The properties of Lyman Continuum candidates through combined spectroscopic and imaging observations

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2025.4.10

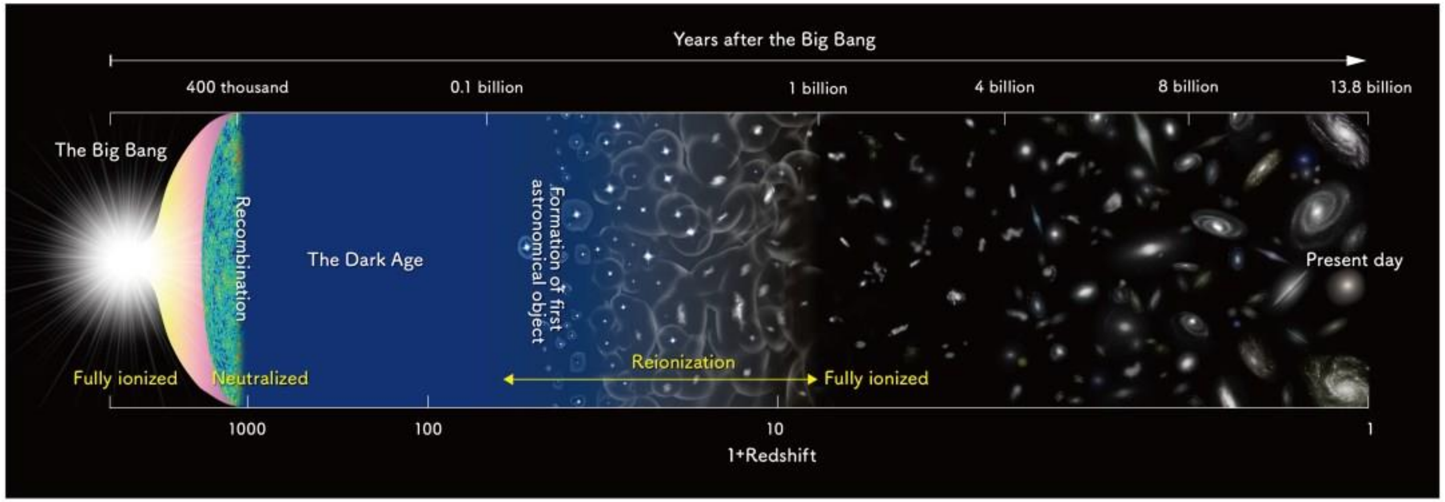
Background

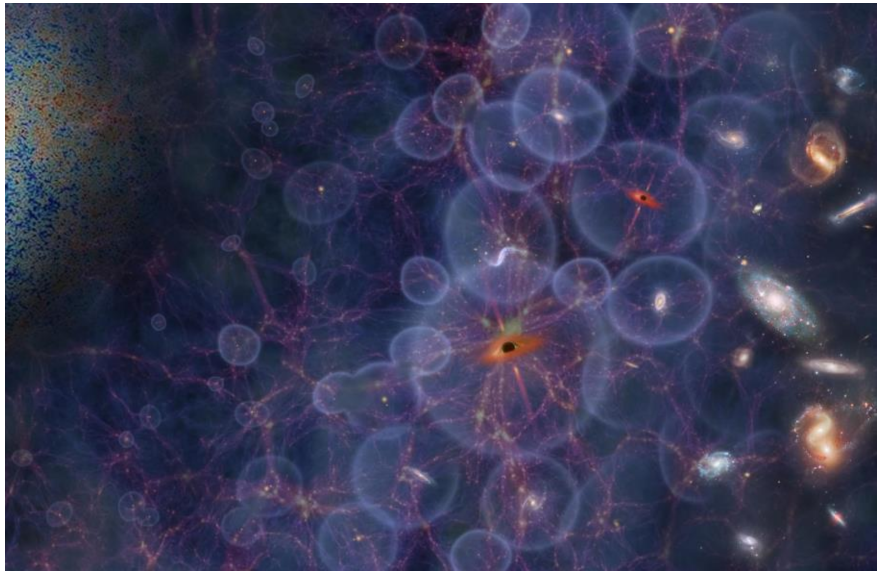
- Ionizing photons & reionization

The Lyman continuum photons (<911.8A) produced by **star-forming galaxies** can account for the majority of the photon budget required to complete reionization (z~6).

Exact contribution?

An average LyC escape fraction of ~10% across all star-forming galaxies would be required. (**dominant contributor,** current knowledge)

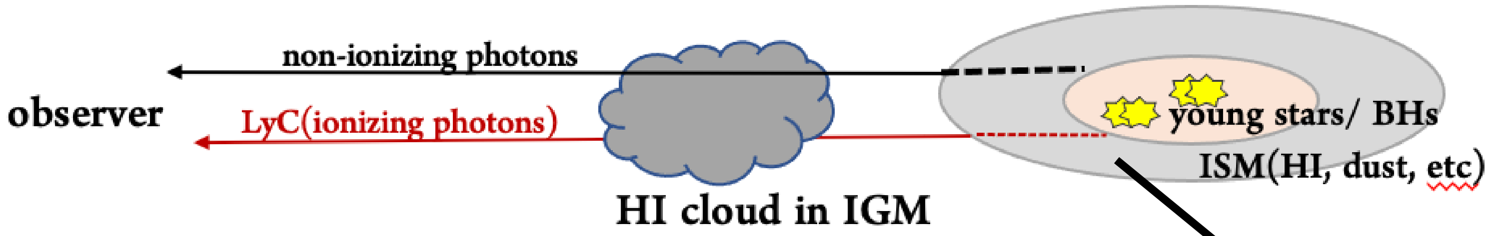


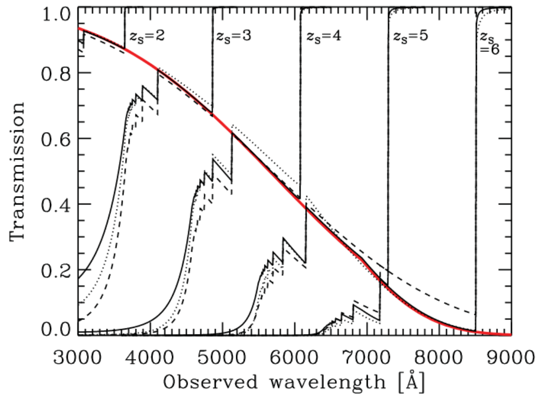


Refs: Fan et al. 2006, Finkelstein et al. 2019, Naidu et al. 2020, Jiang et al. 2022

Background

- LyC escaping process

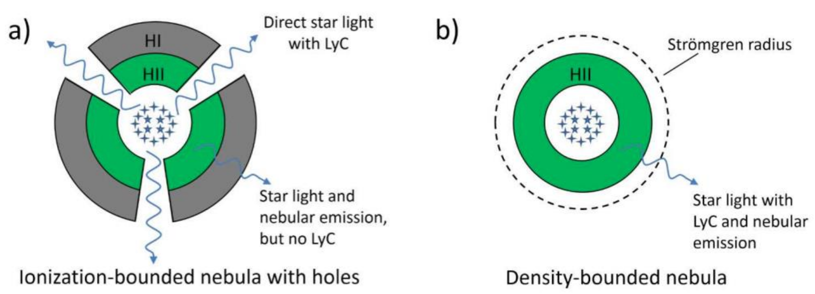




Inoue et al 2014

GOAL:
Find analogs at lower redshifts (z<4.5) to identify key properties and study the correlations and evolution!

Zackrisson et al.2013



IGM absorption[big challenge!]
z>4.5, LyC photons are impossible to observe due to increased IGM opacity.

Possible mechanism:

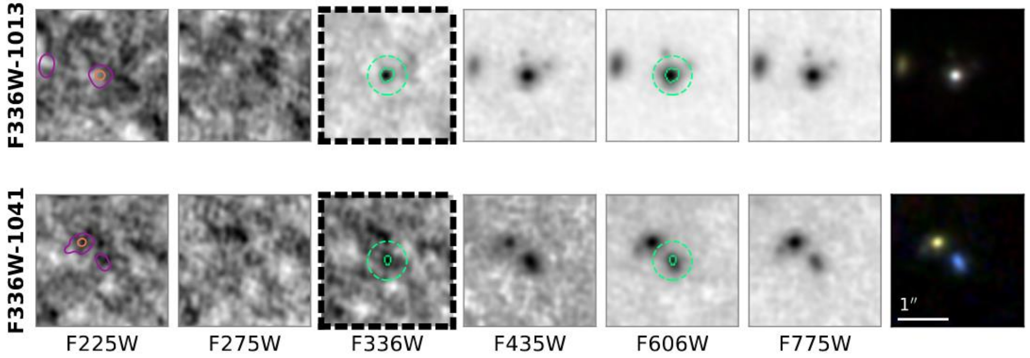
- Nebula with holes [related to stellar winds]
- Optical thin region [related to highly-ionized environment]

Searching for LyC leakers

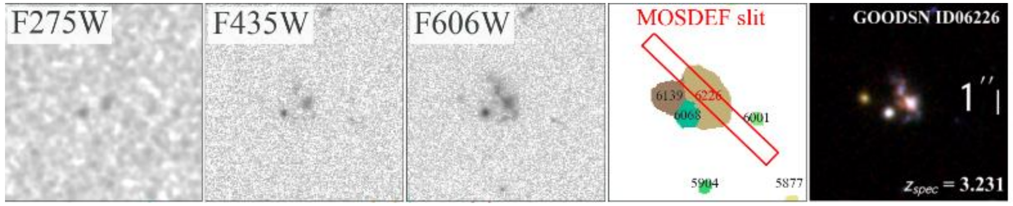
- Direct observation

Deep UV images (z~2-4):

-HST (F275W,F336W)

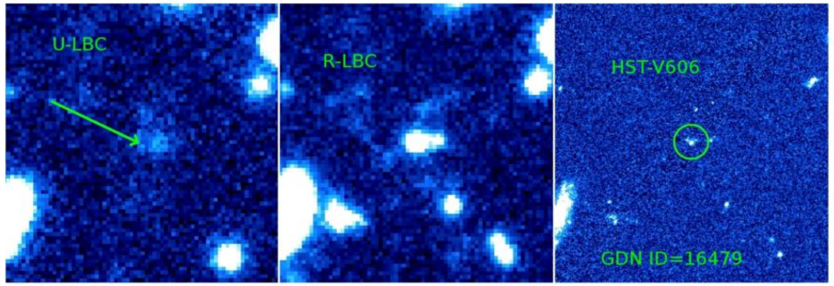


Rivera-Thorsen et al 2022

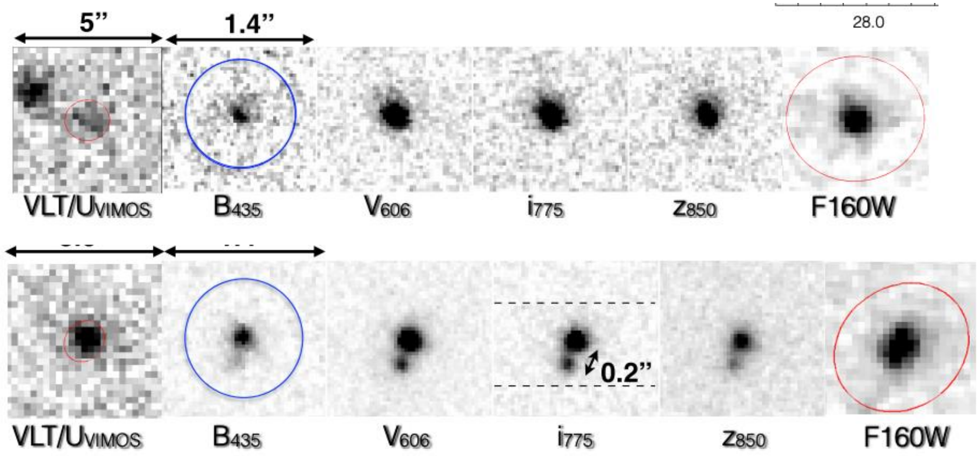


Wang et al 2023

- large ground-based telescope (VLT, LBT,CFHT…)



Grazian et al 2017

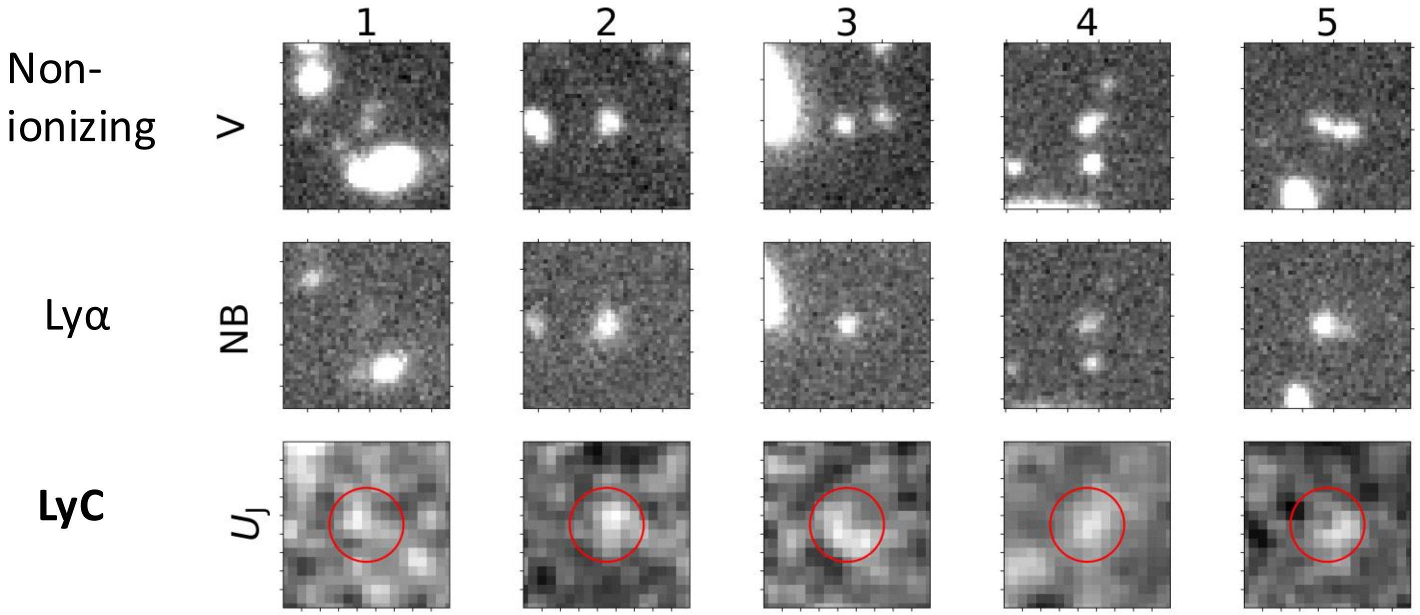


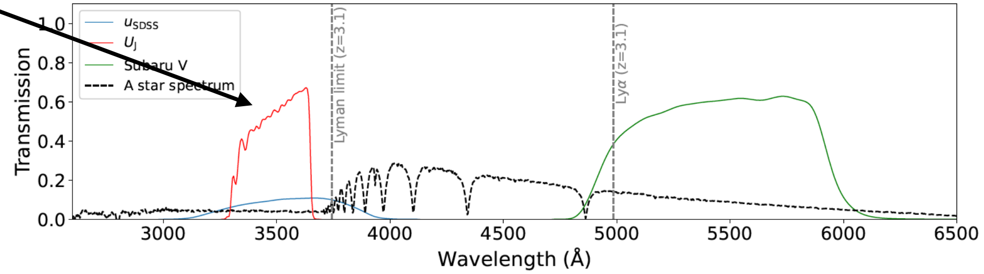
ION1&2

Vanzella et al 2015

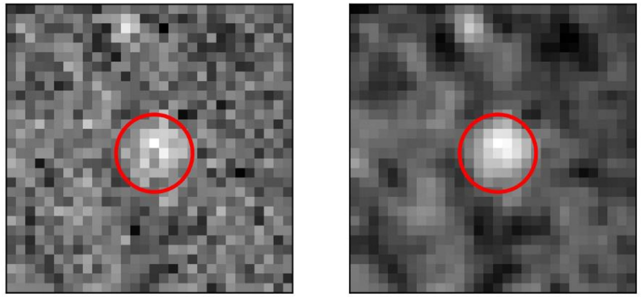
Searching for LyC leakers I [ground-based]

- Sample: ~150 spectroscopically confirmed redshift galaxies in $z \sim 3.1$ in **SXDS field**
- **5 direct LyC detections (S/N>3) by ground-based U filter at z~3.1**[see in Liu et al 2023]





U stack

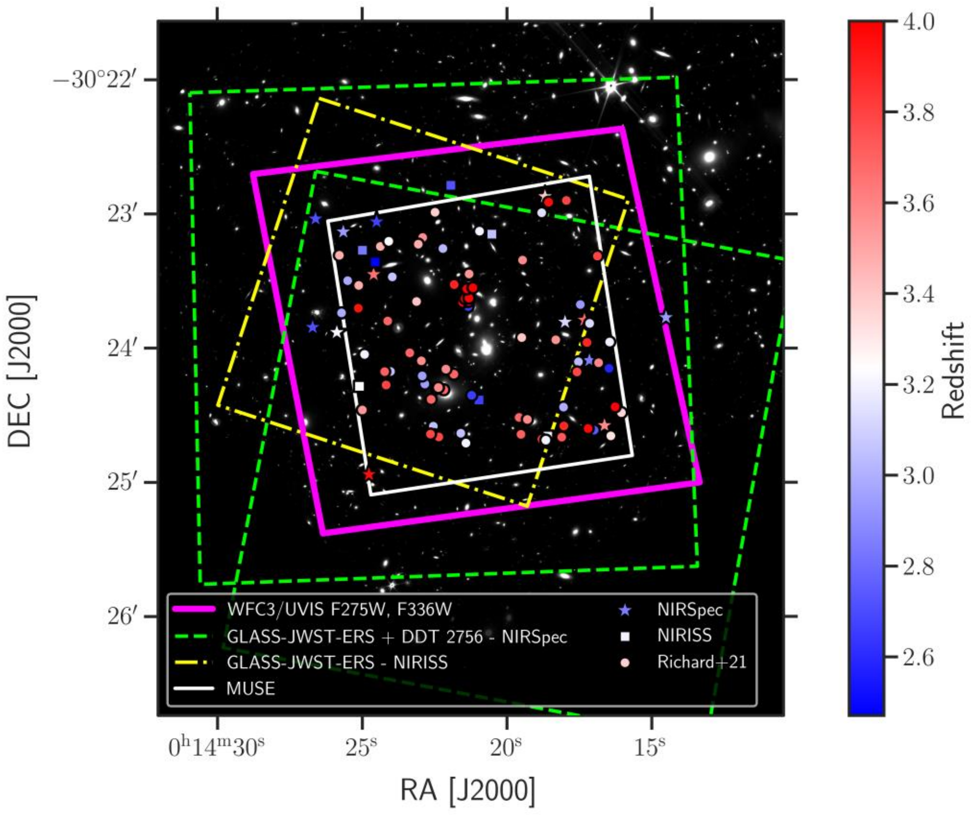


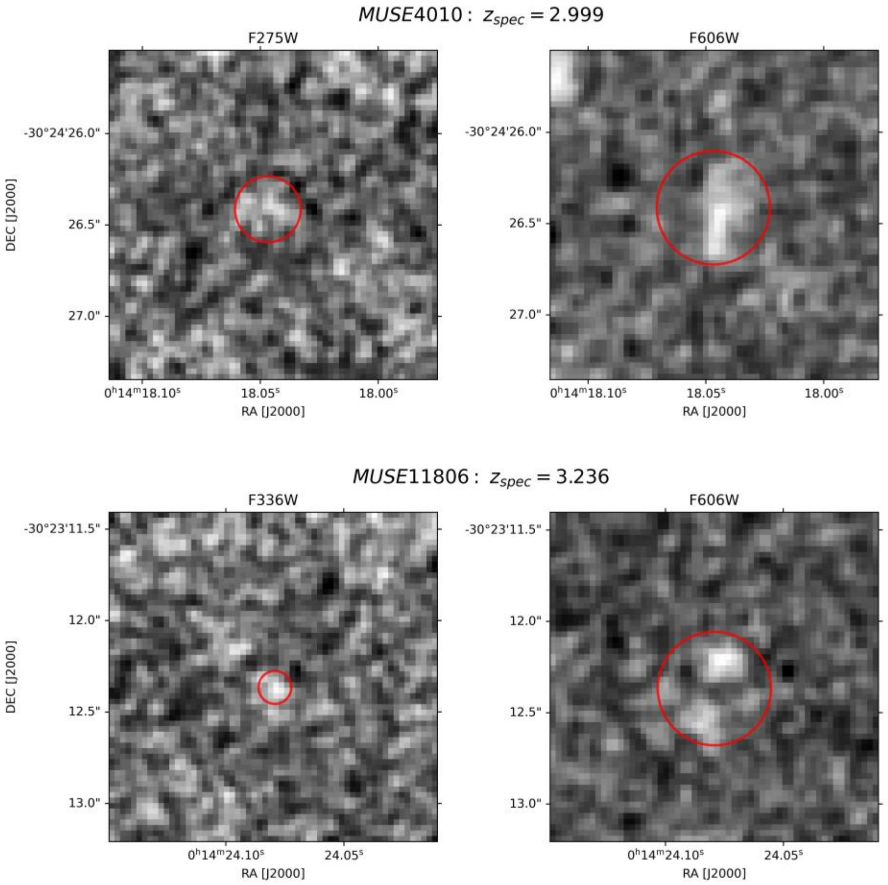
Contamination rate for single one: <0.9%

Liu et al 2023

Searching for LyC leakers II [space telescope]

- Sample: 98 spectroscopically confirmed redshift galaxies in $2.4 \leq z \leq 4.0$ in **Abell 2744** cluster field [GLASS: JWST-NIRSpec, GLASS: JWST-NIRISS and MUSE].





Liu et al 2025 to be submitted

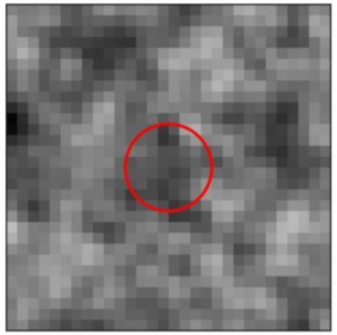
Stack the non-detections

- Method: 3sigma-clipping stack by different redshift range

- **No** significant signal in each stack
- Constrain the 2σ upper limit of non-detections

Ground-based

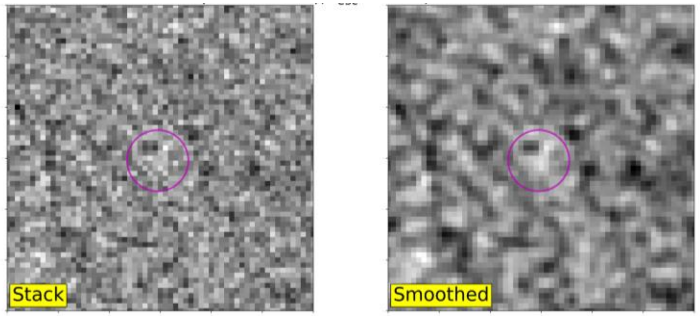
Stack of z~3.1



>28.3

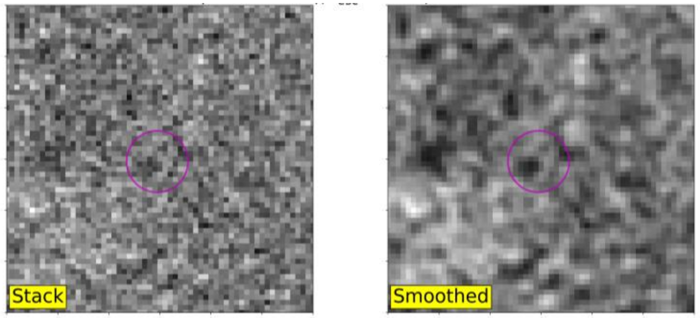
HST

Stack of z~2.4-3.06



>29.9

Stack of z~3.06-4.0



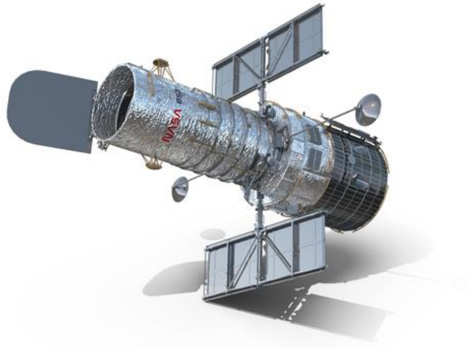
>31.3

After direct detections, we need to analyse their properties……And compare…

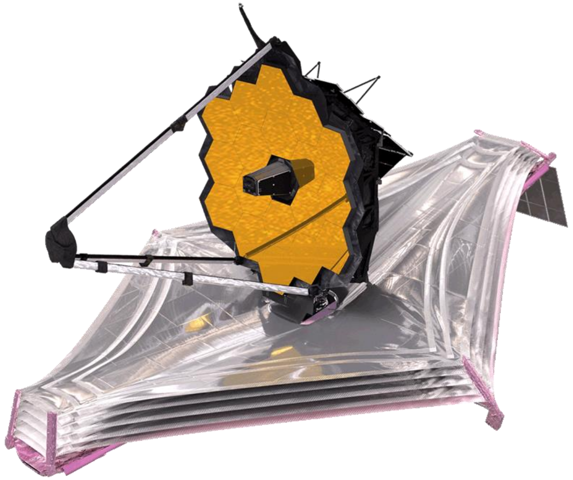
Data: multiple band images + spectra

HST, MUSE spectra, JWST….

Does the escaping correlate with any properties that make these galaxies so special?



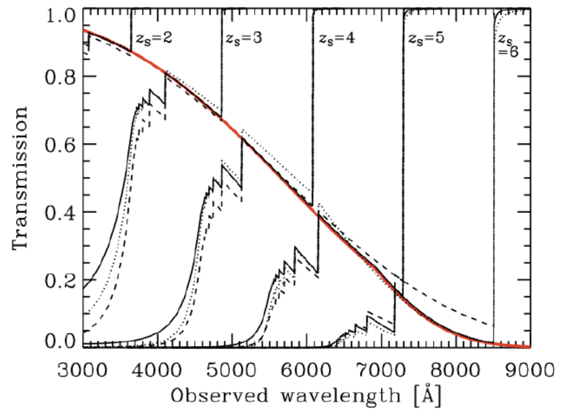
muse
multi unit spectroscopic explorer



Analyze LyC candidates

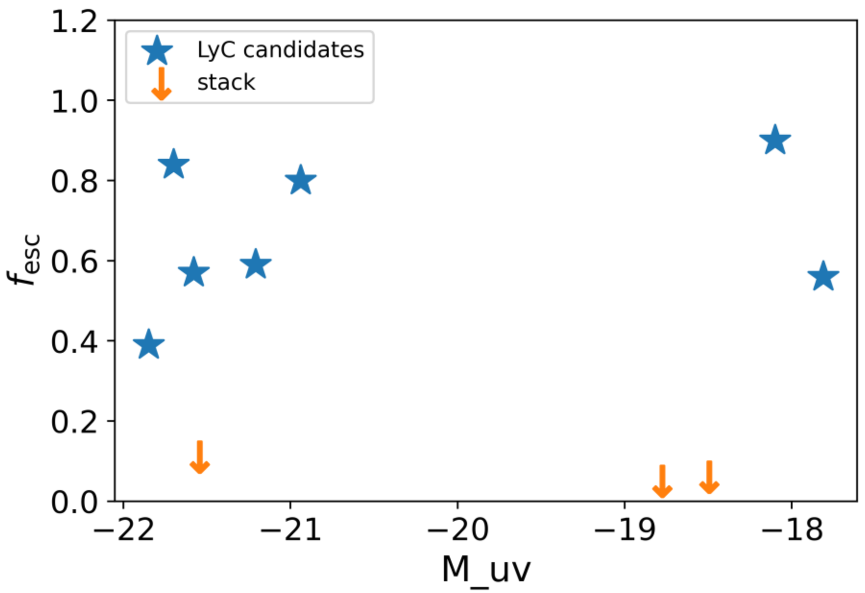
(1) Escape fraction:

$$f_{esc} = \frac{f_{LyC,obs}/f_{UV,obs}}{f_{LyC,intr}/f_{UV,intr}} 10^{-0.4A_{UV}} e^{\tau_{IGM}}$$



Inoue+14

assume model intrinsic ratio, dust attenuation and IGM absorption

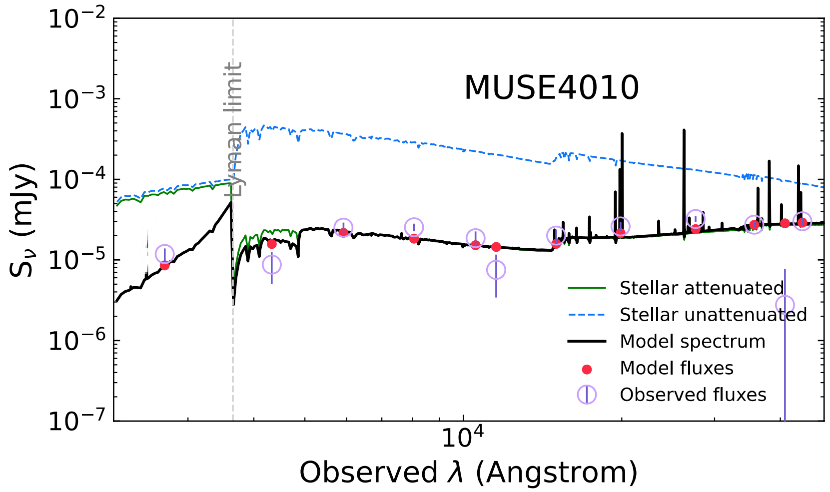


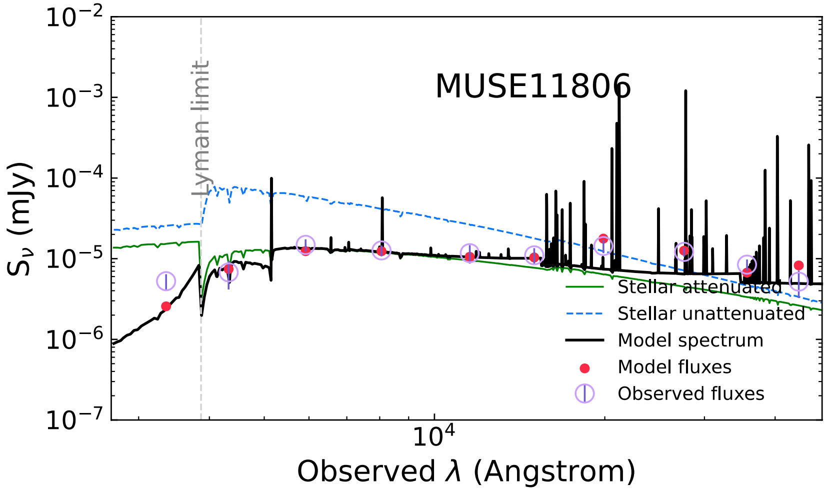
The majority of our galaxies exhibit significantly lower f_{esc} while LyC emitters hold very high f_{esc}

Analyze LyC candidates: SED fitting

- HST: F275W/F336W, F435W, F606W, F814W
- JWST/NIRCam F115W, F150W, F200W, F277W, F356W, F410M, F444W

Liu et al 2025 to be submitted





ID	RA [deg]	DEC [deg]	z_{spec}	LyC $r = 0''.18$	F606W $r = 0''.30$	E(B-V)	M_{1500}	β	M_* $[M_\odot]$	f_{esc}	$f_{esc,SED}$
4010	3.57519	-30.40735	2.998	$28.38^{+0.21}_{-0.21}$	28.4	0.24	$-18.1^{+0.1}_{-0.1}$	$-2.68^{+0.2}_{-0.2}$	$7.73^{+0.10}_{-0.10}$	$0.9^{+0.1}_{-0.8}$	$0.88^{+0.07}_{-0.07}$
11806	3.60033	-30.38675	3.236	$29.60^{+0.5}_{-0.5}$	28.12	0.15	$-17.81^{+0.11}_{-0.11}$	$-2.24^{+0.17}_{-0.17}$	$7.07^{+0.05}_{-0.05}$	$0.6^{+0.5}_{-0.5}$	$0.59^{+0.02}_{-0.02}$

Low mass, blue slope, high escape fraction (consistent)

When we have spectra of longer wavelength, we can measure the emission lines…

NIRSpec

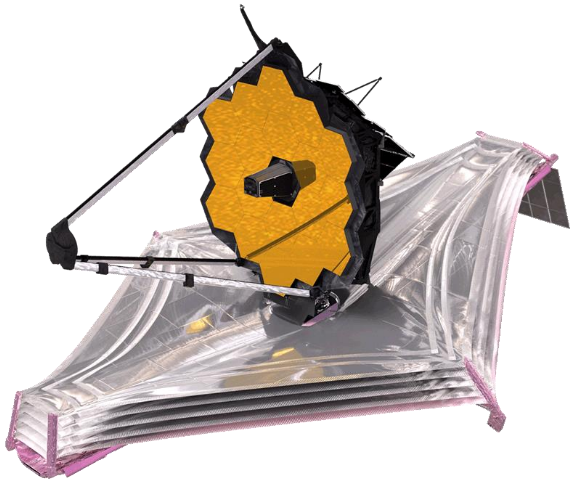
NIRISS

Near-Infrared Imager and Slitless Spectrograph

COMPONENTS

muse

multi unit spectroscopic explorer



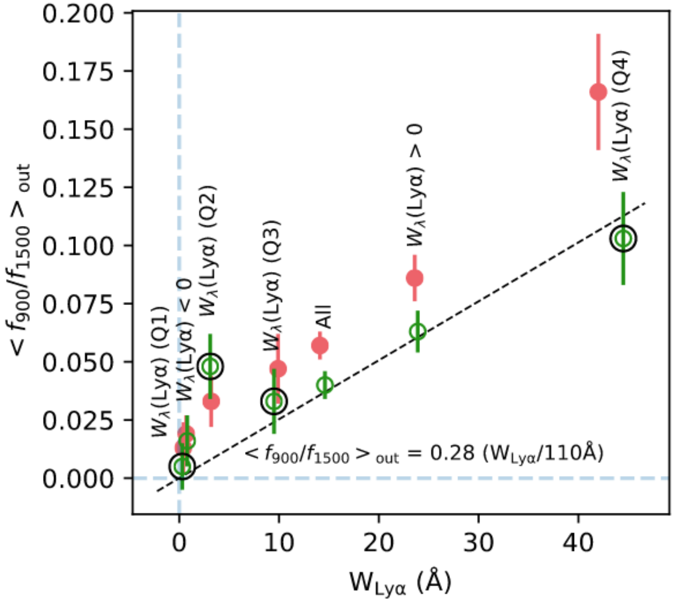
Properties from spectra

- Indirect indicators

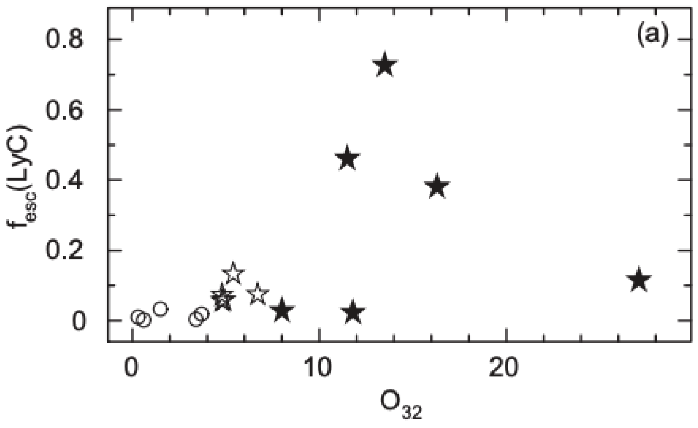
- Lyman alpha
  - ➢ high EW → high f_{esc} ?
  - ➢ Double peak?

- [OIII]/[OII] (low-z)
  - ➢ High O32 → highly ionized → high f_{esc}

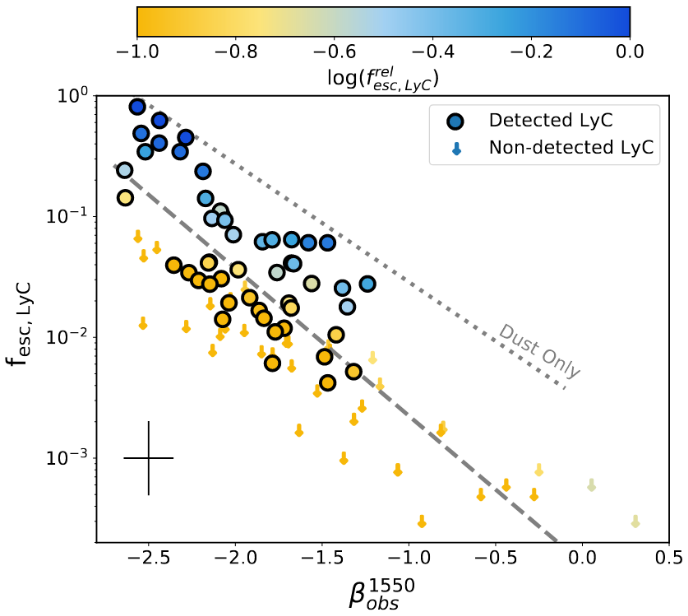
- Beta slope, sSFR…
  - ➢ Young, star forming, more LyC…



Pahl et al 2021



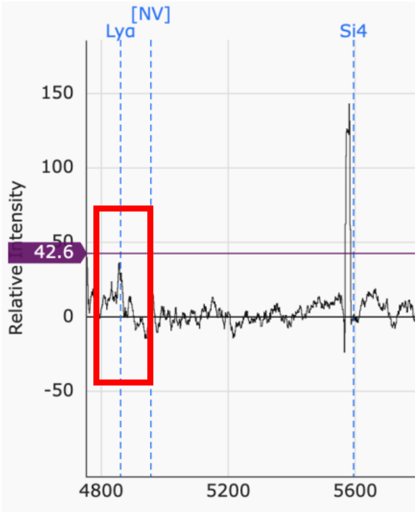
Izotov et al 2018a

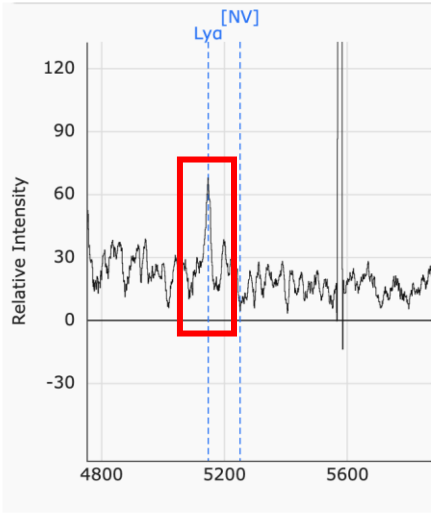


Chisholm et al 2022

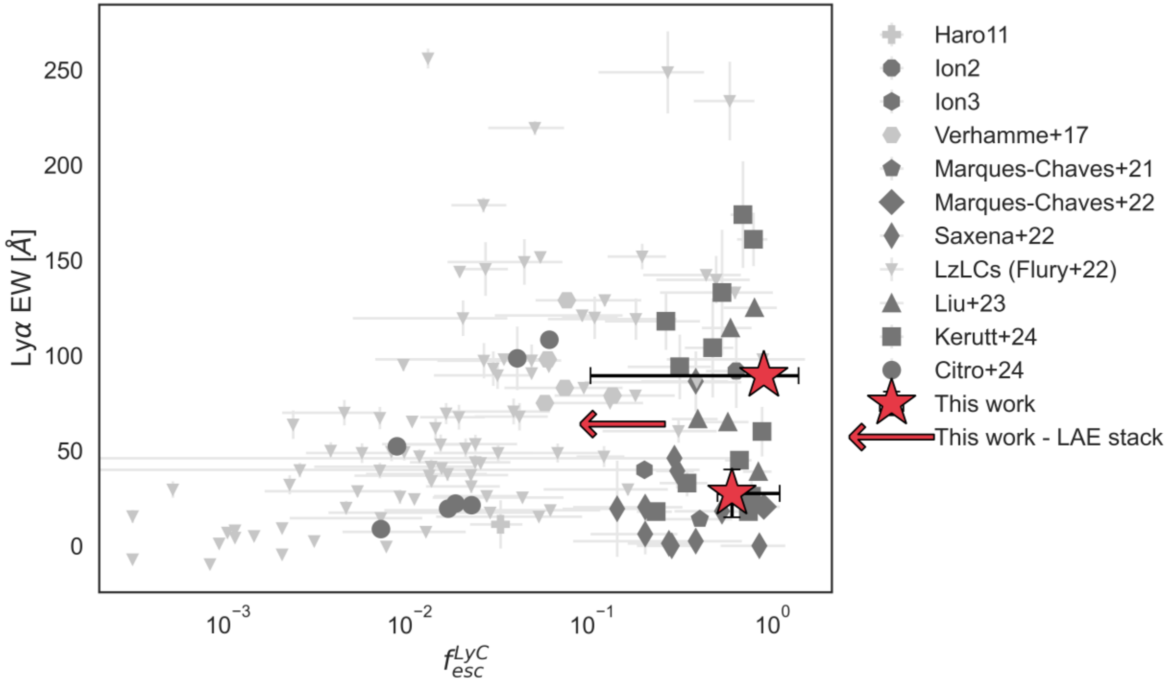
Properties from spectra

- Lyman alpha emission of the two leakers [MUSE]





- In our sample, 63 out of 98 have Lyα emission, **15 of them EW>40A**
- $f_{esc,\ \text{strong Ly}\alpha\ \text{stack}} < 0.15$
- EW-f_{esc} distribution is consistent with high-z LyC in literature.
- High Lyα EW could serve as a clue for high LyC escape.



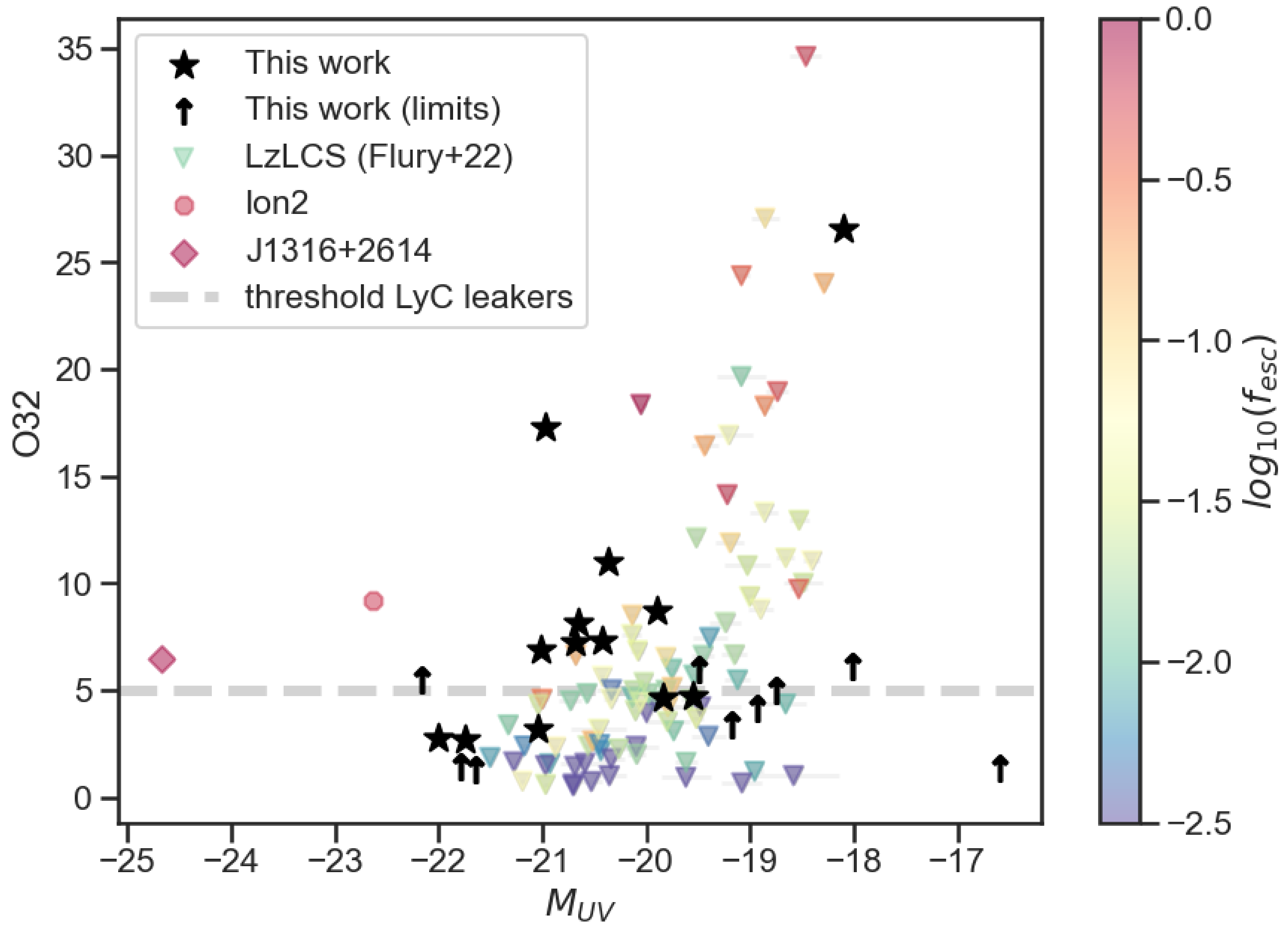
Liu et al 2025 to be submitted

Properties from spectra

- O32 measurements from JWST NIRSpec and NIRISS

Liu et al 2025 to be submitted

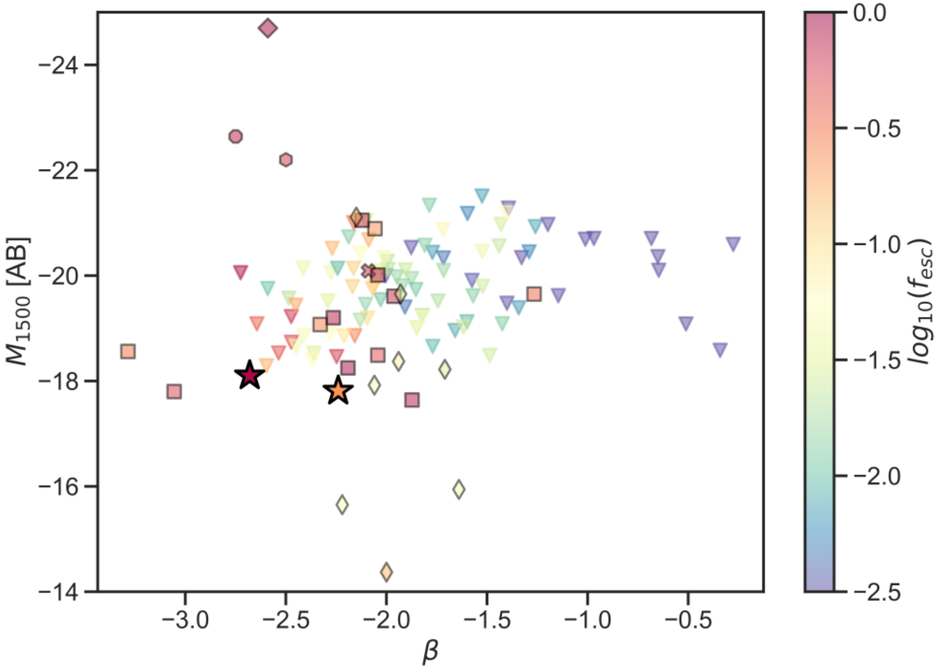
- ***Unfortunately, we do not extract usable spectra for the 2 leakers. Slitless spectra quality is not good.***
- 22 galaxies in the total sample have reliable O32 measurements or limits. They align well with low-z and high-z sources.
- For the sources in the literature, O32>5 sources may indicate a possible connection between high O32 ratios and LyC escape.
- Due to the limited number of O32 measurements for high-z LyC sources, **No definitive conclusion on the correlation between O32 and f_{esc}.**

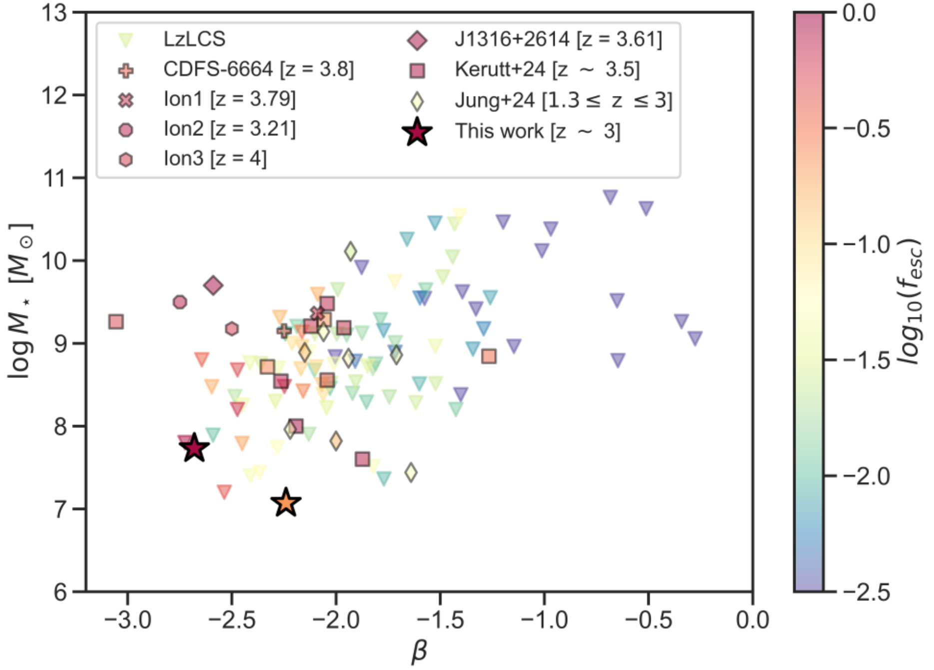


Properties and mechanism

- M*, β, M_{UV} of the two LyC leakers

Liu et al 2025 to be submitted





- No strong correlations with f_{esc} but instead display significant scatter across different redshifts.
- LyC escape is a complex process, with multiple pathways and mechanisms enabling ionizing photon leakage at different epochs and across diverse galaxy populations.

Properties and mechanism

- M*, β, M_{UV} of the two LyC leakers

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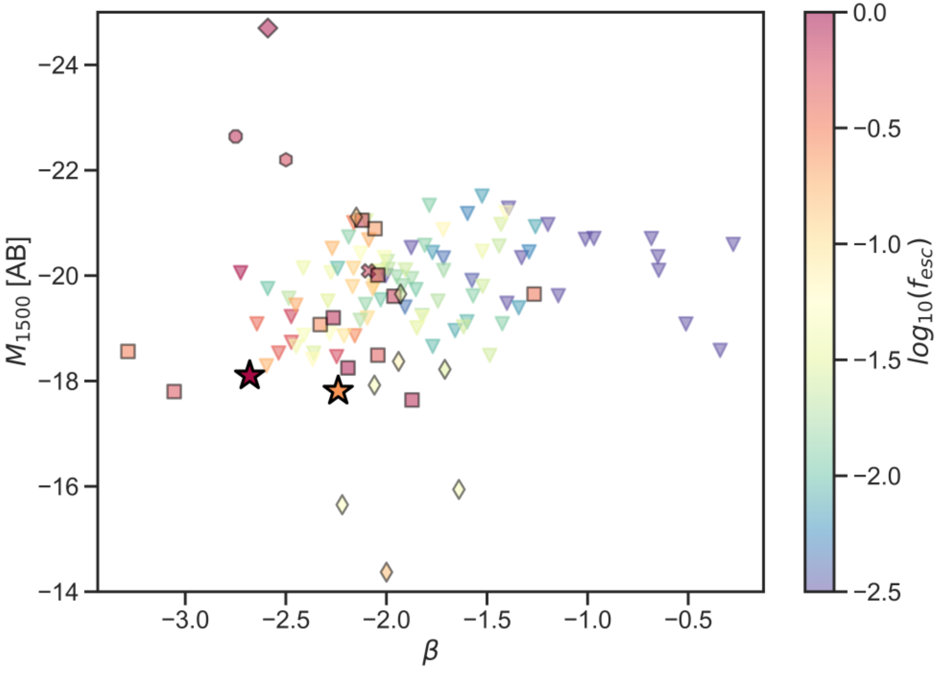

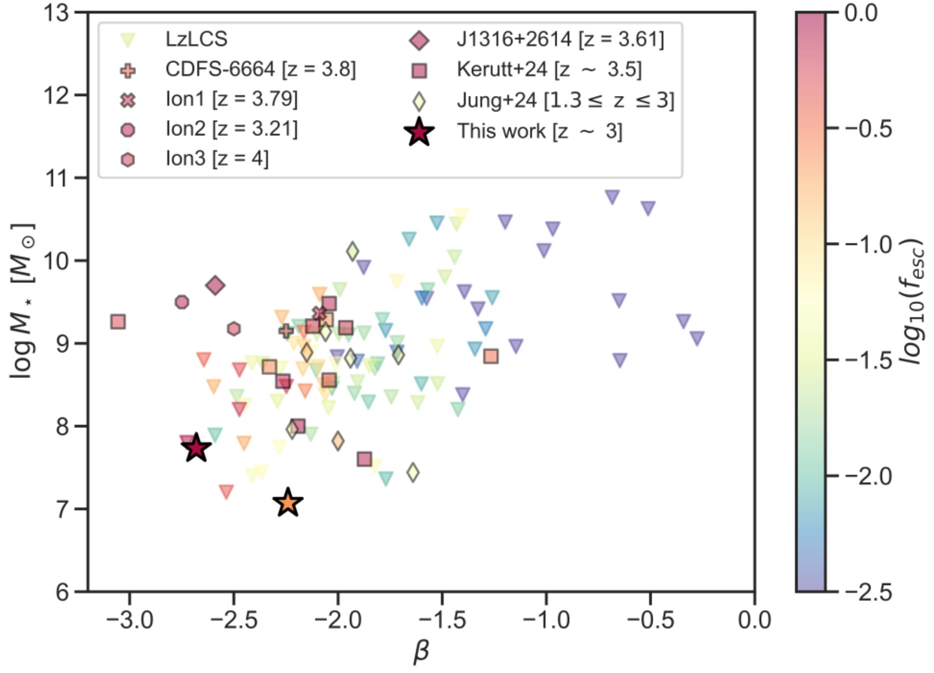

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- LyC escape is a complex process, with multiple pathways and mechanisms enabling ionizing photon leakage at different epochs and across diverse galaxy populations.

more data!

- **Can lower redshift analogs and indirect indicators represent the same situation at EoR?**

Summary

- Found new LyC candidates at z~2.4-4 using U filters. They have low mass, blue beta slope, and large escape fraction.
- The majority of our galaxies exhibit significantly lower f_{esc} while LyC emitters hold very high $f_{esc.}$
- We discuss the possible indirect indicators like Lyα, and O32 ratio. High Lyα EW could serve as a clue for high LyC escape. For O32, there is no definitive conclusion for the high-z sample.
- Some properties like M_* and β display significant scatter across different redshifts, suggesting complex processes and mechanisms.