Merging Signatures in an Offset Lyman Continuum Emitter at Redshift 3.8

FT Fang-Ting Yuan
Collaborate with: Zhen-Ya Zheng, Shuairu Zhu, Ruqiu Lin, Chunyan Jiang and Cheng Cheng

@Lyman2025, OAO, Greece. 2025-04-09

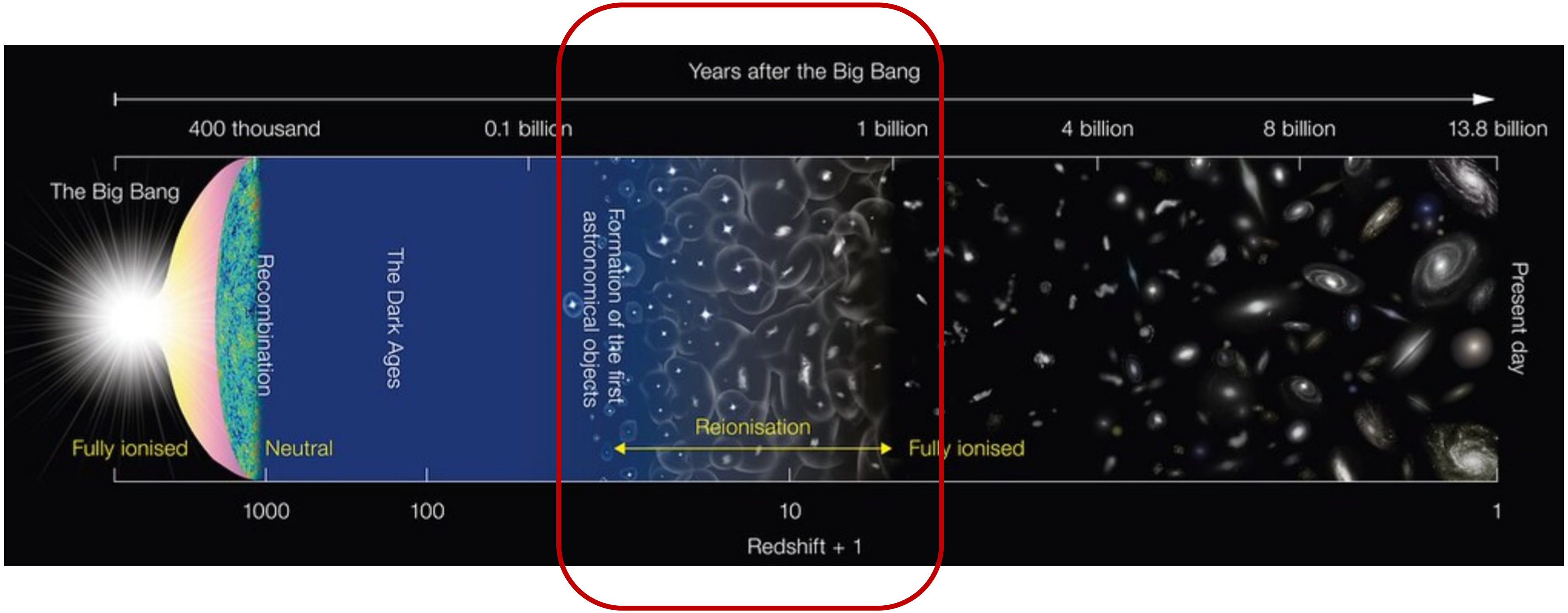
Credit ESO/M. Kornmesser

Outline

1. Background
2. A Candidate LyC Emitter at High Redshift
3. Properties of High-z LyC Emitters
4. Summary and Future Work

Background

Epoch of Reionization (EoR)



- Important process in the evolution of the Universe
- Neutral and opaque to highly ionized and transparent
- Most neutral hydrogen ionized by LyC photons emitted by the first luminous sources

Galaxies are the primary sources of Ionizing Photons

- **Quasars (QSOs)**

Decline sharply in number density at z > 3. Contributes insignificantly to cosmic reionization (<7%).

e.g.: Jiang et al. 2022, Matsuoka et al. 2023

- **Star-forming Galaxies**

The most important sources that can provide the majority of ionizing photons . Quantitative contribution remains controversial.

e.g.: Steidel et al. 2003

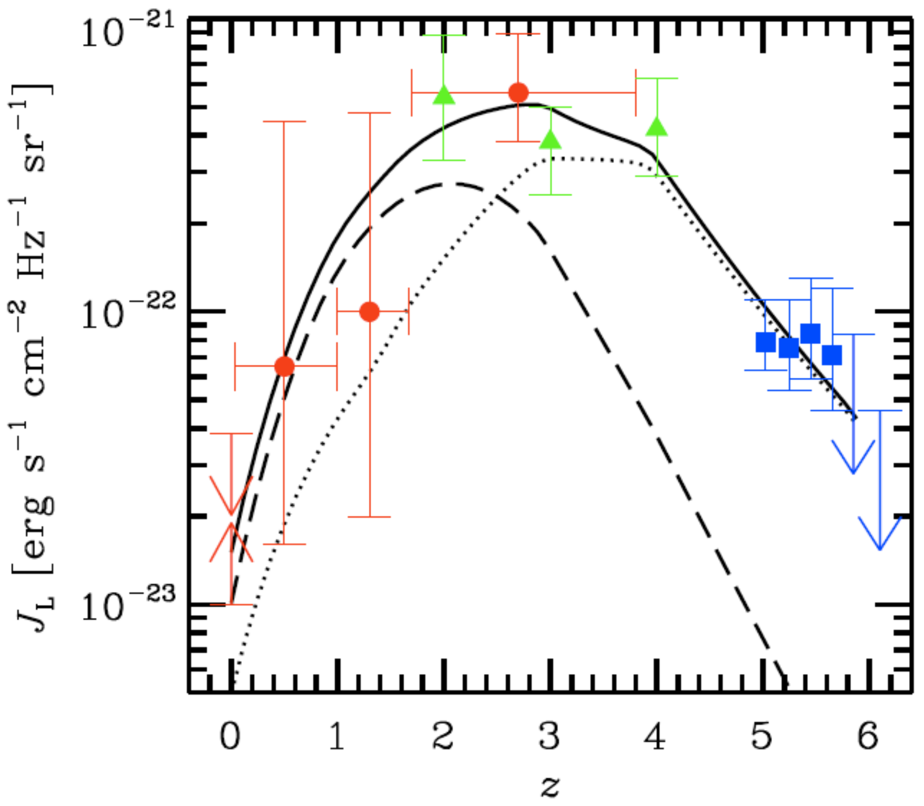
$$\dot{n}_{ion} = f_{esc}\xi_{ion}\rho_{UV}$$

UV LF

Escape Fraction

ionizing photon production rate

Inoue et al (2006)



中国科学院上海天文台 Shanghai Astronomical Observatory, CAS

Observing Lyman Continuum (LyC) Emitters

- **Reionization Era (z ~ 6)**

Impossible due to IGM absorption.

- **Low Redshift (z <~ 0.3)**

HST/COS, FUSE, HUT observations. Not affected by IGM, but complicated selection functions, evolved. (e.g., Bergvall+2006, Leitet+2013, Izotov+2016, Leitherer+2016, Flury+2022)

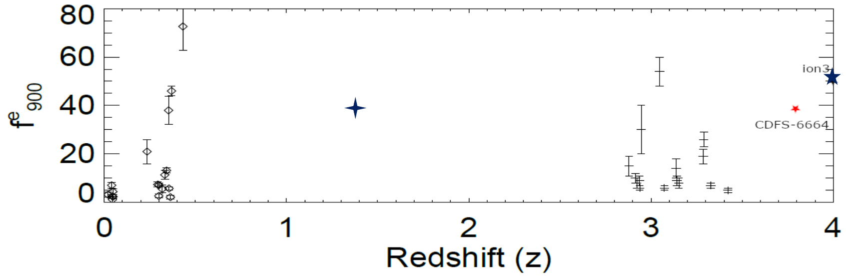
- **Intermediate Redshift (z ~ 1-2.5)**

Rare, limited instruments (GALEX, AstroSat).
(e.g., Saha+2020)

- **High Redshift (z >~ 3)**

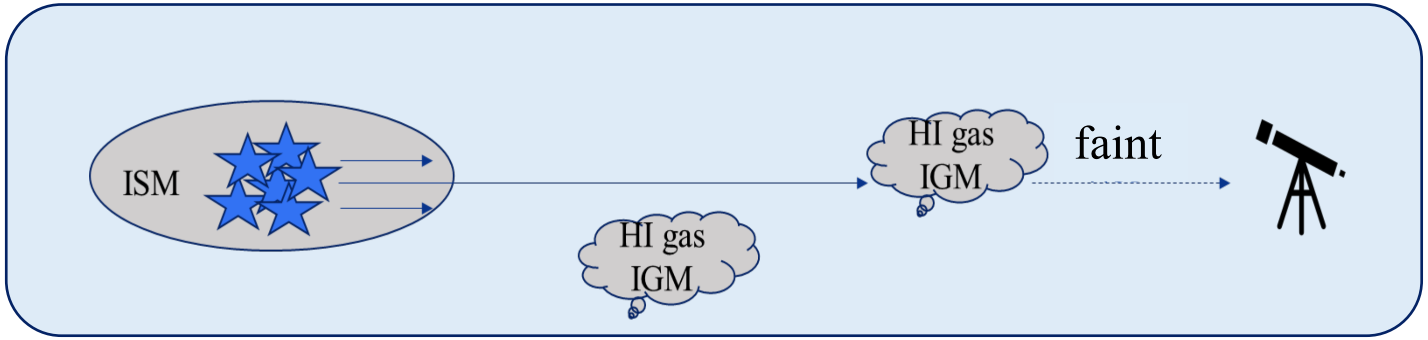
Closest observable to reionization era. Suitable for deep UV and optical observations.

LyC galaxies detected at different Redshifts



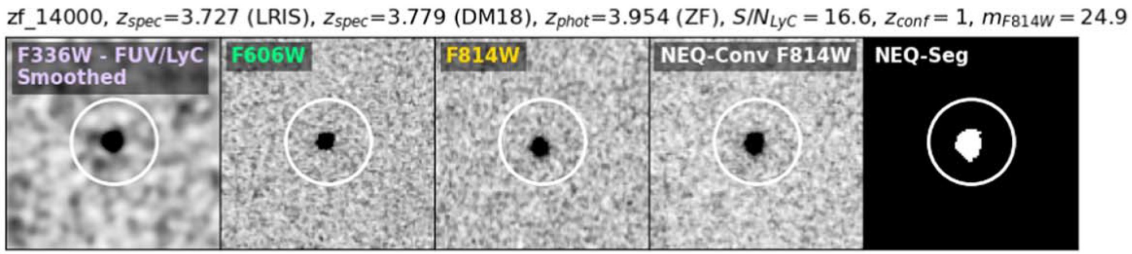
McCandliss, Astro2020

High-z LyC Emitters



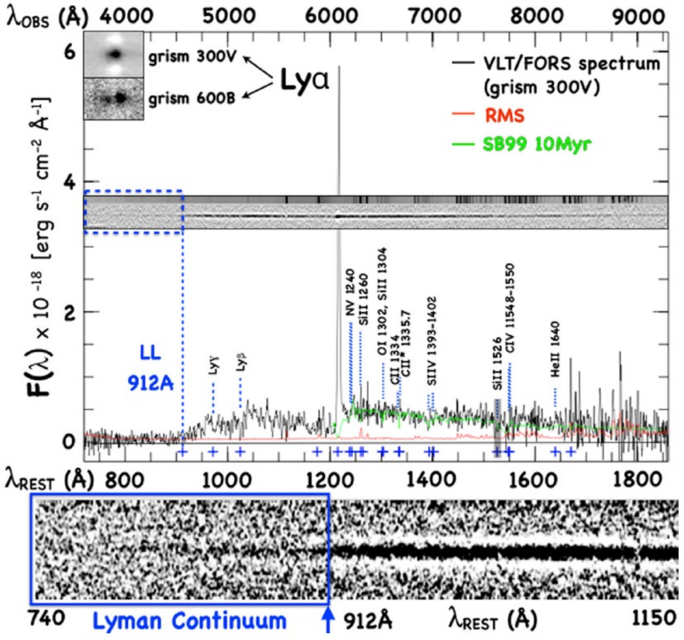
ISM+IGM absorption

- Imaging



Prichard+2022

- Spectroscopy

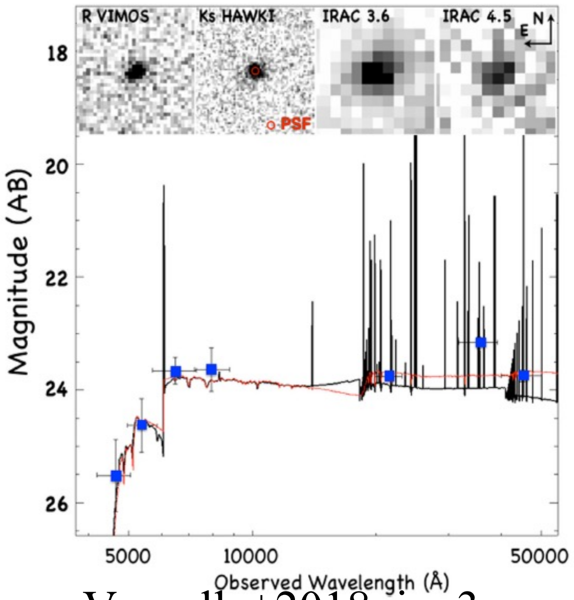


Vanzella+2018

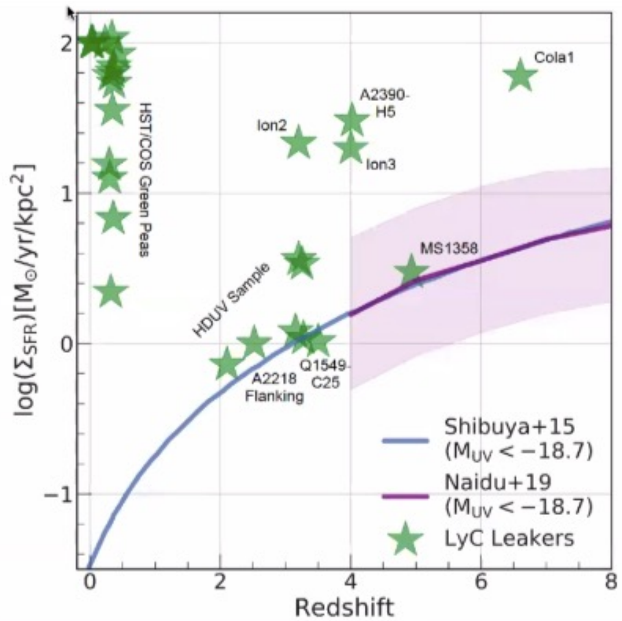
Background

High-z LyC Emitters

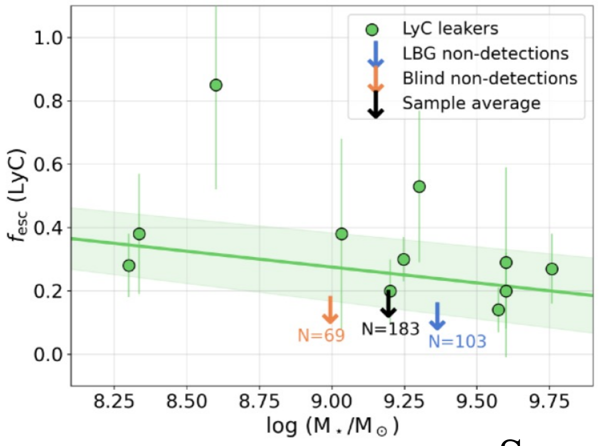
- **Escape fractions, star formation rates, and stellar masses.**
  - Degeneration between IGM, ISM, and stellar population properties
- **Linking escape fractions with galaxy properties.**
- **Research approaches**
  - Case studies (e.g., Vanzella+2010, 2018; Ji+2020; de Barros+2016, Marques-Chaves+2021, Gupta+2024)
  - Statistical Analysis
    - Stacking Analysis → upper limits
    - Systematical studies on known LyC emitters

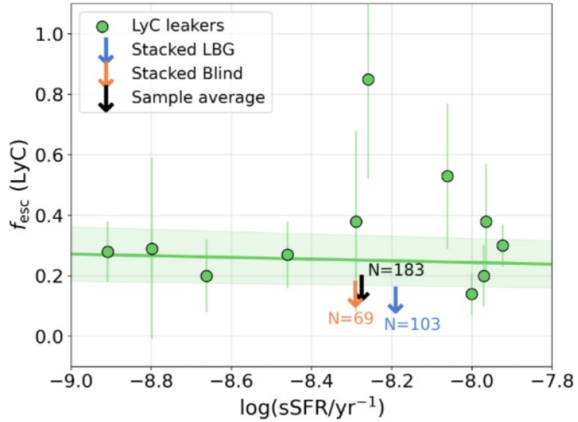


Vanzella+2018, ion3



Naidu+2020



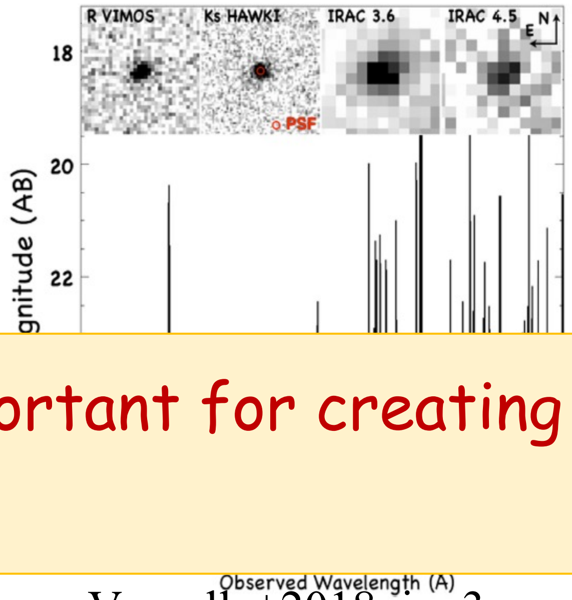


Saxena+2022

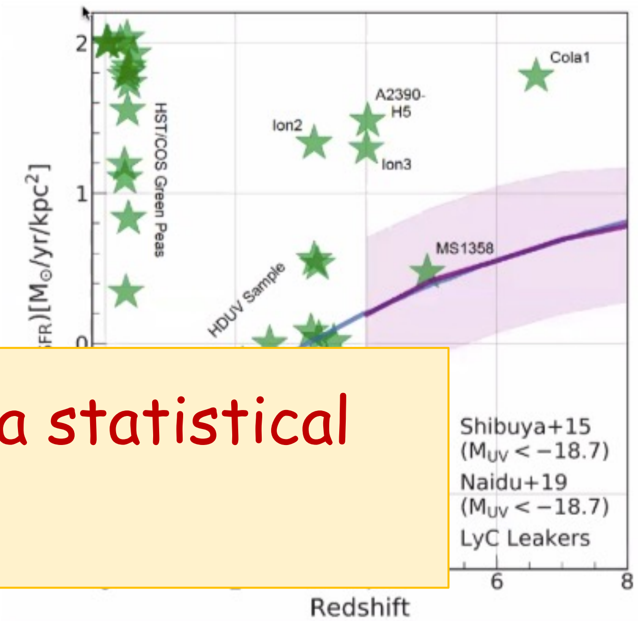
Background

High-z LyC Emitters

- Escape fractions, star formation rates, and stellar masses.
  - Degeneration between IGM, ISM, and stellar



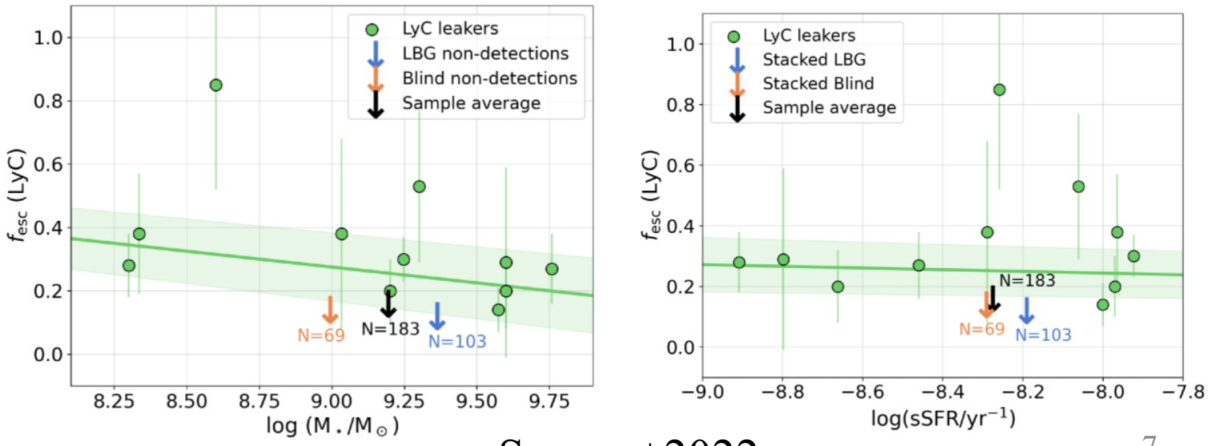
Vanzella+2018, ion3



Naidu+2020

- Detections at high redshift are important for creating a statistical sample of LyC galaxies

- Research approaches
  - Case studies (e.g., Vanzella+2010, 2018; Ji+2020; de Barros+2016, Marques-Chaves+2021, Gupta+2024)
  - Statistical Analysis
    - Stacking Analysis → upper limits
    - Systematical studies on known LyC emitters



Saxena+2022

Detection of a LyC Emitter: CDFS-6664

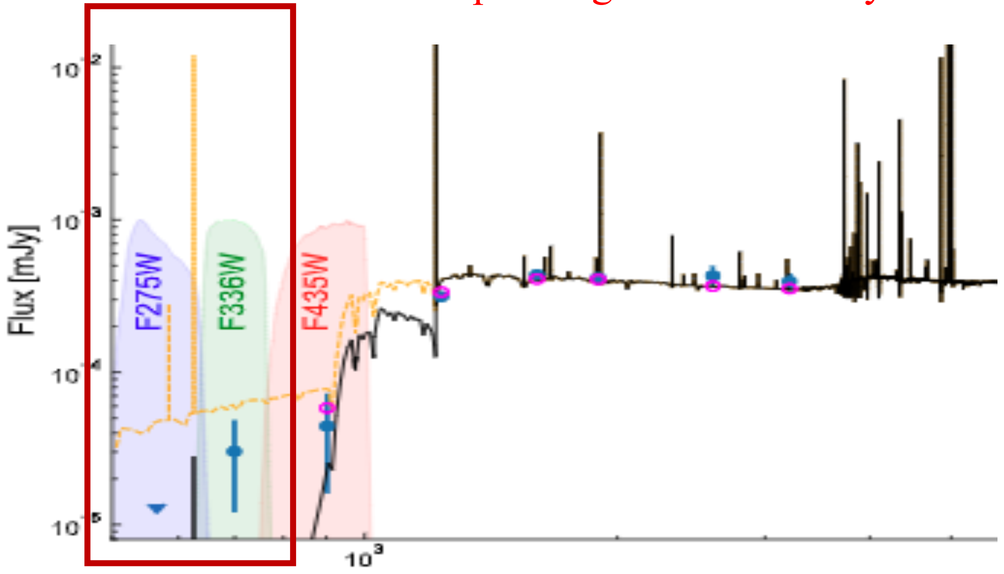
中国科学院上海天文台
Shanghai Astronomical Observatory, CAS

z=3.797

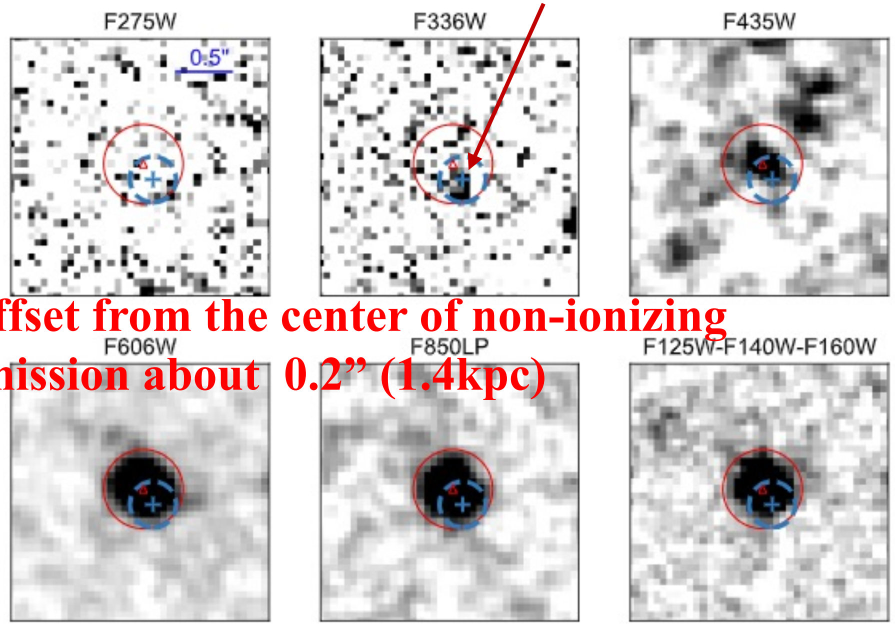
- **Sample Properties**

51 z ~ 3.5 Lyman break galaxies with strong [OIII] emission lines. Only one galaxy (CDFS-6664) has >3 sigma detection

HDUV F336W band corresponding to restframe LyC



LyC detected at z~3.8



Offset from the center of non-ionizing emission about 0.2" (1.4kpc)

- **HDUV Band Detection**

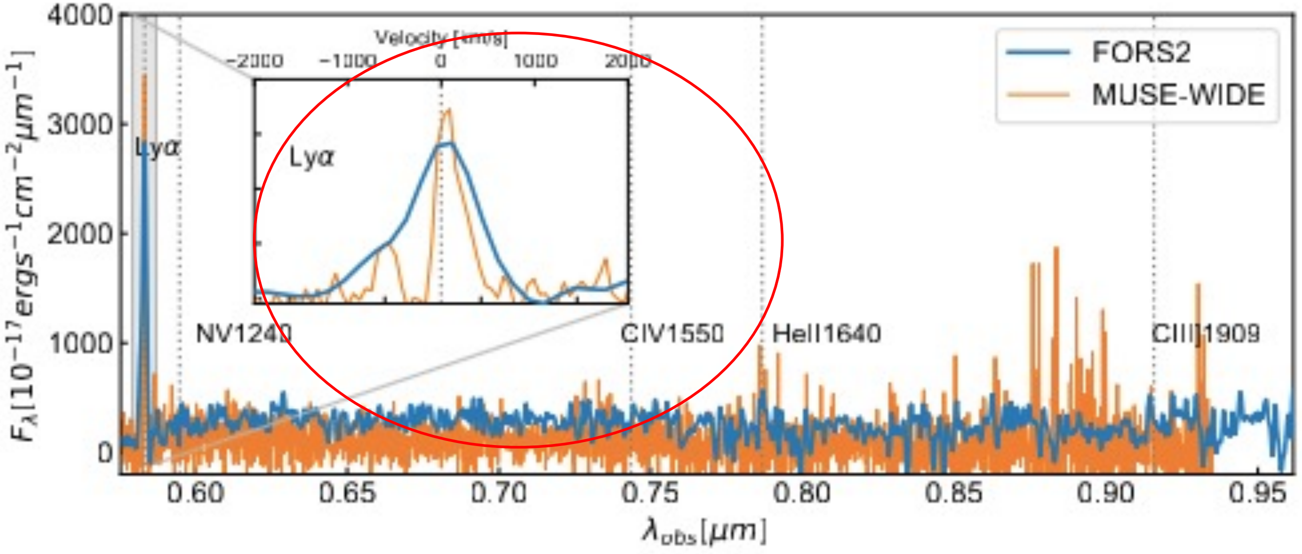
F336W band detection with S/N = 7.9 for isophotal measurement.

M336 = 27.9 ± 0.2 mag @ 0.7" aperture (S/N = 5.0).

Yuan et al. ApJL, 2021, 923, 28

Detection of a LyC Emitter: CDFS-6664

Spectral Features of CDFS-6664 at z ~ 3.8



VLT/FORS2

- Equivalent Width: ~150Å
- Spectral Resolution: R ~660

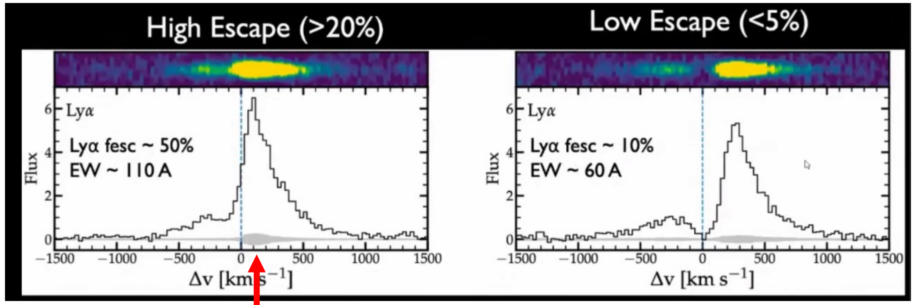
MUSE Observation

- Higher Spectral Resolution: R ~3000
- Lyα Line: Double Peaks

  Blue Peak: Offset by ~–600 km/s

  Red Peak: Offset by 100 km/s

Lya profile



Emission at Systemic Velocity:
Tracer for LyC Leakers
Indicates Clumpy, Multiphase Systems
Non-unity Covering Fractions

Lyα Line Profile Consistent with LyC Leakers (fesc > 20%)

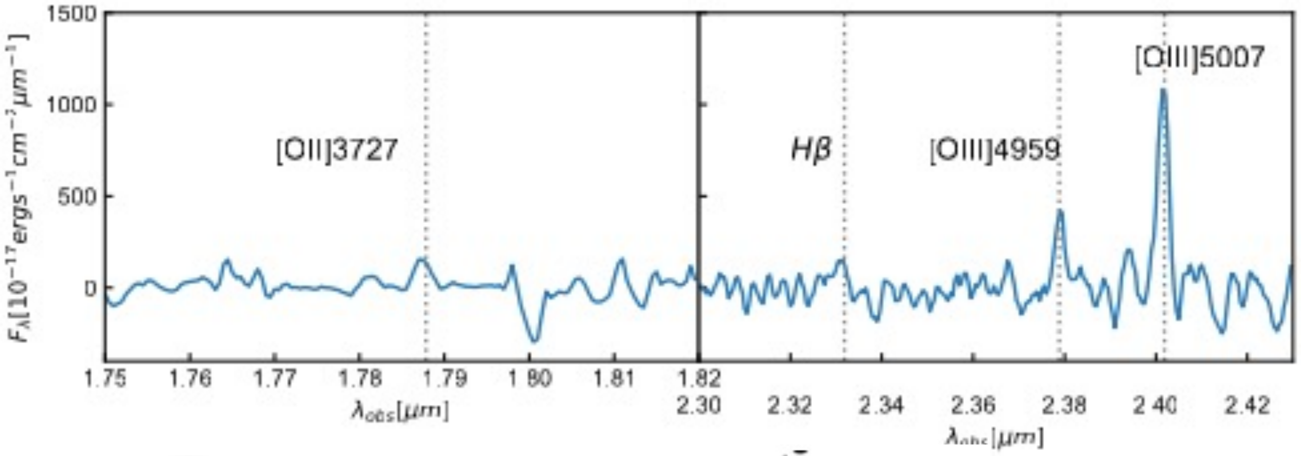
Detection of a LyC Emitter: CDFS-6664

Spectral Features of CDFS-6664 at z = 3.8

NIR spectrum (VLT/SINFONI)

- Maiolino et al. (2008)
- [OIII]/[OII] Ratio: ~10
- Strong [OIII]4959,5007 Emission Lines

AMAZE/SINFONI



Photon Ionization Models:
e.g. Jaskot&Oey (2014) Nakajima & Ouchi (2014)

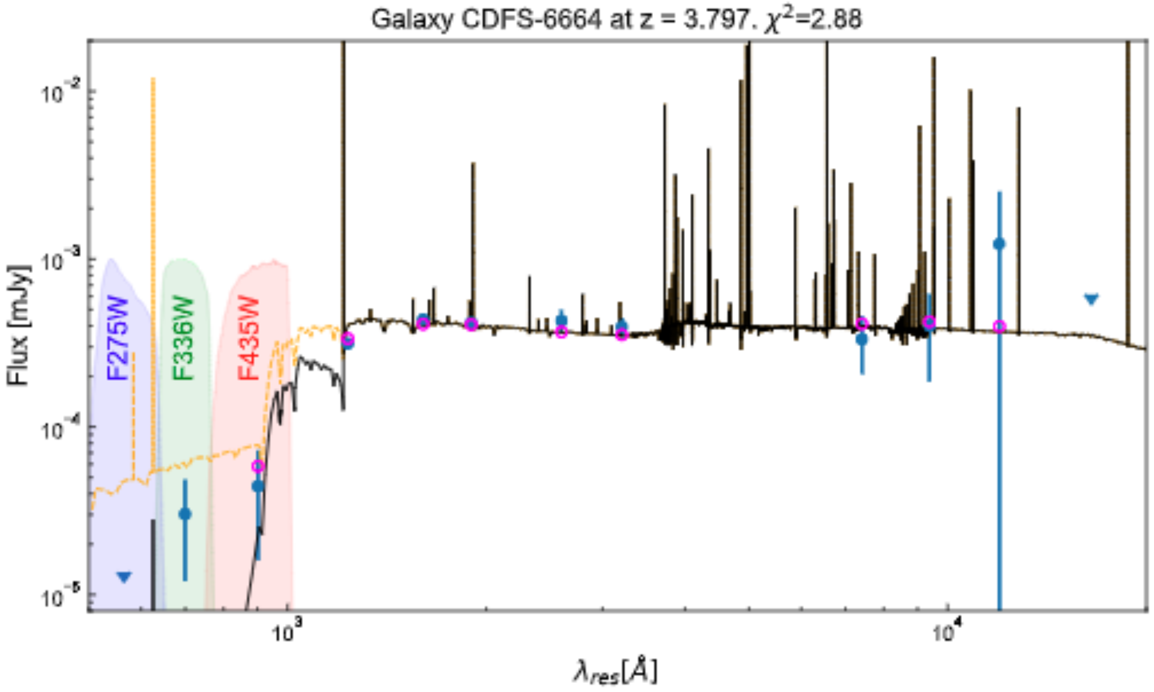
Ionization-bounded nebula *Density-bounded nebula*

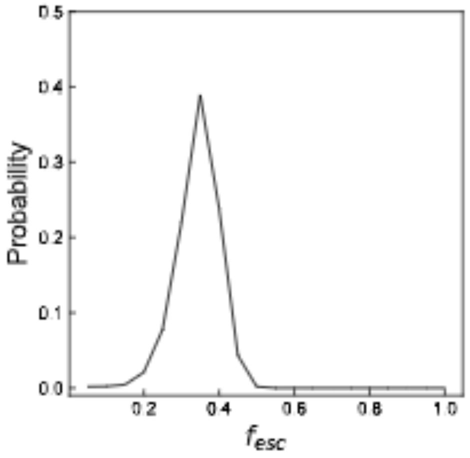
The spectral features also suggest the CDFS-6664 is a LyC emitter

Detection of a LyC Emitter: CDFS-6664

中国科学院上海天文台
Shanghai Astronomical Observatory, CAS

SED fitting for CDFS-6664





CIGALE combines emission-line data in its fitting and can better constrain fesc

$$L_{H\beta}(f_{esc}) = L_{H\beta}(0) \times \frac{1 - f_{esc}}{1 + 0.6 f_{esc}}$$

Inoue2011

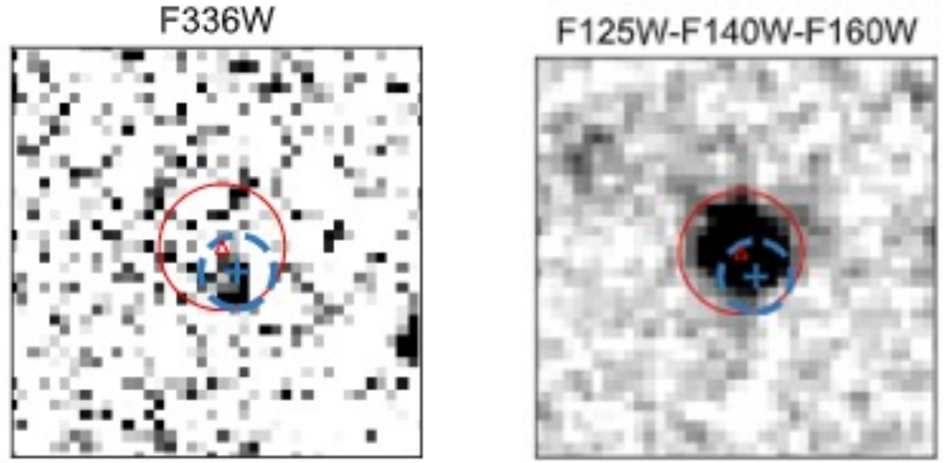
log M*/Msun : 9.15
SFR. : 52.1 M⊙/yr

Detection of a LyC Emitter: CDFS-6664

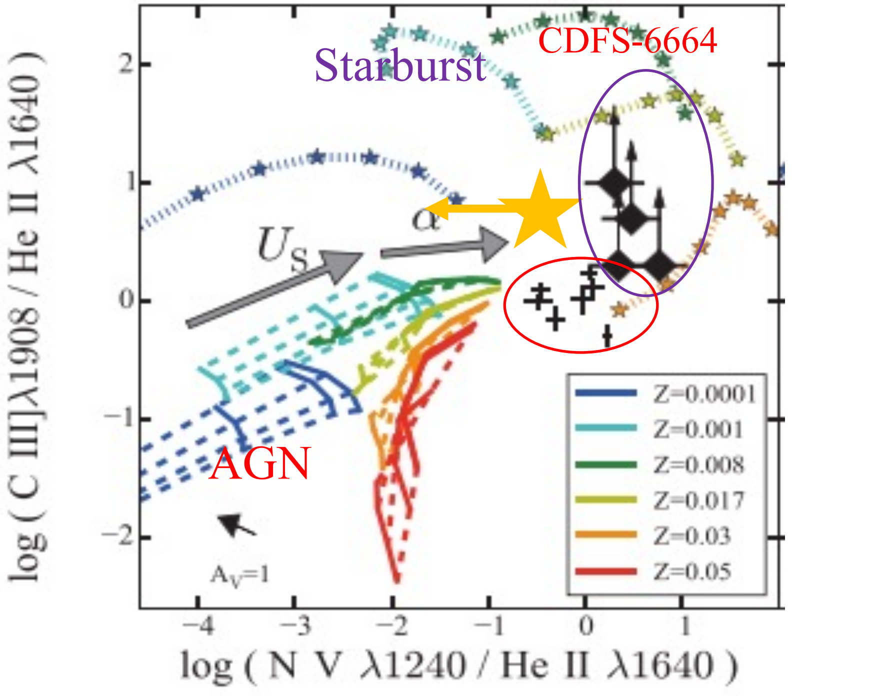
AGN or Starburst

Morphology (F160W)

- Disk-like, Sersic n~1



More like to be starburst than AGN



Feltre+2016

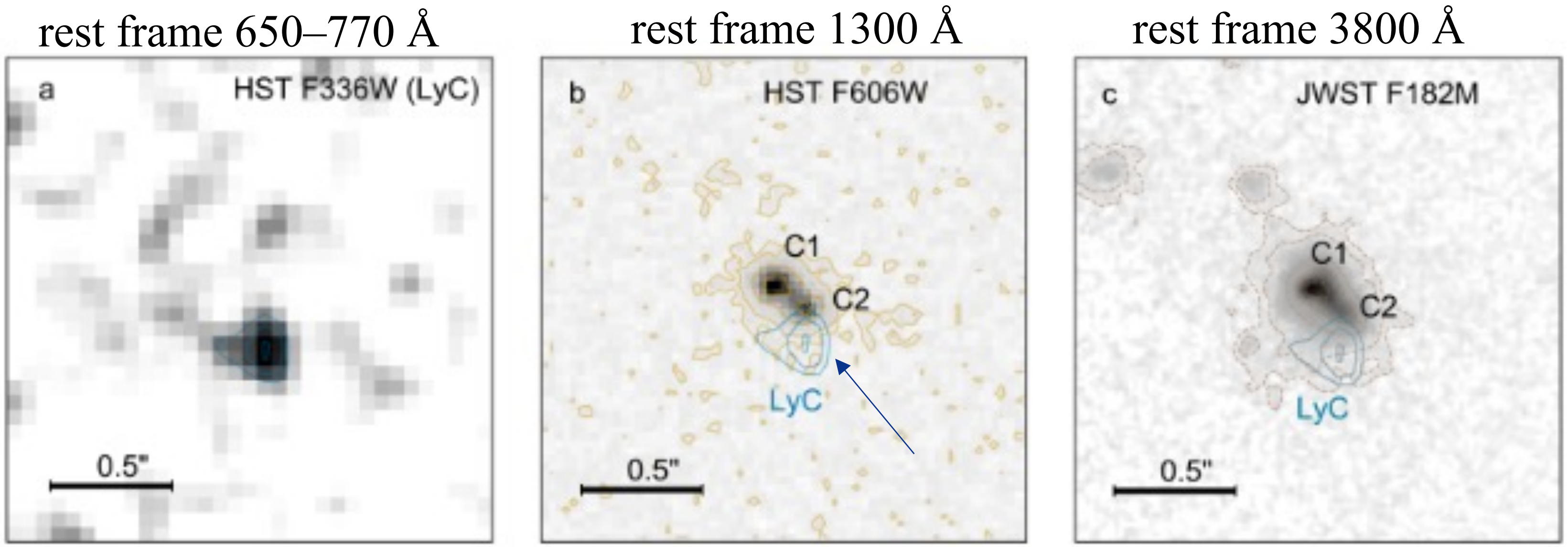
Emission Lines

- Ratio resembles Starburst

UV slope -2.25

Merging Features in CDFS-6664

JWST images reveal merging in CDFS-6664



- LyC (blue, 3σ,4σ, 5σ)
- HST F606W (orange, 2σ,5σ, 15σ, and 30σ)
- JWST F182M (red dashed, 2σ,5σ,30σ, 60σ

LyC Radiation Closer to C2

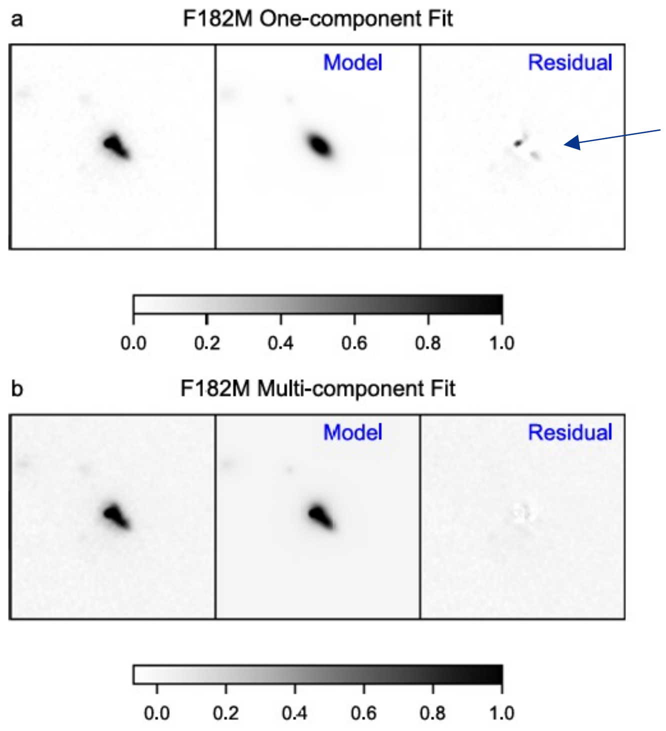
Yuan et al. ApJ, 2024, 975, 53

Merging Features in CDFS-6664

Decomposing Images using GALFIT

One Sérsic

Two Sérsic + a PSF.



Parameters	C1	C2
Effective radius R_e	0.″08	0.″08
Sérsic index n	1.3	0.5
Axis ratio b/a	0.9	0.5
Position angle	6°	45°

- **Image Decomposition**
  - JWST F182M
  - Highest spatial resolution and depth
- **Single component** (poor fit, noticeable residuals)
- **Refined approach**
  - Multiple components until no apparent residuals
  - C1: Sérsic profile + PSF
  - C2: Sérsic profile

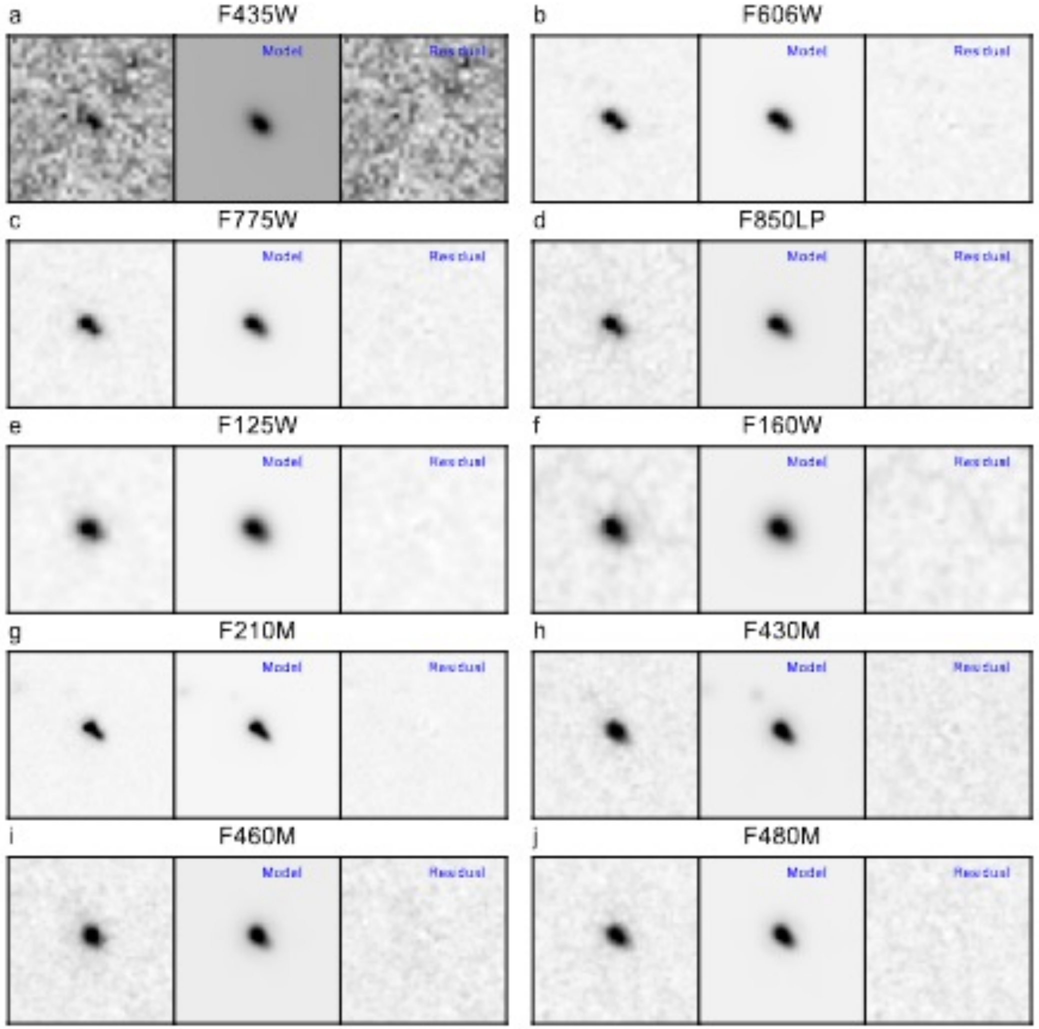
Merging Features in CDFS-6664

中国科学院上海天文台
Shanghai Astronomical Observatory, CAS

Decomposing Images using GALFIT

- **Assumption**
  - Consistent intrinsic light profile across all bands
- **Model Application**
  - Apply F182M models to fit images of other bands
  - Extract flux associated with each model
- **Fitting Process**
  - Convolve models with respective PSF
  - Keep intrinsic light profile parameters fixed
    - Effective radius (Re)
    - Sérsic index (n)
    - Axis ratio (b/a)
    - Position angle (P.A.)
  - Maintain relative positions of components consistent across all bands
  - Allow slight adjustments to absolute positions

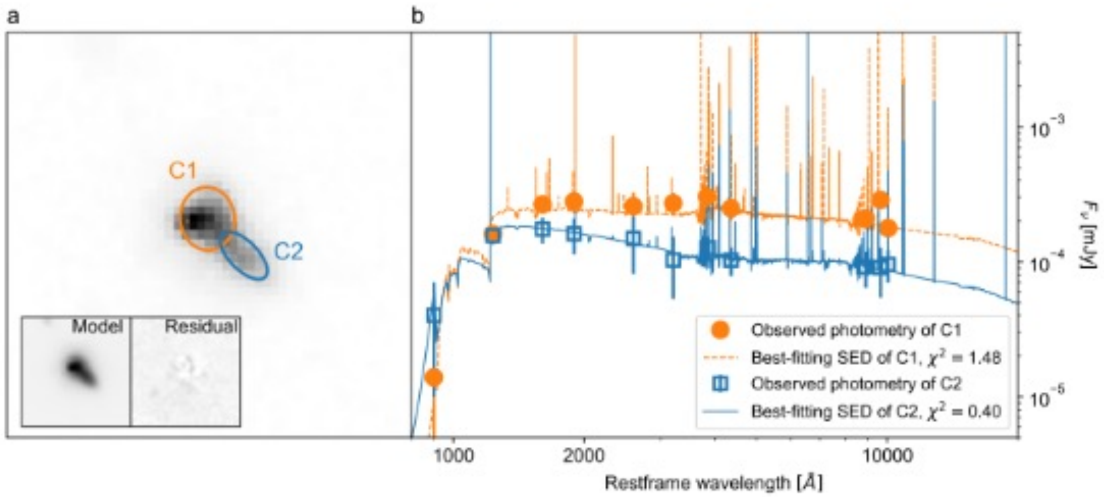
Using the models to fit other bands and extract SEDs



Merging Features in CDFS-6664

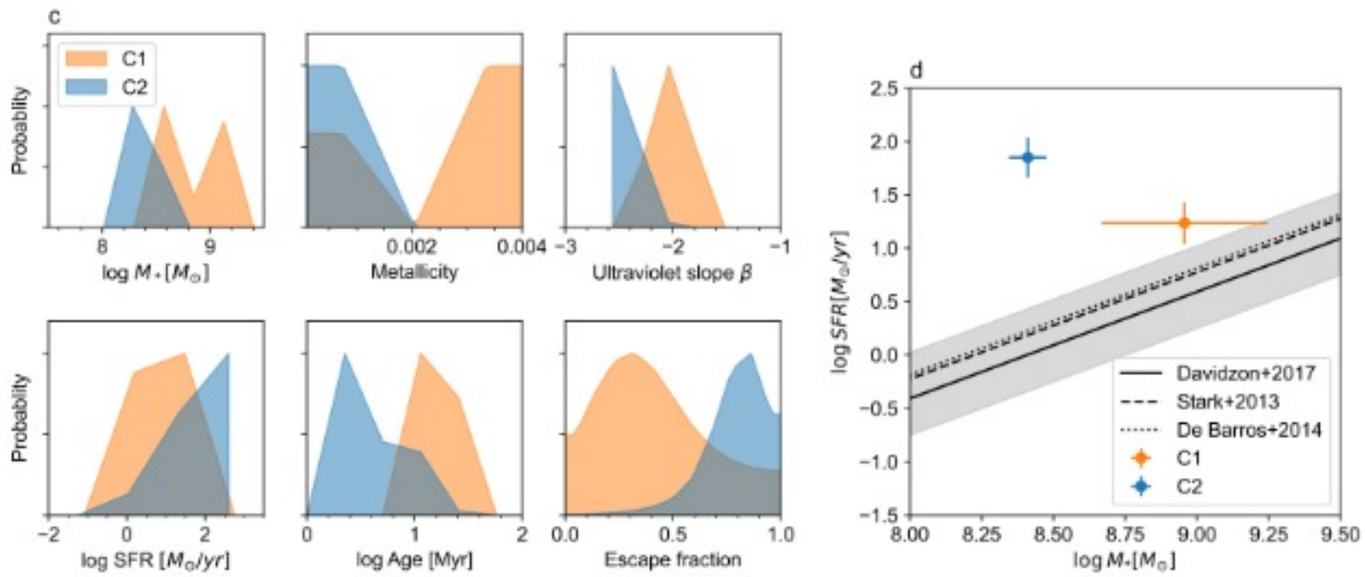
SED fitting

Parameter	Value
Star Formation History, Delayed Form	
Timescale (τ)	10
Age	2, 5, 10, 20, 50, 100, 200, 500, 1000, 1500
Stellar Population (G. Bruzual & S. Charlot 2003)	
IMF	(E. E. Salpeter 1955)
Metallicity	0.0001, 0.0004, 0.004 ($Z_{\odot} = 0.02$)
Nebular (A. K. Inoue 2011)	
LyC escape fraction (f_{esc})	0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0
Radiation strength ($\log U$)	−2.5
Dust Attenuation (Modified Calzetti Dust Attenuation Curve)	
$E(B-V)_{\mathrm{lines}}$	0.075
Modifying the attenuation curve (δ)	−0.4
$E(B-V)$ factor (f_{ebv})	1.0



Merging Features in CDFS-6664

Results



- **Evidence of Merging**
  - Morphology
  - C1 and C2 contribute to system flux > 75%, to stellar mass > 85% → Unlikely to be clumps
  - C1 and C2 have similar photometric redshifts

- C2 compares to C1: younger stellar population，metal poorer，bluer UV slope, more actively star-forming and higher ionizing photon production rate
- **→ C2 responsible for the LyC emission, f_{esc}>37%, offset**

More than Half of z>3 LyC Emitters show LyC Offset

中国科学院上海天文台
Shanghai Astronomical Observatory, CAS

Summary of LyC detections at z>3

Table A1
Collection of Candidate LyC Emitters at $z_{spec} > 3$ in the Literature

No. (1)	ID (2)	Reference (3)	z_{spec} (4)	LyC Band (5)	Reference Band (6)	Offset (7)
1	ion2	E. Vanzella et al. (2016)	3.212	HST F336W	HST F606W	N
2	ion1	E. Vanzella et al. (2012), Z. Ji et al. (2020)	3.794	HST F410M	HST F775W	Y
3	CDFS-6664	F.-T. Yuan et al. (2021)	3.797	HST F336W	HST F606W	Y
4	J0121+0025	R. Marques-Chaves et al. (2021)	3.244	Spec	Subaru SC/R	…
5	Q1549-C25	A. E. Shapley et al. (2016)	3.1526	Spec	HST F606W	…
6	ion3	E. Vanzella et al. (2018)	4	Spec	VLT HAWKI/Ks	…
7	CANDELS-5161	A. Saxena et al. (2022)	3.42	La Silla/NB396	HST F606W	Y
8	CANDELS-9358	A. Saxena et al. (2022)	3.229	CTIO/NB3727	HST F606W	…
9	CANDELS-9692	A. Saxena et al. (2022)	3.47	La Silla/NB396	HST F606W	Y
10	CANDELS-15718	A. Saxena et al. (2022)	3.439	La Silla/NB396	HST F606W	N
11	CANDELS-16444	A. Saxena et al. (2022)	3.128	CTIO/NB3727	HST F606W	N
12	CANDELS-18454	A. Saxena et al. (2022)	3.163	CTIO/NB3727	HST F606W	…
13	CANDELS-19872	A. Saxena et al. (2022)	3.452	La Silla/NB396	HST F606W	…
14	CANDELS-20745	A. Saxena et al. (2022)	3.495	La Silla/NB396	HST F606W	N
15	CANDELS-24975	A. Saxena et al. (2022)	3.187	CTIO/NB3727	HST F606W	…
16	F336W-189	A. Saxena et al. (2022), T. E. Rivera-Thorsen et al. (2022)	3.46	HST F336W	HST F435W	Y
17	F336W1041	T. E. Rivera-Thorsen et al. (2022)	3.329	HST F336W	HST F435W	N

…

Yuan et al. ApJ, 2024, 975, 53

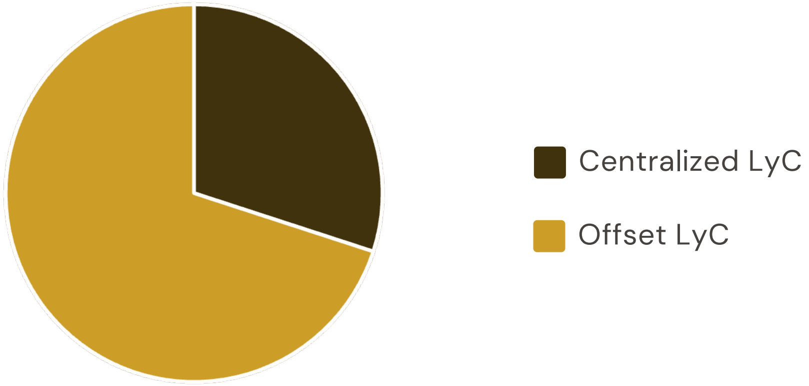
- Candidates of LyC emitters at z>3 from > 20 works
- Remove:
  - Known AGNs
  - Duplicates
  - Possible contaminants
- 89 LyC emitters have both images at LyC and non-ionizing bands
- Identify as offset if the centers separate more than at least 0.1” (depend on the resolution)

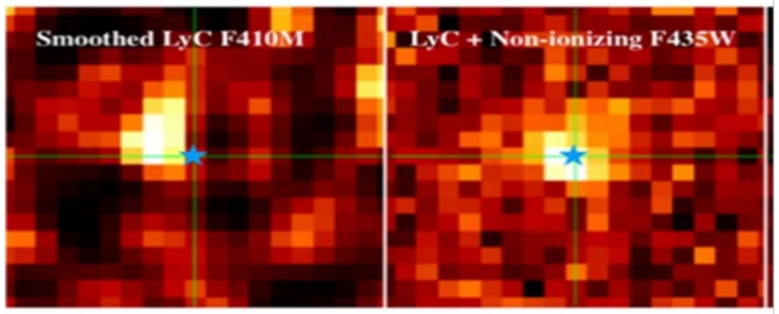
More than Half of z>3 LyC Emitters show LyC Offset

60-70%

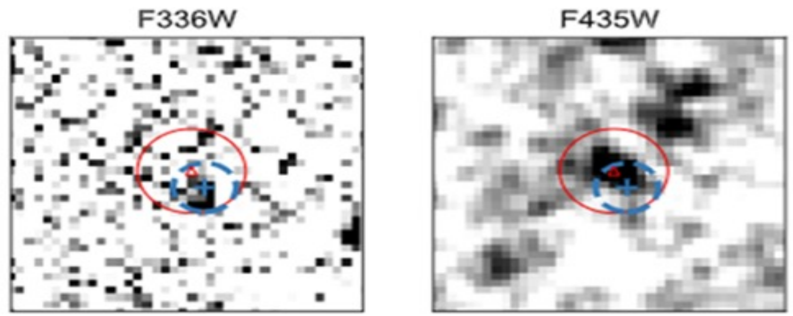
High-z Offset Rate

61 out of 89 galaxies. Even count half of the detections as contaminants (Nestor et al. 2013), the offset rate is still > 50% (~30/58).

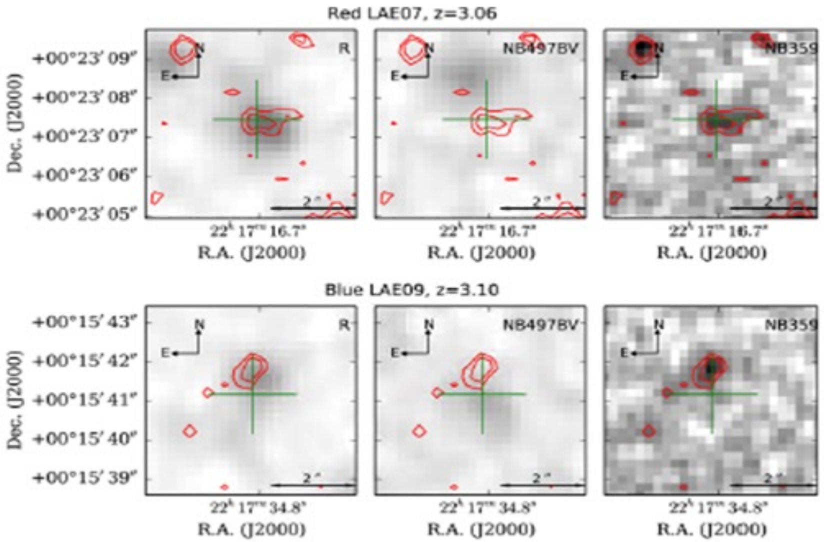




Ji et al. (2020) Ion1



CDFS-6664

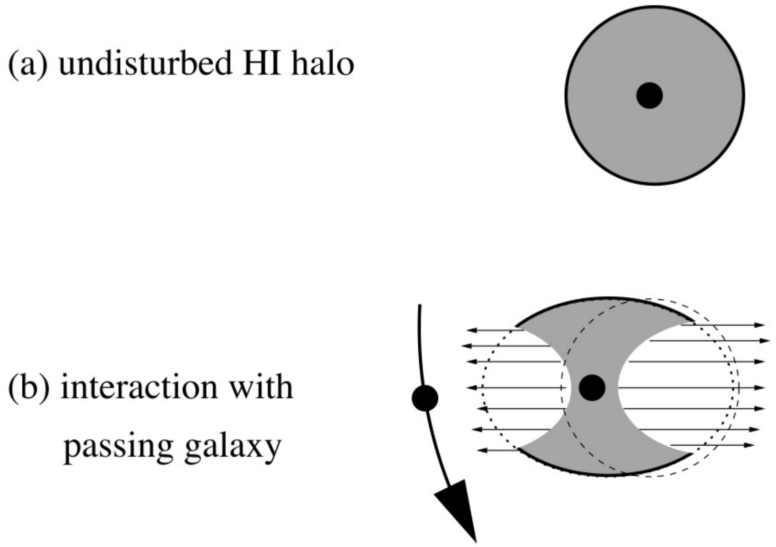


Micheva et al. (2017) SSA22 sample

Galaxy Interaction and LyC leaking

中国科学院上海天文台
Shanghai Astronomical Observatory, CAS

- Galaxy interaction enhances the star formation, creating clumpy ISM and channels for LyC photons to escape
- The anisotropic ISM can also cause the offset between LyC emission and the galactic optical center



Rauch et al. 2013

CDFS-6664: a case that galaxies with high escape fractions can exist in a merging system, with the LyC emission offset from the system center, building a connection between the merging process and the ionizing photon escape.

Properties of High-z LyC Galaxies

中国科学院上海天文台
Shanghai Astronomical Observatory, CAS

Systematic Study

- 23 LyC candidates in GOODS-S
- Systematic study with unified SED modeling

GOODS-S LyC Emitters

Name[b]	R.A.	Decl.	Redshift	f_{esc}	LyC Band	S/N_{LyC}	Offset[d]	Reference
1181371[a]	53.1358	−27.7955	3.084	0.88 ± 0.07	F336W	5.01σ	Yes	K24
z19863[a]	53.1699	−27.7684	3.088	0.24 ± 0.06	F336W	$\sim4\sigma$	Yes	G24
Ion2[a]	53.013515	−27.7552331	3.212	$0.25^{+0.004c}_{-0.000}$	F336W (U, $Spec_{VIMOS}$)	$\sim10\sigma$	No	DB16
109004028[a]	53.0994	−27.8392	3.267	0.34 ± 0.10	F336W	3.03σ	Yes	K24
F336W-189[a]	53.1679012	−27.7979524	3.46	0.36 ± 0.22	F336W (U)	$\sim3.6\sigma$	Yes	RT22
Ion1[a]	53.0693219	−27.7148184	3.794	0.05 ± 0.02	U (F410M)	$\sim10.3\sigma$	Yes	J20
CDFS-6664[a]	53.13885833	−27.83537861	3.797	0.38 ± 0.07	F336W	$\sim5\sigma$	Yes	Y21
126049137[a]	53.2042	−27.8172	4.426	0.69 ± 0.10	F336W	4.39σ	No	K24
CDFS 16444	53.1446546	−27.7711112	3.128	0.30 ± 0.07	NB3727	$>2\sigma$	No	S22
1521589	53.1283	−27.7887	3.152	0.79 ± 0.15	F336W	2.69σ	Yes	K24
CDFS 24975	53.1457298	−27.6869713	3.187	0.27 ± 0.11	NB3727	$>2\sigma$	⋯	S22
CDFS 9358	53.1247187	−27.8245184	3.229	0.14 ± 0.07	NB3727	$>2\sigma$	⋯	S22
119004004	53.1891	−27.8363	3.314	0.26 ± 0.14	F336W	2.59σ	No	K24
CDFS 5161	53.0545613	−27.862915	3.42	0.53 ± 0.24	NB396	$>2\sigma$	Yes	S22
CDFS 15718	53.1595397	−27.7767456	3.439	0.28 ± 0.10	NB396	$>2\sigma$	No	S22
CDFS 19872	53.1995306	−27.7414921	3.452	0.29 ± 0.30	NB396	$>2\sigma$	⋯	S22
CDFS 9692	53.0268389	−27.8209671	3.47	0.38 ± 0.19	NB396	$>2\sigma$	Yes	S22
CDFS 20745	53.0459052	−27.7336266	3.495	0.38 ± 0.30	NB396	$>2\sigma$	No	S22
3452147	53.1541	−27.7988	3.521	0.47 ± 0.14	F336W	2.60σ	Yes	K24
4062373	53.1792	−27.7829	3.663	0.74 ± 0.13	F336W	2.21σ	Yes	K24
4172404	53.1851	−27.7839	3.672	0.31 ± 0.15	F336W	2.88σ	Yes	K24
5622786	53.1604	−27.8174	4.005	0.53 ± 0.11	F336W	2.05σ	Yes	K24
122032127	53.1326	−27.8374	4.348	0.77 ± 0.14	F336W	2.33σ	Yes	K24

Reference	Data	N_{phot}	Wavelength Range (μm)	IMF	SPS Model	SFH	Z ($Z_\odot$)	Extinction Curve	Nebular Model	f_{esc}
S22	HST, Ks, Spitzer	14	0.4–8	KB02(1)	BC03	ExpDec	0–1	C00(5)	F13(8)	No
RT22	HST	11	0.2–1.5	KB02 (1)	BC03	Delayed	0.2	C00(5)	F17(9)	No
Y21	HST, Spitzer	12	0.3–24	Salpeter(2)	BC03	Delayed	0.02–1	C00(5)/CCM89(6)	I10(10)	Yes
DB16	HST, Spitzer	9	0.4–8	Salpeter(2)	BC03	Constant	0.2	S79(14)	⋯	No
J20	HST, Ks, Spitzer	16	0.4–8	K01(3)	FSPS(4)	Delayed	1	C00(5)	F98 (11), F13(8)	No
G24	HST, JWST	18	0.4–4.8	Chabrier(12)	BC03	Delayed	⋯	CF00(13)	⋯	No
K24	HST, Ks, Spitzer	16	0.3–24	Chabrier(12)	BC03	Double exponential	0.005–1	C00(5)/CCM89(6)	I10(10)	Yes
This work	HST, Ks, Spitzer, JWST	26	0.4–8	Chabrier (12)	BC03	Delayed	0.2	C00(5)/CCM89(6)	I10(10)	Yes

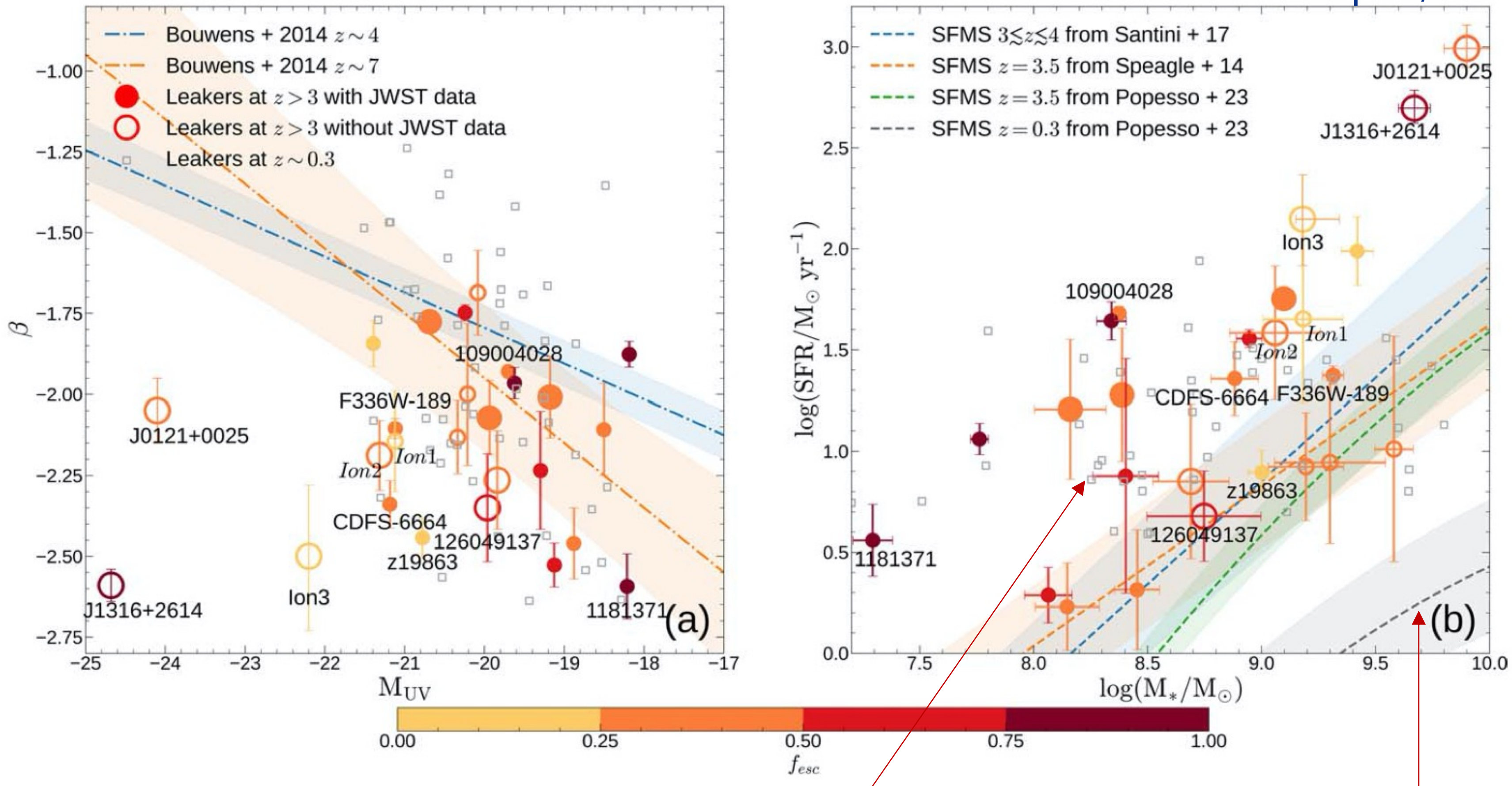
Zhu & Yuan et al. ApJL, 2024, 974, 20

Properties of High-z LyC Galaxies

中国科学院上海天文台
Shanghai Astronomical Observatory, CAS

Blue UV slopes , but not all are Starbursts

Zhu & Yuan et al. ApJL, 2024, 974, 20



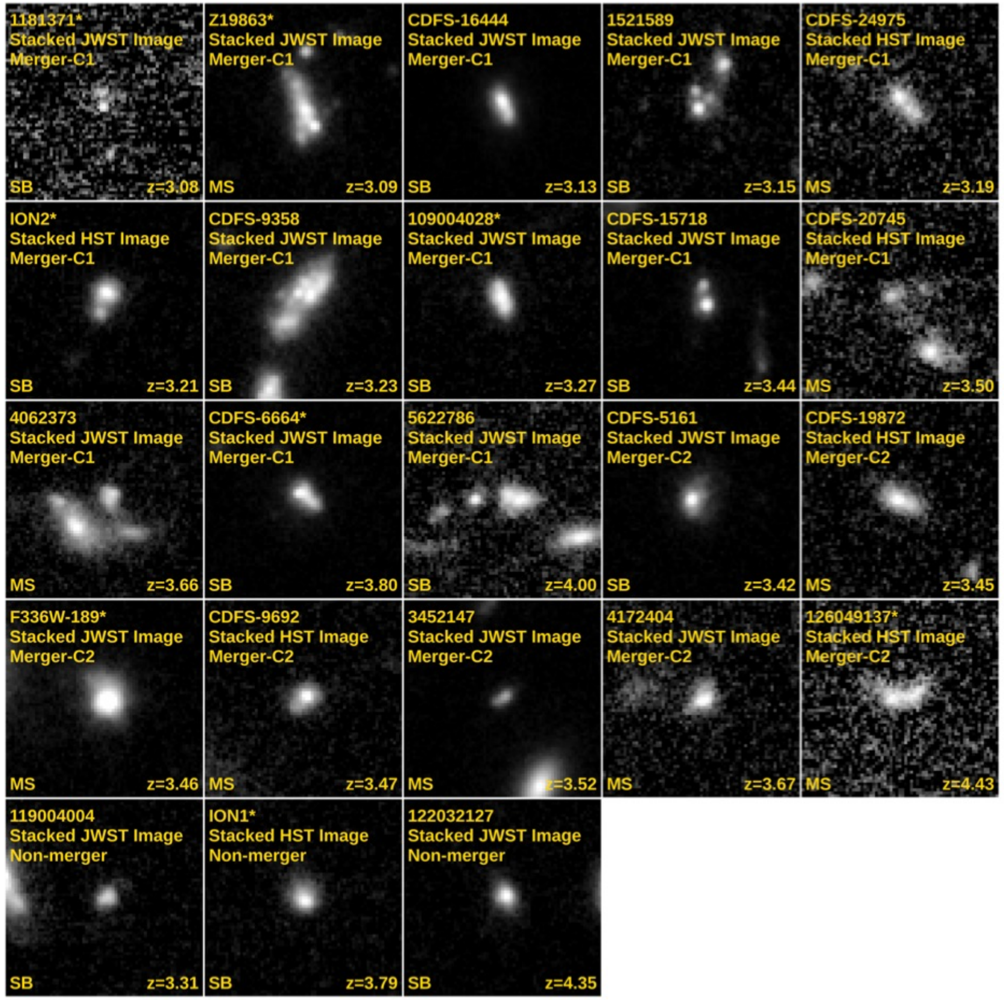
Extremely high SSFR is NOT necessary for LyC photons to escape from galaxies at high-z

low-z LyC

low-z MS

Properties of High-z LyC Galaxies

A high fraction of LyC galaxies shows merging features



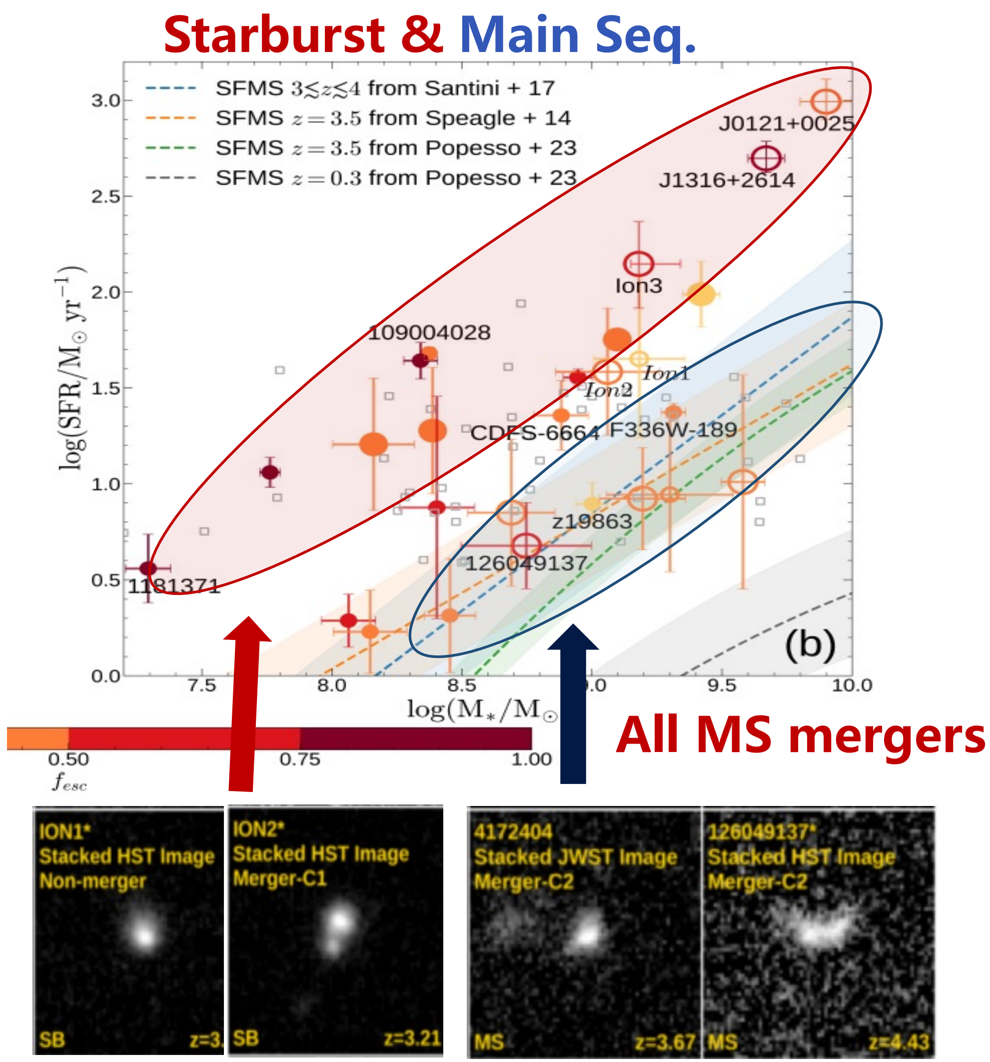
- **Interaction Signatures**

Most high-z LyC emitters in our sample show morphological signatures of recent or ongoing interactions, suggesting mergers may be a primary trigger for creating LyC escape channels.

Zhu, Zheng & Yuan et al. ApJL, 2025，arxiv:2412.08395

Properties of High-z LyC Galaxies

A high fraction of LyC galaxies shows merging features



- **Starburst LyC Leakers:**
  - Composition: Mergers and Compact Galaxies
- **Main Sequence LyC Leakers:**
  - Composition: All Mergers
- **Merging as an Escape Mechanism**
  - Provides an alternative mechanism for LyC photon escape
  - Example: CDFS-6664

Low-z LyC leakers	vs	High-z LyC leakers
	Sample	
LzLCS, ~ 50 galaxies Flury et al., Izotov et al. Wang et al.		>20 works, ~ 100 galaxies
	Redshift	
z~0.3		z~3.5
	Stellar Mass	
$10^7 \sim 10^{10} M_\odot$		$10^7 \sim 10^{10} M_\odot$
	SFR	
All starbursts		Starbursts and main sequence
	Size	
Compact		More extended
	Morphology	
Point source Merging signatures under HST resolution		Merger dominant?

Summary

1

CDFS-6664: a special LyC emitter at z~3.8

CDFS-6664, a LyC emitter at z~3.8 with significant offset ionizing radiation,
provides a crucial laboratory for understanding the mechanisms driving cosmic reionization.

2

Merger-Driven Escape

JWST observations reveal that galaxy interactions and mergers likely create the conditions necessary
for LyC escape, challenging models that depend primarily on global galaxy properties like mass or metallicity.

3

Implications on Mechanism of LyC Escape

The high prevalence of offset LyC emission (60-70%) among high-redshift galaxies suggests that interaction-driven
escape channels may be the dominant mechanism allowing ionizing radiation to reach the intergalactic medium.

Thank you for your attention!

FT yuanft@shao.ac.cn

Related Papers:

Yuan et al. ApJL, 2021, 923, 28

Yuan et al. ApJ, 2024, 975, 53

Zhu & Yuan et al. ApJL, 2024, 974, 20

Zhu, Zheng & Yuan et al. ApJL, 2025，arxiv:2412.08395

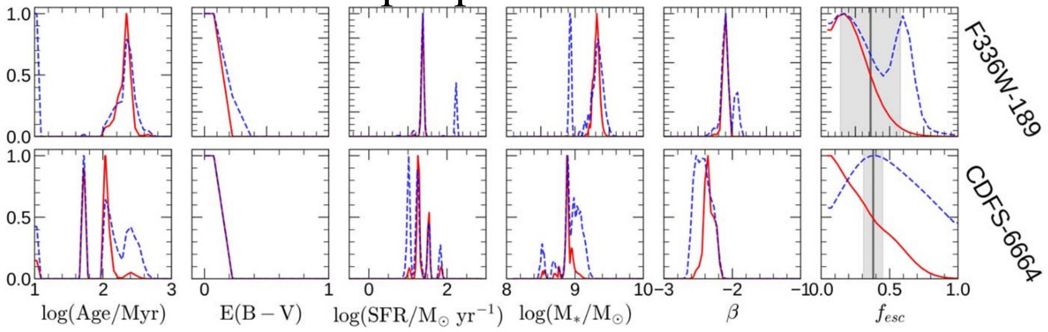
Credit ESO/M. Kornmesser

Properties of High-z LyC Galaxies

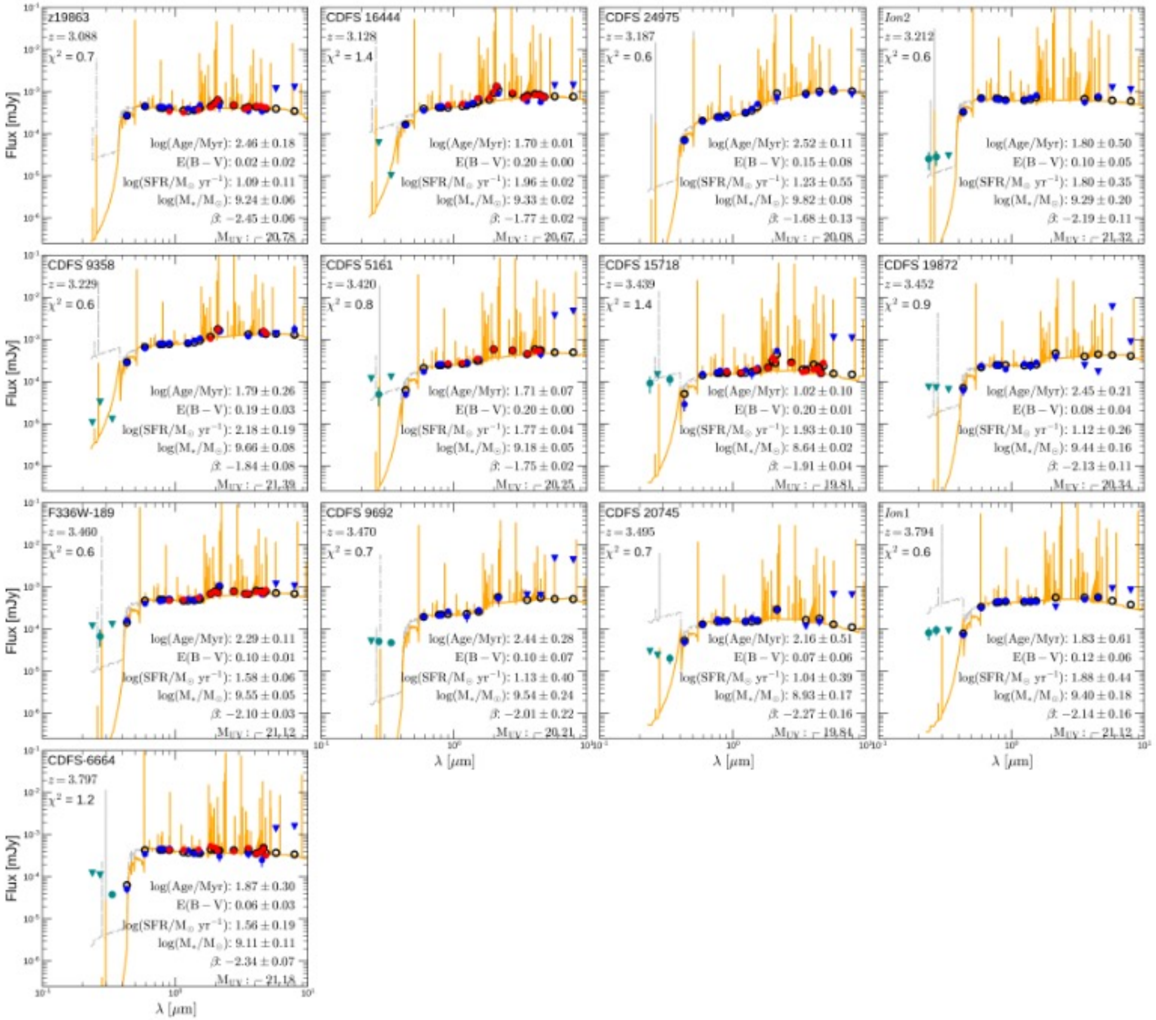
Systematic SED analysis

- UV to IR data, including JWST data
- SED analysis to obtain physical properties
- JWST data help constrain the parameters

PDF of output parameters

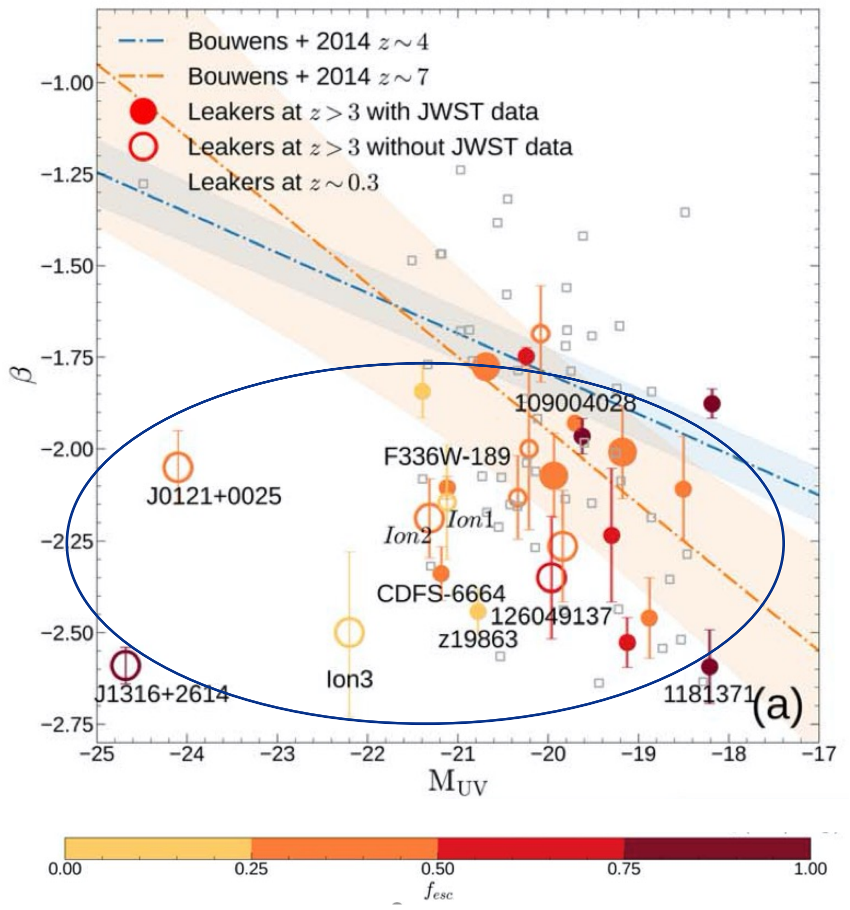


Red: With JWST data
Blue: Without JWST data



Properties of High-z LyC Galaxies

LyC Emitters have bluer UV slopes, but not all starbursts

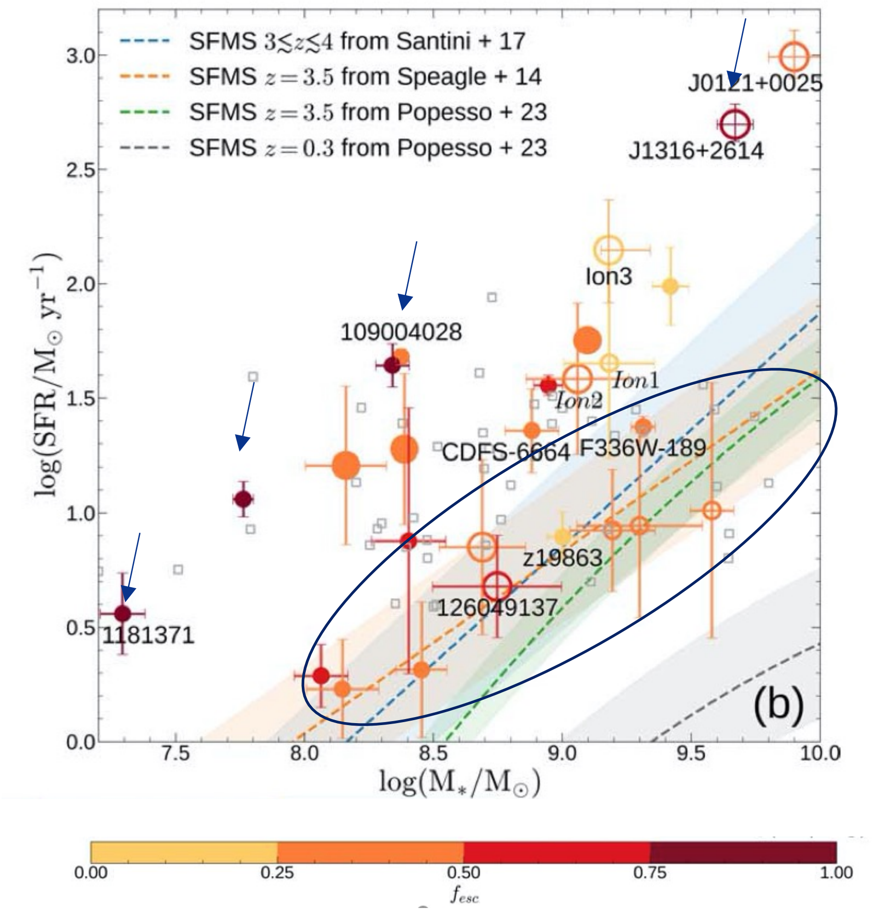


- **High Redshift LyC leakers/emitters (z ~ 3.5)**
  - Below mean LBG relation at z~4→Very blue UV slopes β
  - Reliable: 7 galaxies with high S/Ns (>3)
- **Implications of Blue UV Slopes**
  - Young stellar populations
  - Low metallicity
  - Low dust attenuation
  - Conditions favorable for LyC photon leakage
- **Low Redshift LyC leakers as a comparison**
  - Chisholm et al.: β–MUV relation similar to z~7 galaxies
  - Our findings: z>3 LyC leakers have bluer β slopes than z~7 LBGs or low-z LyC leakers
  - High-z LyC leakers have higher average fesc than low-z leakers

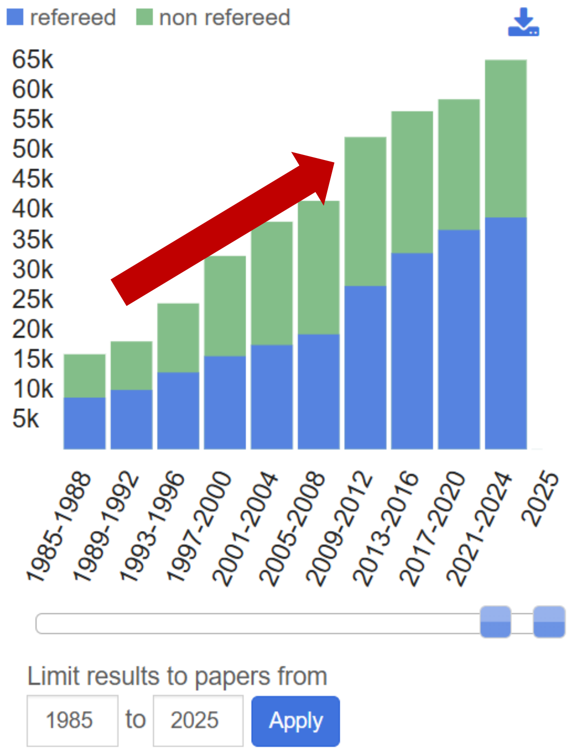
Properties of High-z LyC Galaxies

LyC Emitters have bluer UV slopes, but not all starbursts

- **High-redshift LyC leakers span a wide range of specific SFRs**
  - No clear trend of fesc as a function of sSFR
- **Not all LyC leakers are starbursts (10/26 are on the SFMS), indicating other mechanisms at play**
  - High escape fractions observed in vigorous starbursts (fesc > 75%)
  - Vigorous starbursts generate many ionizing photons, creating escape channels for ionizing photons
  - Comparable average fesc for SFMS and starburst region LyC leakers
- **Different mechanisms for LyC photon escape at high vs. low redshifts**



Abs: galaxies



Title: Lyman continuum

Considering the morphology parameters, like the sersic index and that the light contributions of C1 and C2 to the whole system is about 75%. C1 and C2 are unlikely to be clumpy structures because clumps can only contribute about 20% optical luminosity and stellar mass.

Also, the probability that c1 and c2 are superposed by mere chance is quite low. The photometric redshifts estimated from the SEDs of C1 and C2 are consistent with the spectroscopic redshift, which further supports the hypothesis that C1 and C2 are in the process of merging. The extended features observed around the components in the JWST images provide additional indications of an ongoing interaction between C1 and C2.

Table 1
Observations of CDFS-6664

Observations	References
Optical spectrum (Lyα)	MUSE-Wide (T. Urrutia et al. 2019)
IR spectrum ([O III], [O II], Hβ)	AMAZE VLT/SINFONI (R. Maiolino et al. 2008)
UV images (F275W, F336W)	Hubble Deep UV Legacy Survey (HDUV, v1.0; P. A. Oesch et al. 2018)
HST Optical images (F435W–F850LP)	Hubble Legacy Fields Data (HLF, v2.0) (G. Illingworth 2015; G. Illingworth et al. 2016; K. E. Whitaker et al. 2019)
HST Optical/IR images (F435W–F160W)	3D-HST (v4.0, science images) (A. M. Koekemoer et al. 2011; N. A. Grogin et al. 2011; R. E. Skelton et al. 2014; I. Momcheva 2017)
JWST NIRCam IR images (F182M–F480M)	GO 1963 (C. C. Williams et al. 2023)