New detection of Lyman continuum leaking galaxies at low redshift and comparison with high-z star-forming galaxies

Daniel Schaerer (Geneva Observatory, CNRS)

- *Overview - methods to identify the sources of reionisation*
- *A strong Lyman continuum leaker at z=0.3*
- *Comparison with high-z galaxies*
- *Conclusions*

→ Izotov, Orlitova, Schaerer, Thuan, Verhamme, Guseva 2016, Nature (14 jan 2016)

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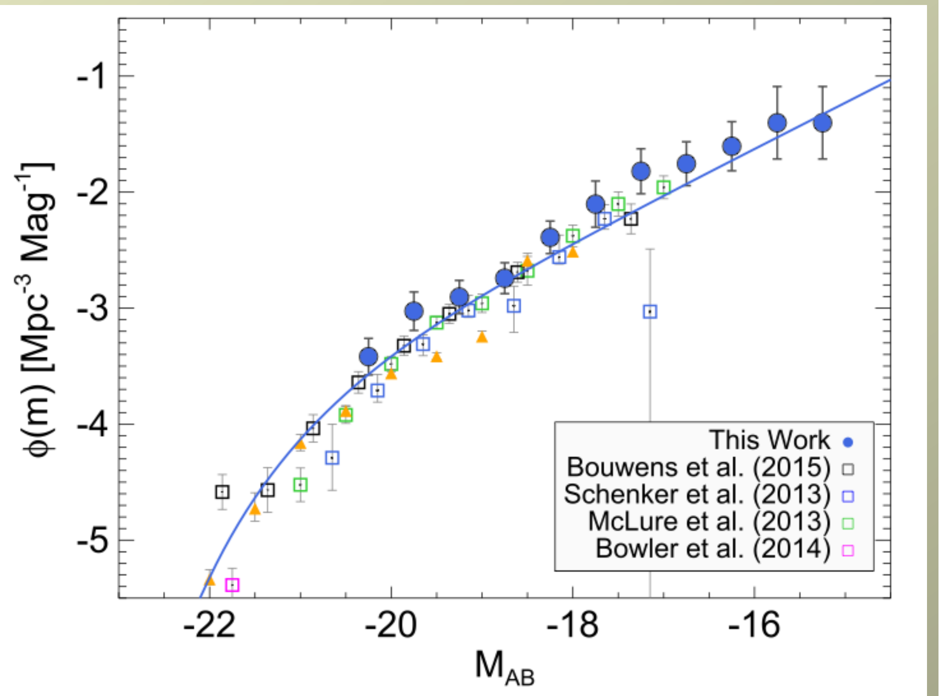
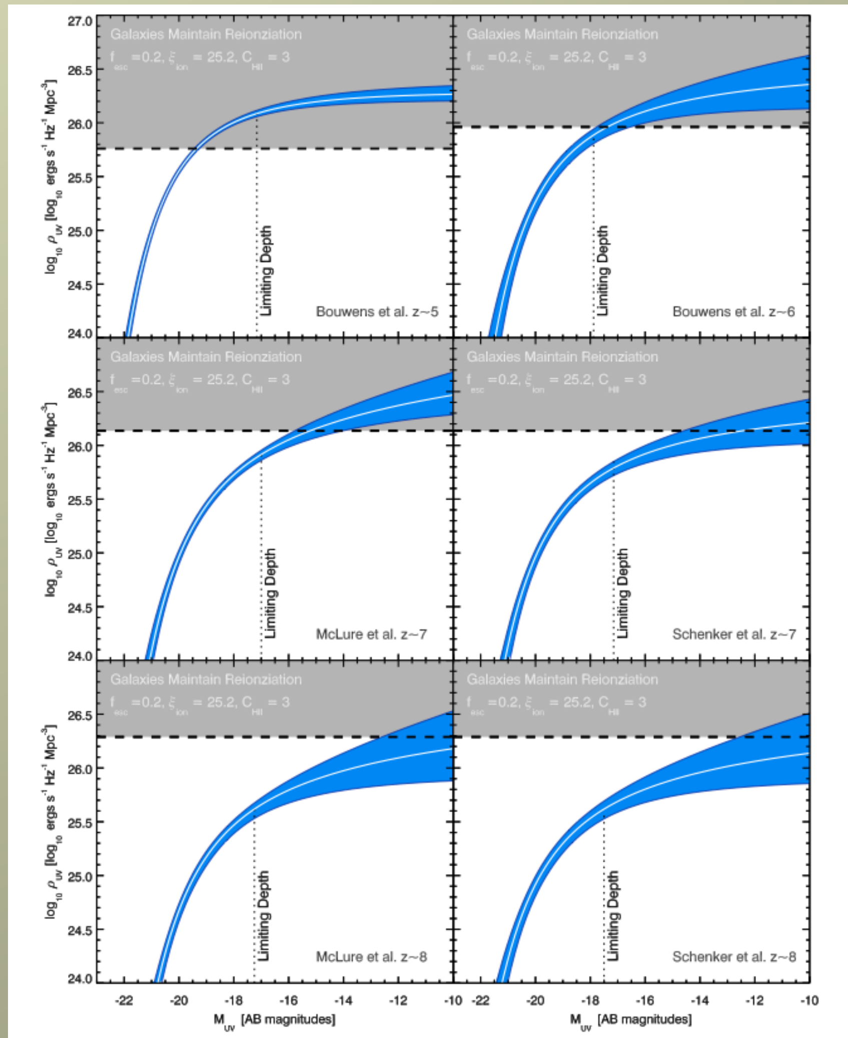
irap astrophysique & planétologie

The quest for the sources of cosmic reionisation

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



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



Robertson et al. (2013)

The quest for the sources of cosmic reionisation

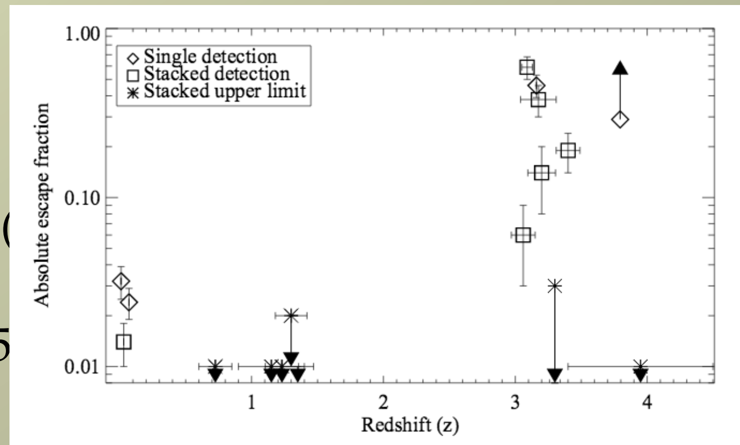
- Faint, low mass galaxies thought to be main contributors to cosmic reionization

- Numerous searches for « Lyman continuum leakage » from star-forming galaxies at low and high-z
  → **sources elusive, so far!**

→ **New strategies needed**
  - → **How to identity and find the sources of reionisation?**
  - → **Study their properties**

The quest for the sources of cosmic reionisation

Criteria to identify Lyman continuum emission



Bergvall+ 2013

DIRECT:

- Imaging or spectroscopy across the Lyman break (
  Many searches/surveys → very few candidates
  (cf. Malkan+, Steidel+, Cowie+ …, Siana et al. 2015
  al. 2015)

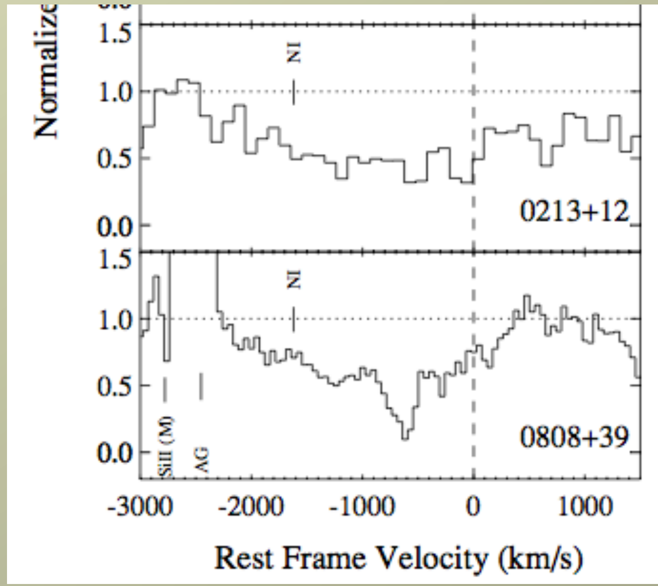
INDIRECT:

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

The quest for the sources of cosmic reionisation

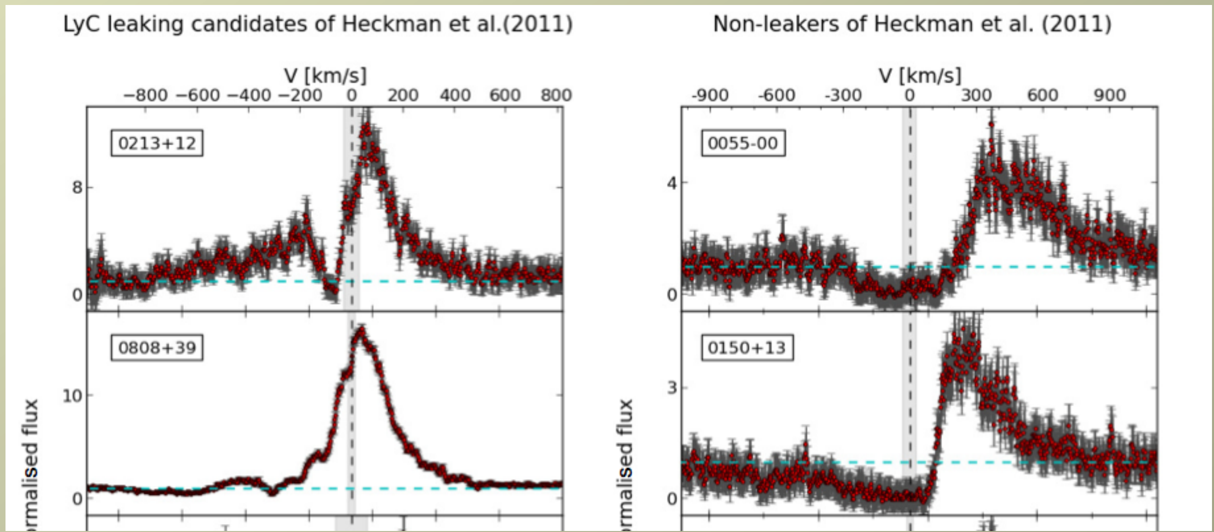
1. UV **low ionisation absorption lines**
→ *low covering factor of the UV continuum* source
(Heckman et al. 2011, Alexandroff et al. 2015)

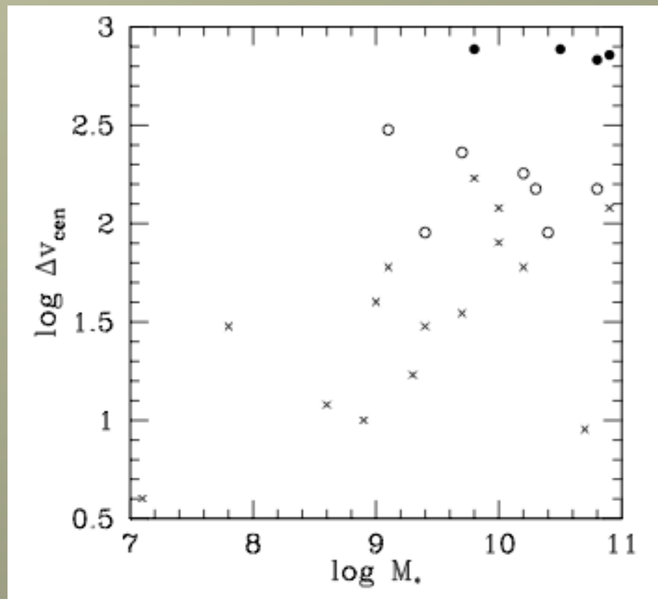
➔ Leakage from Lyman break analogs with dominant central objects ?!



Heckman et al. (2011)

Lyman-alpha line profiles (cf. Verhamme et al. 2015)

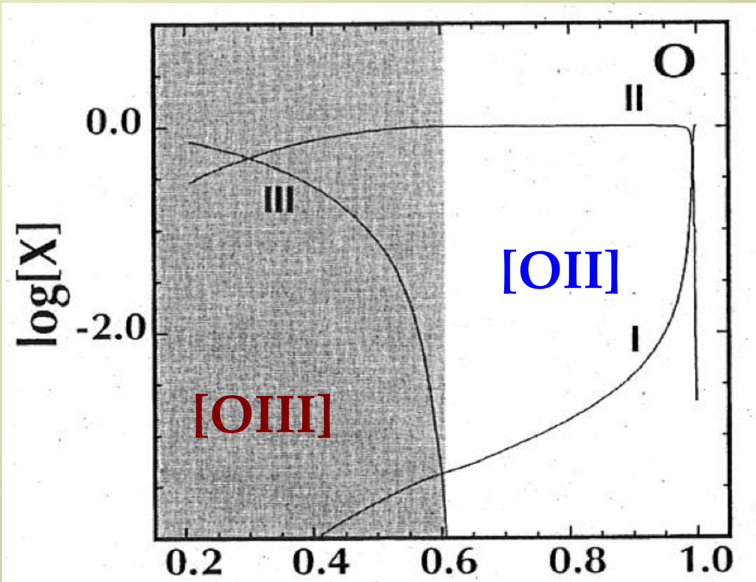




The quest for the sources of cosmic reionisation

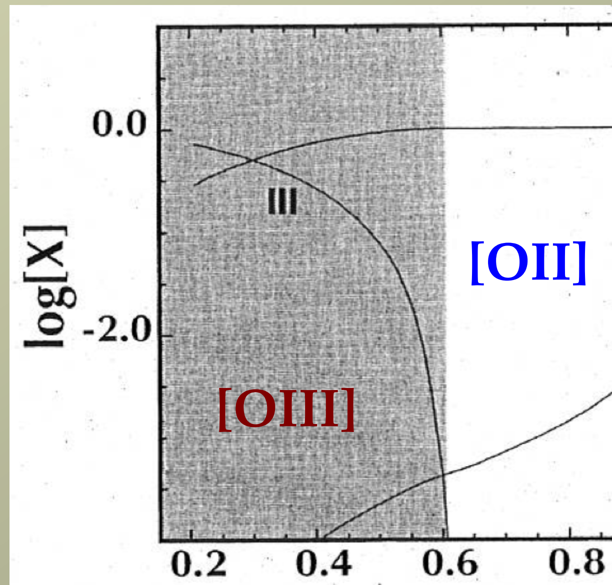
Indirect diagnostics for optical depth of Lyman continuum radiation:

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



Strömgren radius ↑

« Normal » ionisation-bounded HII region



[OII] missing

Strömgren radius ↑

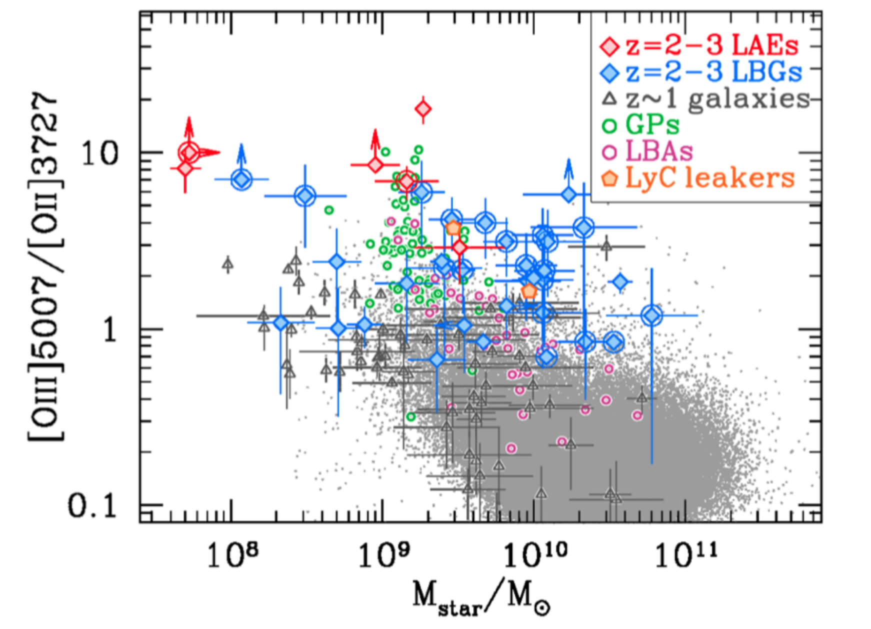
Density-bounded HII region

Nakajima & Ouchi (2014)

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

The quest for the sources of cosmic reionisation

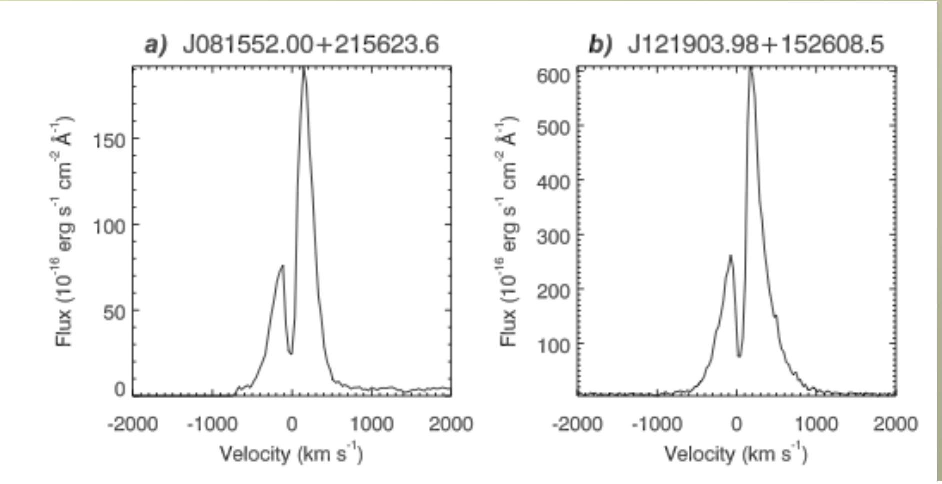
Nakajima & Ouchi (2014)



2. High [OIII]/[OII] ratio
→ *density bounded HII regions*

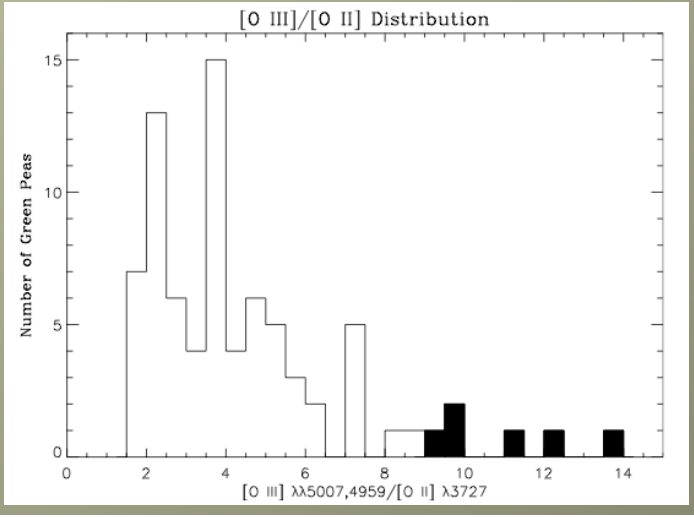
→ Found in « green pea » galaxies

Cardamone et al. (2009), Izotov et al. (2011), Amorin et al. (2012), …



Jaskot & Oey (2013, 2014)

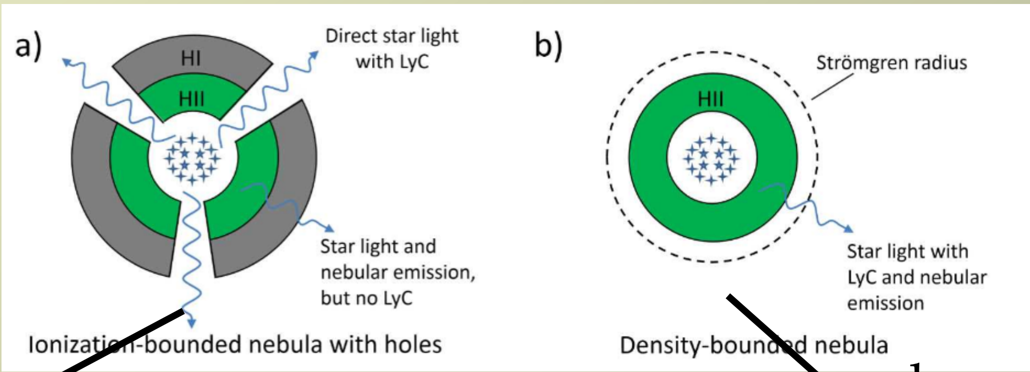
Cf. Henry+ (2015)



The quest for the sources of cosmic reionisation

3. New (indirect) indicator the Lyman continuum escape:

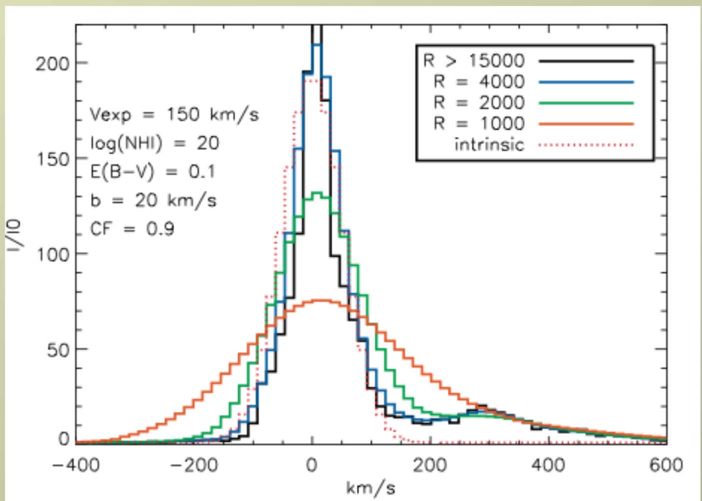
narrow Lya line profile, small separation of peaks

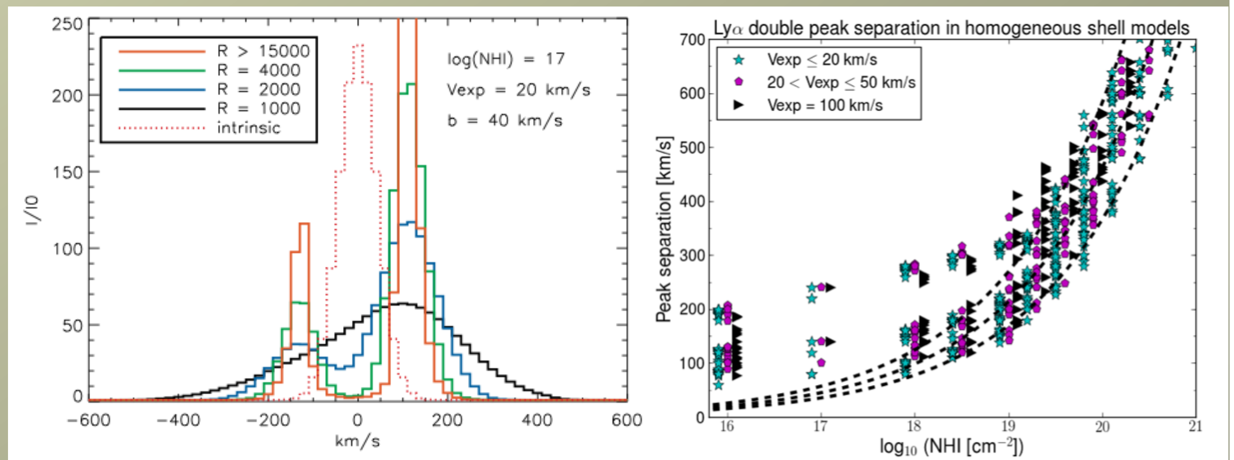


Zackrisson et al. (2013)

clumpy ISM

homogeneous medium or
large covering fraction





Verhamme et al. (2015)

The quest for the sources of cosmic reionisation

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

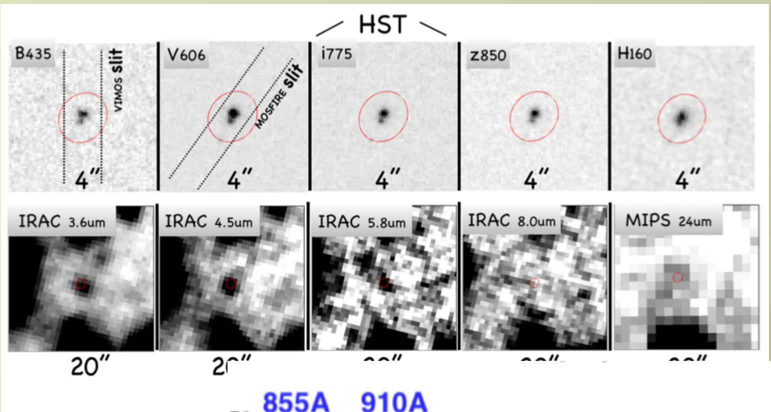
z=3.218 galaxy « Ion2 »in GOODS-S/Candels

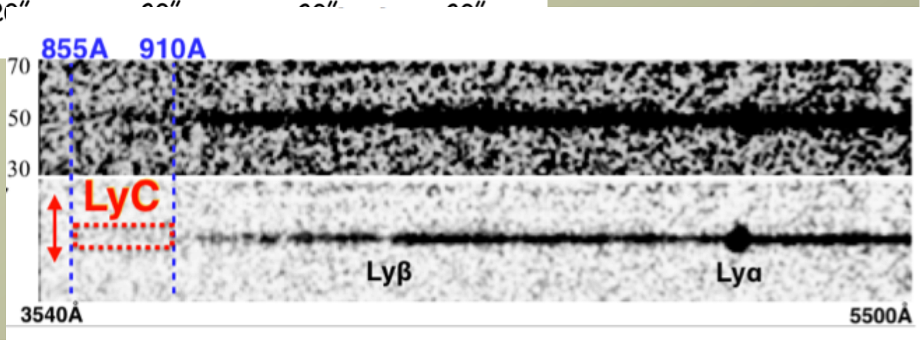
UV rest-frame mag_AB~24.5-25

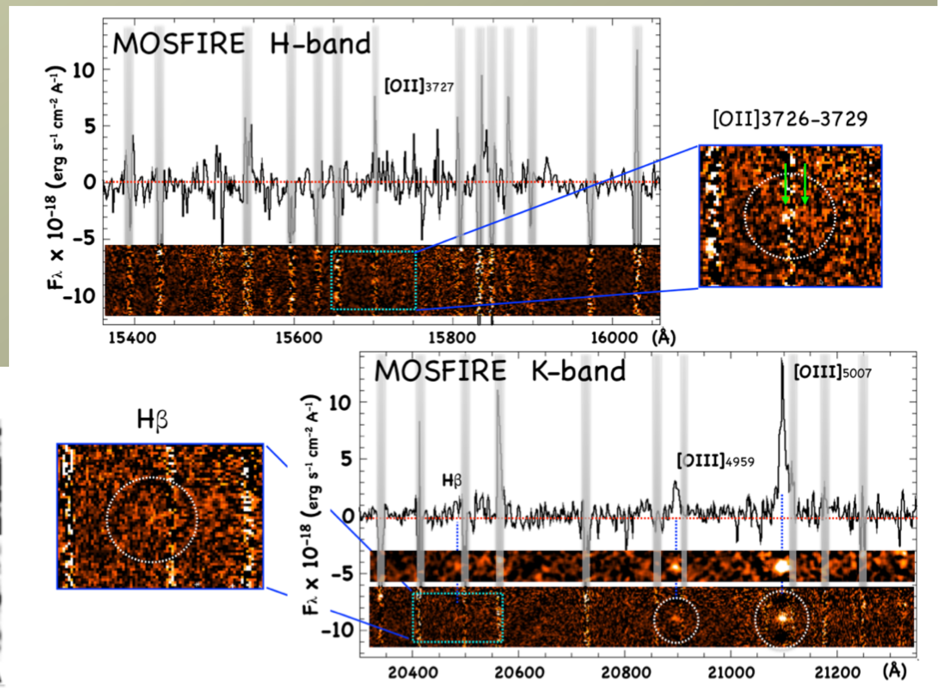
→ Low metallicity (1/6 $Z_{\odot}$), ~low mass (1.6 10^9 $M_{\odot}$)

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

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







The quest for the sources of cosmic reionisation

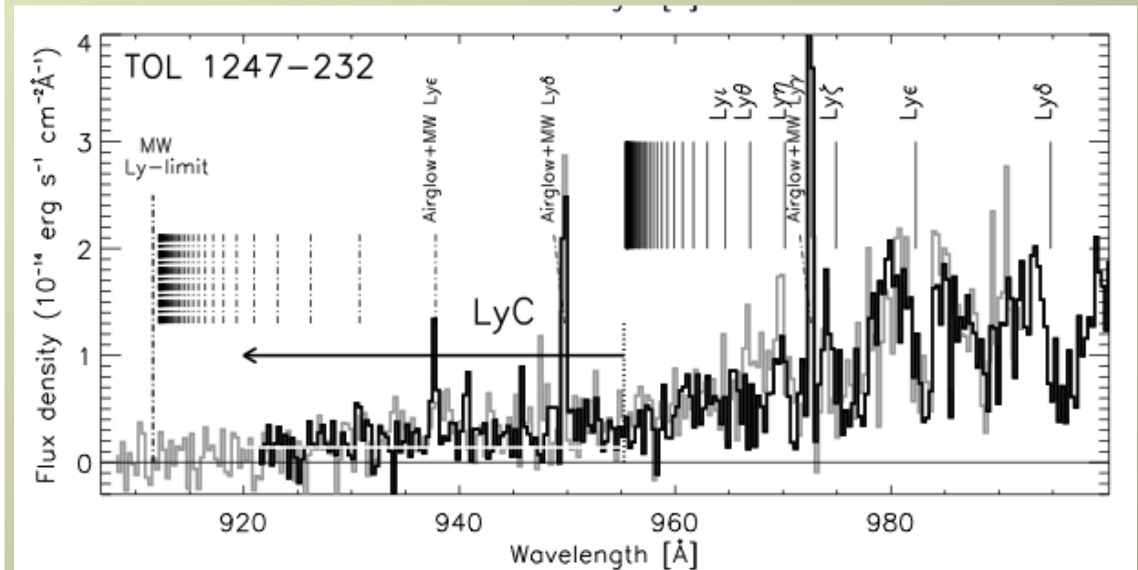
*Best **low-z** Lyman continuum sources:*

FUSE observations: HII/dwarf galaxy Tol 1247-232 - Leitet al. (2013)

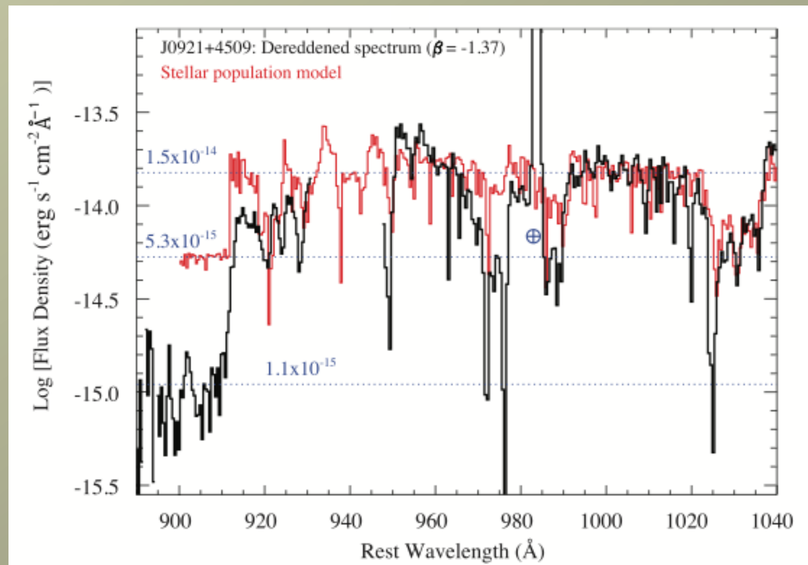
fesc=2.4%

COS/HST: compact Lyman break analog at z=0.2 -- Borthakur et al. (2014)

fesc=1%



Leitet al. (2013)



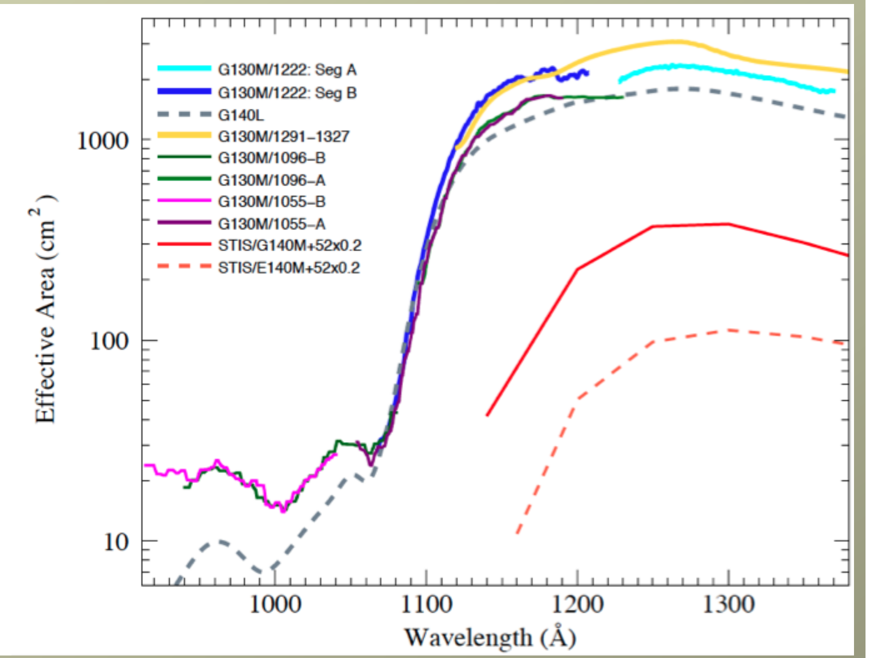
Borthakur et al. (2014)

The quest for the sources of cosmic reionisation

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

Cycle 22 - 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

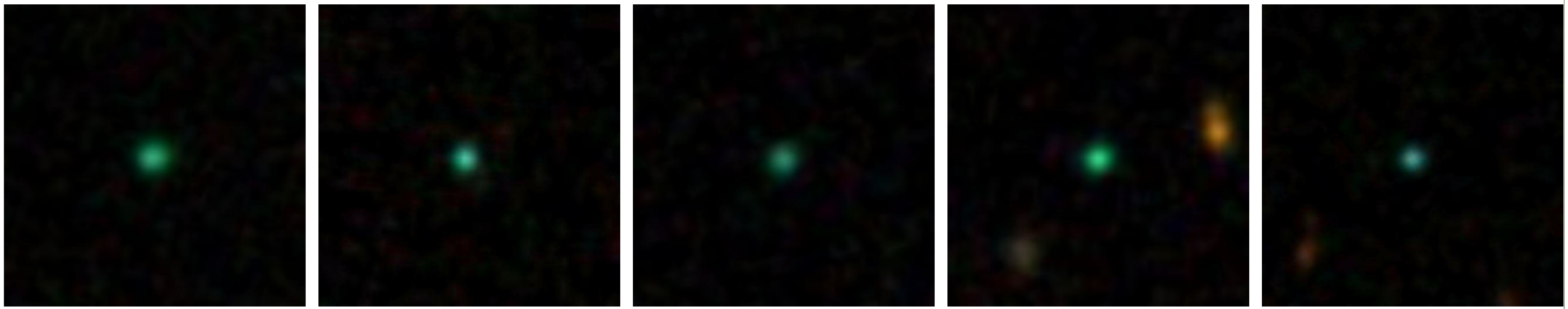
→ 5 galaxies selected

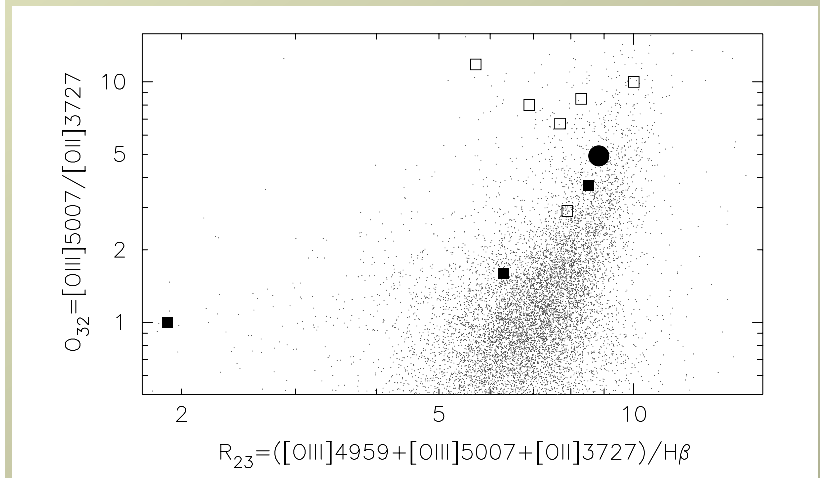
G140M, G160M grism observations to cover:

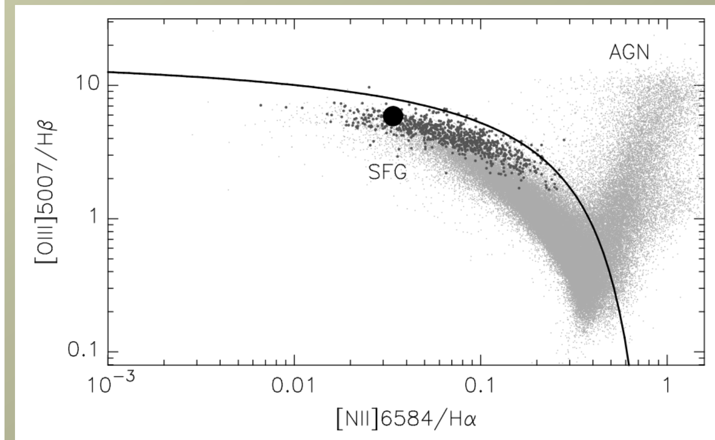
- Lyman continuum
- Lyman alpha
- UV absorption lines

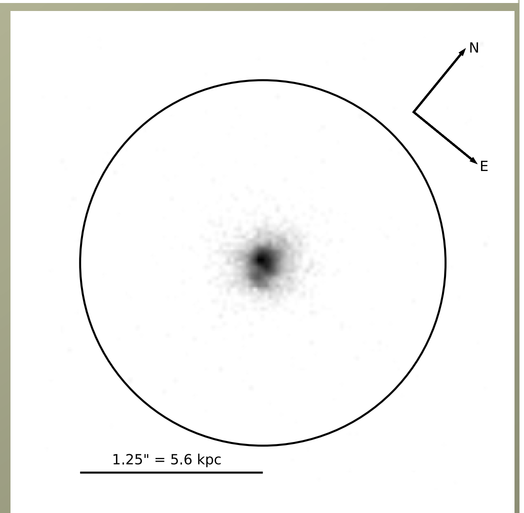
The quest for the sources of cosmic reionisation

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









A strong Lyman continuum leaker at z=0.3

Izotov, Orlitova, Schaerer, Thuan, Verhamme, Guseva, Worseck (2015)

Nature, 2015 ← today

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]

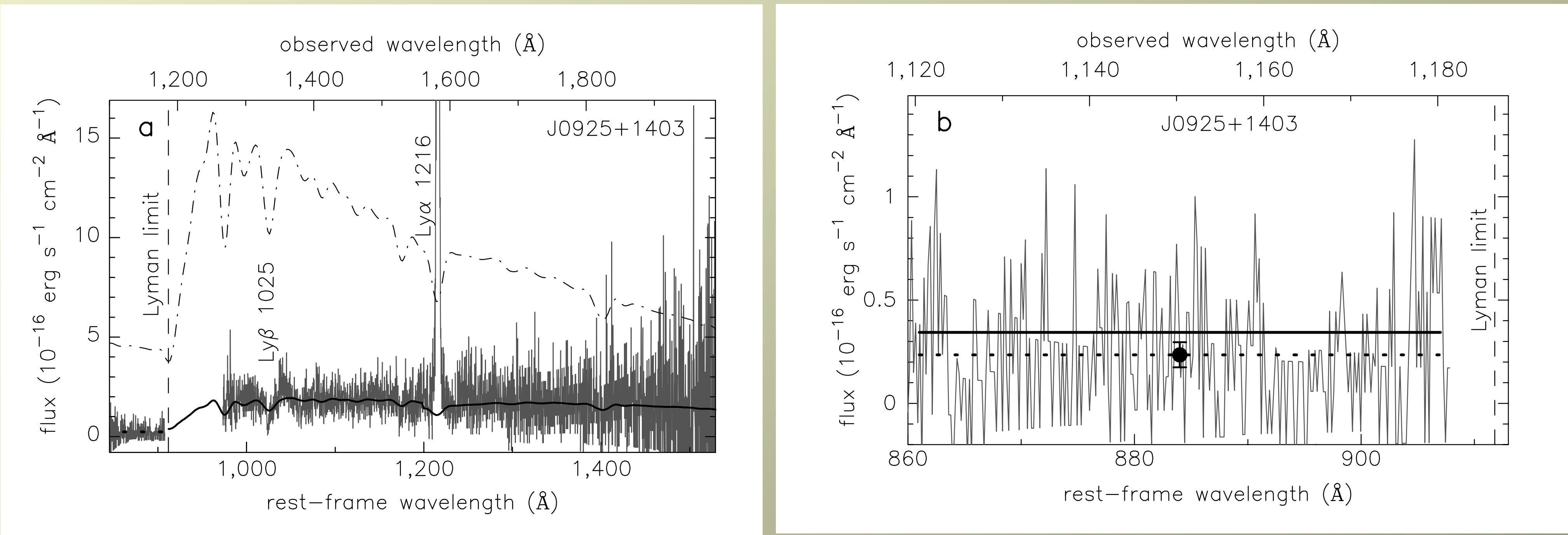
One of the key questions in observational cosmology is the identification of the sources responsible for ionization of the Universe after the cosmic 'Dark Ages', when the baryonic matter was neutral. The currently identified distant galaxies are insufficient to fully reionize the Universe by redshift $z \approx 6$ (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

A strong Lyman continuum leaker at z=0.3

New COS-HST program: *measure Lyman continuum and test indirect indicators*
Izotov, Orlitova, Schaerer, Thuan, Verhamme, Guseva, Worseck (2015)

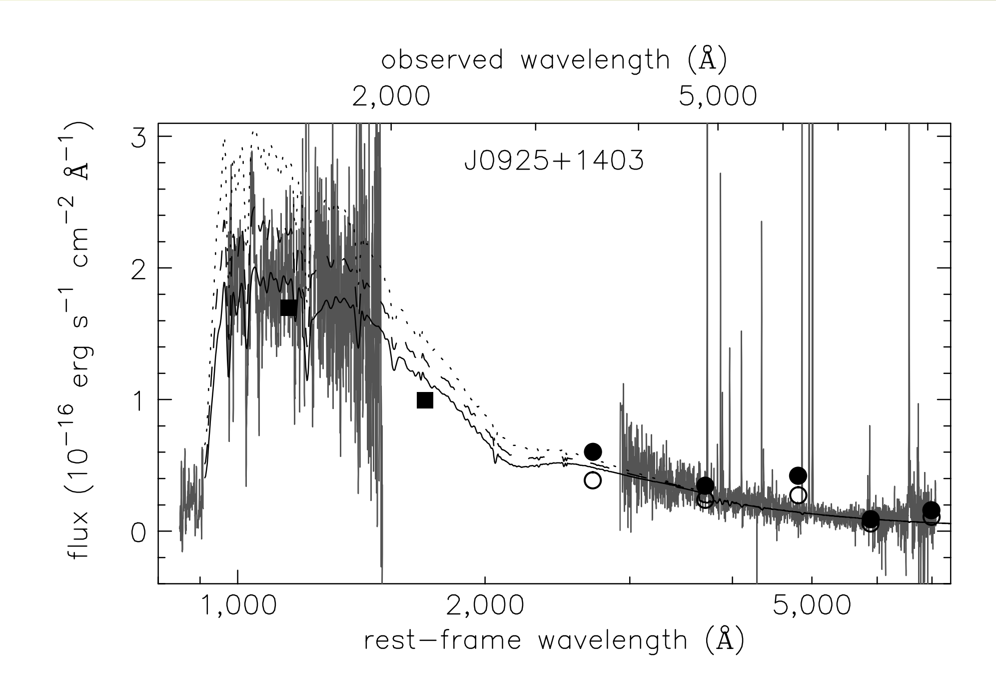


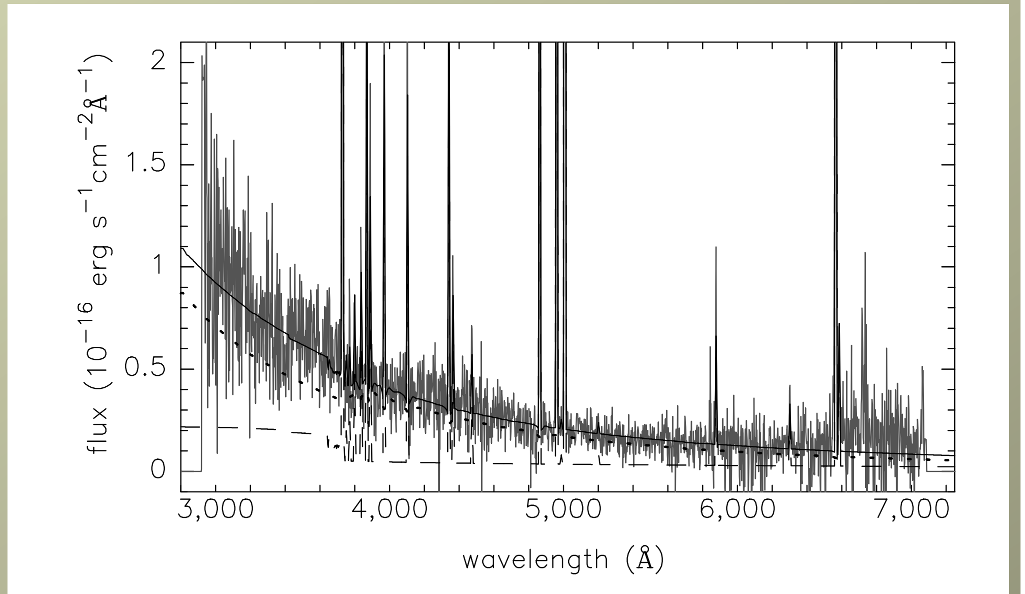
✔ Lyman continuum leakage

- 11.8 sigma detection $(3.43\pm0.29)\times10^{-17}$ erg s^{-1} cm^{-2} Å^{-1}
- Absolute fesc=7.8±1.1 % (highest so far at low redshift)

A strong Lyman continuum leaker at z=0.3

New COS-HST program: *measure Lyman continuum and test indirect indicators*
Izotov, Orlitova, Schaerer, Thuan, Verhamme, Guseva, Worseck (2015)

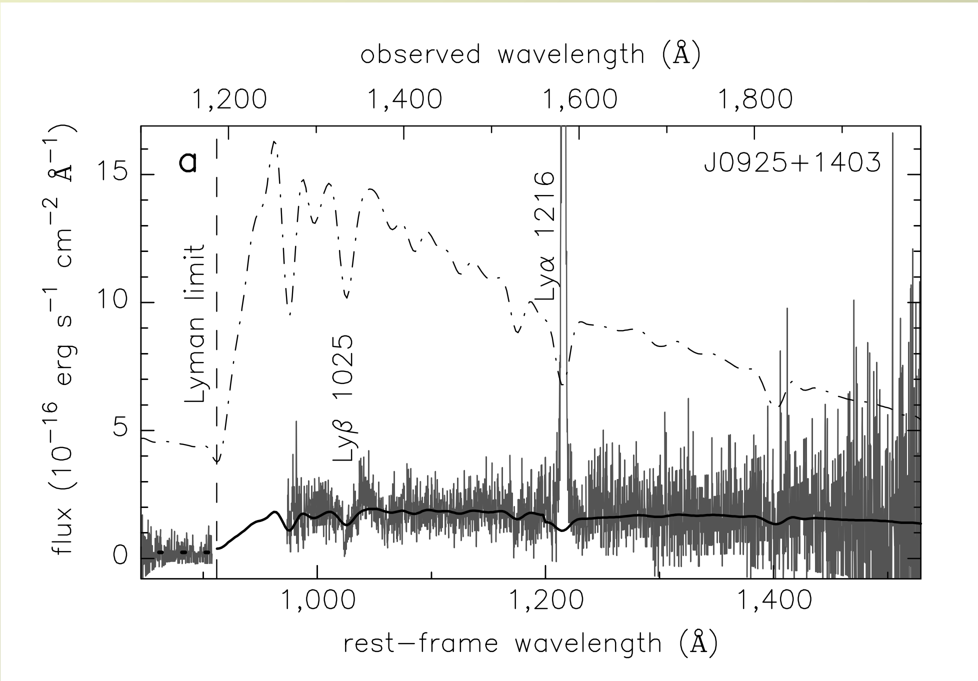


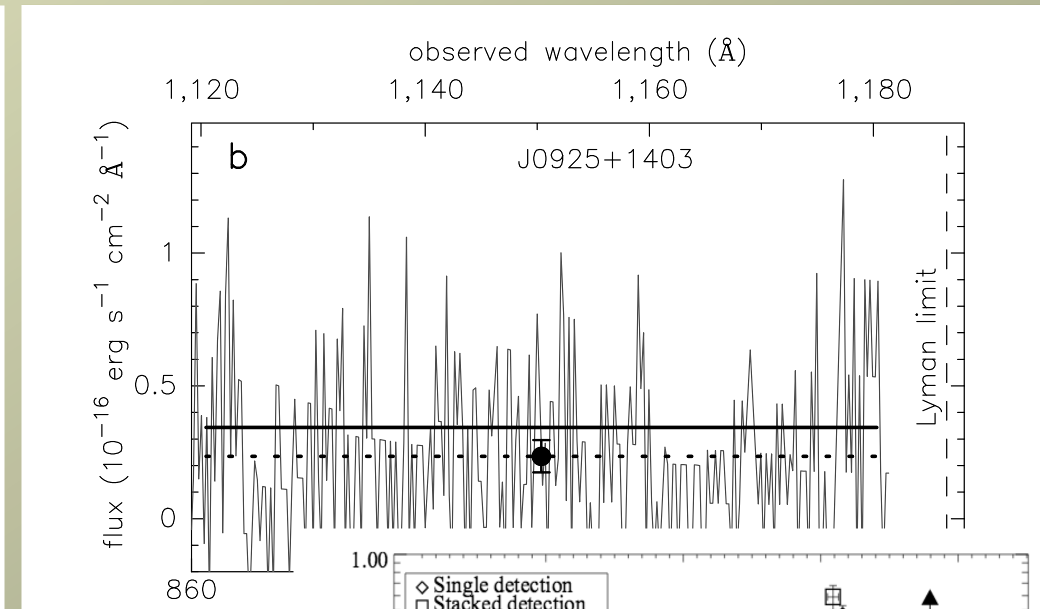


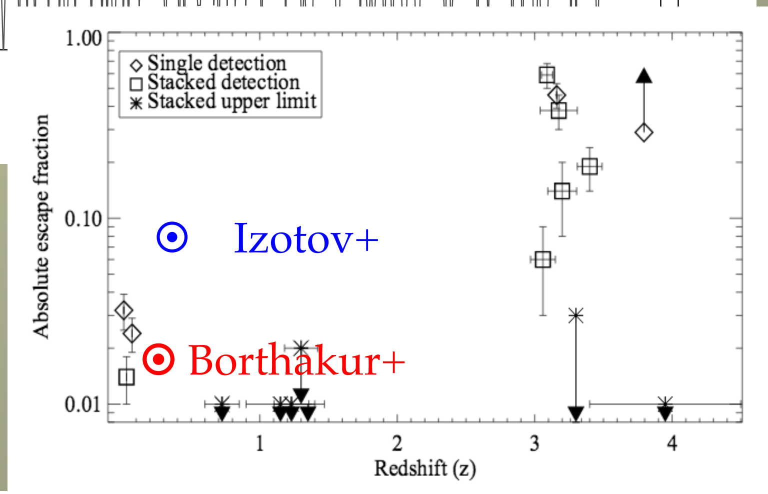
→ **Low extinction**: A_V=0.36-0.38
→ **Metallicity** ~1/5 solar (12+logO/H=7.91+-0.03)
→ Fit of global spectrum → intrinsic UV/Lyman continuum emission

A strong Lyman continuum leaker at z=0.3

New COS-HST program: *measure Lyman continuum and test indirect indicators*
Izotov, Orlitova, Schaerer, Thuan, Verhamme, Guseva, Worseck (2015)



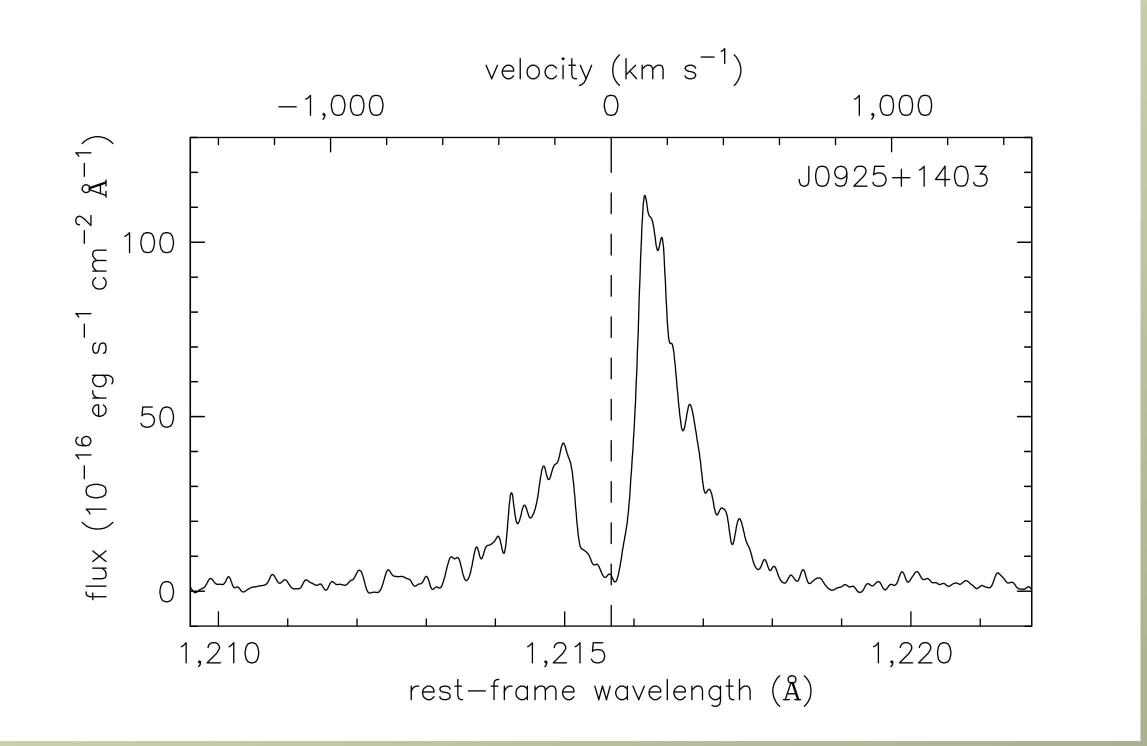




* From intrinsic Lyman continuum emission
→ **Absolute fesc=7.8±1.1 %** (relative fesc=23.6%)
* Intrinsic LyC emission also from H recombination lines

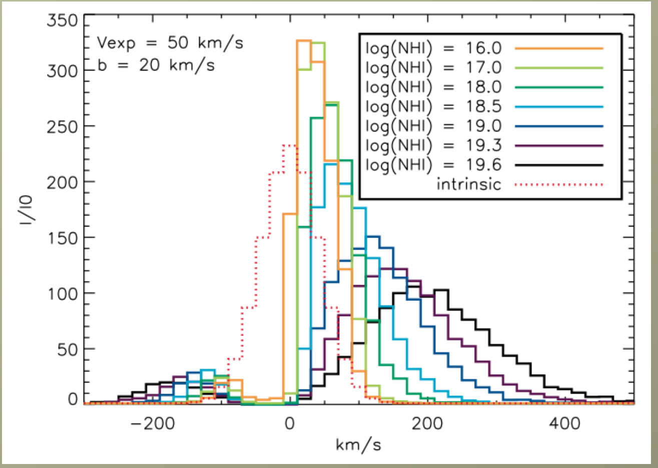
A strong Lyman continuum leaker at z=0.3

New COS-HST program: *measure Lyman continuum and test indirect indicators*
Izotov, Orlitova, Schaerer, Thuan, Verhamme, Guseva, Worseck (2015)



✔ Narrow Lya profile
as predicted by radiation transfer models

Peak separation 300 km/s
→ log(NHI)<~10^19 cm-2



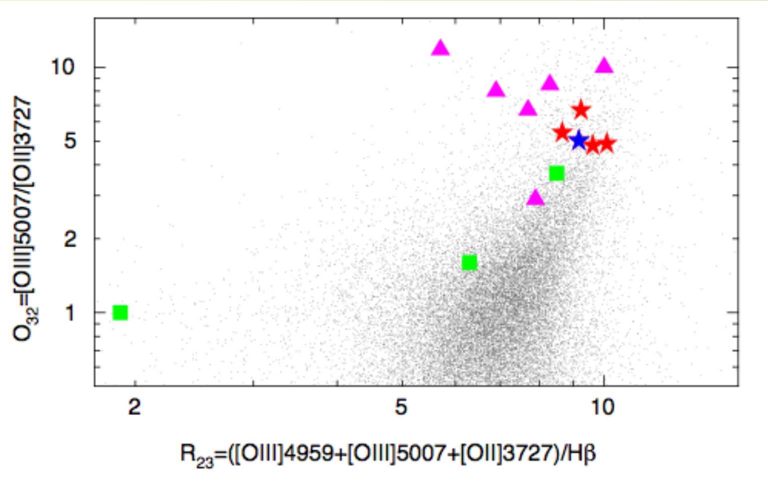
Also: high Lya escape fraction (70%)

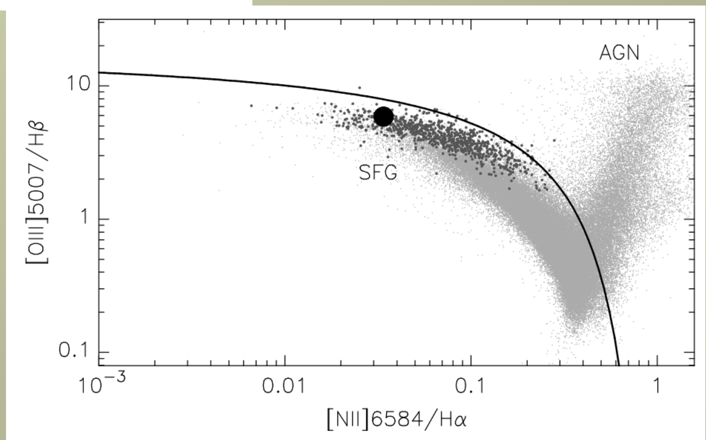
Verhamme et al. (2015)

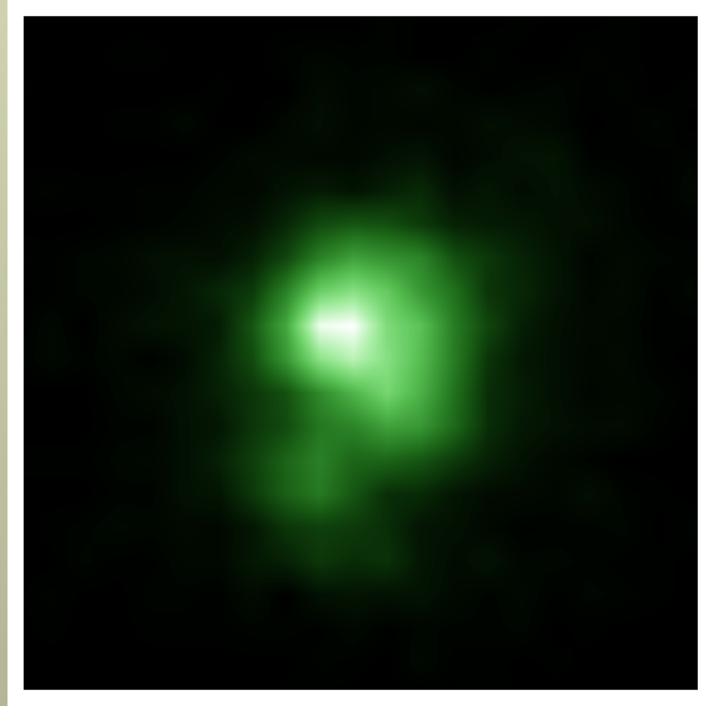
A strong Lyman continuum leaker at z=0.3

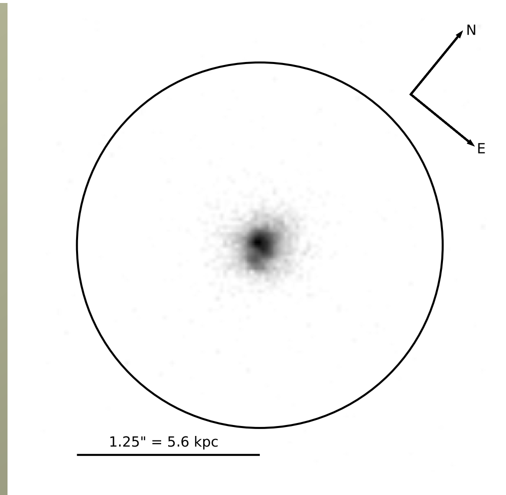
J0925 other properties:

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





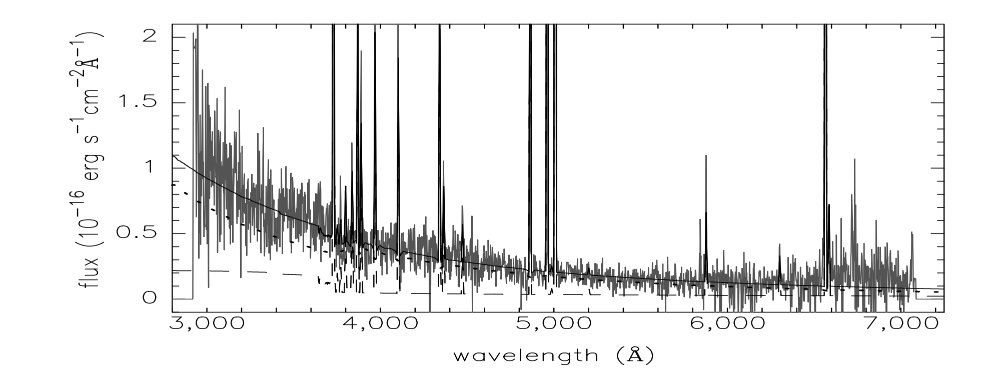


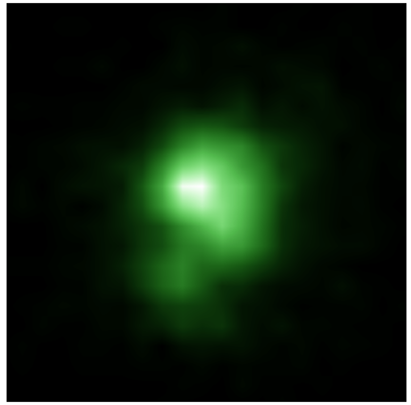


Izotov et al. (2016)

A strong Lyman continuum leaker at z=0.3

J0925+1403 other properties





Extended Data Table 1 | Emission-line fluxes and equivalent widths in the optical spectrum

Line	Wavelength (Å)	100×*I*(λ)/*I*(Hβ)†	EW(Hβ) (Å)
[OII]	3727	125.5 ± 4.6	77
H9	3835	9.1 ± 2.0	7
[NeIII]	3868	47.5 ± 1.9	33
HeI+H8	3889	17.1 ± 2.3	12
[NeIII]+H7	3968	32.0 ± 2.6	22
Hδ	4101	28.7 ± 2.3	22
Hγ	4340	43.7 ± 2.5	36
[OIII]	4363	11.7 ± 0.6	10
HeI	4471	6.1 ± 0.5	6
Hβ	4861	100.0 ± 3.6	177
[OIII]	4959	199.9 ± 6.7	306
[OIII]	5007	608.1 ± 20.	1174
HeI	5876	11.3 ± 0.7	11
[OI]	6300	4.6 ± 0.5	11
Hα	6563	280.2 ± 9.9	732
[NII]	6584	13.2 ± 0.8	26

†Extinction-corrected flux relative to the extinction-corrected flux *I*(Hβ) = 4.92 × 10^{-15} erg s^{-1} cm^{-2} of the Hβ emission line, multiplied by 100.

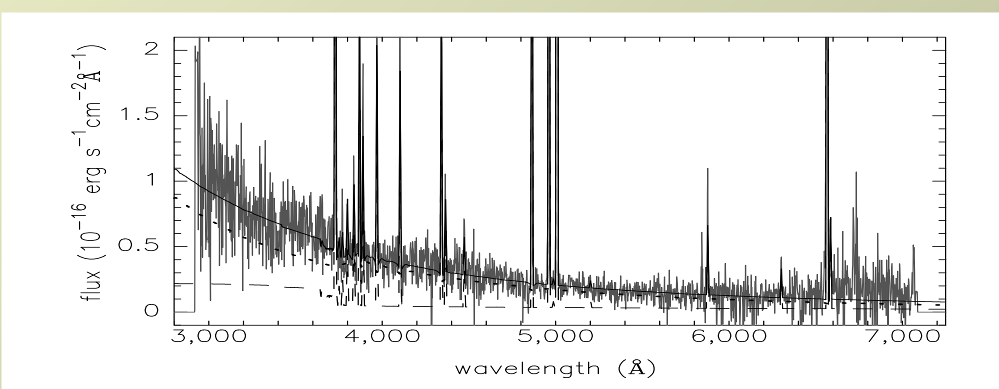
Extended Data Table 2 | Physical conditions and chemical composition

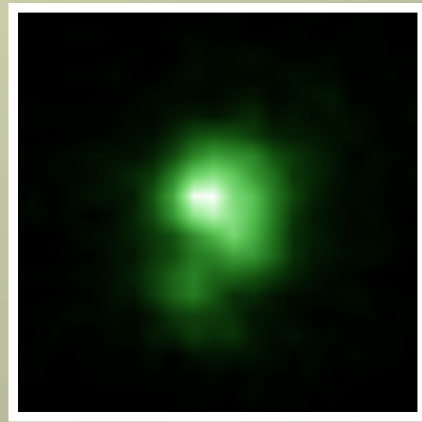
Parameter	Value
T_e(OIII), K	15010 ± 410
T_e(OII), K	14010 ± 360
N_e(OII), K	100†
$O^+/H^+ \times 10^5$	1.42 ± 0.11
$O^{2+}/H^+ \times 10^5$	6.65 ± 0.50
$O/H \times 10^5$	8.06 ± 0.52
12+logO/H	7.91 ± 0.03
$N^+/H^+ \times 10^6$	1.12 ± 0.07
ICF(N)‡	5.42
$N/H \times 10^6$	6.05 ± 0.45
log N/O	-1.12 ± 0.04
$Ne^{2+}/H^+ \times 10^5$	1.27 ± 0.11
ICF(Ne)‡	1.08
$Ne/H \times 10^5$	1.37 ± 0.13
log Ne/O	-0.77 ± 0.05

†Assumed value.
‡Ionization correction factor.

A strong Lyman continuum leaker at z=0.3

J0925+1403 other properties

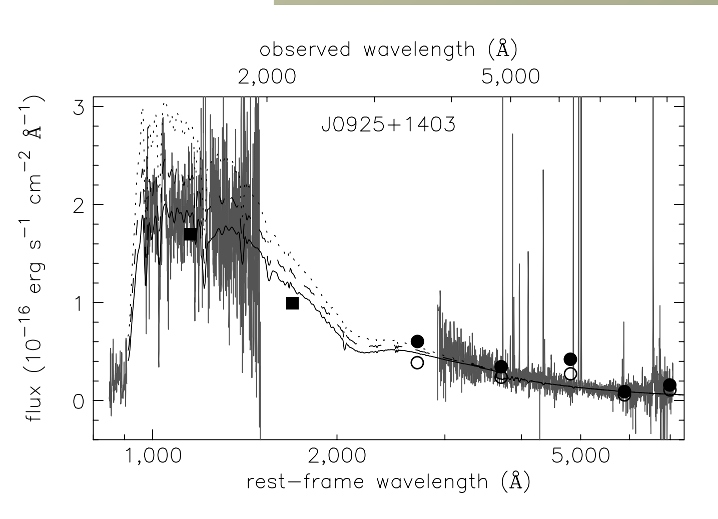




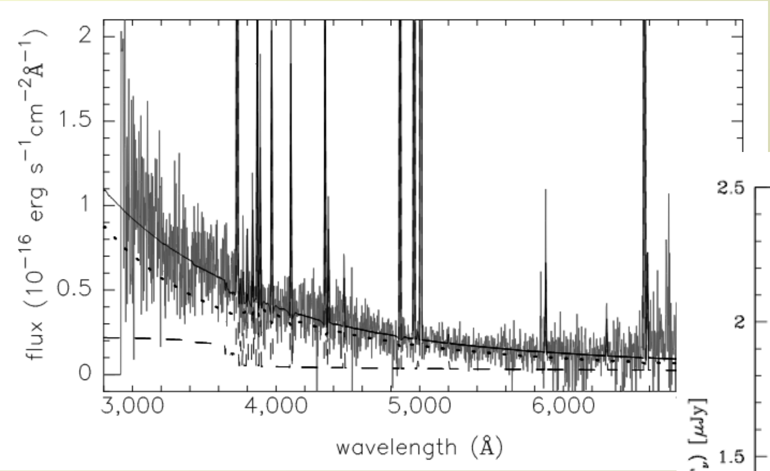
Extended Data Table 3 | Global characteristics of J0925+1403

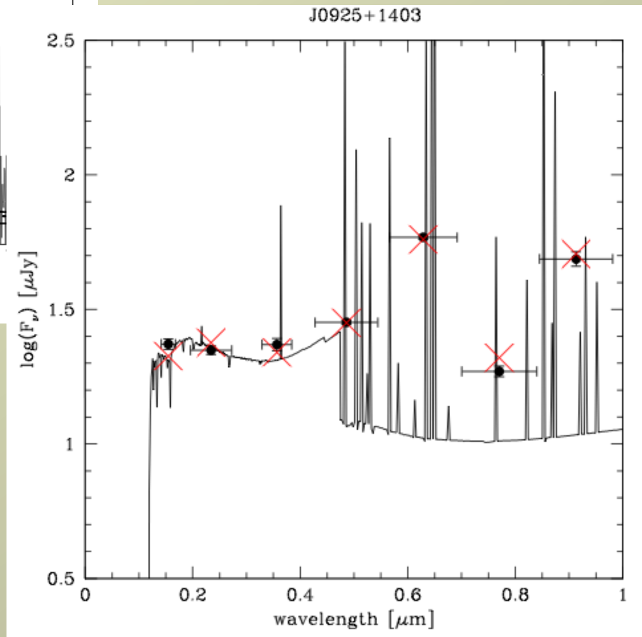
Parameter	Value
$I_{H\beta}$ †	49.2 ± 1.3
Redshift	0.301323
Luminosity distance‡	1620
$L_{H\beta}$ ††	(2.32 ± 0.04) × 10^{42}
SFR‡‡	52.2
Q_H *	4.94 × 10^{54}
Q_H(esc)*	3.86 × 10^{53}
t(burst)**	2.6 ± 0.2
$M_y/M_\odot$	(2.4 ± 0.3) × 10^8
$M_\star/M_\odot$	(8.2 ± 0.7) × 10^8

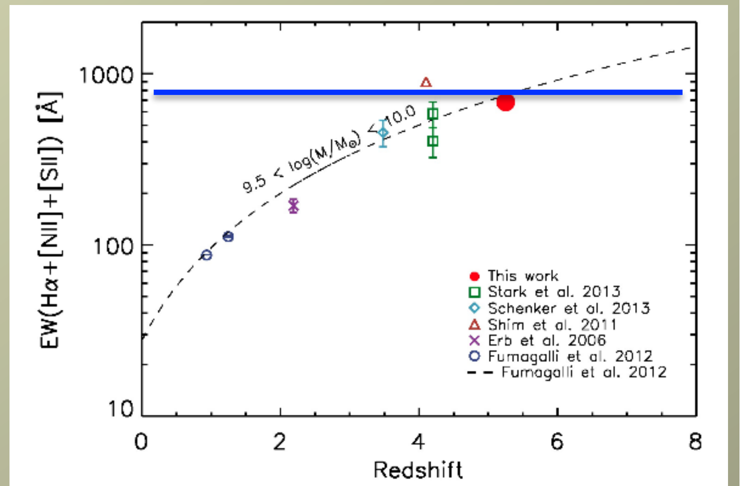
†Extinction-corrected flux density in units of 10^{-16} erg s^{-1} cm^{-2}.
‡In units of Mpc.
††Extinction- and aperture-corrected luminosity in units of erg s^{-1}.
‡‡Star-formation rate in $M_\odot$ yr^{-1} derived from the Hβ luminosity[50].
*Q_H and Q_H(esc) are the numbers of Lyman continuum photons (in units of s^{-1}) emitted by massive stars and escaped from the H II region, respectively.
**Burst age in Myr.



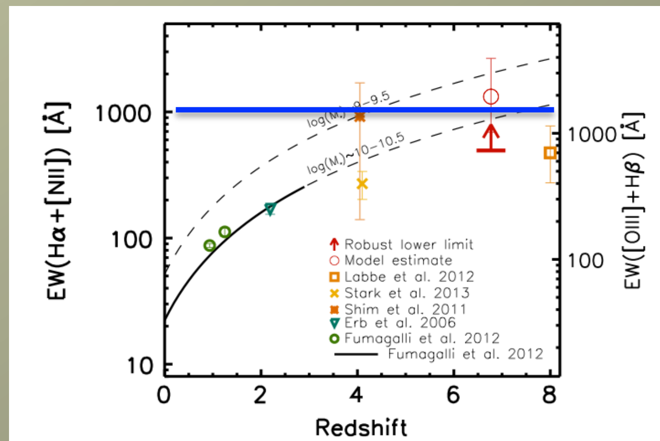
A strong Lyman continuum leaker at z=0.3 -- Comparison with high-z galaxies







z~5 -- Rasappu+ (2015)



z~7 -- Smit+ (2014), Roberts-Borsani+ (2015)

High equivalent widths:

EW(Ha)=730 Å

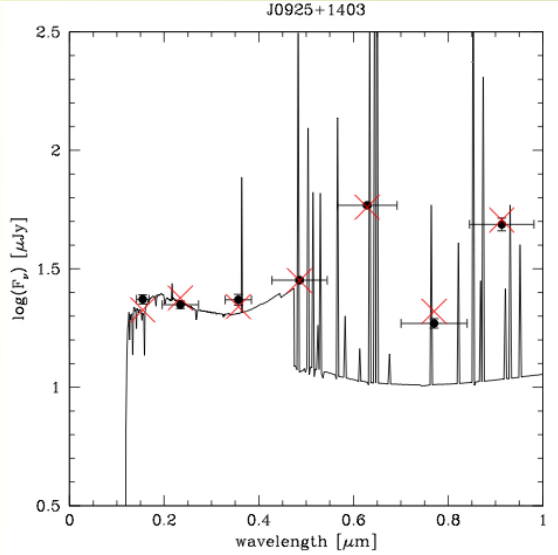
EW([OIII]4959+5007)=1480

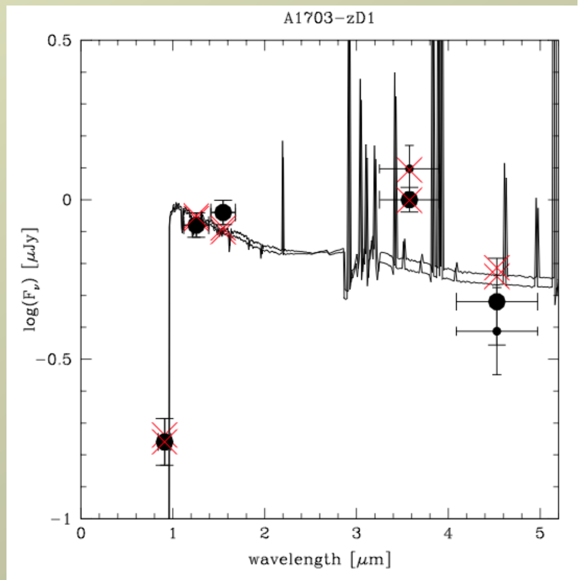
…

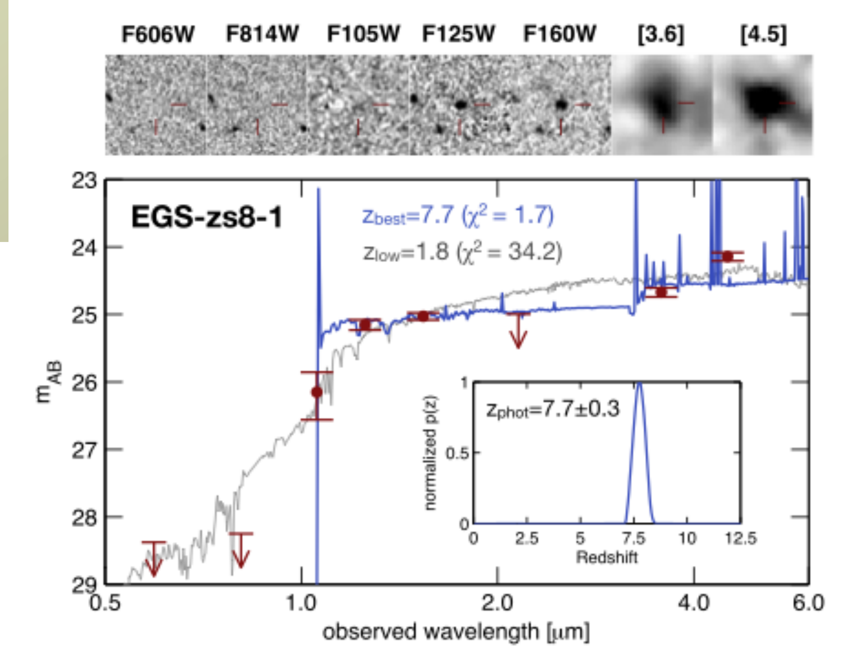
➠ Comparable to high-z galaxies

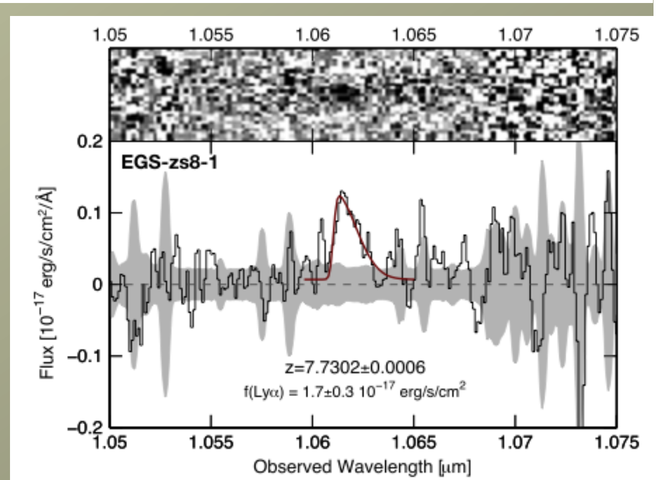
Izotov et al. (2016)

A strong Lyman continuum leaker 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

Comparison with high-z galaxies

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

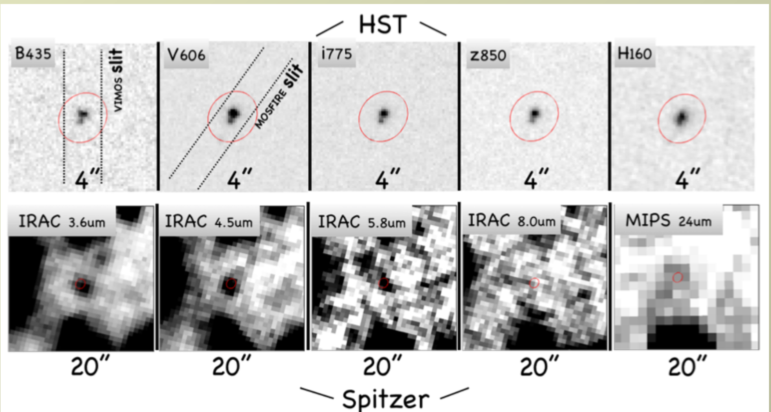
z=3.218 galaxy « Ion2 »in GOODS-S/Candels

UV rest-frame mag_AB~24.5-25

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

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

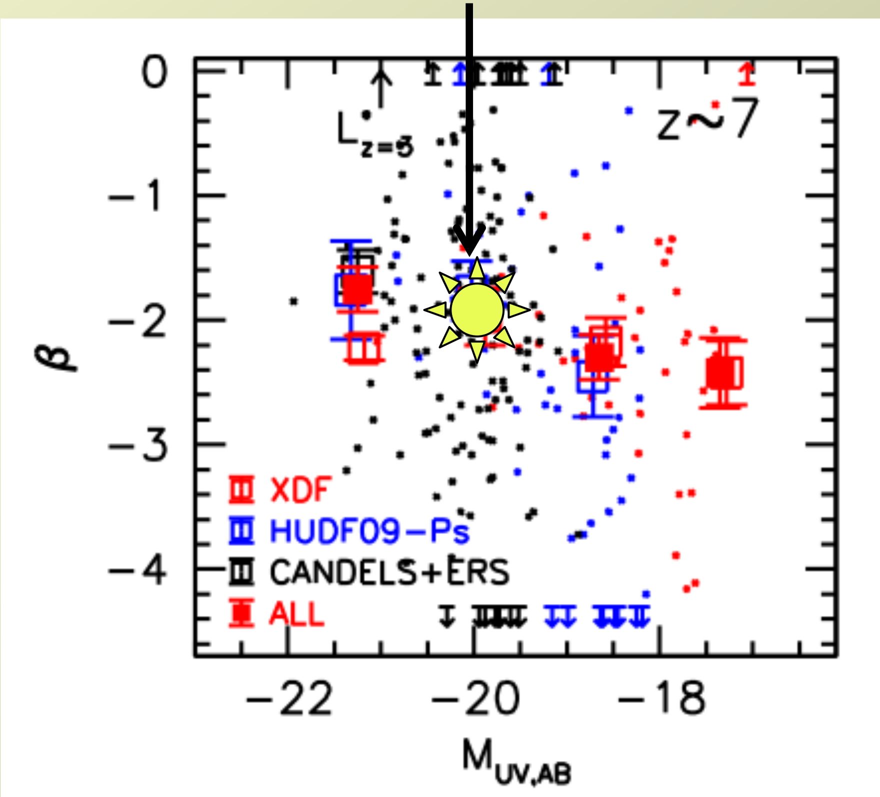
Vanzella et al. (2015), de Barros et al. (2015)



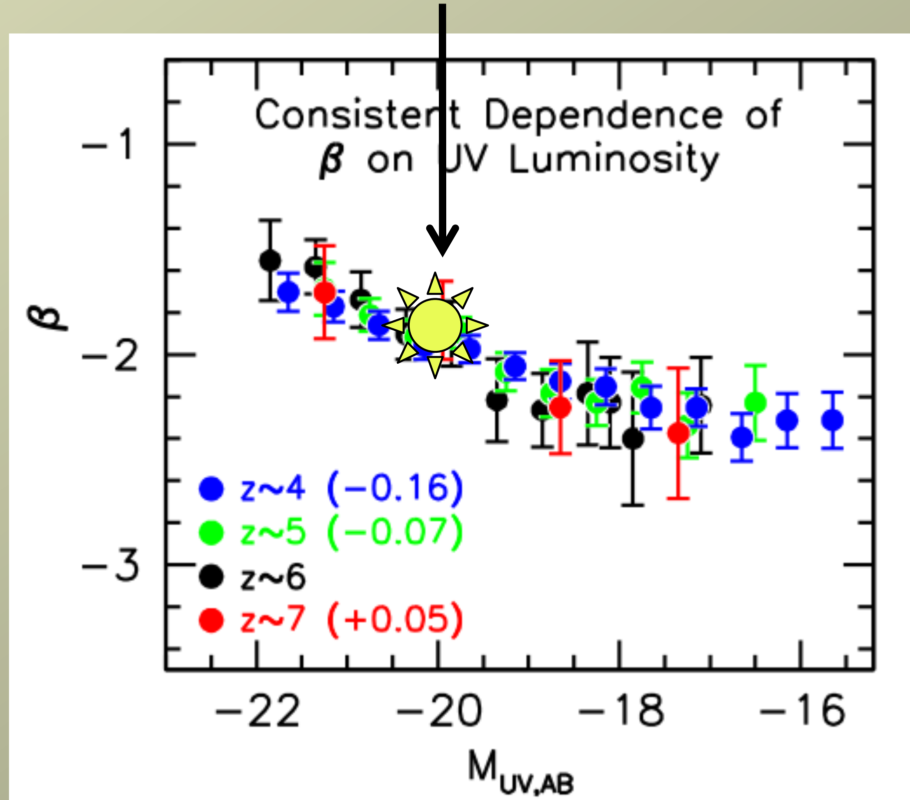
EL ratios, equivalent widths, stellar mass of J0925+1403:
➠ Comparable to Ion2

Comparison with high-z galaxies

Izotov+ leaker

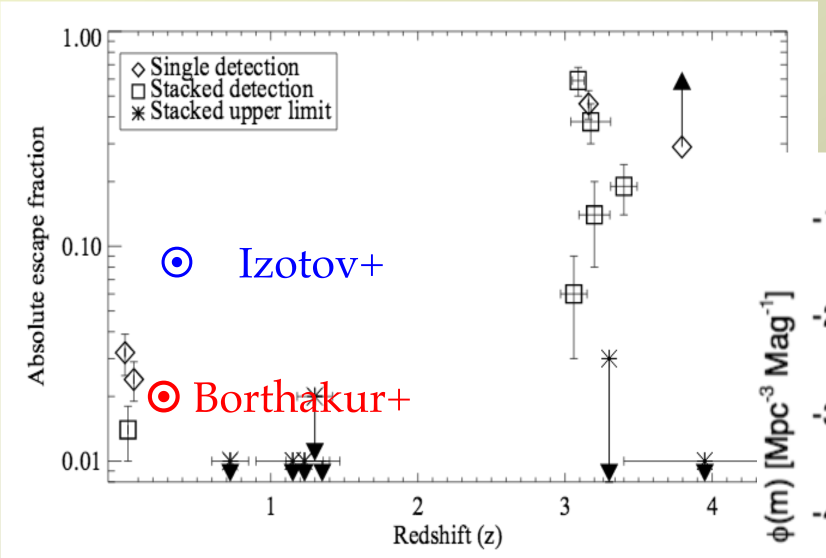


Izotov+ leaker

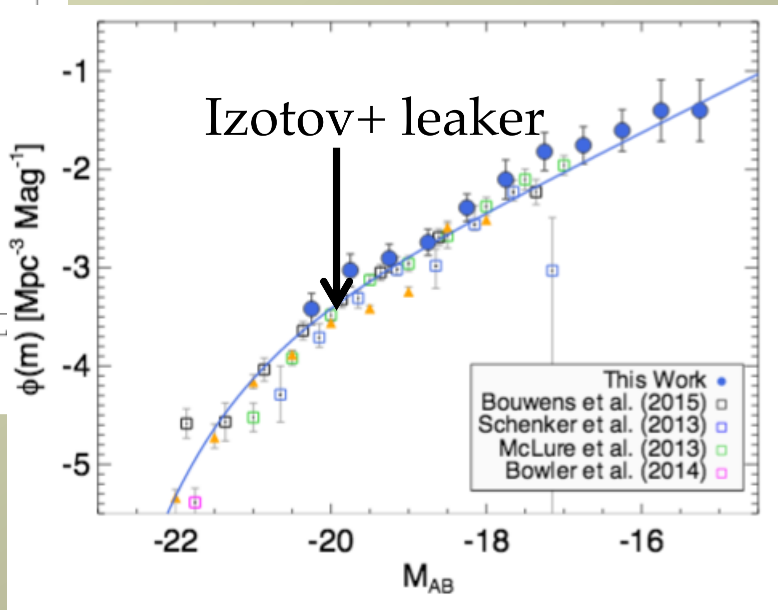


Bouwens+ (2014)

Comparison with high-z galaxies



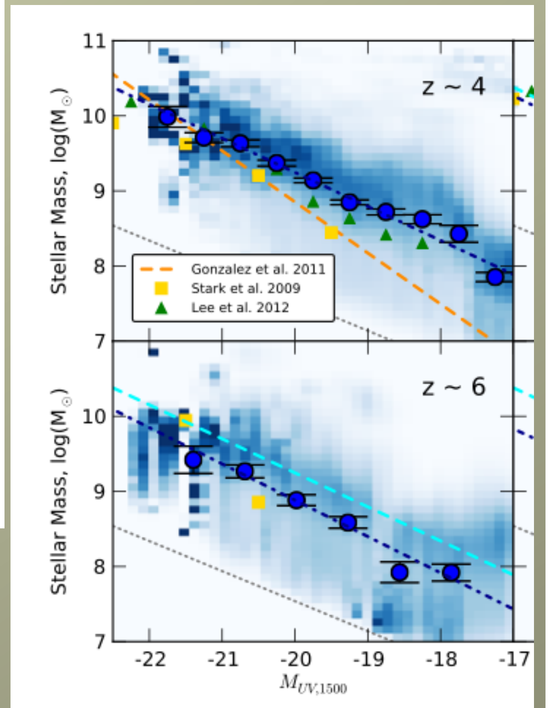
High escape fraction



Atek+ (2015)

Quite bright source

Stellar mass ~1 10^9 Msun



Duncan et al. (2014)

A strong Lyman continuum leaker at z=0.3 -- Comparison with high-z galaxies

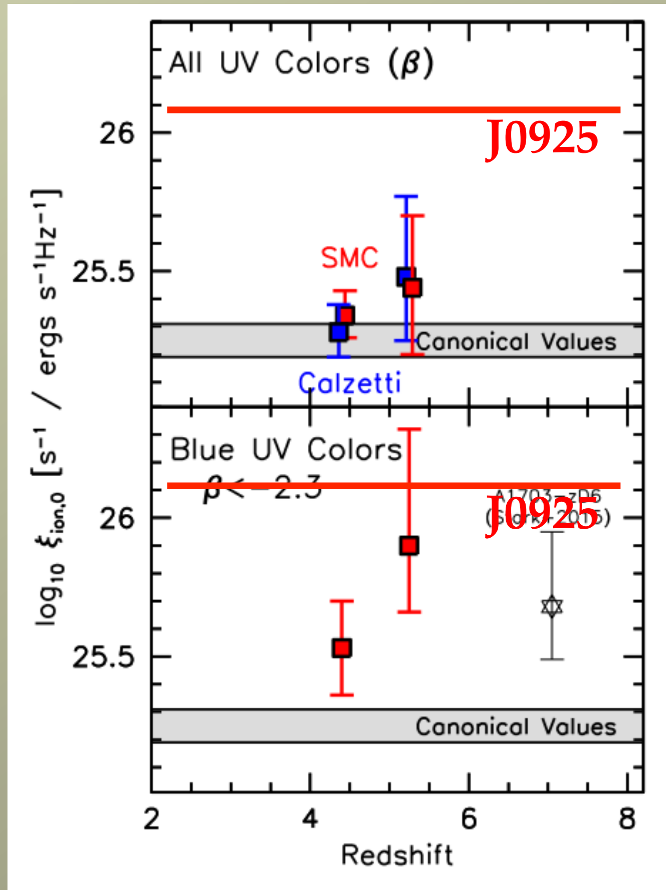
- Observed Lyman continuum / UV emission

→ log(ζ)= 25.0 (photons/s) / (erg/s/Hz)

- fesc=7.8% → intrinsic ionising photon production log(ζ)= 26.1 (photons/s) / (erg/s/Hz)

→ **Factor 6-8 times more ionizing photons produced *per unit UV luminosity than commonly assumed*** (e.g. Robertson+2013)

→ Due to young age of J0925+1403 galaxy



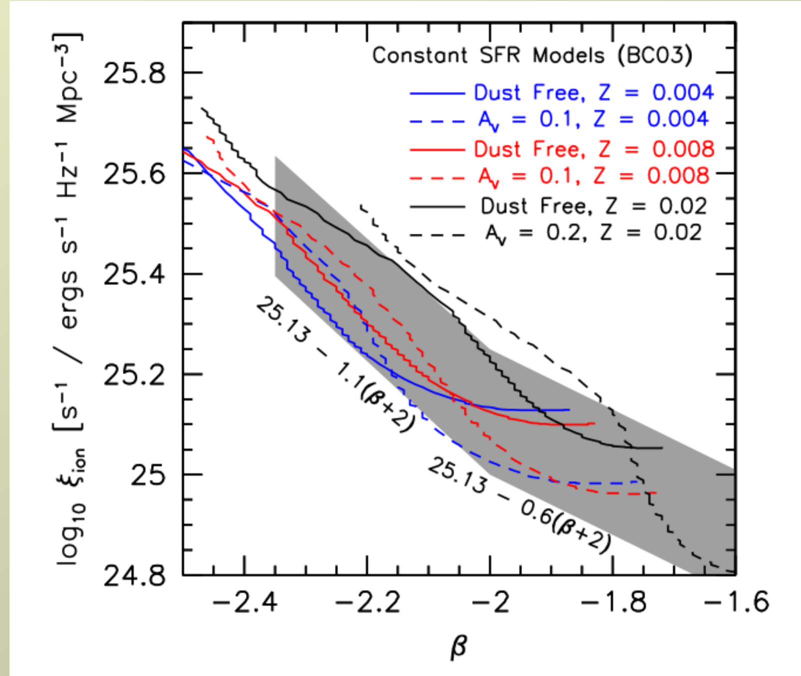
Izotov et al. (2016)

Bouwens et al. (2015)

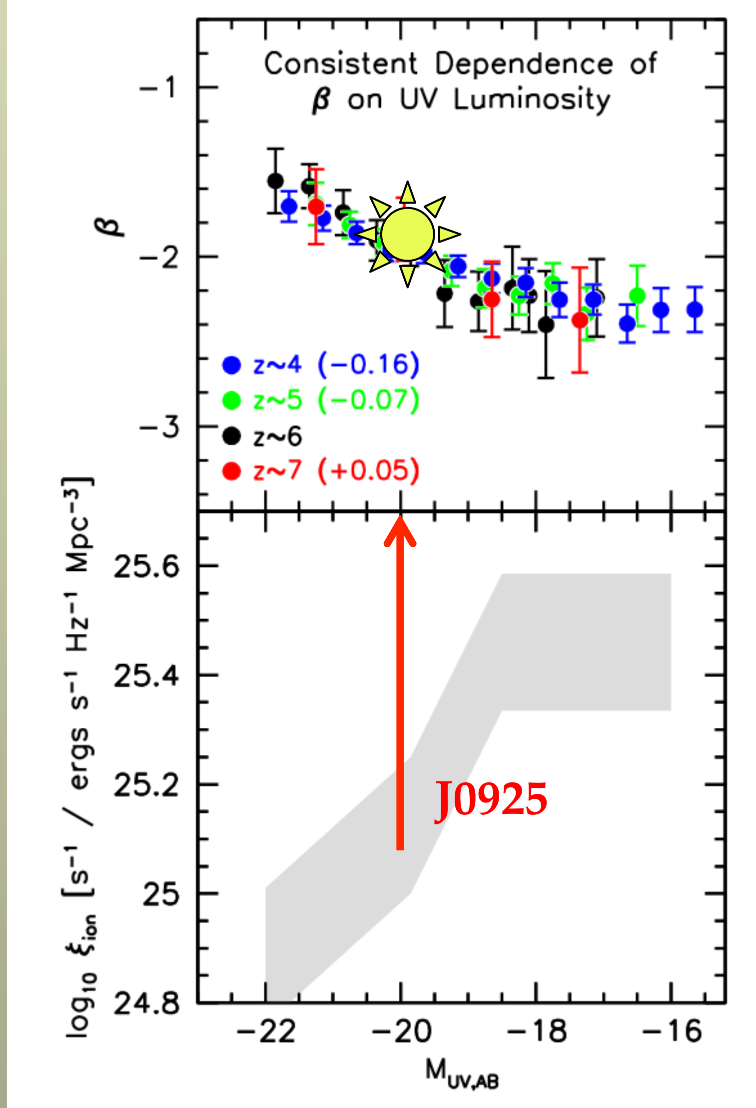
A strong Lyman continuum leaker at z=0.3 -- Comparison with high-z galaxies

Much stonger ionizing photons production

J0925

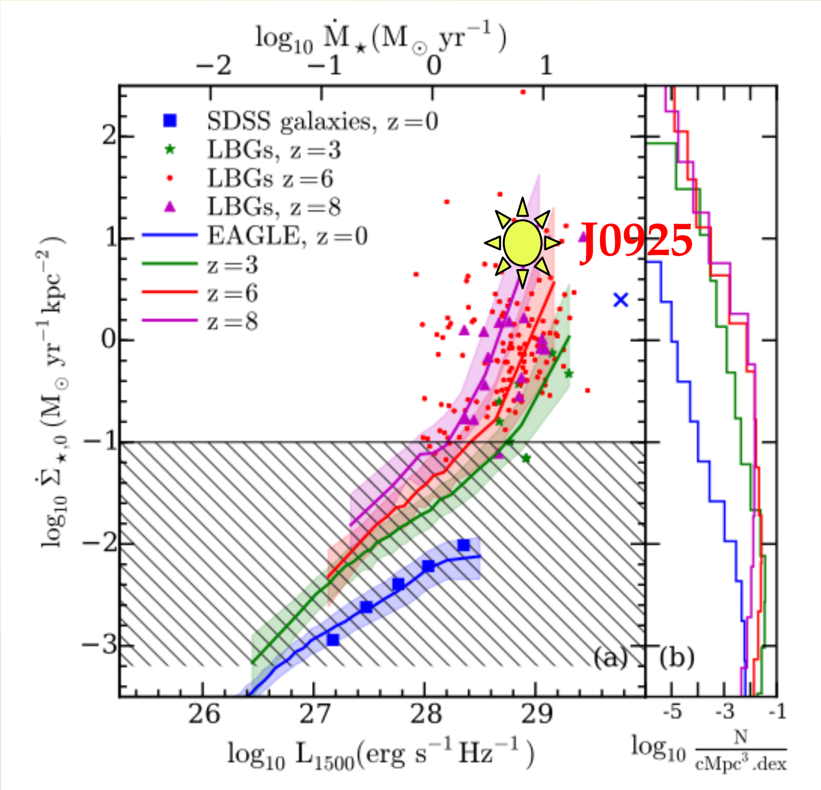


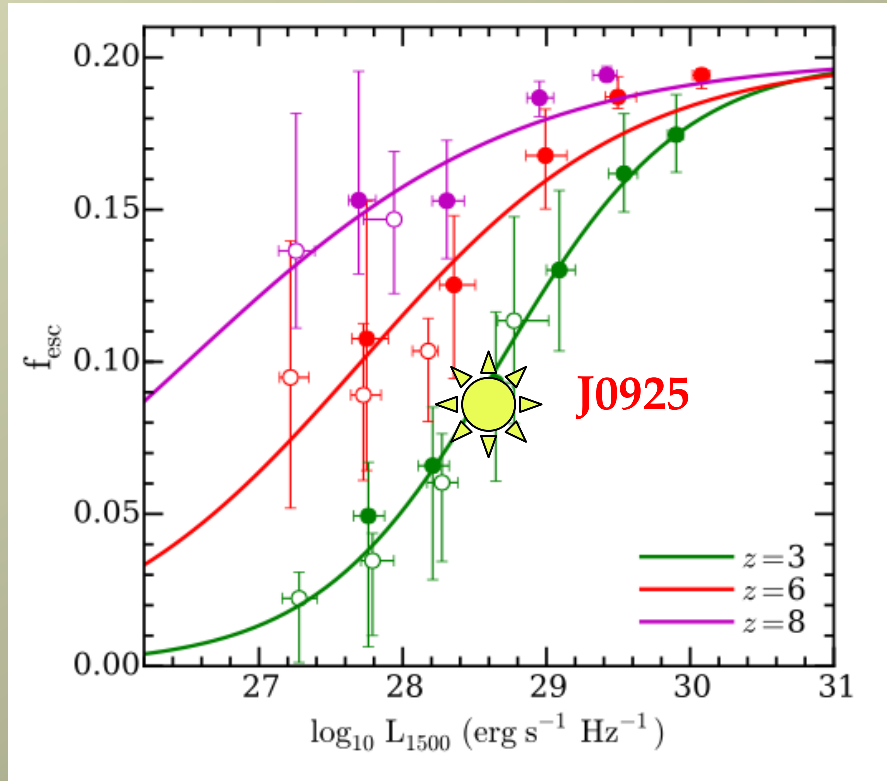
Bouwens et al. (2015)



A strong Lyman continuum leaker at z=0.3 -- Comparison with high-z galaxies

Did brighter galaxies reionise the Universe?





Simulations assume fesc=0.2 in regions with
local SFR surface density >= 20 Msun/yr/kpc^2

Sharma, Theuns, et al. (2015)

Future

- Larger sample
- Detailed study of Lyc escape mechanism
- Dependence of fesc on galaxy properties
- …
- Statistics
- … use of Lya profiles for high-z galaxies
- …

Conclusions

Successfull new methods to identify Lyman continuum leakers at low and high-z

- **High [OIII]/[OII] ratio & compact SF galaxy**
  - → **COS observations find highest fesc value in low-z « green pea » galaxy** J0925+1403
  - → Confirms Nakajima & Ouchi (2014) criterium
- **Narrow Lyman-alpha line profile**
  - → Signature of *low HI column density* and / or holes in the cold ISM
  - → Confirms Verhamme et al. (2015) radiation transfer models

- UV bright SF galaxies can contribute to cosmic reionisation
- Observed properties are very similar to typical high-z galaxies