Lyman continuum escape from the epoch of reionization to now

Daniel Schaerer (Geneva Observatory/University & CNRS)

- Methods to detect Lyman continuum emitters
  (direct + indirect)
- Searches at high-redshift (imaging + spectroscopy)
- Low-z LyC emitters
  - Physical properties of known z~0.3 LyC emitters
  - Comparison with high-z galaxies
- Conclusions

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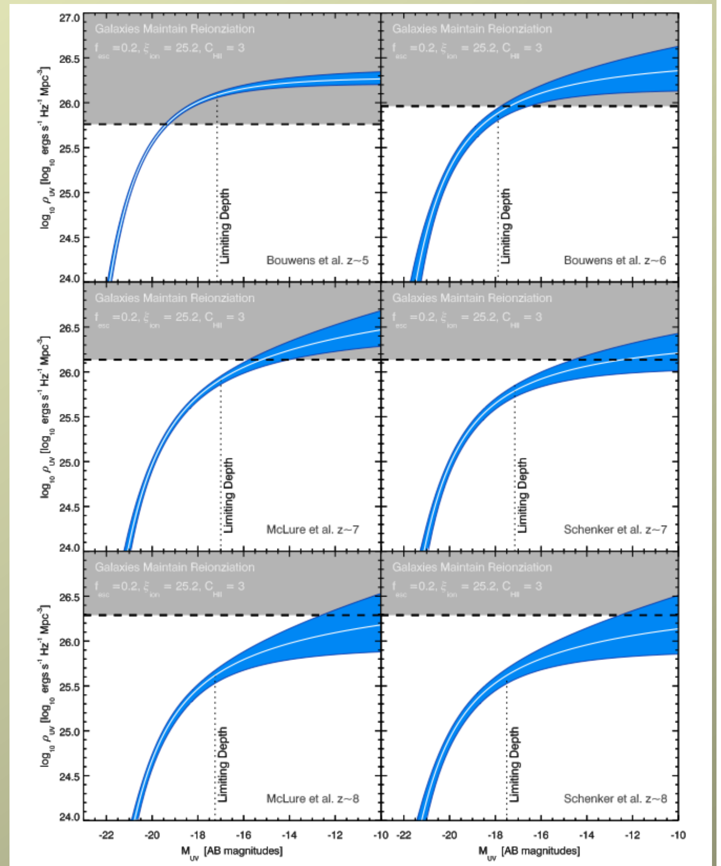
irap astrophysique & planétologie

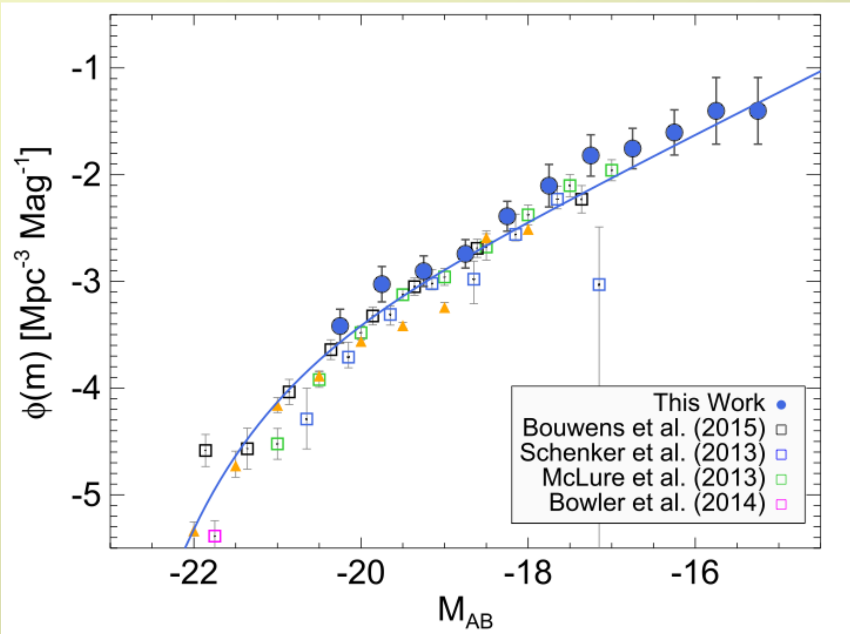
The quest for the sources of cosmic reionisation

Faint, low mass galaxies thought to be main contributors to cosmic reionization

→ **Escape fraction of ~10-20% needed**

Robertson et al. (2013)





z~7 LF: Atek et al. (2015)

escape fraction

ionizing photons / UV luminosity

$$\dot{n} = f_{esc}\, \xi_{ion}\, \rho_{SFR}$$

The quest for the sources of cosmic reionisation

METHODS to identify Lyman continuum emitters

DIRECT:

- **Imaging**
- **Spectroscopy**

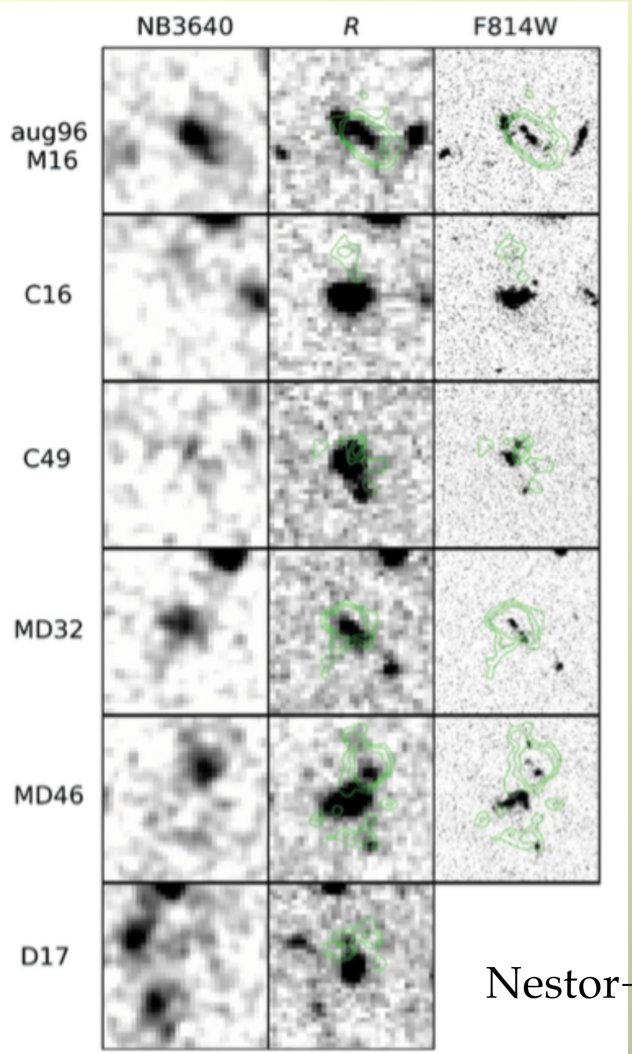
across the Lyman break (HST, FUSE, … ground-based)

INDIRECT:

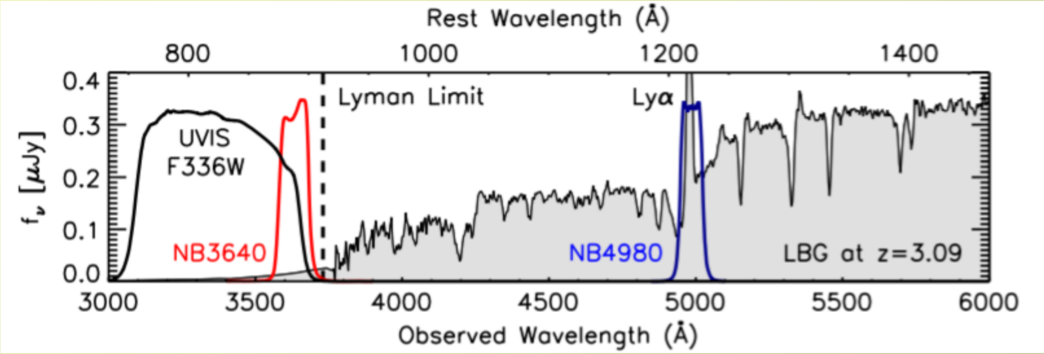
1. UV **low ionisation absorption lines**
   → *low covering factor of the UV continuum* source (Heckman et al. 2011, Jones et al. 2013)
2. **Lyman-alpha line profile**
   → signature of *low HI column density and/or holes* in the cold ISM
   (Verhamme et al. 2015)
3. **High [OIII]/[OII] ratio →** *density bounded HII regions*
   (Nakajima & Ouchi 2014, Jaskot, Oey+ collaborators)
4. Other …

DIRECT methods to identify Lyman continuum emitters

Ground-based LyC images

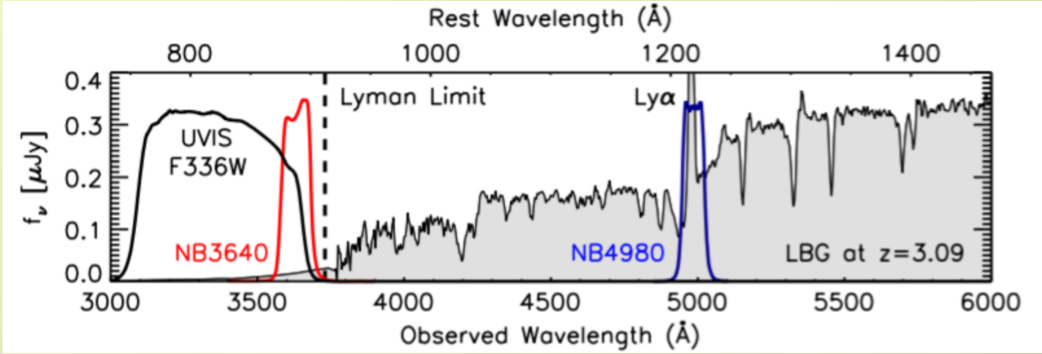


Nestor+ (2011)



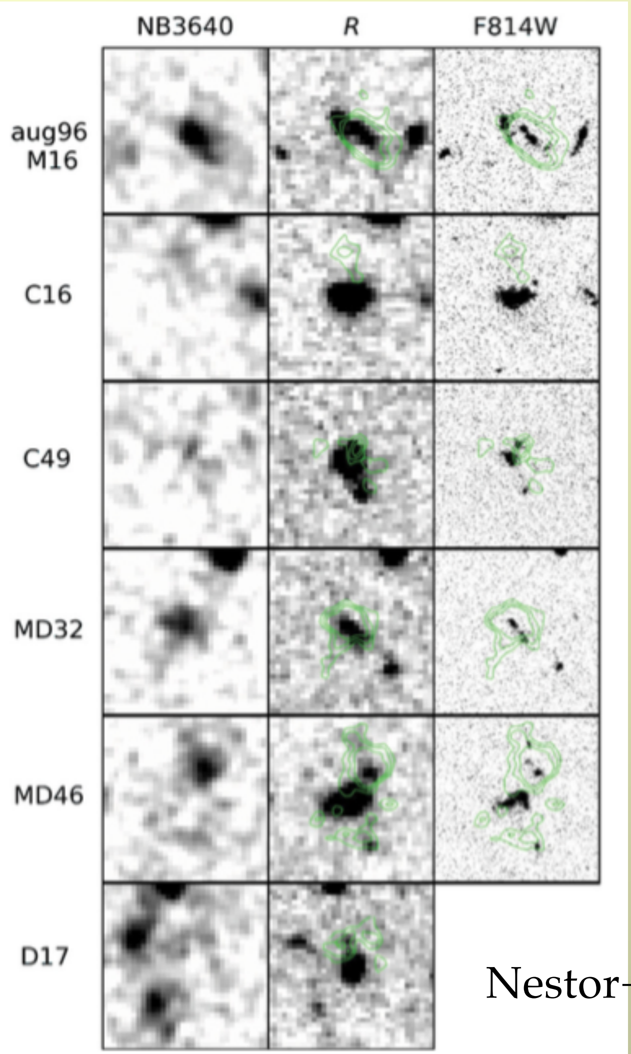
Siana+ (2015)

DIRECT methods to identify Lyman continuum emitters



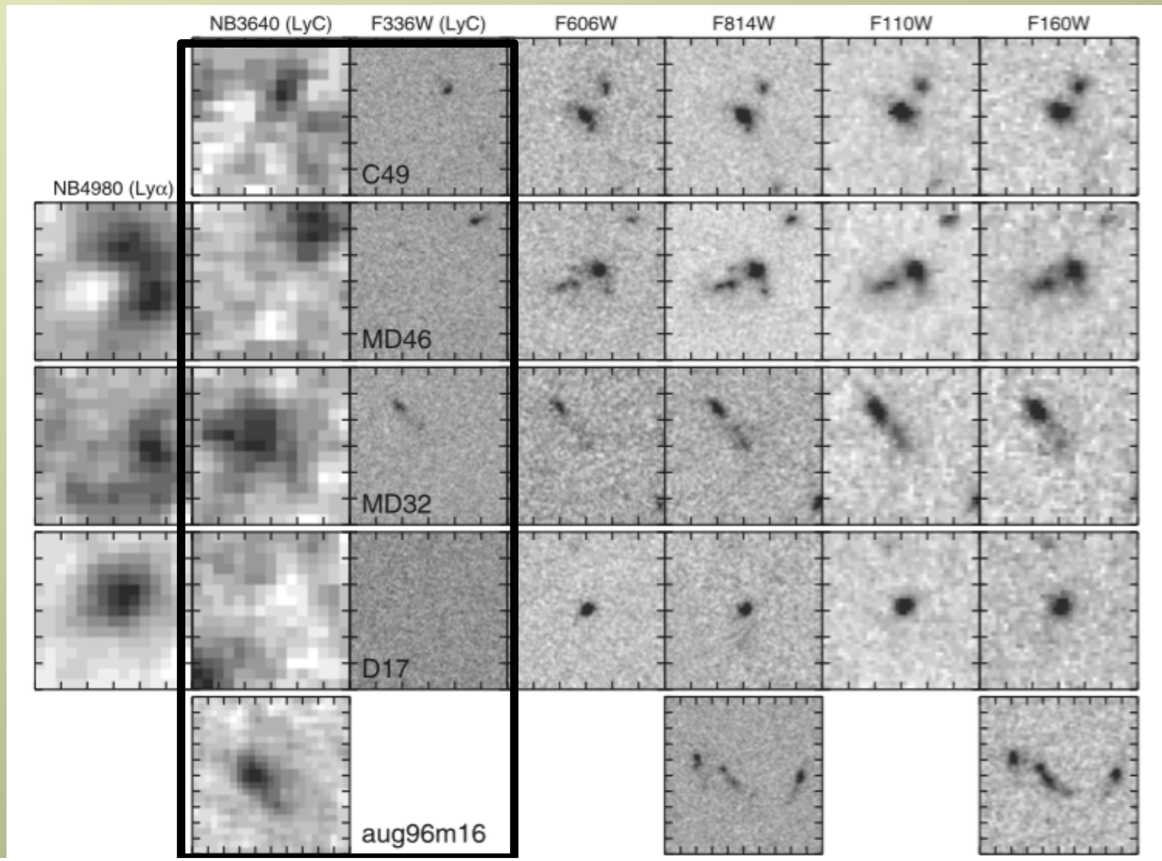
Siana+ (2015)

Ground-based LyC images



Nestor+ (2011)

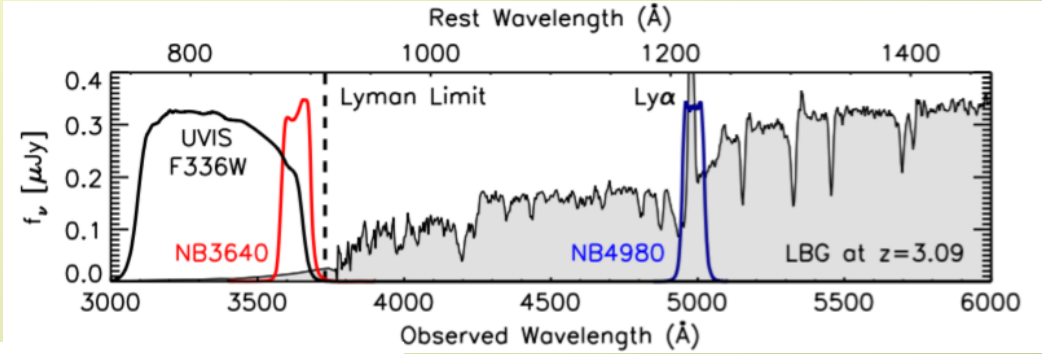
With HST resolution



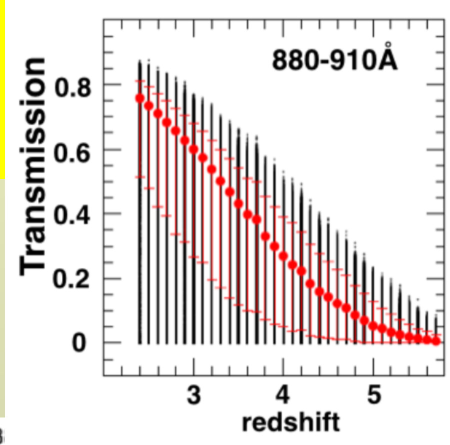
DIRECT methods to identify Lyman continuum emitters

Main ISSUEs:

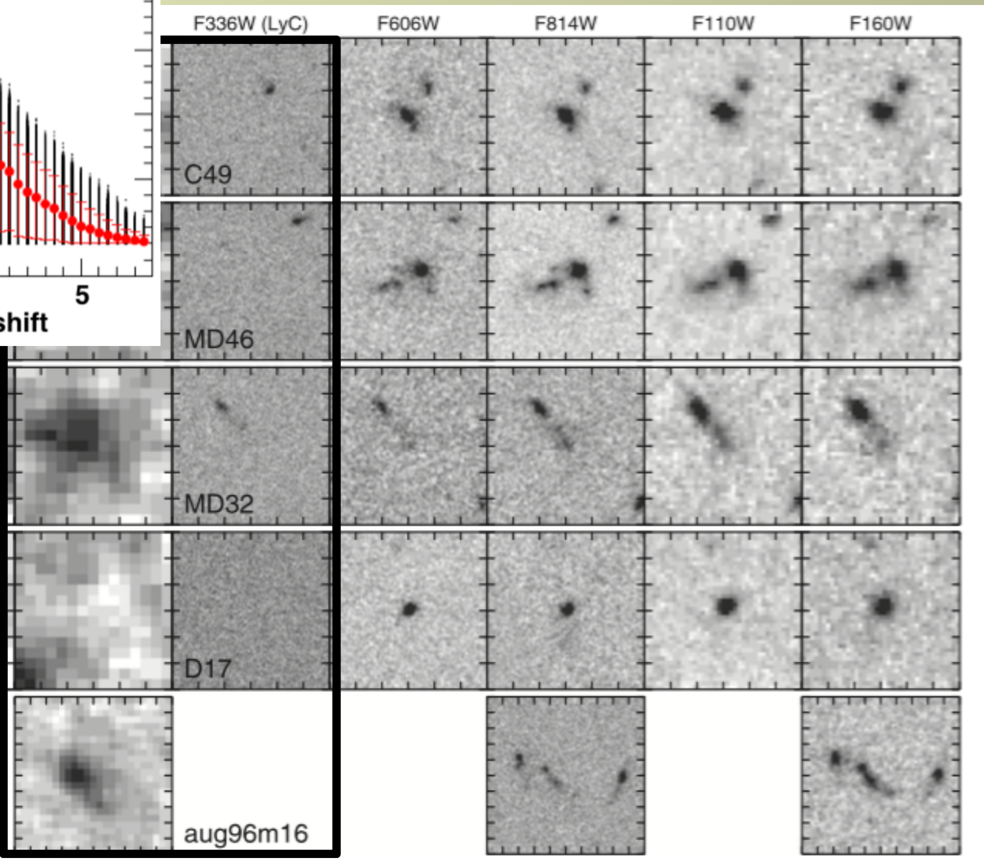
- ***contamination by foreground sources*** (Siana+2007, Vanzella+2010)
- ***Limited to z<~4 due to increasing IGM opacity***



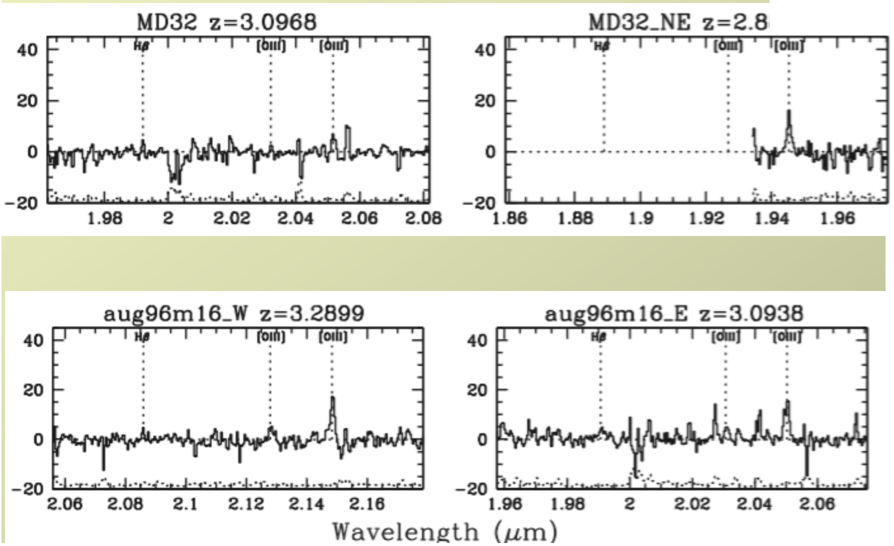
Siana+ (2015)



With HST resolution

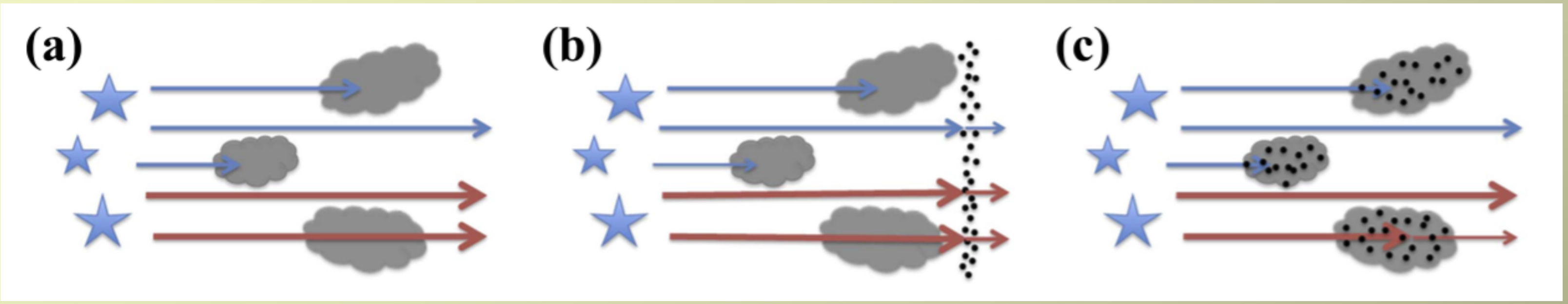


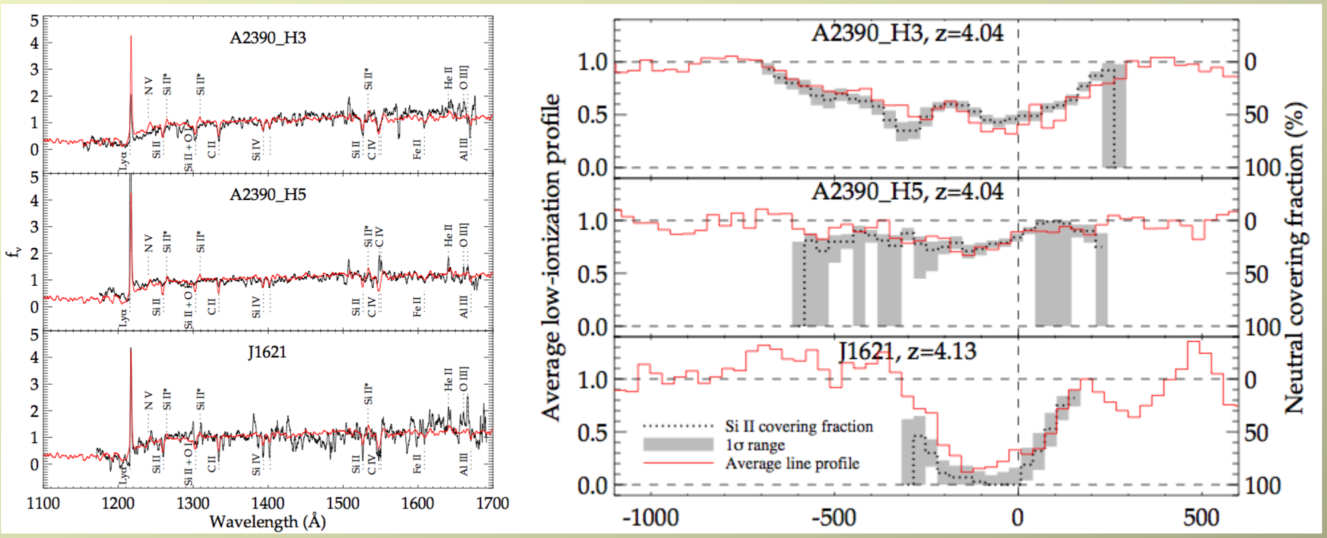
With spectroscopy



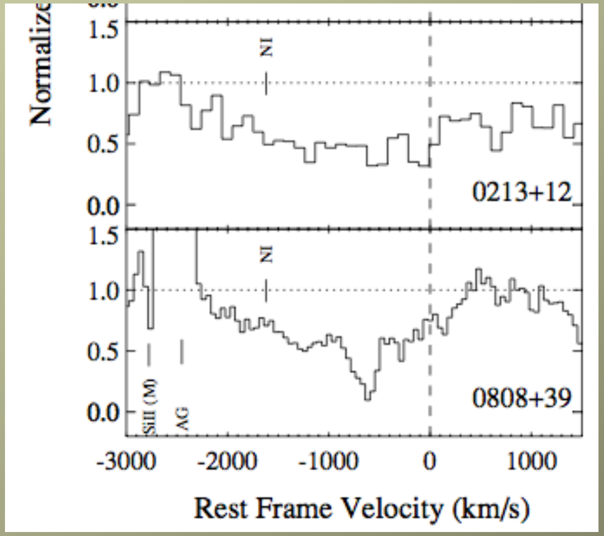
INDIRECT methods to identify Lyman continuum emitters

1. **UV low ionisation absorption lines**
   Using satured lines → *low covering factor of the UV continuum* source
   (e.g. Heckman et al. 2011, Alexandroff et al. 2015)





Jones et al. (2013)

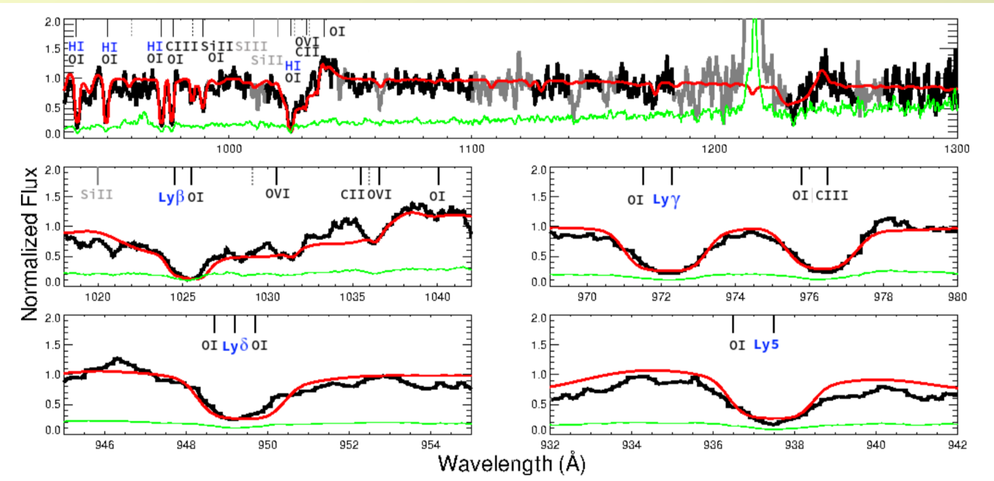


Heckman et al. (2011)

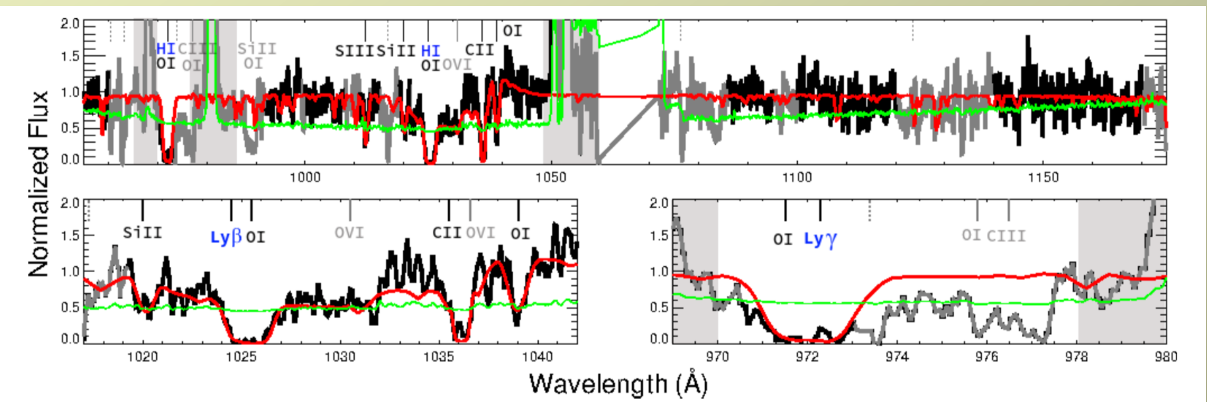
INDIRECT methods to identify Lyman continuum emitters

→ **UV absorption lines – Lyman series and SiII 1190, 1260 Å – can be used to infer LyC escape fraction indirectly** (Gazagnes+ 2018, Chisholm+ 2018)

Consistent modeling of continuum + lines + geometry UV attenuation needed to determine fesc from LIS lines !



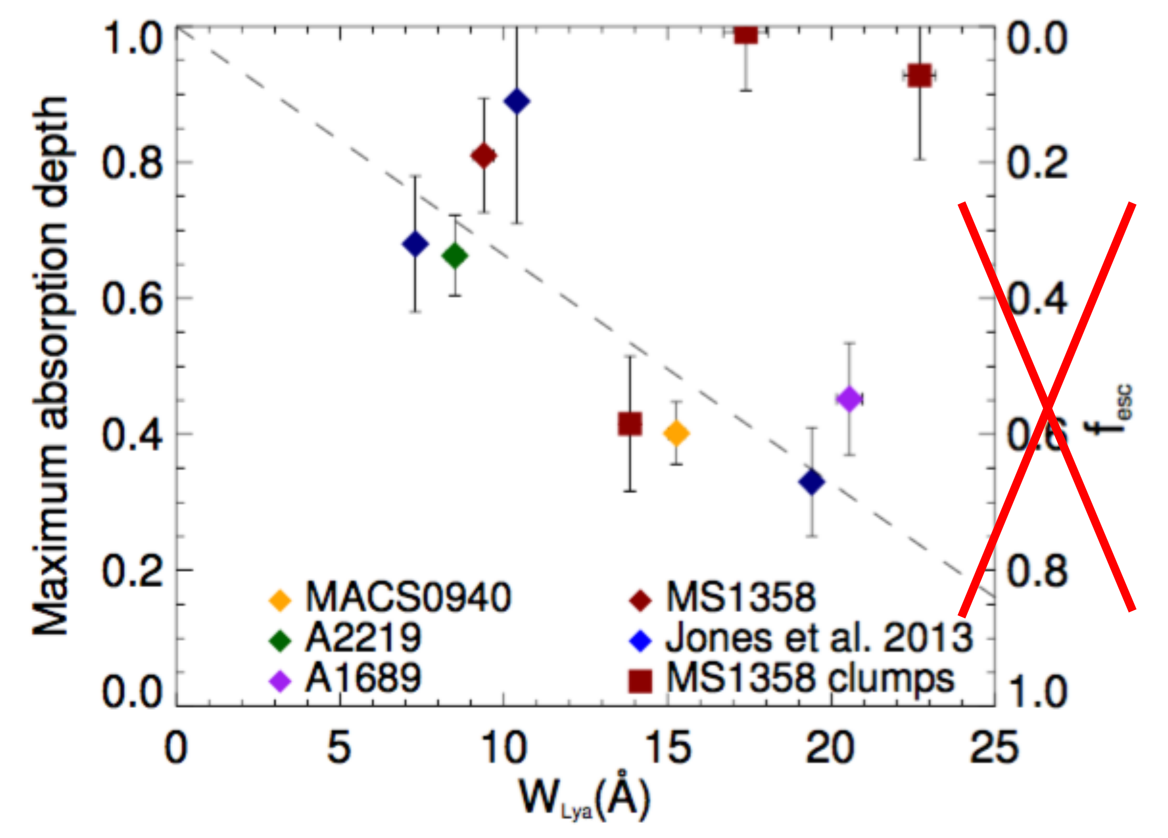
confirmed leaker
J1503+3644
(Izotov+ 2016)



GP 1244+0216
(Henry+ 2015)

INDIRECT methods to identify Lyman continuum emitters

→ **UV absorption lines – Lyman series and SiII 1190, 1260 Å – can be used to infer LyC escape fraction indirectly** (Gazagnes+ 2018, Chisholm+ 2018)



Consistent modeling of continuum + lines + geometry UV attenuation needed to determine fesc from LIS lines !

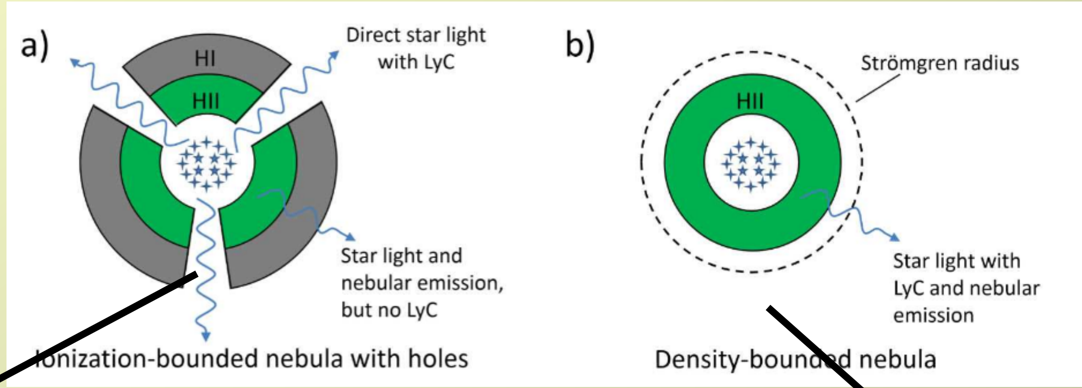
Leethochawalit et al. (2016), Jones et al. (2013)

INDIRECT methods to identify Lyman continuum emitters

2. Lyman-alpha line profile

narrow Lya line profile, small velocity shift, small separation of peaks

→ *cf. talk from Anne Verhamme*

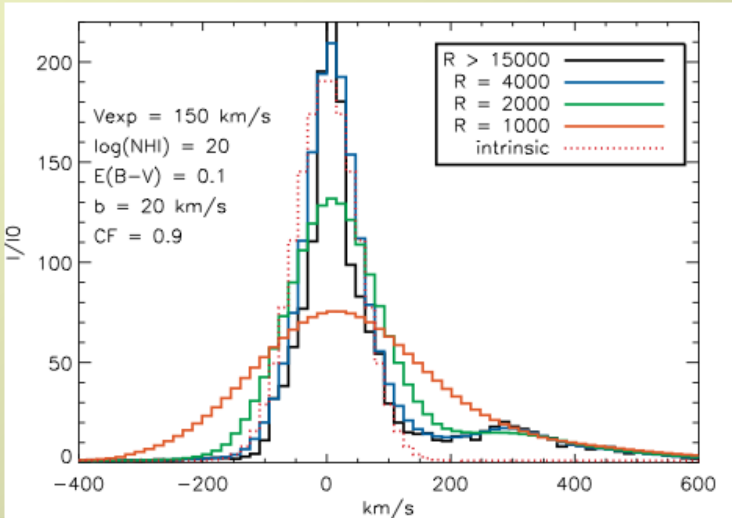


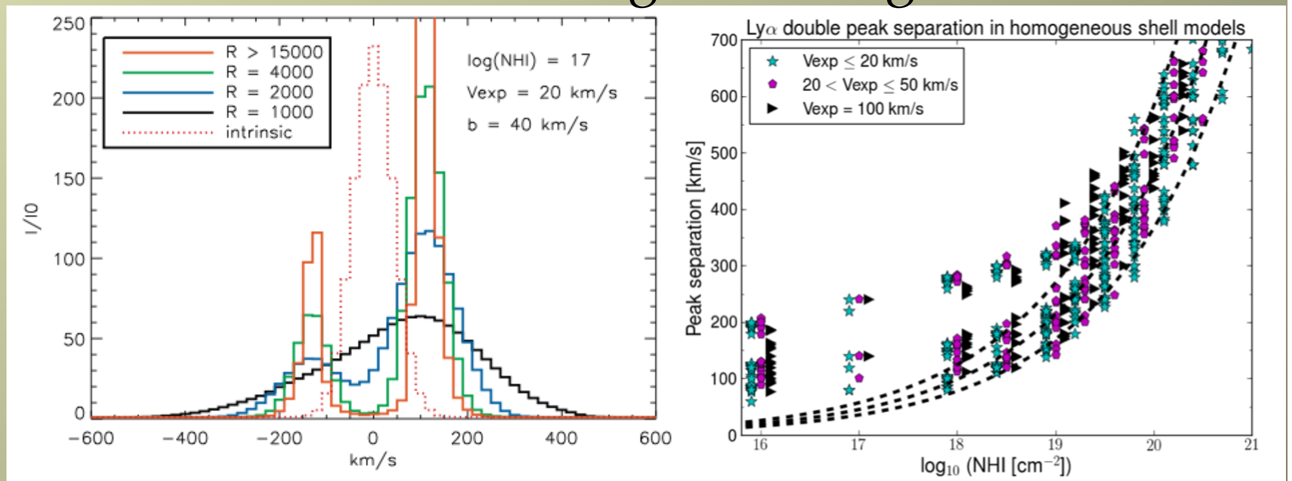
Zackrisson et al. (2013)

clumpy ISM

Verhamme et al. (2015)

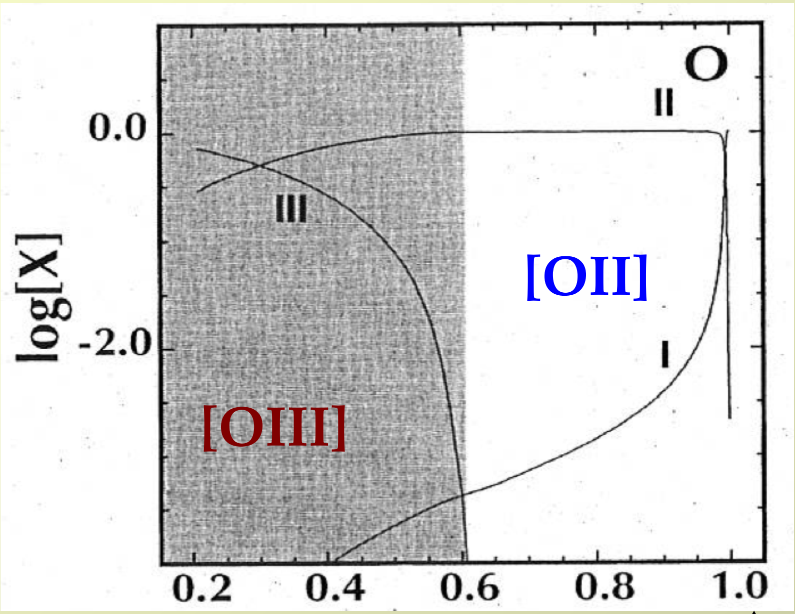
homogeneous medium or large covering fraction





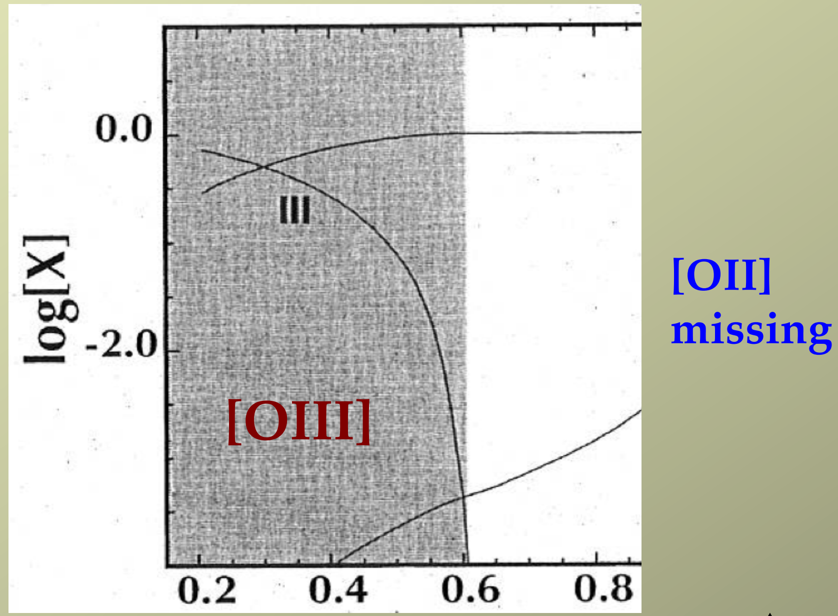
INDIRECT methods to identify Lyman continuum emitters

3. Peculiar emission line ratio, e.g. **high [OIII]/[OII]**



Strömgren radius

« Normal » ionisation-bounded HII region



Strömgren radius

Density-bounded HII region

Nakajima & Ouchi (2014), also Jaskot & Oey (2013)

Also for other line ratios … cf. ionization mapping of local HII regions (Oey+)

Direct searches for LyC emitters at z>1 -- imaging

Many studies, e.g.:

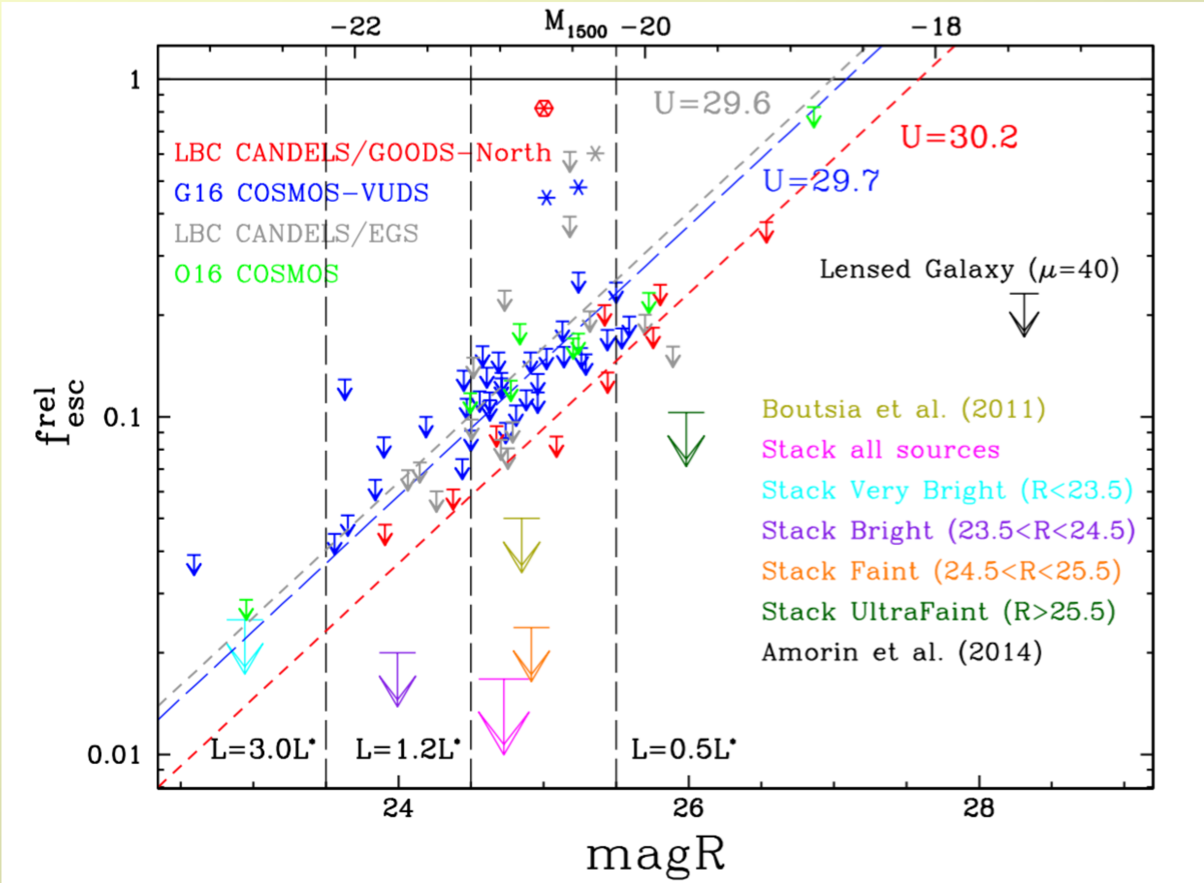
- z~1 using HUT, SBC@HST, GALEX
  (Leitherer+1995, Malkan+2003, Siana+ 2007,2010, Bridge+ 2010, Cowie+ 2009, Rutkowski+ 2016)
- z~1.3 using HST UV imaging (Siana+ 2007), ***AstroSat observations*** (Saha+ 2018)
- z~2 and 3 using WFC3 UVIS@HST (**Naidu+ 2017**, Fletcher+ 2018)

- z>~3 using deep ground-based U and HST optical imaging:
  Vanzella+ (2010), Boutsia+ (2011), Grazian+ (2016, 2017)
- z>~3 using deep ground-based narrow-band photometry:
  Iwata+ (2019), Nestor+ (2011), Mostardi+ (2013), Micheva+ (2017)

➔ Generally: few LyC detections, LyC candidates to be confirmed
➔ Upper limits on LyC escape fraction (for bright sources, or from stacking)

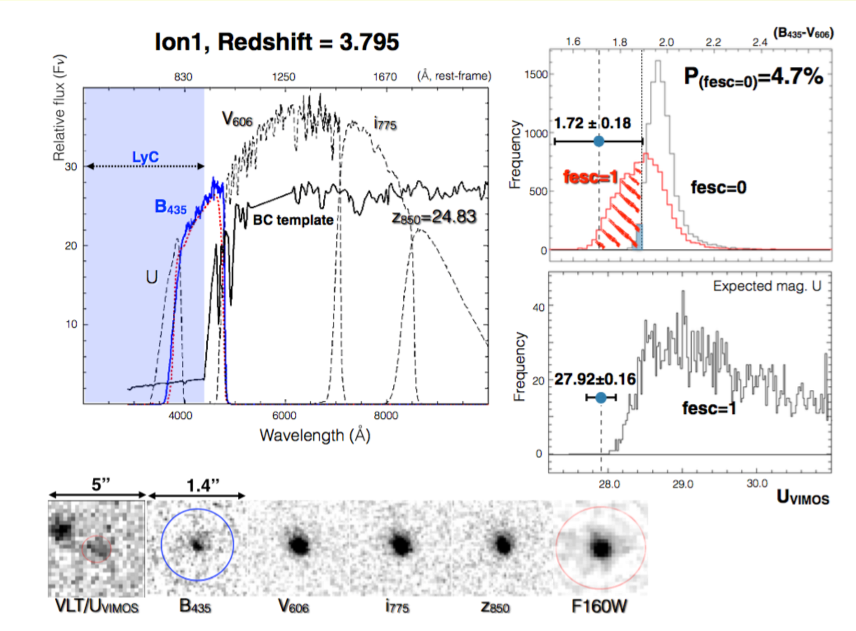
« Best » confirmed high-z LyC sources:
Vanzella+ (2017), de Barros+ (2016), Bian+ (2017), Shapley+ (2016), Fletcher+ (2018)

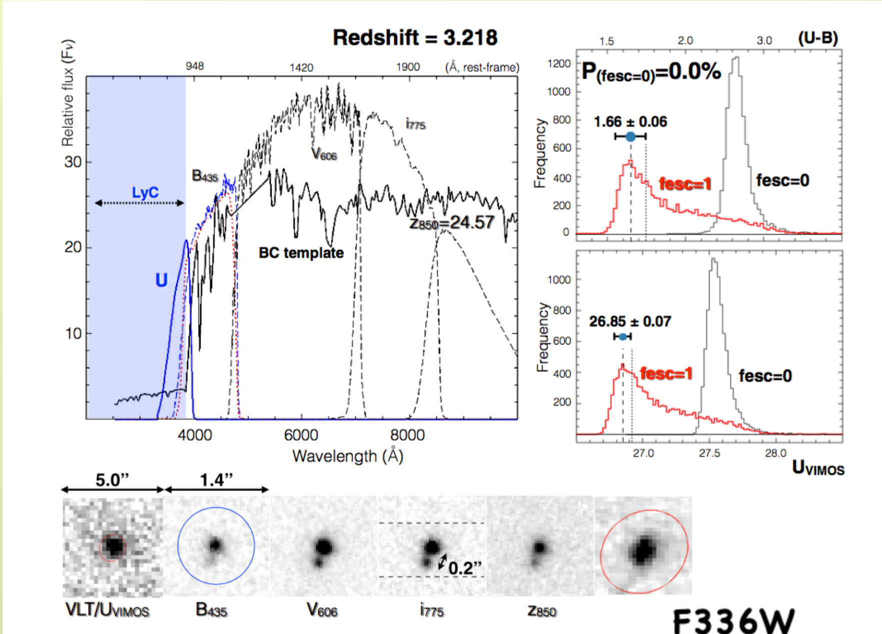
The quest for the sources of cosmic reionisation - z~3



COSMOS+EGS+GOODS-N -- z~3.3: Grazian+ 2017

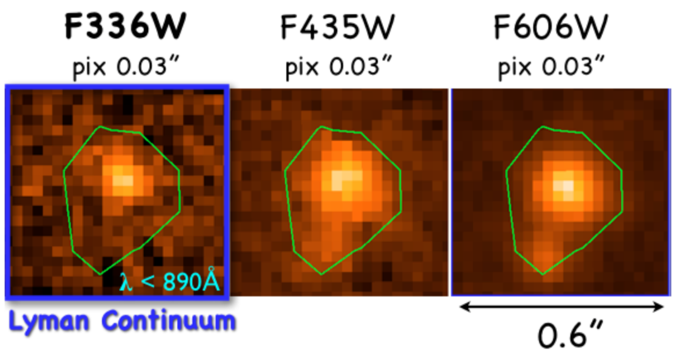
The quest for the sources of cosmic reionisation - z~3

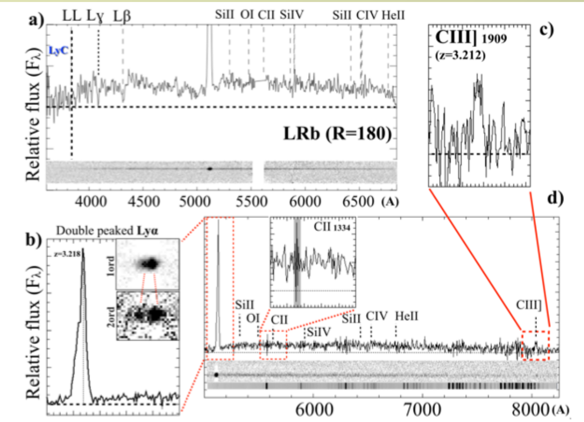


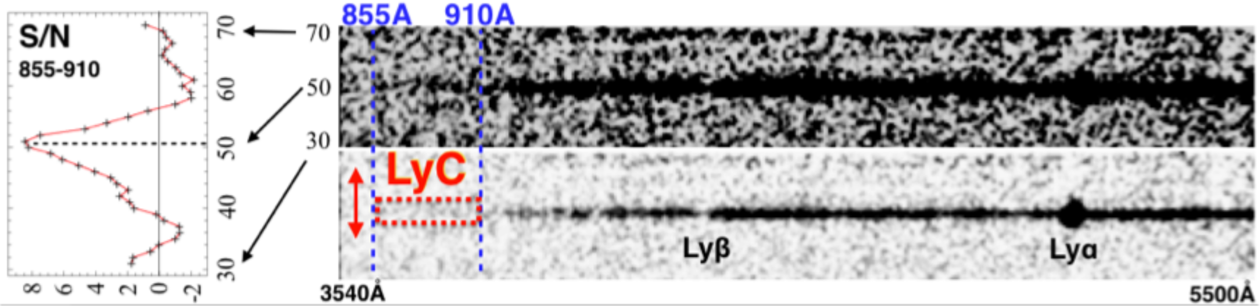


GOODS-S – z>3 search: **2 good candidates**
Vanzella+ (2015, 2016)

Ion2
« best » high-z
LyC source
(cf. de Barros+ 2016)



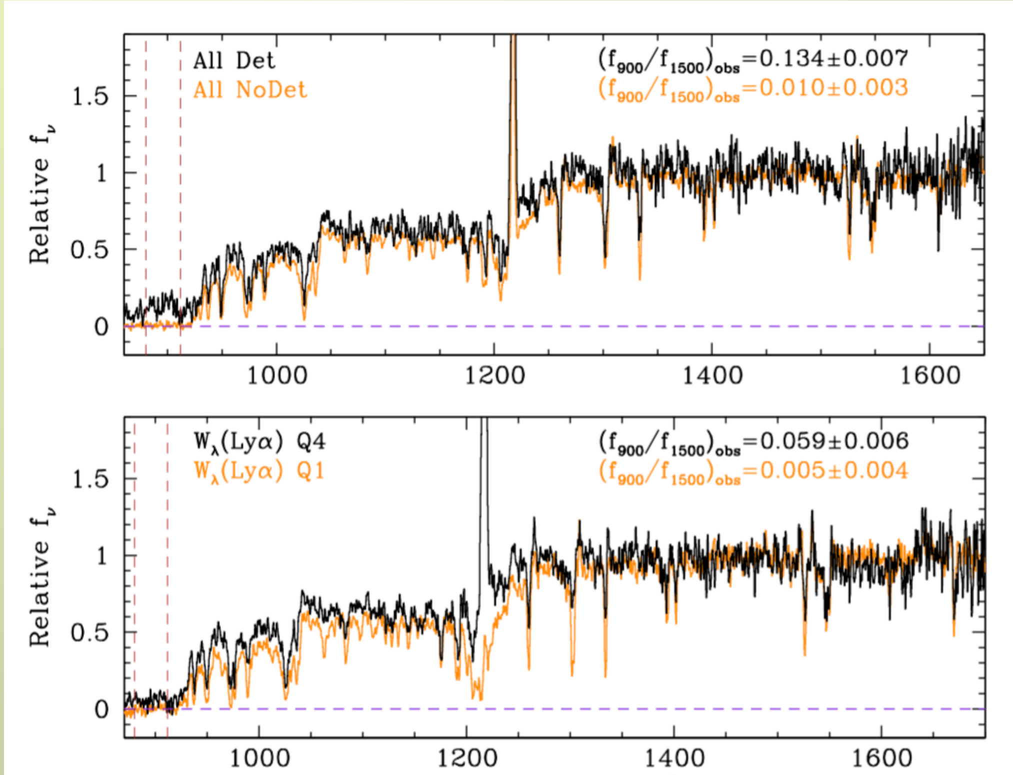




The quest for the sources of cosmic reionisation - z~3

Keck survey: 124 z~3 SF galaxies
→ spectroscopy more sensitive to LyC
→ significant LyC detection in stacked sub-samples

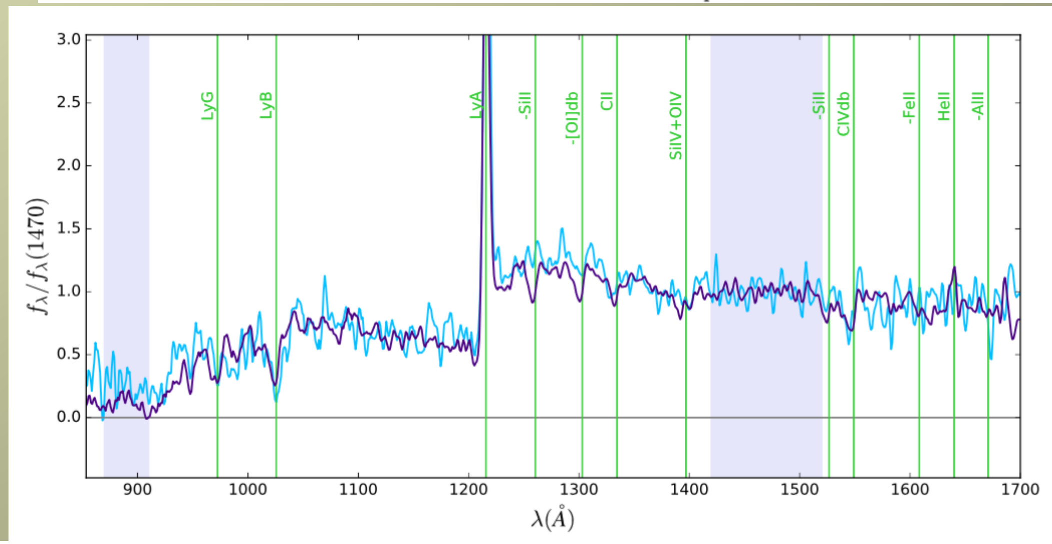
Steidel et al. (2018)



VIMOS/VLT survey:

- ~200 z~3.5-4.4 SF galaxies
  → possible LyC detection in sub-samples
- 33 z~4 galaxies also with HST imaging
  → no individual LyC detection
  → faint/no LyC signal in stack

Marchi et al. (2017, 2018)

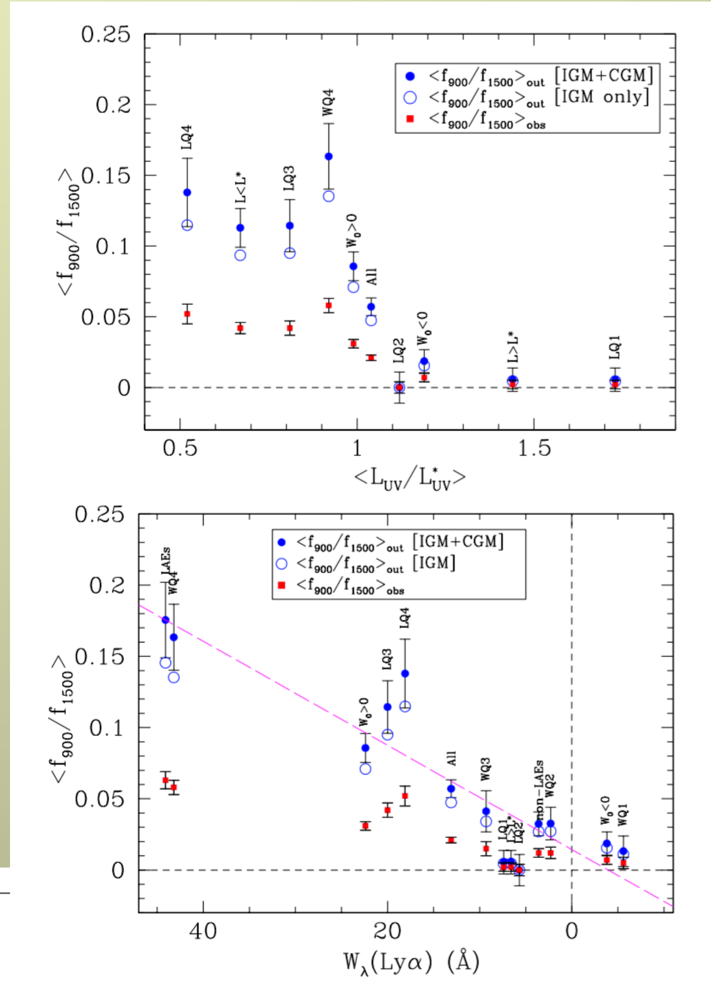


The quest for the sources of cosmic reionisation - z~3

Keck survey: 124 z~3 SF galaxies
→ increase of f(Lyc)/f(1500) with increasing EW(Lya)

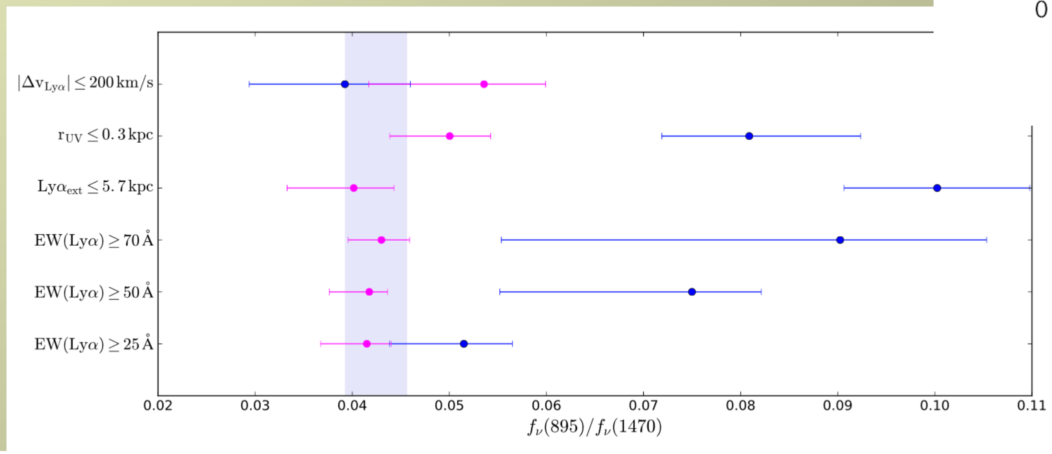
VIMOS/VLT survey:
~200 z~3.5-4.4 SF galaxies
→ higher f(Lyc)/f(1500) in compact and strong EW(Lya) sources

Further confirmation of LyC candidates needed (HST imaging)



Steidel et al. (2018)

Marchi et al. (2018)

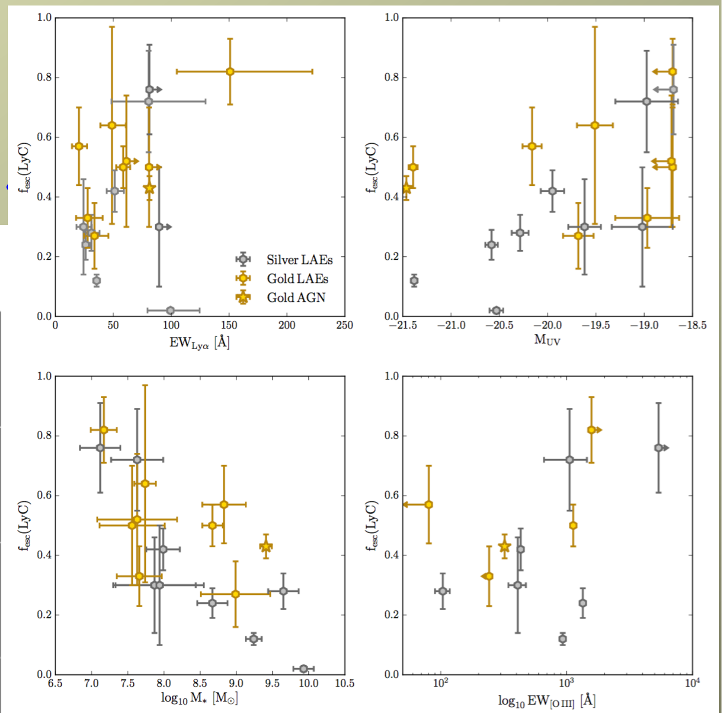


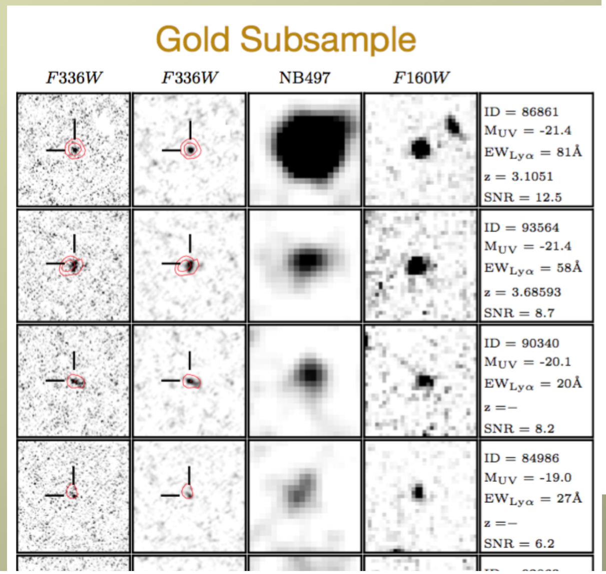
The quest for the sources of cosmic reionisation - z~3

***HST LyC survey (PI Robertson)*:**
61 z=3.1 SF galaxies in SSA22 field – 54 selected as Lyman-alpha emitters (NB)
- HST: WFC3/F336W UVIS imaging
- Near-IR rest-frame optical spectroscopy ([OIII],[OII], Hb)

→~30% LyC detections
→ fesc(LyC) ~ 2-82 %, average fesc~20 %
→ ~half of sample **not** detected in LyC (stacked fesc<0.3%) → anisotropic LyC escape?
→ possible correlations of fesc with EW([OIII]), Lya …

Fletcher et al. (2018)



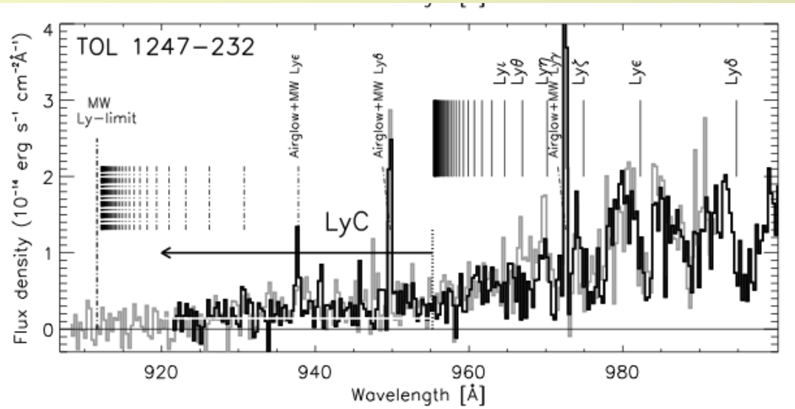


Possible concerns:
- Correlated noise
- AGN-like [OIII]/Hb

LyC emitters at low redshift: 2016 status

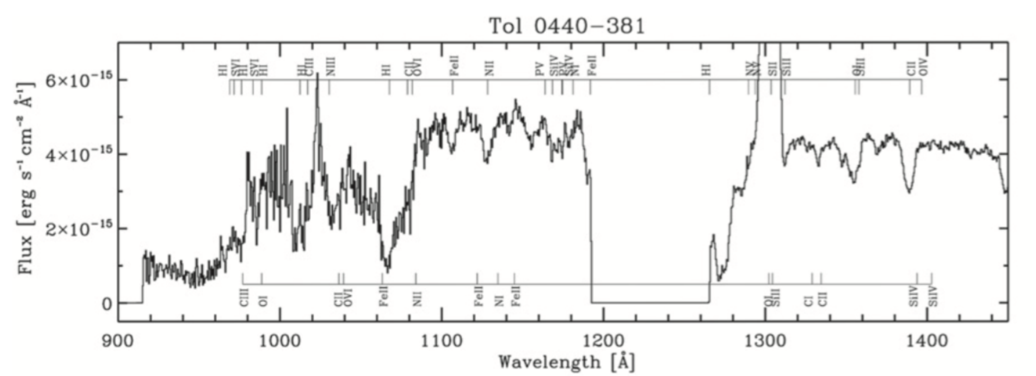
Best low-z Lyman continuum sources:

- FUSE observations: Haro11 (LBG analog) +
  HII/dwarf galaxy Tol 1247-232 - Leitet al. (2013) **fesc=2.4%**
  Revisited with COS/HST: Leitherer+ (2016), Chisholm+ (2017) → **fesc=0.4 %**
- COS/HST: compact Lyman break analog at z=0.2 -- Borthakur et al. (2014) **fesc=1%**
- COS/HST: 2 other z~0 sources (Tol 0440-381, Mrk 54), possible detection (Leitherer+ 2016), but **low fesc** and low significance (Chisholm+2017)

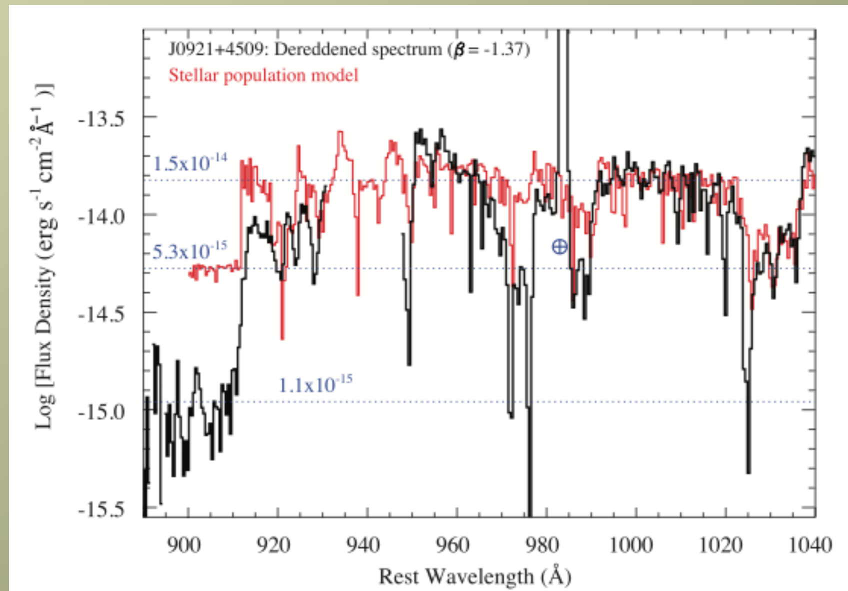


Leitet al. (2013)

Leitherer al. (2016)



Borthakur et al. (2014)



The quest for the sources of cosmic reionisation - a recent breakthrough

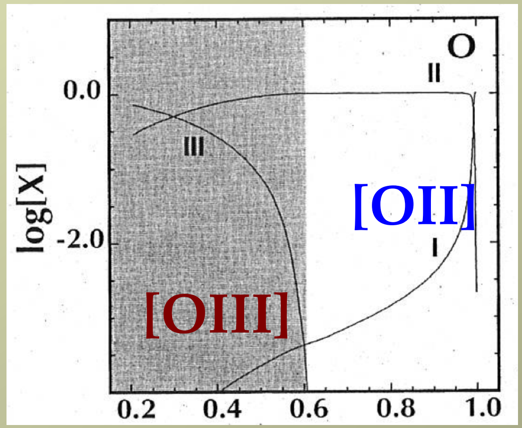
COS-HST cycle 22 program: *measure Lyman continuum and test indirect indicators*

Thuan, Izotov, Orlitova, Verhamme, Schaerer, Guseva
17 orbits, 5 galaxies

Object selection (from Sloan):

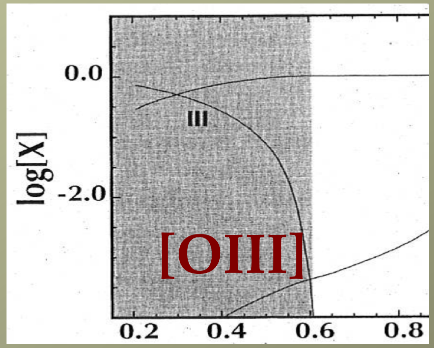
- **High [OIII]/[OII] ratio**
- **Compact SF galaxy – « Green Pea » like**
- z~0.3 and UV-bright for « easy » Lyman-continuum detection with COS

→ 5 galaxies selected



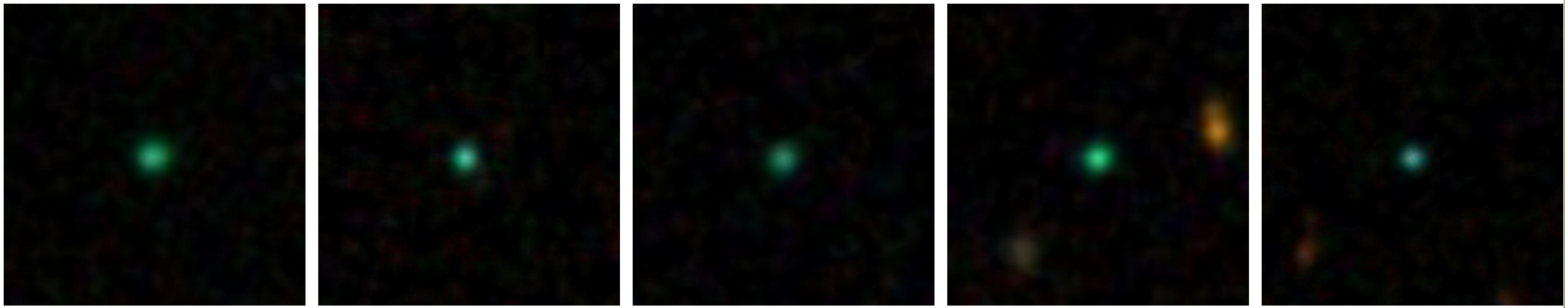
G140M, G160M grism observations to cover:

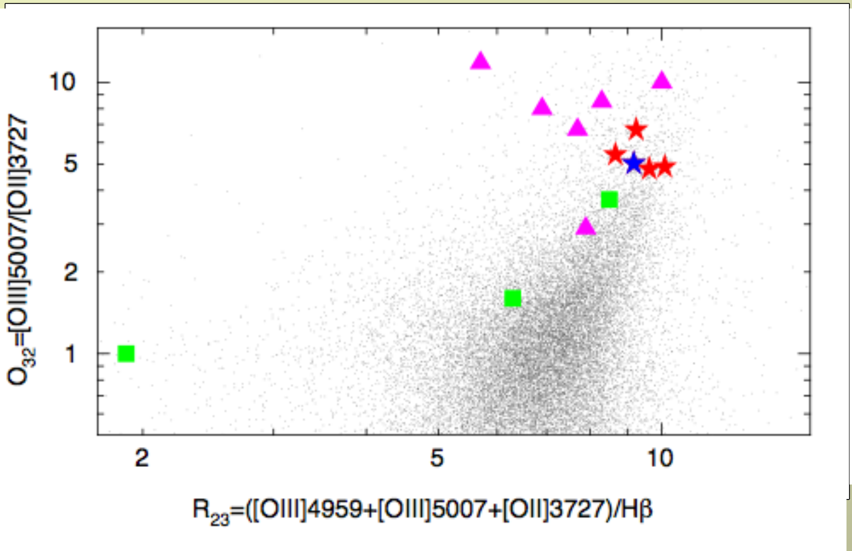
- Lyman continuum
- Lyman alpha
- UV absorption lines

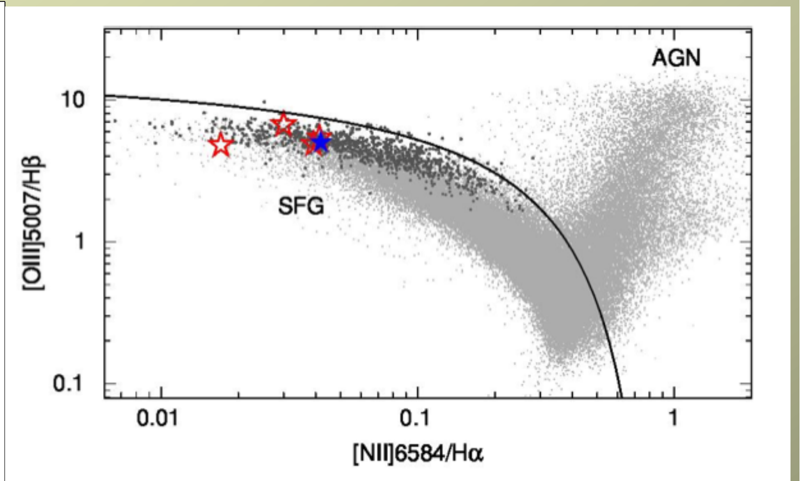


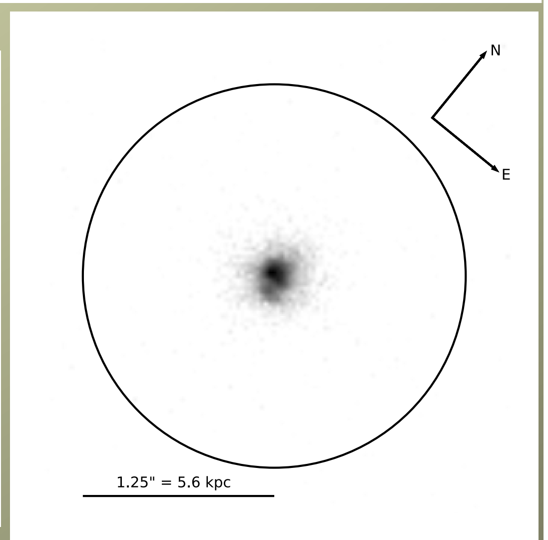
The quest for the sources of cosmic reionisation

Cycle 22 COS-HST program: *measure Lyman continuum and test indirect indicators* (Thuan, Izotov, Orlitova, Verhamme, Schaerer, Guseva)









Strong Lyman continuum leakers at z=0.3

Izotov, Orlitova, Schaerer, Thuan, Verhamme, Guseva, Worseck (2016)
Nature, 529, 178

LETTER

doi:10.1038/nature16456

Eight per cent leakage of Lyman continuum photons from a compact, star-forming dwarf galaxy

Y. I. Izotov[1], I. Orlitová[2], D. Schaerer[3,4], T. X. Thuan[5], A. Verhamme[3], N. G. Guseva[1] & G. Worseck[6]

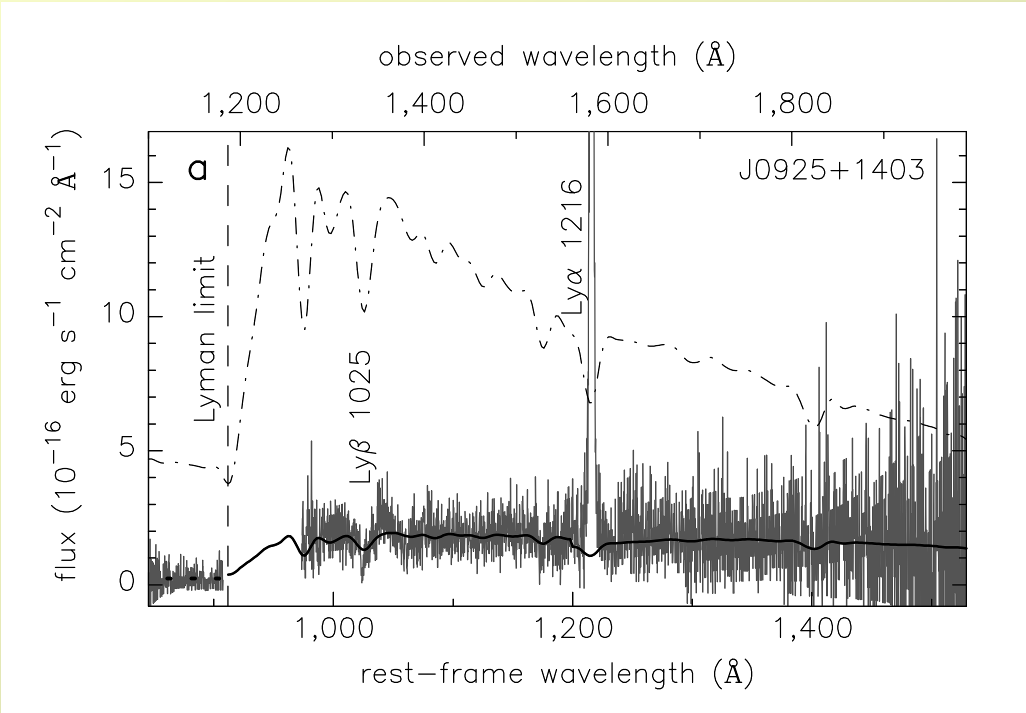
One of the key questions in observational cosmology is the identification of the sources responsible for ionization of the Universe after the cosmic 'Dark Ages', when the baryonic matter was neutral. The currently identified distant galaxies are insufficient to fully reionize the Universe by redshift $z \approx 6$ (refs 1–3), but low-mass, star-forming galaxies are thought to be responsible for the bulk of the ionizing radiation[4–6]. As direct observations at high redshift are difficult for a variety of reasons, one solution is to identify local proxies of this galaxy population. Starburst galaxies at low redshifts, however, generally are opaque to Lyman continuum photons[7–9].

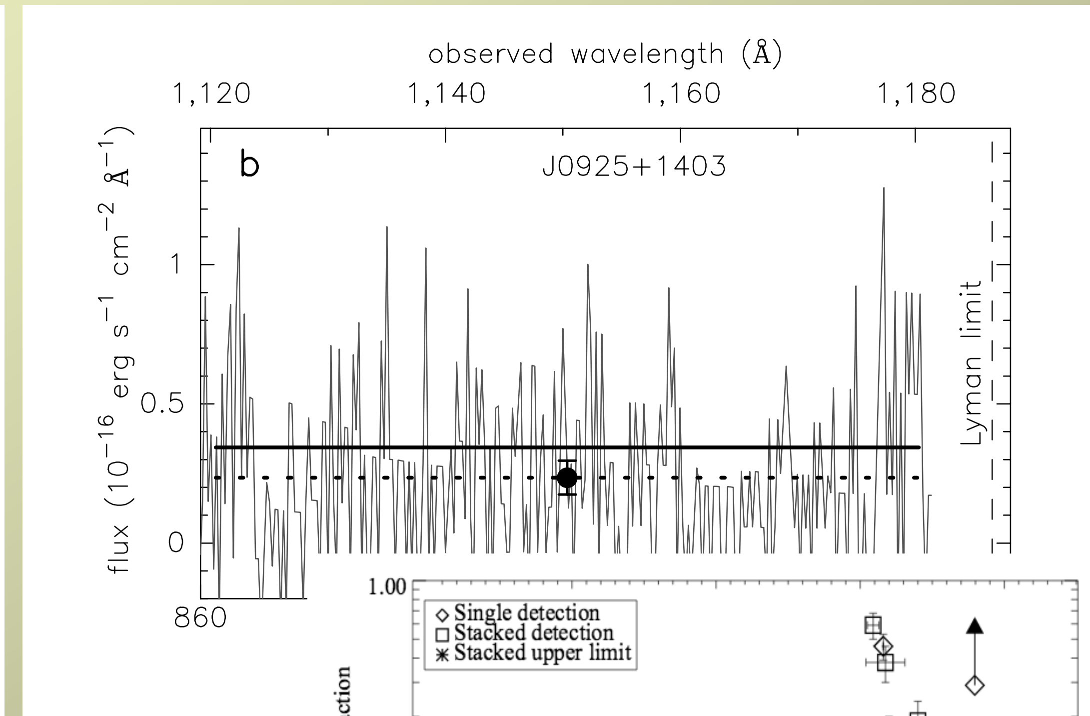
star-formation rate, J0925+1403 shares many of the properties of high-redshift Lyman-α (Lyα) emitters.

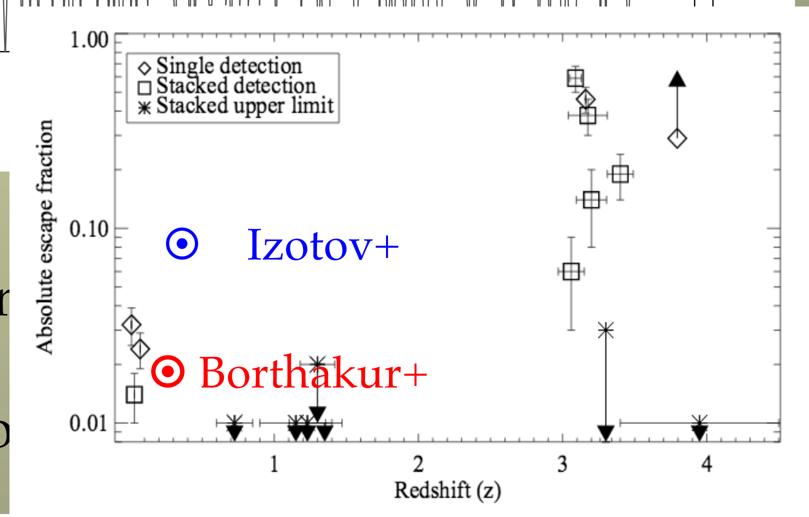
GPs with $O_{32} \geq 5$ have been observed before by HST[17,18], but their low redshifts $z < 0.3$ were not optimal for Lyman continuum observations. The HST/COS observations of J0925+1403 were obtained on 28 March 2015 (program GO13744; PI, T.X.T.). The near-ultraviolet acquisition image shows the galaxy to have a very compact structure, with a half-light angular diameter of ~0.2″, much smaller than the spectroscopic aperture of 2.5″ (Fig. 2). This angular diameter corresponds to a linear diameter of ~1 kpc at the angular diameter distance

Strong Lyman continuum leakers at z=0.3

COS-HST program: *measure Lyman continuum and test indirect indicators*
Izotov, Orlitova, Schaerer, Thuan, Verhamme, Guseva, Worseck (2016)

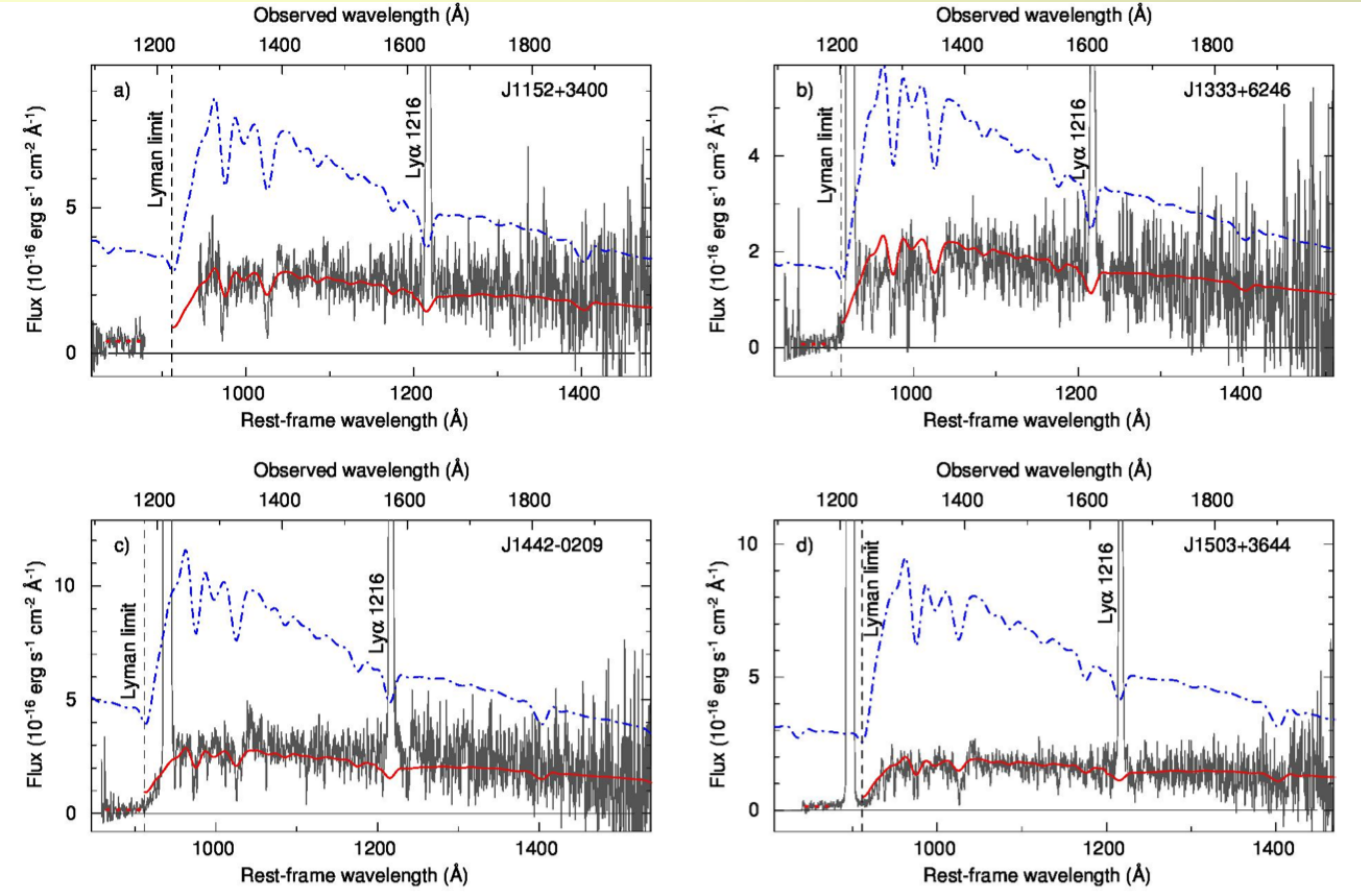






✔ Lyman continuum leakage

- 11.8 sigma detection (3.43±0.29)×10^{-17} erg s^{-1} cr
- Absolute **fesc=7.8±1.1** %
- Intrinsic LyC emission also from H recombinatio

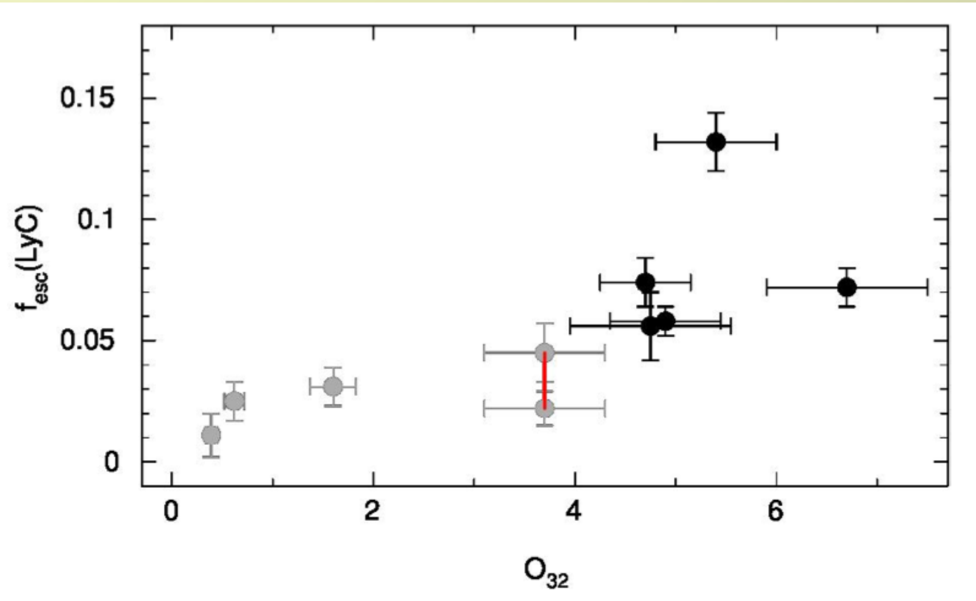


Larger sample: Izotov et al. (2016b) → **fesc=6-13** %

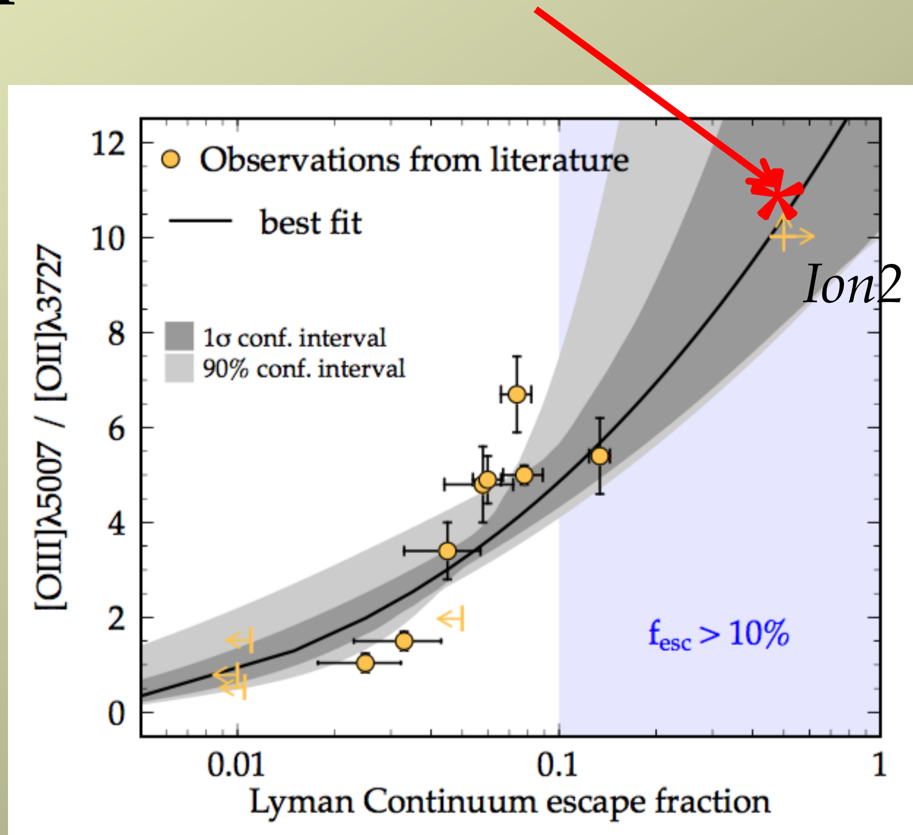
Strong Lyman continuum leakers at z=0.3

All known LyC leakers:
Correlation of fesc(Lyc) with O32
→ High OIII/OII is the best predictor of LyC escape fraction

Izotov et al. (2018) source with fesc=46%



Izotov et al. (2016b)



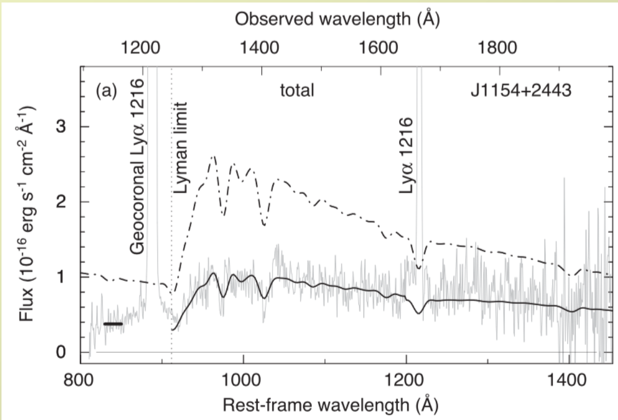
Faisst (2016)

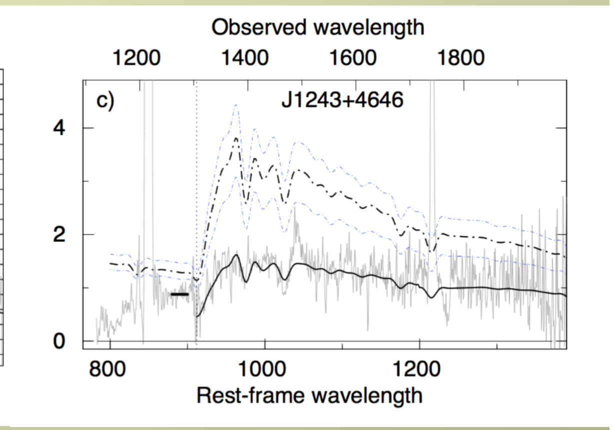
Strong Lyman continuum leakers at z=0.3

Cycle 25 observations:

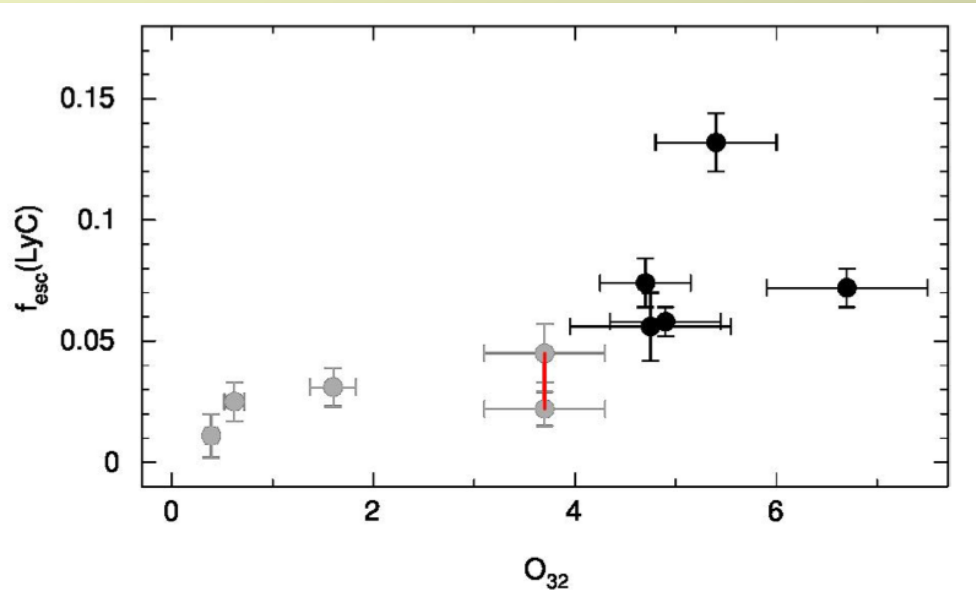
6 new sources with O32>10

- **100% LyC detection → efficient selection criteria** (O32/>4, compact, strong EL)
- **3 sources with fesc > 40%**
- **Wide range of fesc**

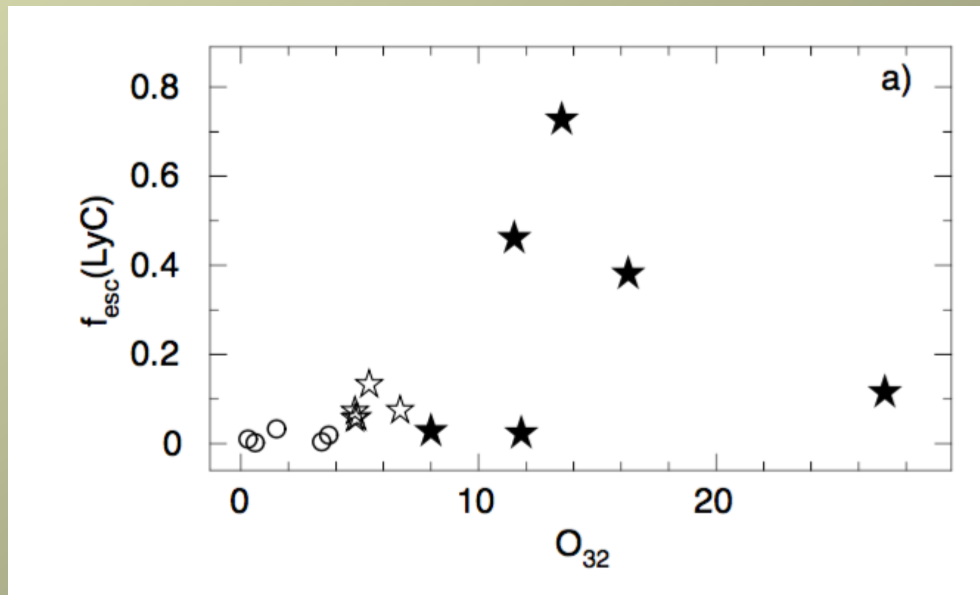




Izotov et al. (2016b)



Izotov et al. (2018ab)



Lyman-alpha properties of Lyman continuum leakers

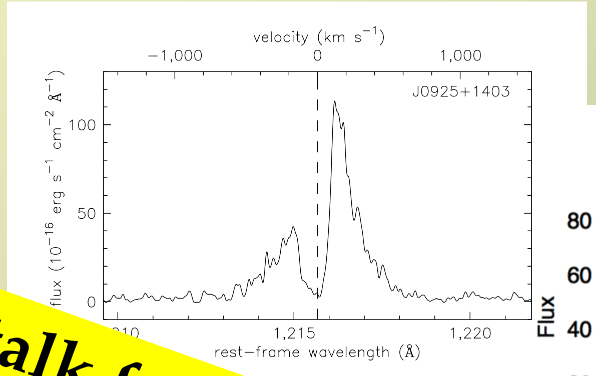
Verhamme et al. (2017, A&A 597, A13)

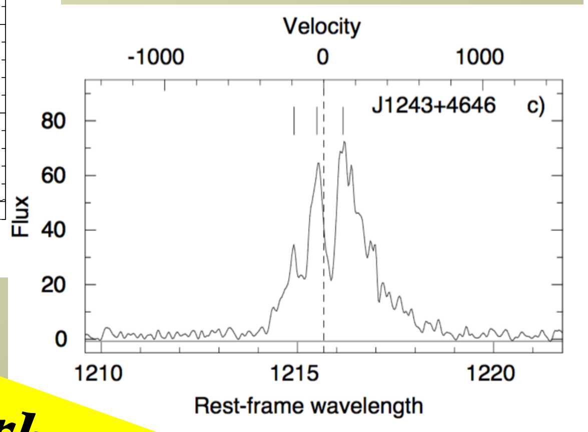
- **Strong Lyα emission (EW>70 Ang)**
- **Double-peaked profiles**
- **Small peak separation**

  as predicted by Verhamme et al. (20

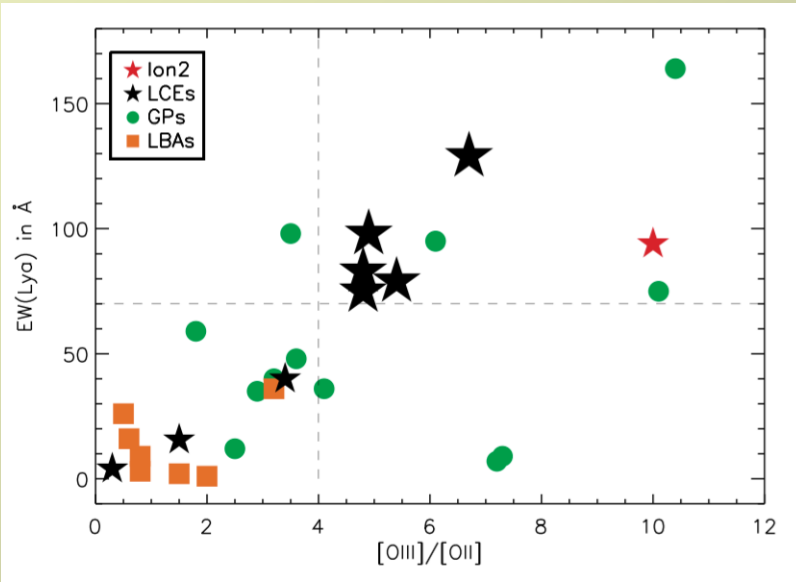
→ **Intense star formation, low dust content**

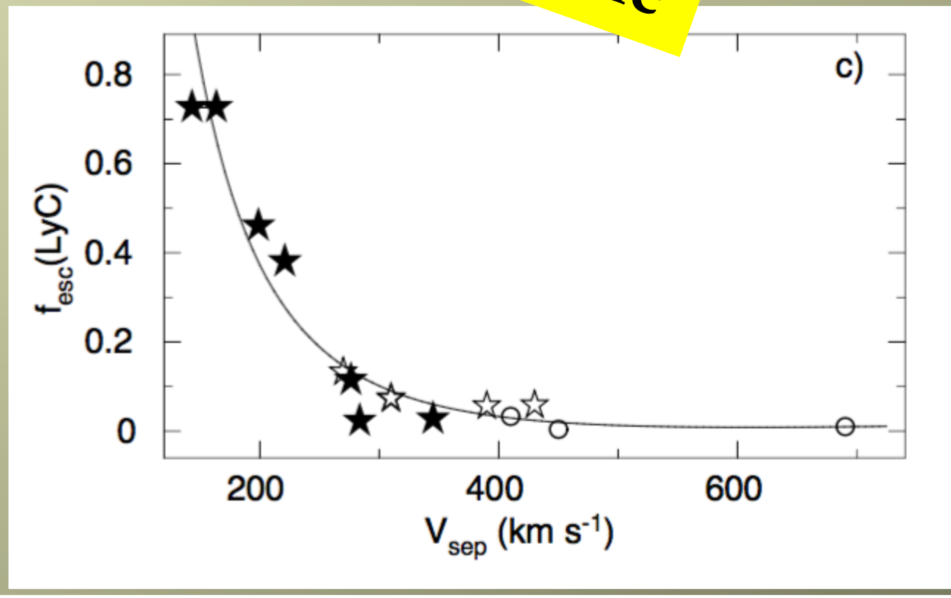
→ **Low HI column density**





→ Cf. talk from Anne Verhamme

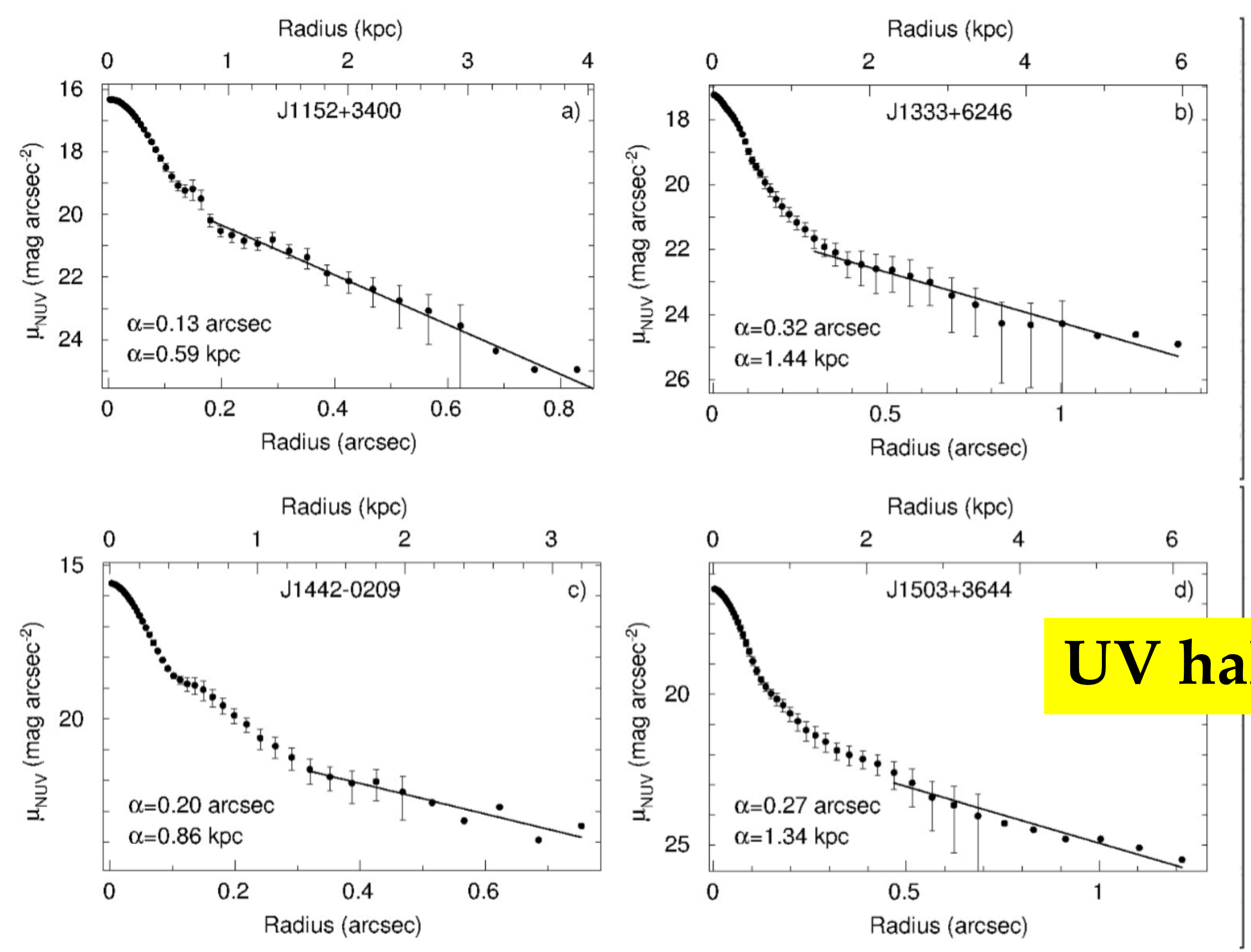


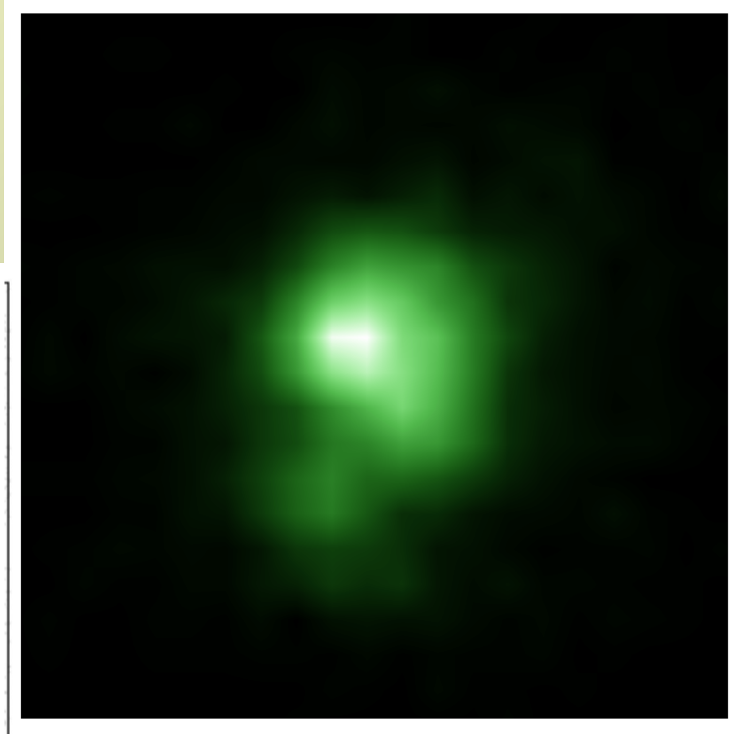


Properties of strong LyC leakers at z=0.3

J0925 + other sources -- other properties:

- High [OIII]/[OII] ratio
- Compact SF galaxy – « Green Pea » like

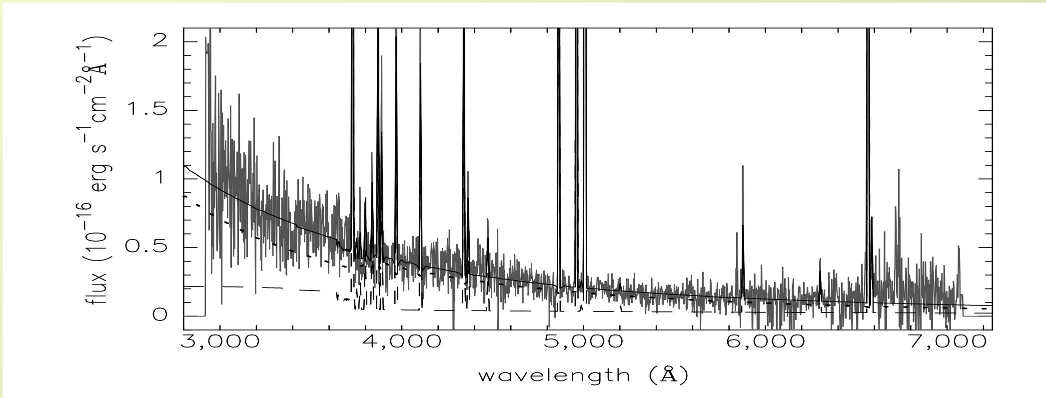


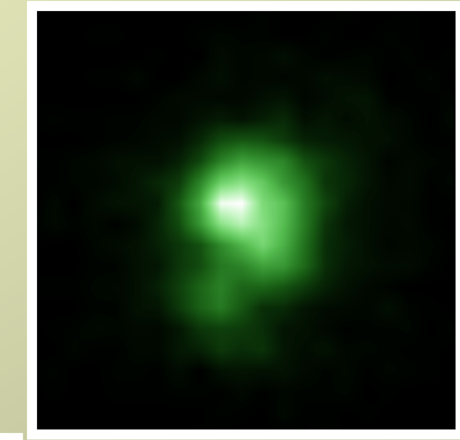


UV half-light radii <0.4 kpc

Properties of strong LyC leakers at z=0.3

J0925+1403
other properties

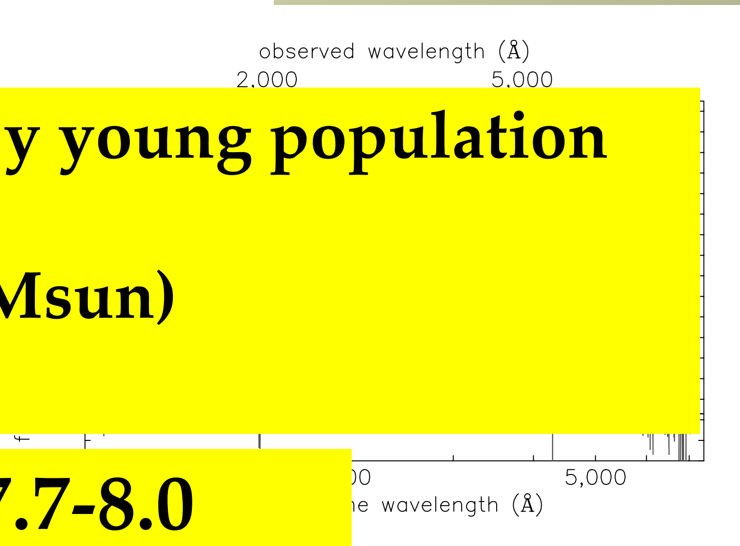




Extended Data Table 3 | Global characteristics of J0925+1403

Parameter	Value
$I_{H\beta}$[†]	
Redshi…	
Lumino…	
$L_{H\beta}$[††]	
SFR[‡‡]	
Q_H[*]	
Q_H(esc…	
t(burst)…	
$M_y/M_\odot$	
$M_*/M_\odot$	

[†]Extinction-corrected flux densit…
[‡]In units of Mpc.
[††]Extinction- and aperture-corre…
[‡‡]Star-formation rate in $M_\odot$ yr^{-1} derived from the Hβ luminosity…
[*]Q_H and Q_H(esc) are the number…
[**]Burst age in Myr.



- **UV-optical spectrum dominated by young population (3-5 Myr)**
- **Low stellar masses (median ~10^9 Msun)**
- **High SFR (~14-40 Msun/yr)**

Metallicity 12+log(O/H)~7.7-8.0
~(0.12-0.25) solar

Low extinction: A_V~0.18-0.36

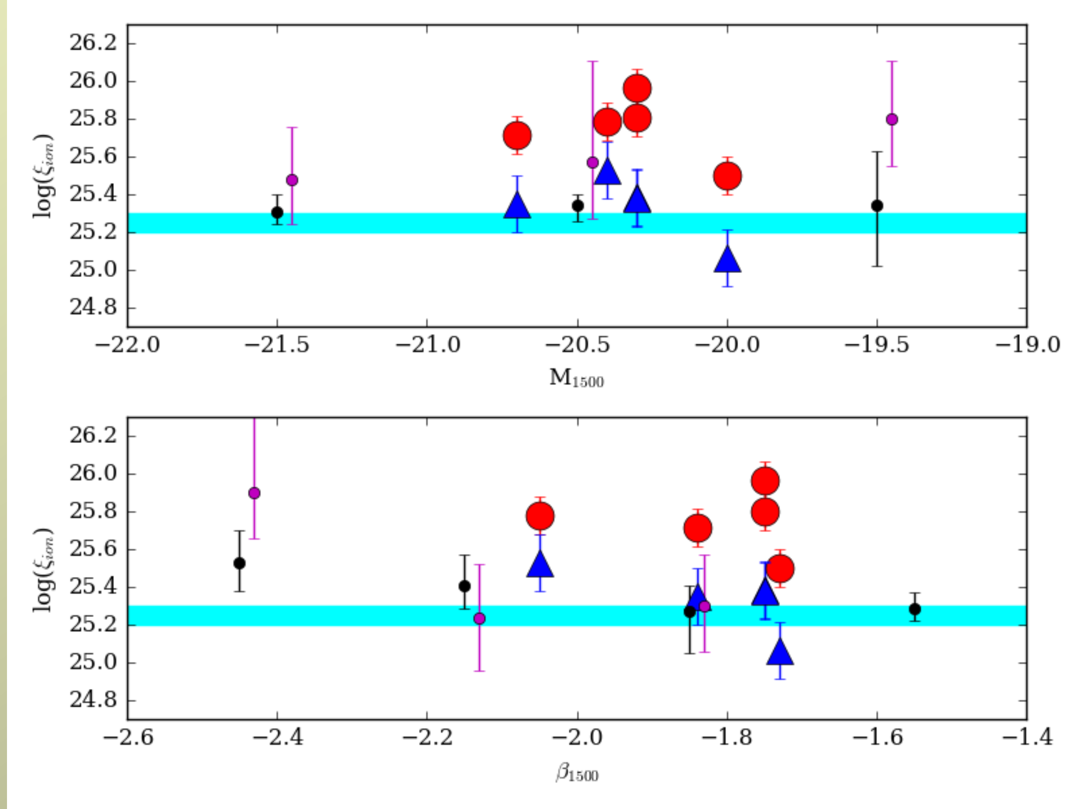
Lyman continuum leakers at z=0.3: Ionising photon production

Direct measure of ξ_{ion} :

→ **Factor ~2-5 times more ionizing photons produced** ***per unit UV luminosity than commonly assumed***

→ ***Intrinsic*** ξ_{ion} – corrected for extinction – is ~(1-2) times « standard » value

Best analogs for sources of cosmic reionisation

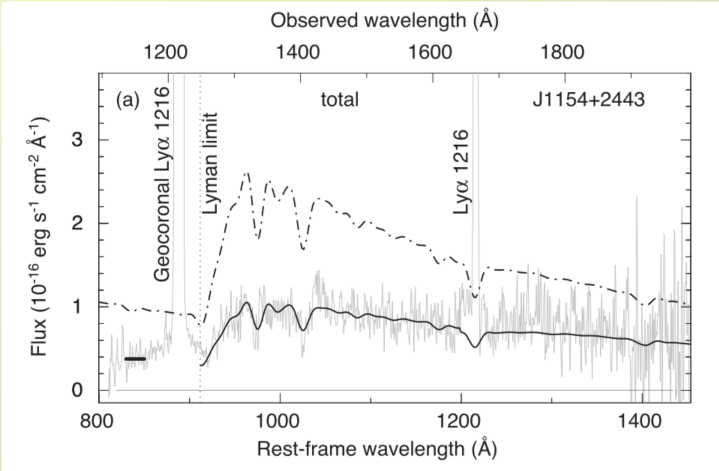


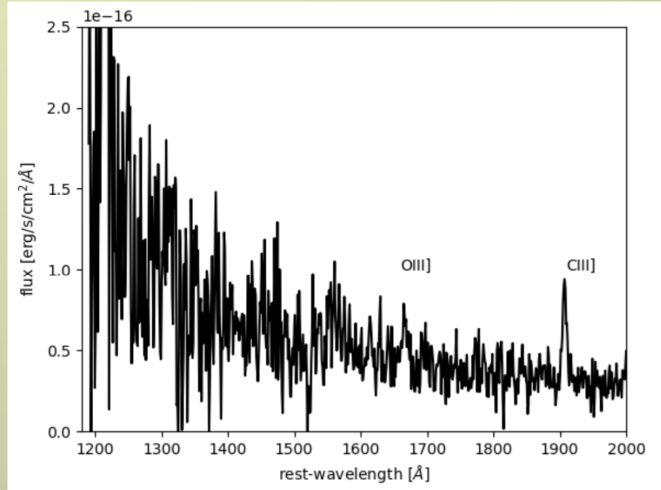
Schaerer et al. (2016, 2018)

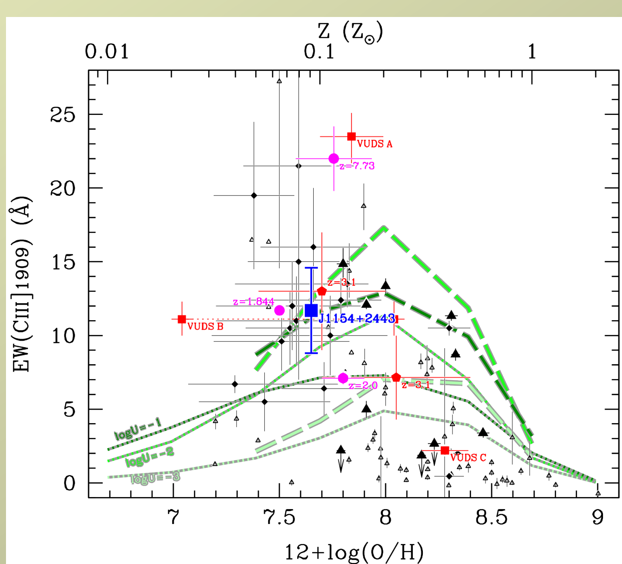
First « complete » UV spectrum of a strong low-z LyC leaker

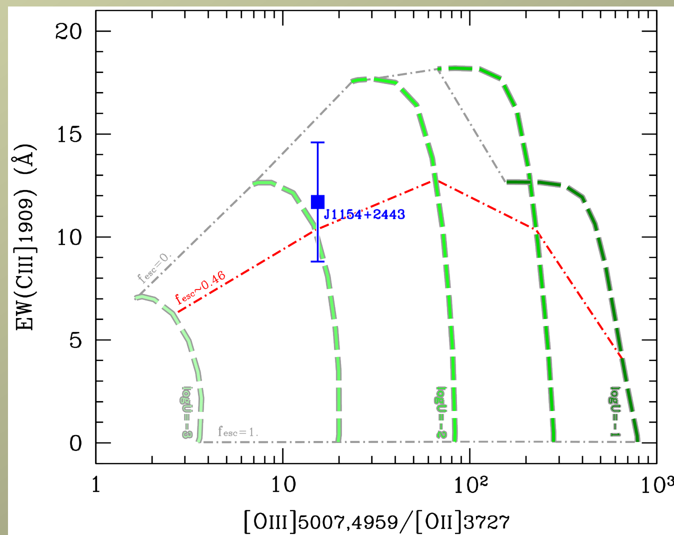
Strong LyC emitter at z=0.349 – fesc=46%

→ Schaerer et al. (2018, A&A 616, L14)





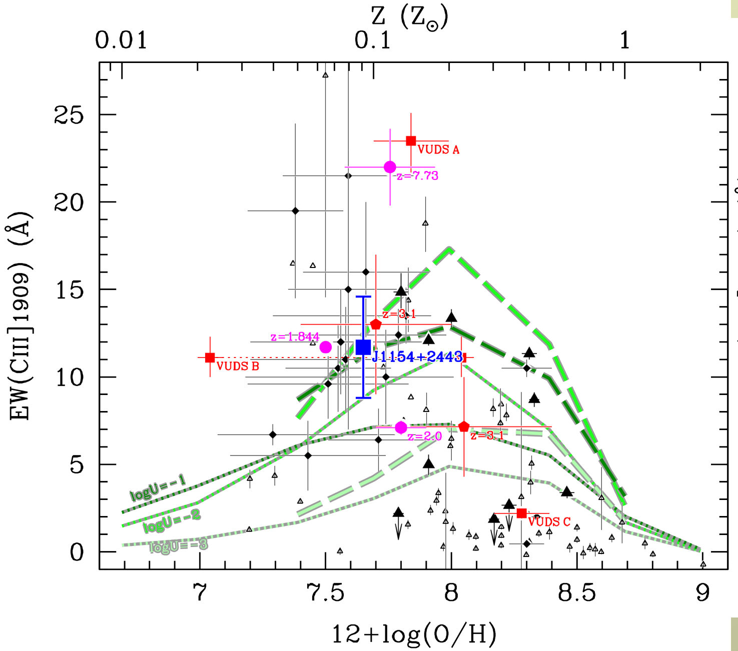


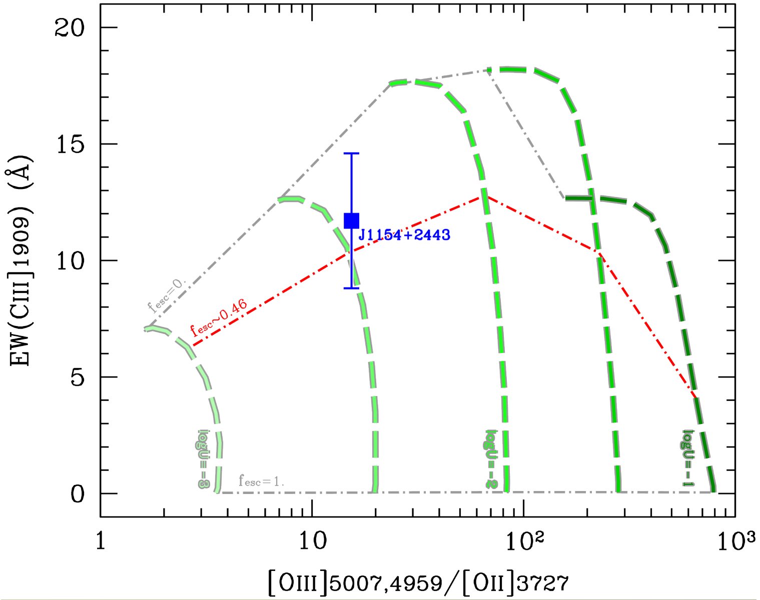


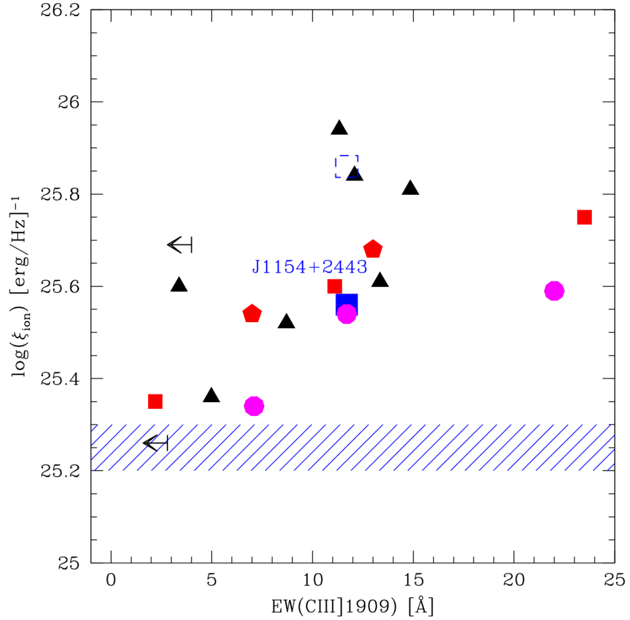
First « complete » UV spectrum of a strong low-z LyC leaker

Strong LyC emitter at z=0.349 – fesc=46%
→ Schaerer et al. (2018, A&A 616, L14)

- Strong CIII] 1909 emission found despite ~46% escape
- Compatible with photoionization models
- Possible correlation of ionizing photon production with EW(CIII])







LyC leakers at z=0.3: comparison with high-z galaxies

→ Schaerer et al. (2016, A&A 591, L8)

*Best **high-z** Lyman continuum source:*

z=3.218 galaxy « Ion2 »in GOODS-S/Candels

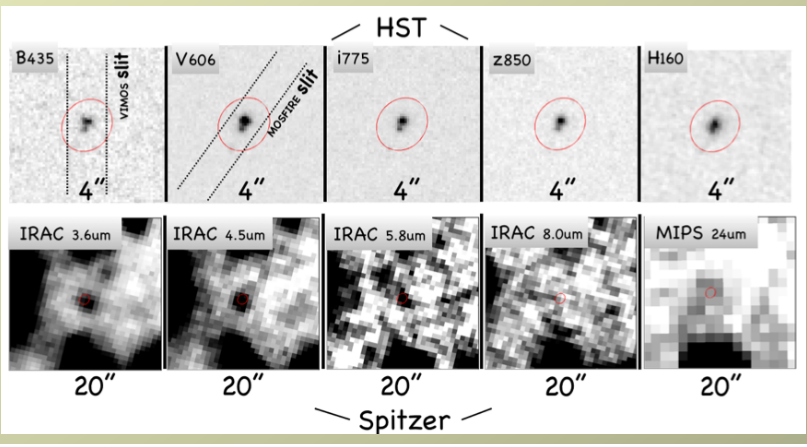
UV rest-frame mag_AB~24.5-25

→ Low metallicity (1/6 $Z_{\odot}$), ~low mass (1.6 10^9 $M_{\odot}$)

→ Strong Lya emission

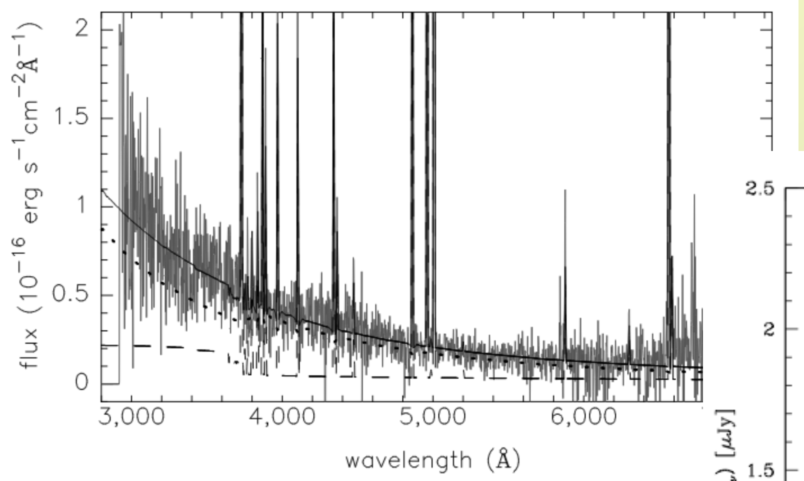
→ **High ratio [OIII]/[OII]>10, high [OIII]+Hb equivalent width (~1600 Ang)**

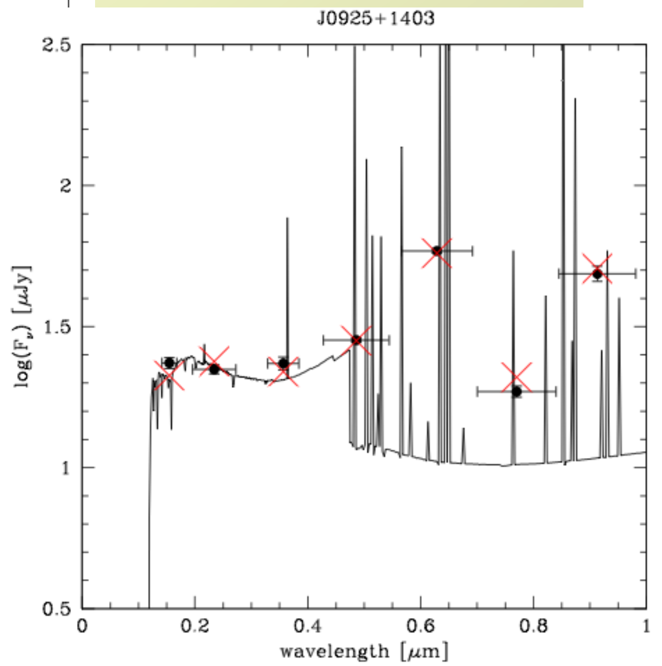
Vanzella et al. (2015), de Barros et al. (2016)

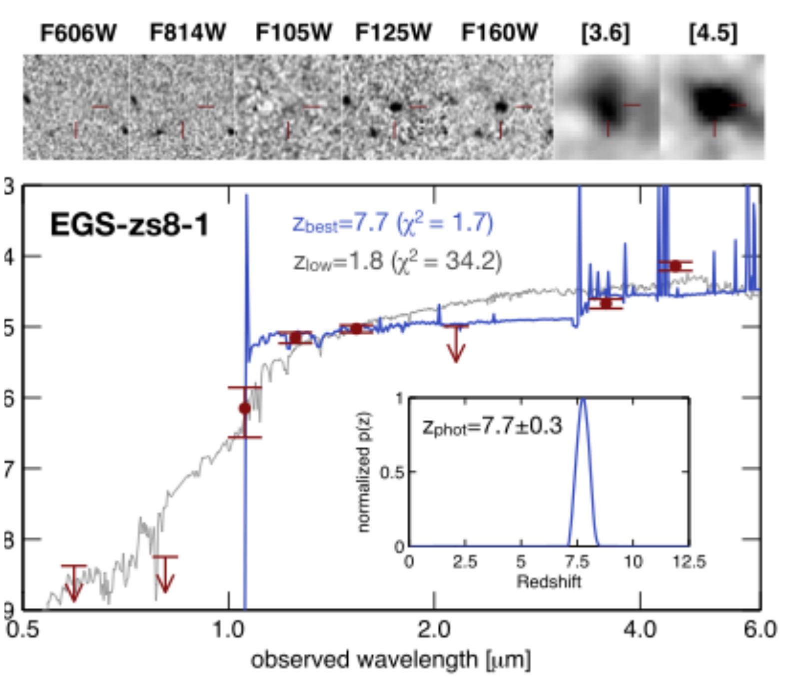


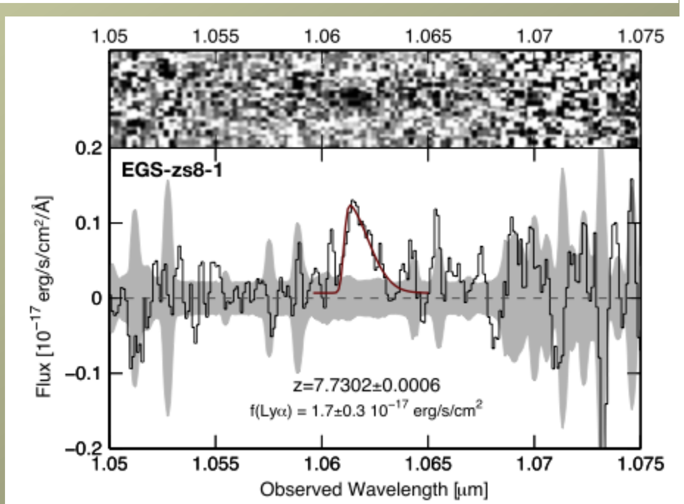
EL ratios, equivalent widths, stellar mass of our z~0.3 LyC leakers:
→ Comparable to Ion2

Strong Lyman continuum leakers at z~0.3
Comparison with high-z galaxies









High equivalent widths:

EW(Ha)=730 Å

EW([OIII]4959+5007)=1480

…

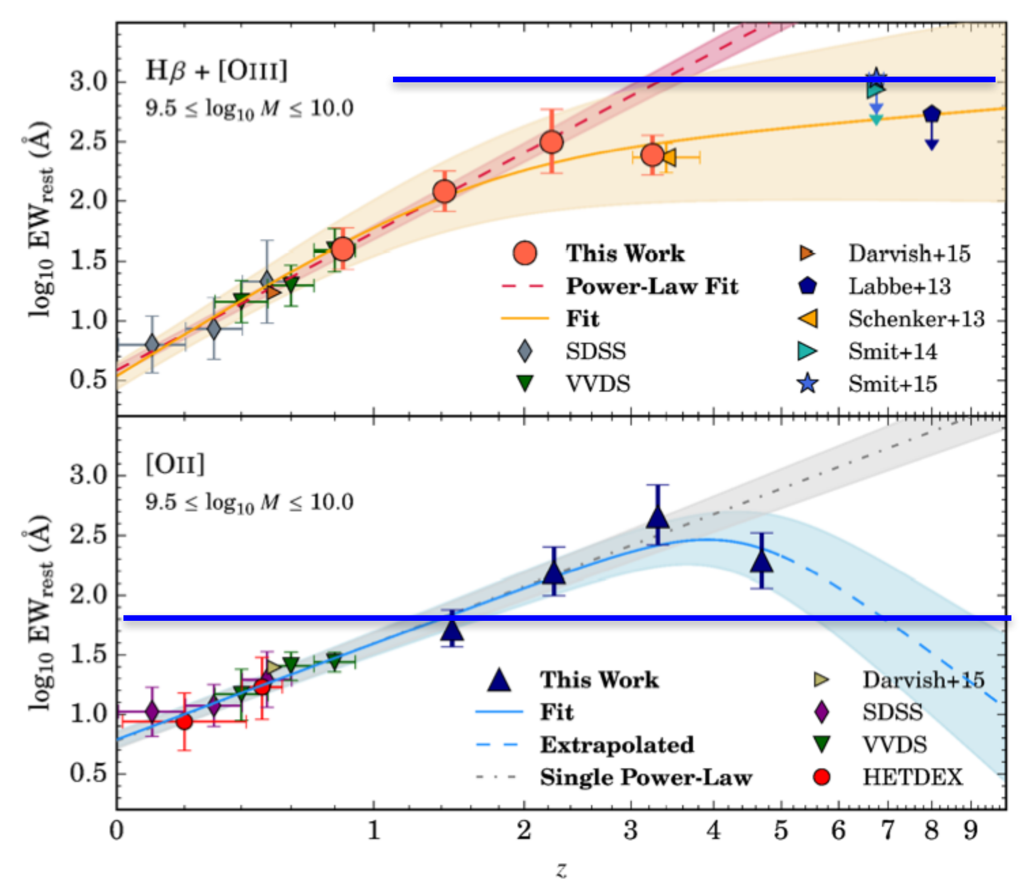
→ Comparable to high-z galaxies

Izotov et al. (2016)

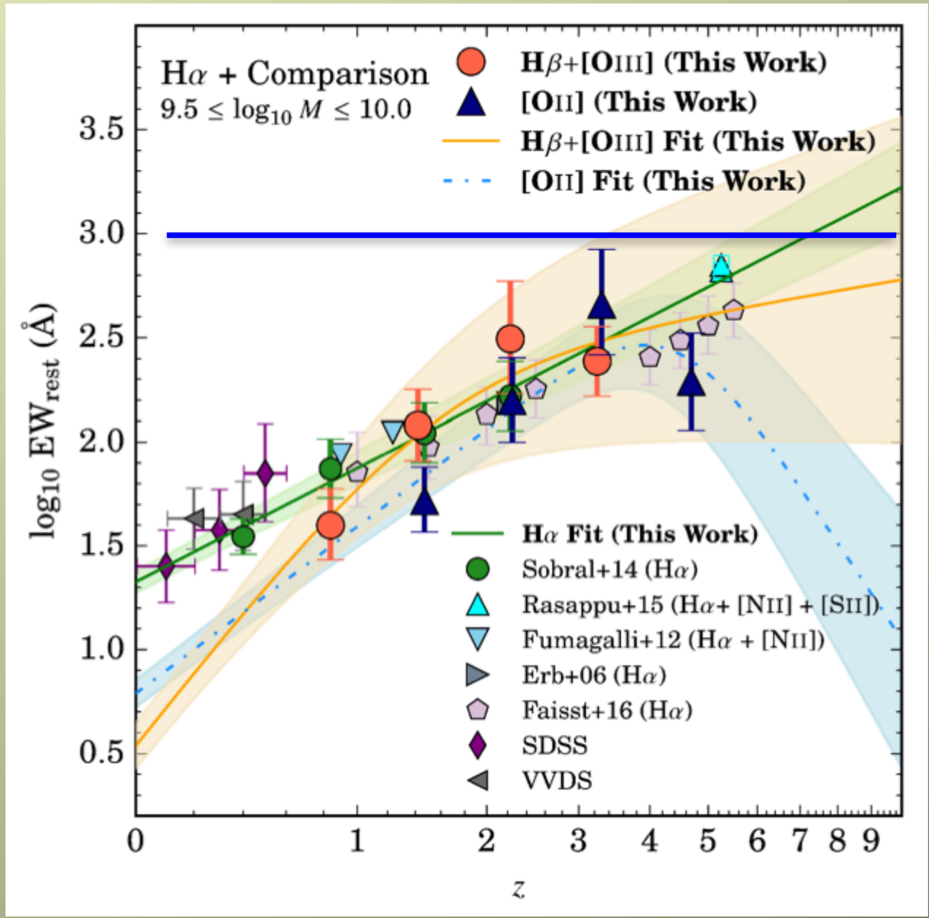
z=6.8: Schaerer et al. (2015)
Smit+ (2014)

Oesch et al. (2015) z=7.73

Strong Lyman continuum leakers at z~0.3
Comparison with high-z galaxies



Khostovan et al. (2016)



Properties of **rare** z~0.3 leakers are comparable to **typical** z~7 galaxies

Neutral gas properties of LyC emitting galaxies

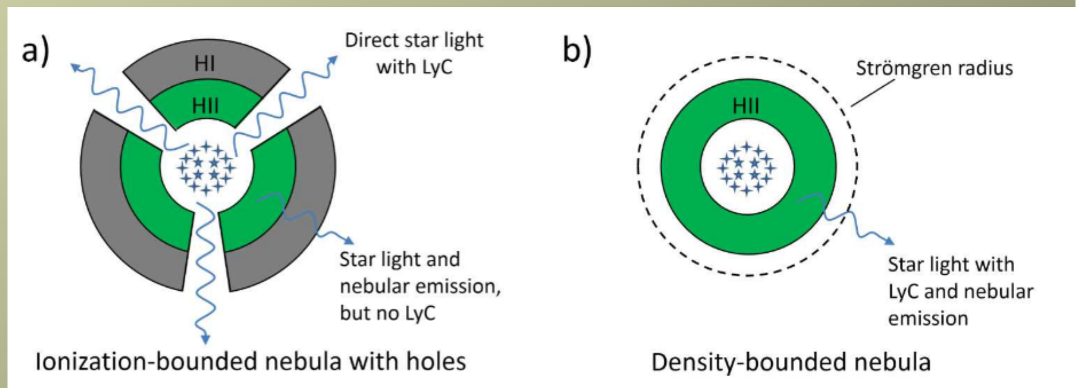
Analys of UV absorption lines (Lyman series, and metal lines) of known LyC leakers and comparison sources:

- 9 known LyC leakers (COS spectra, z~0-0.3)
- 6 other star-forming galaxies with COS Lyman-series coverage (z~0.1-0.3)
- High-res (R~3000-4000) rest–UV spectra of lensed galaxies at z~2-3 including ‘Cosmic Horseshoe’ (MEGASAURA, Rigby+ 2017)

==> Determination of ISM covering fraction, HI and OI column densities

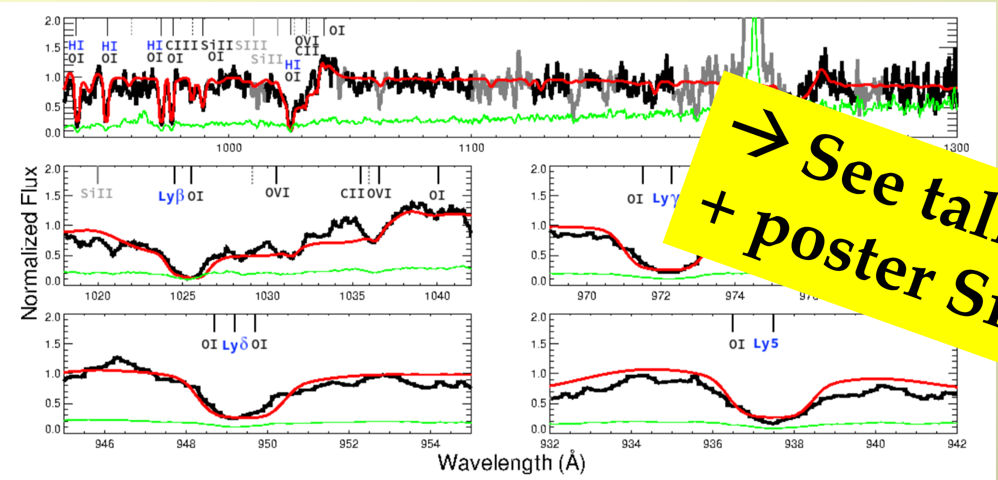
→ Also outflow properties

→ Gazagnes et al. (2018), Chisholm et al. (2017, 2018)



INDIRECT methods to identify Lyman continuum emitters

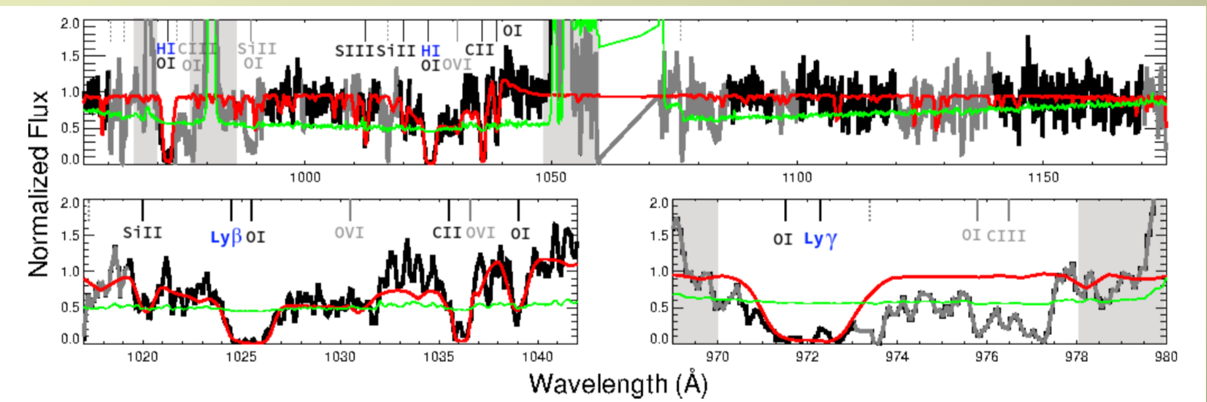
→ **UV absorption lines – Lyman series and SiII 1190, 1260 Å – can be used to infer LyC escape fraction indirectly** (Gazagnes+ 2018, Chisholm+ 2018)



Consistent modeling of continuum + lines + geometry UV attenuation needed to determine fesc from LIS lines !

(Izotov

→ **See talk from John Chisholm + poster Simon Gazagnes**



GP 1244+0216
(Henry+ 2015)

Comparison with other studies

z~3.5 SFGs with strong [OIII} emission +deep U image
Stacking of ~50-74 sources (Naindu et al. 2018):

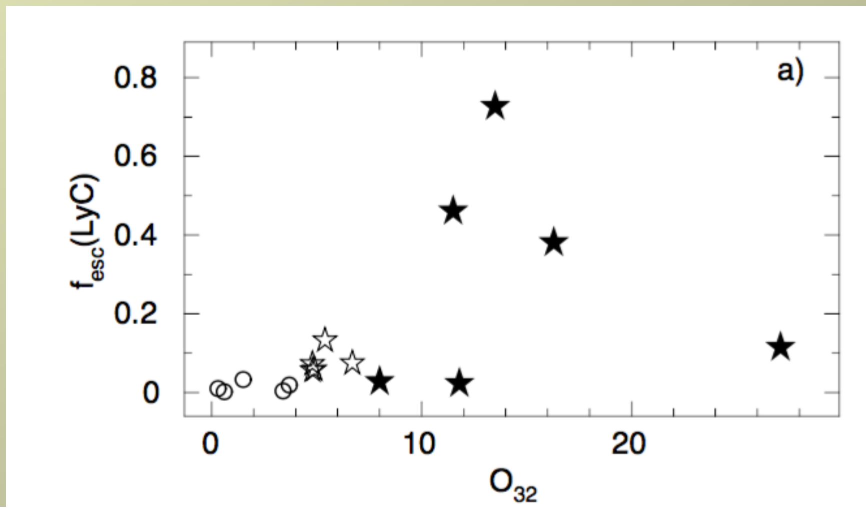
- 1 sigma limit fesc<8.2 % for « strong » emitters
- [OIII]/[OII]~4.3 (no extinction correction)

→ [OIII]/[OII] not a good LyC tracer

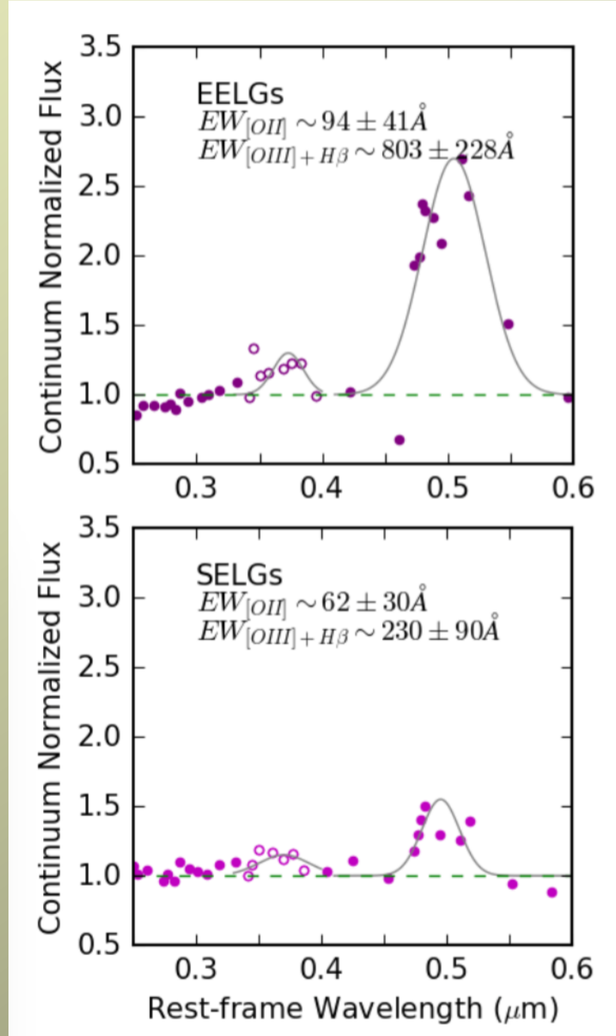
Izotov+ leakers:

- All strong leakers have [OIII]/[OII]>4
- Much stronger ELs ! EW(5007)~1400-2100 A

→ Not incompatible with Naindu+



Izotov et al. (2018)



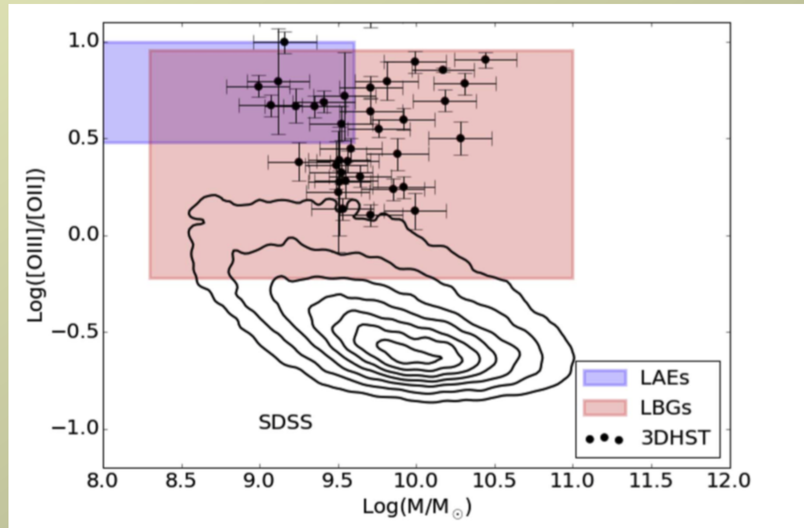
Naindu et al. (2018)

Comparison with other studies

z~2.5 emission-line selected galaxies (HST grism + UV images)
Stacking analysis, Rutkowksi et al. 2017:

- All sources (208): fesc<5.6%
- [OIII]/[OII]>5: fesc<14%
- Observations ***not deep enough*** to
  * detect fesc=10% Izotov-sources
  * detect Ion2

Rutkowksi et al. (2017)

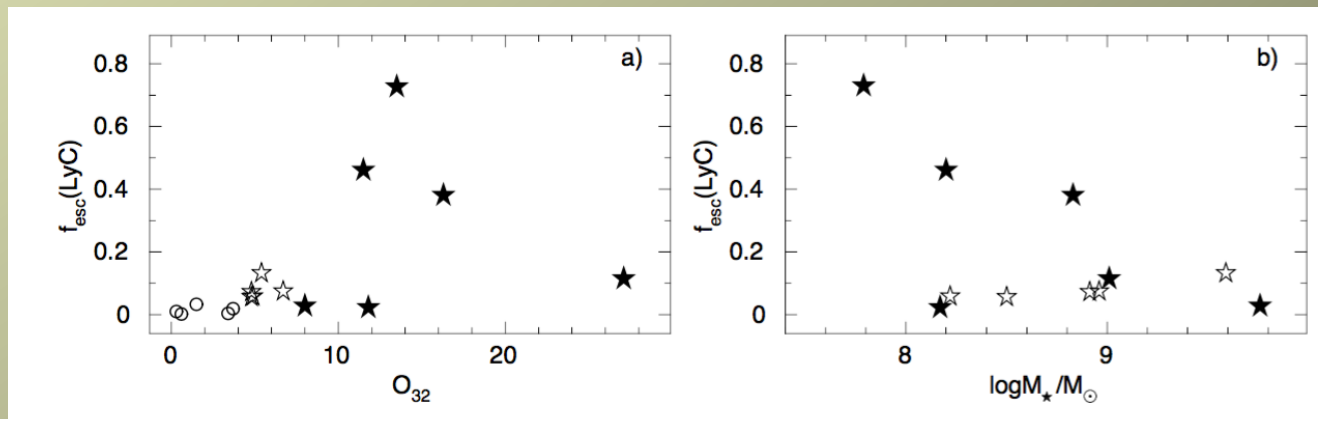


Izotov+ leakers:

- Stellar masses lower
- fesc(LyC) higher in low-M* galaxies ?

→ **Not incompatible with Rutkowski+**

Izotov et al. (2018)



Conclusions

- **Significant recent progress in identifying LyC emitters at high-z**
  - New and robust leakers identified with different methods
  - Increasing fesc(LyC) with increasing EW(Lya)
- **Strong Lyman continuum emitters found at z~0.3:**
  - Compact, young, low mass, low metallicity galaxies with high SFR/surface
  - Best analogs of the sources of cosmic reionisation
  - High [OIII]/[OII] + compactness: efficient selection
- **Demonstrated three INDIRECT probes of LyC escape**:
  - Narrow, double peaked Lyman-alpha profiles
  - Very high [OIII]/[OII] ratio
  - UV absorption lines (low UV coverage)
- **High- and low-z results consistent**