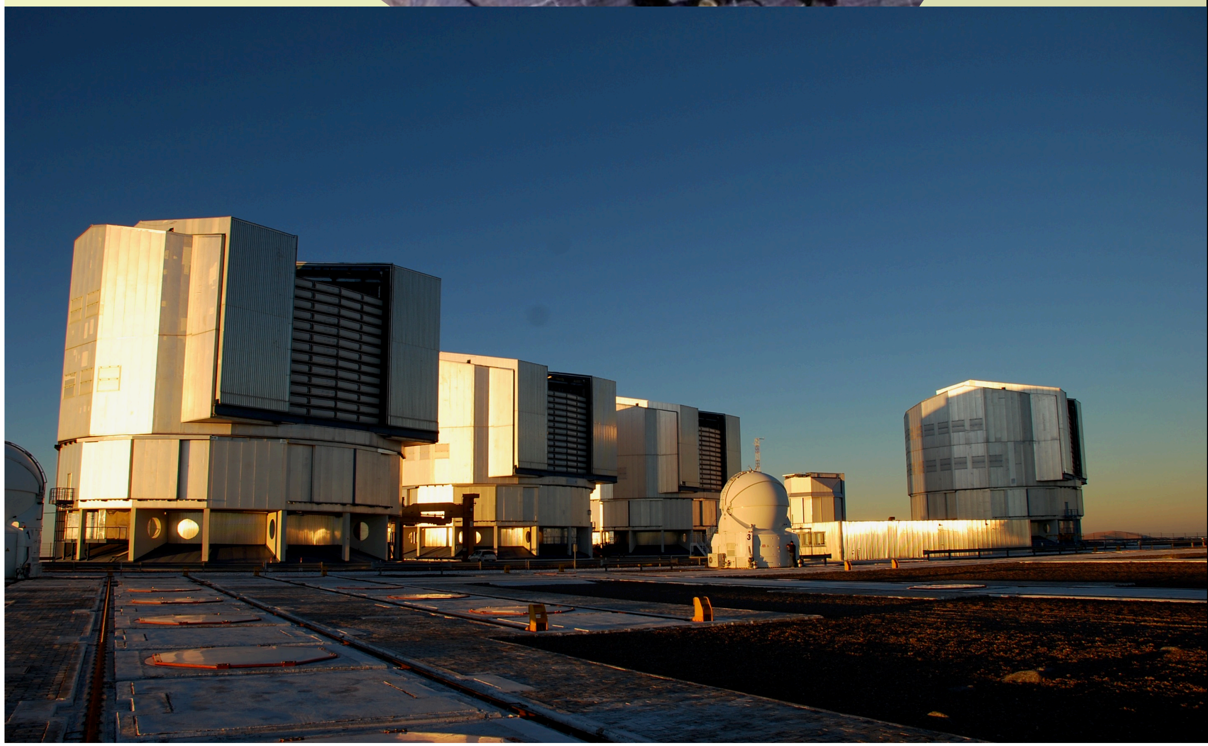
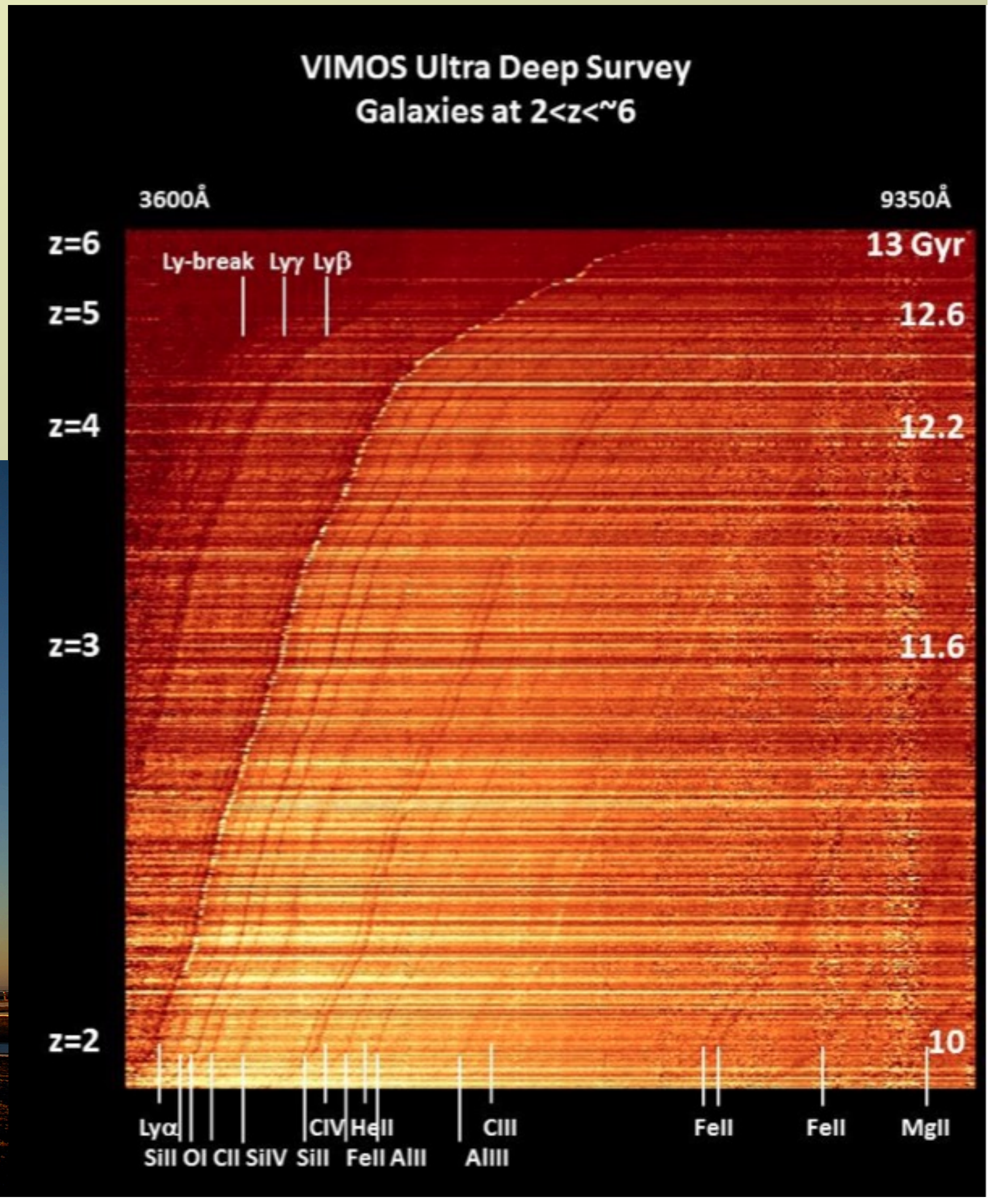
From VUDS to ALPINE

…with all my gratitude and admiration for Olivier !



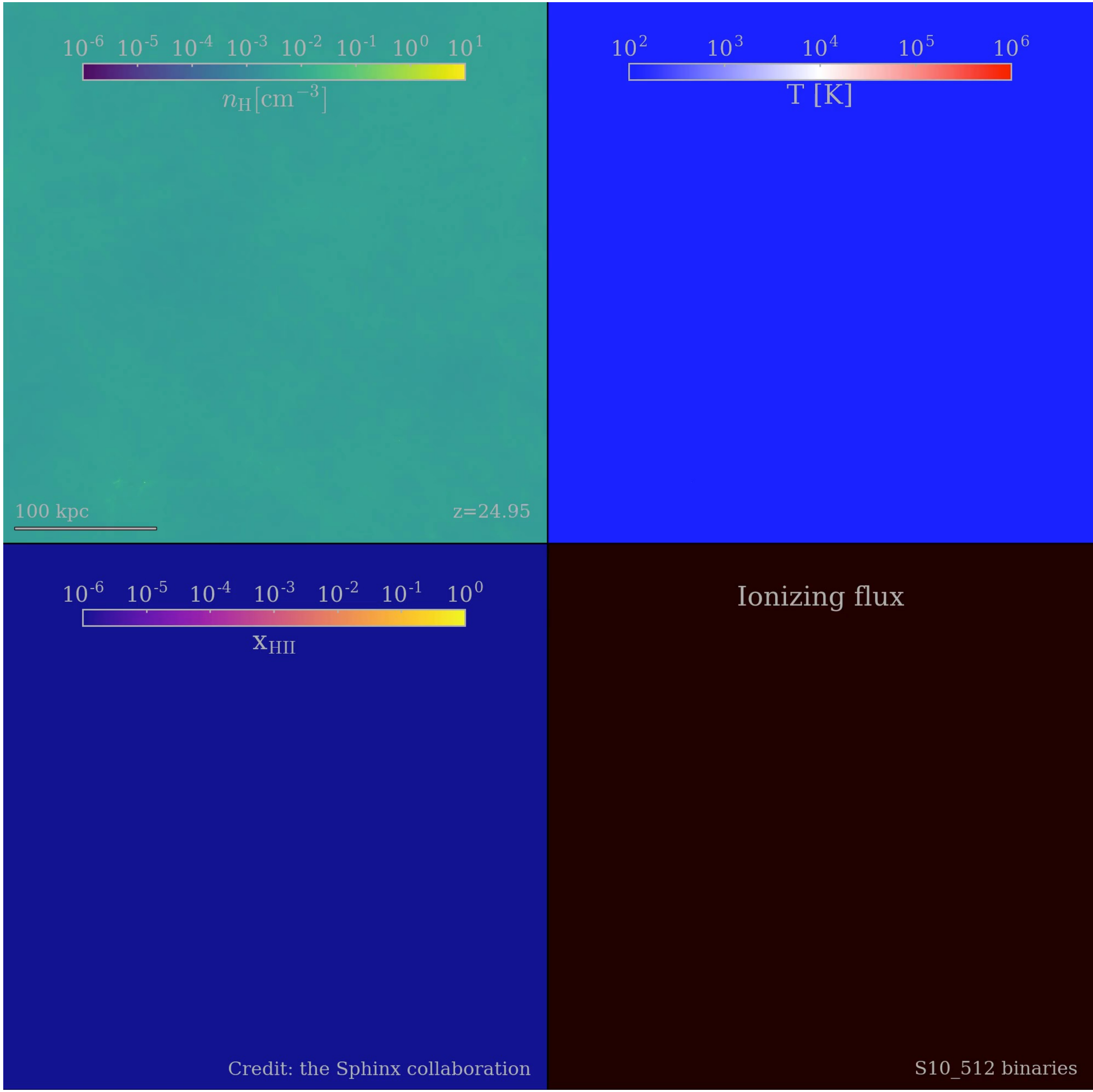


Empirical and physical properties of Lyman continuum emitters

Daniel Schaerer (Geneva Observatory/University & CNRS)
Alberto Saldana-Lopez, Rui Marques Chaves

+ Yuri Izotov, Gabor Worseck
+ John Chisholm, Sophia Flury, Anne Jaskot,
+ *LzLCS team*

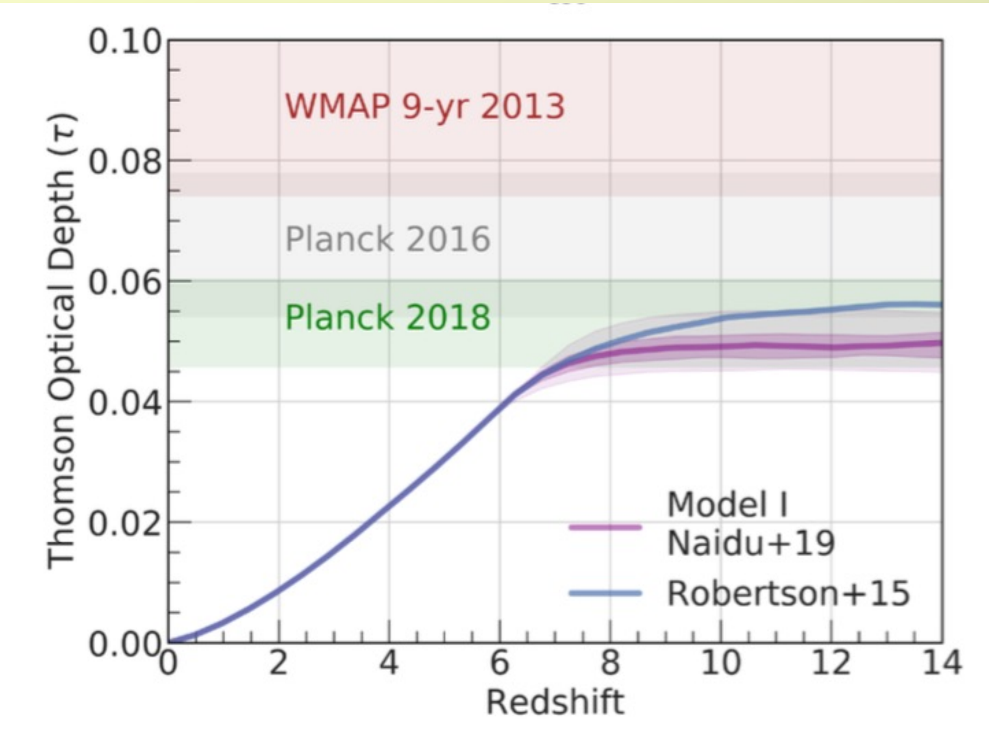
- Introduction
- From 2016 to the Low-z Lyman Continuum survey
- Properties of LyC emitters
- Indirect LyC indicators
- Conclusions

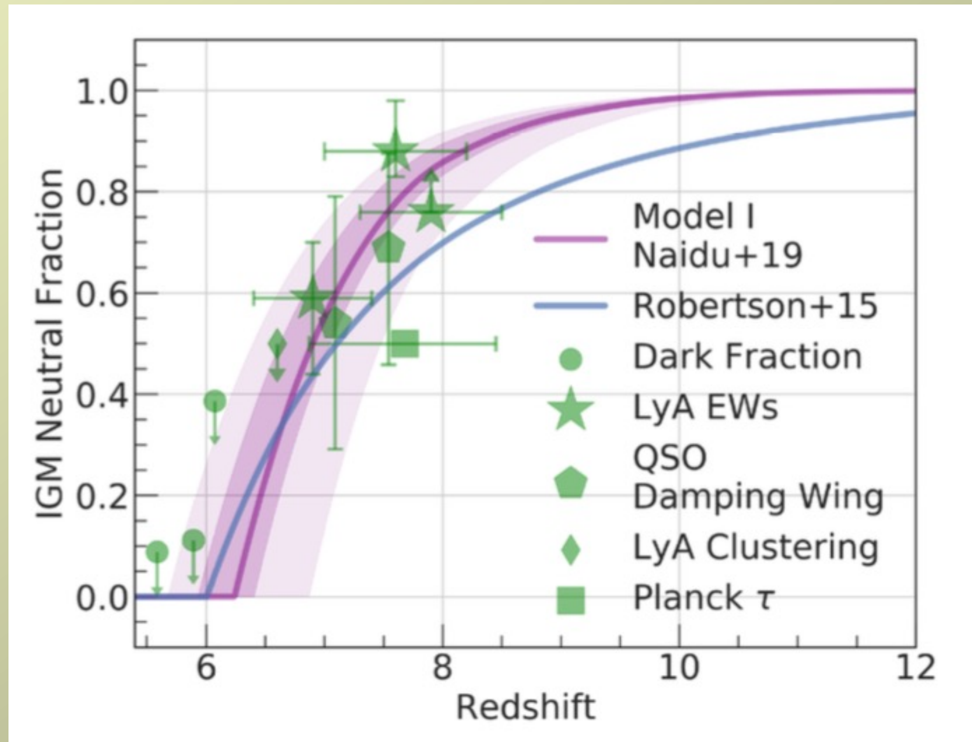


Cosmic reionisation

SPHINX simulations
Rosdahl et al. (2018)

Constraints on cosmic reionization

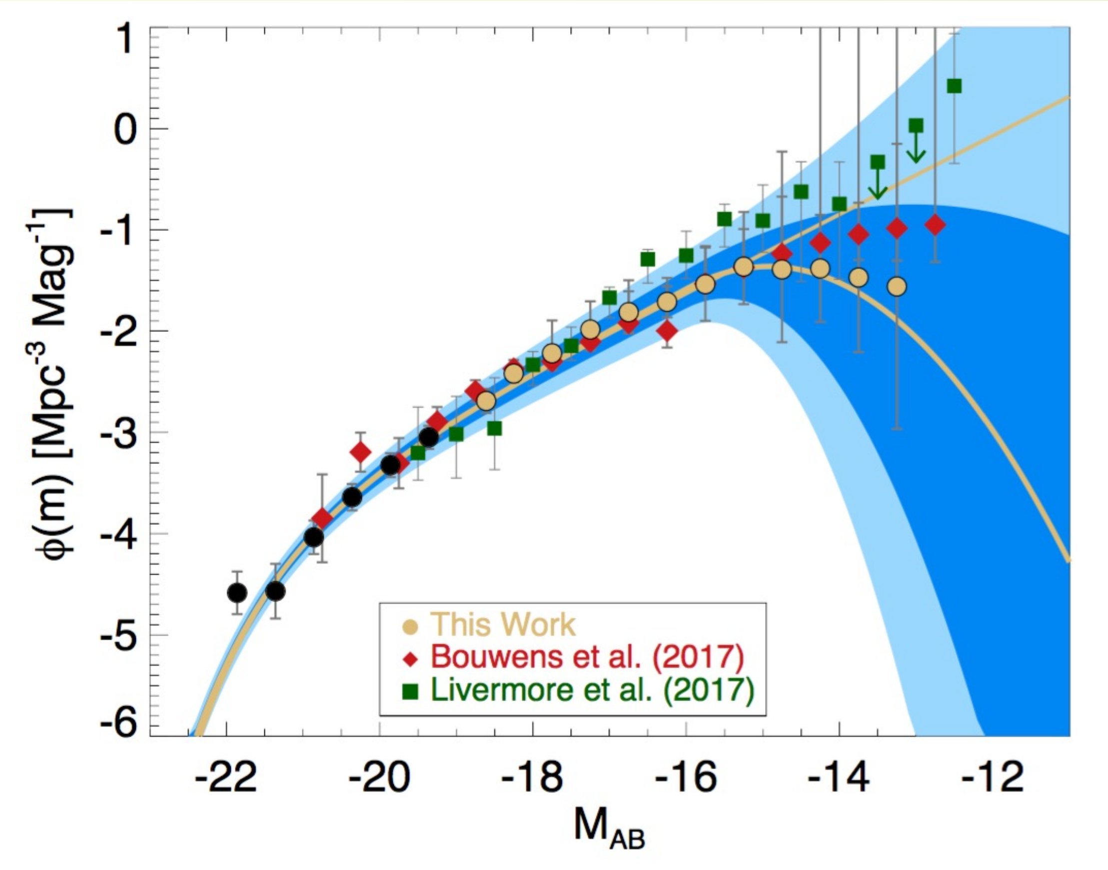




Planck collaboration (2018)

Naidu+ (2019)
+many earlier+later papers

The quest for the sources of cosmic reionisation



z~7 LF: Atek et al. (2015, 2018)

Faint, low mass galaxies are thought to be responsible for cosmic reionisation

→ Average escape fraction of ~10-20% needed

Ouichi+
Robertson et al. (2013)
Bouwens+2015
…

The quest for the sources of cosmic reionisation

- Faint, low mass galaxies thought to be main contributors to cosmic reionization (but cf. Sharma+ 2016, Naidu+ 2019)
  → **Average escape fraction of ~10-20% needed**

- Numerous searches for « Lyman continuum leakage » from star-forming galaxies at low and high-z
  → **sources elusive for long … Now new era !**

→ **Immediate Objectives:**

  → **How to identity and find the sources of reionisation?**

  → **Study their properties**

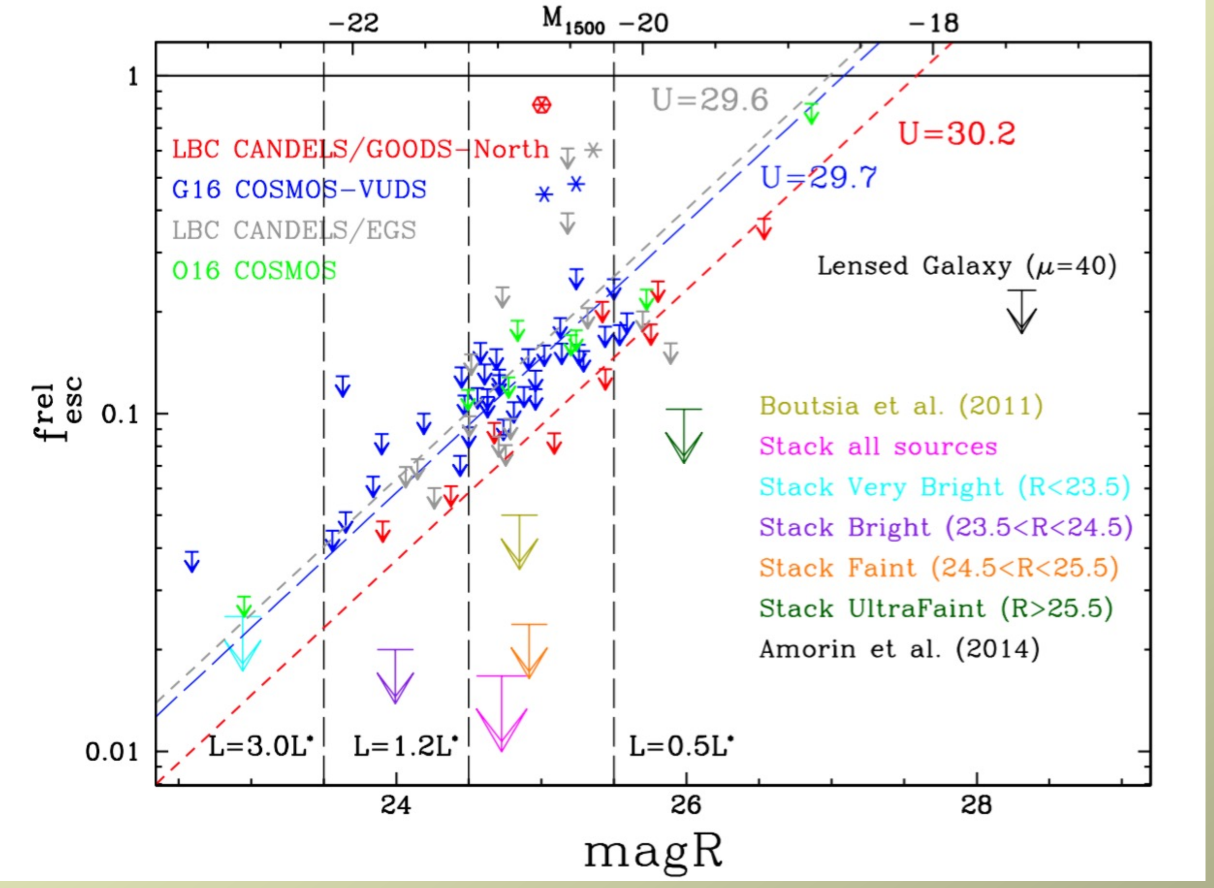
escape fraction

ionizing photons / UV luminosity

UV luminosity density

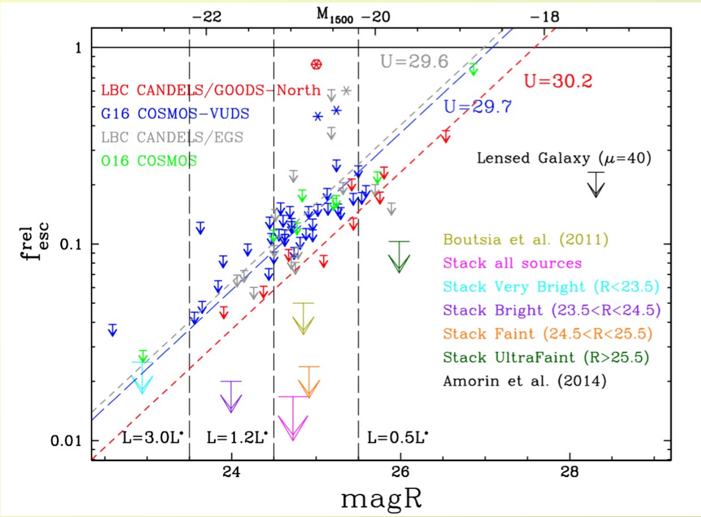
$$\dot{n} = f_{\rm esc}\, \xi_{\rm ion}\, \rho_{\rm SFR}$$

The quest for the sources of cosmic reionisation -- z~3 in <=2016

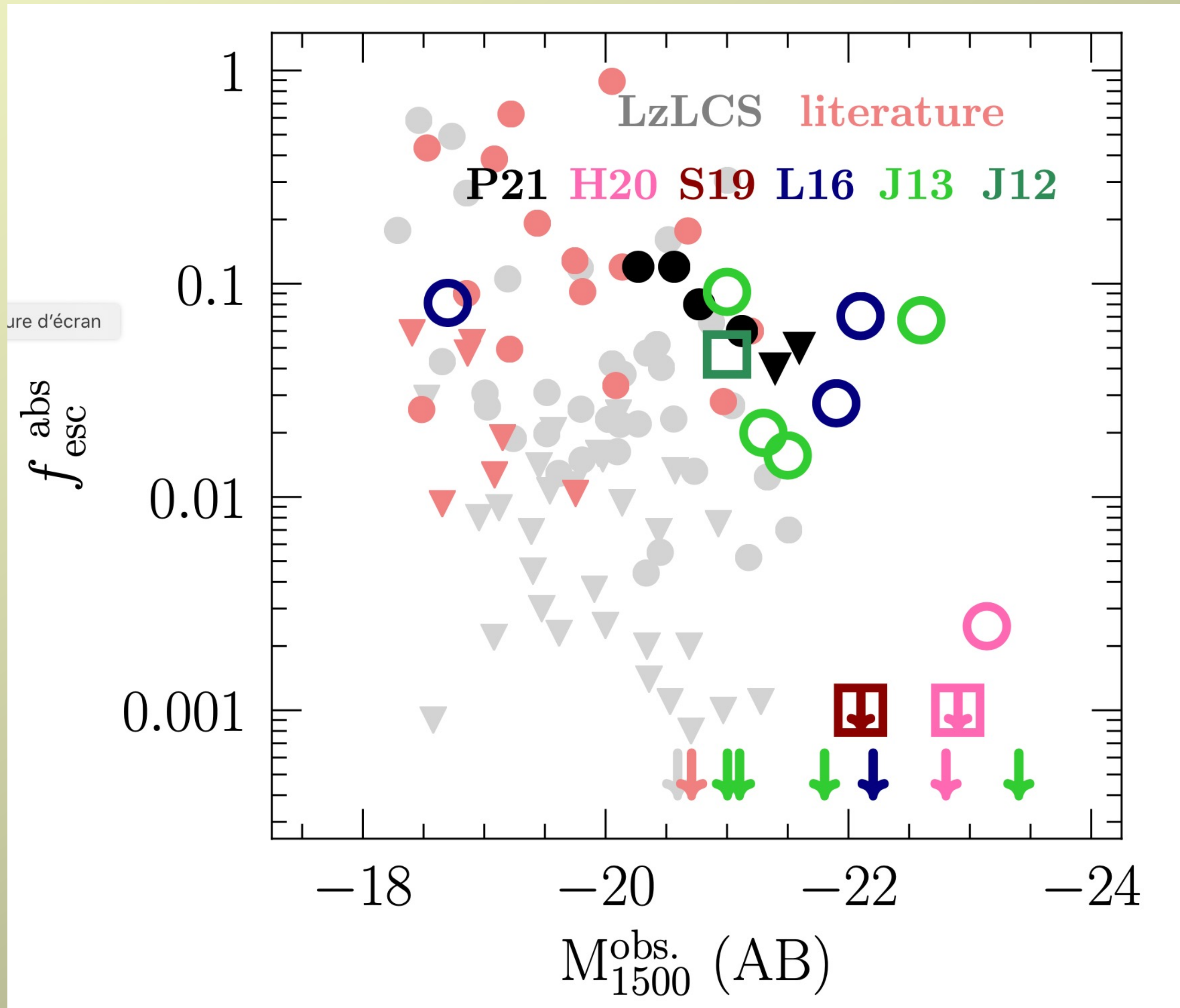


COSMOS+EGS+GOODS-N -- z~3.3: Grazian+ 2017

The quest for the sources of cosmic reionisation
-- and progress from 2016-2022 !



Grazian+ 2017



→ New high-z discoveries

→ HST low-z studies

Saldana-Lopez+2022

A robust high-z LyC emitter

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

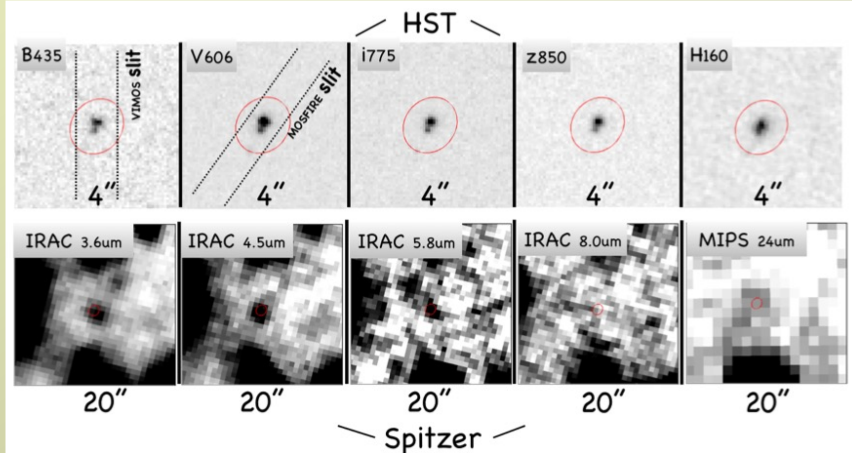
z=3.218 galaxy « **Ion2** »**in GOODS-S/CANDELS**

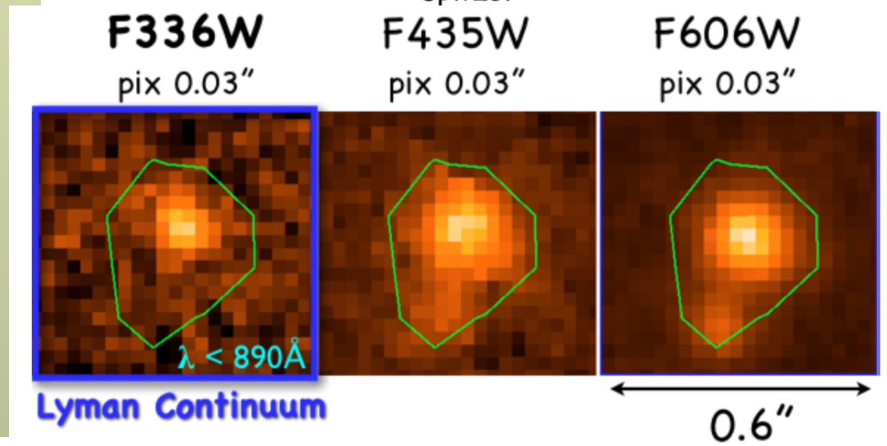
UV rest-frame mag_AB~24.5-25

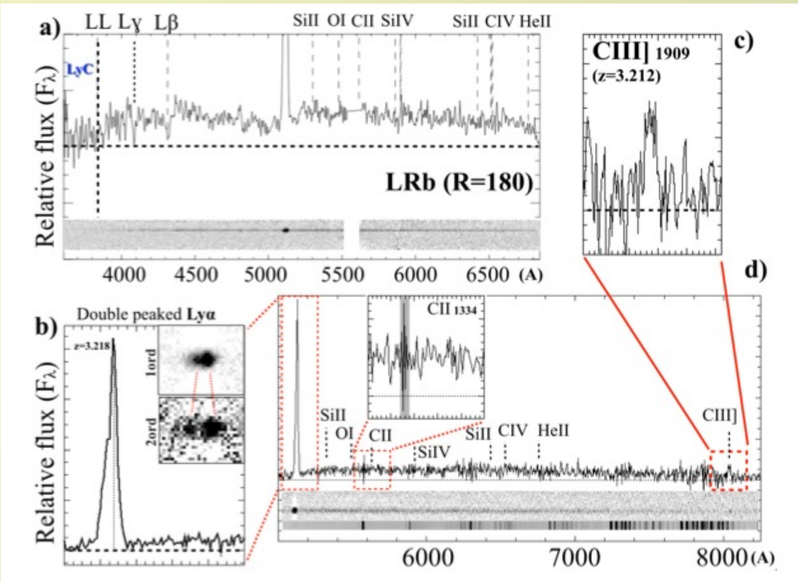
→ Low metallicity (1/6 $Z_\odot$), ~low mass (1.6 10^9 $M_\odot$)

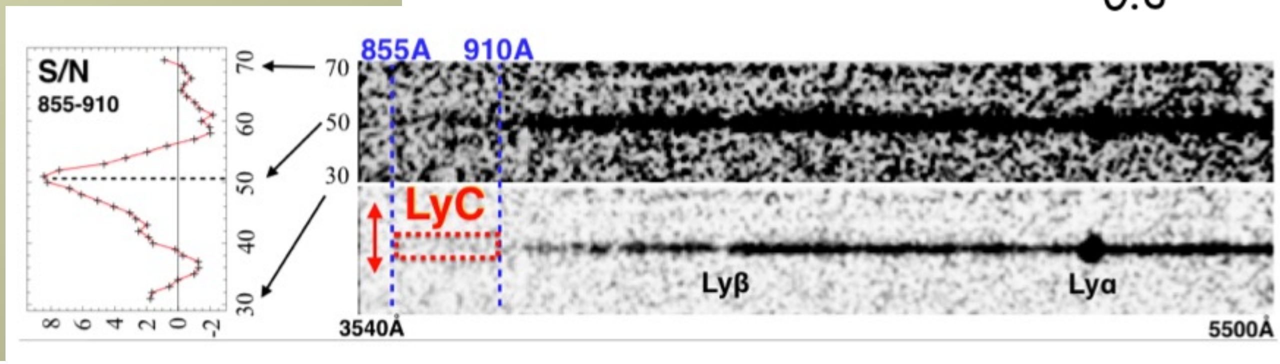
→ High excitation

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









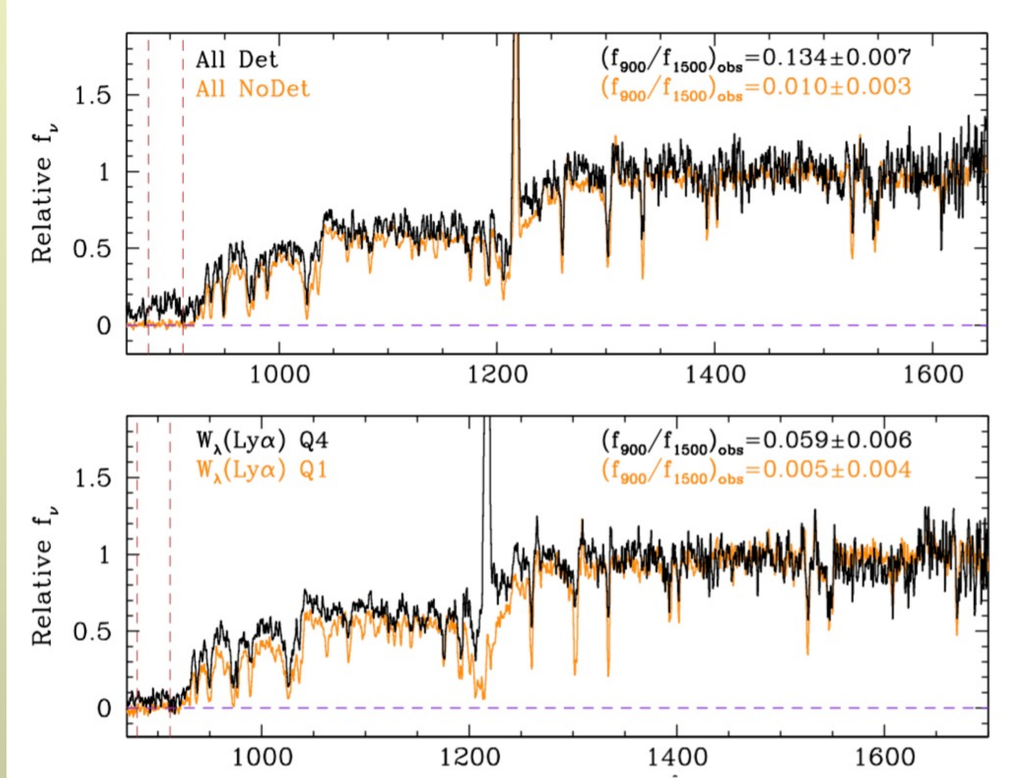
The quest for the sources of cosmic reionisation - z~3

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

Steidel et al. (2018), Pahl et al. (2021)

VLT surveys (VIMOS + imaging)
- Marchi et al. (2017, 2018)
- Saxena et al. (2021), Begley et al. (2022)
- …

HST surveys (VIMOS + imaging) --
Lyman-alpha emitters at z=3
- Micheva et al. (2017)
- Fletcher et al. (2019)

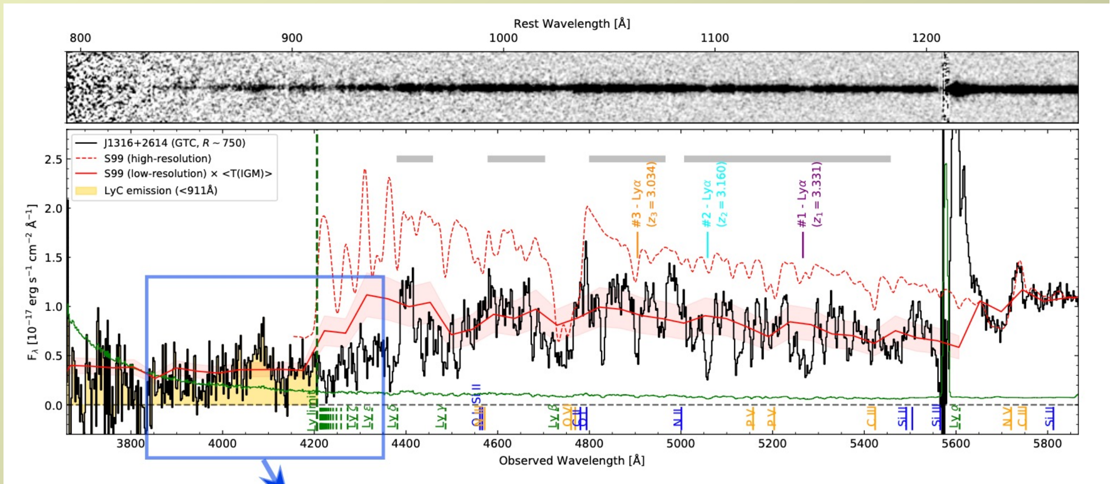


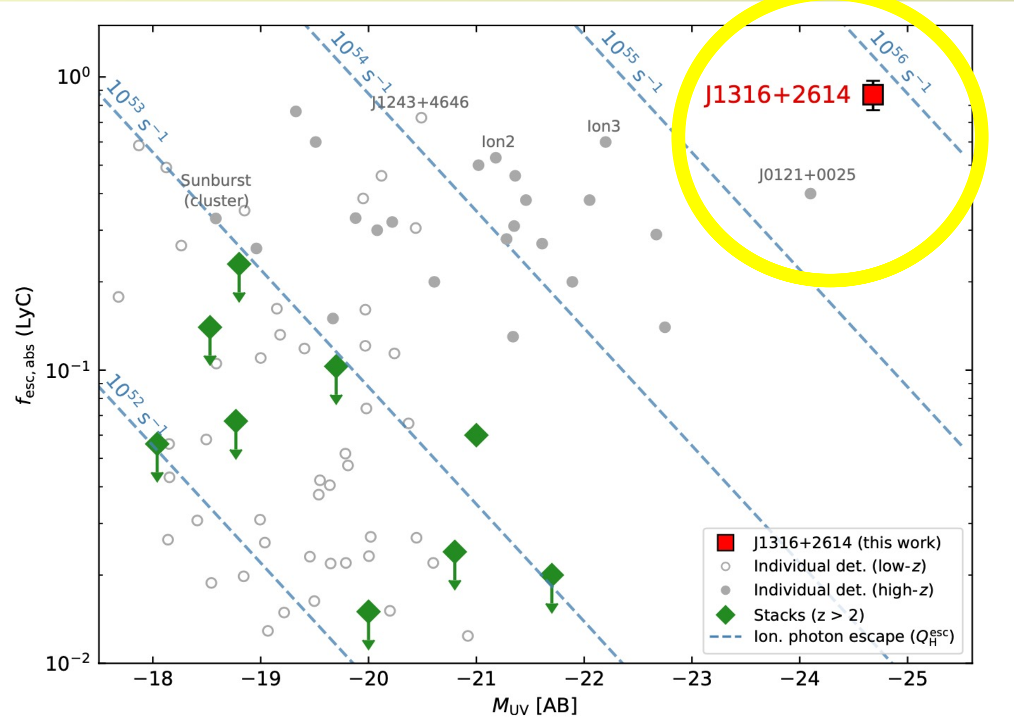
Steidel et al. (2018)

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

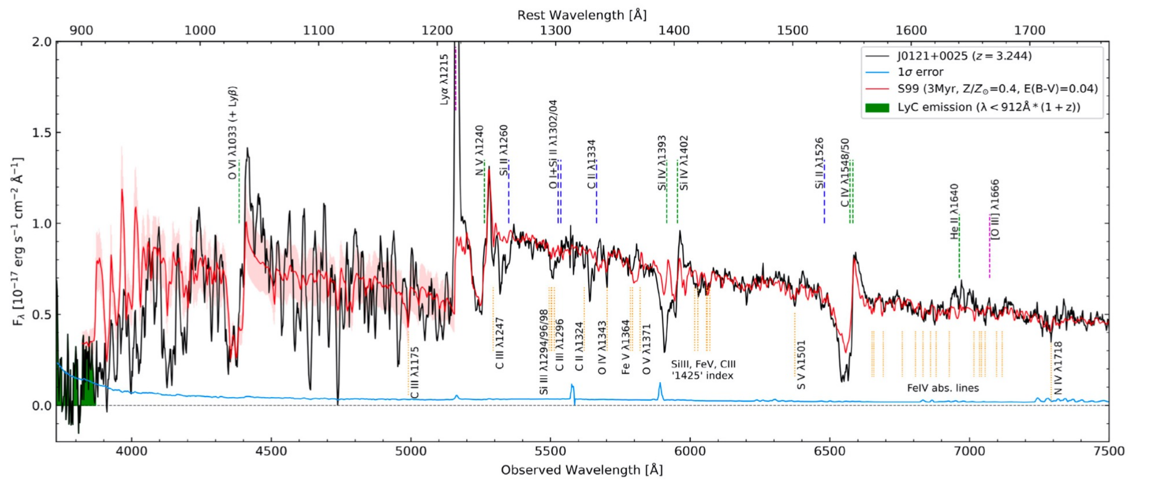
Discovery of rare UV-bright SF galaxies with LyC leakage

Marques Chaves et al. (2021, 2022)





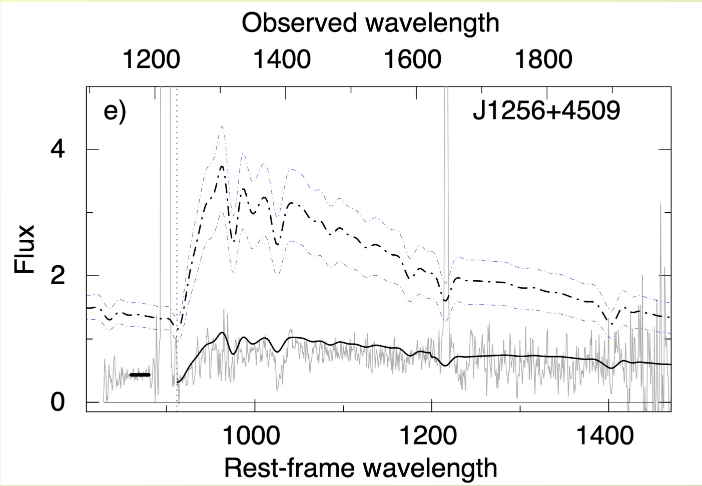
A strong LyC leaker at z = 3.24 527

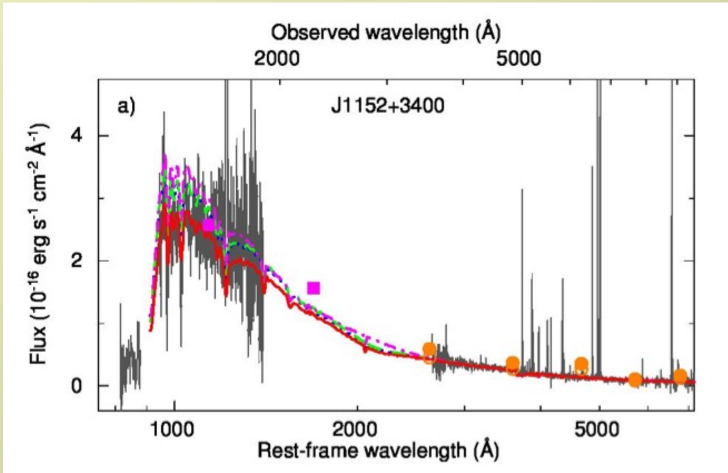


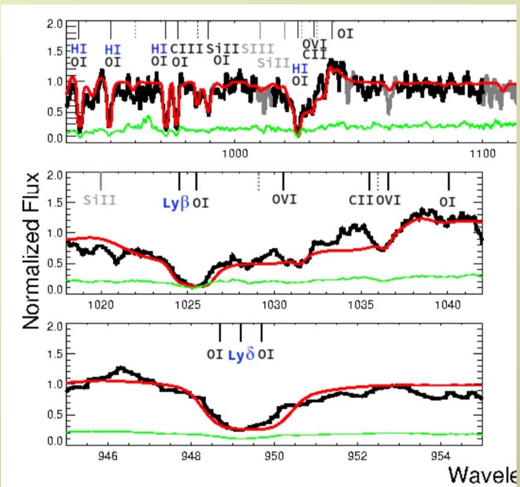
HST studies of Lyman continuum emitters at z~0.3

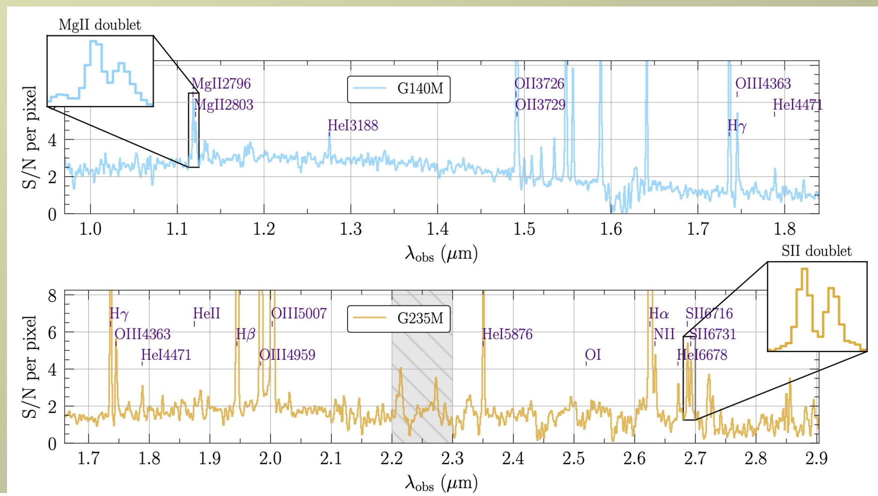
Rich dataset:
* LyC-UV-optical spectroscopy
* ground-based multi-lambda imaging

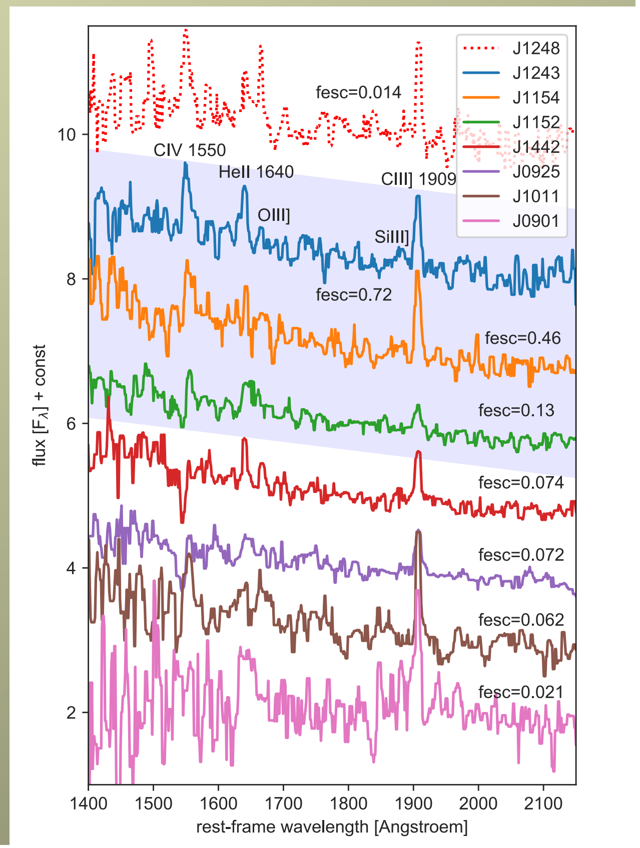
Izotov+ (2016, 2018, 2021, 2022)
Gazagnes+ (2018, 2020), Chisholm (2018)
Schaerer+ (2016, 2018, 2022)
Xu+2022
→ **Low-z Lyman Continuum Survey**





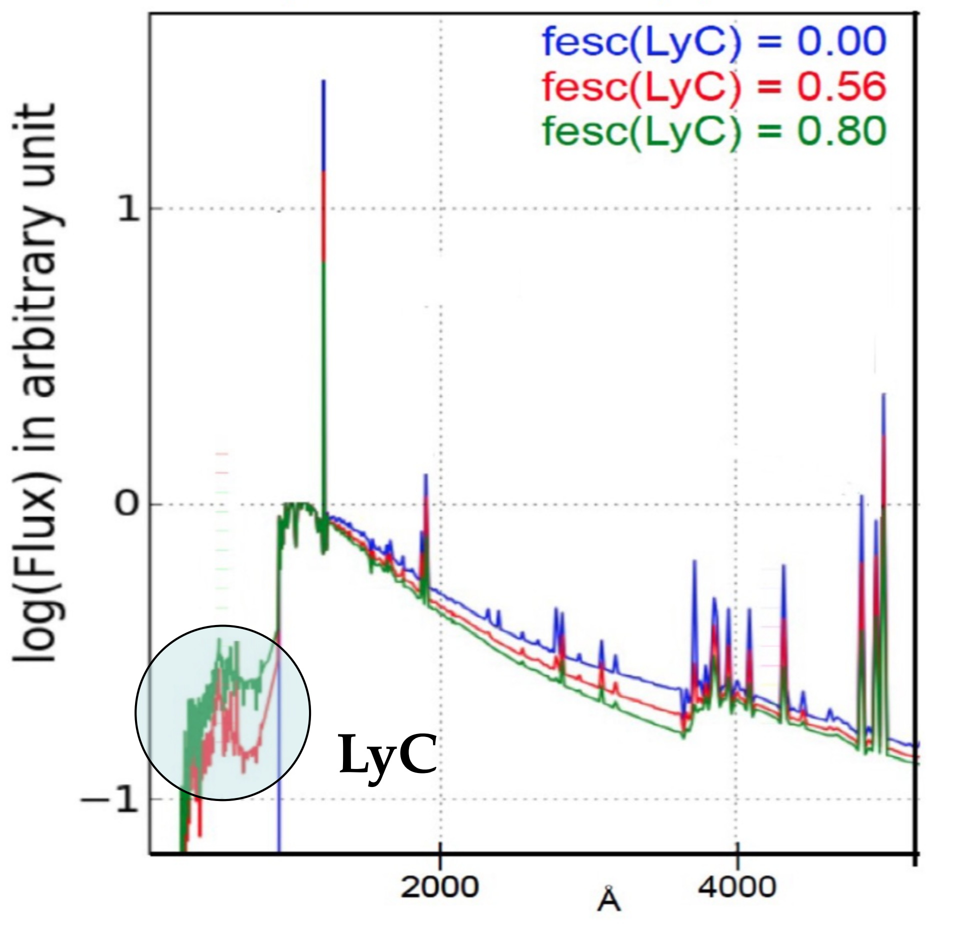






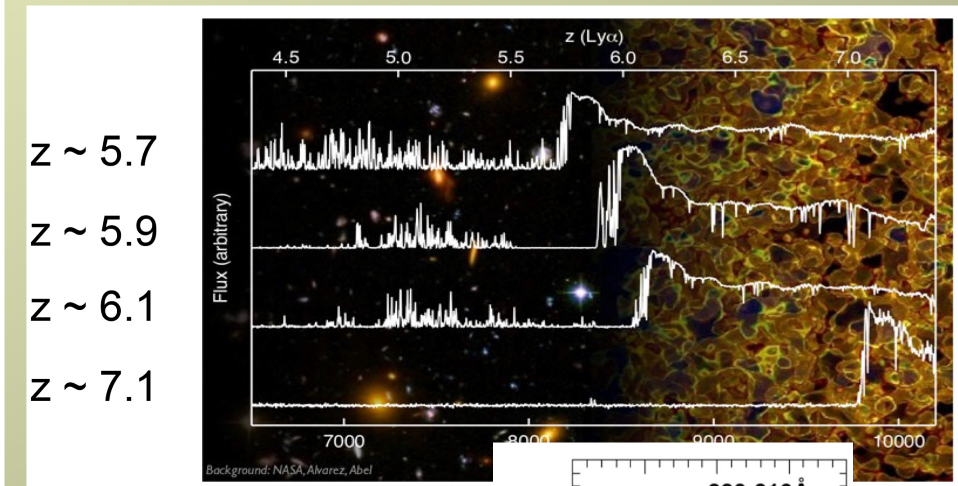
Signatures of the sources of cosmic reionisation

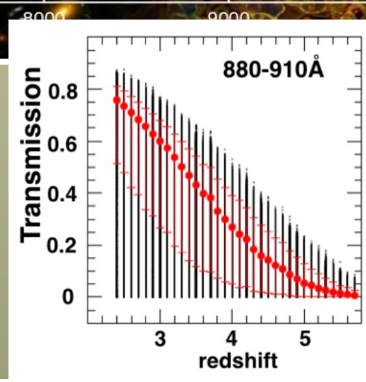
adapted from de Barros+18 in prep



Direct Lyman continuum (LyC) detection impossible at high redshift

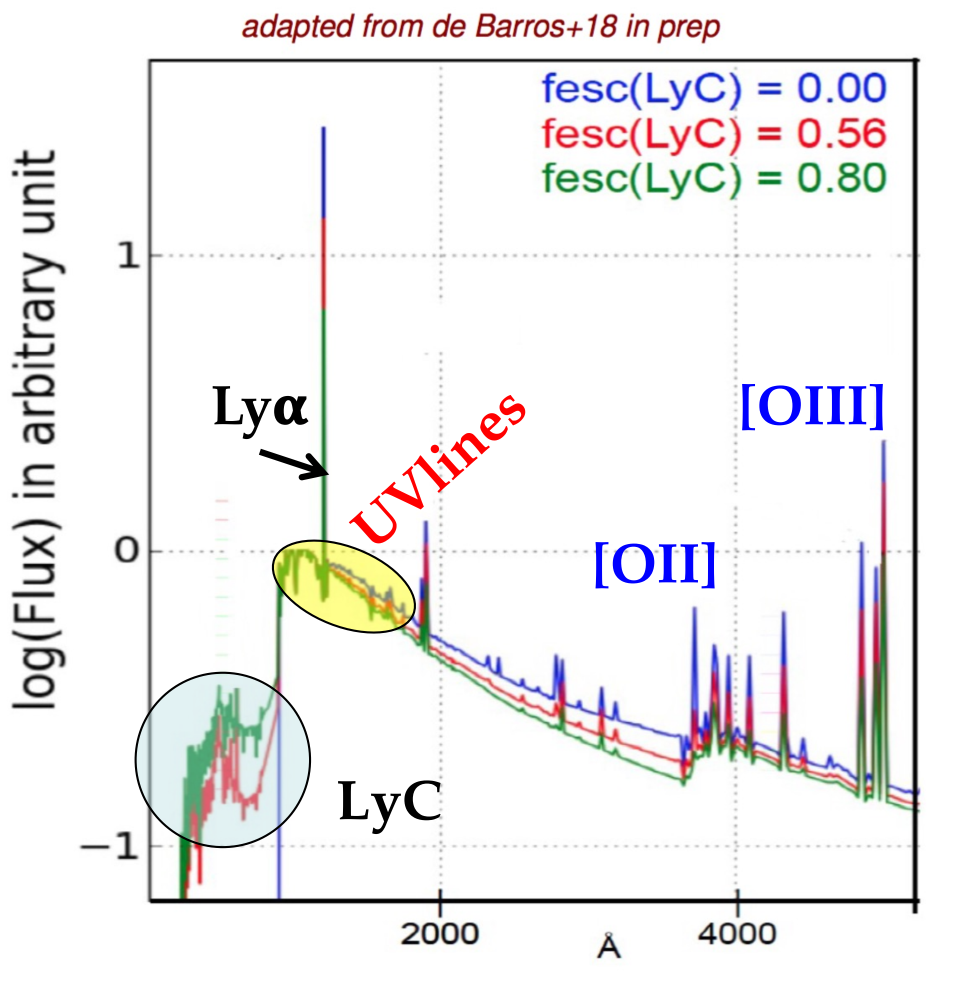
→ Need *indirect* LyC probes !





Inoue+, Siana+

Signatures of the sources of cosmic reionisation



Indirect LyC probes – *status in 2016*:

- High [OIII]/[OII] ratio
  Jaskot & Oey 2013, Nakajima+ 2014
- Lyman-alpha emission
  Verhamme+ 2015, Djikstra & Gronke 2016
- UV absorption lines
  e.g. Heckman+ 2011

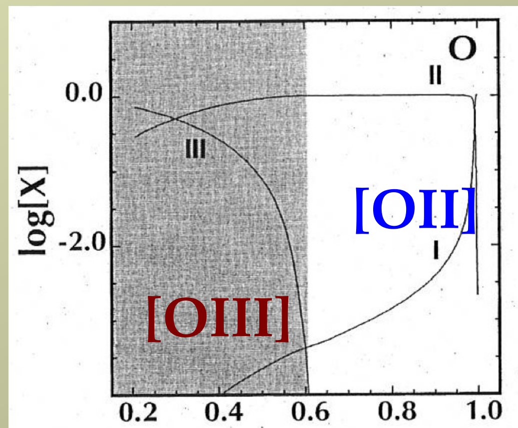
The quest for the sources of cosmic reionisation - a recent breakthrough

COS-HST cycle 22+24 programs: *measure Lyman continuum and test indirect indicators* (Izotov, Schaerer, Verhamme, Thuan, Orlitova, Guseva)

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

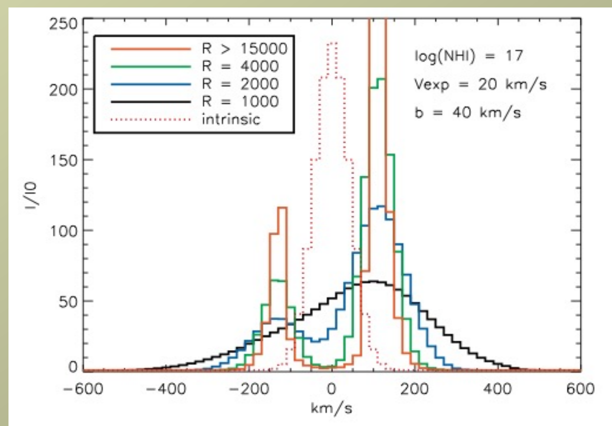


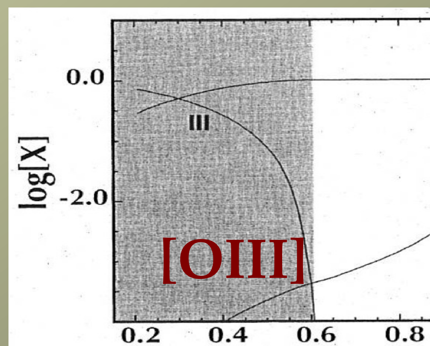
Strömgren radius ↑

G140M, G160M grism observations to cover:

- Lyman continuum
- Lyman alpha
- UV absorption lines

Verhamme et al. (2015)



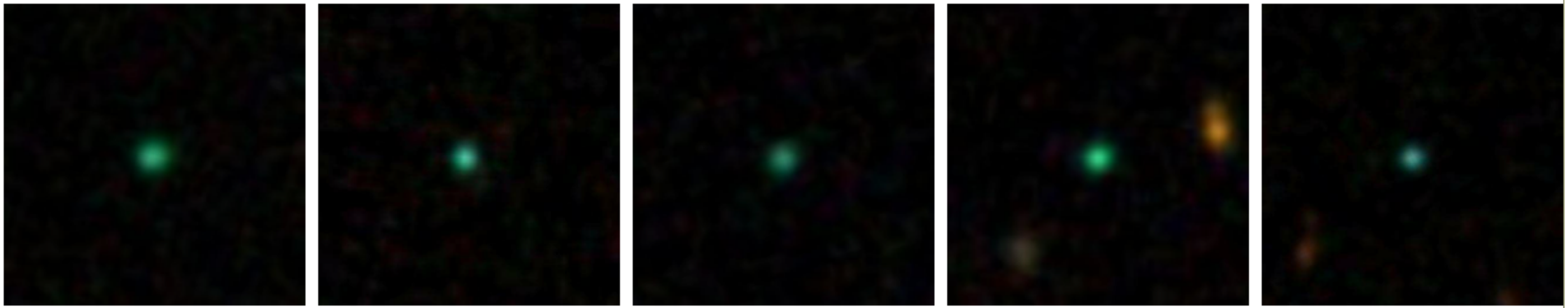


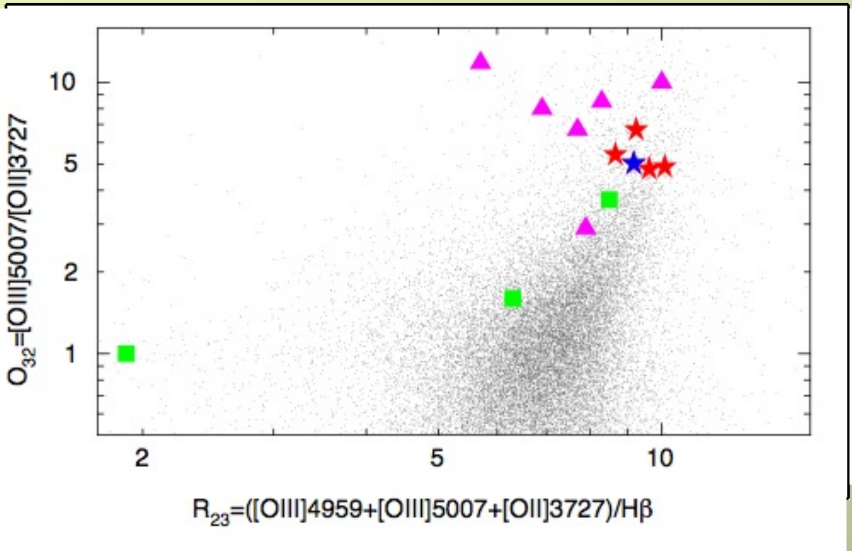
[OII] missing

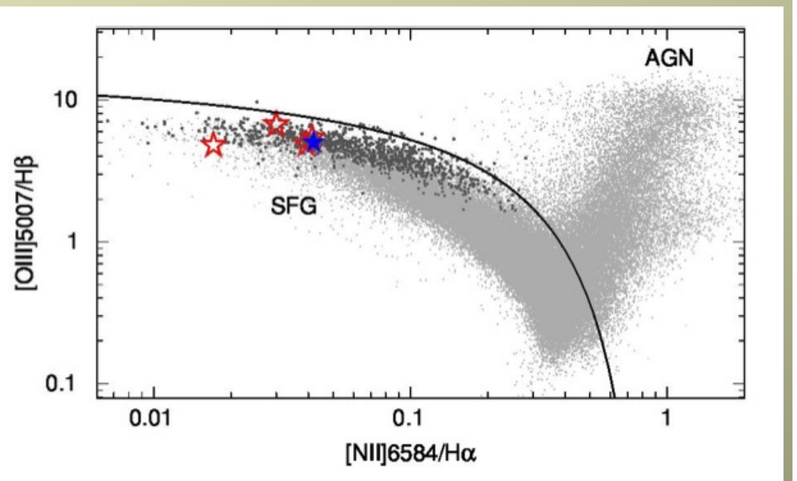
Strömgren radius ↑

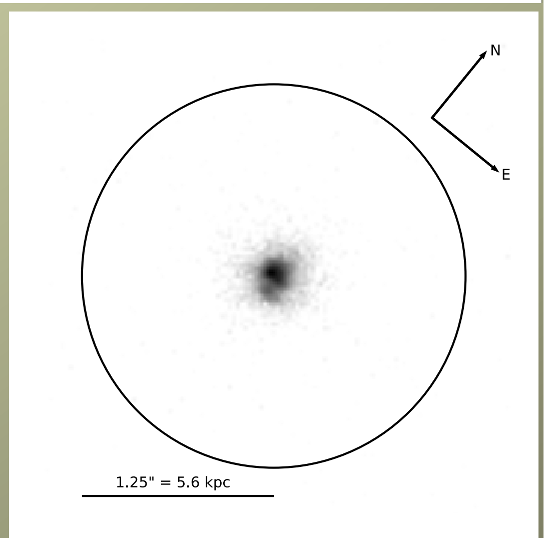
The quest for the sources of cosmic reionisation

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

HST/COS discoveries

Izotov, Orlitova, Schaerer, Thuan, Verhamme, Guseva, Worseck (2016)

Izotov et al. (2016b, 2018ab, 2021)

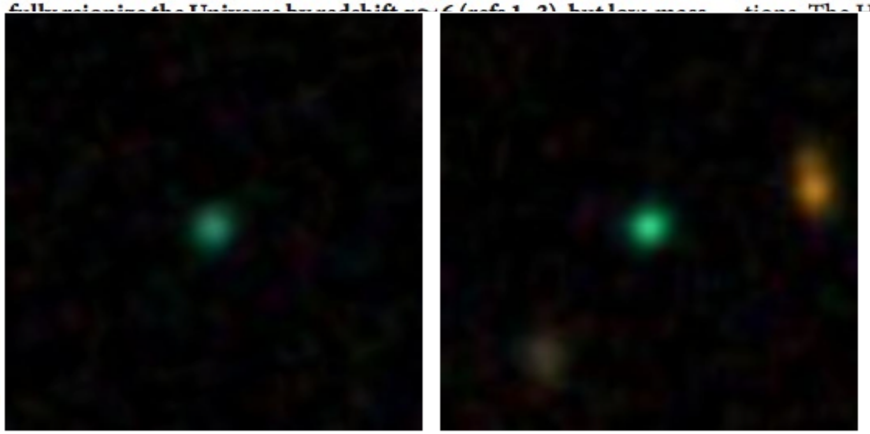
LETTER

doi:10.1038/nature16456

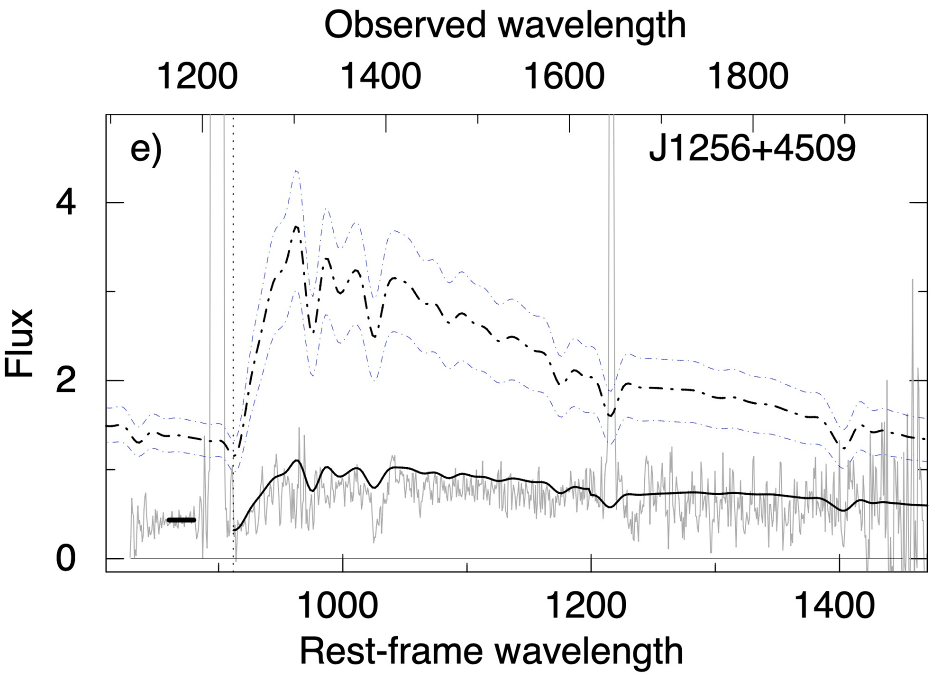
Eight per cent leakage of Lyman continuum photons from a compact, star-forming dwarf galaxy

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



star-formation rate, J0925+1403 shares r
high-redshift Lyman-α (Lyα) emitters.
GPs with $O_{32} \geq 5$ have been observed be
low redshifts $z < 0.3$ were not optimal for Ly
5 (program GO13744; PI, T.X
age shows the galaxy to have
ght angular diameter of ~0.2
aperture of 2.5″ (Fig. 2). Thi
ear diameter of ~1 kpc at the
erived from the redshift $z = 0$
ological parameters $H_0 = 67.1$
8 (ref. 19).
J0925+1403 were obtained
n G140L grating (<900 − 2,
that includes the redshifted Ly
ure time of 5,649 s. The mediu
796 Å) was used to obtain the s
α λ1,216 Å line, with an exp



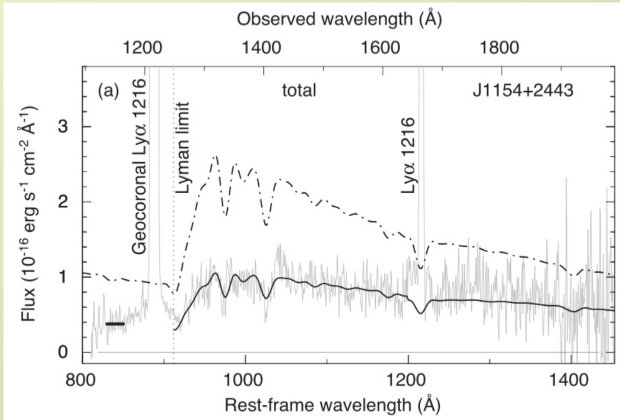
Strong Lyman continuum leakers at z=0.3

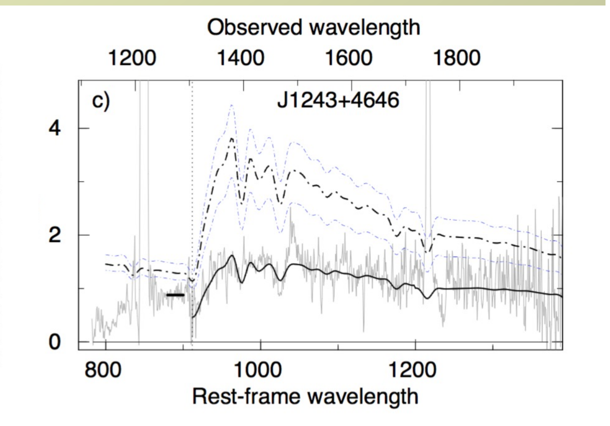
Cycle 24 observations:

6 new sources with O32>10

→ Total 11 z~0.3-0.4 galaxies

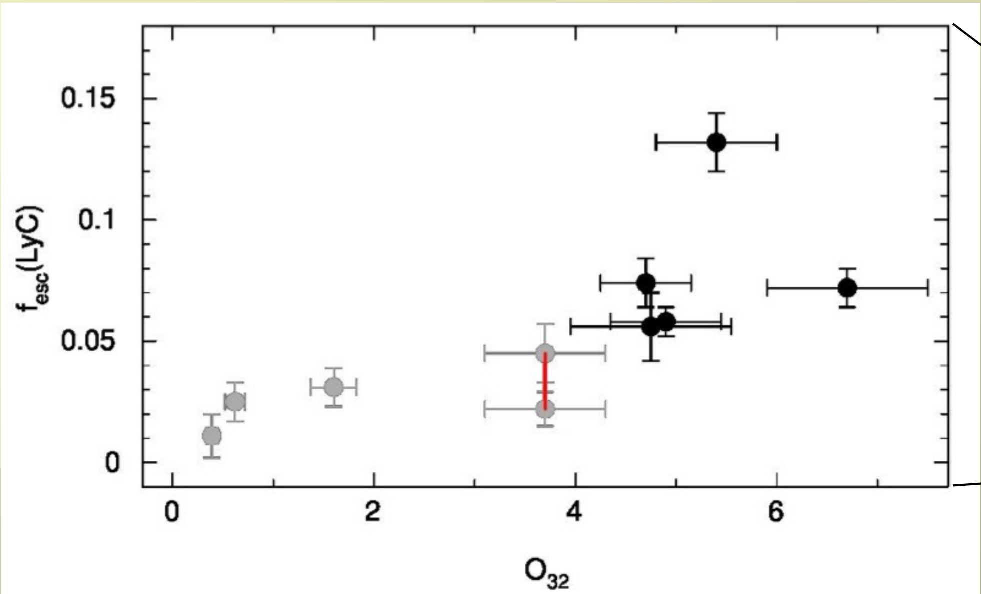
- **100% LyC detection →** **efficient selection criteria** (O32/>4, compact, strong EL)
- **3 sources with fesc > 40%**
- **Wide range of fesc**

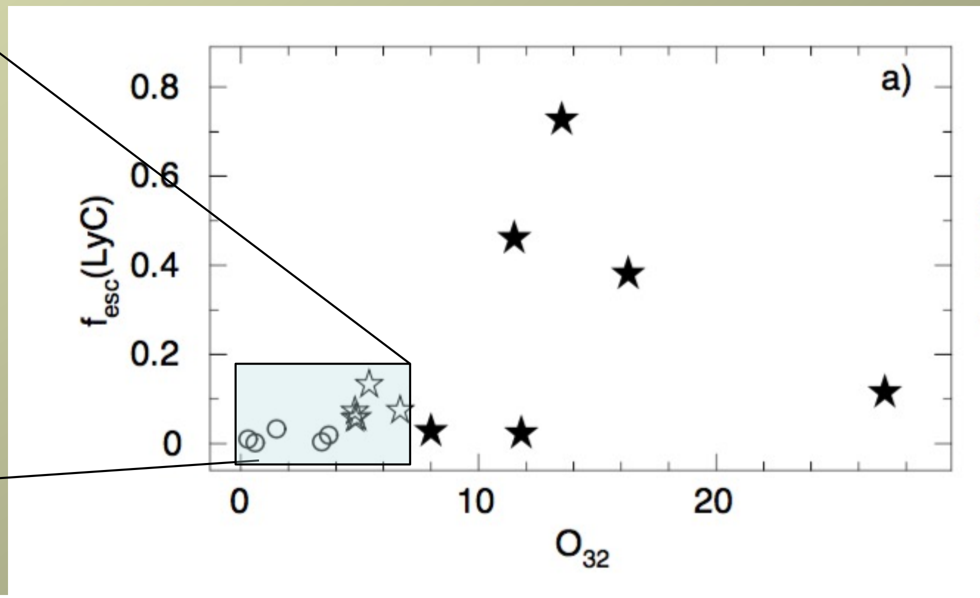




Izotov et al. (2016b)

Izotov et al. (2018ab)





Lyman-alpha properties of Lyman continuum leakers

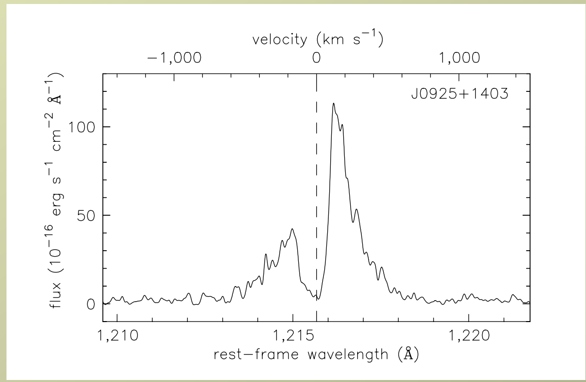
Verhamme et al. (2017, A&A 597, A13)

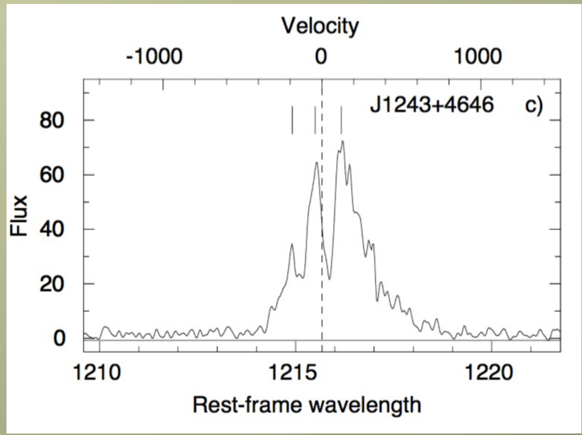
- **Strong Lyα emission (EW>70 Ang)**
- **Double-peaked profiles**
- **Small peak separation**

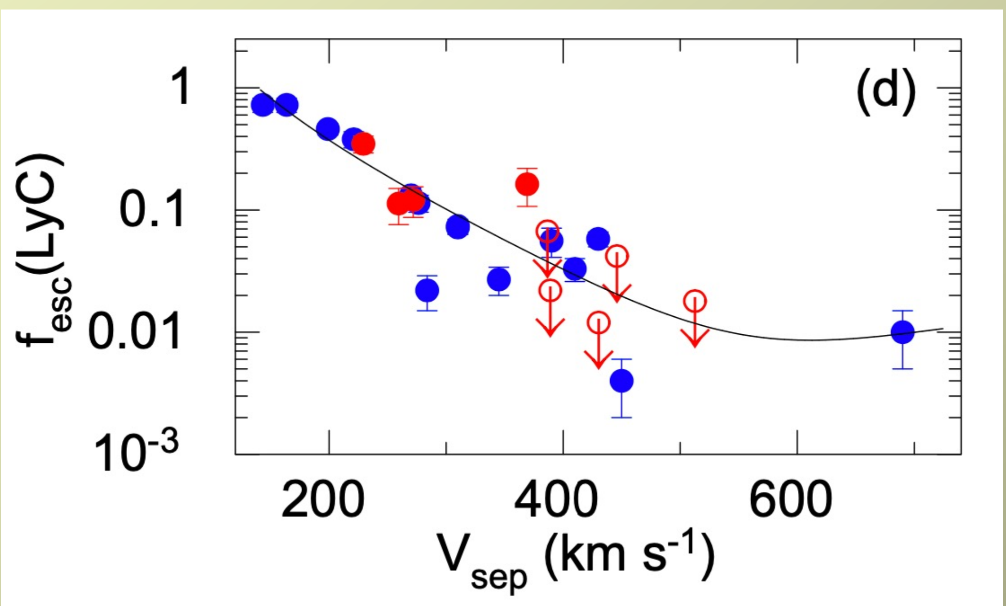
  as predicted by Verhamme et al. (2015)

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

→ **Low HI column density**







Izotov et al. (2021)

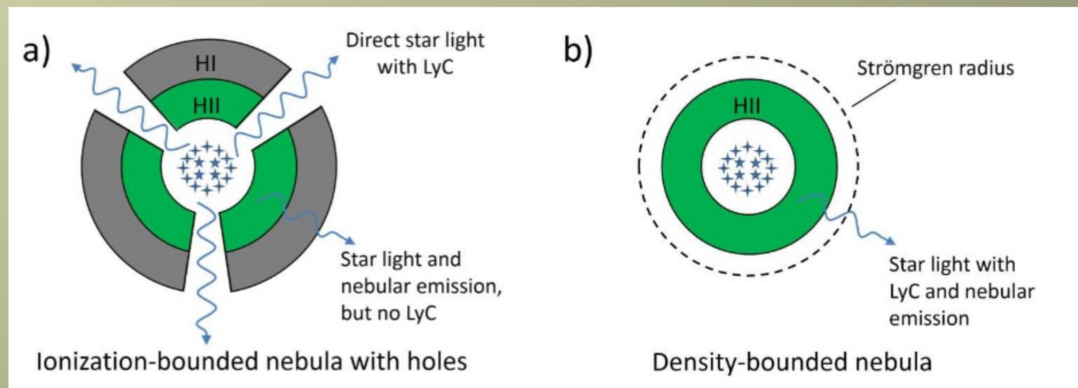
Neutral gas properties of LyC emitting galaxies

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

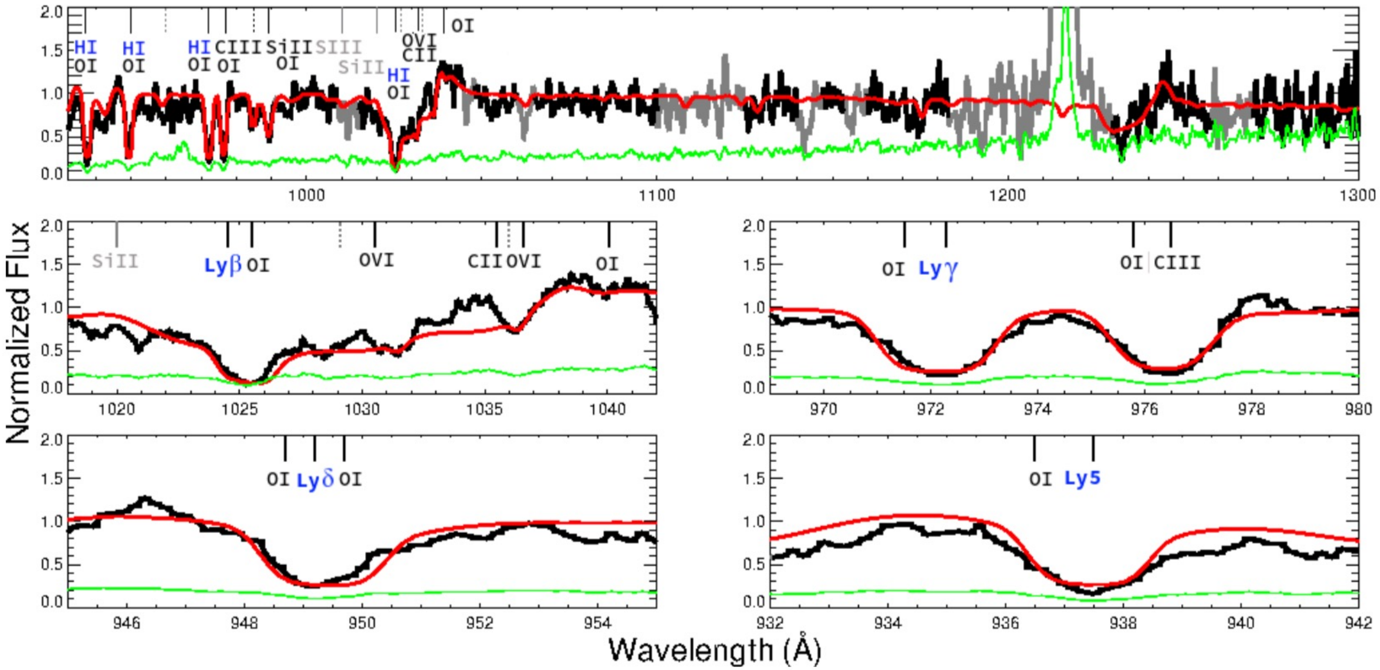
- 9 known LyC leakers (COS spectra, z~0-0.3)
- 6 other star-forming galaxies with COS Lyman-series coverage (z~0.1-0.3)
- High-res (R~3000-4000) rest–UV spectra of lensed galaxies at z~2-3 including 'Cosmic Horseshoe' (MEGASAURA, Rigby+ 2017)

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

→ Gazagnes et al. (2018), Chisholm et al. (2018)
Large sample:
Saldana-Lopez et al. (2022)

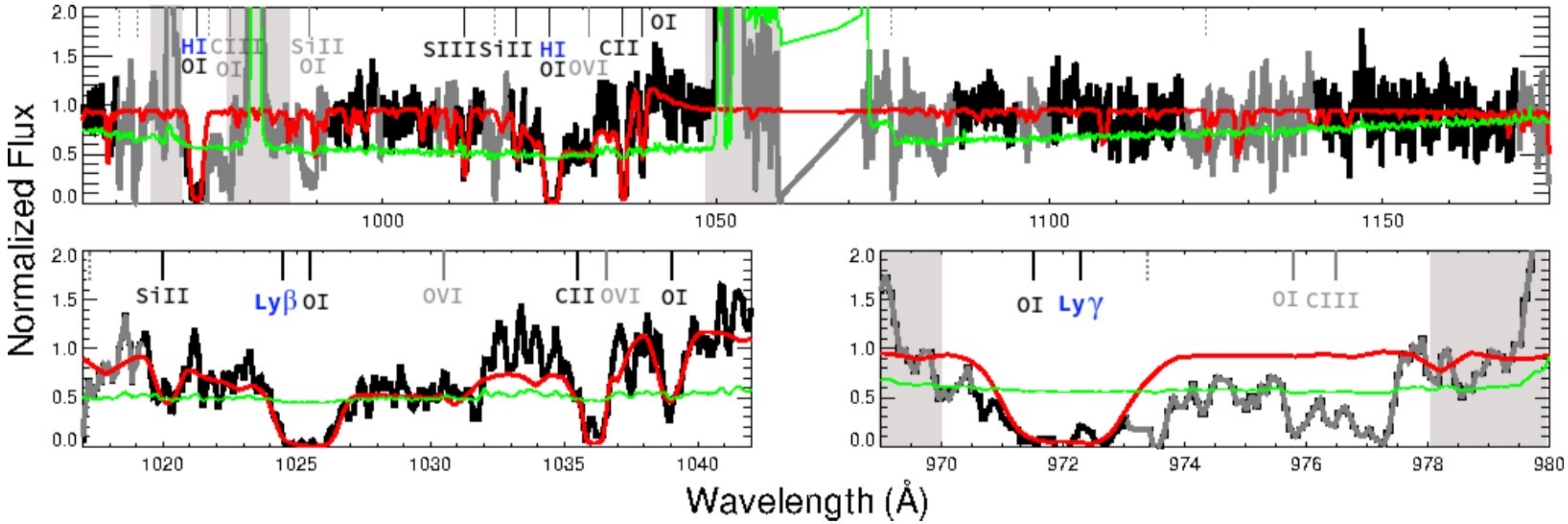


Neutral gas properties of LyC emitting galaxies



confirmed leaker
J1503+3644
(Izotov+ 2016)

GP 1244+0216
(Henry+ 2015)



Gazagnes
et al.
(2018)

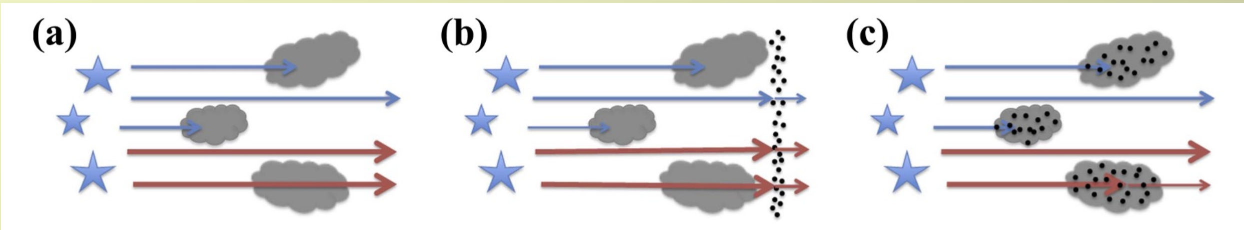
Neutral gas properties of LyC emitting galaxies

UV spectral fitting of:

- stellar continuum + lines (theoretical Starburst99)
- UV attenuation (Reddy+ 2017 + other laws)
- ISM absorption lines (HI, OI, OVI, CII, CIII, SiII)

Picket-fence ISM model:

- Described by geometric covering fraction C_f
- Assumption on spatial distribution of dust



Vasei+ 2016

Consistent solution of the transfer equation:

(b)
$$F_\lambda = F_\lambda^\star \times 10^{-0.4 k_\lambda E_{\mathrm{B-V}}} \times \left(C_f \exp(-\tau_\lambda) + (1 - C_f)\right),$$

(c)
$$F_\lambda = F_\lambda^\star \times 10^{-0.4 k_\lambda E_{\mathrm{B-V}}} \times C_f \exp(-\tau_\lambda) + F_\lambda^\star \times (1 - C_f),$$

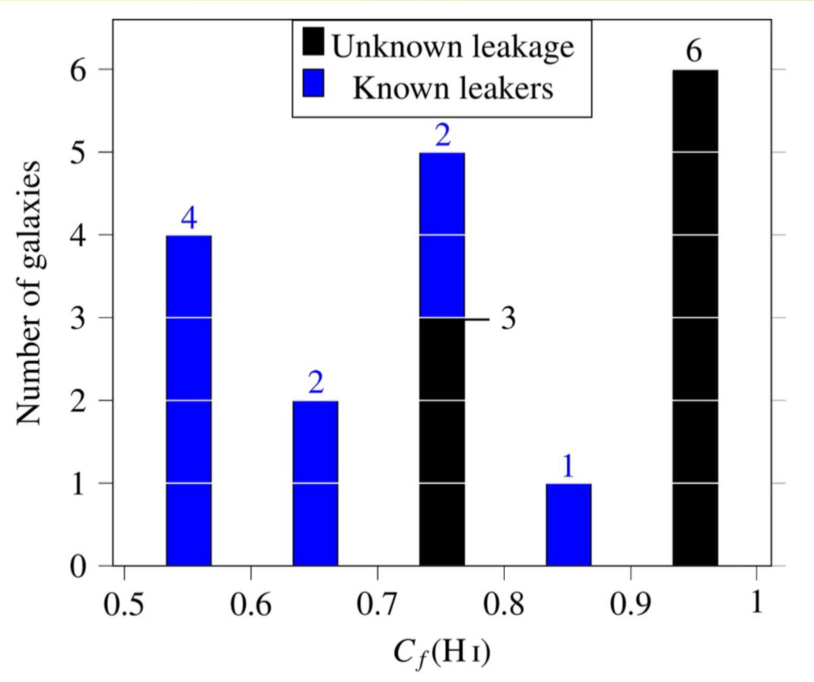
Table 2: Fitted absorption lines

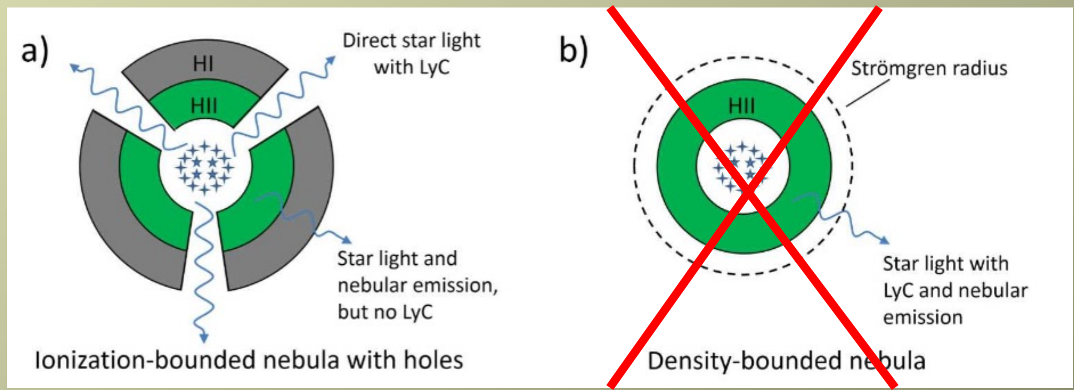
Atom	λ_{rest} [Å]
H I	920.947[a]
	923.150[a]
	926.225[a]
	930.748
	937.803
	949.743
	972.536
	1025.473
O I	924.950[a]
	929.517
	930.256
	936.629
	948.685
	950.885
	971.738
	976.448
	988.578
	988.655
	988.773
	1025.762
	1039.230
	1302.168[b]
O VI	1031.926
	1037.616
C II	1036.337
C III	977.030
Si II	989.870
	1020.70
	1190.42[c]
	1193.28[c]
	1260.42[c]

Neutral gas properties of LyC emitting galaxies

Main results (Gazagnes et al. 2018):

- **HI lines are saturated** (but mostly not damped; $N_{HI} \sim 10^{16}$ to 10^{20} cm^{-2})
  N(HI) values from unsatured OI lines (using known metallicity O/H)
- LyC leakers have covering fraction < 1
  → **escape of photons through holes**
- SiII 1190, 1260 Å covering fraction is lower than HI C_f
  → empirical relation between SiII and HI





Predicting ionizing photon escape from UV absorption lines

Predicting fesc(Lyc) from the measured UV line + continuum fits
→ Chisholm et al. (2018)

→ Absolute escape fraction of Lyman continuum photons
Uniform dust screen:

$$f_{\rm esc}^{\rm pre} = 10^{-0.4 \mathrm{E}_{B-V} k_{912}} \times \left(1 - C_f^{\rm H}\right)$$

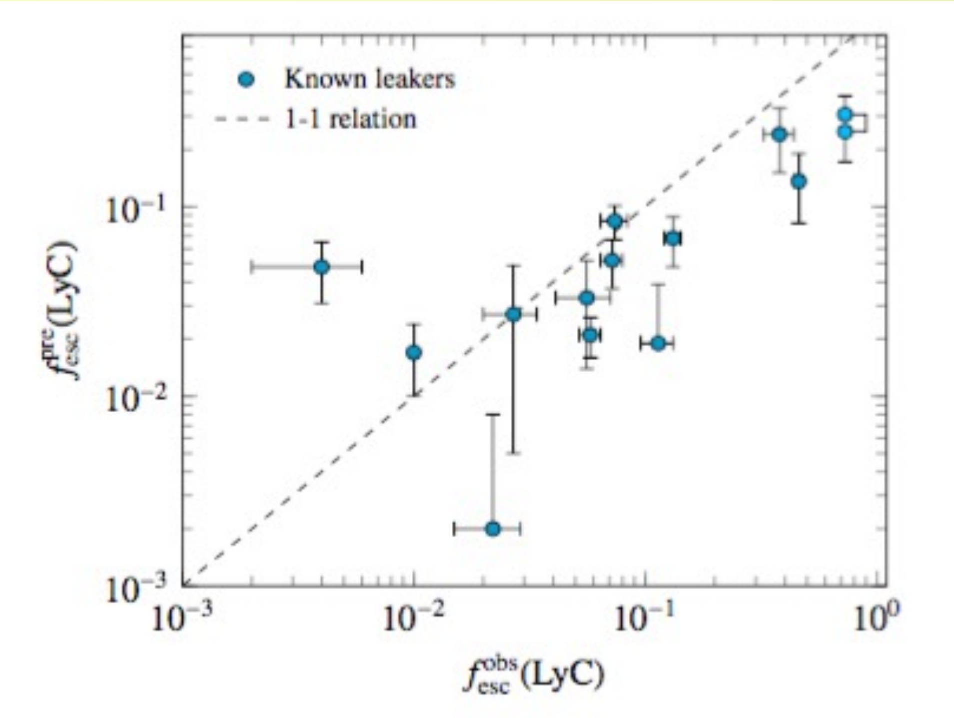
Clumpy dust distribution:

$$f_{\rm esc}^{\rm pre,\,clumpy} = C_f^{\rm H} \times 10^{-0.4 E_{\rm B\text{-}V} k_{912}} \times \mathrm{e}^{-\tau_\lambda} + \left(1 - C_f^{\rm H}\right)$$

~(1-C_f) for saturated HI
=! (1-R)

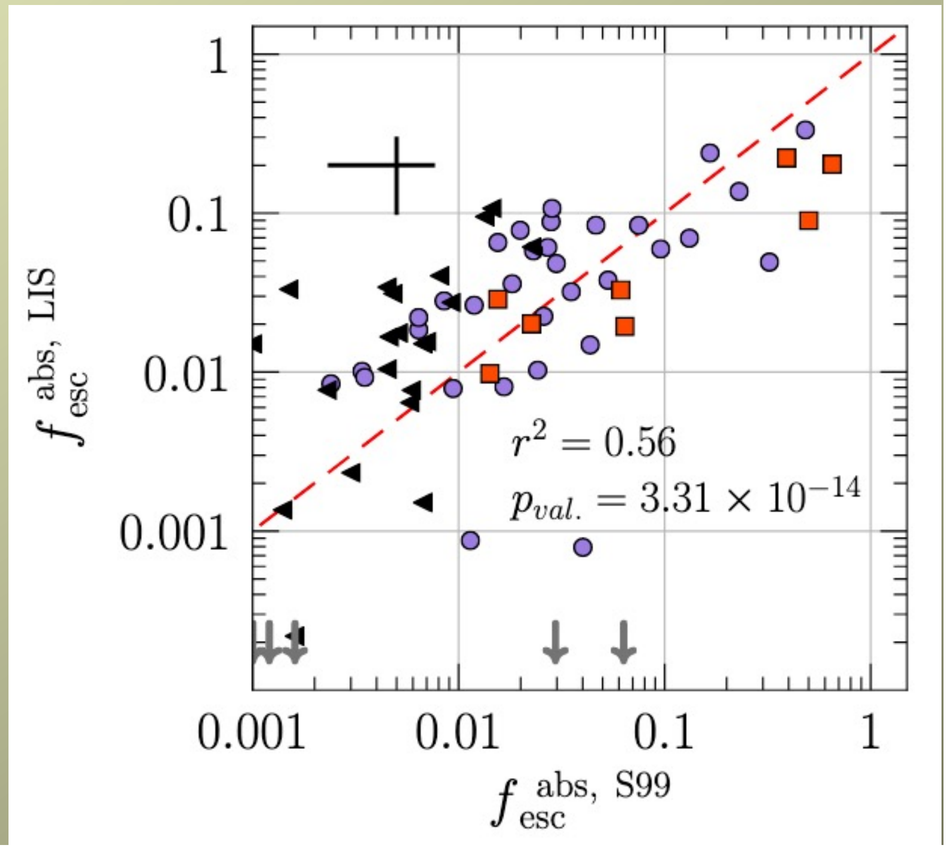
➔ Consistent modeling of continuum + lines + geometry UV attenuation needed !

Predicting ionizing photon escape from UV absorption lines (+UV modeling!)



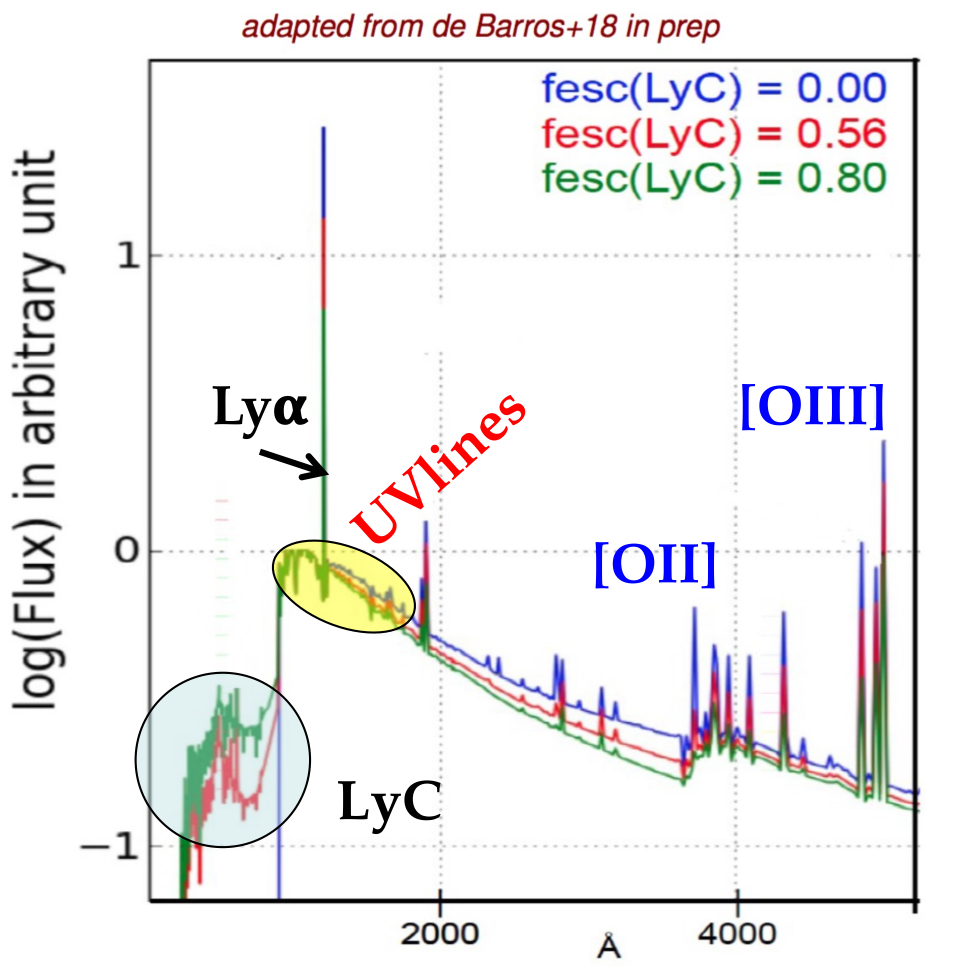
Gazagnes et al. (2020)

- Measured HI covering fraction
  → **good agreement with observed LyC escape fraction**
- UV attenuation fundamental for accurate fesc prediction (consistent modeling!)



Saldana-Lopez et al. (2022)

Signatures of the sources of cosmic reionisation



Indirect LyC probes:

✓ High [OIII]/[OII] ratio
Jaskot & Oey 2013, Nakajima+ 2014

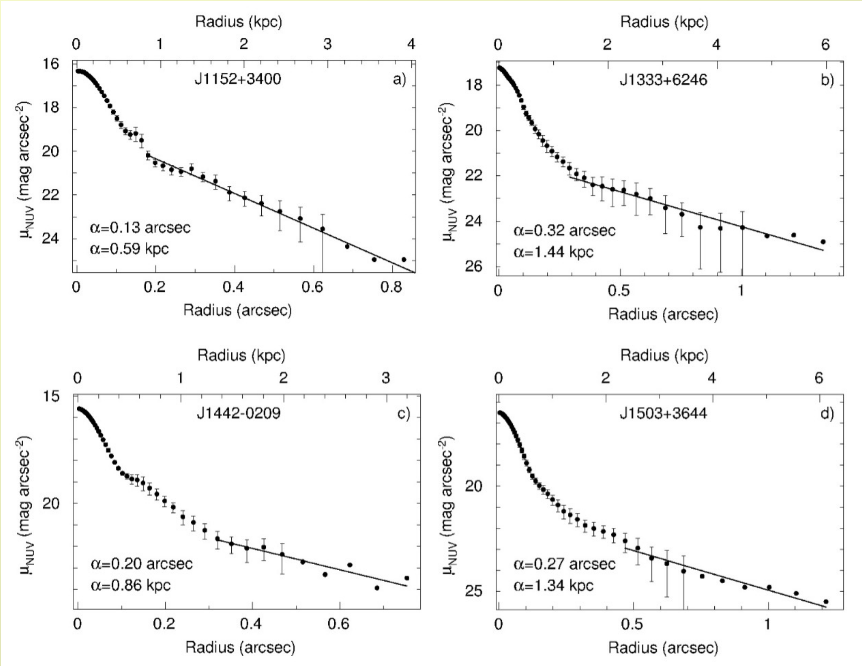
✓ Lyman-alpha emission
Verhamme+ 2015, Djikstra & Gronke 2016

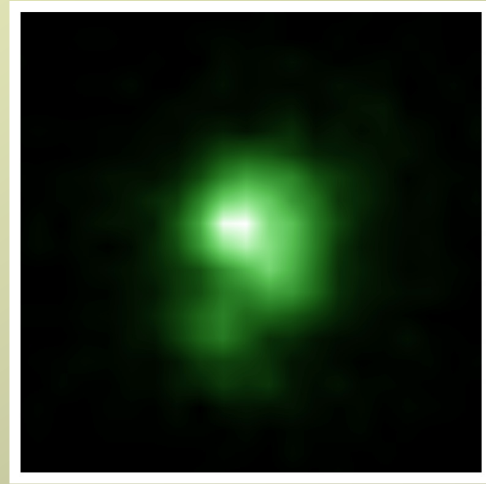
✓ UV absorption lines
e.g. Heckman+ 2011, Gazagnes+2018, Chisholm+ 2018

→ Diagnostics validated for JWST + ELTs!!

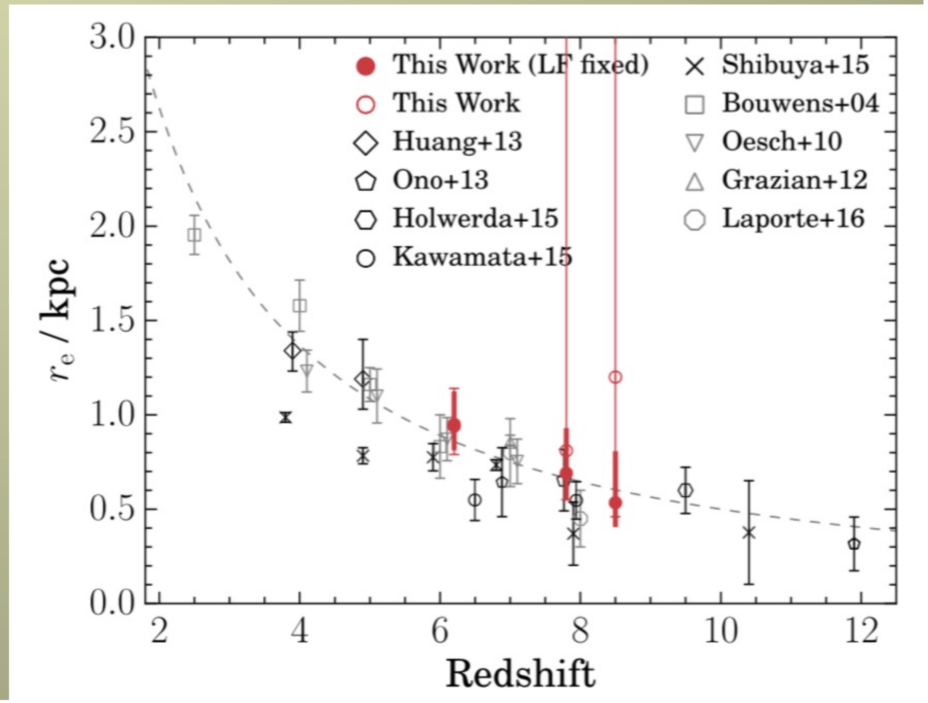
Properties of strong LyC leakers at z=0.3

Compact SF galaxies – « Green Pea » like





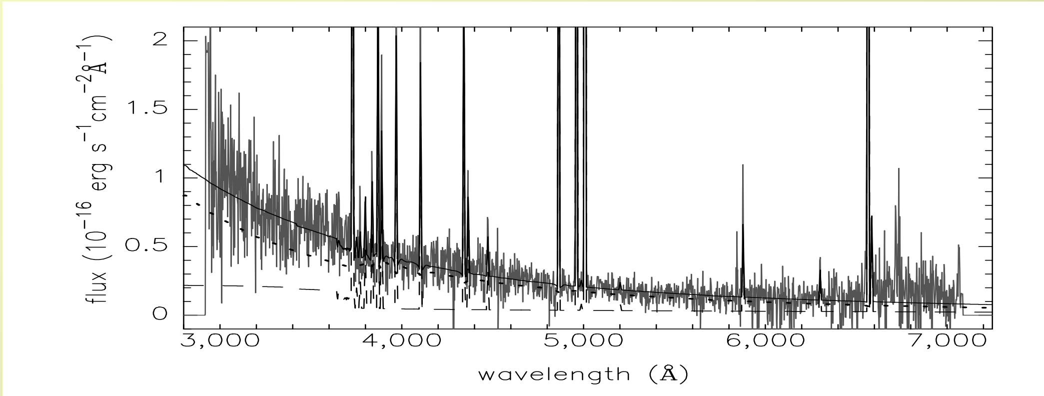
UV half-light radii <0.4 kpc

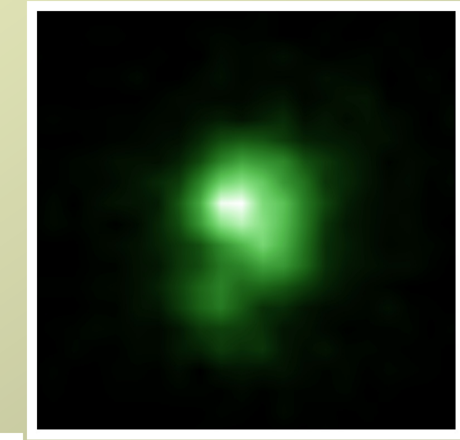


Kawamata et al. 2018

Properties of strong LyC leakers at z=0.3

J0925+1403
other properties

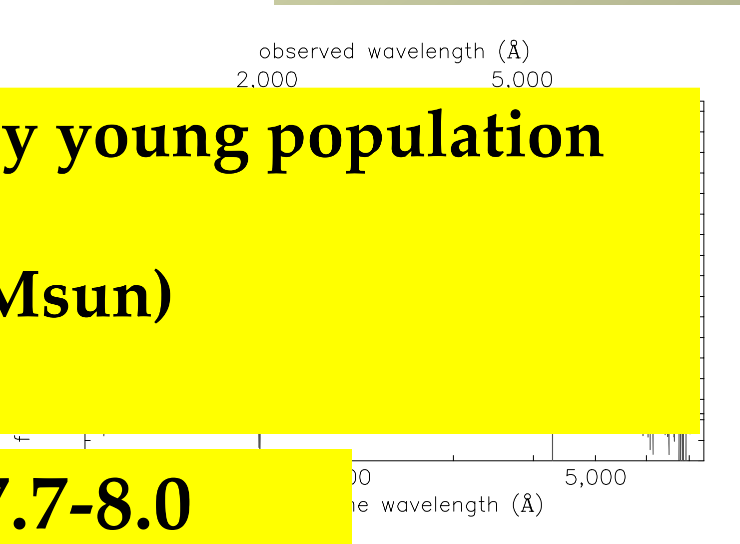




Extended Data Table 3 | Global characteristics of J0925+1403

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)**

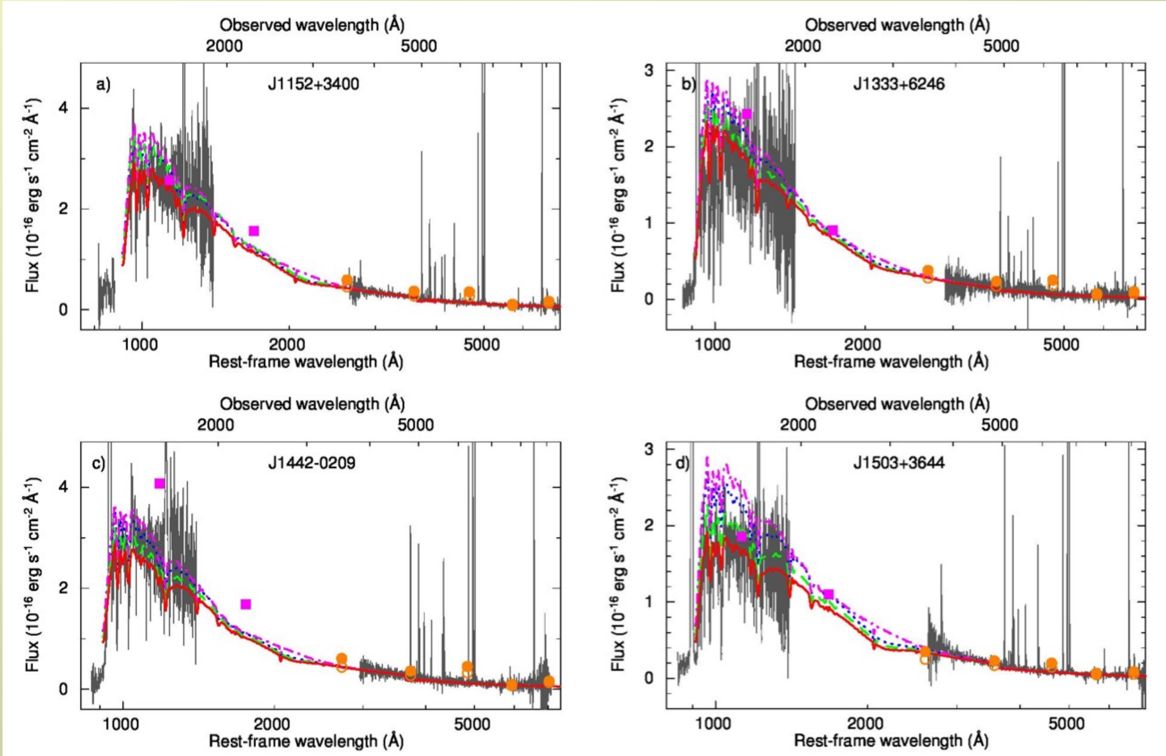
Metallicity 12+log(O/H)~7.7-8.0
~(0.12-0.25) solar

Low extinction: A_V~0.18-0.36

UV attenuation law

Steep UV attenuation law is required:

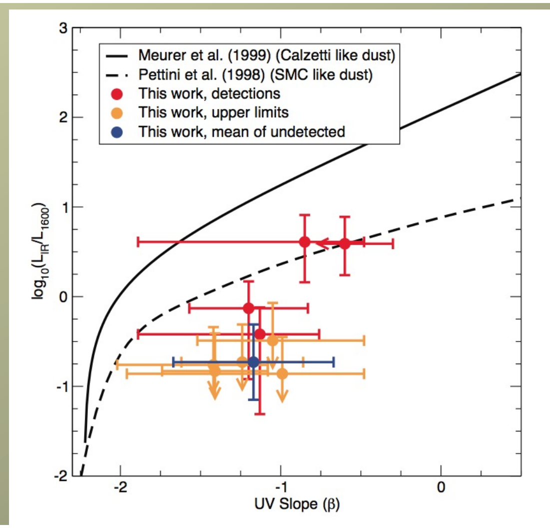
- R_V~2.4- 2.7 (not classical R_V=3.1)
- **Similar to SMC law**
- **Significantly steeper than Calzetti law**
- More appropriate for low metallicities?!



SMC type law also suggested for (**some**) high-z galaxies:

- young galaxies at z~2-3 (e.g. Reddy et al.
- Recent ALMA observations at z~5-6 (Capak et al. 2015)
- Other studies

Capak et al. (2015)



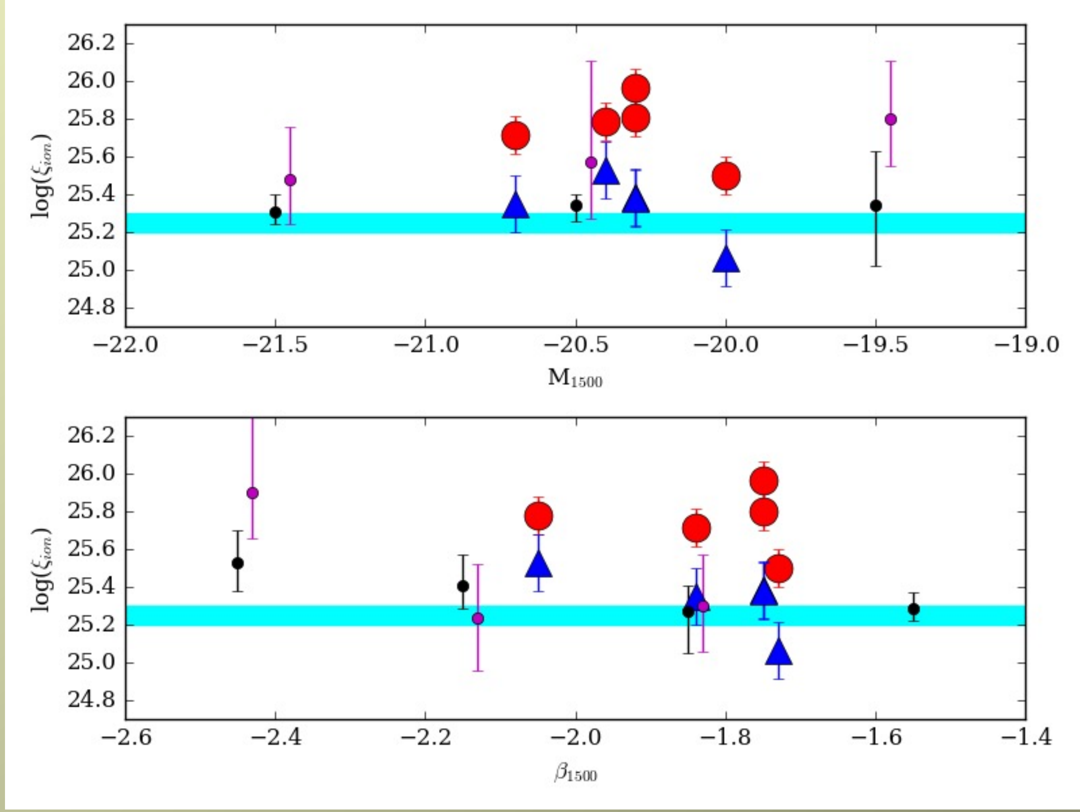
Lyman continuum leakers at z=0.3: Ionising photon production

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)

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

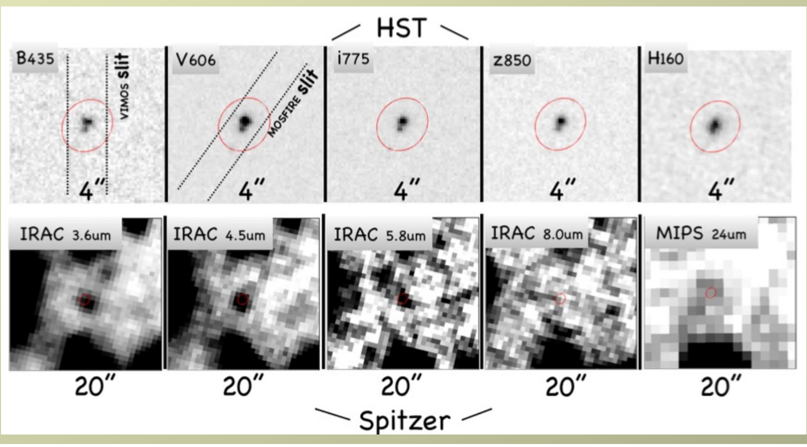
UV rest-frame mag_AB~24.5-25

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

→ Strong Lya emission

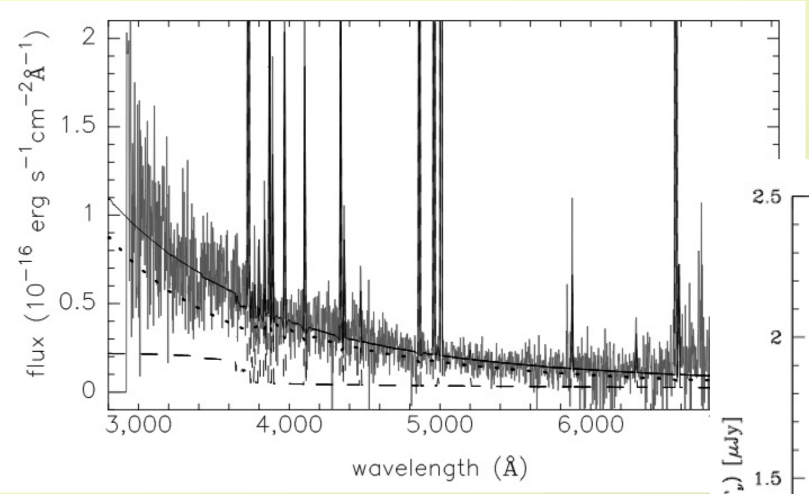
→ **High ratio [OIII]/[OII]>10, high [OIII]+Hb equivalent width (~1600 Ang)**

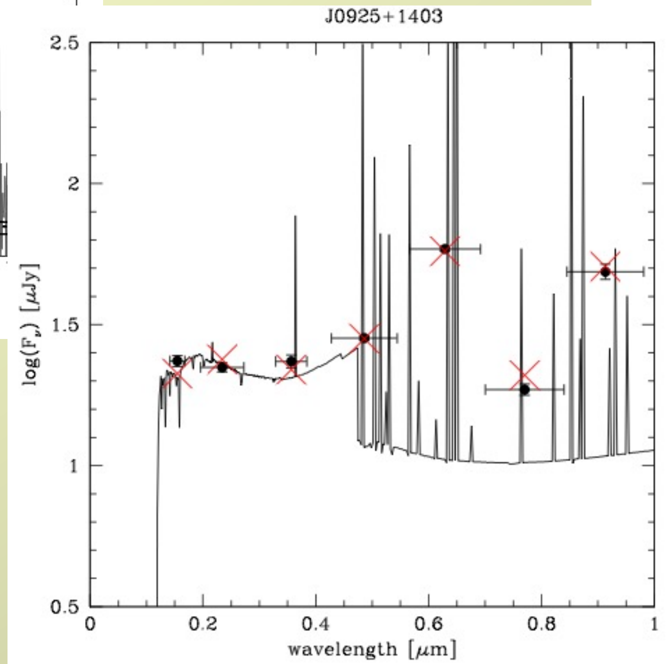
Vanzella et al. (2015), de Barros et al. (2016)

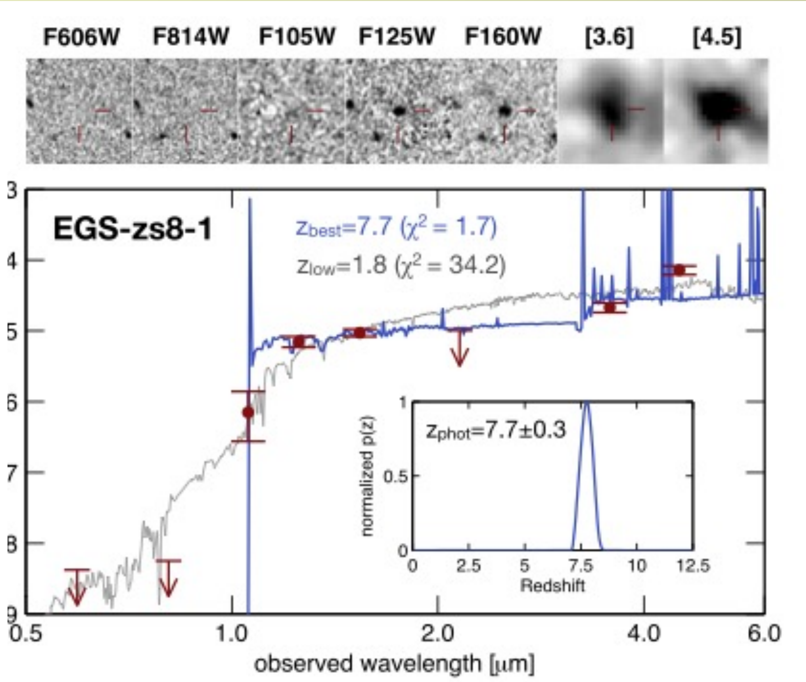


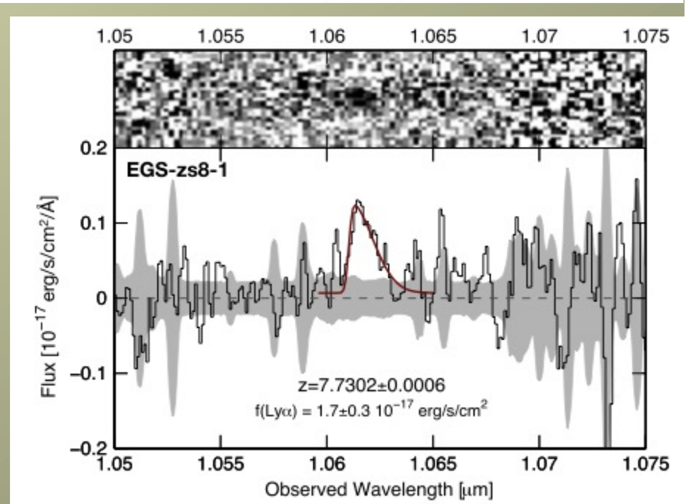
EL ratios, equivalent widths, stellar mass of our z~0.3 LyC leakers:
→ Comparable to Ion2

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)

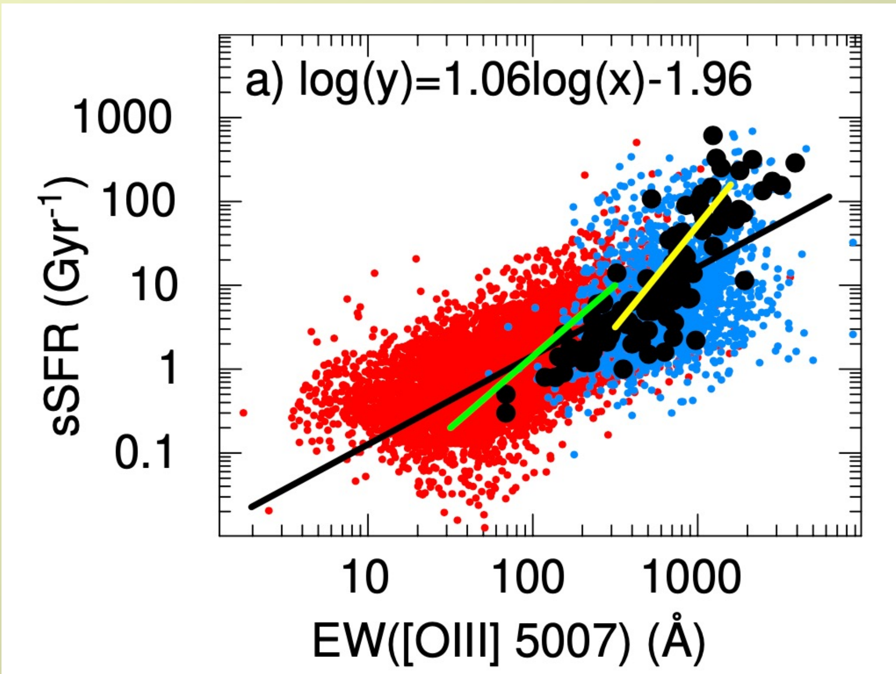
z=6.8: Schaerer et al. (2015)
Smit+ (2014)

Oesch et al. (2015) z=7.73

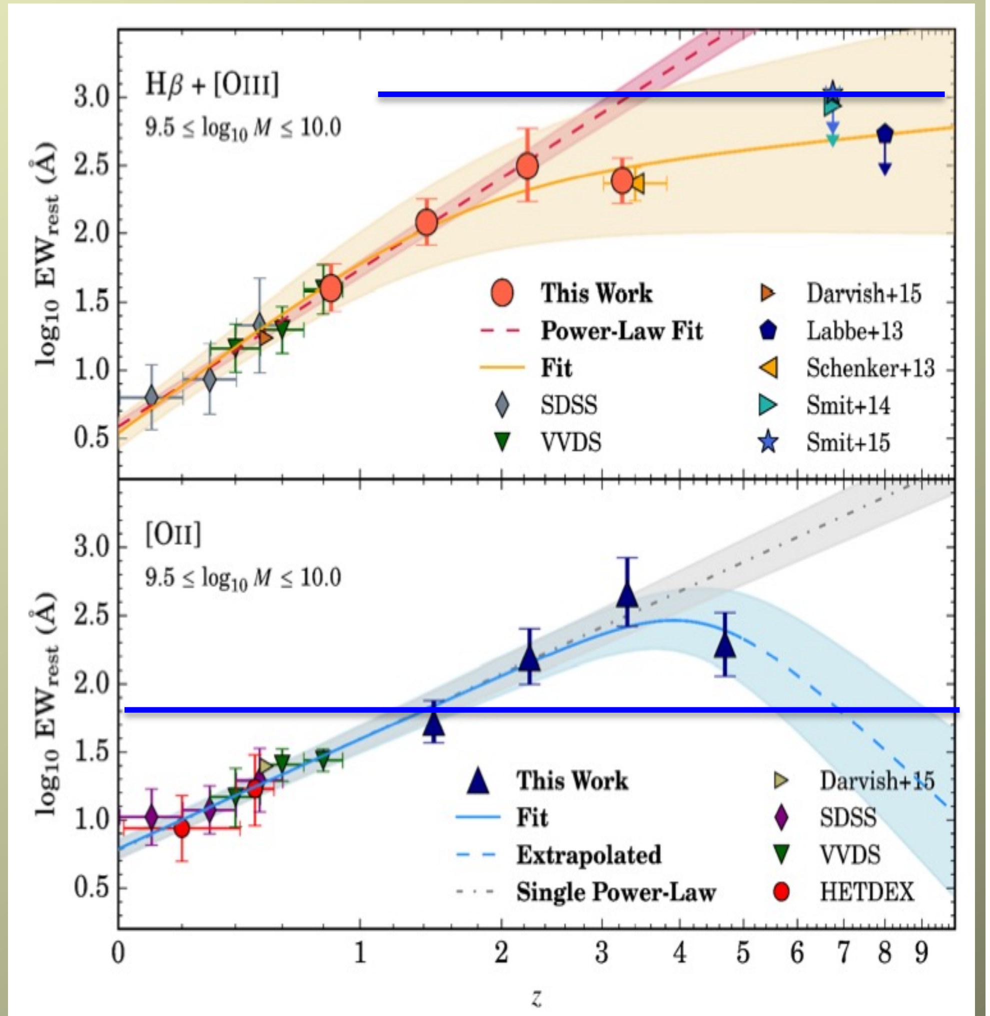
Strong Lyman continuum leakers at z~0.3: Good analogs of high-z galaxies

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

EW, stellar mass, size, SFR, SFR/area
…high gas density
See Schaerer et al. (2016),
Izotov et al. (2021)

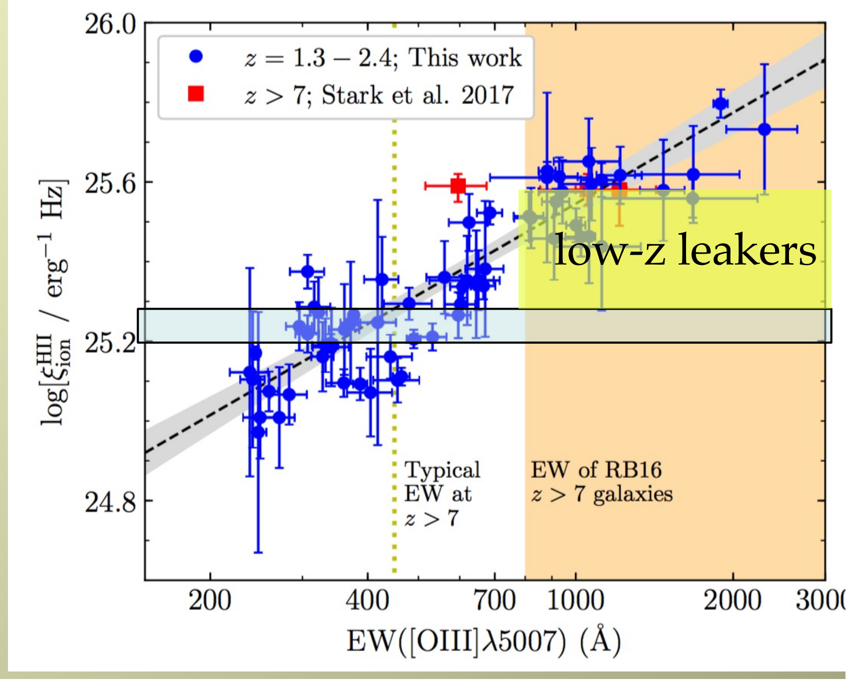


Khostovan et al. (2016)



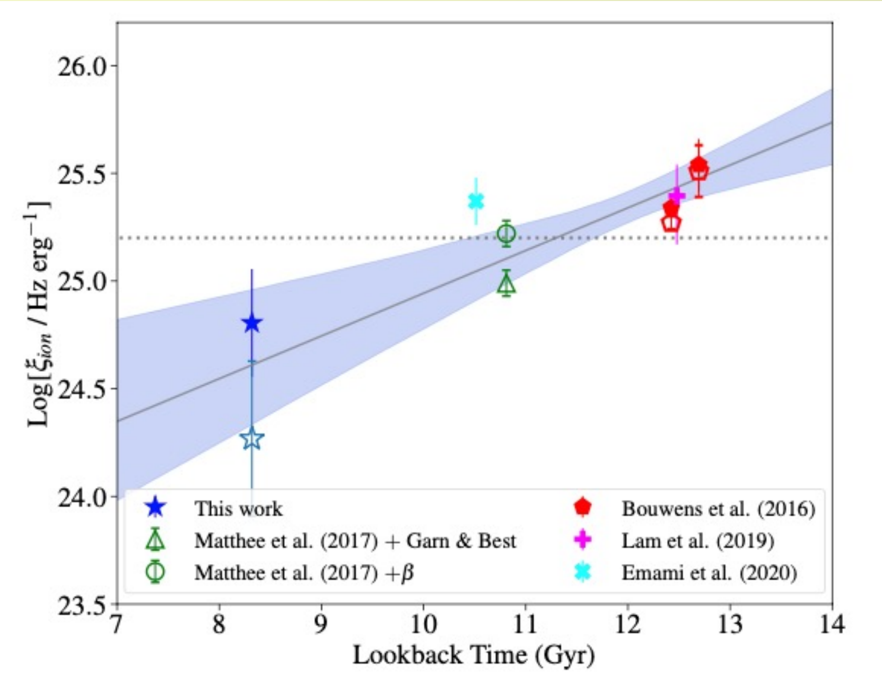
Ionizing photon production: the emergent picture

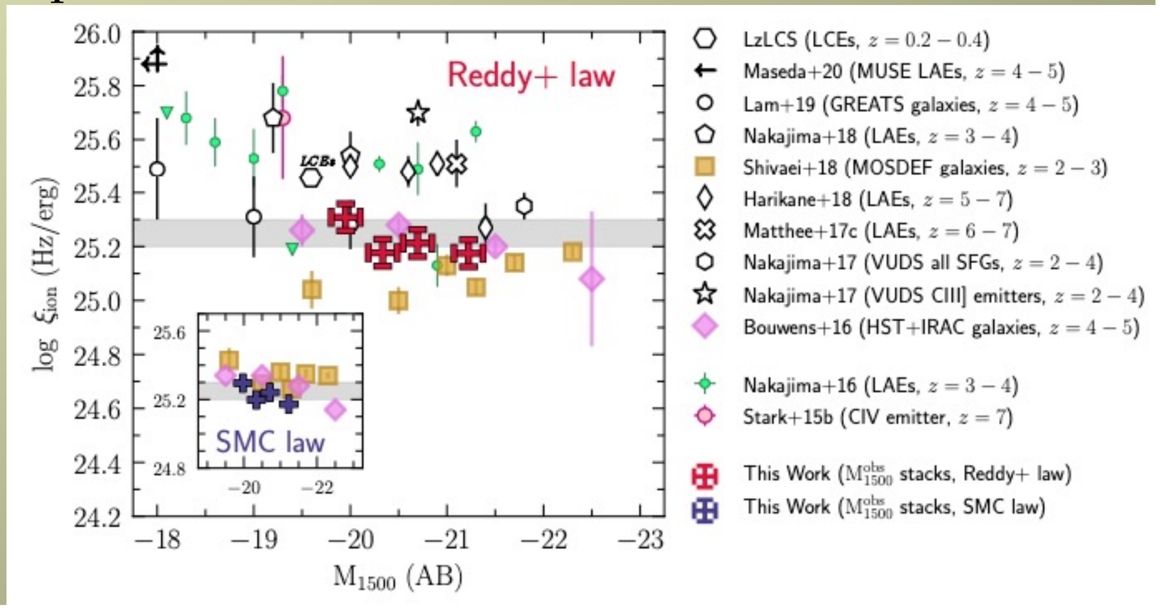
Increased H ionizing photon production at/in:
- **high-z**
- **faint galaxies**
- **strong emission line galaxies**



Tang et al. 2019

Saldana-Lopez+ in prep



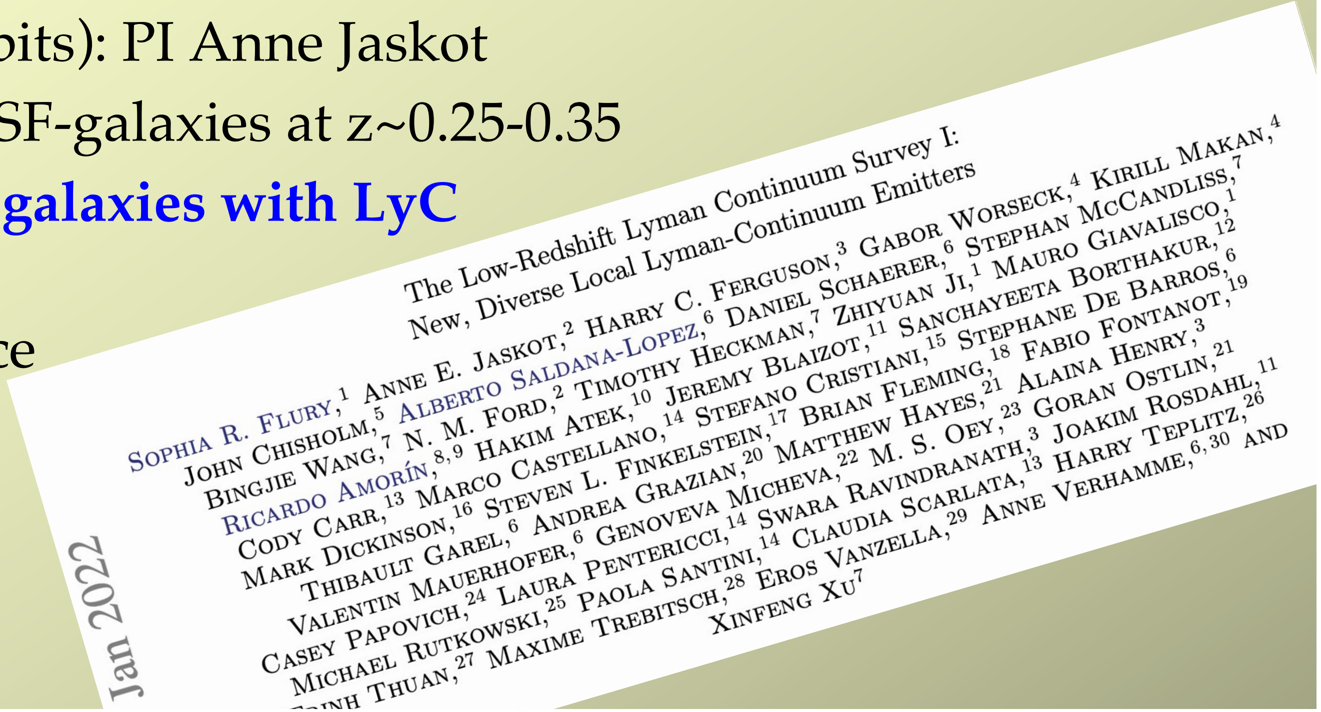


Atek et al. 2022, …Matthee et al. 2017

Low-z Lyman Continuum Survey (LzLCS)

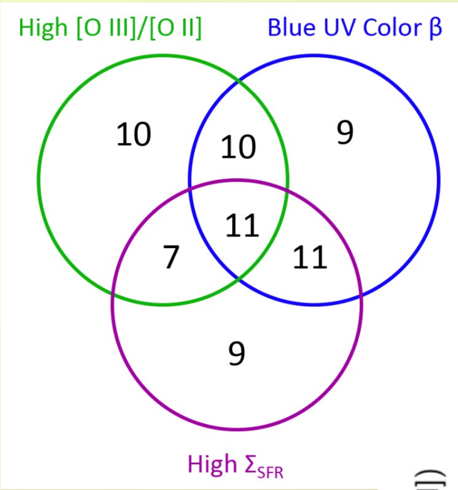
- HST Large program (136 orbits): PI Anne Jaskot
- COS UV observations of 66 SF-galaxies at z~0.25-0.35
- +other COS data → **total 89 galaxies with LyC**

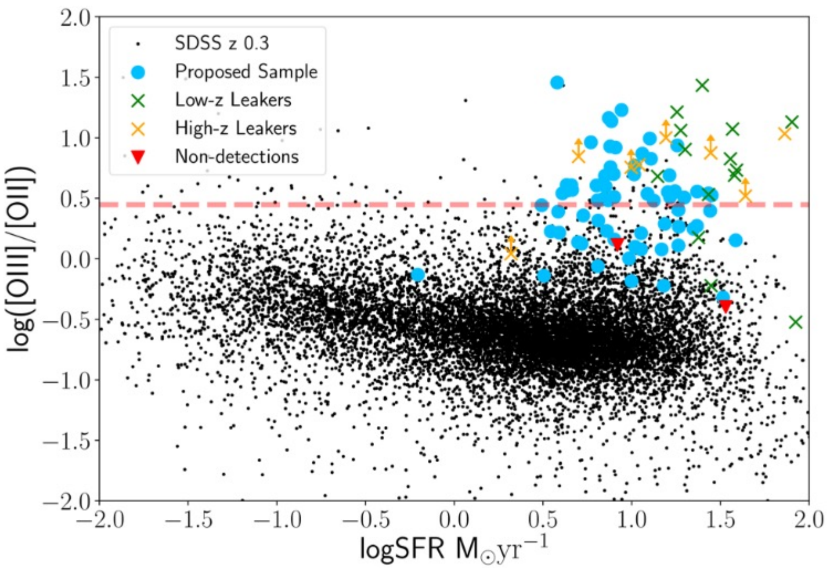
→ LyC to ~1400 Ang spectra
→ Probe ~wide parameter space

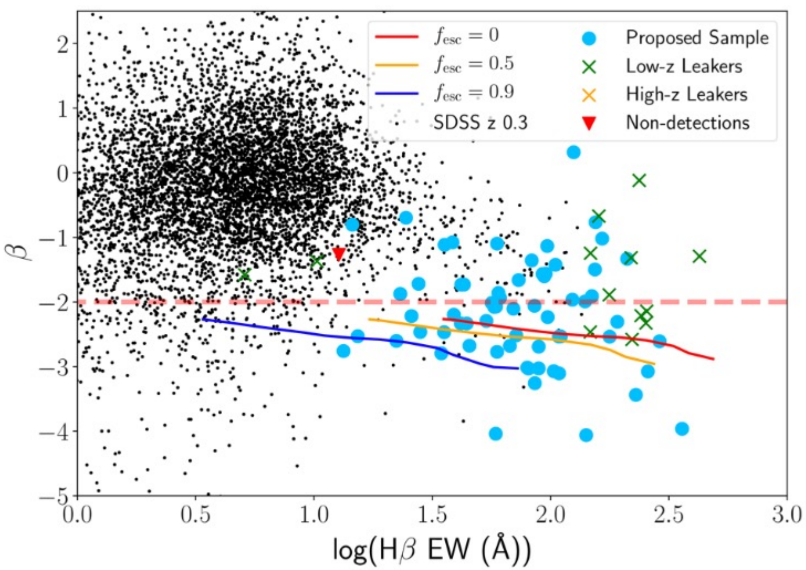

The Low-Redshift Lyman Continuum Survey I:
New, Diverse Local Lyman-Continuum Emitters

Sophia R. Flury,[1] Anne E. Jaskot,[2] Harry C. Ferguson,[3] Gabor Worseck,[4] Kirill Makan,[4] John Chisholm,[5] Alberto Saldana-Lopez,[6] Daniel Schaerer,[6] Stephan McCandliss,[7] Bingjie Wang,[7] N. M. Ford,[2] Timothy Heckman,[7] Zhiyuan Ji,[1] Mauro Giavalisco,[1] Ricardo Amorín,[8,9] Hakim Atek,[10] Jeremy Blaizot,[11] Sanchayeeta Borthakur,[12] Cody Carr,[13] Marco Castellano,[14] Stefano Cristiani,[15] Stephane De Barros,[6] Mark Dickinson,[16] Steven L. Finkelstein,[17] Brian Fleming,[18] Fabio Fontanot,[19] Thibault Garel,[6] Andrea Grazian,[20] Matthew Hayes,[21] Alaina Henry,[3] Valentin Mauerhofer,[6] Genoveva Micheva,[22] M. S. Oey,[23] Goran Ostlin,[21] Casey Papovich,[24] Laura Pentericci,[14] Swara Ravindranath,[3] Joakim Rosdahl,[11] Michael Rutkowski,[25] Paola Santini,[14] Claudia Scarlata,[13] Harry Teplitz,[26] ...inh Thuan,[27] Maxime Trebitsch,[28] Eros Vanzella,[29] Anne Verhamme,[6,30] and Xinfeng Xu[7]

Jan 2022







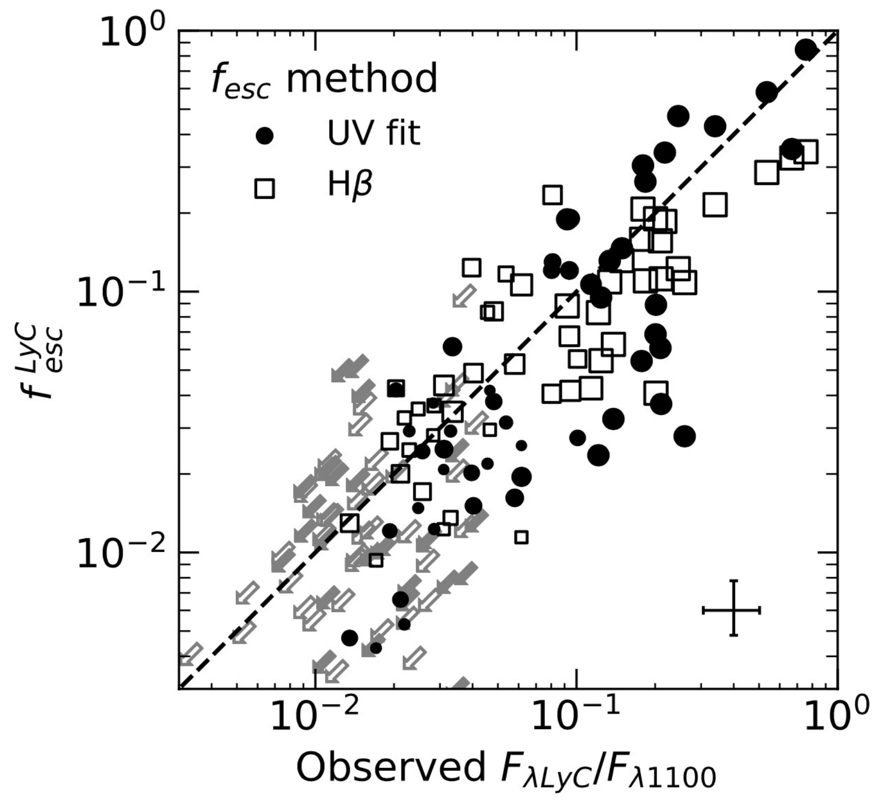
Low-z Lyman Continuum Survey (LzLCS)

First papers:

- Flury et al. (2022ab) – survey paper + LyC diagnostics
- Saldana-Lopez et al. (2022) – fesc determinations, UV fits, ISM properties
- Wang et al. (2021) – [SII] deficiency
- Marques-Chaves et al. (2022) - Hardness of LyC spectra
- …

Statistics/impact of LzLCS+ sample:

- 50 (39) LyC >2 (3) σ detections
- Wide range of escape fractions
- ~18-20 « strong » leakers (fesc>0.1)



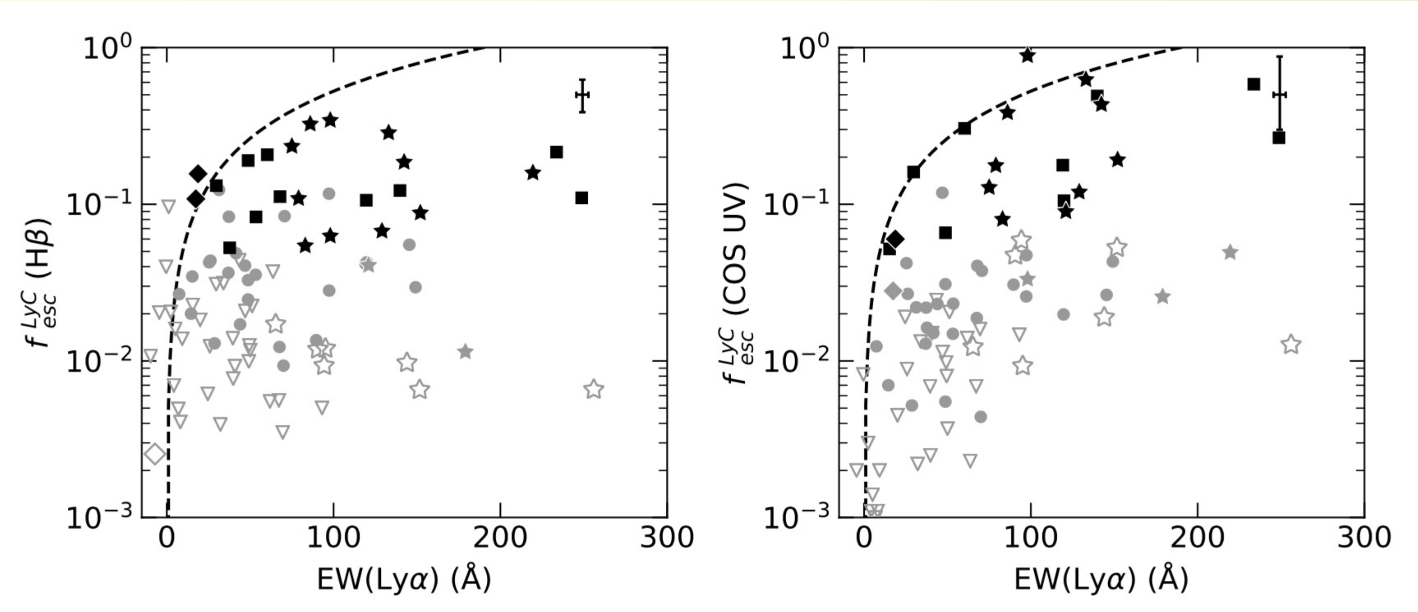
Quality	Signif.	max $P(>N\|B)$	LzLCS	Pub.
Good	>5	2.867×10^{-7}	12	14
Fair	3-5	1.350×10^{-3}	13	0
Marginal	2-3	2.275×10^{-2}	10	1
Detected	>2	2.275×10^{-2}	35	15
Upper limit	≤ 2	1	31	8

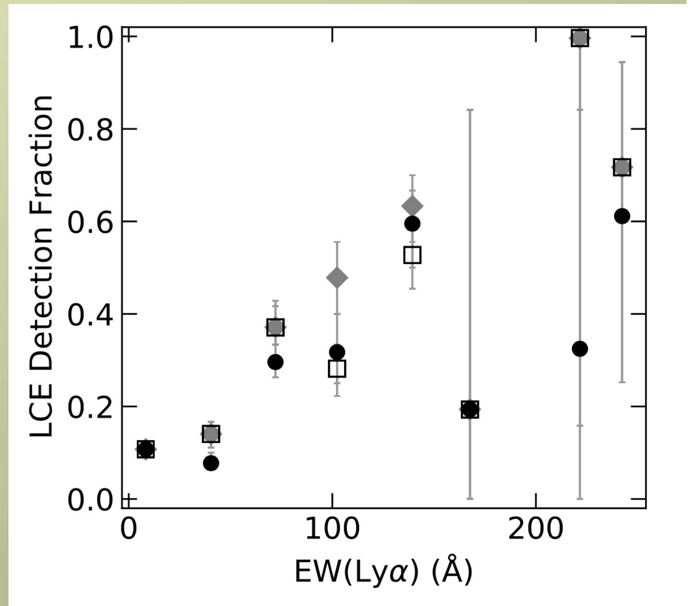
→ 50 galaxies with >2σ detection in LyC
→ 39 non-detections

Low-z Lyman Continuum Survey (LzLCS)

Correlations of the absolute LyC escape fraction (fesc) with other properties

Flury et al. (2022)





Escape fraction

LyC detection fraction

→ **Correlate with EW(Lyman-alpha)**

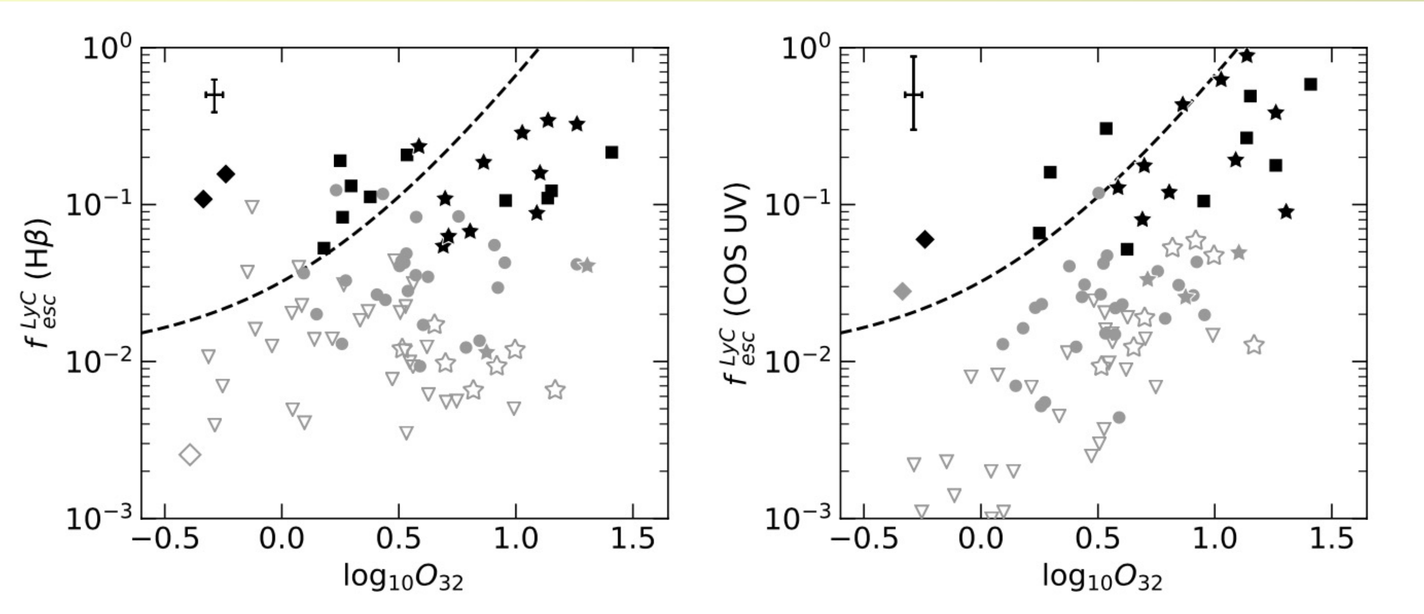
→ **Lya line profile + escape depends on HI column density**

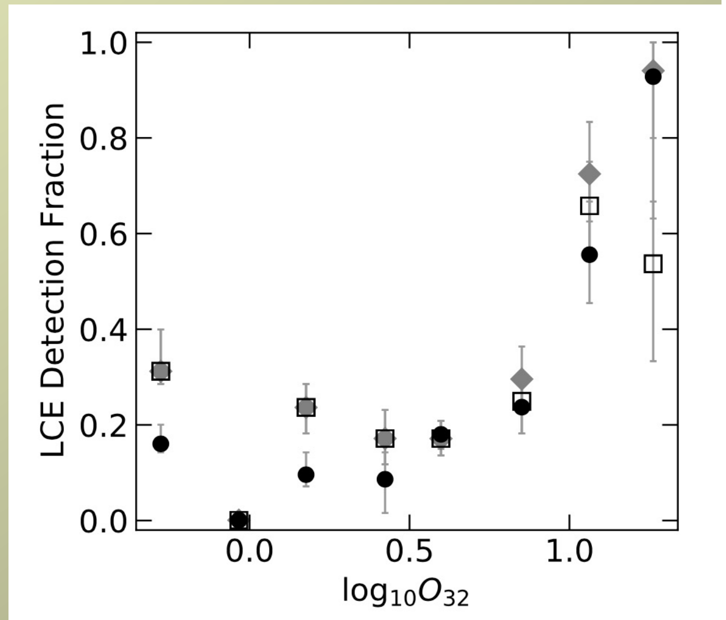
Also: very strong correlation of fesc with Lya peak separation (Verhamme+2017 , Izotov+2018)

Low-z Lyman Continuum Survey (LzLCS)

Correlations of the absolute LyC escape fraction (fesc) with other properties

Flury et al. (2022)





Escape fraction

LyC detection fraction

→ **Correlate with O32=[OIII]/[OII]**

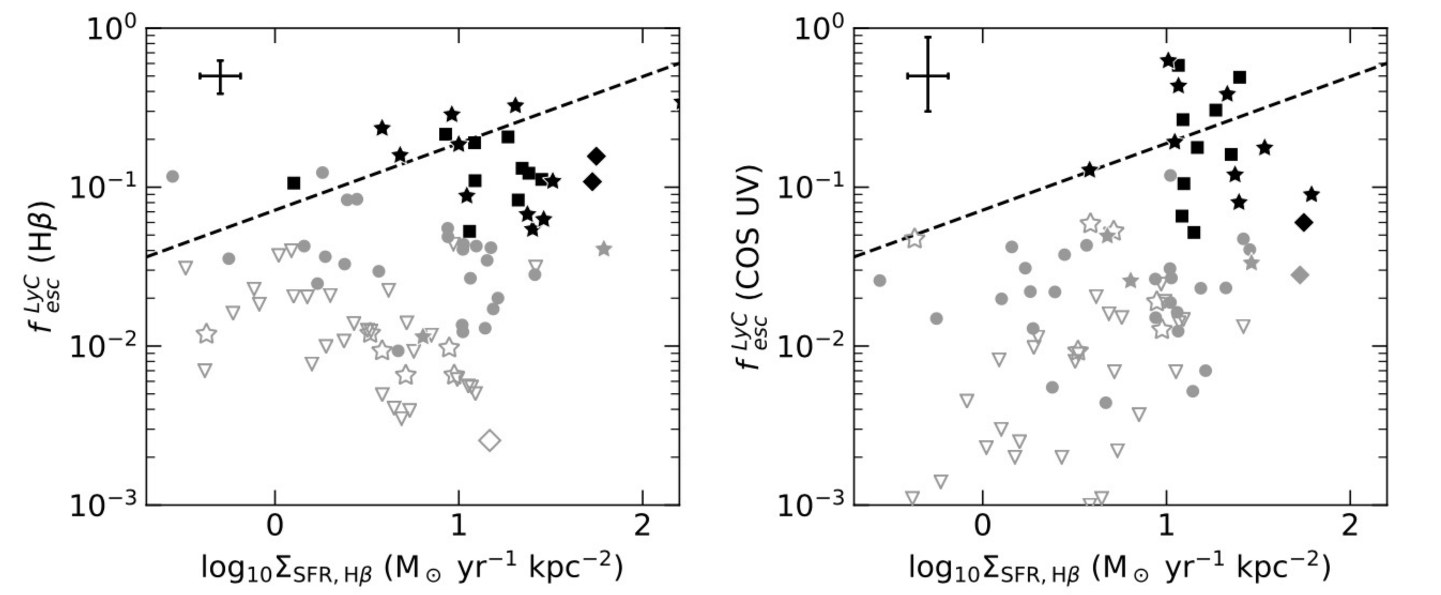
→ **O32 possible indicator of density-bounded regions**

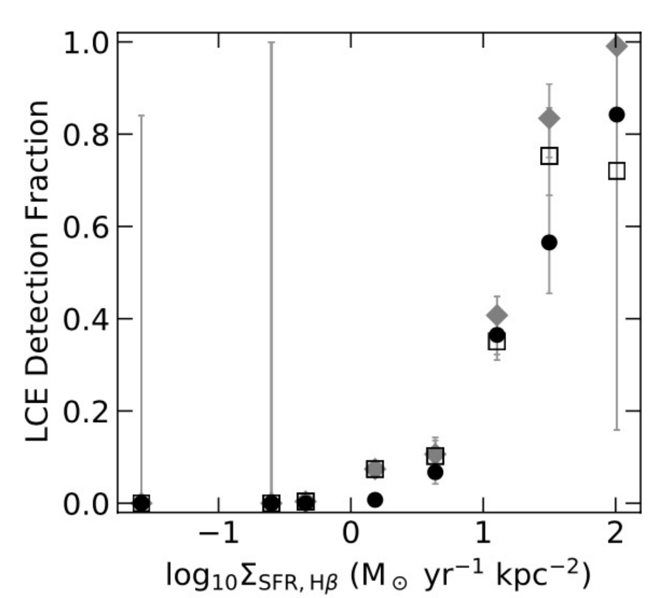
cf. Nakajima & Ouchi 2014, Jaskot & Oey 2014

Low-z Lyman Continuum Survey (LzLCS)

Correlations of the absolute LyC escape fraction (fesc) with other properties

Flury et al. (2022)





Escape fraction

LyC detection fraction

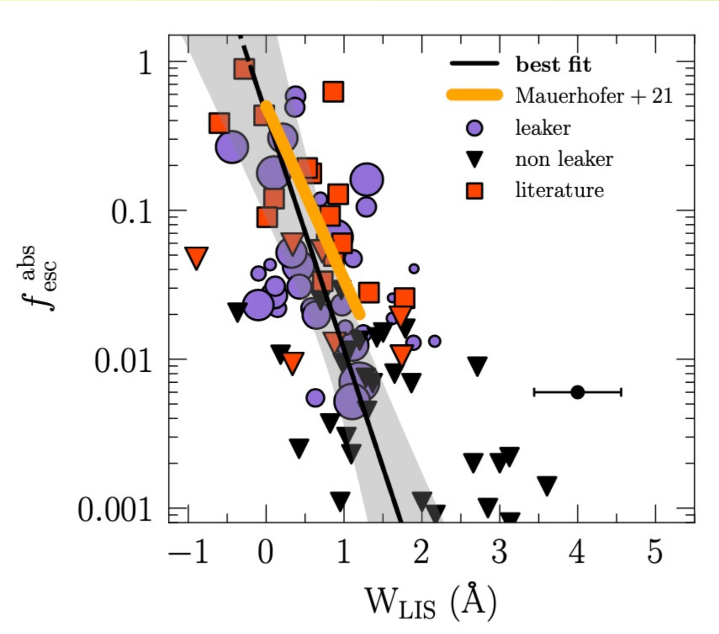
→ Correlate with SFR surface density

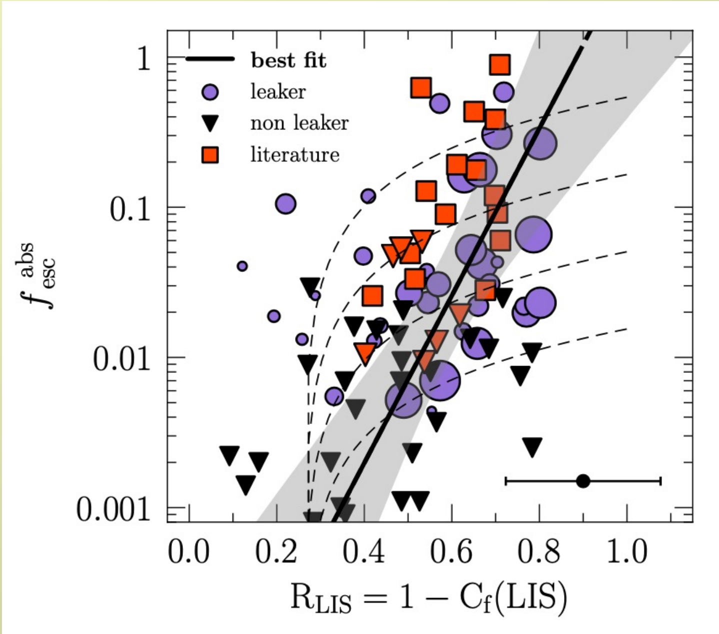
→ Compactness + intense SF drive channels/holes in ISM ?!

e.g. Heckman et al. 2001, Cen 2020

Low-z Lyman Continuum Survey (LzLCS)

Correlations of the absolute LyC escape fraction (fesc) with other properties





Saldana-Lopez et al. (2022)

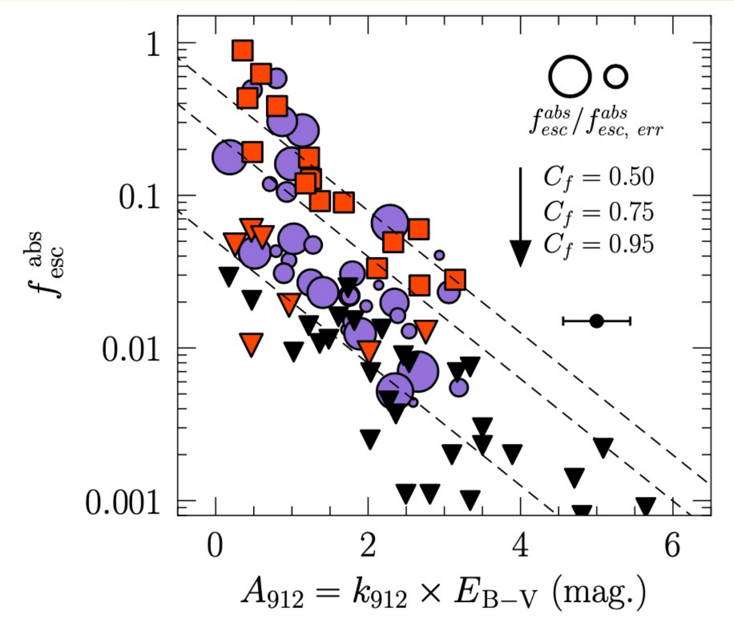
Escape fraction

→ Correlates with UV absorption line strengths + covering fractions
→ Evidence for channels/holes in ISM !

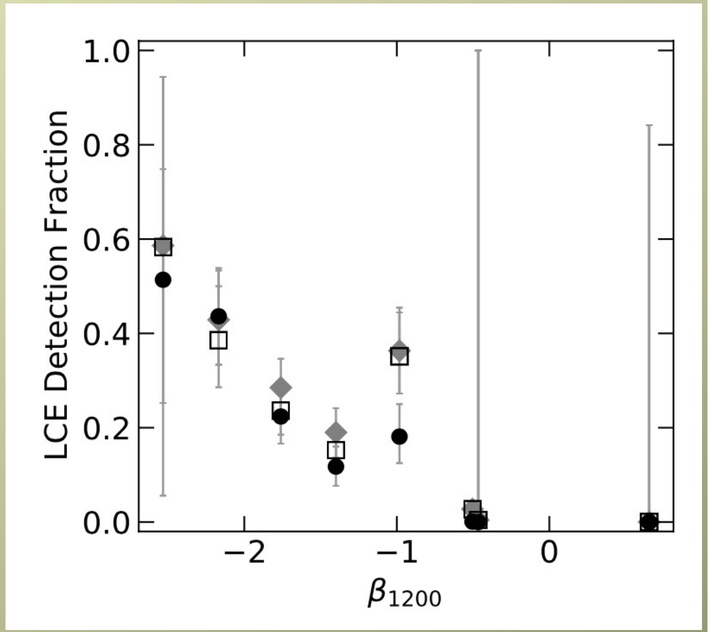
Low-z Lyman Continuum Survey (LzLCS)

Correlations of the absolute LyC escape fraction (fesc) with other properties

Saldana-Lopez et al. (2022)



Flury et al. (2022)



Escape fraction

LyC detection fraction

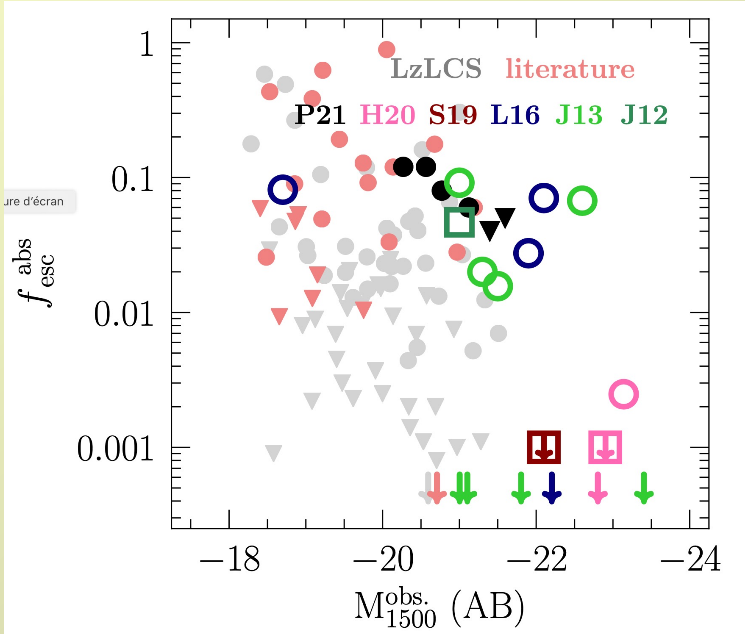
→ (Anti-)correlates UV attenuation and UV slope

→ UV photons (ionizing + non-ion) are absorbed by dust

Low-z Lyman Continuum Survey (LzLCS)

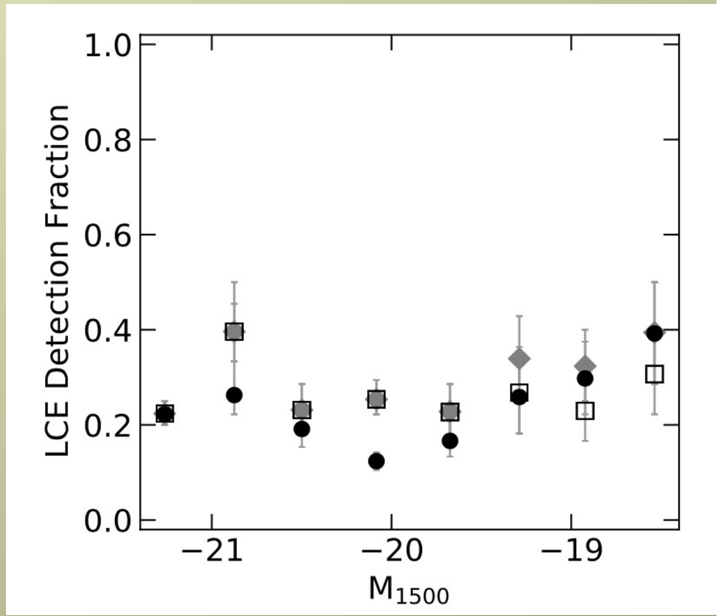
Correlations of the absolute LyC escape fraction (fesc) with other properties

Saldana-Lopez et al. (2022)



Escape fraction

Flury et al. (2022)



LyC detection fraction

→ **NO strong correlation of fesc with absolute UV mag**

→ « **Absolute scale** » **(SFR, mass …) does not matter to 1st order**

Low-z Lyman Continuum emitters – main lessons (I)
physical properties + general

- Strong LyC emitters – with cosmologically important fesc - exist at low-z
- Many galaxies with weak LyC emission detected
- UV bright SF galaxies can contribute to cosmic reionisation

- Majority of known strong leakers are/have:
  - *Compact, high SFR surface density*
  - *Strong emission lines* (rest-optical and EW(Lyα)>~70 Å)
  - *(0.1-0.25) solar metallicity, ~low stellar mass (10^8-10^9) Msun*
  - *Relatively dust-poor*

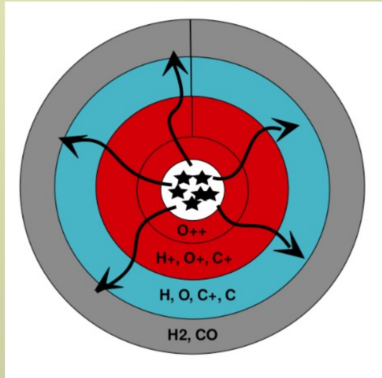
- Observed properties of the rare low-z leakers are very similar to typical high-z galaxies – good analogues ! (e.g. Schaerer+2016, Izotov+2021)

Low-z Lyman Continuum emitters – main lessons (II)

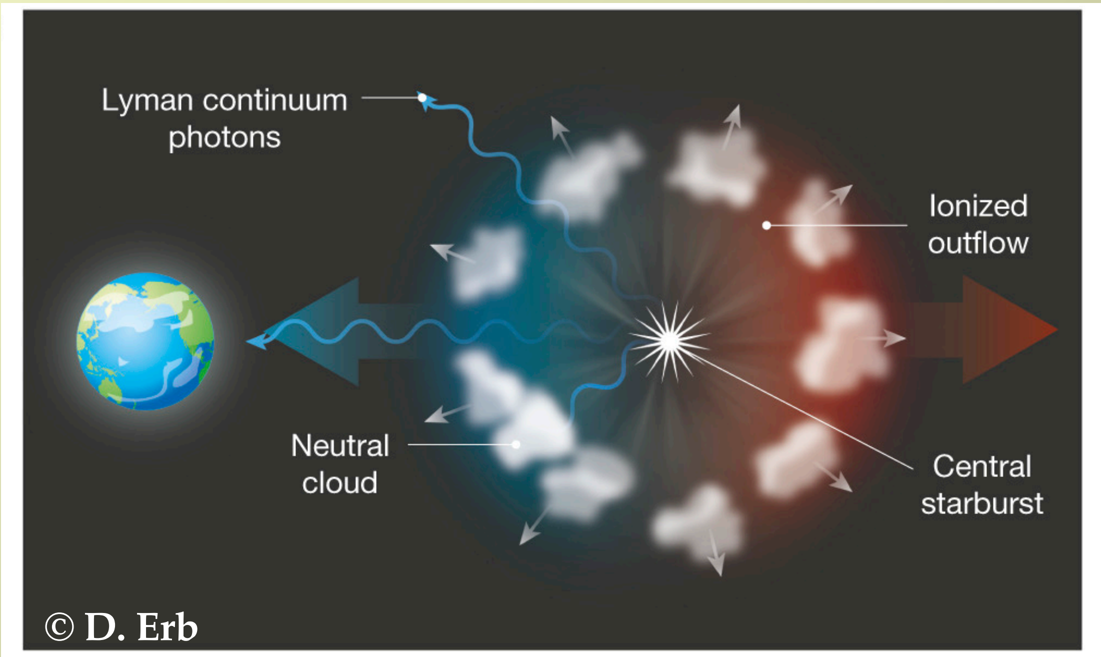
escape mechanism + feedback

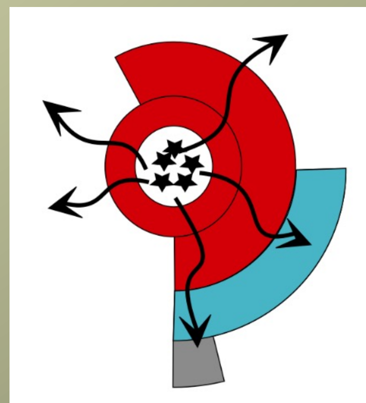
LyC photons escape via low column density channels/holes between gas+dust clouds

→ PhD Alberto Saldaña-López



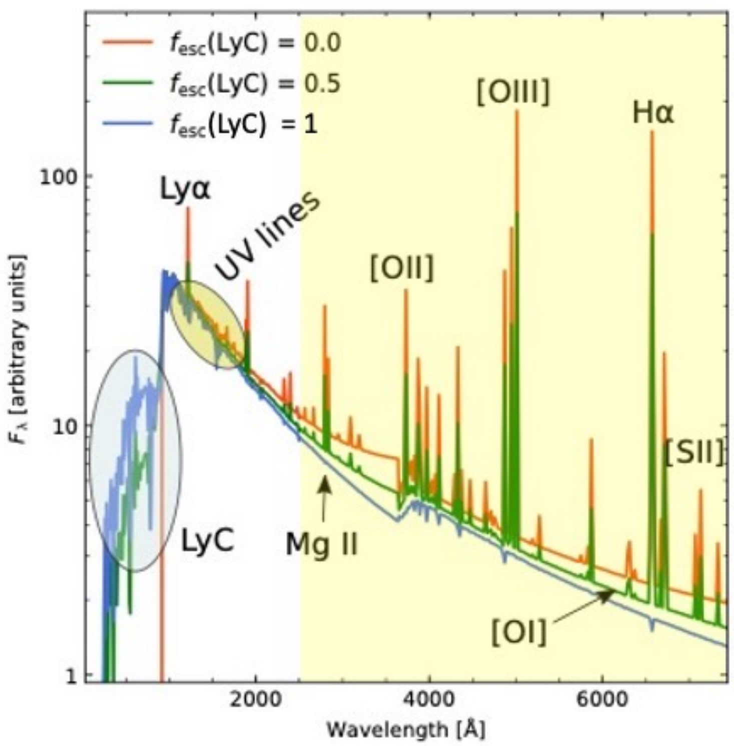
→ Need multi-sector models
(e.g. SL2022, Ramambason+2020, Gazagnes+2020)





Low-z Lyman Continuum emitters – main lessons (III)
Indirect LyC indicators

Indirect LyC indicators established at low-z

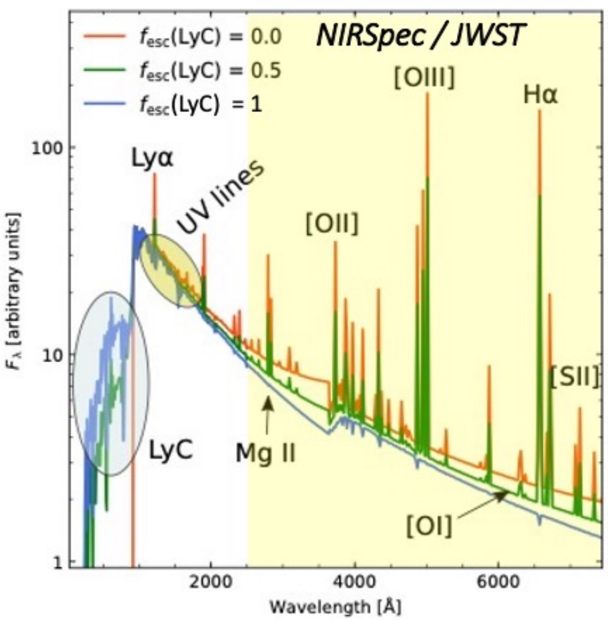


- ✓ Lyman-alpha emission
  Verhamme+ 2015, Djikstra & Gronke 2016, Izotov+ 2018, 2021
- ✓ UV absorption lines
  Heckman+ 2011, Steidel+2018, Gazagnes+ 2018, Chisholm+ 2018, Saldana-Lopez+ 2022
- ✓ High CIV/CIII] ratio
  Schaerer+2022
- ✓ Mg II
  Henry+2018, Chisholm+2020, Xu+2022
- ✓ [SII] deficit
  Wang+ 2019, 2021; Ramambason +2020
- ✓ HeI lines
  Izotov+ 2017, Guseva+ 2020
- ✓ High [OIII]/[OII] ratio
  Jaskot & Oey 2013, Nakajima+ 2014, Izotov+ 2018, Flury+ 2022
- ✓ [OI] ?
  Plat+ 2019, Ramambason +2020, Flury+ 2022

LyC22: the last frontier to test indirect LyC indicators

LyC22 survey
JWST, cycle 1, 73.5h NIRSpec, PI Schaerer
→ Spectroscopy of known z~3 LyC emitters
(LBGs + LAE from Steidel+, Fletcher+) + large control sample

Indirect LyC indicators established at low-z



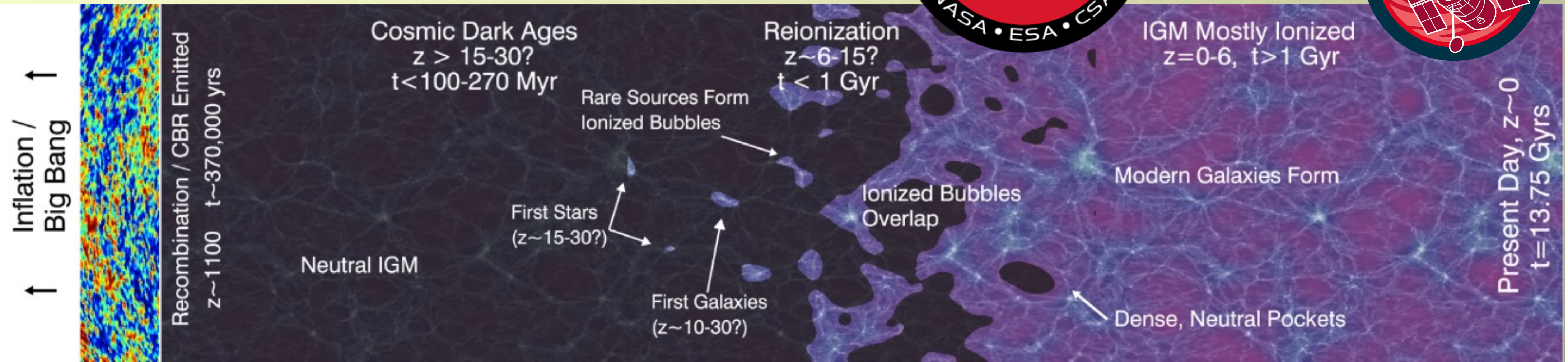
- ✓ Lyman-alpha emission
  Verhamme+ 2015, Djikstra & Gronke 2016, Izotov+ 2018
- ✓ UV absorption lines
  Heckman+ 2011, Steidel+2018,
  Gazagnes+ 2018, Chisholm+ 2018, Saldana-Lopez+ 2021
- ✓ High CIV/CIII] ratio
  Schaerer+2022

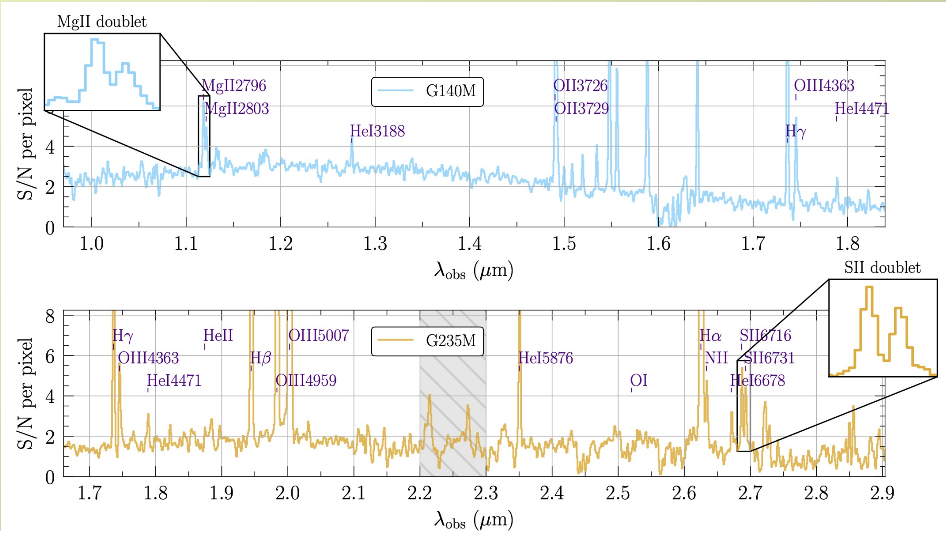
NIRSpec / JWST LyC22 survey

- ✓ Mg II
  Henry+2018, Chisholm+2020
- ✓ [SII] deficit
  Wang+ 2019, 2021; Ramambason +2020
- ✓ HeI lines
  Izotov+ 2017, Guseva+ 2020
- ✓ High [OIII]/[OII] ratio
  Jaskot & Oey 2013, Nakajima+ 2014, Izotov+ 2018, Flury+ 2021
- ✓ [OI] ?
  Plat+ 2019, Ramambason +2020, Flury+ 2021

Lyman continuum emitting galaxies across cosmic time

LyC22 survey
JWST, cycle 1, 73.5h
NIRSpec, PI Schaerer





Conclusions

- Strong LyC emitters – with cosmologically important fesc - exist at low-z
- Many galaxies with weak LyC emission detected
- UV bright SF galaxies can contribute to cosmic reionisation

- Majority of known **strong** leakers are/have:
  - *Compact, high SFR surface density*
  - *Strong emission lines* (rest-optical and EW(Lyα)>~70 Å)
  - *(0.1-0.25) solar metallicity, ~low stellar mass (108-109) Msun*
  - *Relatively dust-poor*
- Strong low-z leakers are good analogues of high-z galaxies

- LyC photons escape via low column density channels/holes
- Multiple spectral diagnostics for Lyman continuum emitters validated (rest-UV and optical) → go JWST !