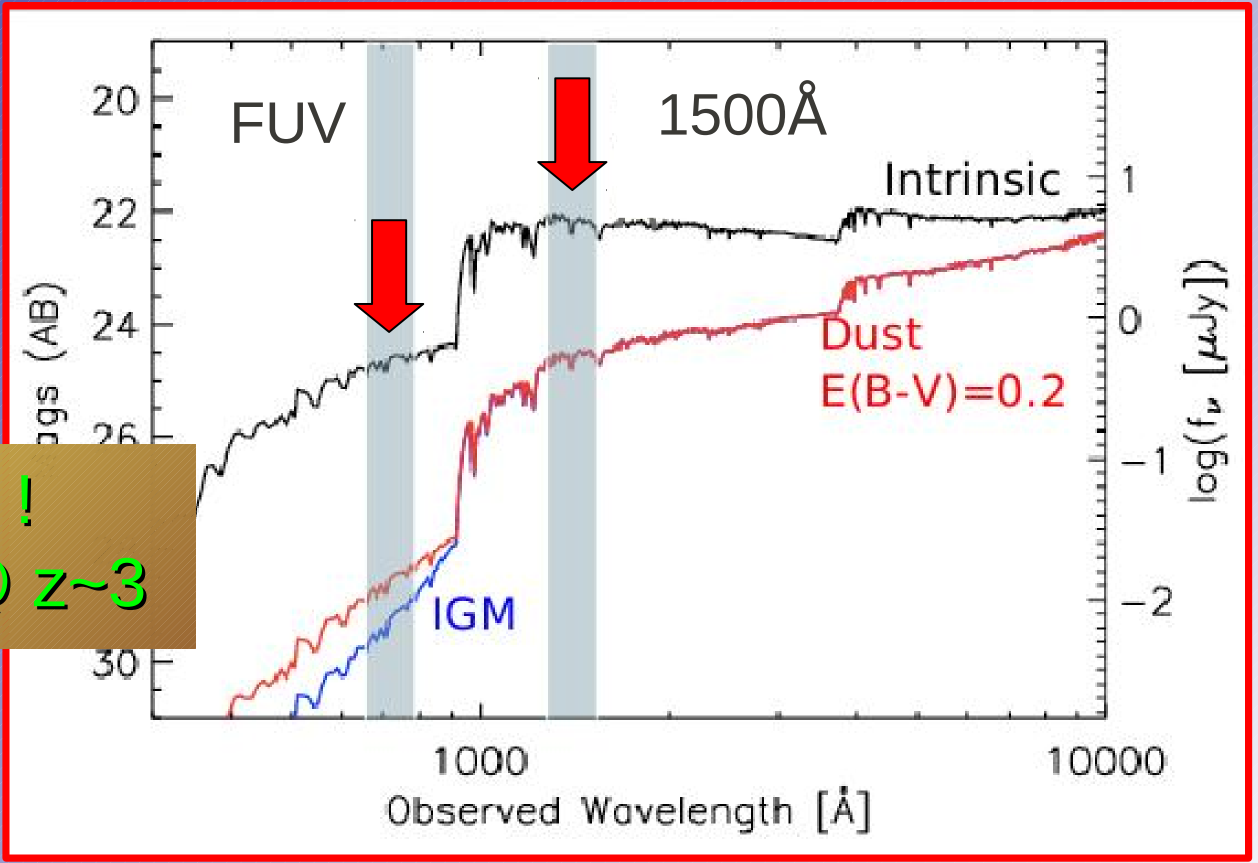
Estimating fesc: Method

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

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

(Steidel et al. 2001, Shapley et al. 2006)

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.



Difficult measure !

Δm~5 → fesc~8% @ z~3

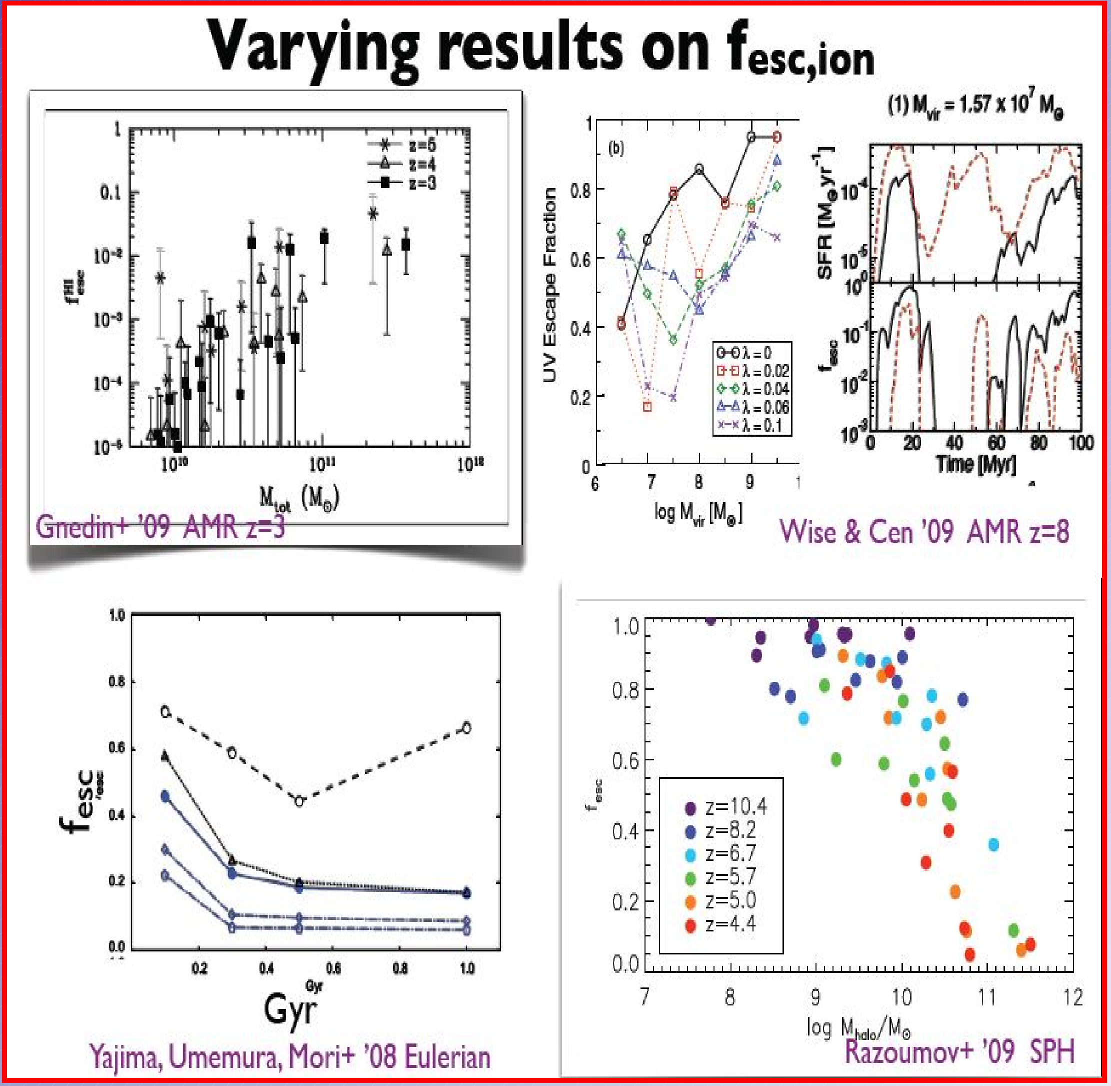
fesc from galaxies: theoretical predictions

Theoretical modeling (RT+SPH):

fesc ↓ if redshift ↑ (Wood & Loeb+00)
fesc ↑ if redshift ↑ (Razoumoz+06)
fesc ↓ if halo mass ↑ (Yajima+10)
fesc ~ with redshift (Yajima+10)
fesc ↓ if halo mass ↓ (Gnedin+08)
fesc ↑ for dwarf galaxies
(Wise&Cen+09)
?

Large variance on the predictions

SF, feedback, radiation transfer and geomery of the ISM distribution, all important ingredients.
Require a treatment of Radiative transfer



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; Grimes+07)

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

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)

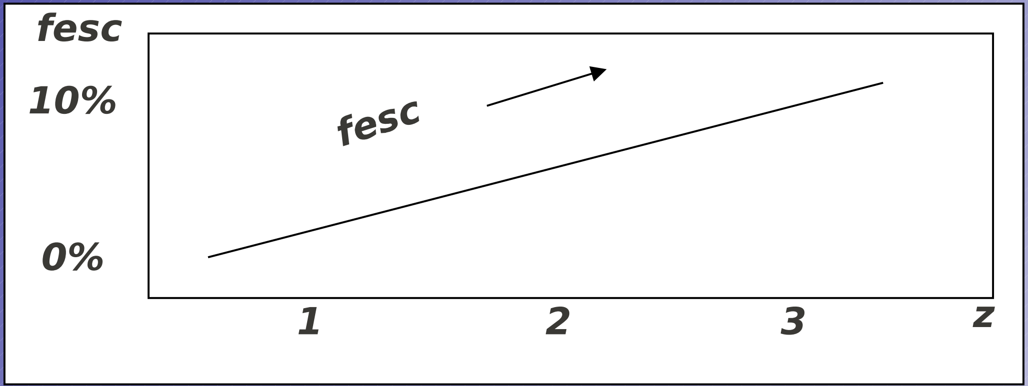
< 0.05 Boutsia+11 (phot, 11 LBGs) (LBT deep, ApJ accepted)

< 0.03 Vanzella+10c (phot, 102 LBGs, ApJ, 725, 1011)

fesc ~ 1.0 ! (spec. Stacking; 30 LBGs, Steidel+01)

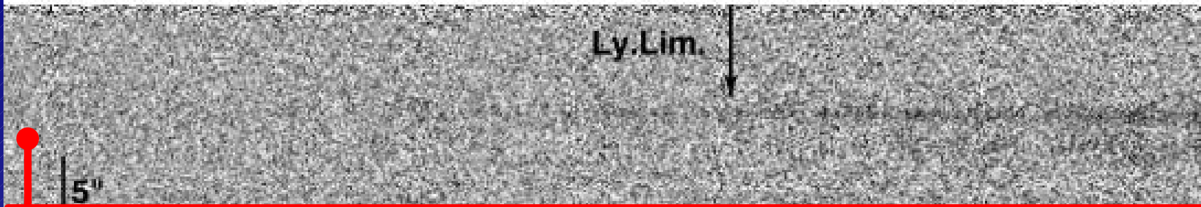
fesc ~ 0.2 (spec. Stacking; 14 LBGs, Shapley+06)

fesc > 0.2 (phot. NB, Iwata+09; Nestor+11 ~ 40 LBGs)

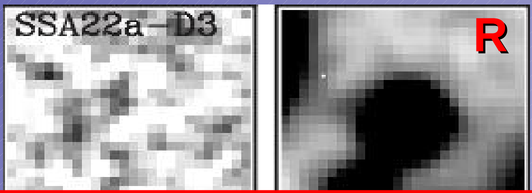


fesc from z~3 galaxies: problems

(Shapley+06) 2 LBG with LyC out of 14



NB imaging, Nestor+11;Iwata+09



STILL (BIG) UNCERTAINTIES ON THE CURRENT LyC EMITTERS !

- *SPEC*: Stack Steidel+01: not control of foreground contaminants
- *SPEC*: Shapley+06: one source not confirmed, the other unknown z
- *PHOT*: Iwata+09 and Nestor+11 (LAEs with NB):
  - A) Many are still high-z candidates
  - B) Not clear the AGN contribution
  - C) Majority (>70%) show LyC offset from UV, and anomalous (f1500/f900) ratio (i.e. f900>f1500) !

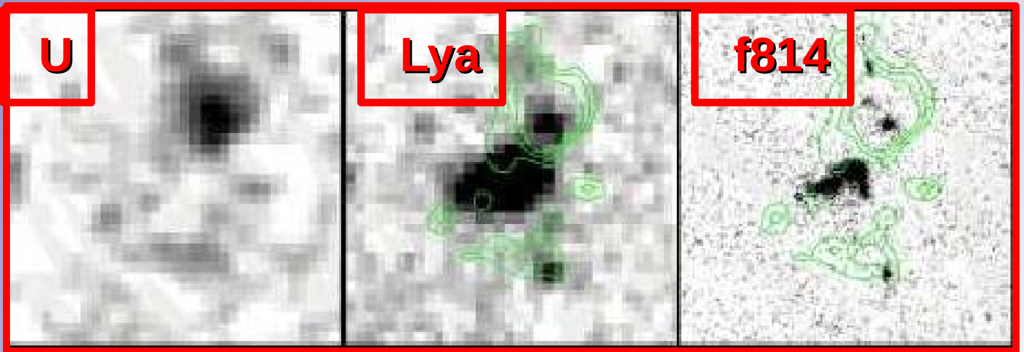
$$f_{esc,rel} \equiv \frac{(L1500/L900)_{int}}{(F1500/F900)_{obs}} \exp\left(\tau_{900}^{IGM}\right)$$

LyC offset from UV (the majority)

(Iwata+09 and Nestor+11

•~40 LyC detections SSA22)

!?



Example

fesc from galaxies: current observations

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

fesc < 0 … rimes+07)

Z~1 fesc < 0.0

Z~3 fesc < 0.7

< 0.1

< 0.1

< 0.0

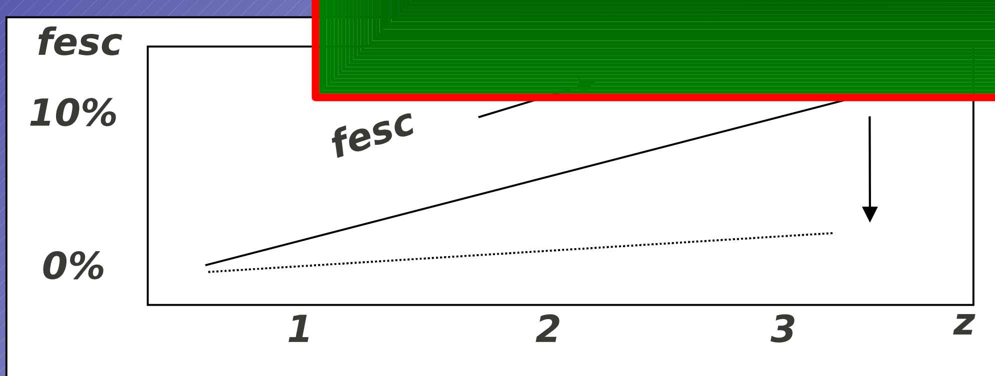
< 0.0

fesc ~ 1.0

fesc ~ 0.2

fesc > 0.2

With GOODS we can monitor systematics and derive deeper constraints !



Less evident evol.

GOODS & HUDF are currently the deepest panchromatic surveys!

The Great Observatories Origins Deep Survey (GOODS) started in ~ 2000:

see www.eso.org/sci/activities/garching/projects/goods.html

Two fields, in the north and south, 320 sq. arcmin in total.

The Spitzer Legacy Program (P.I. M. Dickinson, Dickinson+03)
The HST Treasury Program (P.I. M. Giavalisco, Giavalisco+04)

…

2008-2010 : ESO optical spectroscopy releases
2009 : ESO Ultra-deep U-band imaging (GOODS-S) ESO/VLT
Dec. 2009 : First *Herschel* observations of the GOODS fields

Future:

2011 - … : CANDELS survey, HST Multicycle Treasury Program/ WFC3 (P.I. H. Ferguson, S. Faber)
2011 - … : Gemini / FLAMINGOS-2 infrared spectroscopic survey of GOODS-South

GOODS-S

Wavel.	Observatory
- X-ray	Chandra (4Ms) + XMM
- UV	GALEX
- 0.3 um	ESO/VLT (U-band VIMOS)+KPNO+CTIO
- 0.4-0.9 um	HST/ACS + ESO/VLT (new B-band ongoing)
- 1.0-2.2 um	HST/WFC3 (CANDELS)+ESO/VLT (K,Y-bands)
- 3.6-8.0 um	Spitzer/IRAC
- 24,70 um	Spitzer/MIPS
- 110,160um	Herschel/PACS
- 250-500um	Herchel/SPIRE
- 850um	Scuba (Sub-mm)
- Radio	VLA (ALMA is coming)

+ Hubble Ultra Deep Field + Narrow band imaigng, e.g. Cardamone et al. 2010; Hayes et al. 2010; …

ESO-GOODS Team

ESO:
P. Rosati
I. Balestra
C. Cesarsky
V. Mainieri
P. Padovani
P. Popesso
A. Renzini
J. Retzlaff
A. Rettura
B. Vandame

ESO/ST-ECF:
Bob Fosbury
J. Haase
R. Hook
H. Kuntschner

INAF/TRIESTE:
E. Vanzella
M. Nonino
S. Cristiani

US:
M. Dickinson
M. Giavalisco

ESO-GOODS Observations

Campaign	Description (Instrument/Technical Specs)	Observing Time	Data Release/ date	Data Presentation Publications & PRs
Near IR Imaging	ISAAC in J,H,K_s bands, 170 arcmin^2 to ~25 AB mag (5σ) ISAAC Ks-band of the HUDF to 25.6 AB, 0.36" seeing	476 h 25.3 h	ISAAC v2.0/ 2007-09-10 ISAAC HUDF v1.0/ 2010-03-02	Retzlaff et al. 2010
U&R-band Imaging	VIMOS U and R-band, 400 arcmin^2 to U~29.8 and R~29 AB mag (1σ)	40 h	VIMOS img v1.0/ 2009-04-24	Nonino et al. 2009 [ESO PR 39/08]
FORS2 Spectroscopy	FORS2/300I grism (5500-10000 Å) 1635 spectra of 1236 targets, 887 redshifts out z=6.3	130 h	FORS2 v3.0/ 2007-10-31	Vanzella et al. 2008 Spectra search engine
VIMOS Spectroscopy	VIMOS LR Blue (3500-6900 Å) 3634 spectra of 3271 targets, 2040 redshifts (1.8<z<3.5) VIMOS MR (4000-10000 Å) 1418 spectra of 1294 targets, 882 redshifts (z<1 & z>3.5)	120 h	VIMOS v1.0/ 2008-02-18 VIMOS v2.0/ 2009-12-15	Popesso et al. 2008 Balestra et al. 2010

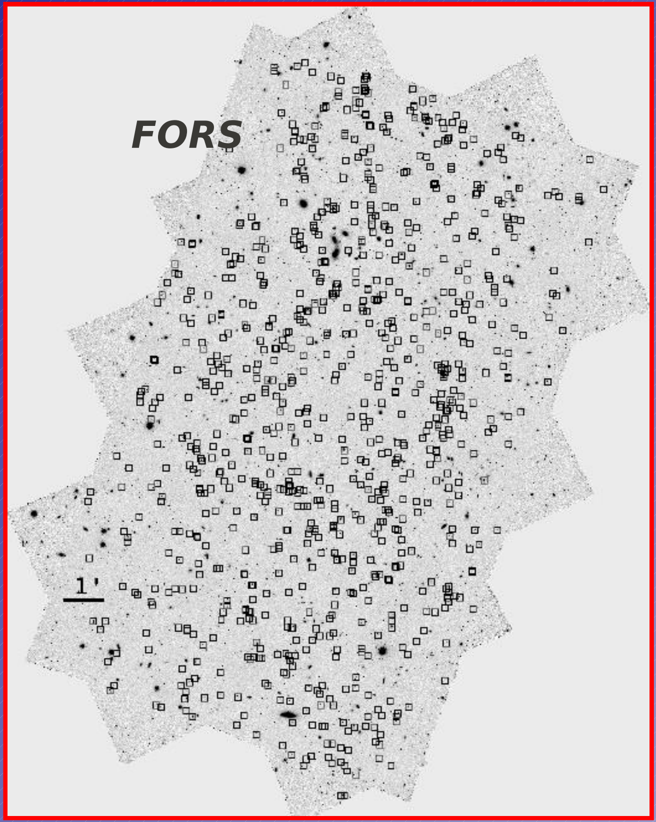
Strong constraints on fesc at 3.4<z<4 Vanz+10

The ESO spectroscopic contribution to GOODS-S

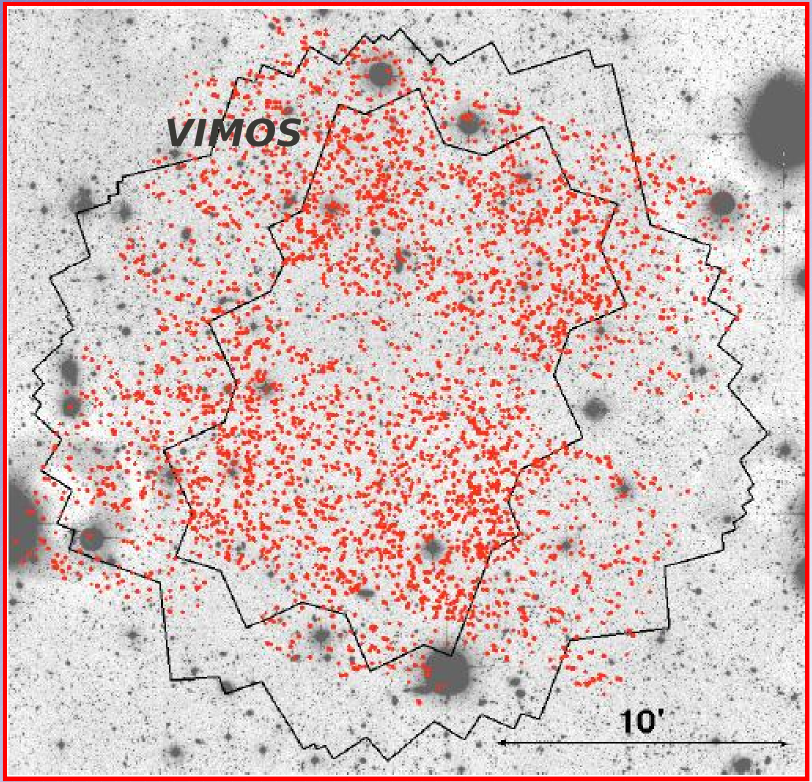
Releases available here: http://www.eso.org/sci/activities/garching/projects/goods.html

VLT/FORS2 (Vanzella et al. 2005, 2006, 2008): 38 MXU masks
~1000 redshifts $0.5 < z < 6.2$ (R=660)

VLT/VIMOS (Popesso et al. 2009; Balestra et al. 2010):
~3000 redshifts $0 < z < 4.5$ (MR and LR)

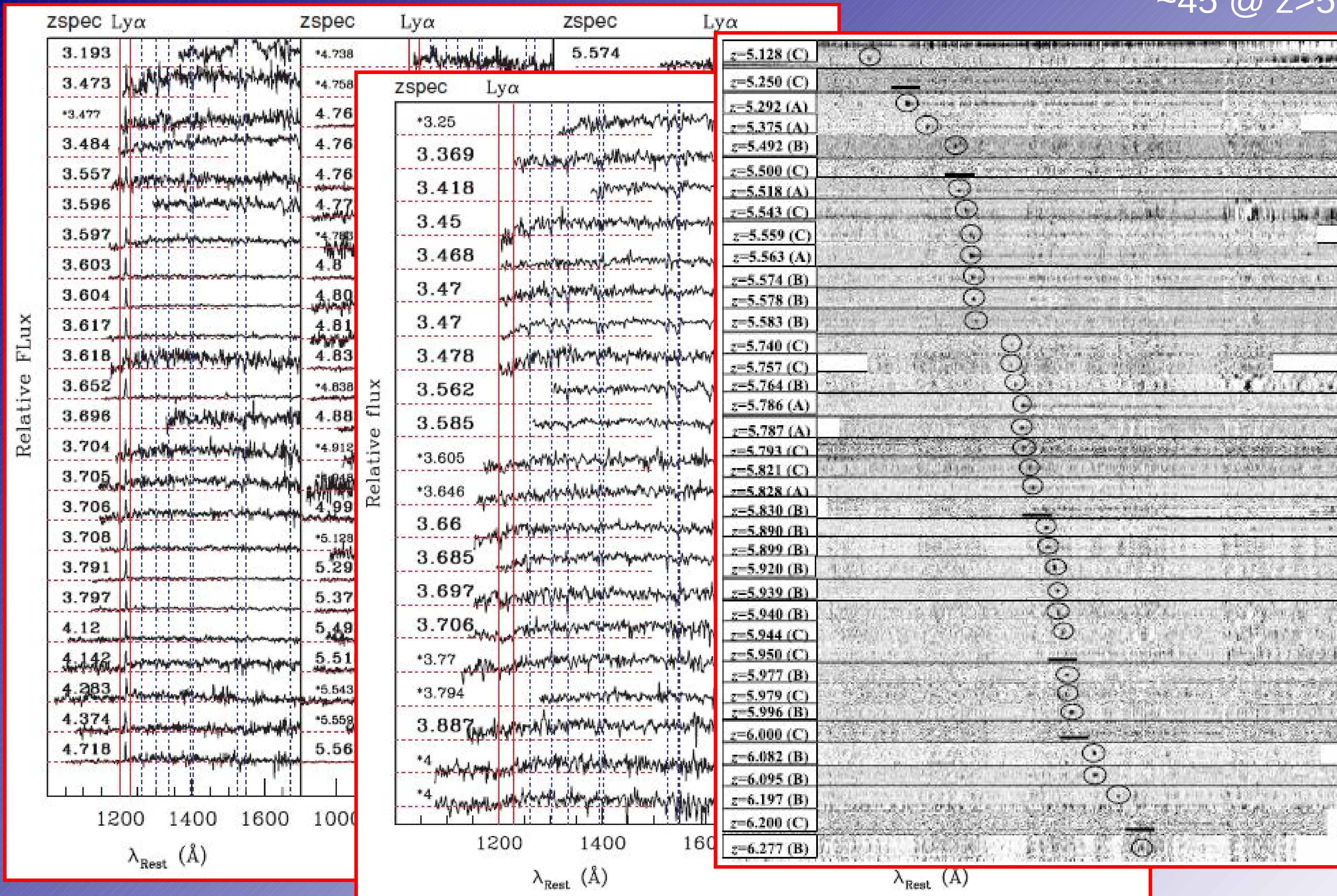


4000 redshifts released!



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

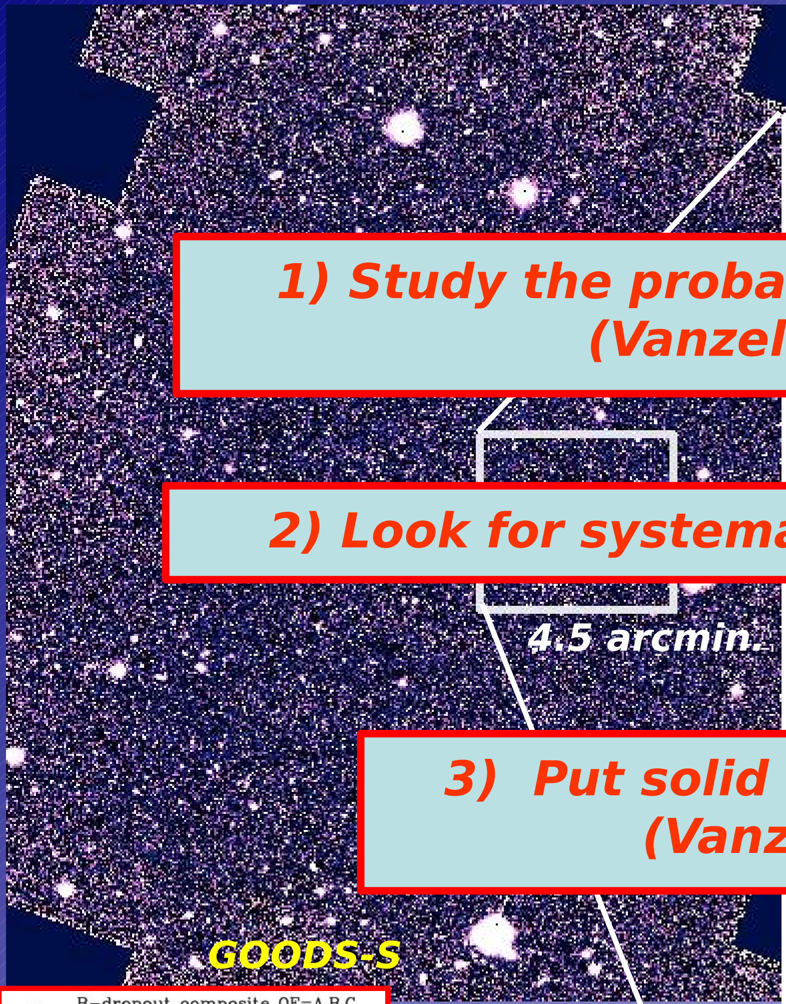
~45 @ z>5

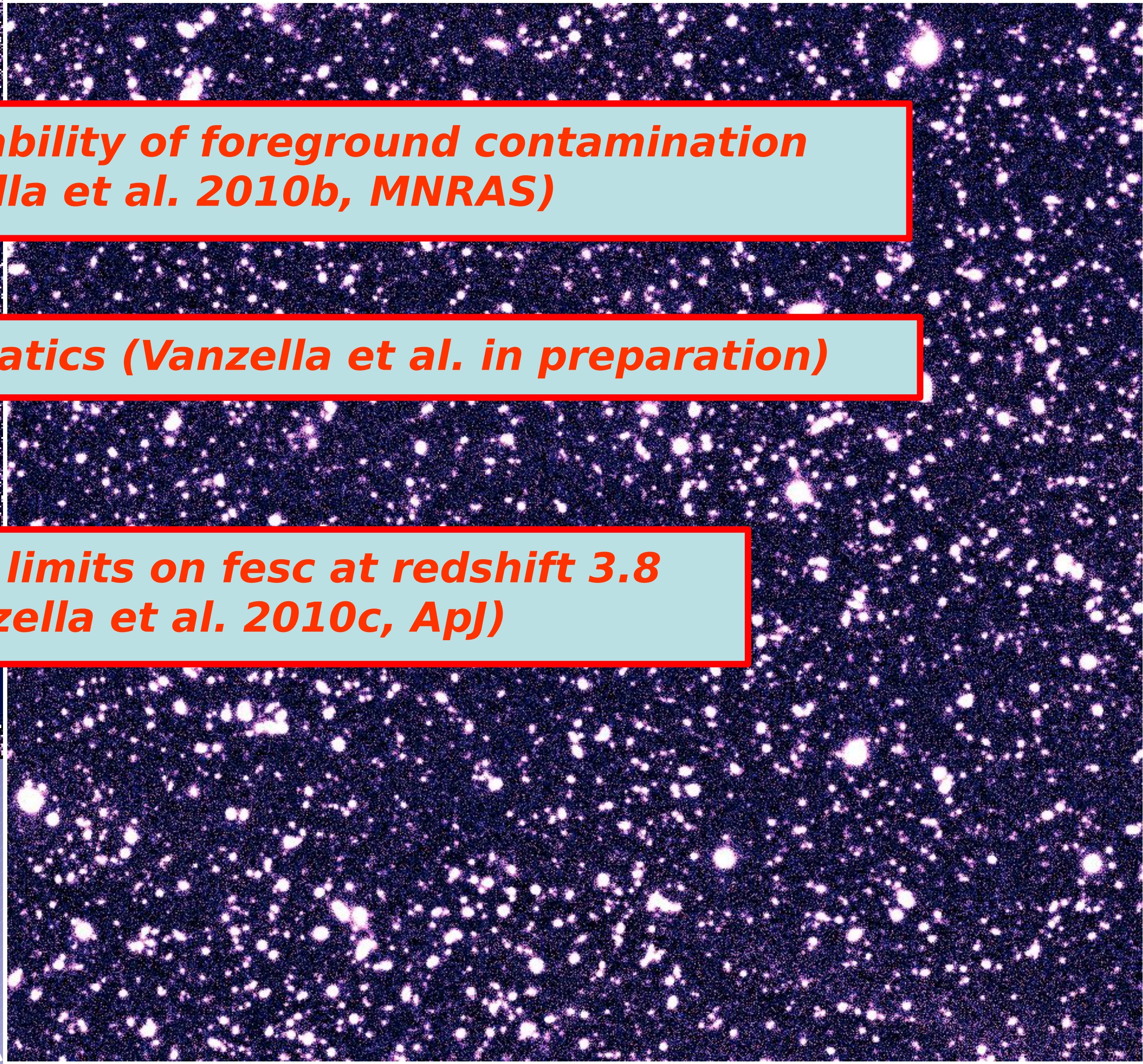


Ultra-deep VLT/VIMOS U-band survey (Nonino+09)

Mag-U 30.5 AB at 1σ (1.2'' diam.)

It is probing LyC 700A-900A for galaxies at 3.4<z<4.5

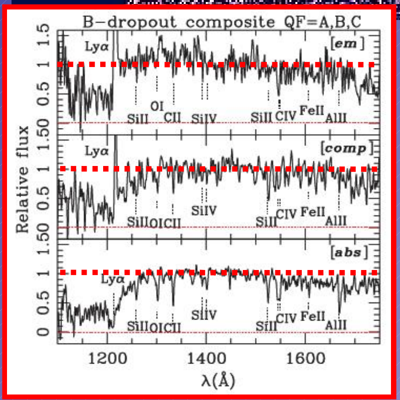




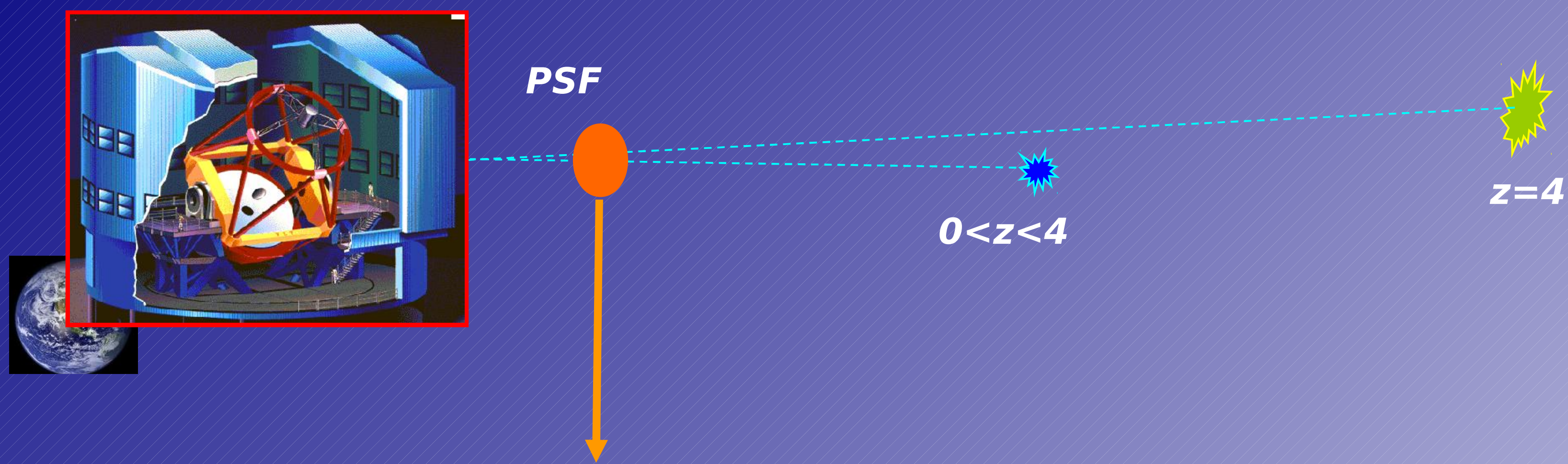
1) Study the probability of foreground contamination (Vanzella et al. 2010b, MNRAS)

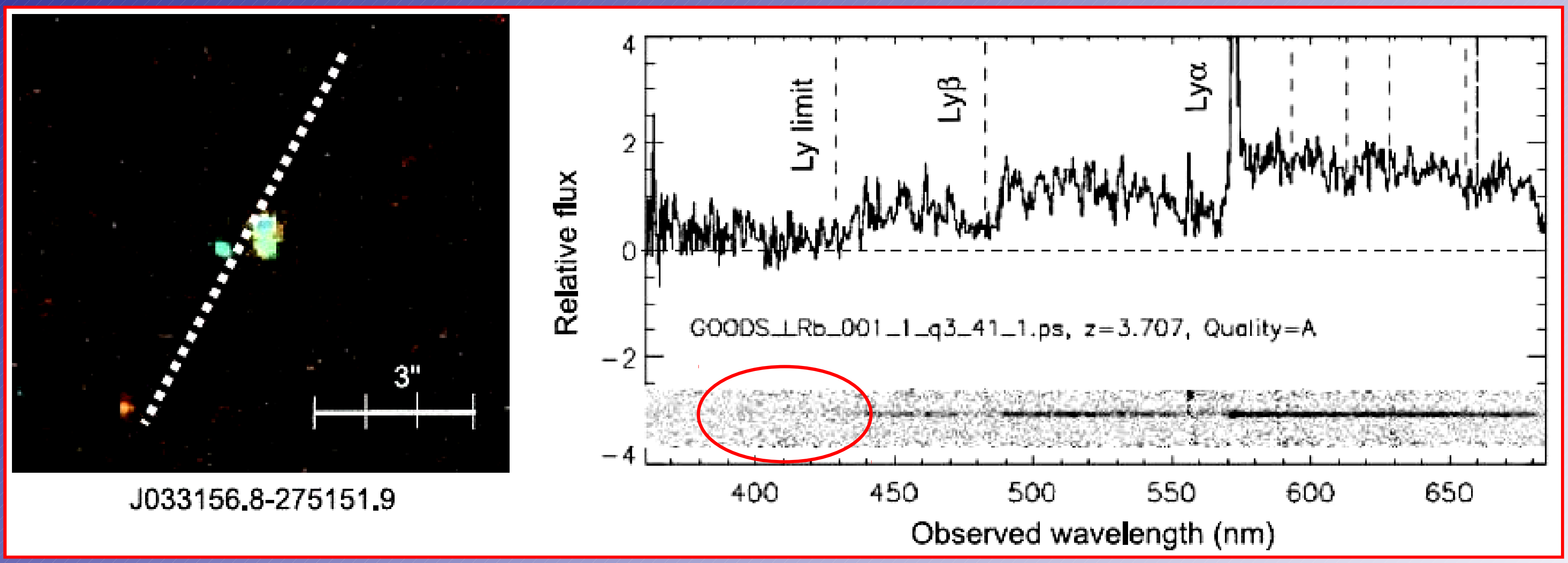
2) Look for systematics (Vanzella et al. in preparation)

3) Put solid limits on fesc at redshift 3.8 (Vanzella et al. 2010c, ApJ)



Foreground LyC contamination: example I



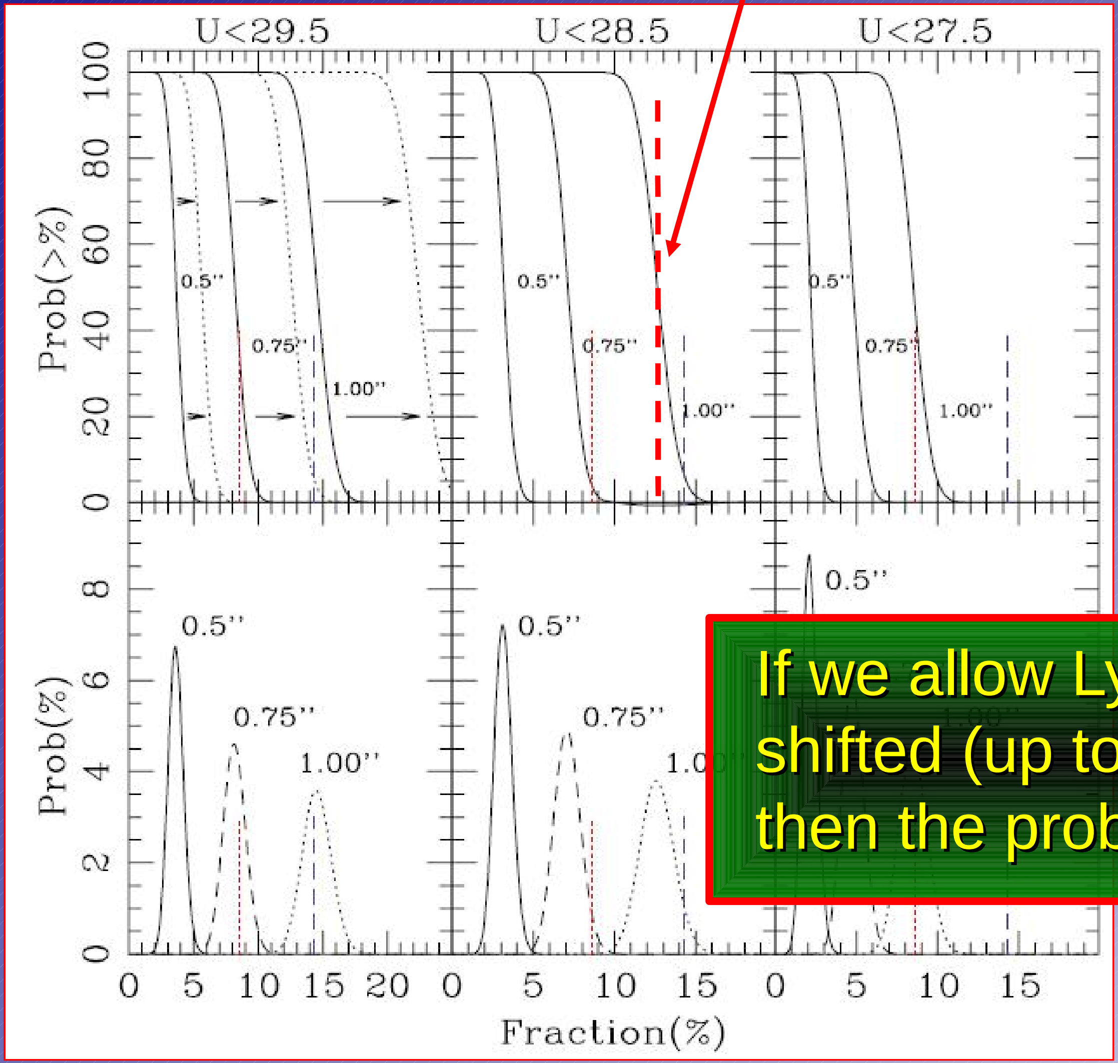


zphot+IGM transverse test + fesc<100% – Vanzella et al in preparation

Foreground contamination: expected probability (Vanzella et al. 2010b)

1) Given the (ultra-deep) U-band number counts
2) Assuming an image spatial resolution (PSF - seeing)

50% prob. that at least 13% is cont.



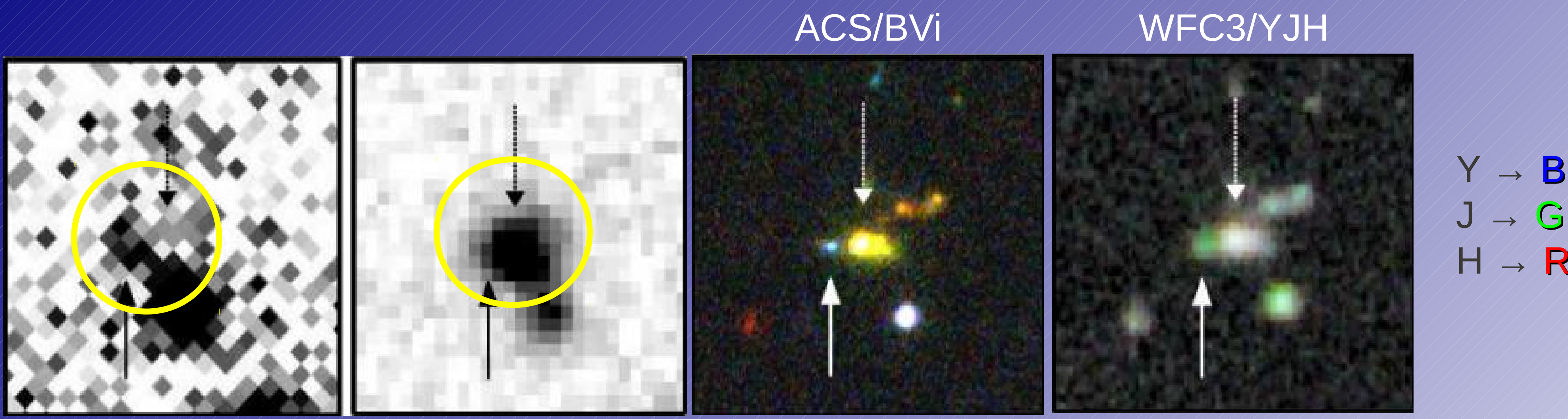
*Probability to observe **K** contaminated sources **f(K),** or at least **K** contaminated sources P(≥K) in a sample of **N** high-z Galaxies, given the probability **p** of the single case :*

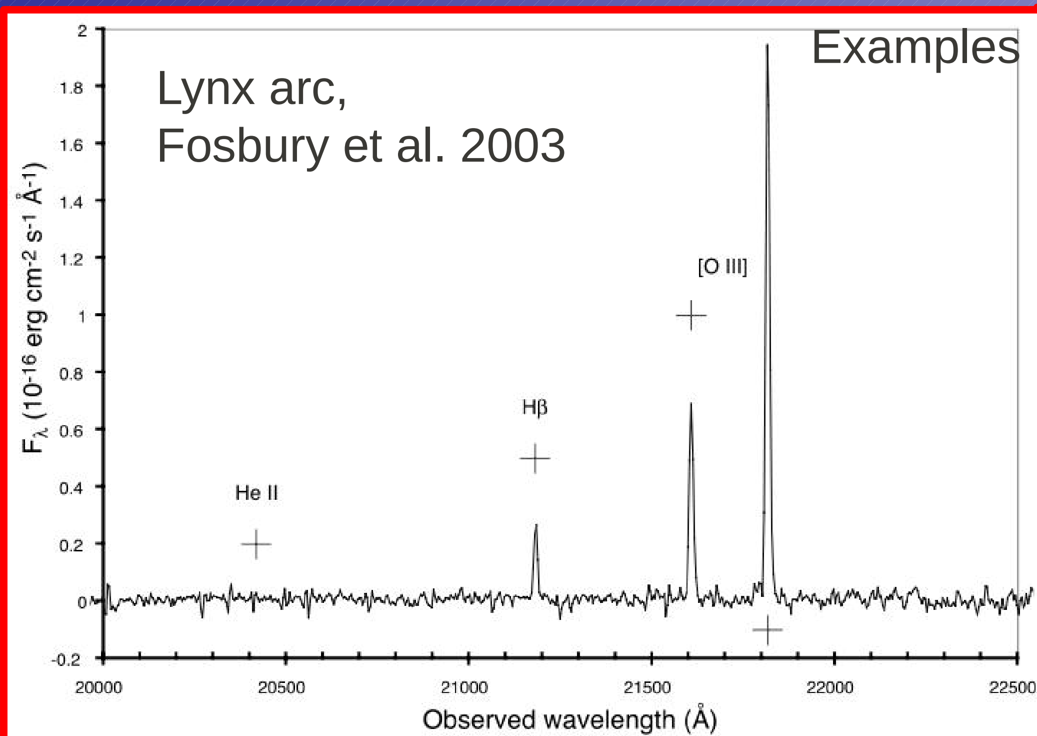
$$f(K) = \binom{N}{K} p^K (1-p)^{N-K}; \qquad P(\geq K) = \sum_{i=k}^{N} f(i).$$

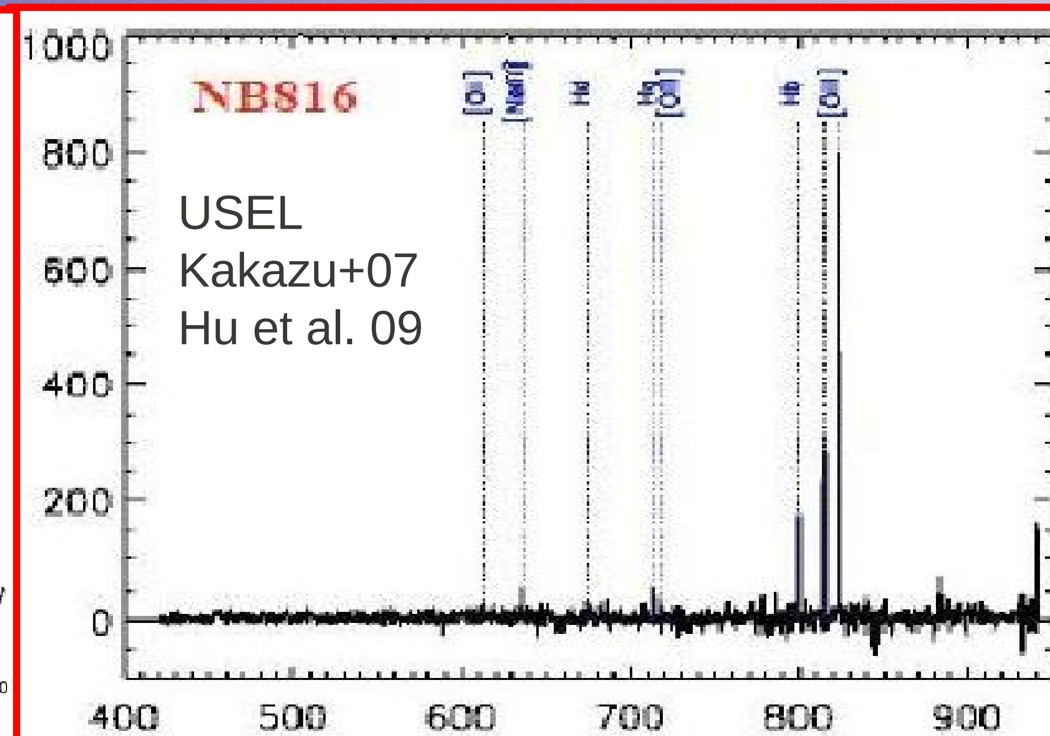
If we allow LyC to be spatially shifted (up to 2") form UV then the prob. are even more higher!

Vanzella+10b

Foreground LyC contamination: extreme example U(AB)~28.63 (z=3.8)

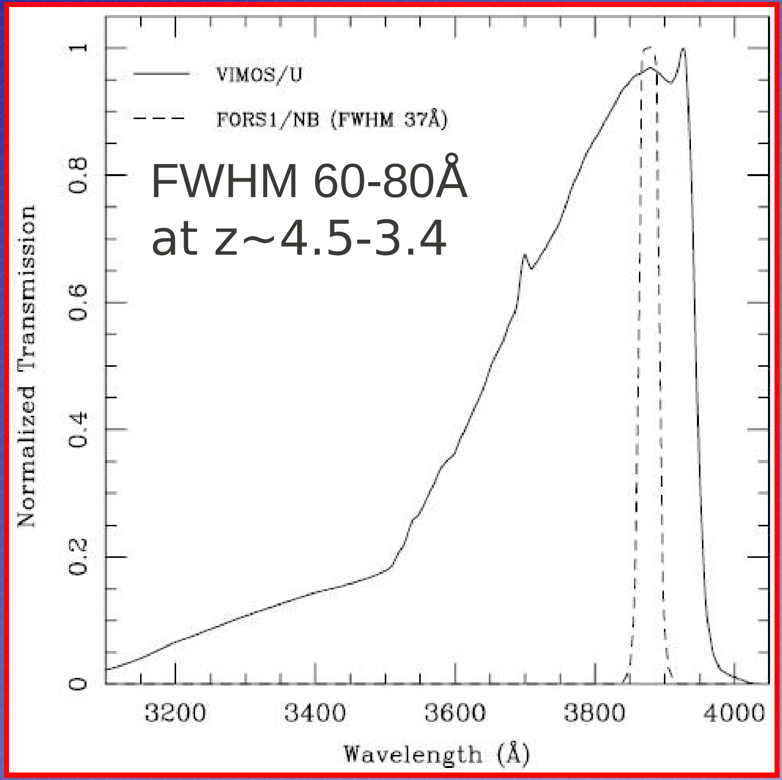






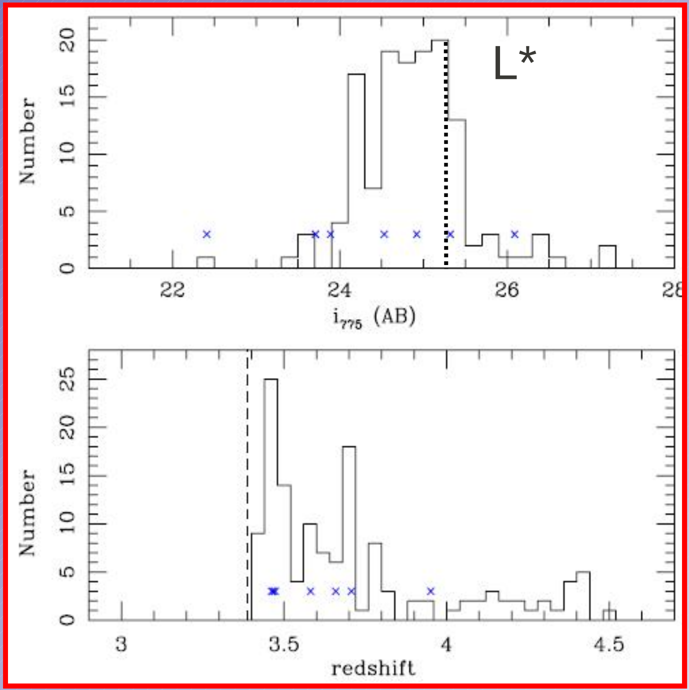
Estimating the fesc distribution of LBGs at z~3.7 from GOODS

1) Select sources with secure redshift in the range 3.4<z<4.5 **(136)**
2) Clean the sample from foreground contamination
3) Exclude AGNs (but very useful as a control sample about IGM…)
4) Run MC simulations in order to determine the expected number of U-band detections (i.e. LyC detections) for the observed sample as a function of fesc
5) Derive limits on fesc stacking all sources



3.4<z<4.5 => probing λrest 912A - 700A

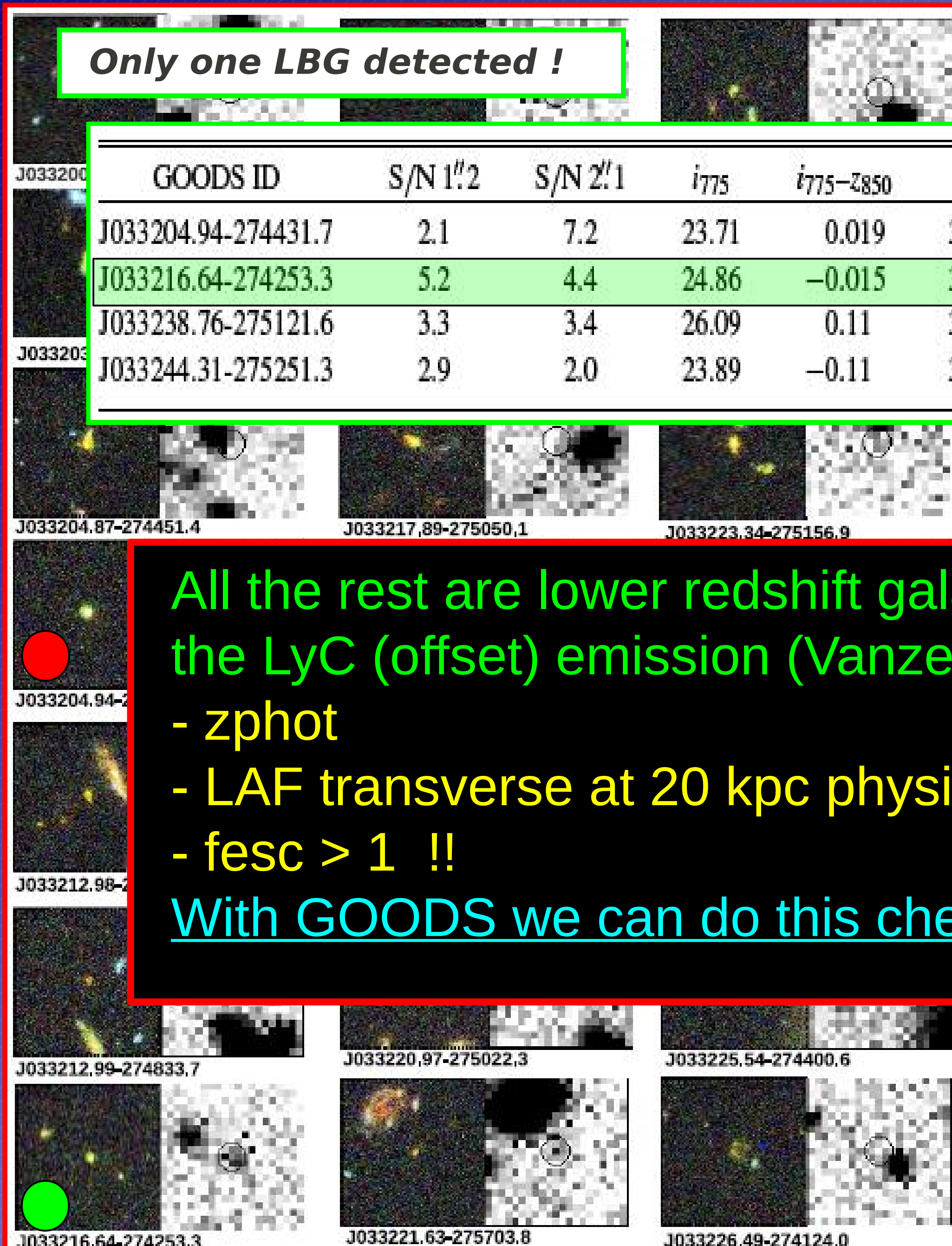
134 objects with 3.4 < z < 4.5

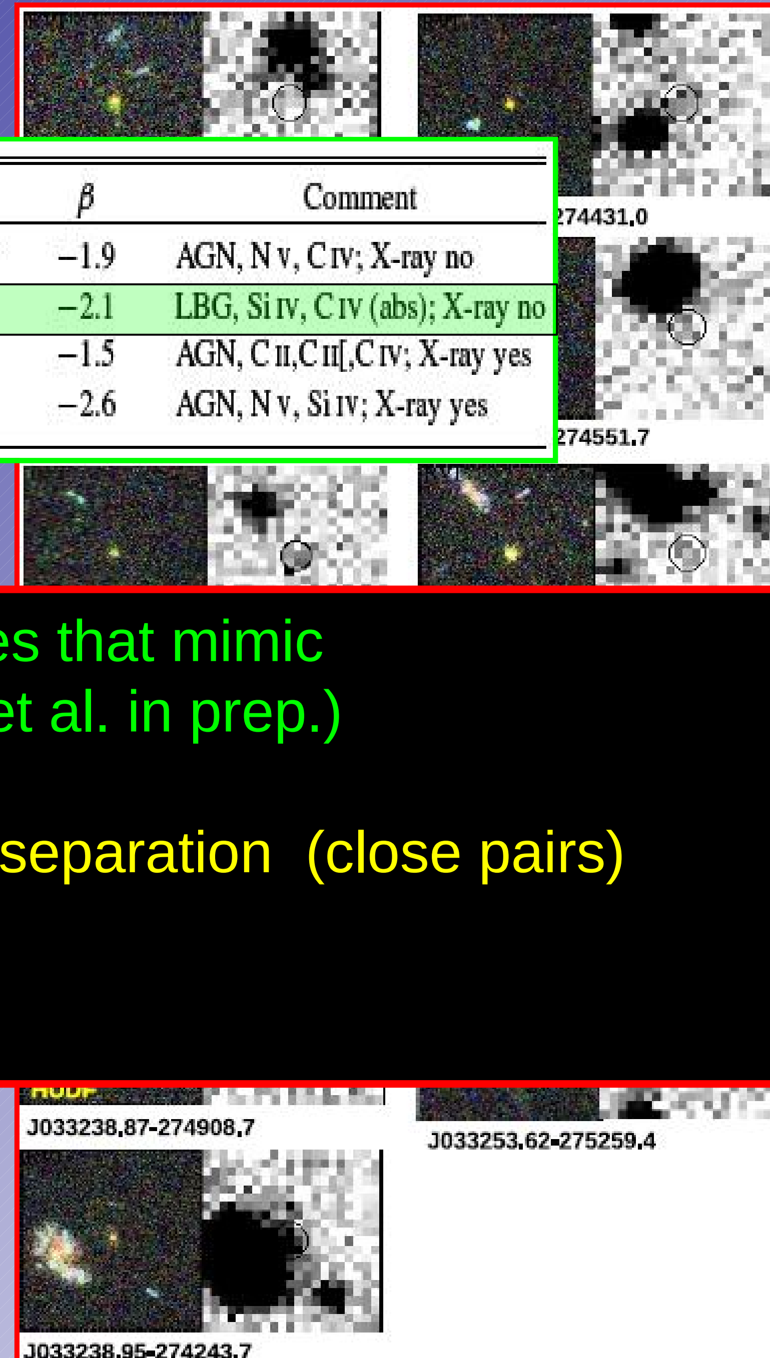


Vanzella et al 2010c

<u>Cleaning the sample:</u> 32 out of 134 sources with > 2σ detection

Only one LBG detected !





GOODS ID	S/N 1″.2	S/N 2″.1	i_{775}	$i_{775}-z_{850}$	zspec	β	Comment
J033204.94-274431.7	2.1	7.2	23.71	0.019	3.462[d,b]	−1.9	AGN, N v, C IV; X-ray no
J033216.64-274253.3	5.2	4.4	24.86	−0.015	3.795[c]	−2.1	LBG, Si IV, C IV (abs); X-ray no
J033238.76-275121.6	3.3	3.4	26.09	0.11	3.951[f,a]	−1.5	AGN, C II,C III[,C IV; X-ray yes
J033244.31-275251.3	2.9	2.0	23.89	−0.11	3.466[c,e]	−2.6	AGN, N v, Si IV; X-ray yes

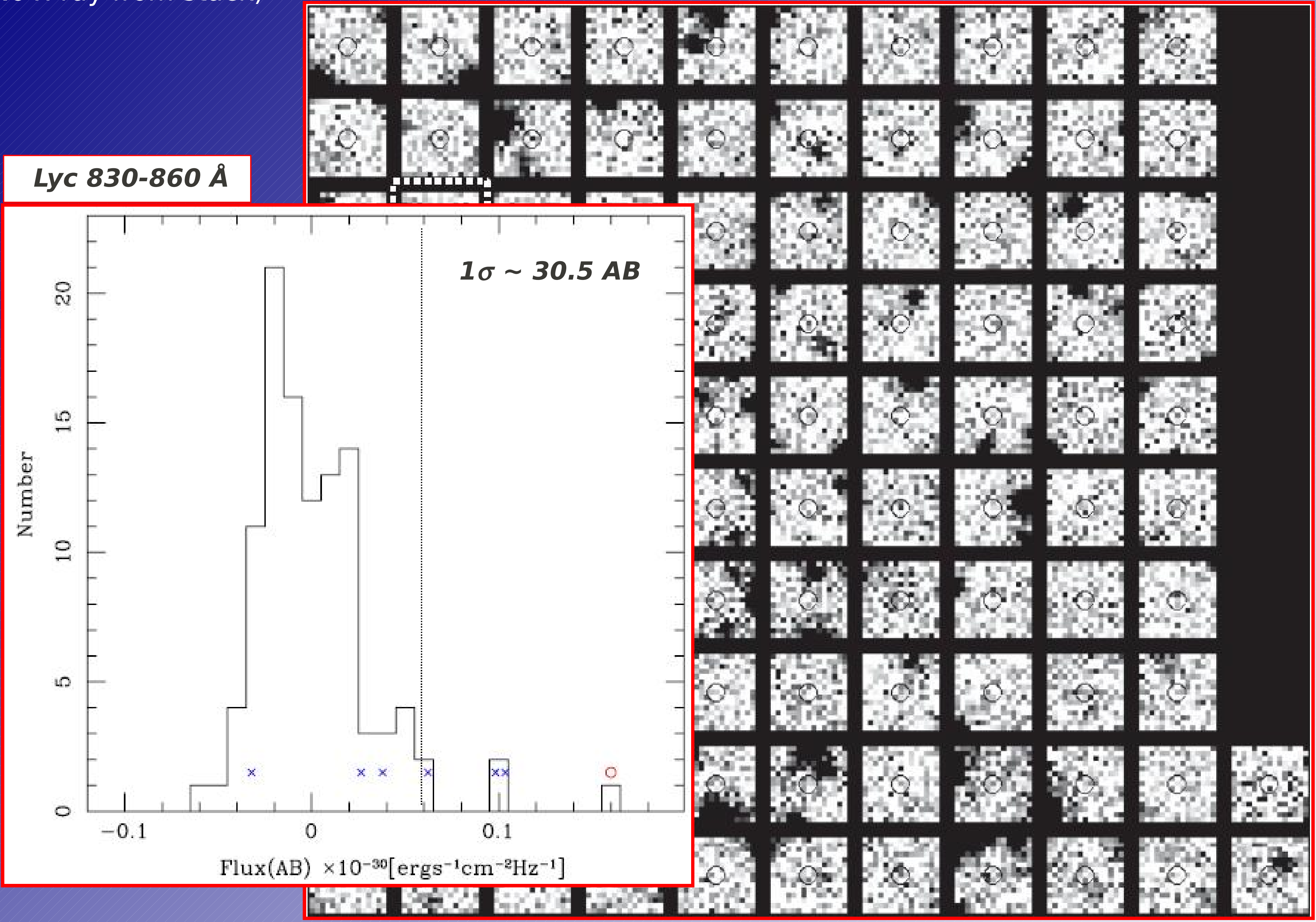
All the rest are lower redshift galaxies that mimic the LyC (offset) emission (Vanzella et al. in prep.)

- zphot
- LAF transverse at 20 kpc physical separation (close pairs)
- fesc > 1 !!

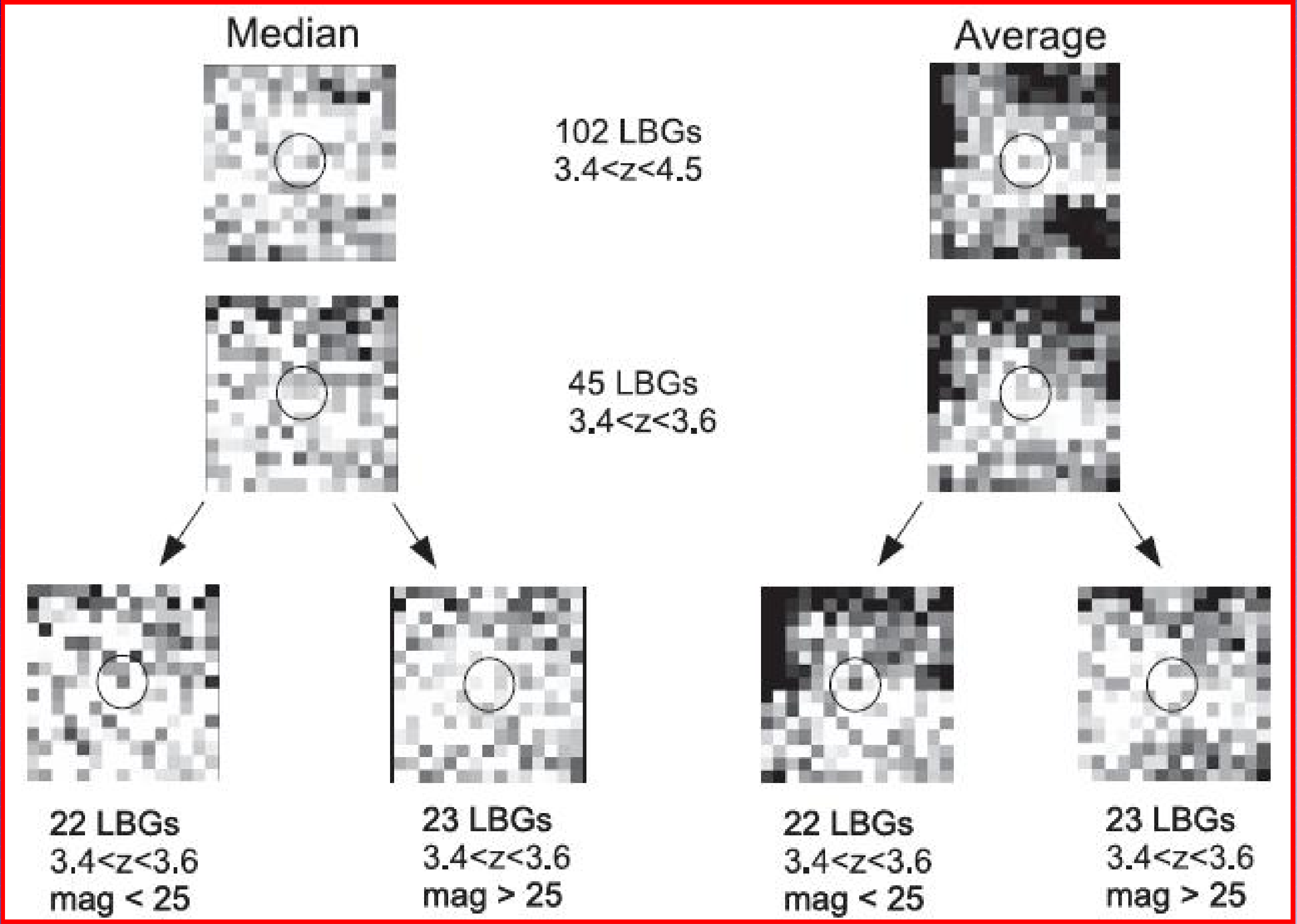
<u>With GOODS we can do this check</u>

The clean sample: 102 LBGs <z>=3.8

(No x-ray from stack)



Stacking all sources: f1500/f900 > 1400 !



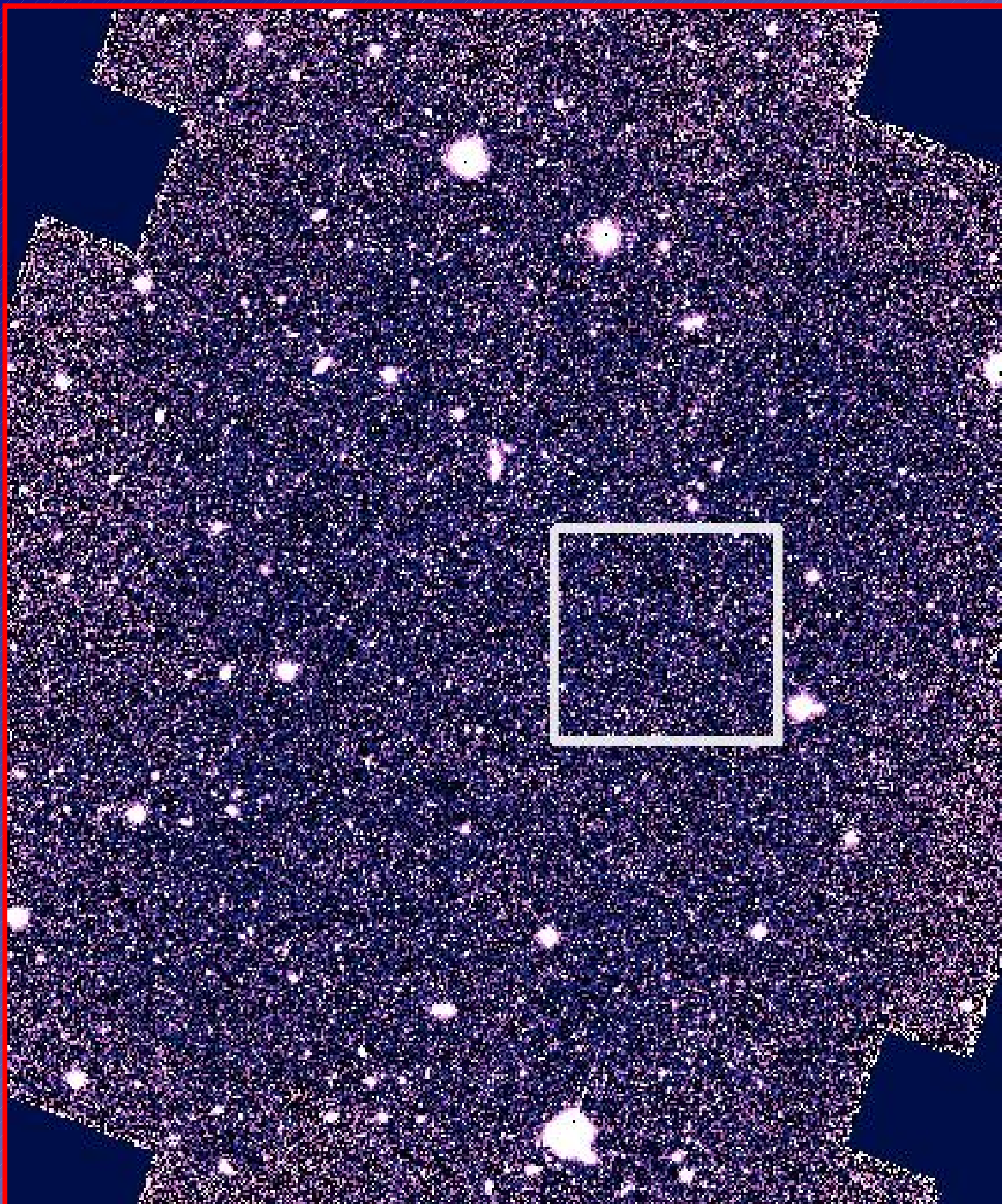
Δm ~ 8 mags
Down to U(AB)~33

fesc < 0.02

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

Assumed an Tigm=exp(-τ)=0.2 at <z>=3.6
- **and L1500/L900=7, and Av~0.7 from SED fit**
- **fesc < 0.02.**

MC simulations to constrain the fesc distribution



Given the 102 LBGs how many of them do we expect to detect in the ultra-deep U-band image? I.e. how many of them do we expect to detect in their LyC ?

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

Steidel+01

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

$$F_{LyC} = \left(\frac{L\lambda_{rest}}{L1500}\right)_{int} f_{esc} \times (F1500)_{obs} \times e^{-\tau_{\lambda}^{IGM}} \times 10^{0.4 \times A1500}$$

From BC,S99 models (Siana+07; Inoue+05)

Observed

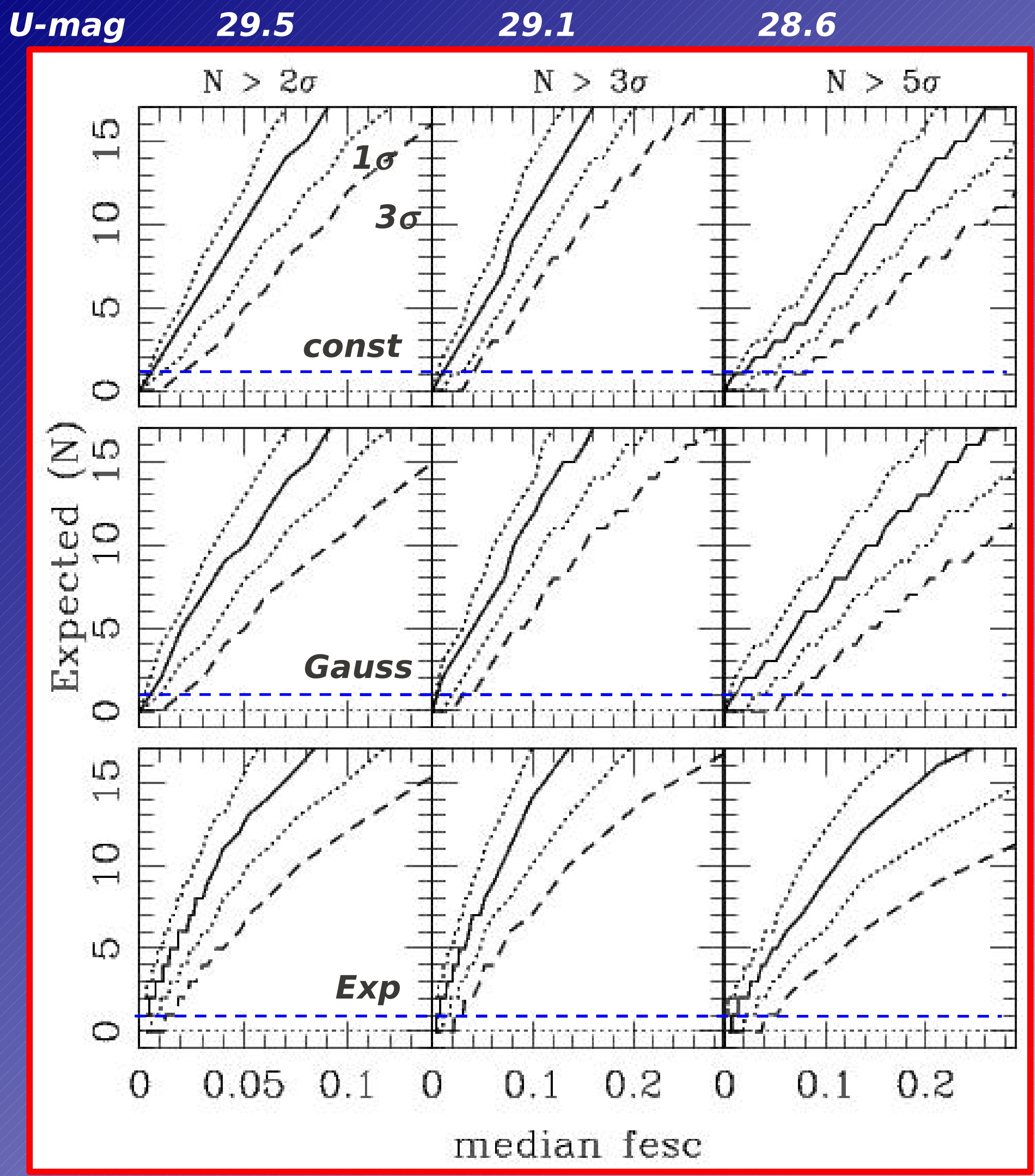
Inoue+08,+10, IGM convolved with filter

From SED fitting

It is investigated: Exp, Gauss, logNorm: Median and 84-percentile 10000 relizaztions for each distr.

Photometric noise is also added

MC simulations: results



Including recent IGM transmission

- Prochaska+10; Songaila+10
- (LLS statistics @ z~3 - 4)

fesc < 3-4% and 1σ disp. < 15% at 3 sigma depth

Vanzella et al. 2010c, ApJ

Contribution to the UV background

$$\rho_{900,esc} = \rho_{1500} \frac{L_{900}}{L_{1500}} f_{esc}^{rel} = \rho_{1500} \left(\frac{f_{900}}{f_{1500}}\right)_{obs} exp(\tau_{900}^{IGM})$$

erg/s/Hz/Mpc3

From ou ***a+11):***

... we have one LyC detection !

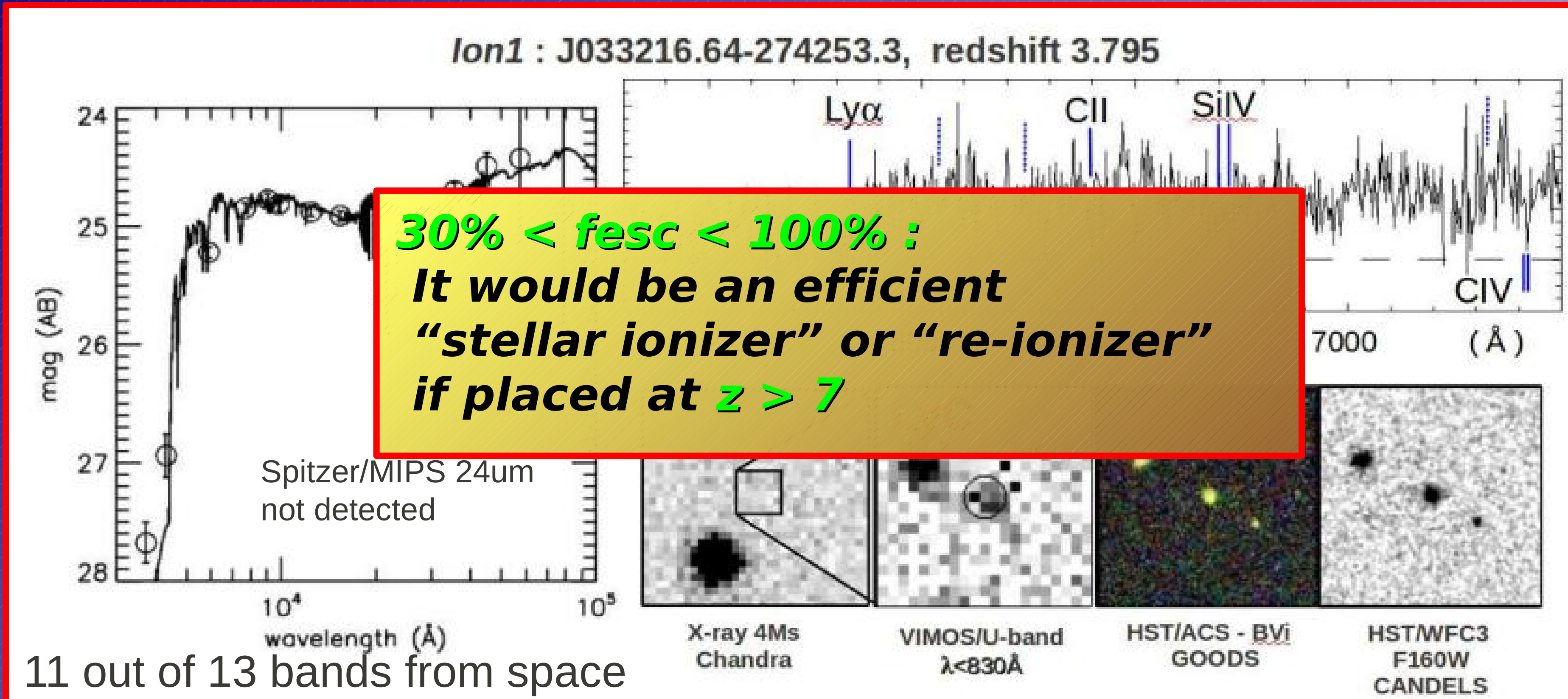
Assumi
(LF Bou

Galaxies contribute to <10-15% at z~3.7 (Bolton+05)

a) Either we need more QSOs, but in tension with observations, (e.g. Prochaska+09; Siana+09; Haardt+11) or faint AGNs... (but see Glikman+11)

b) if star-forming galaxies are doing the job, then <u>fesc has to increases at lower luminosites</u>

LyC detection at z~3.8 *(unique in the 102 LBG sample)*



30% < fesc < 100% :
It would be an efficient "stellar ionizer" or "re-ionizer" if placed at z > 7

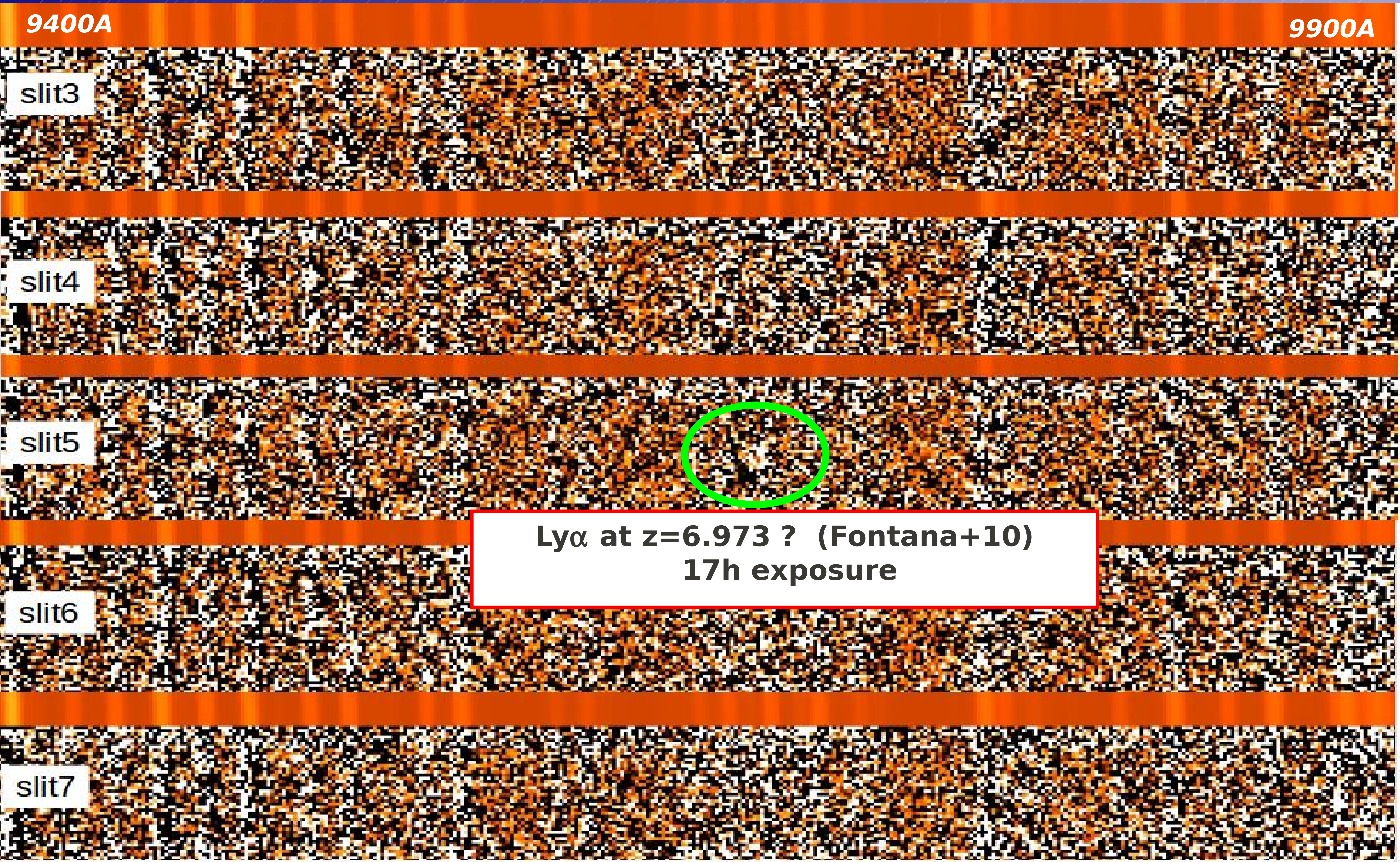
Note:
NOT SELECTABLE WITH NB Lya IMAGING

Deviation from the LBG population ?

From SED fitting & optical specturm:
- ***M* ~ 2x10⁹ Msol,***
- ***SFR~50 Msol/yr***
- ***EBV~0.0-0.03, β = -2.1***
- ***Rhlr 0.9 kpc (B-band rest-frame),***
- ***No Lya,***
- ***weak ISM lines,***
- ***No X-ray (4Ms,)***

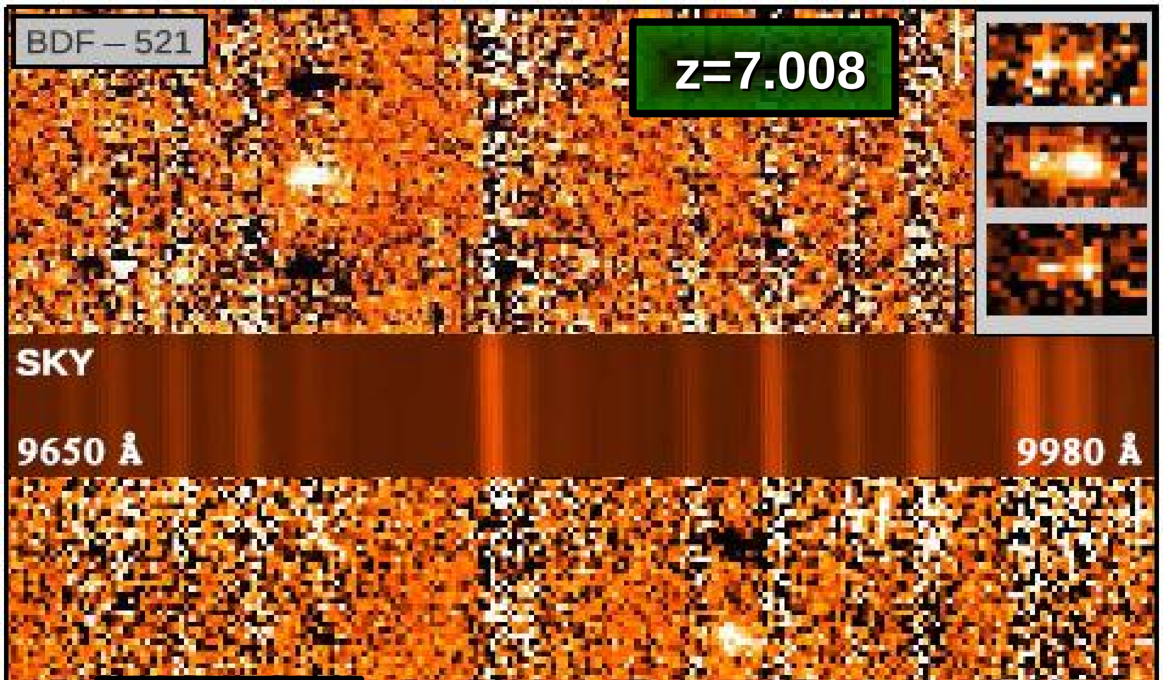
Looking at z~7 galaxies (P.I. A. Fontana) (Castellano+10; Fontana+10)

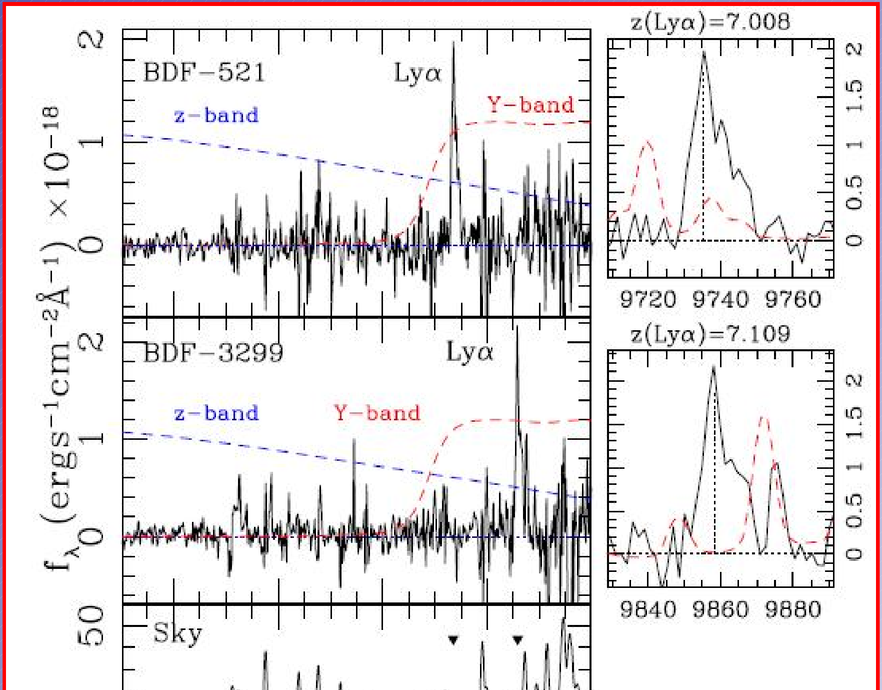
Deep spectroscopic survey with VLT/FORS2, 3 masks 17h exposure each :
GOODS-S (Giavalisco+04), NTTDF (Arnouts, D'Odorico+98), BDF



Spectroscopic confirmation of two LBGs at z > 7

(Vanzella+11, ApJL)





***Only 2 confirmed z~7 candidates with Lya EW >~ 50A out of 17 solid z~7 candidates in three fields** (the two are in the same field, sep. 4.4 Mpc proper)*
(2 out 17 => prob < 5% if the observed trend at z<~6 is assumed)

See also yesterday paper (Clement et al. 2011):
zero candidates @ z=7.7 with deep NB imaging with ESO/HAWK-I,
expected 13 if Lya LF of Ouchi+10 @ z~6 is assumed

<u>WHY ? Possible options:</u>
1) A significant fraction (at least 50%) of z-drop candidates are not at z~7
2) Change in emission properties: the fraction of Lya emitters suddenly drops from z~6 to z~7, reversing the observed trend
3) Lya is quenched by IGM

Conclusions

- Ionizing UVB (I): Redshift evolution of fesc is not clear at all
  (foreground contamination is not negligible → GOODS data + CANDELS

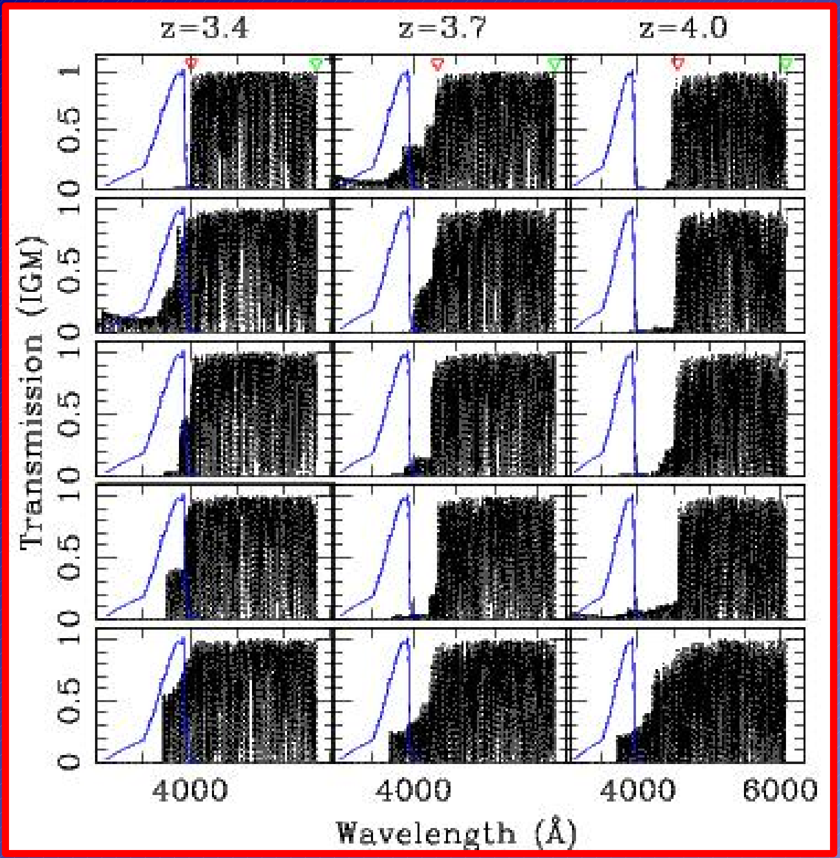
- Ionizing UVB(II): LBGs with $3.4<z<4.5$ with $L \geq L^*$ have fesc < 3 %
  Galaxies are not sufficient to account for the total UV
  ionizing background @ z~4 if these limit apply for all luminosities.

- If we think that stars are the main responsible $z>3.5$, the
  fesc in galaxies (stellar ionization) has to increase at fainter luminosities.

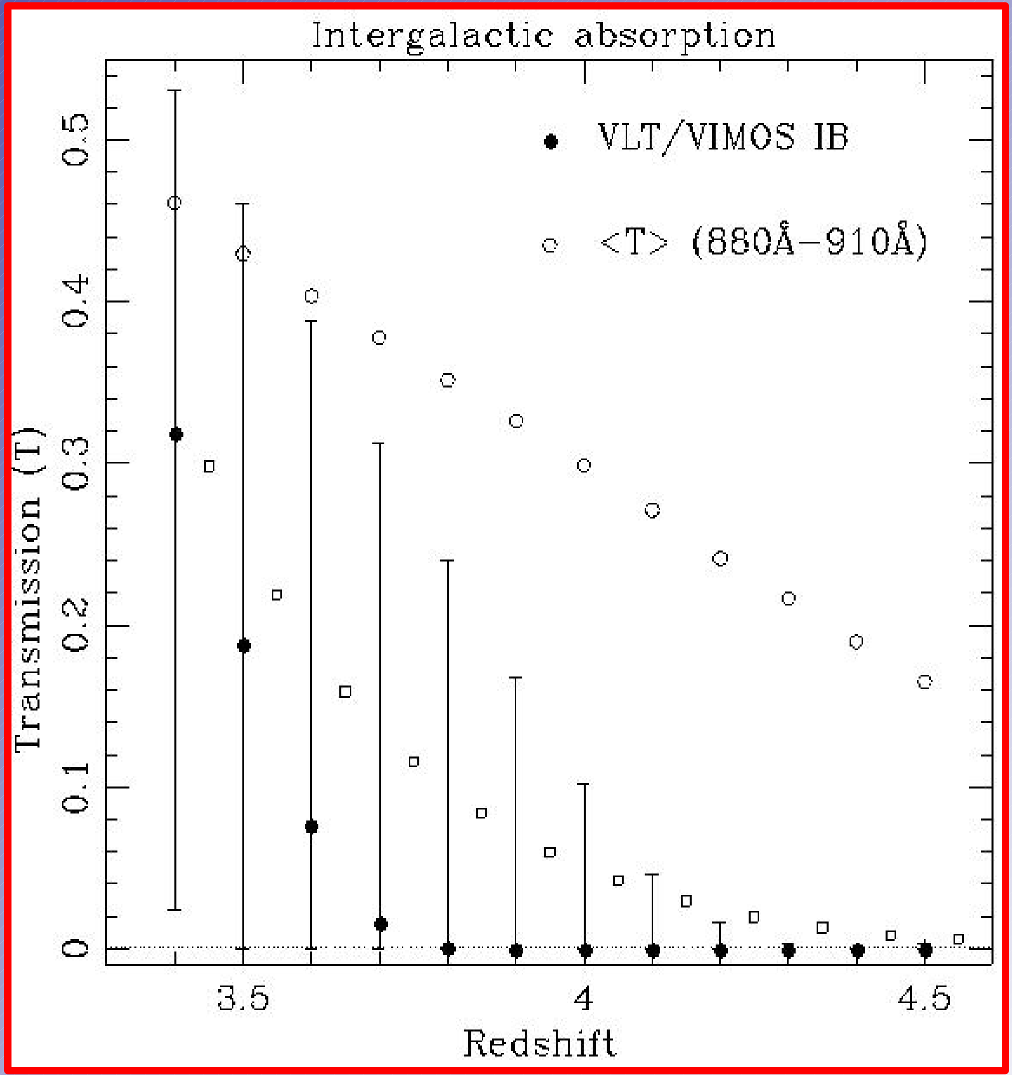
- Possible identification of a "stellar ionizer" at $z=3.8$
  with 30%<fesc<100% (the highest-z known so far). Further investigations
  are needed... (ESO proposal).

- Identification of redshift 7 galaxies maybe difficult because the
  re-ionization is still in progress (Lyα photons attenuated by HI) :
  however the discovery of 2 redshift > 7 LBGs is promising:
  a) validate the selection technique, study their physical properties
  b) the occurence of Lya emission increases with redshift $3<z<6$, the
     absence of Lyα lines may be a signature of an IGM not flully
     ionized at z~7 (work in progress, Pentericci et al. in prep.)

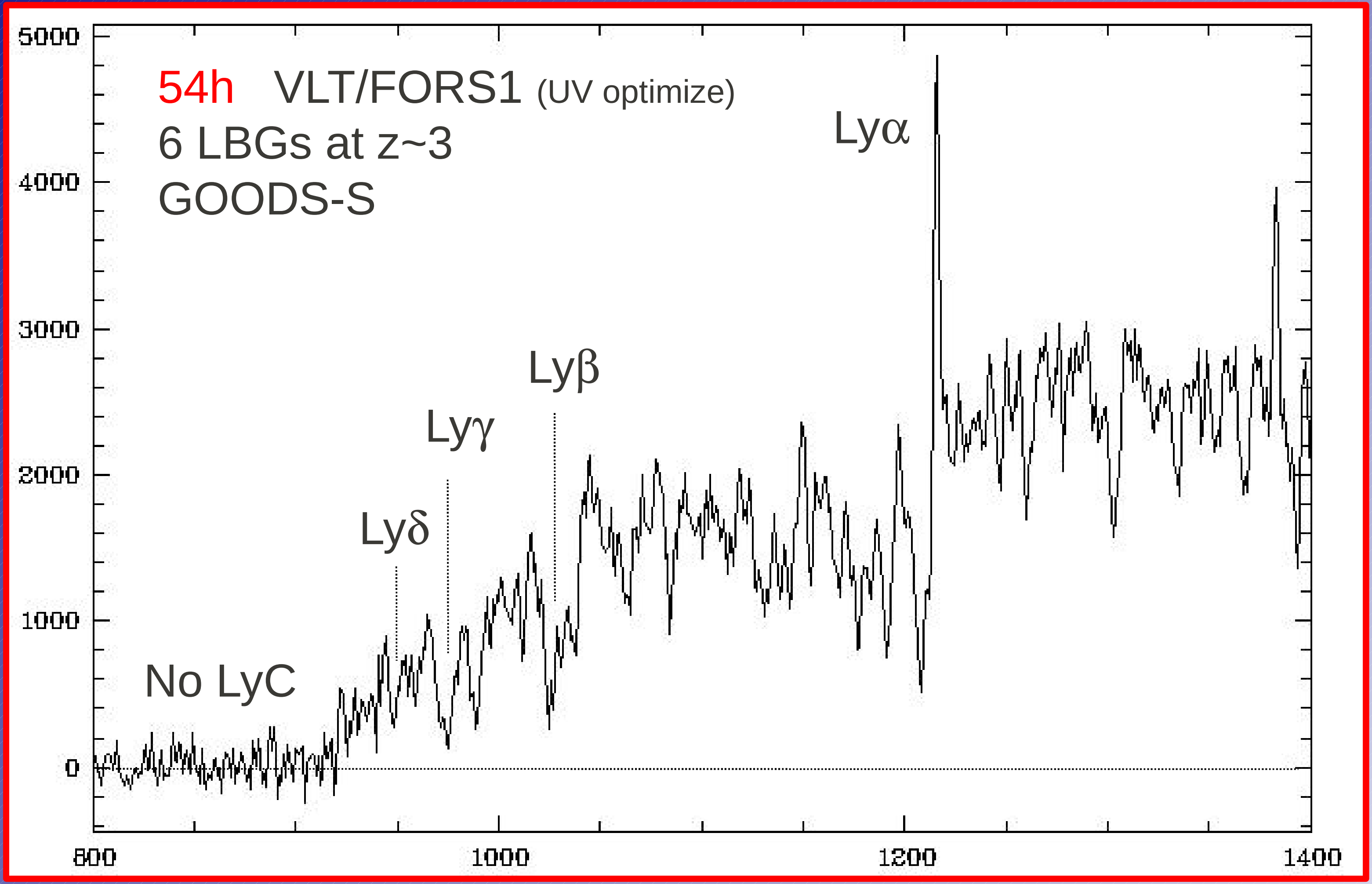
IGM LyC TRANSMISSION
(Inoue et al. 2008; 2011)



10000 random line of sights
for each redshift (Δz=0.1)



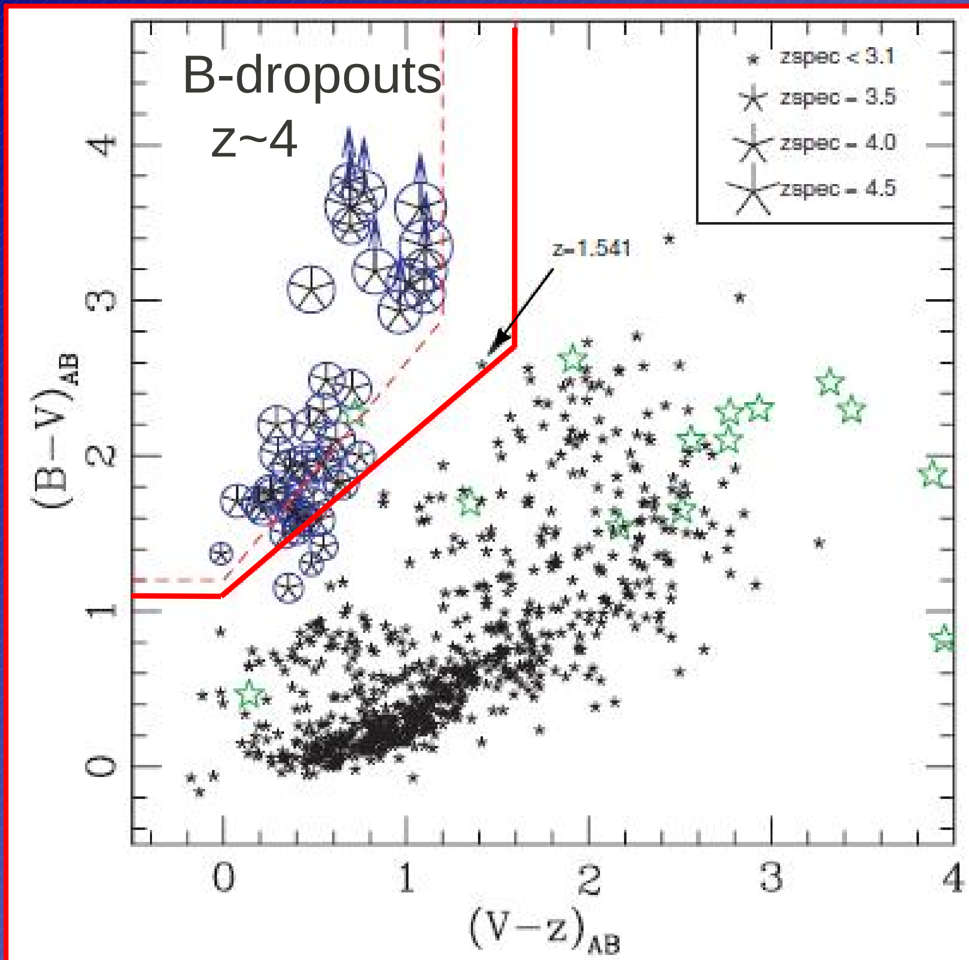
Future ...

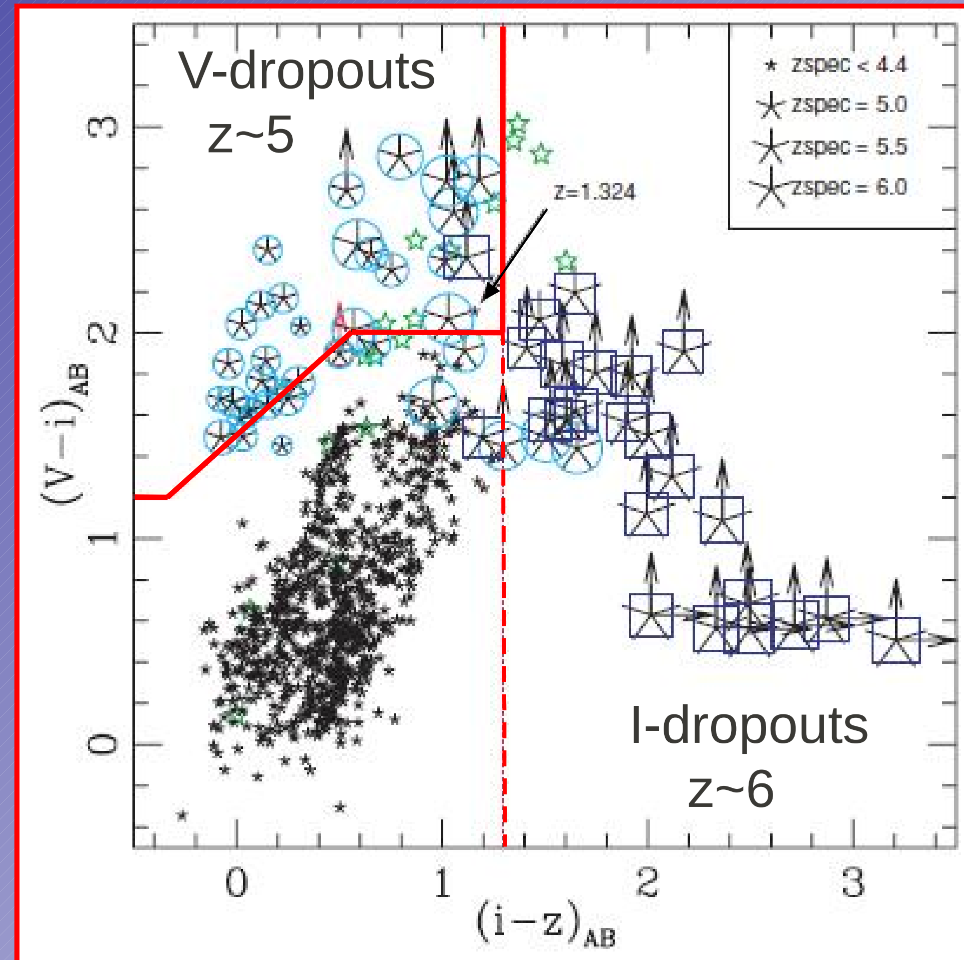


Nonino, Vanzella et al. in prep.

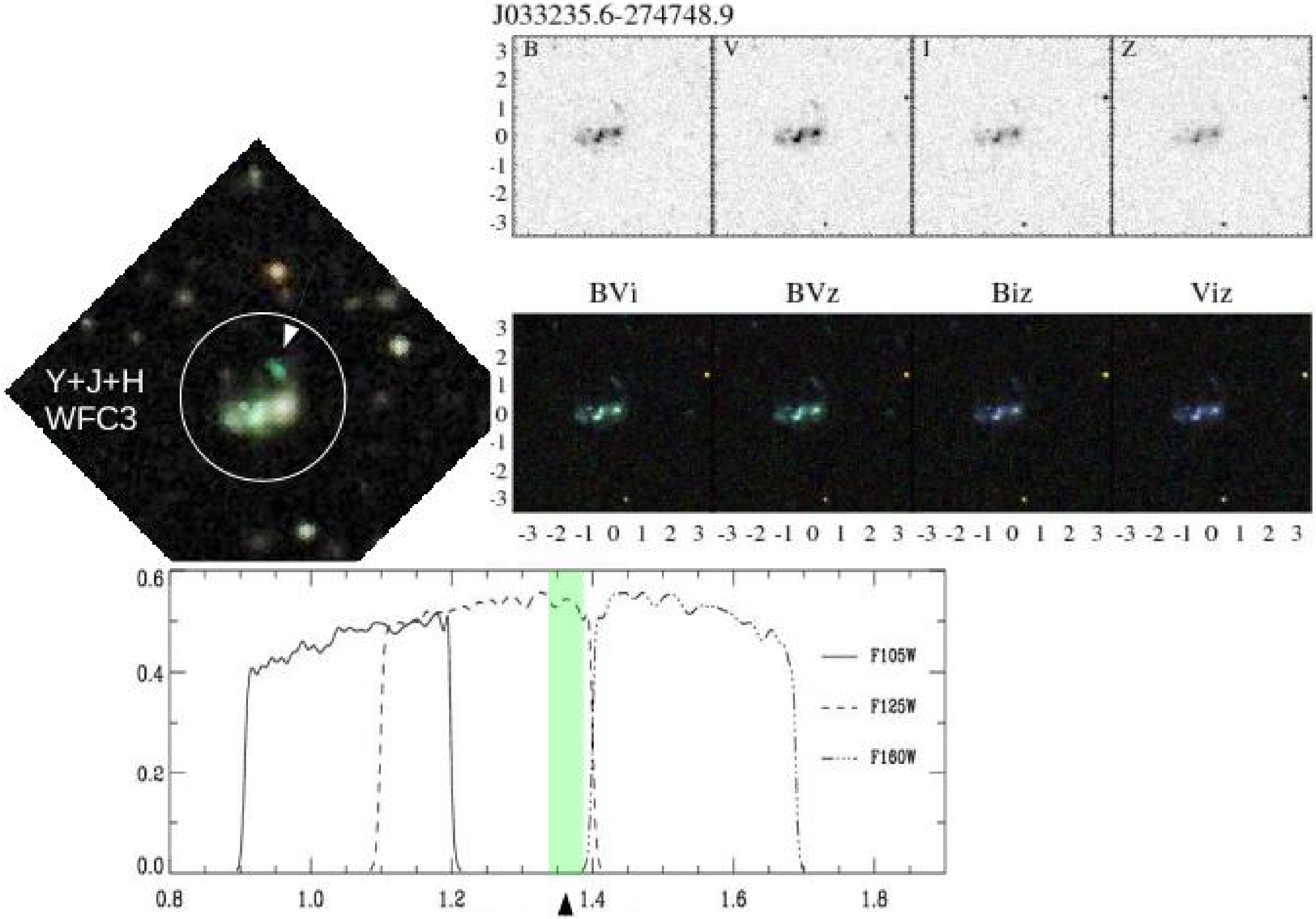
Color selection of galaxies at redshift 4, 5 and 6

(Vanzella+09):





- 109 out of 202 selected targets have measured redshift (54% 65 $z_{850}>26$ - $z<3.6$ critical).
- 96% , 89% and 82% of B,V and I-drops have redshift in the expected range.
- 12 low-z interlopers: 10 stars and two z<2 gal.
- 5 high-z serend. discovered.



HUDF J033235.62-274748.9

Hb, [OIII]4959-5007 zspec = 1.765, QF=1, ref. 61

"With increasing distance our knowledge fades and fades rapidly. Eventually we reach the dim boundary, the outmost limits of our telescope. The search will continue. Not until the empirical resources are exhausted need we pass on to the dreamy realm of speculation."

Edwin Hubble, Realm of the Nebulae, 1936

Thank you !