Investigating sources of ionizing radiation

Eros Vanzella

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Vanzella+10(a,b,c)

Vanzella+11, Pentericci,EV et al. +11

Vanzella+12(a,b)

Outline

- The issue of HI reionization: brief introduction

- Current situation about ionization from star-forming galaxies and AGNs at z<4 and new results from deep observations at z~3.6 (GOODS+CANDELS).

- Recent and ongoing spectroscopic observations of z~7 candidate galaxies: probing reionization process with Lya emission statistics (FORS2 survey).

- Future

Motivation: HI reionization

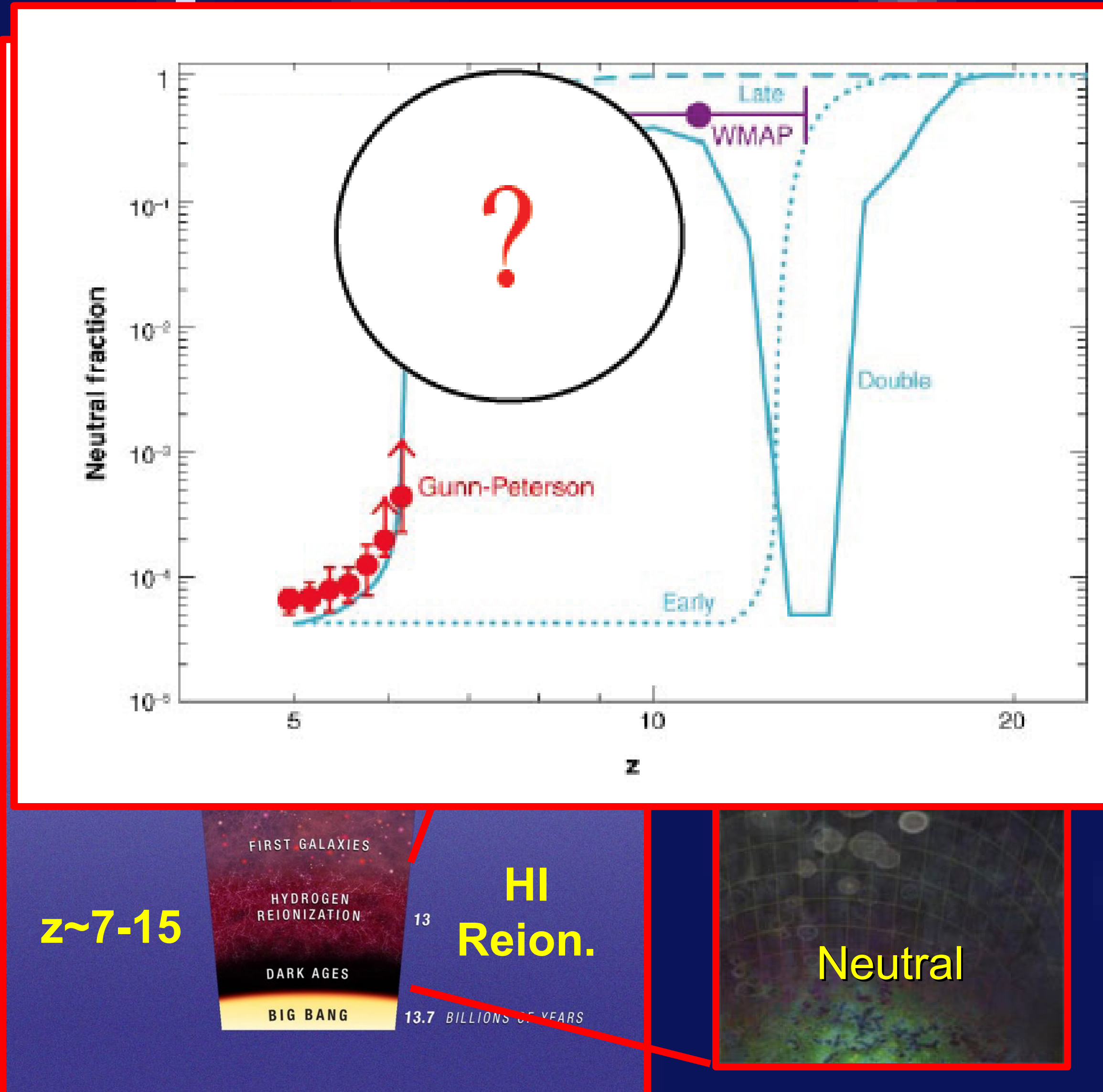
Loeb, SA 2006

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 ? Were galaxies responsible of that ?
- When and how did reionization occur ?
- What keeps the Universe ionized down to present epoch ?

Motivation: HI reionization



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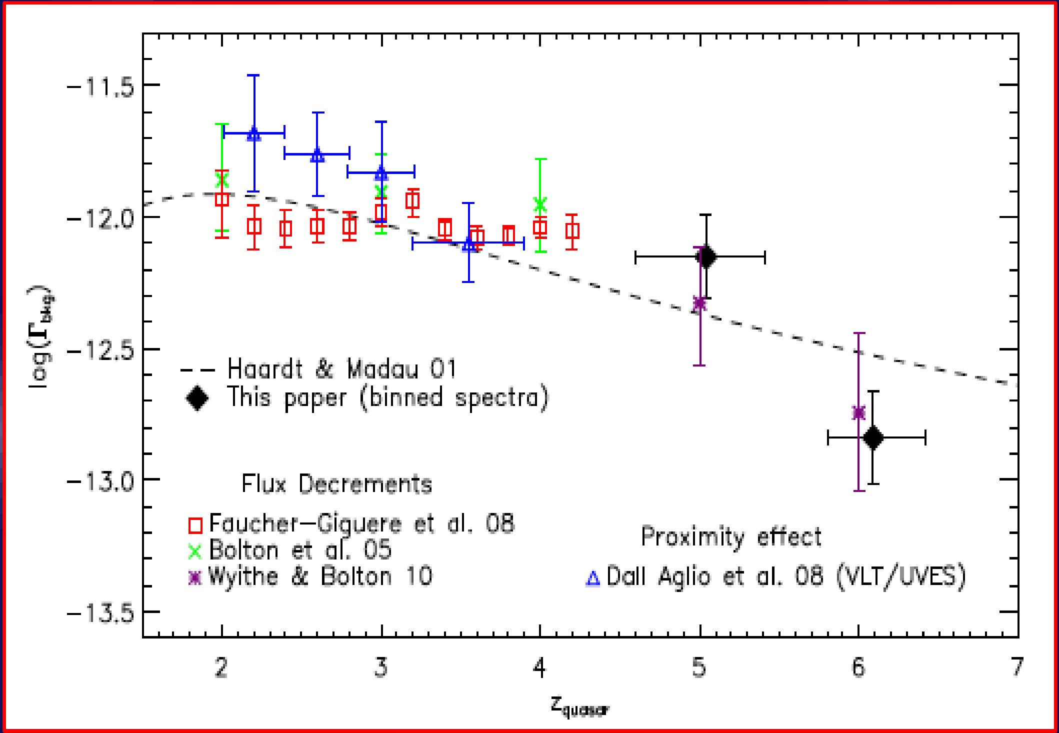
Ionizing background

$$\Gamma(z) = 4\pi \int_{\nu_{\rm HI}}^{\infty} \frac{d\nu}{h\nu} J_\nu(z)\sigma(\nu),$$

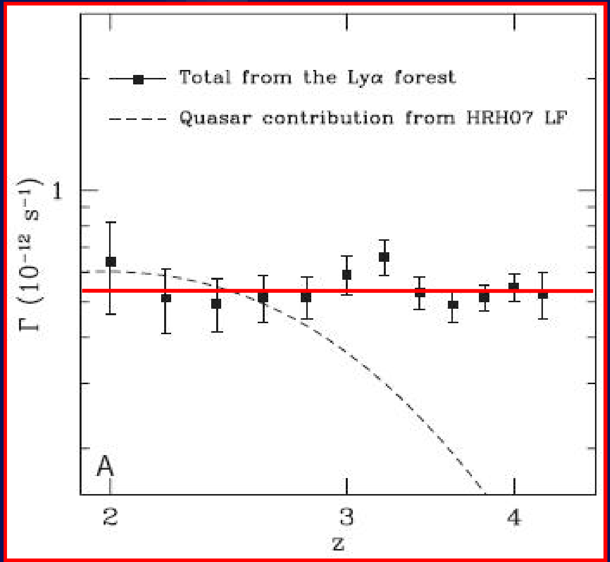
Jv(z) = angle-avergaed specific intensity

Γ = photoionization rate (s^{-1})
integral of all sources of UV

Calverley, Becker, Haehnelt, Bolton 2010 (proximity)



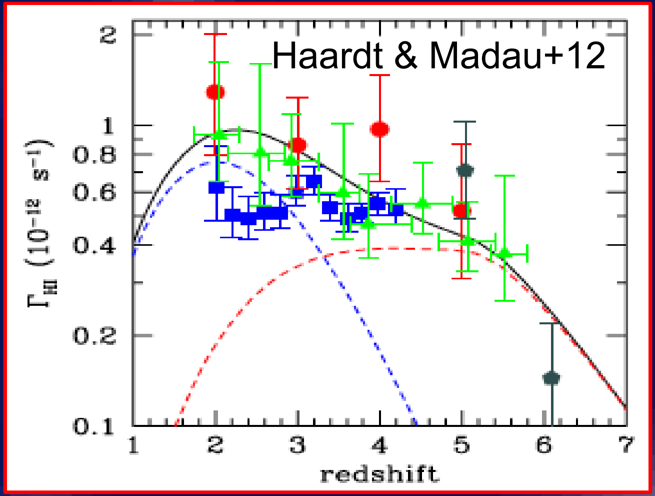
Proximity effect: QSO lumnosity + size of the sphere of influence give UVB.

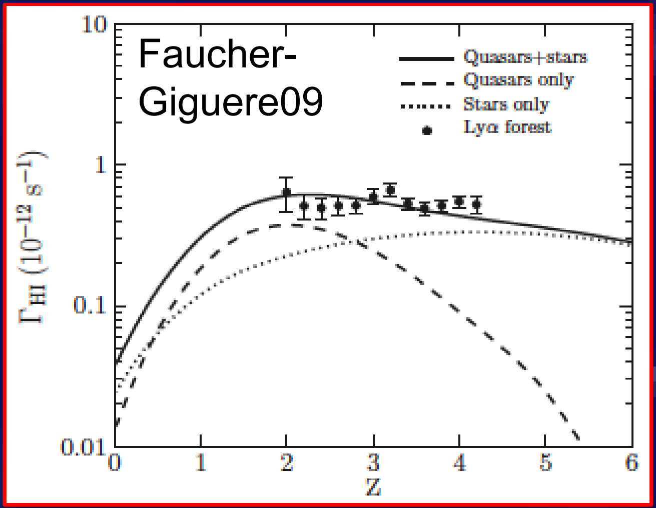


Faucher-Giguere+08/09
(flux decrement - opacity LAF)

LAF opacity is a balance between Γ and recombination, modulo cosmology, thermal history, gas density distribution (Gunn & Petersn 1965)

What reionize (and keep ionized) the Universe ?





<u>z>3 stars dominate</u>

- Fontanot+12 (in press)
- Finkelstein+12 (yesterday)
- Prochaska+09
- Cowie+09
- Siana+08
- F.Giguere+08,09
- Dall'Aglio+09
- Srbinovsky & Wyithe 2007
- Bolton & Haehenelt 2007
- Khulen+12
- Ciardi+12

Critical: fesc, IMF, LF

<u>z>3 AGN/QSO can still contribute significantly</u>

- Glikman 2011
- Giallongo et al. in prep.

Critical: redshift evolution of the num. density
faint end slope of AGN LF
\+ fesc for AGN not well understood
\+ He reionization

Starforming galaxies as sources of ionizing radiation

If there is a rapid decline in number density of QSO/AGNs at z>3

Then star-forming galaxies are the leading candidates

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

Volume filling factor of ion. HI (Q_{HII})

Question:

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

$C = \langle\rho^2\rangle / \langle\rho\rangle^2$ <>=spatial aver

$C \sim 2.9\,[\,(1+z)/6\,]^{-1.1}$ (Shull12)

$C \sim 1+43z^{-1.7}$ (Pawlik09, Haardt12)

C ~ 2 (z=8), 3 (z=6), 6-7 (z=3)

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

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

fesc varies from 1% to 100%, large uncertainty in the predictions (see summary in Fernandez & Shull 2011)

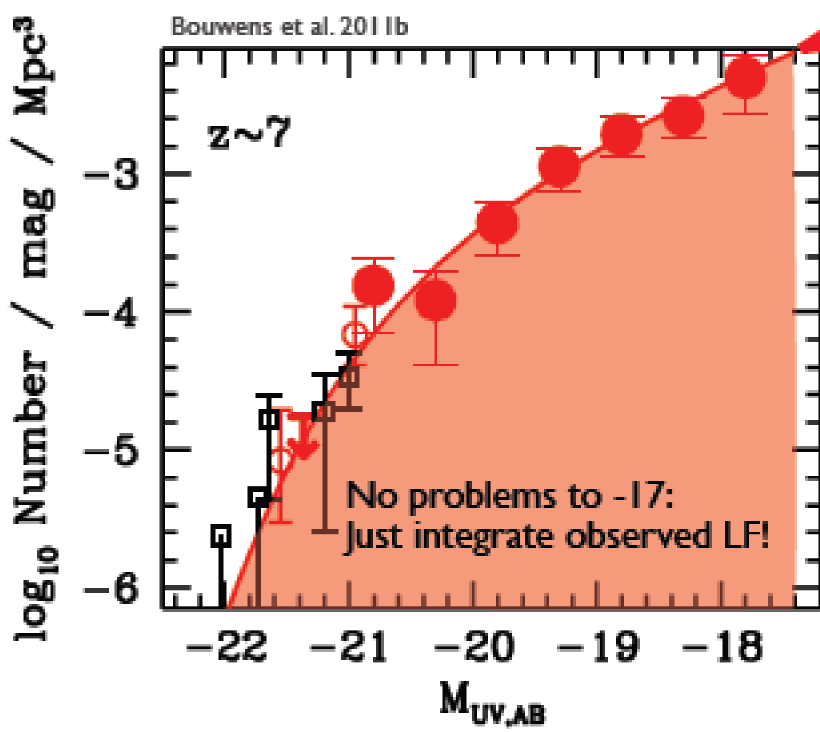
Can galaxies reionize the Universe ?

Finkelstein+12 (yesterday): if we stop at M ~ -17, fesc >~ 30%

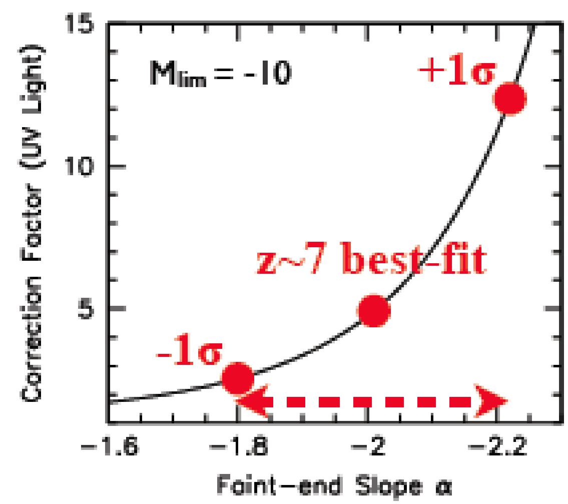
The Ionizing Flux Density from Galaxies

$$\phi(M_{1400}) \xrightarrow[\text{integrate; assume } M_{lim}]{} \rho_{L1400} \xrightarrow[\langle N_{\gamma<912}/N_{\gamma1400}\rangle]{} \dot{N}^{int}_{ion} \xrightarrow[f_{esc,rel}]{?} \dot{N}_{ion}$$

? Faint contribution: Have to extrapolate to below detection limits



With these steep faint-end slopes as observed: luminosity density completely dominated by faint galaxies



fesc from galaxies

HI reionization, attack the problem from two sides, low (z<~4) and high (z>7) redshift :

The transmission of the IGM (at λ<912A) is extremely low during reionization, it is unfeasible to observe LyC emission directly:

→ Look for LyC at z <~ 4.. (~1 Gyr after the end of Reioniz.)
- Investigate the physical conditions and geometry that allow ionizing photons to escape (*LyC regime*)
- Look for diagnostics/links between ionizing and *non*-ionizing *LyC* regimes and connect to higher-z Universe (z>6) where direct observations are not possible

→ Measure UVB: one can put constraints on the evolution of the source population with redshift (gal+agn) 0 < z < 6.

Estimating fesc: Method

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.

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

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

(Steidel et al. 2001)

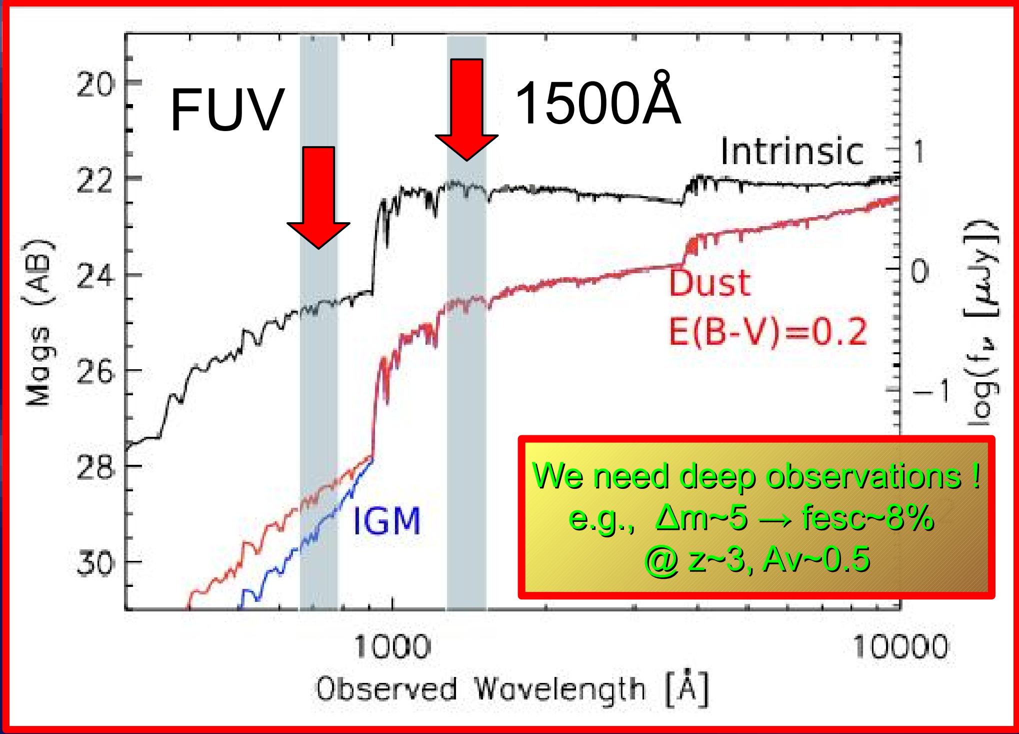
Ionizing photons UV (λ<912A) LyC

Attenuation by ISM (HI , dust)

Attenuation by the IGM (LAF, LLS, DLAs)

NON-ionizing photons UV (λ~1500A)

Attenuation by ISM (dust)



We need deep observations !
e.g., Δm~5 → fesc~8%
@ z~3, Av~0.5

Escape fraction of ionizing radiation: relation with physical quantities

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

Vanzella (2012a)

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

Steidel+2001

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

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

< 1   < 1

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

< 1

Any assumpion or observational constraint on fesc is related to the internal properties and cosmic evolution of galaxy population

Note: fesc < 1 by definition

fesc,rel < 1 (otherwise $A_{900} < A_{1500}$)

Open questions

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

- Is <fesc> evolving with cosmic time ? Or the fraction of gal. with high fesc is evolving ?
  And at fixed redshift, is it luminosity (or mass) dependent ?

- Which are the more relevant physical processes of galaxy evolution that modulate the fesc quantity ? (e.g., feedback, SFH, etc.)

- What is the spatial distribution of escaping ionizing radiation and its connection with the other non-ionizing components (geometry) ?

- Can AGN and star-formation cooperate toward higher values of fesc at faint luminosities ?

Big effort in the last 12 years on modelling and observations:

Ionizing radiation from galaxies: theoretical predictions

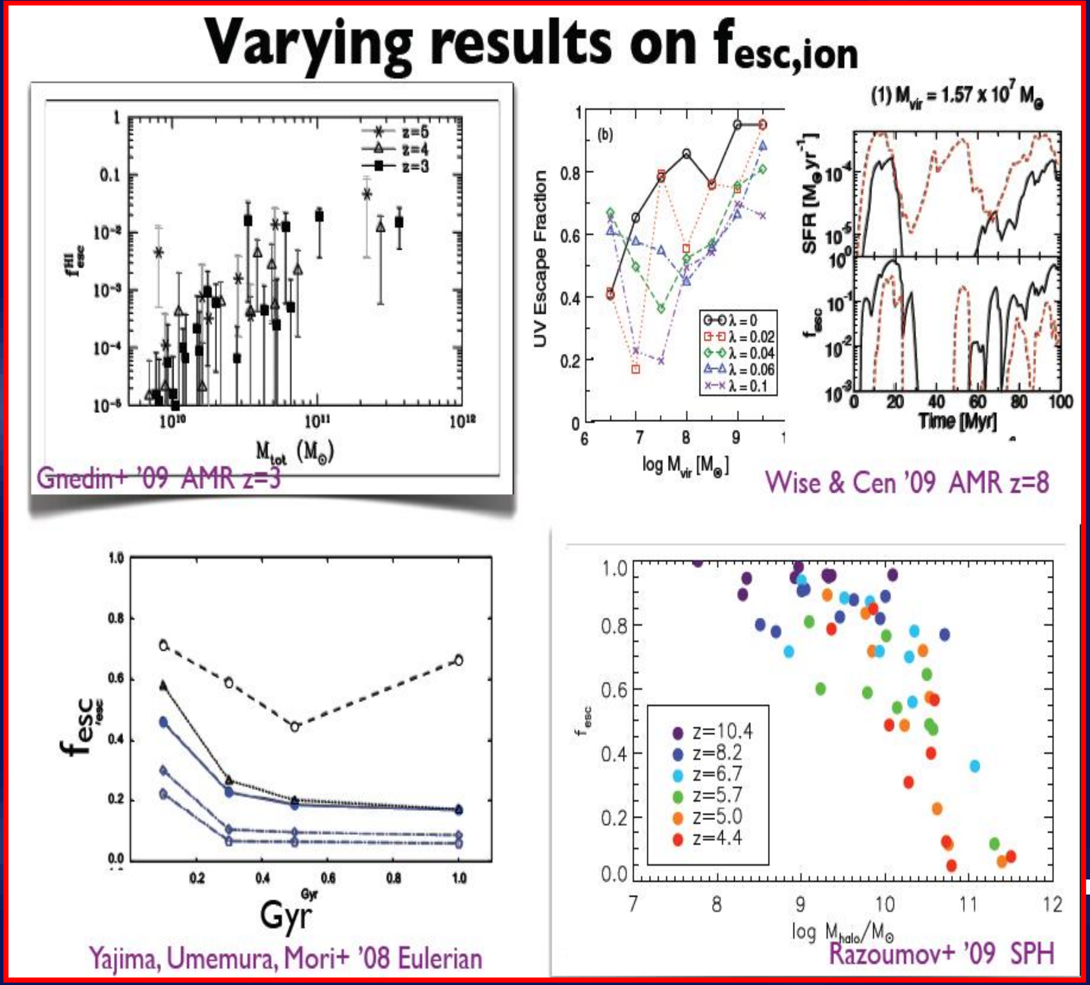
Theoretical modeling (RT+SPH):

fesc ↓ if redshift ↑ (Wood & Loeb+00)
fesc ↑ if redshift ↑ (Razoumov+06,+10)
fesc ↑ if redshift ↑ (Haardt+11)
fesc ~ with redshift (Yajima+10)
fesc ~ with redshift (Gnedin+08)

fesc ↓ if halo mass ↑ (Wood & Loeb+00
Ricotti & Shull+00
Yajima+10,
Razoumov+10)
fesc ↓ if halo mass ↓ (Gnedin+08a,b)

fesc ↑ for dwarf galaxies
(Wise & Cen+09)
fesc ↑ for small galaxies
(Fernandez & Shull +11)
(e.g, Choudhury & Ferrara 07)
fesc ↑ with runaway stars (Conroy+12)

Large variance on the predictions:
May reflect the uncertainties on SF, feedback, radiation transfer and geomery of the ISM distribution, all important ingredients.



fesc from galaxies: current observations

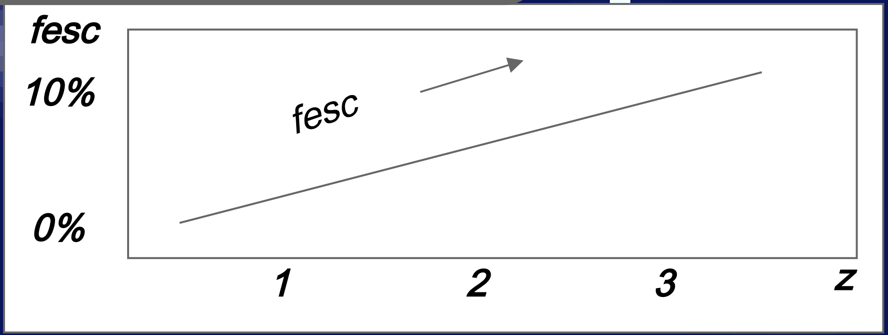
Z~0 fesc ~ 0.01-0.02 MW (Bland-Hawthorn & Maloney 1999; BH et al. 2001)
fesc < 0.02-0.05 (spec. Leitherer+95, HUT; Deharveng+01, Grimes09, FUSE)
fesc <~ 0.03 Haro11 (Leitet+11, but see Grimes+07, fesc<~2%) (FUSE)
fesc ~ 0.15 Heckman+11 (FUSE+COS, but not direct observations)

Z~0.7-1.2 fesc < 0.01-0.05 (Siana+10; Malkan+03; Cowie+09; Bridge+11; Ferguson+01) (Solar Blind Channel HST, Galex, STIS)

Z>~2 <fesc> < 0.075 (c.l. 95%) (Chen+07; Fynbo+09) 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 U)
< 0.05 Vanzella+10 (phot, ~100 LBGs) (VLT, deep U) (1 detected)

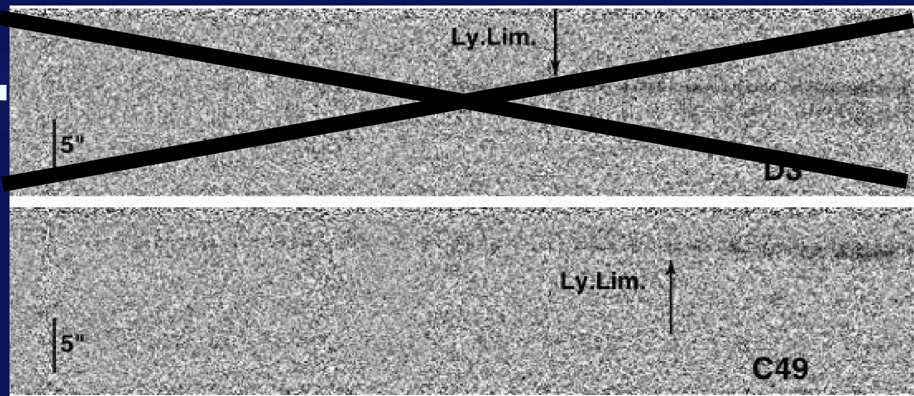
fesc > 0.5 (spec. Stacking; 29 LBGs, Steidel+01)
fesc ~ 0.1-1 (spec. Stacking; 14 LBGs, Shapley+06)
fesc ~ 0.2-1 (phot. NB, Iwata+09; Nestor+11) ~ 50 LyC



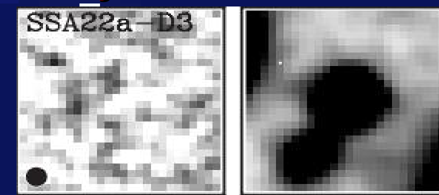
See Inoue+06, Siana+10

z~3 LyC: last 12 years (Shapley+06, Iwata+09, Nestor+11)

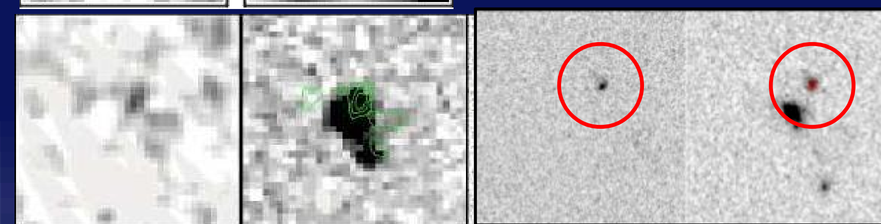
(Shapley+06) 2 LBG with LyC out of 14



LyC R



Not confirmed with deep NB of **Iwata+09** and **Nestor+11**



NB U-band R F336W WFC3 F814 ACS

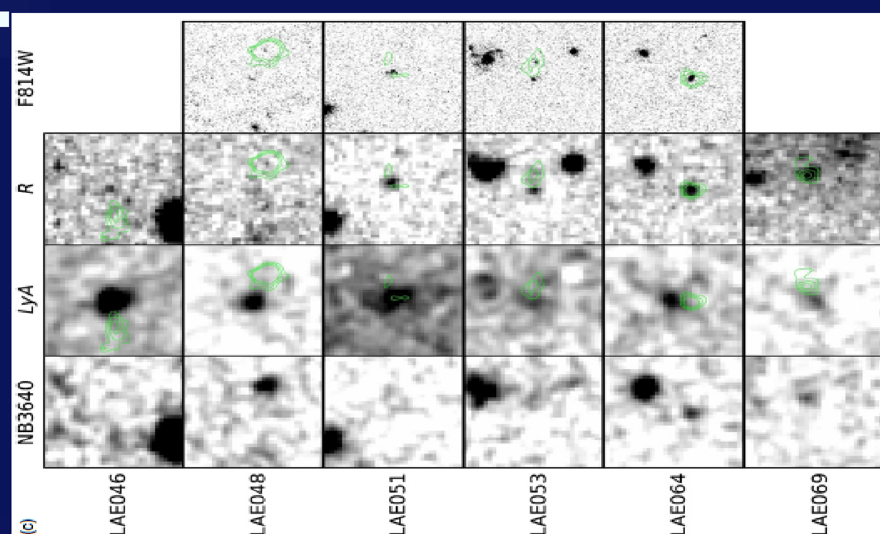
~ 50 candidates
Shapley + Iwata + Nestor

Criticalities:

→ more than 80% show spatially offset emission

→ f1500 / f900, extreme UV ratios (~1) PopIII stars !? (Inoue+11)

→ not independent works



Example from Nestor+11

Are the spatially offset U-band emitters at the same redshift of the main (targeted) counterpart high-z galaxy ?
i.e. , are they 0.1-0.5L* LyC emitters ? (Vanzella et al. 2012a)

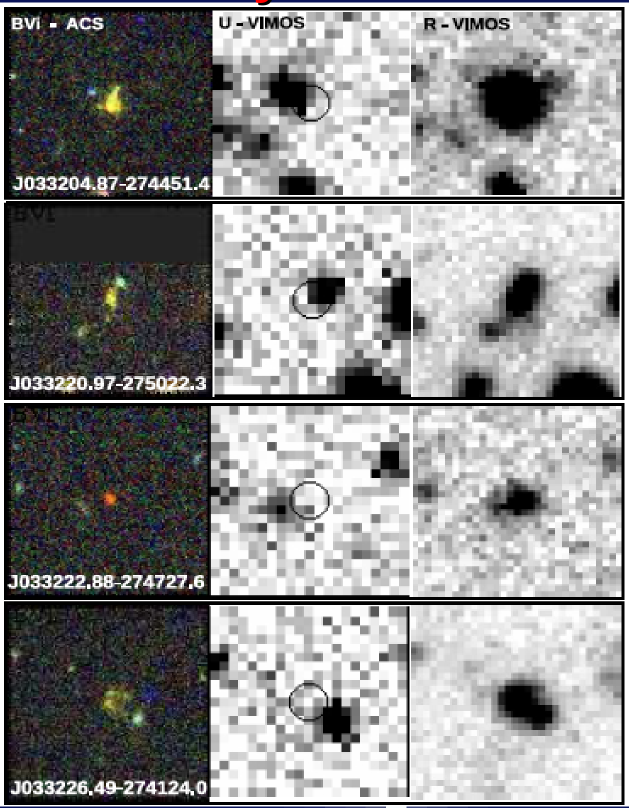
GOODS+CANDELS survey is ideal to study this: high spatial resolution deep phancromatic imaging:

(1) **zphot**, ACS + WFC3 (GOODS+CANDELS)

(2) ***fesc*** measured properly $(F1500/FLyC)_{obs}$

(3) Transverse LAF attenuation Δ(B-V)

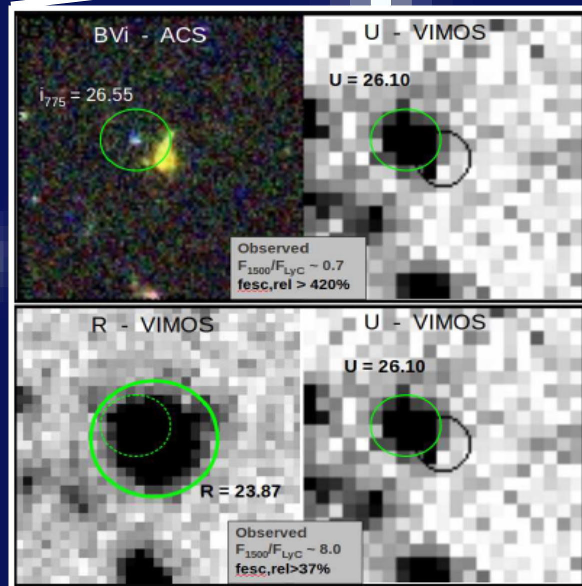
ACS LyC ?! R-band

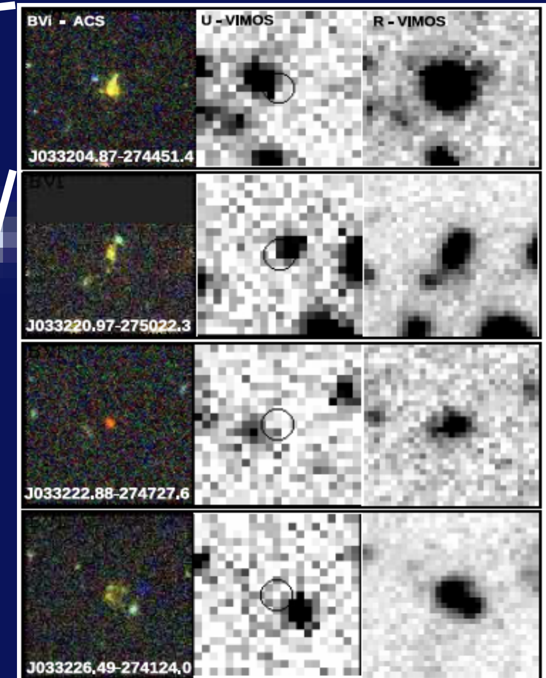


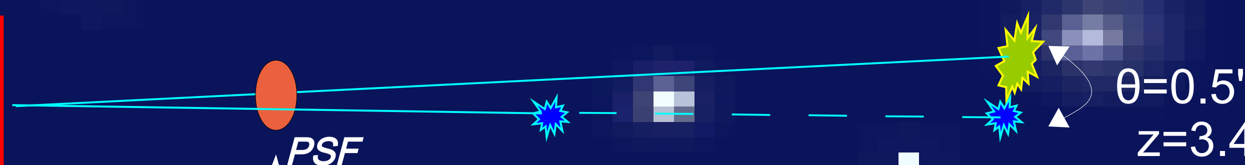
Subarcsec separation
U-band emitters - example

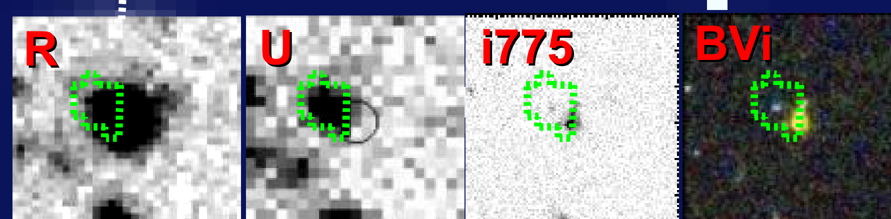
Anomalous *fesc*:

Sub-arcsecond cases







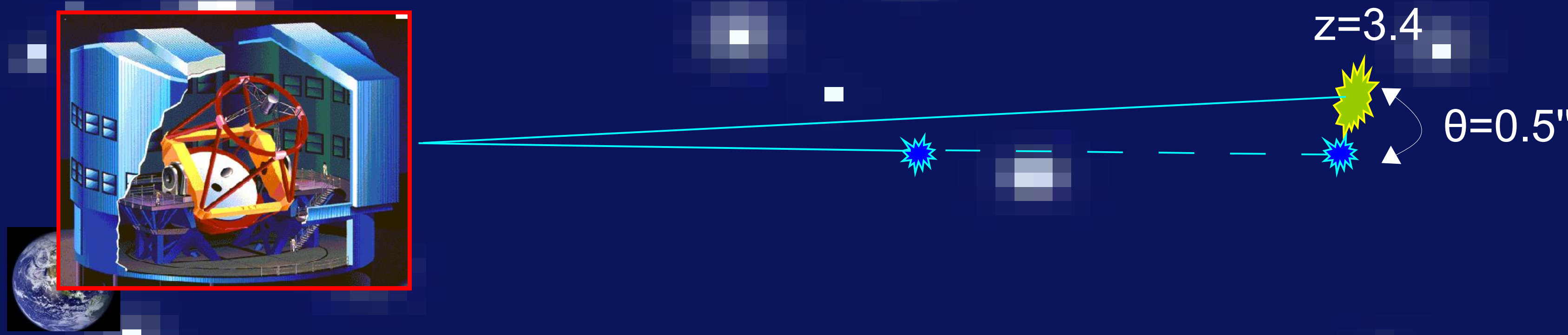


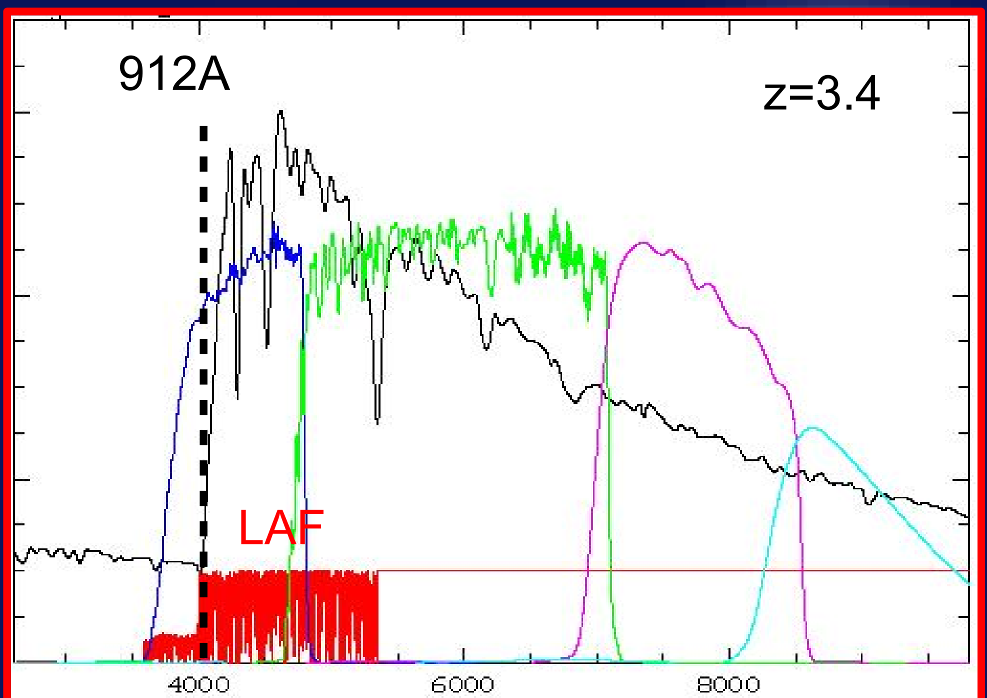
$$f_{esc,rel} \equiv \frac{(L1500/L900)_{int}}{(F1500/F900)_{obs}} \exp\left(\tau_{900}^{IGM}\right)$$

fesc,rel>25%

fesc,rel >430% (fesc>230%)

Anomalous transverse IGM attenuation



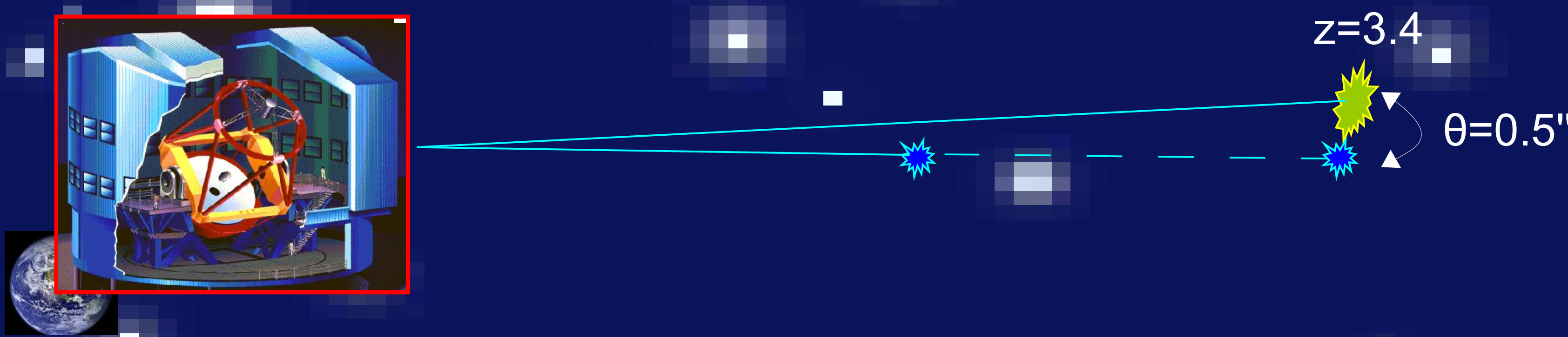


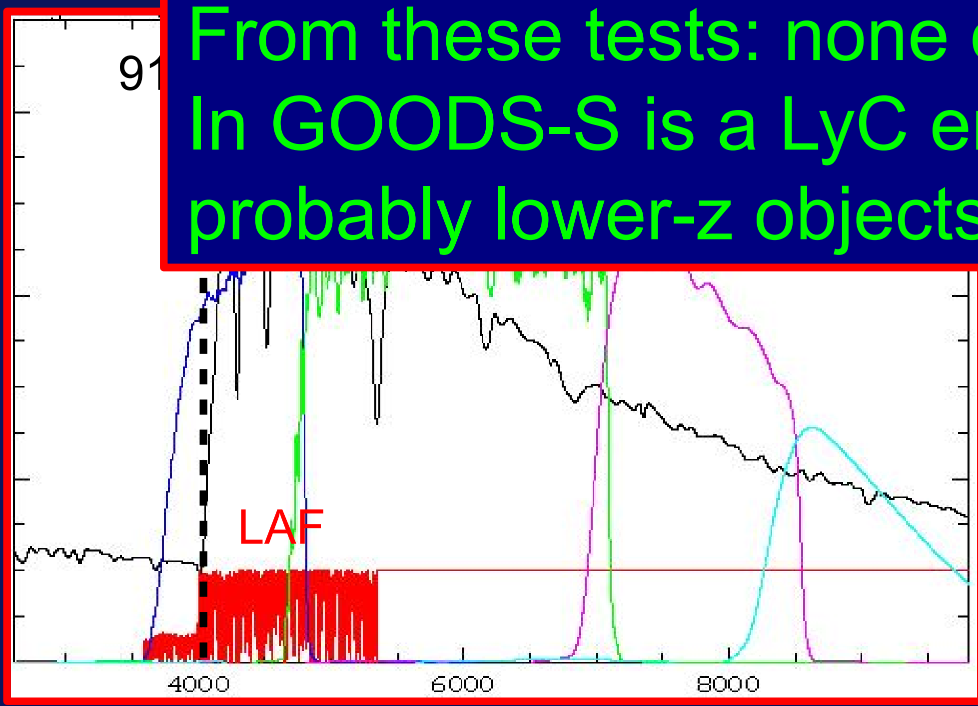
$\Delta(B-V) = (B-V)_{LBG} - (B-V)_{Uem}$ corrected for LyC em. probes the transverse IGM decrement.

Our close pairs probe **ΔT(IGM) @ small transverse separations,~ 20kpc**

All show Δ(B-V) > 1 =>
Large variation of IGM transmission at too small scales

Anomalous transverse IGM attenuation





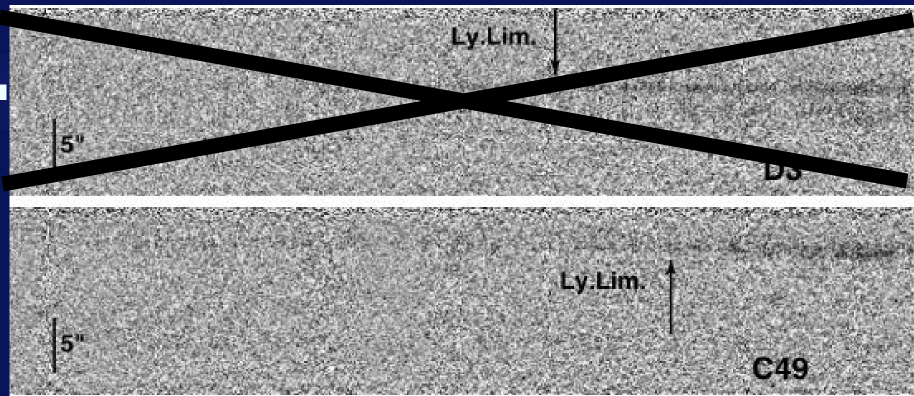
From these tests: none of our U-band emitters In GOODS-S is a LyC emitter → they are most probably lower-z objects

Our close pairs probe **ΔT(IGM) @ small transverse separations,~ 20kpc**

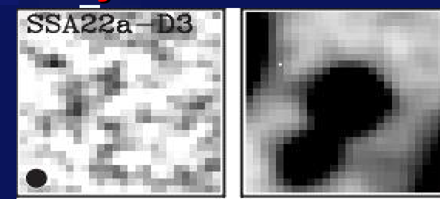
All show Δ(B-V) > 1 => Large variation of IGM transmission at too small scales

z~3 LyC (Shapley+6; Iwata+09; Nestor+11) still problematic

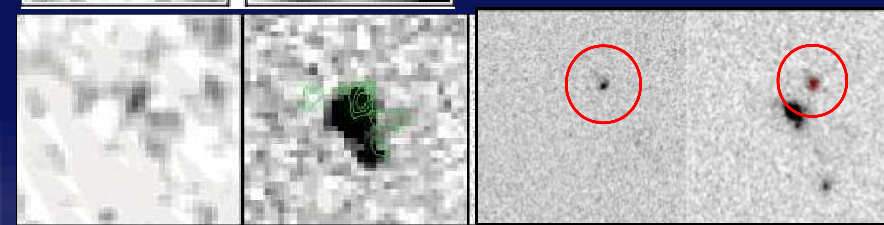
(Shapley+06) 2 LBG with LyC out of 14



LyC R



Not confirmed with deep NB of **Iwata+09** and **Nestor+11**



NB U-band 26.84 | **R 23.81** | **F336W WFC3** | **F814 ACS**

Siana in prep.

- SSA22-C49 candidate 1 out of 14, prob. ~ 22% of superposition (z is needed)

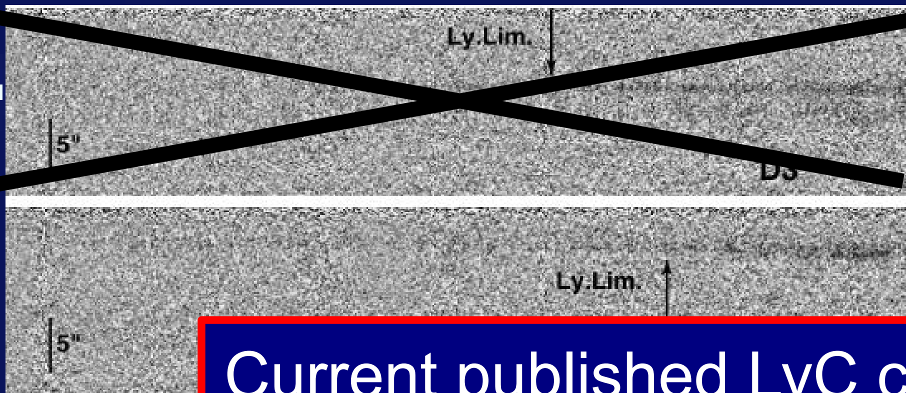
From ground-based phot. F_{1500}/F_{LyC} **= 16.4 (Nestor+11)** **fesc,rel ~ 65 %**

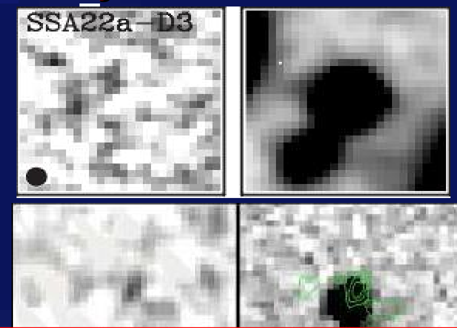
From HST WFC3 + ACS, F_{1500}/F_{LyC} **~ 2-4 (B. Siana private comm.)** **fesc,rel ~ 250-500 % !**

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

z~3 LyC (Shapley+6; Iwata+09; Nestor+11) still problematic

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





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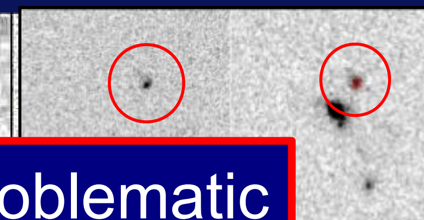


F814
ACS

- SSA22-(
prob. ~ 2

From gro … **%**

From HS … **-500 % !**

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

private comm.)

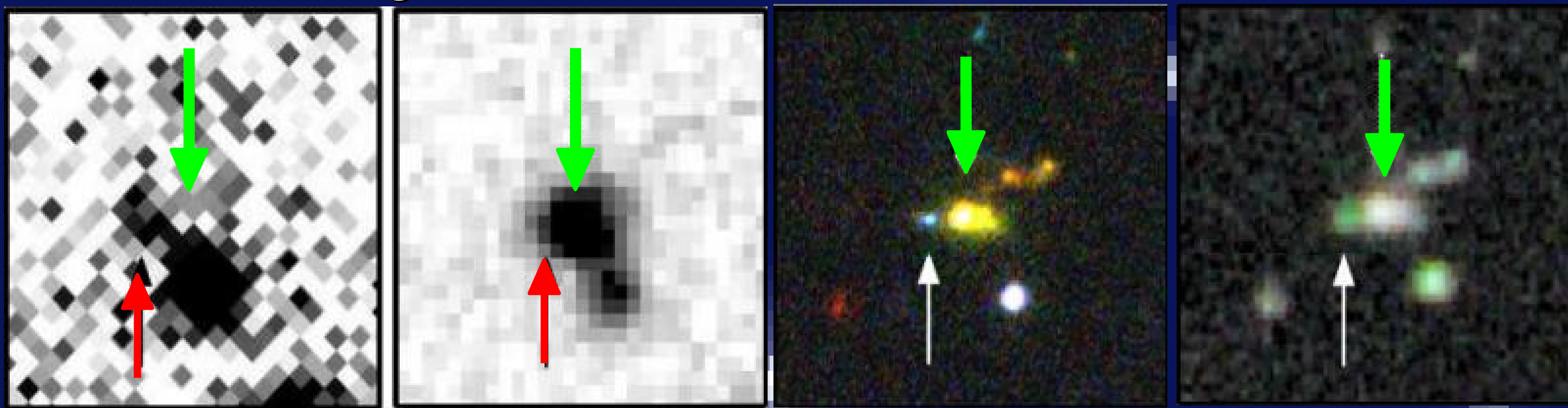
Current published LyC candidates are problematic

1) the zspec are unknown
2) the method used to measure *fesc* is biased (Vanz.+12a) → extreme UV colors !
3) previous works (S01, S06, I09, N11) are not independent results

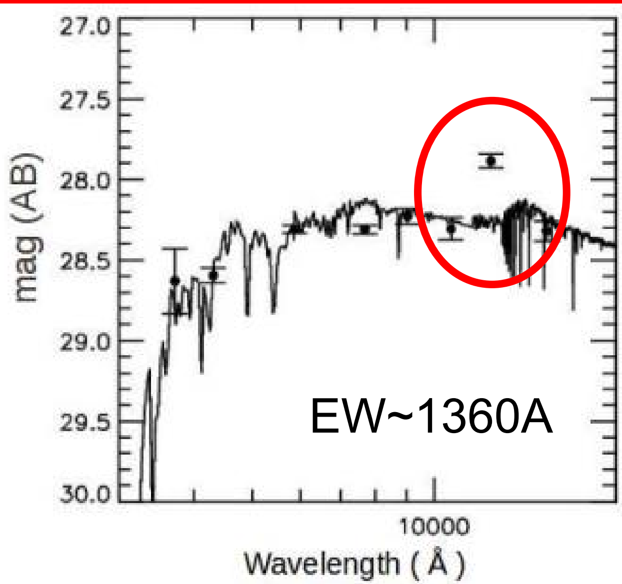
LyC emission from a LBG at z=3.8 ? (example II)

(a faint case in the HUD, U(AB)~28.63)

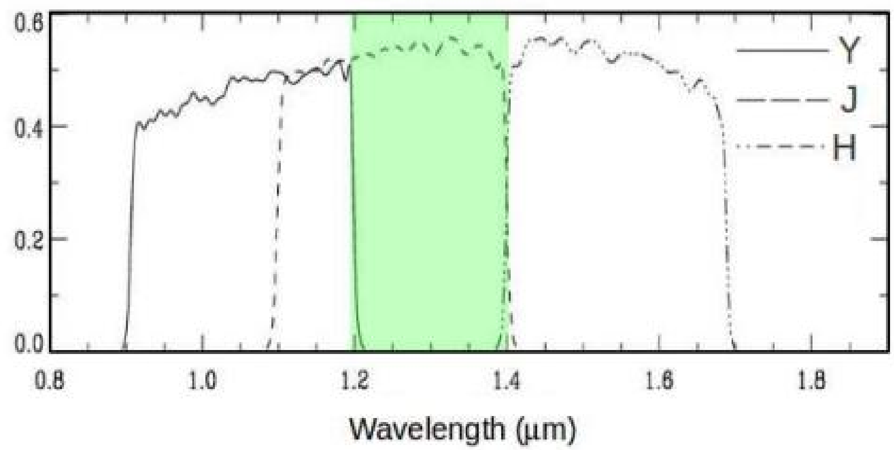
U-band → seeing~0.8" → R-band **ACS/BVi** **WFC3/YJH**



Y → B
J → G
H → R



2500 2900A @ z=3.8



[OII] or Hb, [OIII]4959-5007 in the filter ?

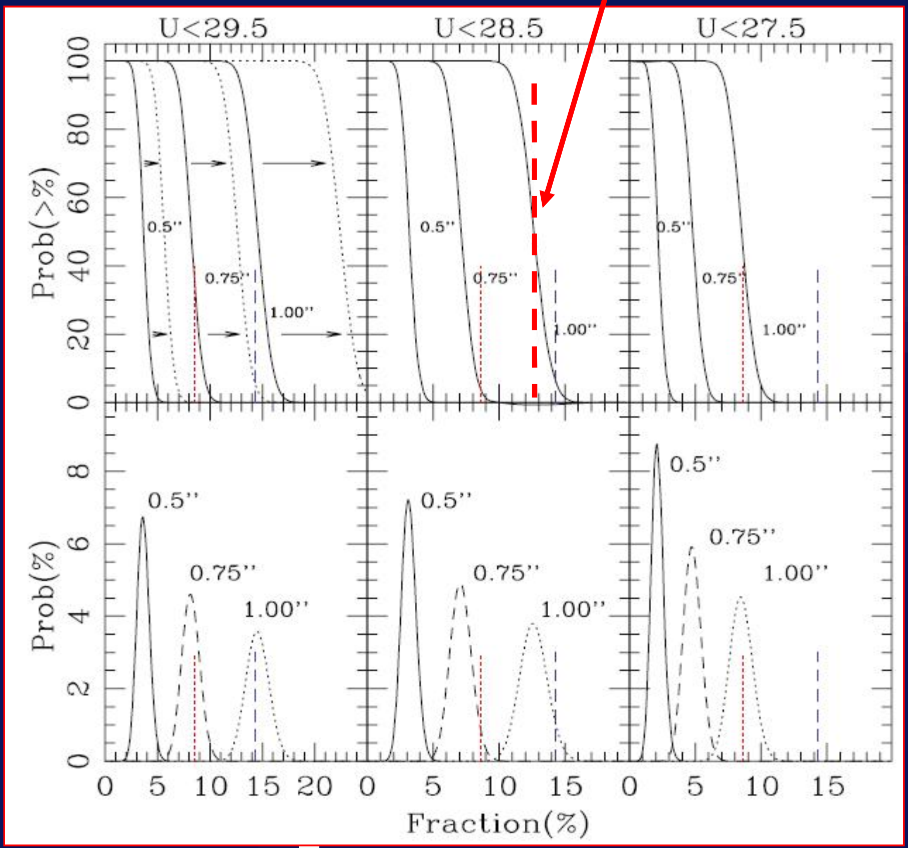
Δ(B-V)=1.69
fesc>200%

See
van der Wel+11
And Kakazu+
USEL galaxies.

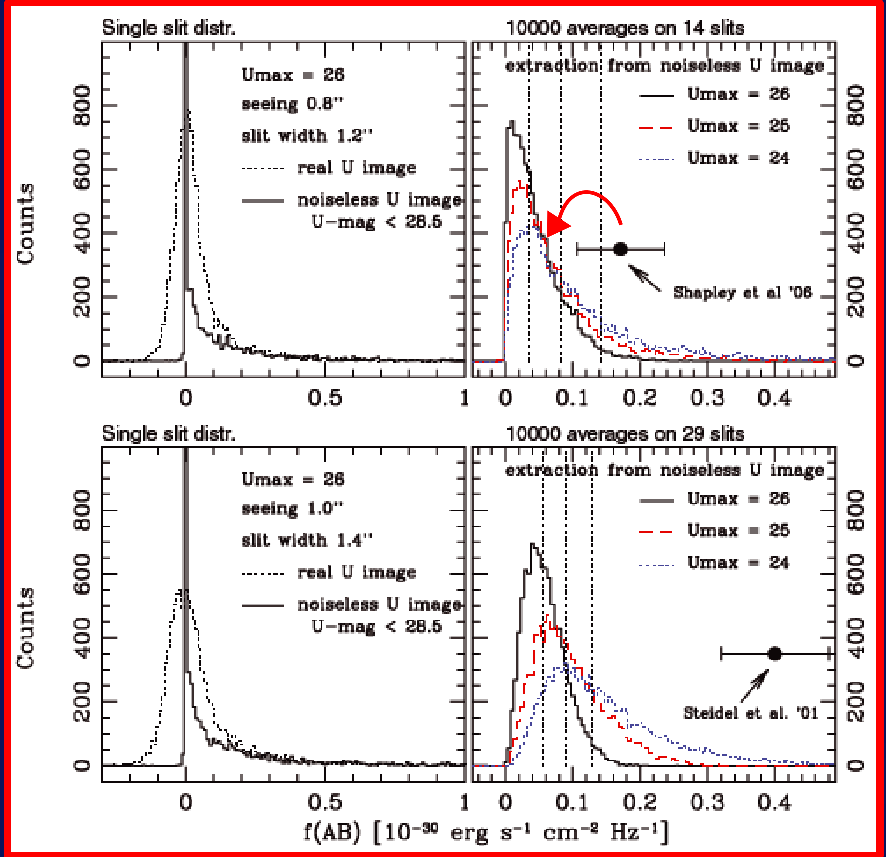
Foreground contamination: expected probability (Vanzella et al. 2010b) → consistent with our analysis in GOODS-S

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

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



MC simulations



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 :

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

Eros Vanzella - Bologna 2012

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, HUT; Deharveng+01, Grimes09, FUSE)
fesc <~ 0.03 Haro11 (Leitet+11, but see Grimes+07, fesc<~2%) (FUSE)
fesc ~ 0.15 Heckman+11 (FUSE+COS, but not direct observations)

Z~0.7-1.2 fesc < 0.01-0.05 (Siana+10; Malkan+03; Cowie+09; Bridge+11; Ferguson+01) (Solar Blind Channel HST, Galex, STIS)

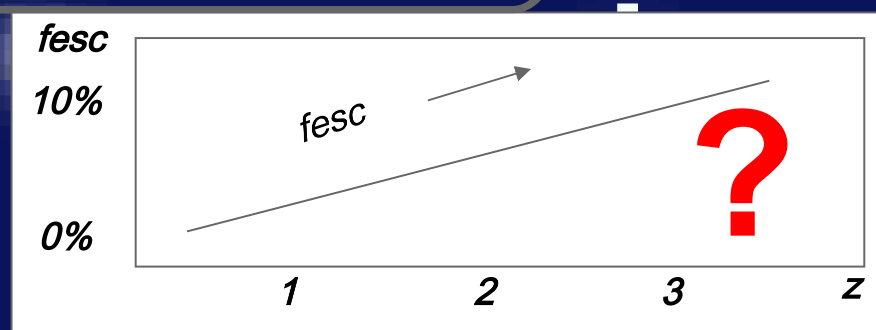
Z>~2 <fesc> < 0.075 (c.l. 95%) (Chen+07; Fynbo+09) from GRBs

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 U)
< 0.05 Vanzella+10 (phot, ~100 LBGs) (VLT, deep U) (1 detected)

fesc > 0.5 (spec. Stacking; 29 LBGs, Steidel+01)
fesc ~ 0.1-1 (spec. Stacking; 14 LBGs, Shapley+06)
fesc ~ 0.2-1 (phot. NB, Iwata+09; Nestor+11) ~ 50 LyC

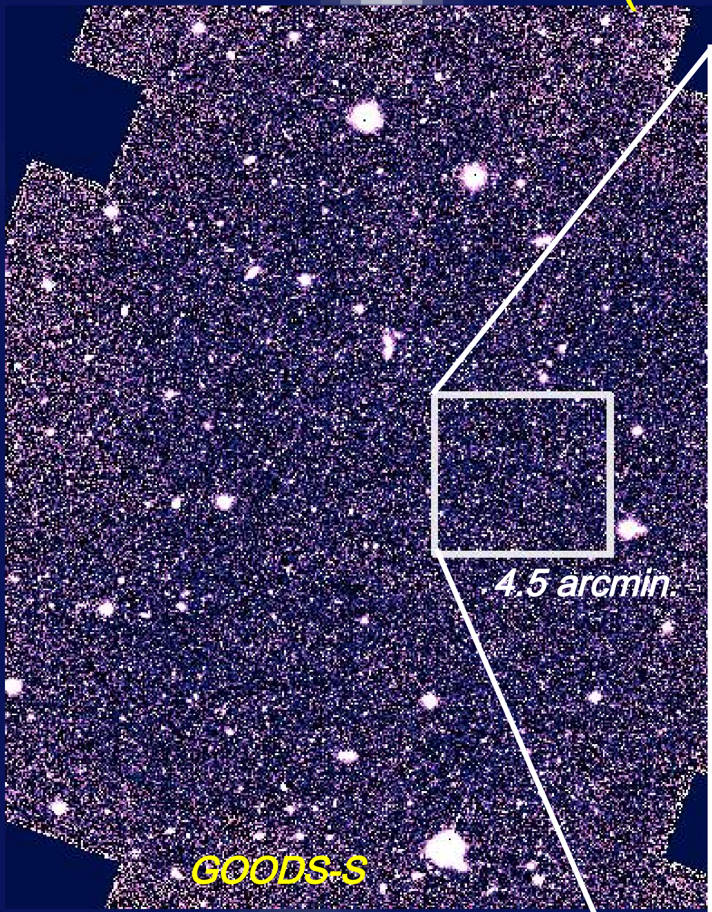
?

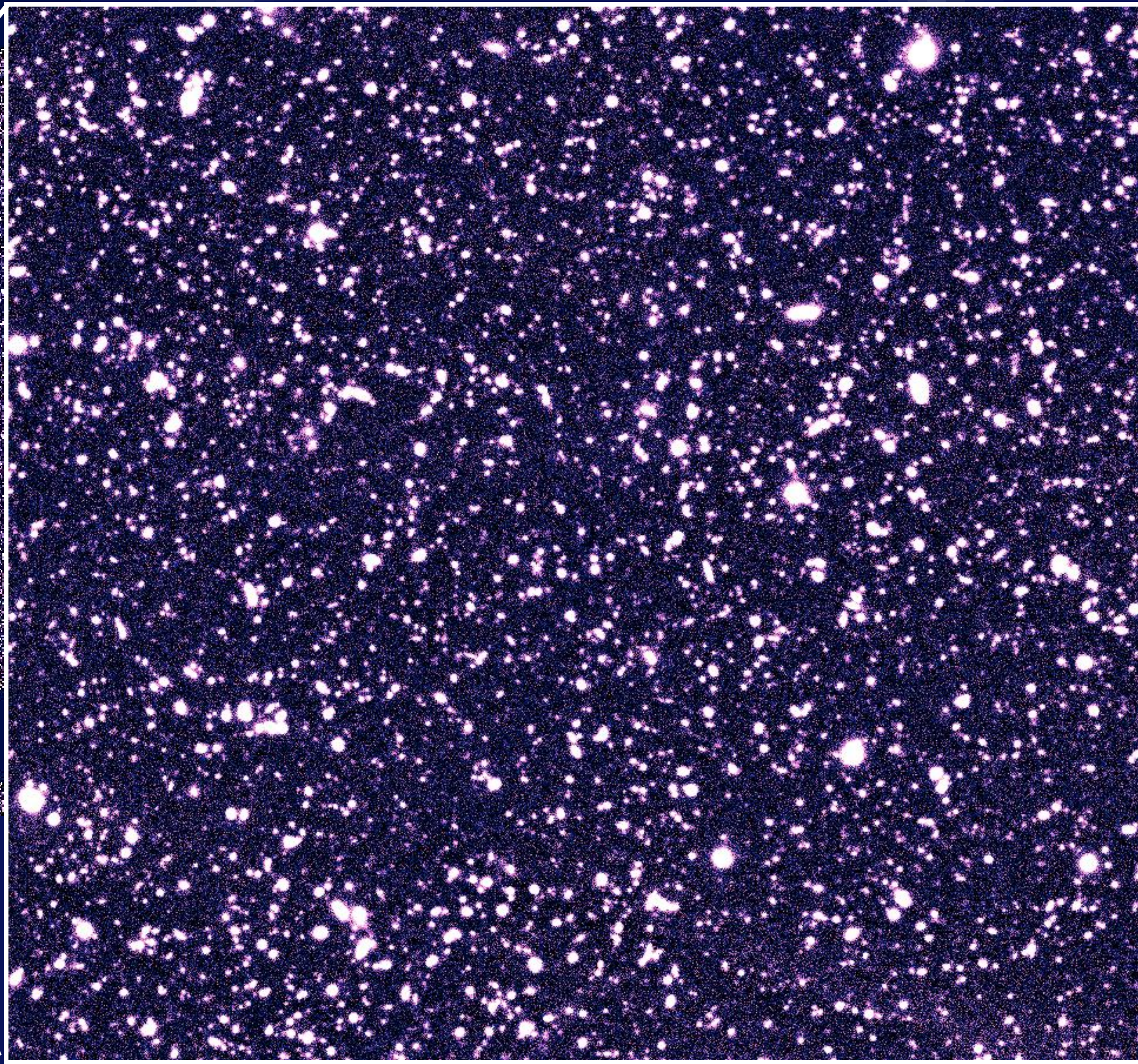
Still candidates, need redshift, extreme UV colors?



See Inoue+06, Siana+10

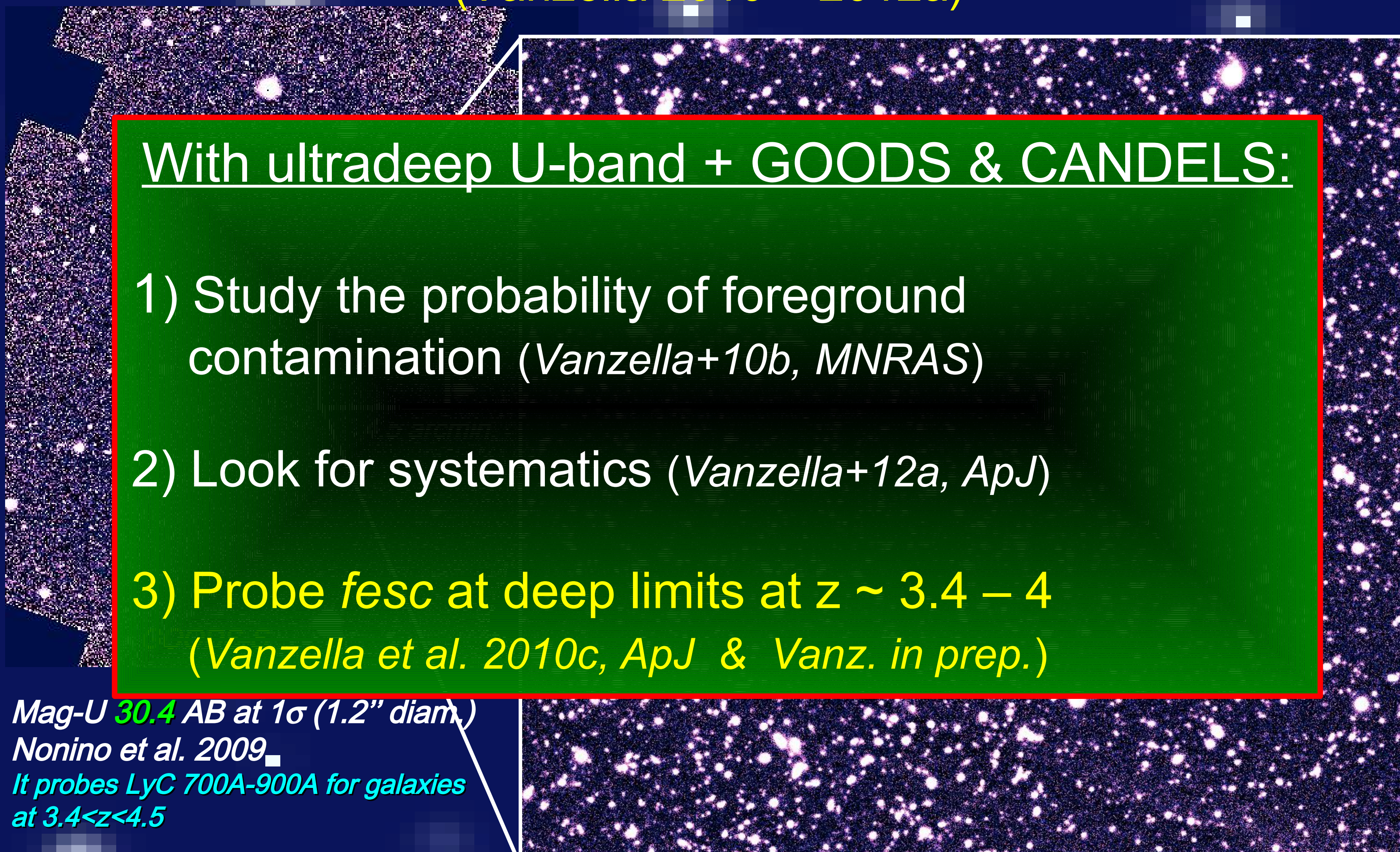
LyC at 3.4<z<4.5 with ultradeep VIMOS U & deep NB FORS1 (Vanzella 2010 + 2012a)





Mag-U 30.4 AB at 1σ (1.2" diam.)
Nonino et al. 2009
It probes LyC 700A-900A for galaxies at 3.4<z<4.5

LyC at $3.4<z<4.5$ with ultradeep VIMOS U & deep NB FORS1 (Vanzella 2010 + 2012a)



With ultradeep U-band + GOODS & CANDELS:

1) Study the probability of foreground contamination (*Vanzella+10b, MNRAS*)

2) Look for systematics (*Vanzella+12a, ApJ*)

3) Probe *fesc* at deep limits at z ~ 3.4 – 4 (*Vanzella et al. 2010c, ApJ & Vanz. in prep.*)

Mag-U 30.4 AB at 1σ (1.2" diam.)
Nonino et al. 2009
It probes LyC 700A-900A for galaxies at $3.4<z<4.5$

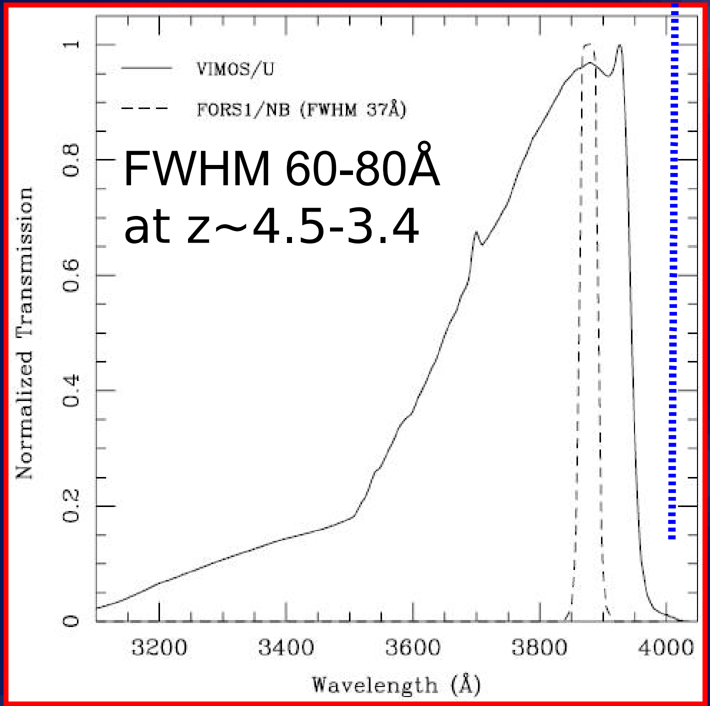
Estimating the fesc distribution of LBGs at z>3.4 from GOODS-S

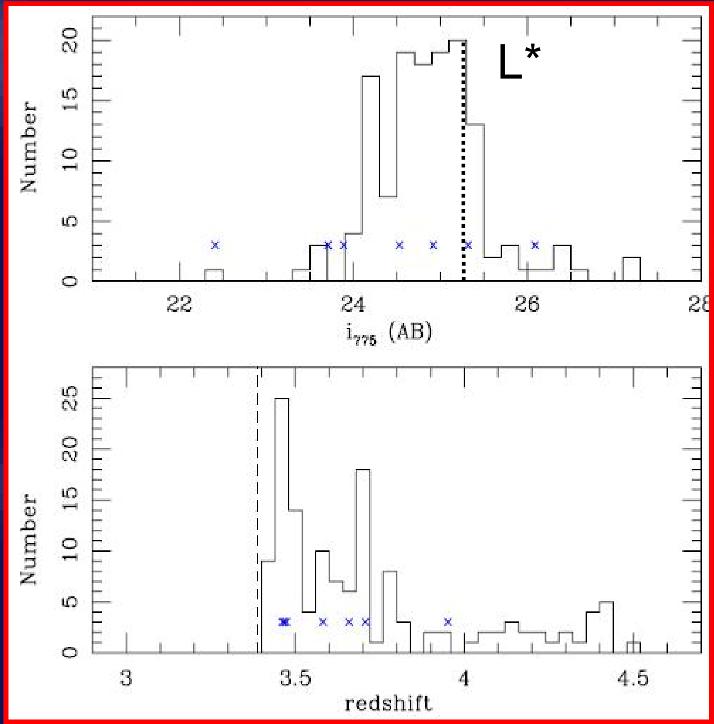
1) Select sources with secure redshift in the range 3.4<z<4.5 (134) (Vanz+09;Balestra+10)
2) Clean the sample from foreground contamination (Vanzella+12a)
3) Exclude AGNs (but very useful as a control sample about IGM transmission…)
4) Estimate fesc with MC and stack (grouping sources)

3.4<z<4.5 => U-band is probing λ_{rest} 912A - 700A

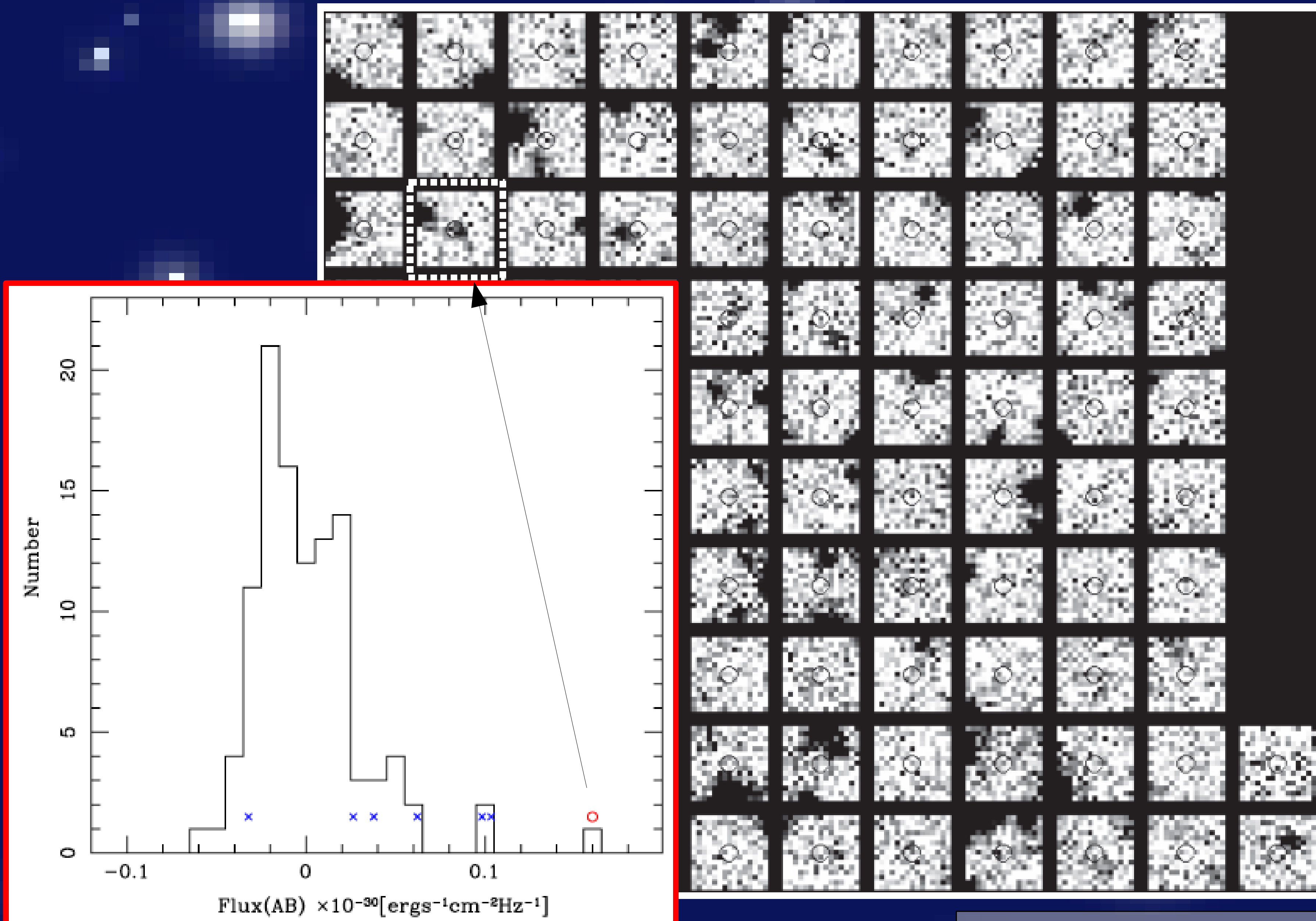
134 in total

LL@ z=3.4

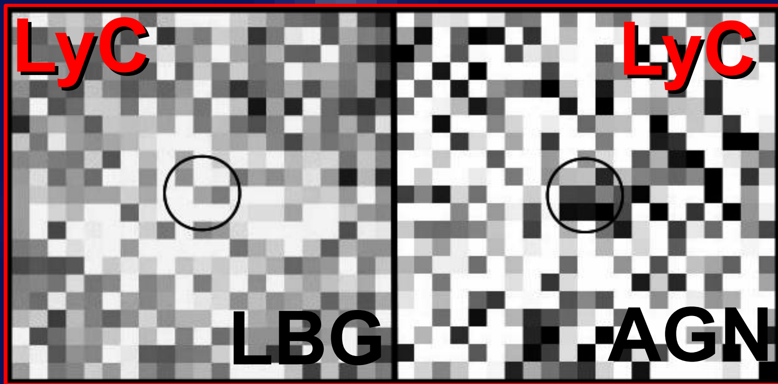




102 LBGs observed in their LyC



Stacking LyC radiation of LBGs and AGNs (z~3.5)

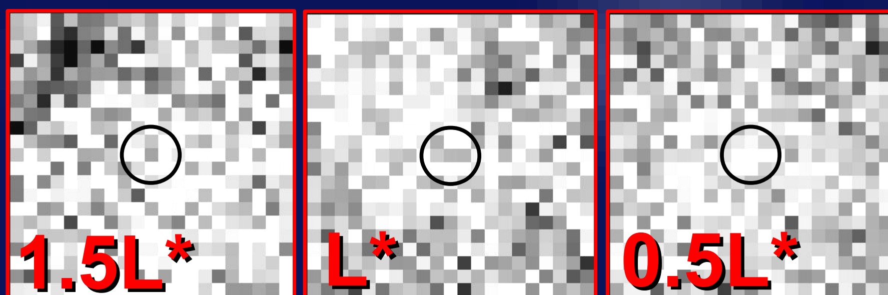


3.4<z<3.7

From AGN:
We can observe ionizing radiation up to z~4
(3 direct LyC detections)

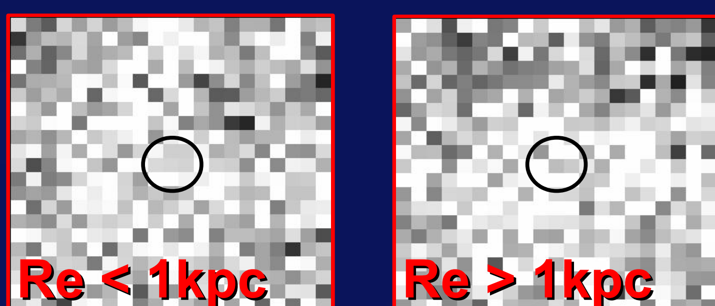
Lum.

<Δm>=7.5 <Δm>=6.9 <Δm>=6.3



fesc < 3% fesc < 5% fesc < 9%

Size

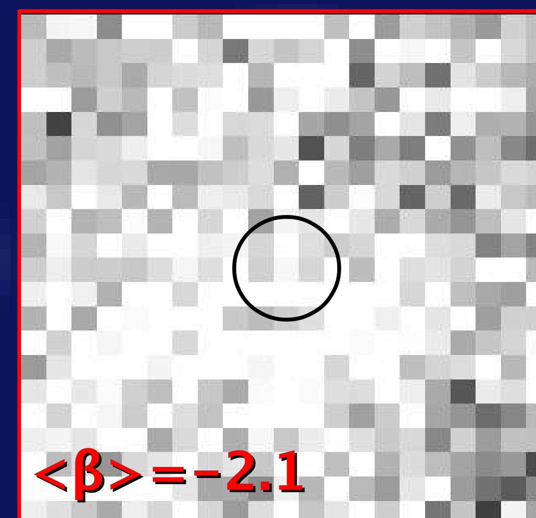


fesc < 5% fesc < 3%

~32 AB in U
~24.7 AB in R
Δm ~ 7 mags !

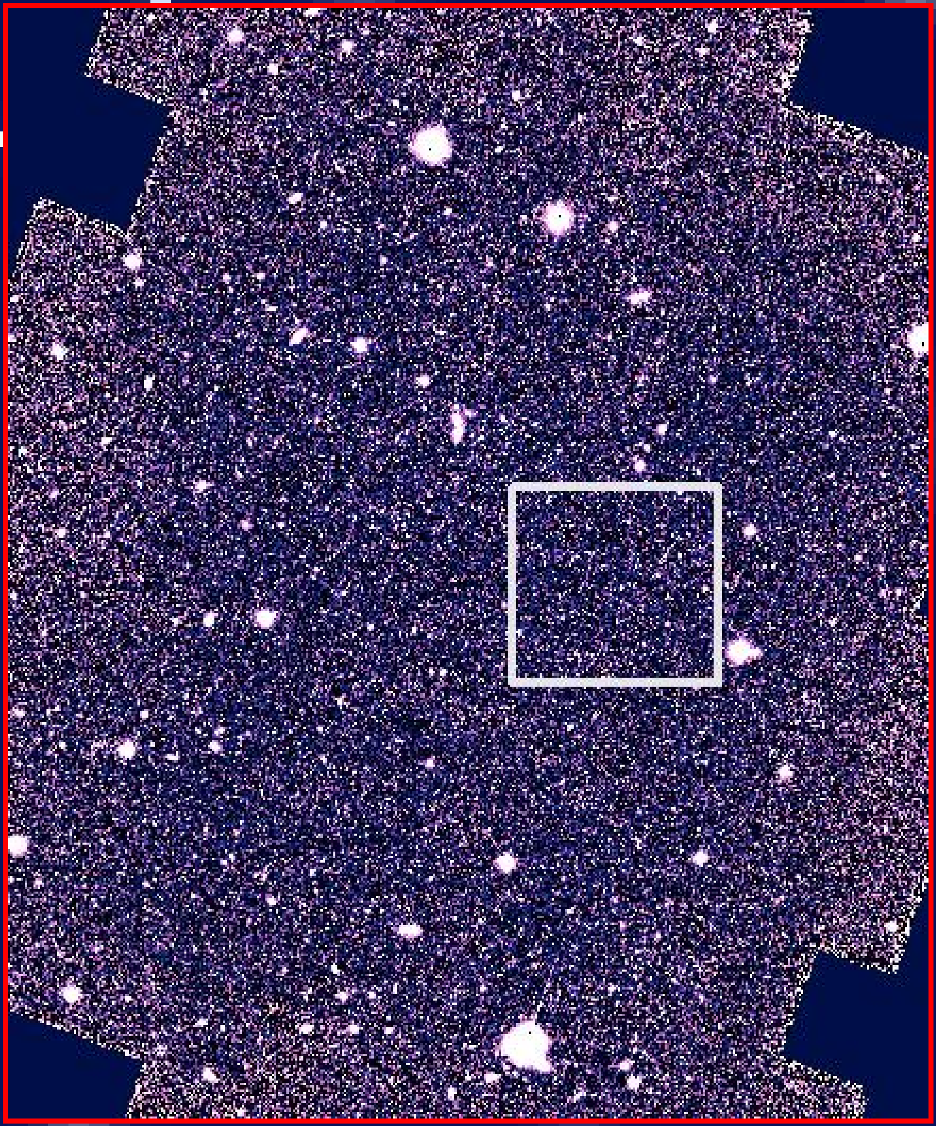
UV slope

<β> = –2.10 [-1.91,-2.40]
β derived from Castellano+12



fesc < 6%

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 ?

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

Steidel+01

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

Inoue+08,+10, IGM convolved with filter

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

From SED fitting

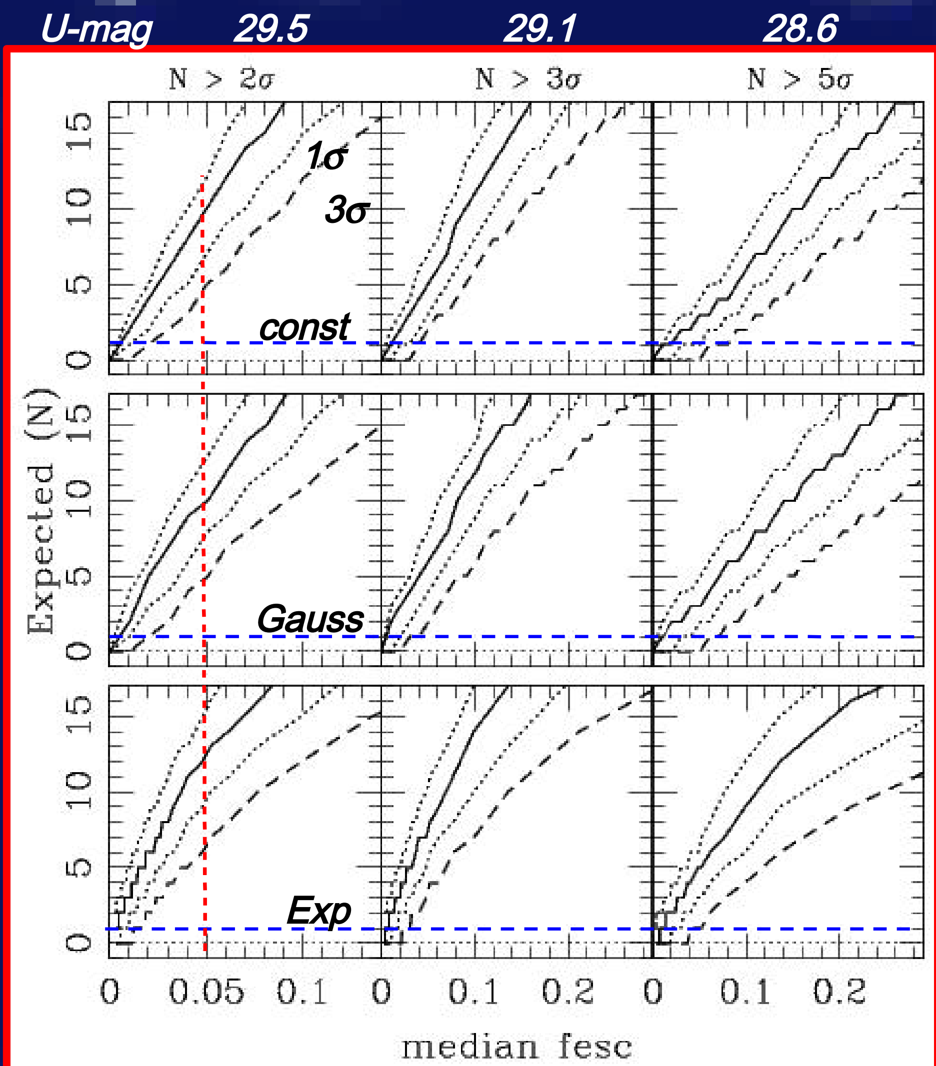
Observed

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

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

Photometric noise is also added

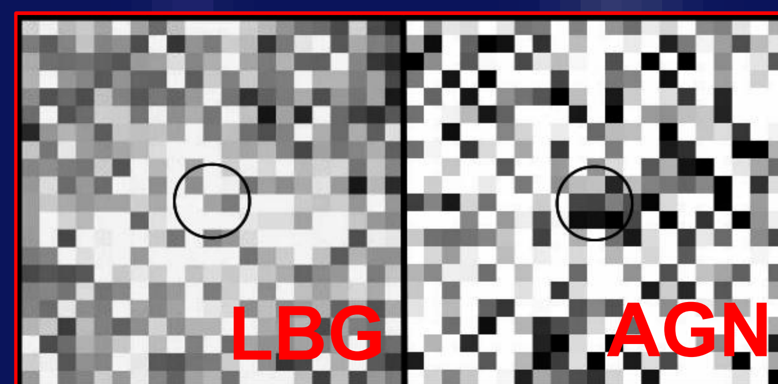
MC simulations: expected number of LyC detections in the U-band as a function of *fesc*



Vanzella et al. 2010, ApJ

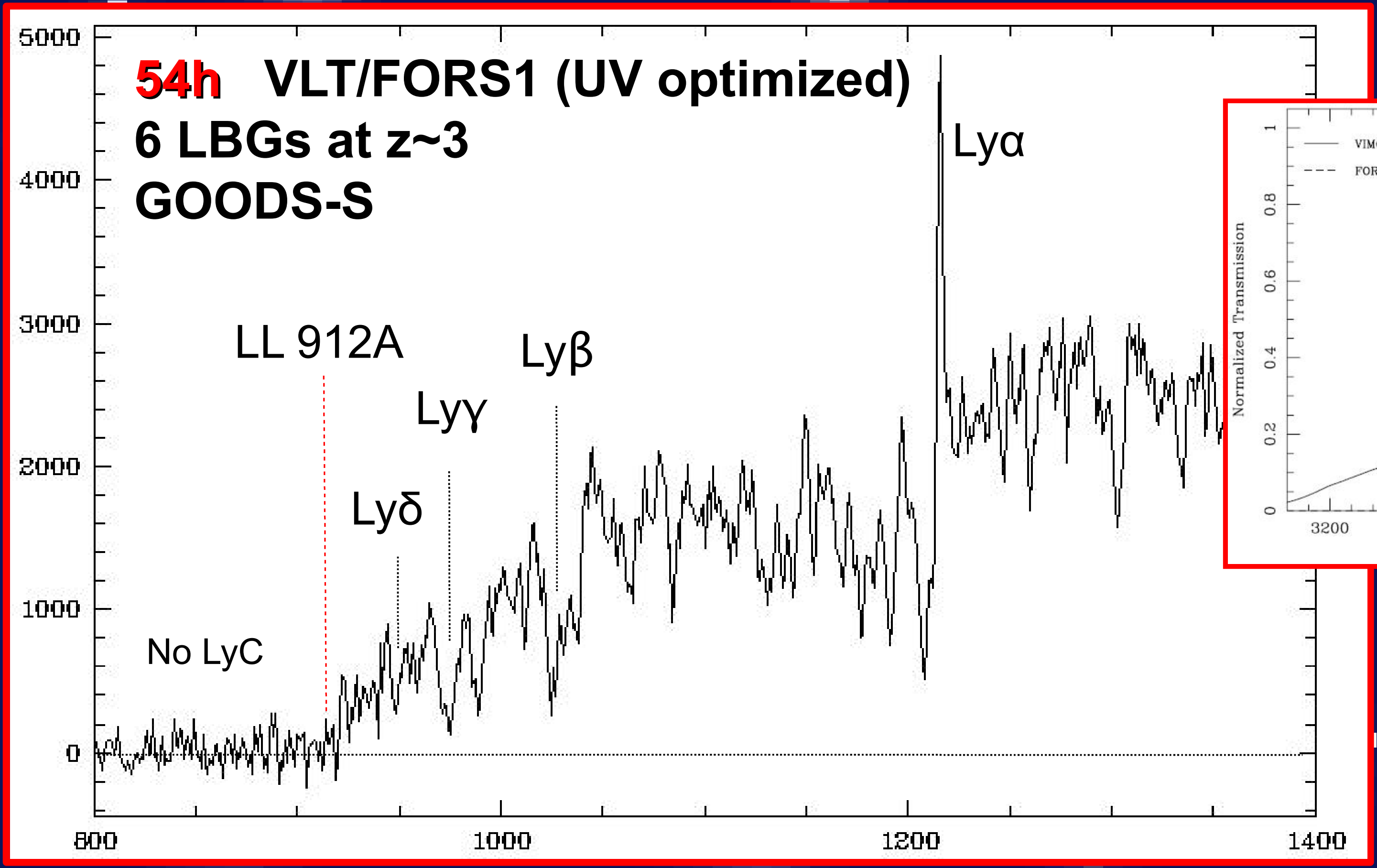
Including IGM transmission of Prochaska+10; Songaila&Cowie+10 (LLS statistics @ z~3 – 4)
SEE INOUE 2008, 2011

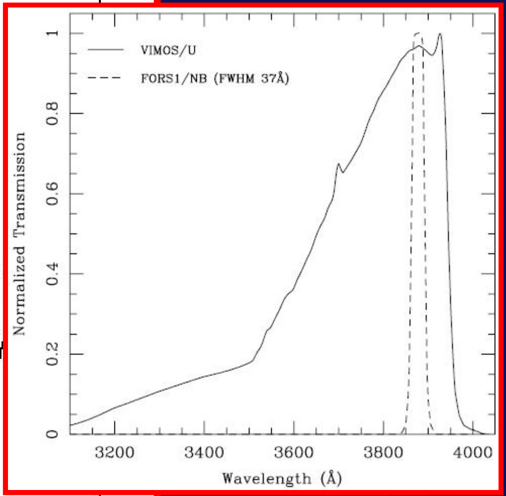
FROM STACKING and MC simulations
***fesc* for L>0.5L* is very low, < 5%**



LyC at z~3 with deep spectroscopy (54h VLT/FORS1)

we can properly follow the LyC just below the Lyman limit (912A)

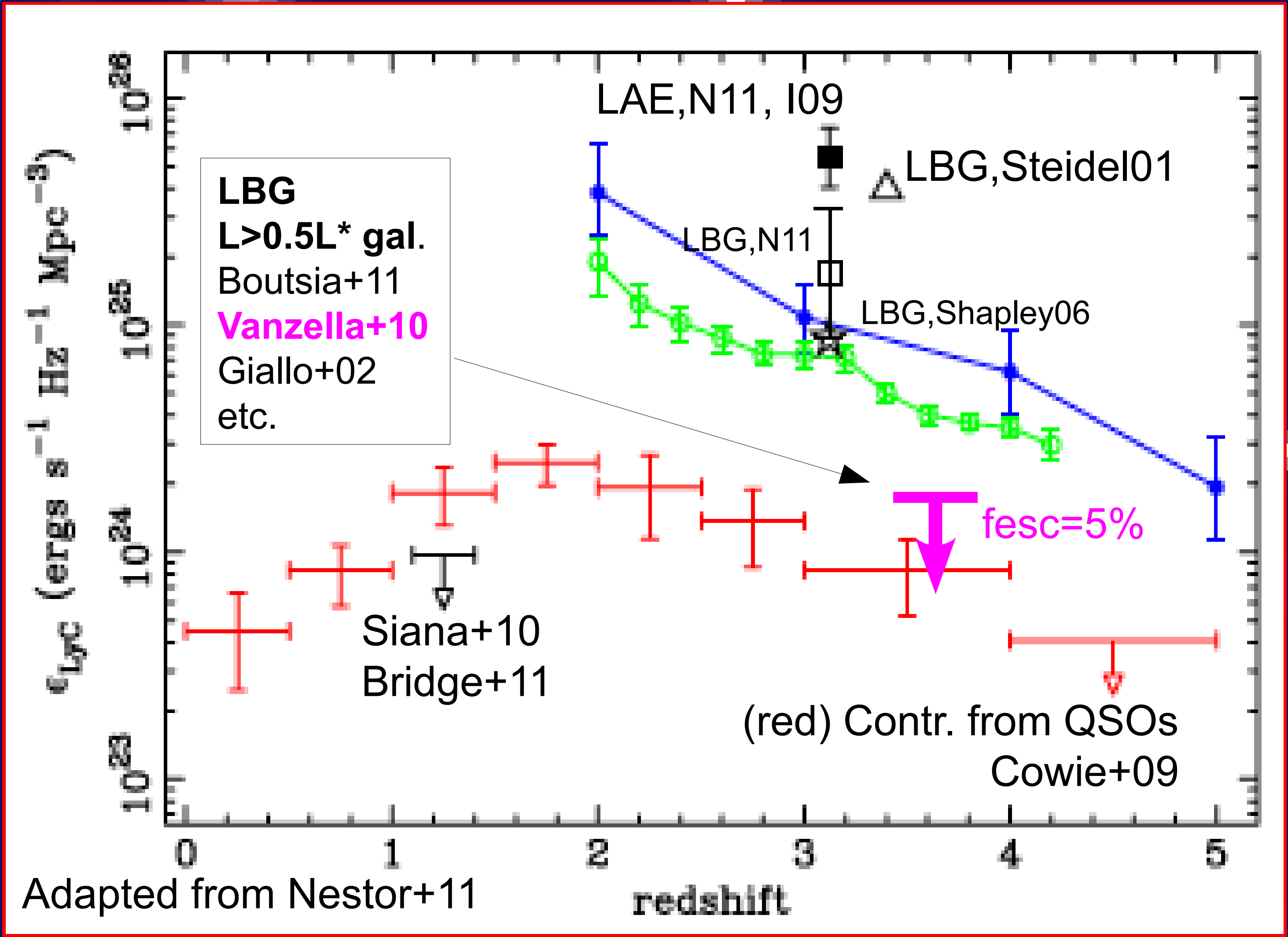




Vanzella/Nonino et al. in preparation

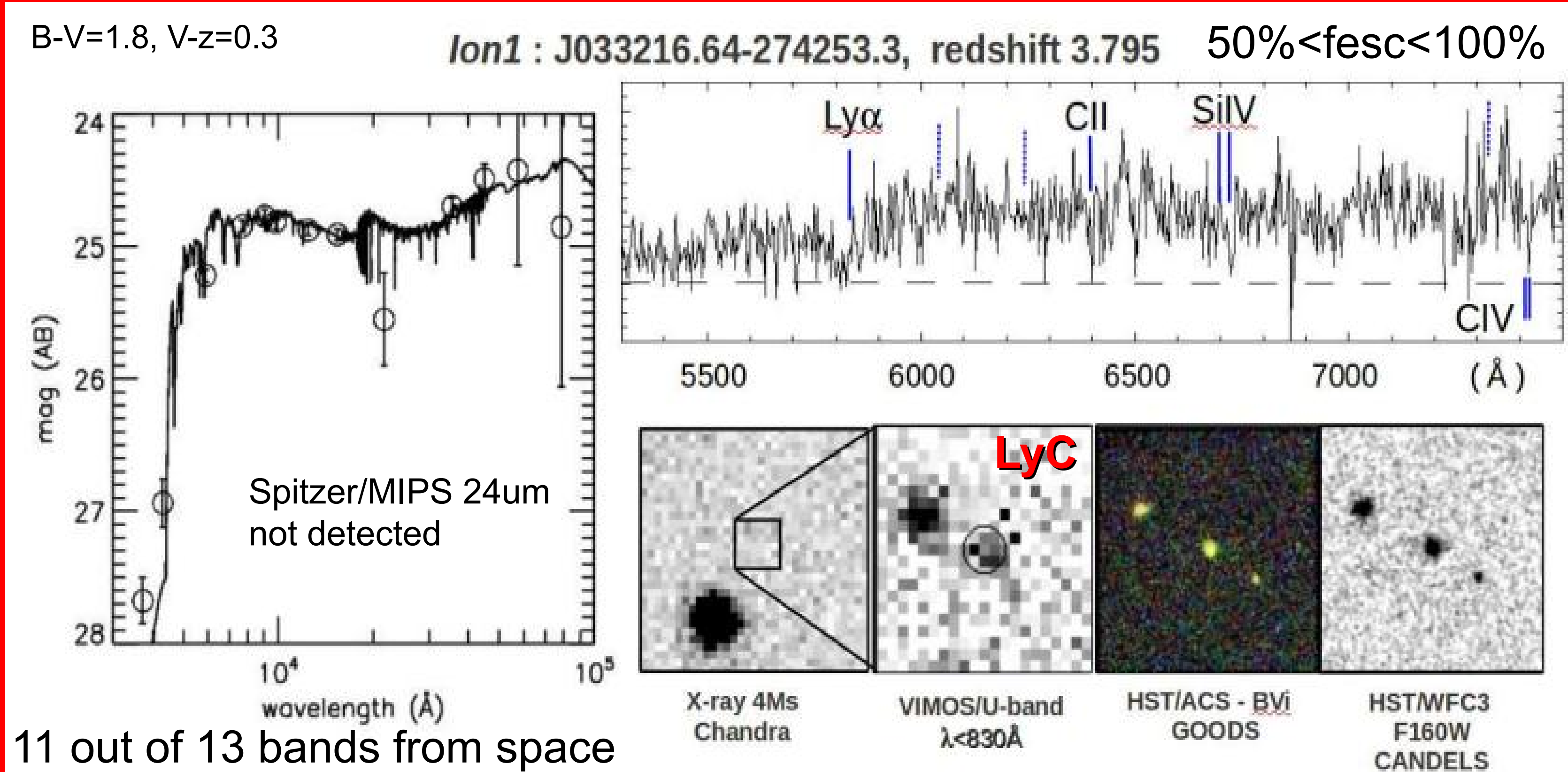
Preliminary: fesc (850-900A) < 3%

Contribution to the comoving emissivity @ z~3.6



(assuming fesc,rel=5% for all lum. down to M = -10 and LF of Bouwens+07 galaxies cannot reionize the universe)

LyC detection at z=3.795 (Ion1) *(unique in the 102 LBG sample)*



Note:
- The highest-z known so far.

- Not selectable with NB Lya surveys.

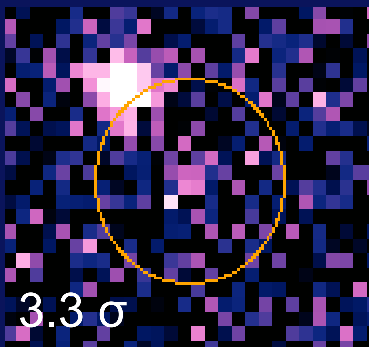
From SED fitting & optical specturm and imaging:
- *M* ~ 2x10⁹ Msol, Age<0.1Gyr*
- *SFR~26 Msol/yr, EBV~0.0-0.03,*
- *β = -2.1*
- *Rhlr 0.9 kpc (UV and U-band rest-frame),*
- *No Lya, weak ISM and nebular lines (?),*
- *No X-ray (4Ms) (Lx [2-10kev] < 3x10^{42} erg/s)*

→ e.g., Schaerer+02,+03 fesc-nebular link...

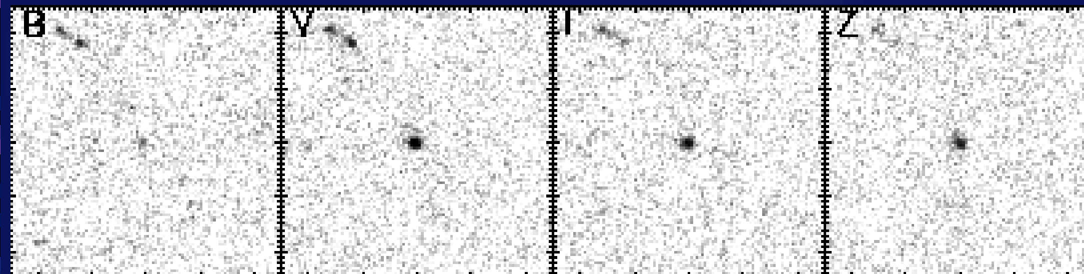
LyC detection at z=3.95 (Ion2 - AGN)

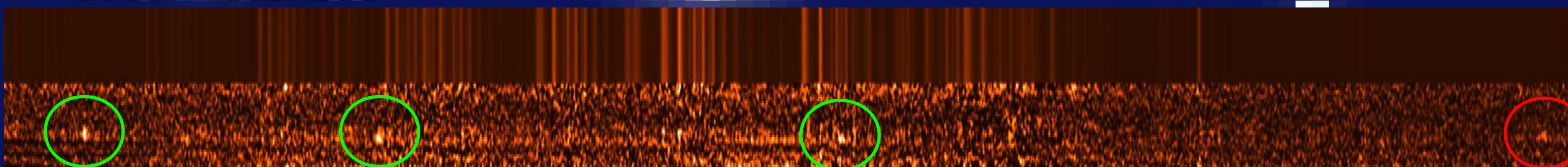
J033238.76-275121.6 (Ion2) z=3.95 -- CII,CIV,CIII, Lya (2d ord.)

U-band λ<810A

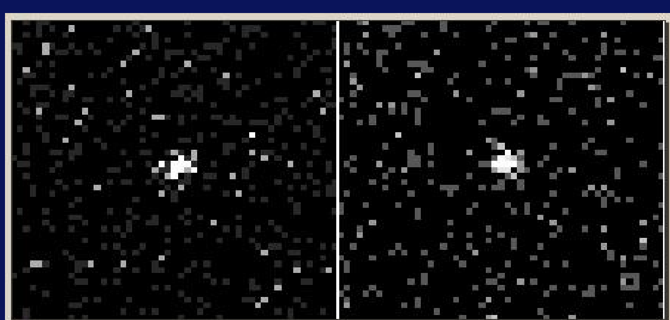


B435 V606 i775 z850





CII CIV CIII Lya 2d ord.



0.5-2 keV 2-8 keV

fesc,rel ~ (3/10)*(1/0.1) => 1

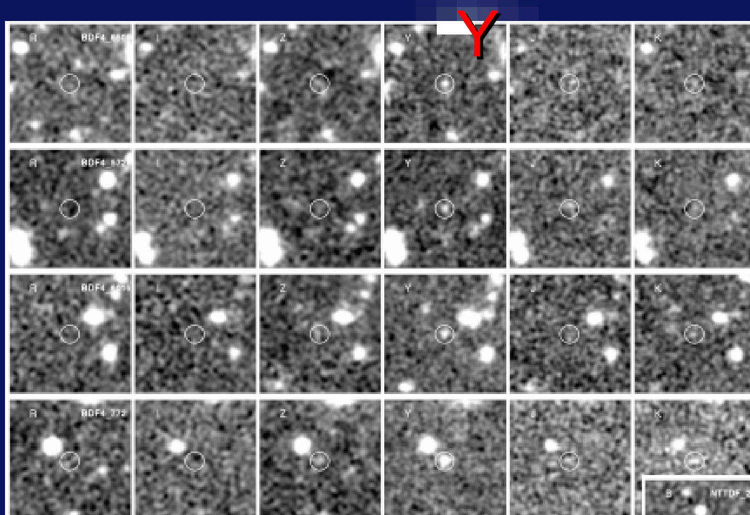
Chandra 4Ms , NH ~ 8×10^{23} cm^{-2}

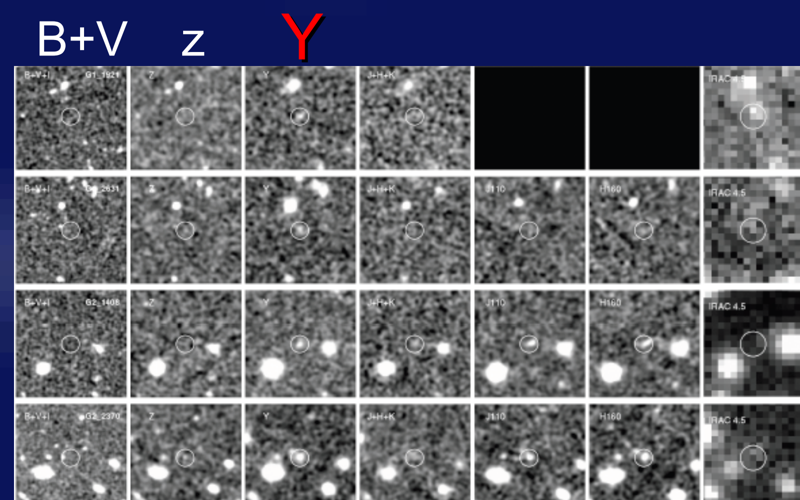
F. Vito et al in preparation

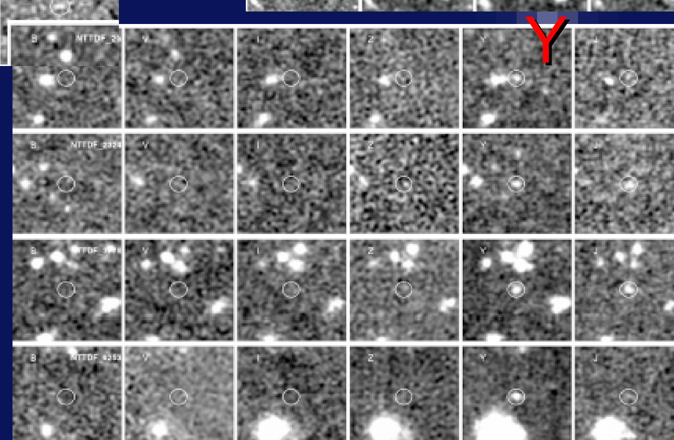
Looking at *z* >~ 7 Universe

Select z~7 galaxies: dropout technique (similar to z<6.5) Castellano et al. 2010a,b

1) compute LF at z>~7
2) Probe HI reionization process with Lya emission fraction





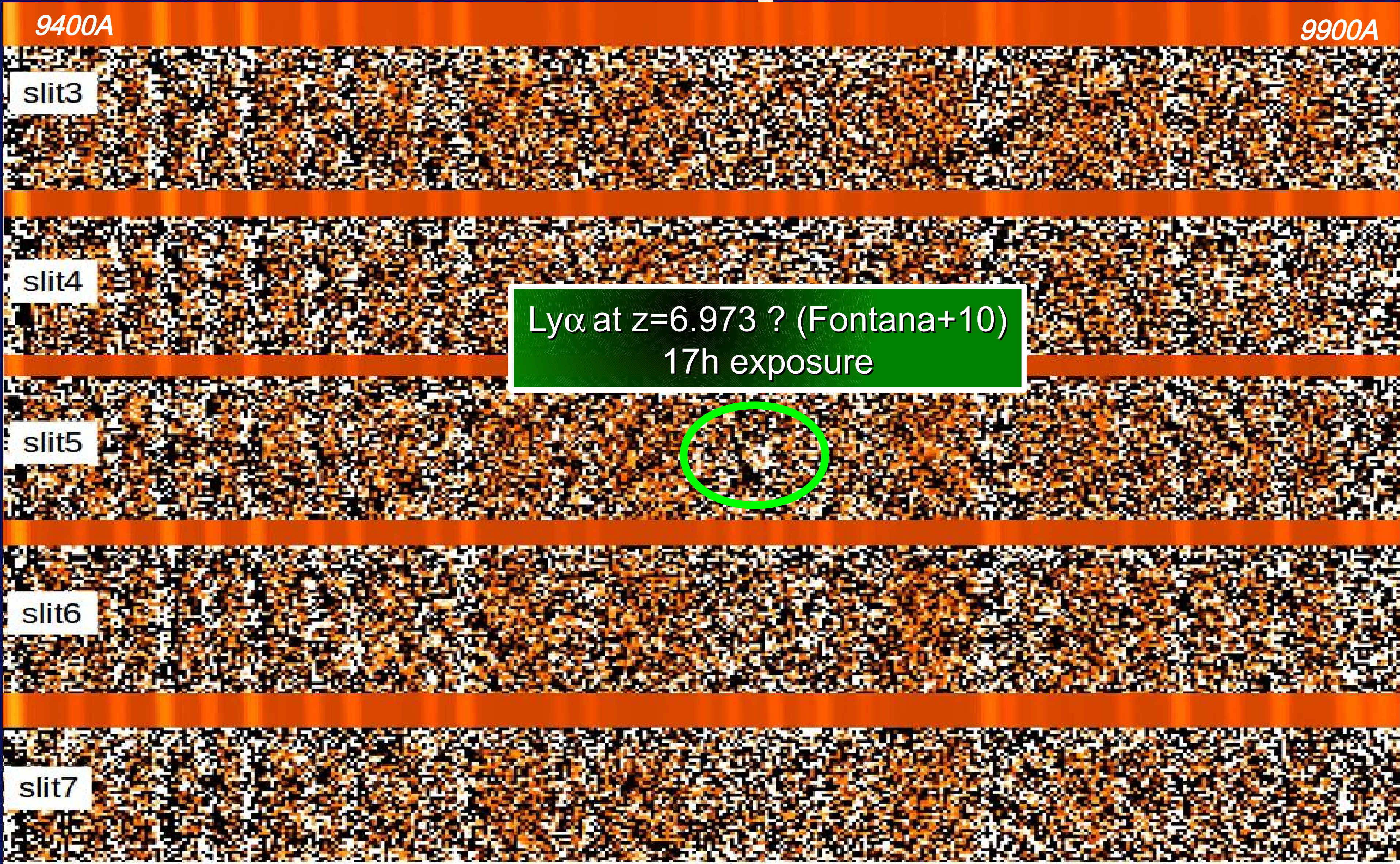


Started a spectr. survey
27 targets in 4 fields,
60hr in total, 15hr per target
(red-enhanced FORS2)
Observations of the fourth
field are ongoing

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

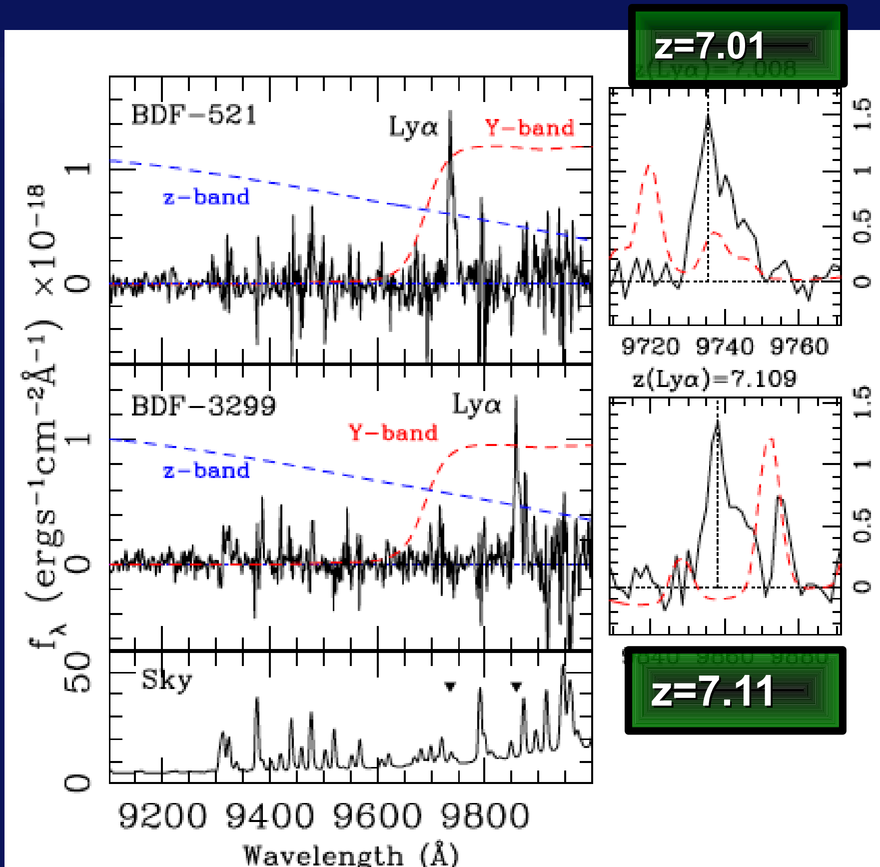
Deep spectroscopic survey with VLT/FORS2

4 fields: GOODS-S , NTTDF , BDF (+ UDS, will collect photons soon)

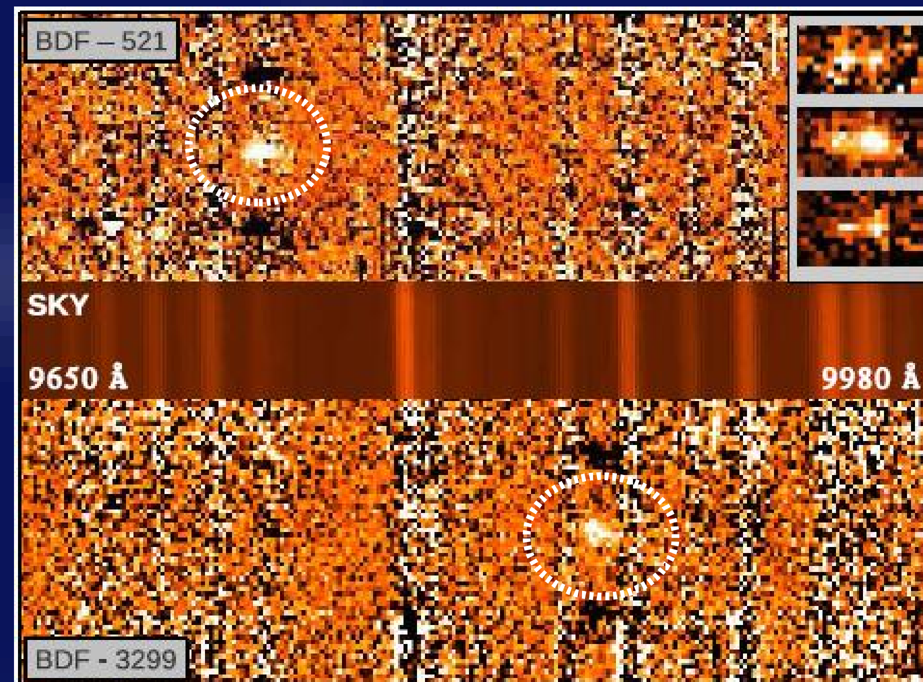


SPECTROSCOPIC CONFIRMATION OF TWO LYMAN BREAK GALAXIES AT REDSHIFT BEYOND 7

E. Vanzella,[1] L. Pentericci[2], A. Fontana[2], A. Grazian[2], M. Castellano[2], K. Boutsia[2], S. Cristiani[1], M. Dickinson[3], S. Gallozzi[2], E. Giallongo[2], M. Giavalisco[4], R. Maiolino[2], A. Moorwood[5], D. Paris[2], and P. Santini[2]



Vanzella+11



Emission lines show typical asymmetry expected for Lyα

EW =50-60Å - L ~ 10^{42} erg/s/cm^2 SFR ~ 5-10 Mo /yr

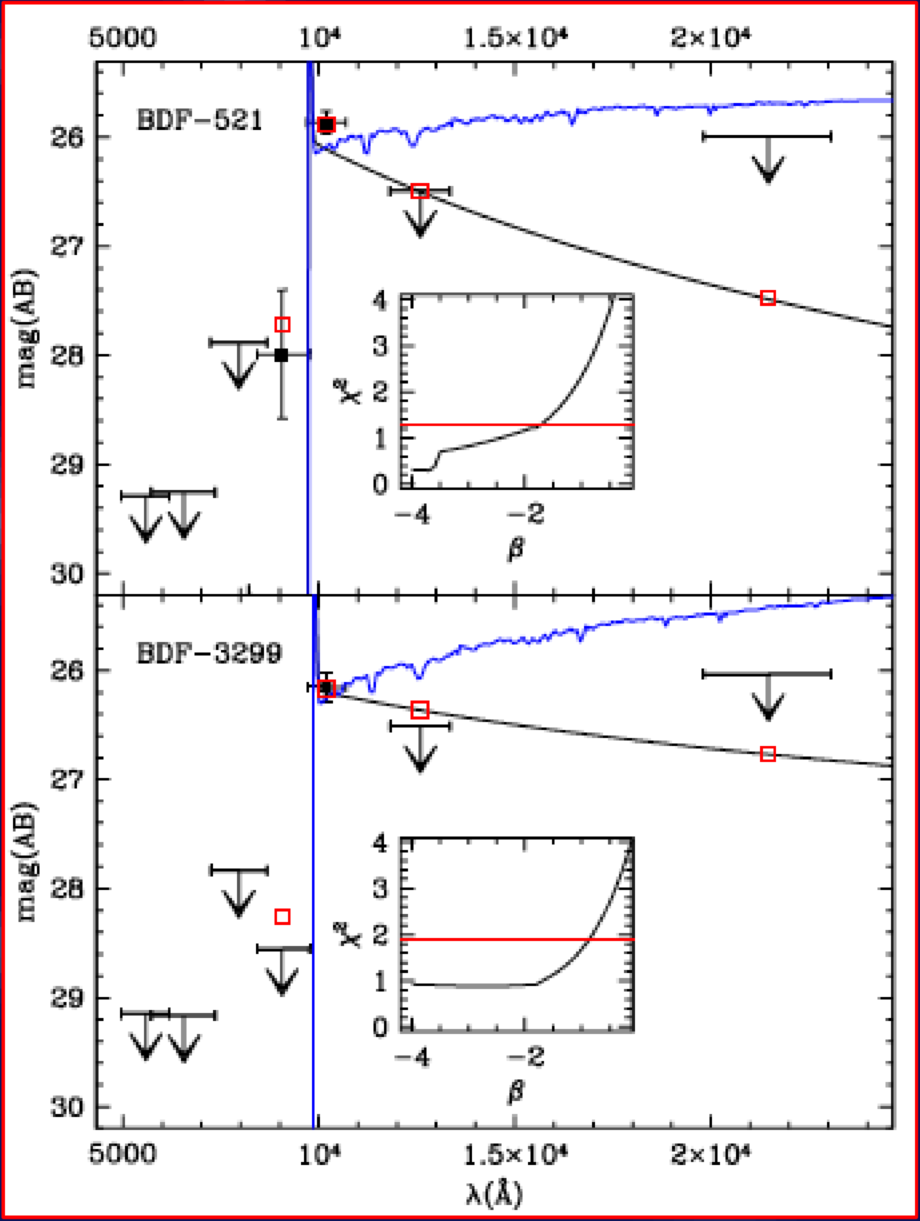
z ~ 7 galaxies

Two z ~ 7 galaxies in the BDF4 field
separated by 4.4Mpc (proper)

Apparently these galaxies are not luminous enough to produce their surrounding HII bubbles, unless intrinsic SFR is much BUT... *no evidence for dust*.

Possible evidence for a very steep UV slope, from limits in H and K band (HAWKI data).

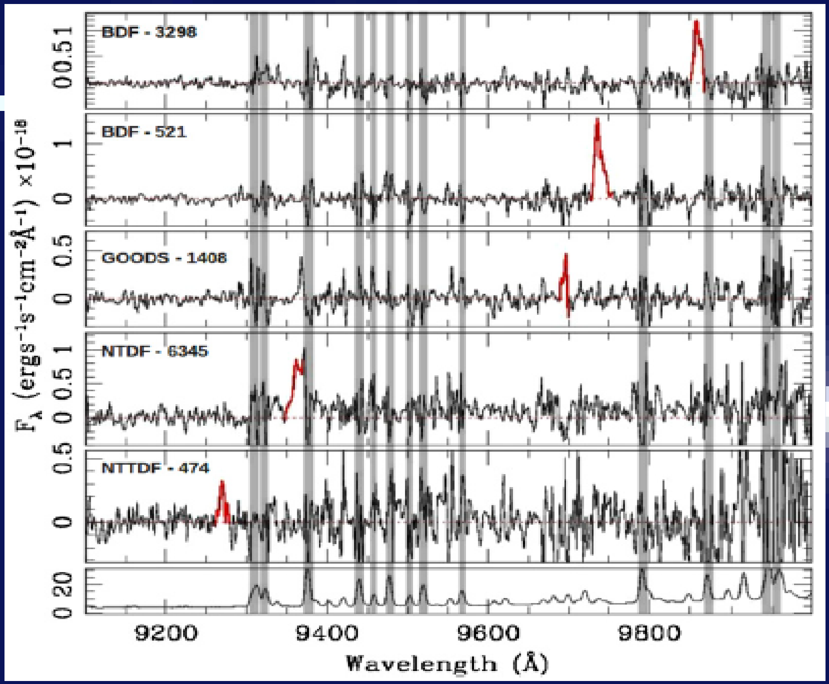
Deeper WFC3 images are needed to determine the slopes.

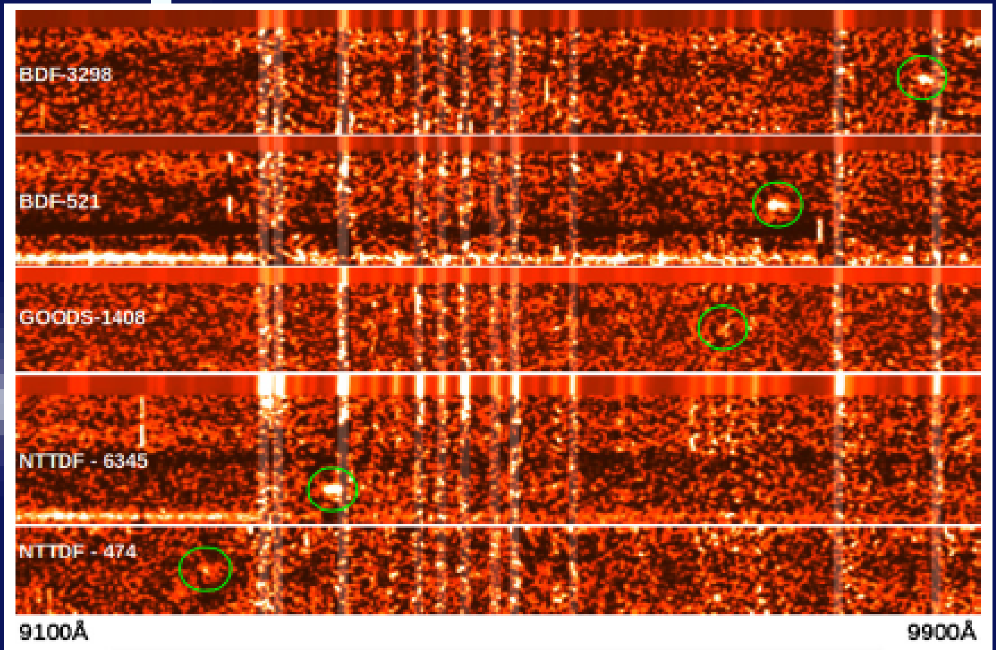


Vanzella+11

Final sample: combination of three fields GOODS-S, NDF, BDF + Ongoing UDS (two belong to CANDELS survey)

Pentericci+11

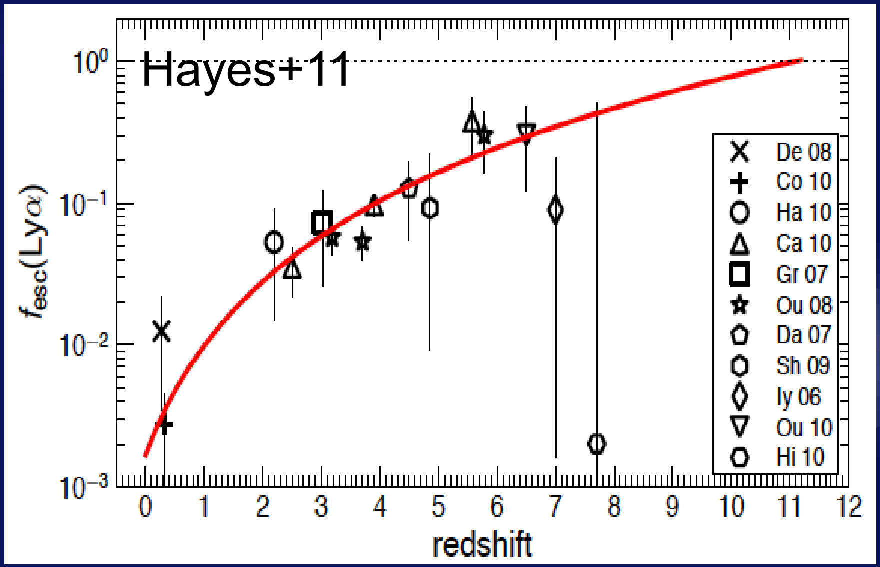


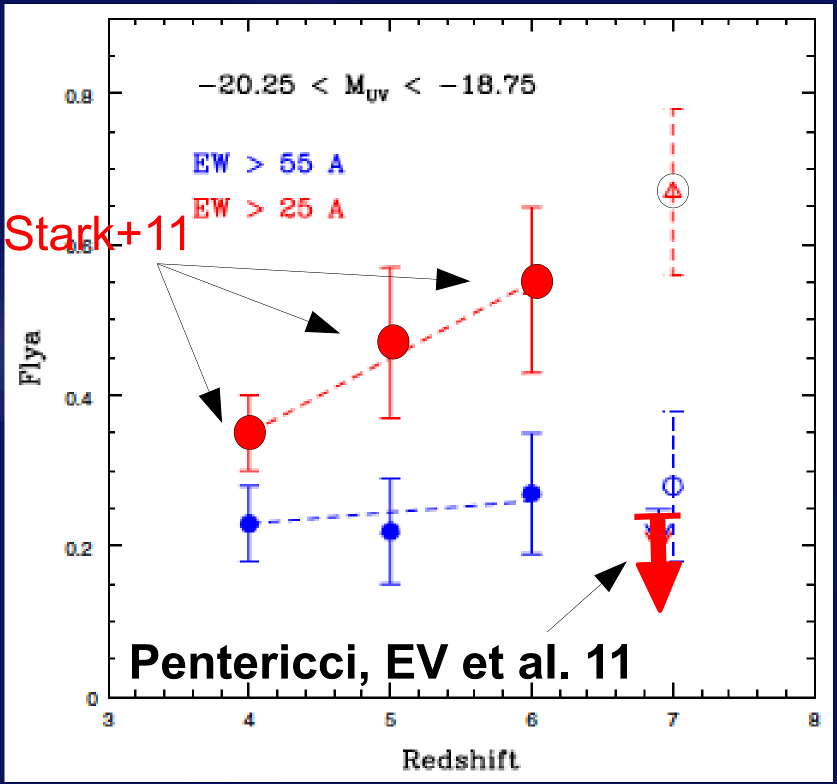


- Targets: 20 high quality candidates
- 5 confirmed redshifts 6.7<z<7.1
- Only 3 with EW~50Å
- 1 confirmed interloper at low-z (z=5.8)

In addition, many i-dropout used as slit fillers were confirmed at z~6, including several faint continuum-only objects (with Lyman break)→ interloper rate is below 20%

First indications of a decline in the fraction of Lyα emitters in LBGs at redshift above 6 (Pentericci, EV et al. 2011)



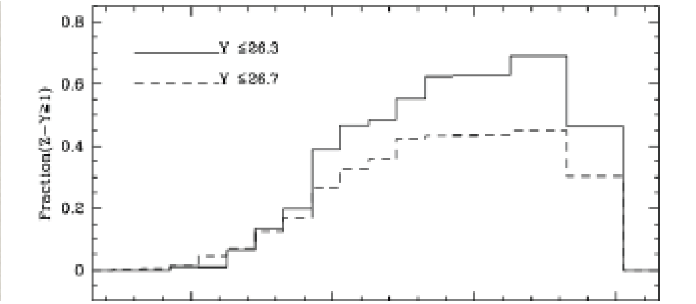


Only 3 out of 20 have Lya(EW) > 25A

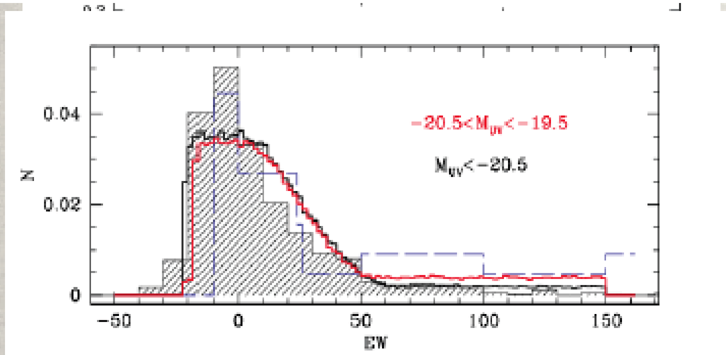
Estimating the probability of detecting so few Lyα

Pentericci, EV et al. +11

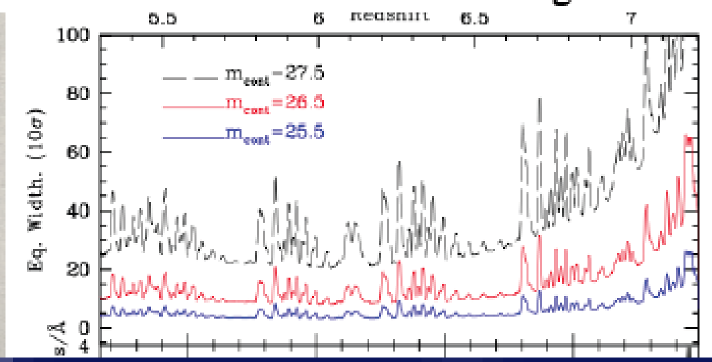
Redshift distribution for different Y mag



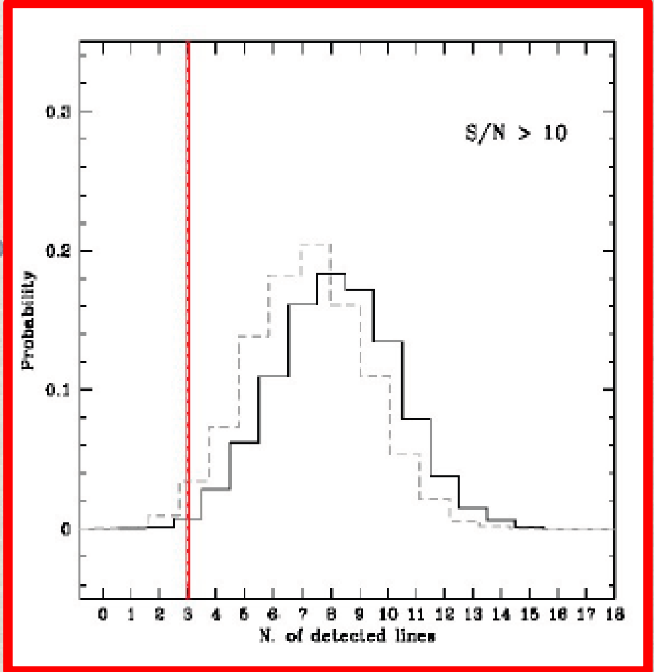
EW distribution at z=6 as a function of UV mag



Mimimum detectable EW in our observations for different continuum magnitudes



Expected average number of lines for given S/N and EWmin

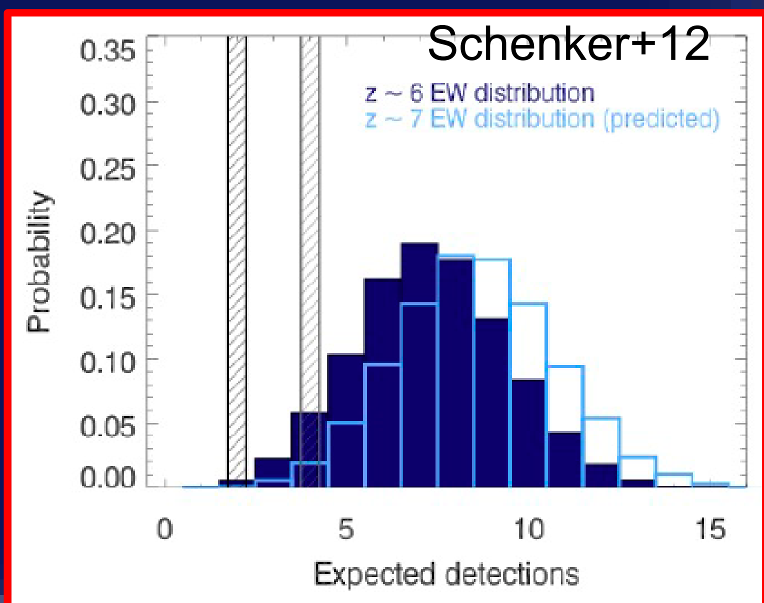


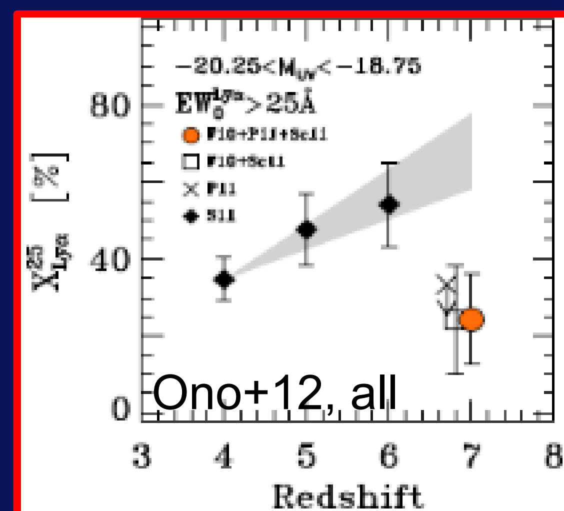
Very low probability of detecting so few emission lines (1-6% depending on the assumptions (solid curve no interlopers, dashed curve 20% interlopers)

Similarly complemetary work by other groups

Ono et al. 2012: bright z-drops in SDF+GOODS-S, 25.1<Y<25.7
3 confirmed out of 11, Lyα EW~30-35A

Schenker et al. 2012: faint z~6-8 galaxies, lensd+ERS+HUDF
2 confirmed z=7 galaxy (of which 1 tentative) out of 19 candidates observed. Very broad red selection (6.3 <z<8.8)





→ Observations are fesible and require deep exposures

→ Observed distribution is consistent with photometric selection criteria

→ The fraction of LBGs with Lyα amission is much lower than expected

What does it means ? Among possible options:

1 ✗ A significant fraction of (al least 50%) of z-dropout are not z~7
→ **unlikely** given that up to z=6 the LBG technique works in an excellent way (interlopers are less than 20% at z=5-6, LP2011, Vanzella et al. 2010)

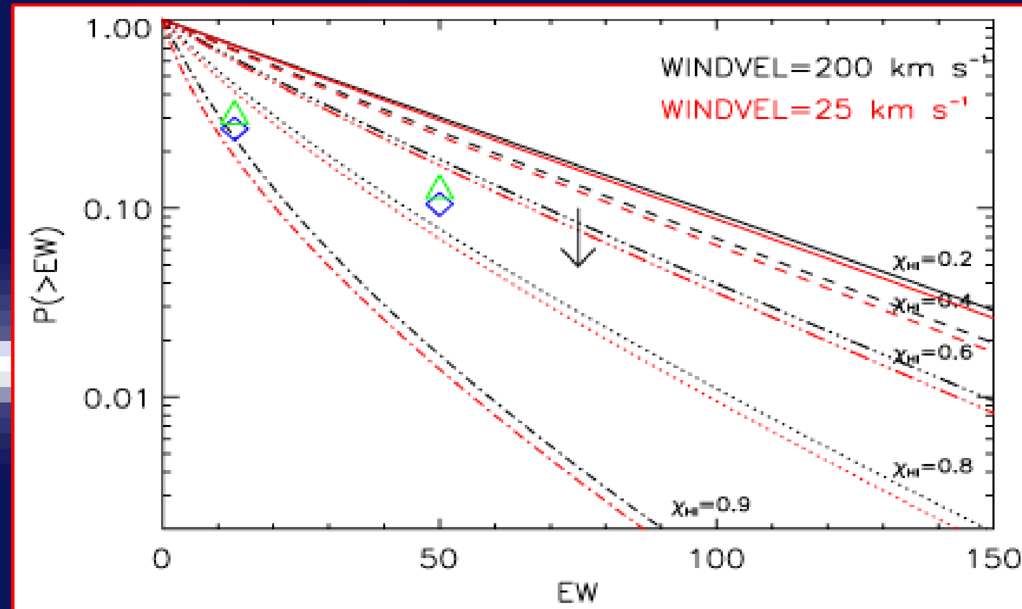
2 ✗ A sudden change in emission properties due to intrinsic change in the galaxy population, e.g., increase of the extinction in the galaxies' ISM
→ unlikely: from observational and theoretical results on UV continuum slopes the opposite should be true (e.g. Finkelstein+11, Dunlop+11, Bouwens+!1)

3 √ Evolution in the hydrogen neutral fraction in the IGM quenches the Lyα emission

4 √ An increase of escaping fraction of ionizing photons (possible, but less probable, related to point 2)

Setting constrains on the neutral hydrogen fraction

We employ the models developed by Dijkstra e& Whyithe (2010) which couple the large scale semi-numeric simulations of reionization with galactic outflows



Assumptions:

- universe is completely ionized by z=6
- fesc of LyC photons does not change
- EW distribution at z=6 is modeled as an exponential function (to match Stark et al. 10, Vanzella et al. 09)
- Halos of our LBGs are 10^{10} < Mhalo < 3 x 10^{10} Mo
- No dust

Observations are consistent with a neutral hydrogen fraction change of X_{HI} ~ 0.5 between z ~ 6 and z ~ 7

Variables:

* outflowing wind velocity
* neutral hydrogen fraction (by volume)
* column density of HI gas

- Ota+12, XHI~0.3-0.6 from Santos+04 models
- McQueen+08 X_{HI}>0.35 at z~6.7
- Mortolok+11, z=7.08 QSO, X_{HI} >~ 0.1

Fiducial model : $N_{HI} = 10^{20}$ cm^{-2}

Conclusions from z~4 and 7

- Big uncertainties in the modeling of *fesc* from galaxies (e.g., ↑ ↓ with halo mass)
  Past (S01 and S06) and current (I09 & N11) observations are problematic
  → biased measure of *fesc* (flux ratio f1500/f900)
  → spectroscopic redshift of faint U-band emitters is mandatory

- We have investigated similar situations in GOODS-S/CANDELS:
  Among 20 cases, none is a LyC emitter. (zphot, anomalous fesc, transverse IGM)

  Ultradeep observations (U~30) put strong limit on *fesc*<5% for L > ~ 0.5L*
  => insufficient photon budjet => *fesc* may increases for L<<L* (lower halo mass)
  and/or fesc has to increases with redshift
  (typically *fesc* ~ 30-80% is required at z>7, e.g., Oesh, Fiknelstein+12, Shull+11)

- Lya emission fraction as a test for HI reionization. A drop is observed at z~7.
  One probable interpretation is the increases of X_{HI} from z~6-7 of ΔX_{HI}~ 0.3-0.6
  (other interesting (or coupled) possibility is an increase of fesc).

Are we entering the EoR ?
We have confirmed few galaxies at z>~7. The door is opened for their investigation...

Future ...

Future

- invetigate phisical properties of spectroscopically confirmed z~7 galaxies
  (MOS-NIR : X-shooter, KMOS, MOONS, etc.)
  (ALMA: CII, CO, NI : coolants tracers, gas properties, winds, etc.
  New MOS-NIR will exted the Lya test up to z~8 (CANDELS)
  We have applied for a WSO/LP FORS2, waiting for responce ...

- identify a sample of solid LyC emitters at z<4. Useful as a test sample for z~7
  (e.g., nebular emission, property of the gas and its filling fraction, UV slopes, etc).

→ There is the need to investigate faint luminosity regimes,
both at z~3-4 (*fesc*) and >~7 (Lya statistics & faint-end of LF)
The only way to probe sub-L* sources before the advent of JWST and ELT
is to exploit the STRONG LENSING

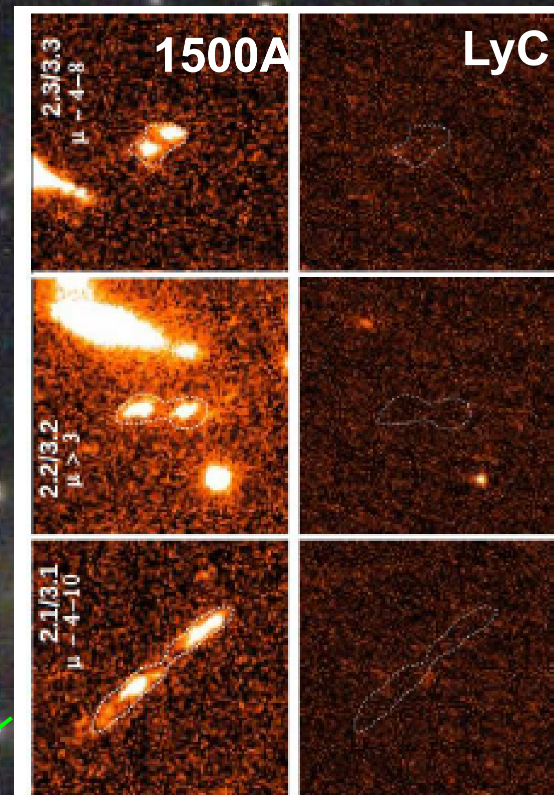
In particular to probe *fesc* down to 10-15% for L<~0.1L* galaxies we need
about 5 galaxy clusters → (e.g., CLASH project, 524 orbits, 25 clusters,
phancromatic survey + spectroscopy).

All this pave the way for future JWST , ELT and SKA (21cm tomography during EoR).

Probing fesc for faint galaxies through strong lensing

(Vanzella et al. 2012, MNRAS)

Observations.: L>~L* small fesc < 5%, fesc(z,L)?
Models: higher fesc for faint gal.



From CLASH

Probing fesc with strong lensing

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

Assuming σ_{lens} = 10 arcmin^2 (within which μ>1) corresponds to ~4-5 galaxy clusters

LF of Reddy & Steidel @ z~3 (α=-1.73, Φ*=1.71 x 10^{-3} Mpc^{-3}, M*=-20.97)

We extract sources 10000 times and calculate for each of them

Magnified R band < 26

$$F_{LyC}^{Lens} = \left(\frac{L\lambda_{rest}}{L_{1500}}\right)_{int} \frac{f_{esc} \times (F_{1500} \times \mu)_{obs}}{e^{\tau_{\lambda}^{IGM}}} \times 10^{0.4 \times A1500} \quad (2)$$

1) a magn. factor extracted from its probability density - P(μ) ~ 1/μ^3 (P(>μ) ~ 1/μ^2) (Lima et al. 2010; Schneider 1992)

2) a redshift in the interval 3-3.5 (uniformly) [depending on the U-band filter adopted]

3) a transmission of the IGM convolved with the U-band filter (extracted from 10000 IGM realizations, Inoue+08,+11)

4) 1500A magnitude (i.e., r-band) in the range 26.5 - 32.5 accordingly with LF

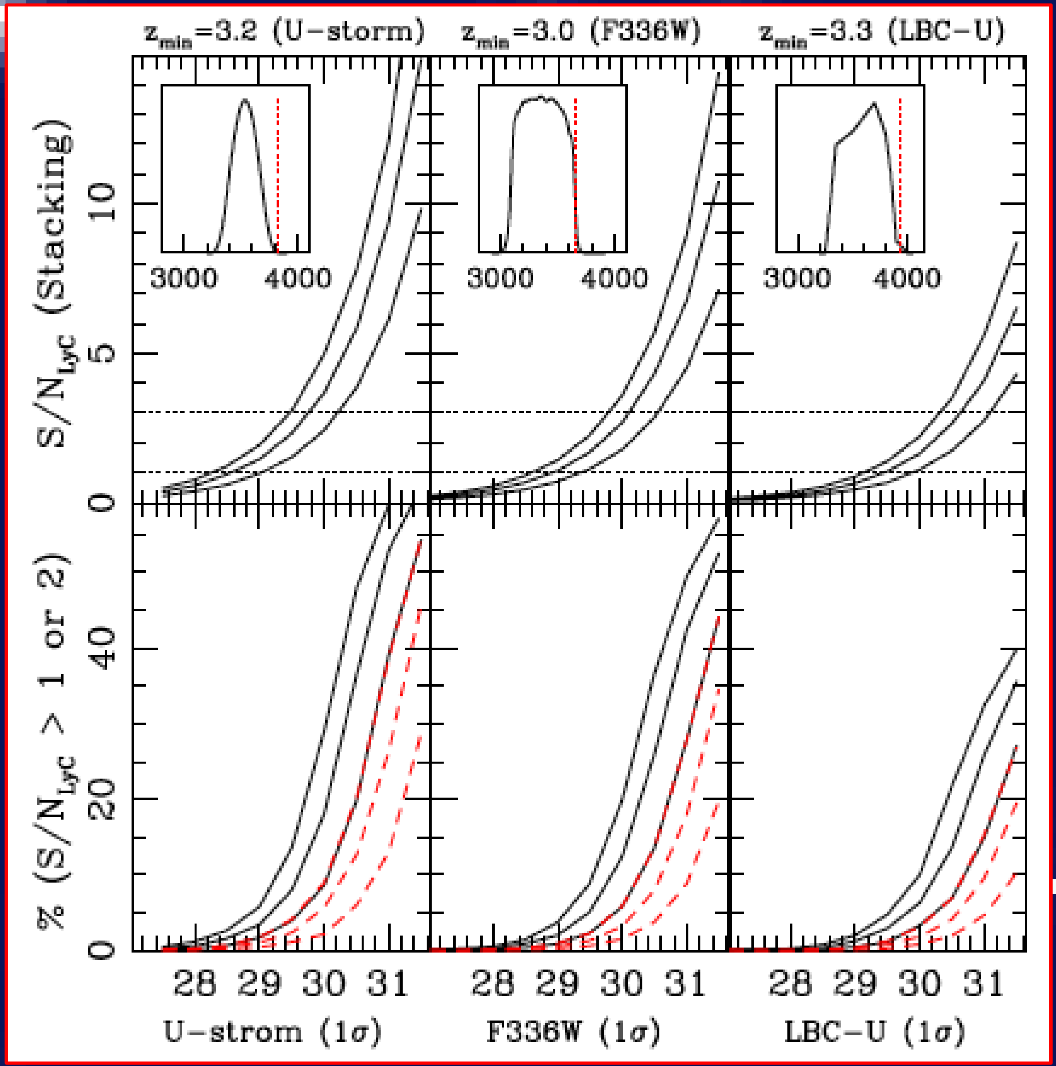
5) an intrinsic luminosity density ratio, Gaussian with mean 7 and std 2 (Siana+07).

6) fesc is explored in the range (0 - 1) step=0.01

(7 we assume no dust, i.e., fesc,rel ~ fesc, with dust we probe lower fesc)

Deep U-band imaging of (~5) galaxy clusters,

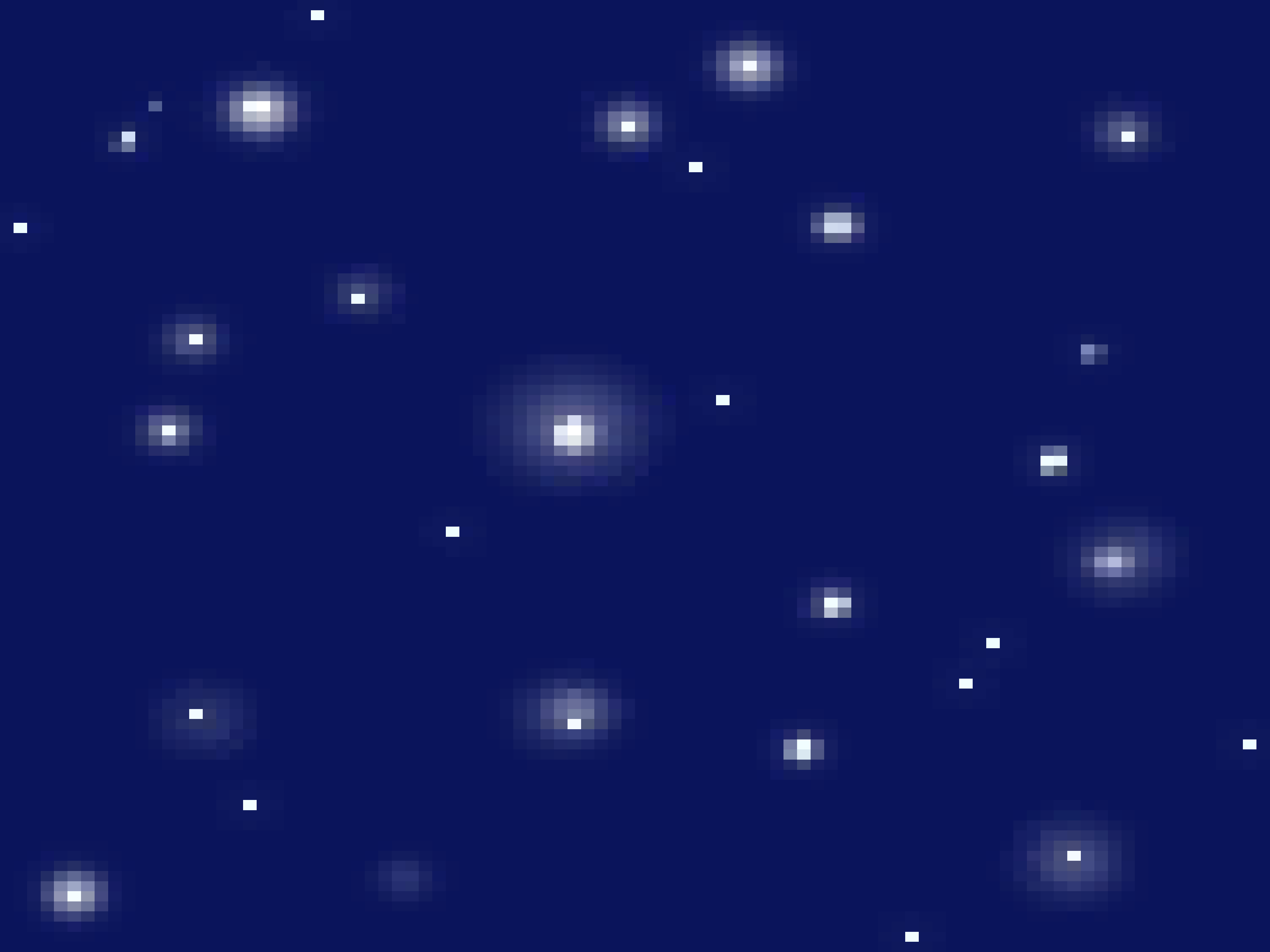
Probe fesc down to 10-15% for L~0.05-0.1L* galaxies



fesc 20,15,10% from top to bottom

Vanzella et al., 2012 (MNRAS)

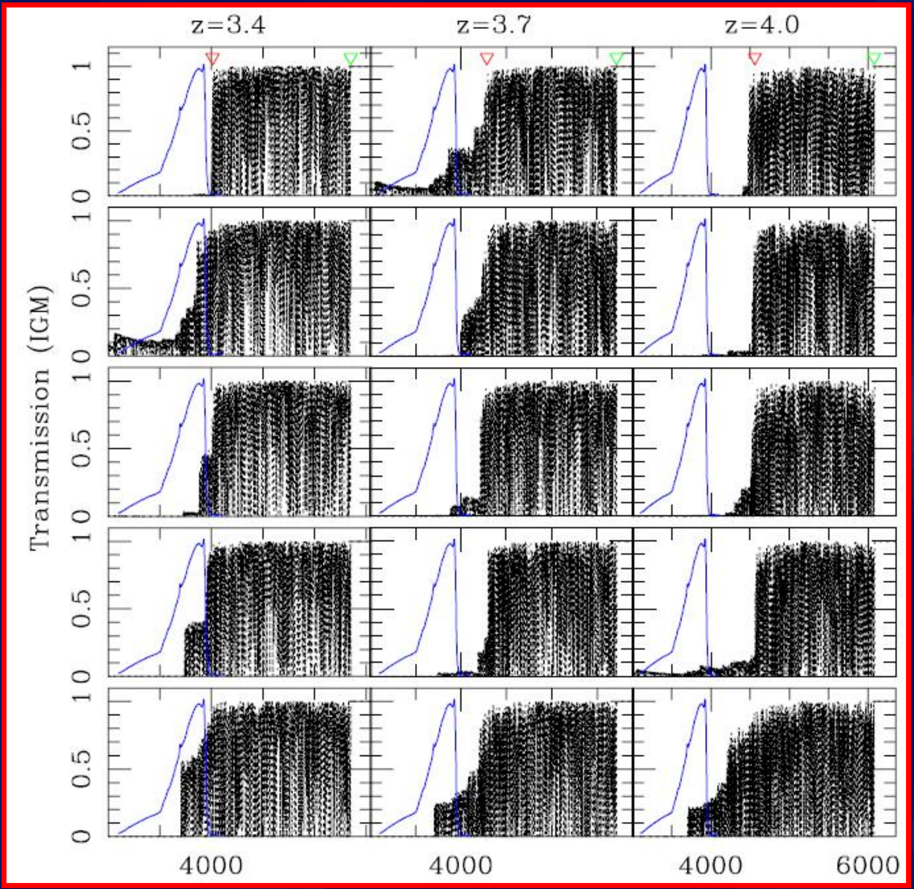
Galaxy clusters with large Einstein radius exist, e.g., A1689, J1707, Bullet cluster, ...
→ MACS survey; CLASH project => will provide panchromatic info + magnification maps

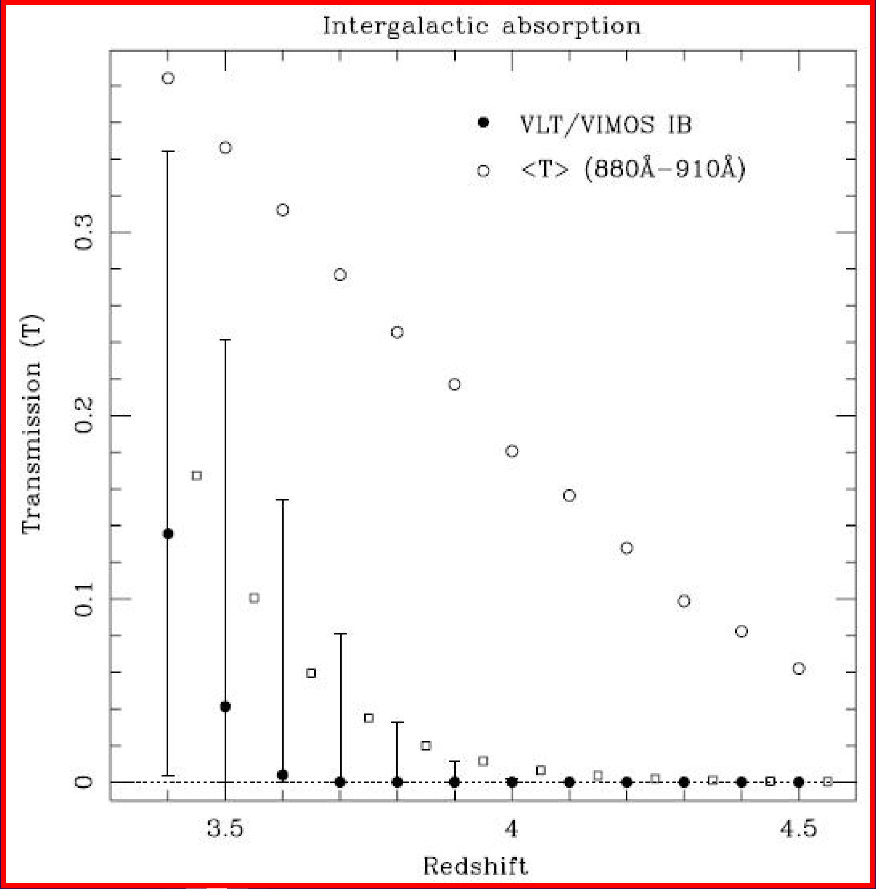


MC simulation of Inoue+08,+11 (Transmission of the IGM)

Examples

10000 realizations for each z





$$\tau_{\rm eff}(\nu_S, z_S) = \int_0^{z_S} dz \int_{N_l}^{N_u} dN_{\rm HI} \frac{\partial^2 \mathcal{N}}{\partial z \partial N_{\rm HI}} (1 - e^{-\tau_{\rm cl}})$$

Paresce+08

n. abs. per unit z and NHI

$$\tau_{\rm cl} = \sigma_{\rm HI}(\nu_S(1+z)/(1+z_S))N_{\rm HI}$$

Opt. depth of an abs. at z and NH

N_{HI} & LLS distr. Prochaska+10; Songaila&Cowie+10