

Lyman continuum escape during the onset of galactic winds in compact starbursts

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The abundance of UV-bright, compact star-forming galaxies in the early Universe indicates that high-energy (Lyman continuum (LyC); $\lambda < 912 \text{ \AA}$) photons from massive stars alone could have re-ionized the intergalactic medium. However, the efficiency with which LyC photons escape these systems—and the relative roles of radiation, stellar winds and supernovae in regulating that escape—remain uncertain. Here, using medium-resolution spectra of six otherwise similar local star-forming galaxies spanning a range of starburst ages, we directly trace the launch of a multiphase galactic wind through individual spectral lines alongside measurements of the LyC escape fraction. We find that LyC escape peaks early ($< 3 \text{ Myr}$), during a period dominated by intense radiation and strong stellar winds but lacking a fast galactic wind. In more evolved systems ($> 3 \text{ Myr}$), we detect faster galactic winds of greater equivalent width and dust content. These observations suggest that LyC escape peaks early and is later suppressed by the launch and subsequent mass loading of a supernova-driven wind during the first $\sim 10 \text{ Myr}$ of star formation in compact star-forming galaxies.

We use the Cosmic Origins Spectrograph (COS) aboard the Hubble Space Telescope (HST) to obtain deep follow-up medium-resolution spectra of six galaxies selected from the Low- z Lyman Continuum Survey+ (LzLCS+)^{1,2}. The targets span a wide range of Lyman continuum (LyC) escape fractions ($0 < f_{\text{esc}}^{\text{LyC}} (\%) < 20$) while occupying a narrow range in metallicity ($8.2 \leq 12 + \log O/H \leq 8.5$), star-formation rate (SFR) ($1.3 \leq \log \text{SFR} (M_{\odot} \text{ yr}^{-1}) \leq 1.6$) and stellar mass ($9.13 \leq \log M_{\star} (M_{\odot}) \leq 9.75$). These parameters govern the forces that drive galactic winds³, allowing us to compare the evolution of $f_{\text{esc}}^{\text{LyC}}$ with the development of galactic winds in similar systems prior to the quenching of star formation. The sample was selected to have high SFR surface densities ($\log \Sigma_{\text{SFR}} > 0.5 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$) and compact sizes ($R_{\text{UV}} < 1 \text{ kpc}$), properties that are ubiquitous among strong LyC emitters in LzLCS+⁴ and linked

to efficient stellar feedback capable of clearing the interstellar medium (ISM) quickly of neutral gas and dust: the two primary sinks of LyC radiation^{3,5}. Aside from the UV size and SFR surface density (Σ_{SFR}) constraints, specific galaxy parameter values were chosen based on sample availability; namely, the galaxies had to be part of LzLCS+, have similar properties and require reasonable observing time. We show our sample alongside the full LzLCS+ sample in Fig. 1, with galaxy properties listed in Extended Data Tables 1–3.

To rank the ages of recent star-formation episodes, we model each galaxy's spectral energy distribution (SED). UV light fractions⁶—the fraction of total UV luminosity produced by stellar populations in three age bins (< 3 , $3\text{--}5$ and $5\text{--}10 \text{ Myr}$)—and the resulting light-weighted ages are listed in Table 1. Model fits are shown in Extended Data Figs. 1 and 2,

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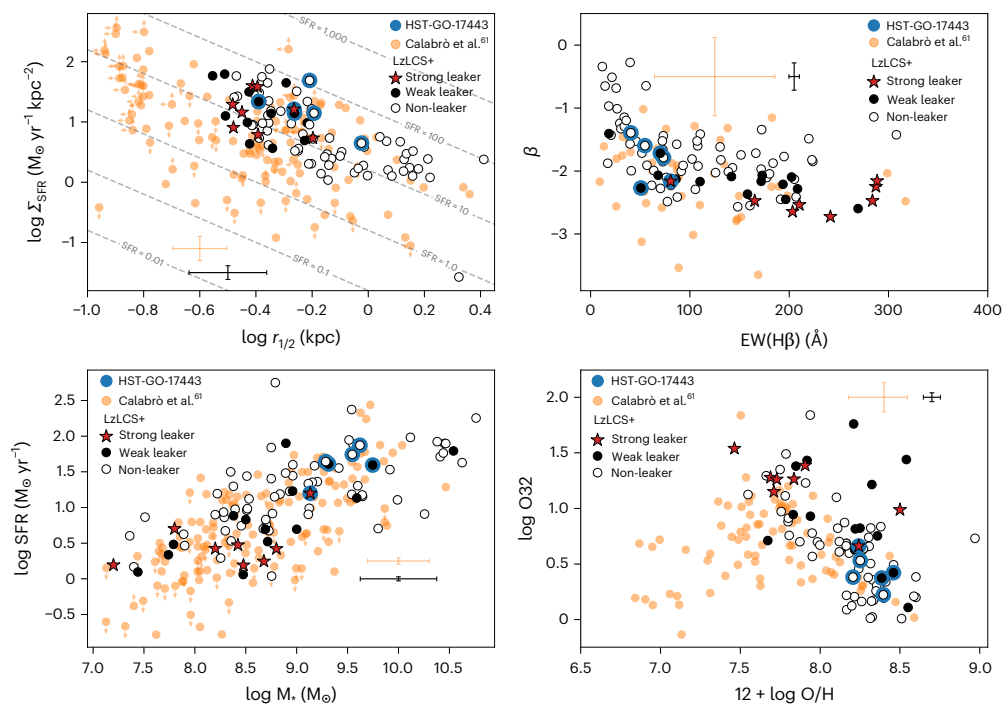


Fig. 1 | Comparison of local LyC emitters and non-emitters with re-ionization-era galaxies. A sample of 89 local galaxies from LzLCS+⁶¹ is classified into strong leakers ($f_{\text{esc}}^{\text{LyC}} \geq 20\%$), weak leakers ($5\% \leq f_{\text{esc}}^{\text{LyC}} < 20\%$) and non-leakers ($f_{\text{esc}}^{\text{LyC}} < 5\%$), shown as red stars, black-filled circles and black open circles, respectively. Galaxies from our sample (HST-GO-17443) are highlighted with a blue shadow. A comparison sample of 161 galaxies at $z > 5$ from early JWST

spectroscopic surveys (CEERS and GLASS⁶¹) is shown in orange. Upper and lower limits are indicated by arrows, and crosses denote the mean measurement uncertainties. Upper left: Σ_{SFR} versus UV half-light radius ($r_{1/2}$). Upper right: Far-ultraviolet continuum slope (β) versus EW of H β . Lower left: SFR versus stellar mass (M_*). Lower right: O32 ratio versus metallicity ($12 + \log \text{O}/\text{H}$).

along with the individual stellar-age components and metallicities. In general, the strongest LyC leakers—J103344+635317, J091703+315221 and J115855+312559—host younger stellar populations (< 4 Myr), with J103344+635317 being the youngest. In contrast, the weakest leakers—J105331+523753, J144010+461937 and J154050+572442—contain older populations (> 4 Myr), with J154050+572442 being the oldest. We examine complementary stellar-age diagnostics drawn from radio, optical and UV wavelengths, with details provided in Extended Data Table 3 and further discussion in Supplementary Note 1. To define a single age metric, we use the light fraction from stars older than 3 Myr, corresponding to the onset of supernova activity. This metric decreases monotonically with increasing $f_{\text{esc}}^{\text{LyC}}$. We note that narrower age bins (specifically, 3–5 and 5–10 Myr) show no significant correlation with $f_{\text{esc}}^{\text{LyC}}$ and are considerably noisier. We therefore present this metric as a summary statistic rather than as evidence for a resolved, continuous relationship between $f_{\text{esc}}^{\text{LyC}}$ and stellar age from 3 to 10 Myr.

We show spectra and the best-fitting SED models from 1,010–1,050 Å, covering the H I Ly β λ 1026, C II λ 1306 and O VI λ 1032, 1038 lines in Fig. 2. The model SEDs reveal two key stellar features: (1) a large-scale (~ 25 Å) P Cygni profile, with absorption blueward and emission redward of the O VI λ 1,032-Å line^{6–8} and (2) a more rarely resolved small-scale (~ 3 Å) photospheric absorption feature centred on each line. The large-scale features arise from young (< 3 Myr) massive O-type stars, with broad absorption produced in their fast ($\sim 3,000$ km s^{−1}) winds⁹, where O VI is generally attributed to Auger ionization induced by X-rays from shocks¹⁰. We searched the Sloan Digital Sky Survey optical spectra for signs of Wolf–Rayet stars but found no notable broadening indicative of their fast winds (also see ref. 11). As $f_{\text{esc}}^{\text{LyC}}$ decreases, the P Cygni profiles weaken and the photospheric features begin to underpredict the total absorption—signalling the onset of supernova-driven galactic winds, consistent with our inferred time sequence. As the starbursts age, massive stars die—either exploding as supernovae or

collapsing directly into black holes^{12,13}—leading to a decline in fast stellar winds and the emergence of fast supernova-driven galactic outflows in the oldest starbursts.

We isolate and study the evolution of galactic winds as a function of $f_{\text{esc}}^{\text{LyC}}$ in Fig. 3 by comparing spectral cutouts, normalized by the best-fitting SED models, that include the H I λ 1026, N III λ 990 and O VI λ 1032 absorption lines. These features trace gas spanning a temperature range of $\sim 10^2$ – 10^6 K. Equivalent widths (EWs) and v_{90} values—the velocity enclosing 90% of the EW—are listed in Extended Data Table 4. We note that the inferred trends are unchanged when the spectra are instead normalized by the adjacent continuum surrounding the lines, suggesting our results are independent of the SED fits.

Each H I λ 1026 line profile reaches zero residual flux, indicating that the line of sight to each object is fully covered by neutral gas. This allows us to rule out partial covering as the primary driver of variations in $f_{\text{esc}}^{\text{LyC}}$. The presence of a P Cygni profile in the H I λ 1026 line of the strongest leaker, J103344+635317, suggests a spherical outflow¹⁴. The persistence of emission further implies relatively low column densities, as higher columns would trap Ly β photons and lead to conversion into H α . In contrast, the weaker leakers, such as J154050+572442, exhibit purely absorptive H I profiles with strong redshifted components—signatures of non-resonant absorption in the wings of the interaction cross section that arise at higher column densities¹⁵. These radiative transfer effects imply that the differences in $f_{\text{esc}}^{\text{LyC}}$ are linked to differences in H I column density and dust content of the winds.

With the exception of J115855+312559 (N III) and J154050+572442 (O VI), the velocities traced by N III λ 990 and O VI λ 1032 broadly follow the H I profiles, consistent with multiphase outflows. The additional absorption feature in J115855+312559 near 1,000 km s^{−1} is not seen in other transitions, likely indicating contamination from an intervening gas cloud. Conversely, the lack of high-velocity O VI

Table 1 | Fractional light contributions from different-aged stellar populations and the light-weighted age

Object	$f_{\text{esc}}^{\text{LyC}}$ (%)	0–3 Myr	3–5 Myr	5–10 Myr	Mean age (Myr)
J103344+635317	$21.0^{2.2}_{2.0}$	0.72 ± 0.20	0.17 ± 0.10	0.11 ± 0.06	2.71 ± 0.75
J115855+312559	$14.7^{3.7}_{1.5}$	0.59 ± 0.17	0.32 ± 0.18	0.10 ± 0.07	3.39 ± 1.11
J091703+315221	$12.0^{2.1}_{1.5}$	0.47 ± 0.20	0.53 ± 0.20	0.00 ± 0.04	3.70 ± 1.13
J105331+523753	$2.2^{2.4}_{0.7}$	0.43 ± 0.12	0.00 ± 0.06	0.57 ± 0.10	5.38 ± 0.94
J144010+461937	$0.4^{0.5}_{0.1}$	0.34 ± 0.18	0.60 ± 0.16	0.07 ± 0.14	3.97 ± 1.50
J154050+572442	< 0.4	0.33 ± 0.05	0.13 ± 0.08	0.55 ± 0.08	5.43 ± 0.83

The columns show the object name, the fractional contribution to the total UV light from stars in a given age range in Myr and the light-weighted age.

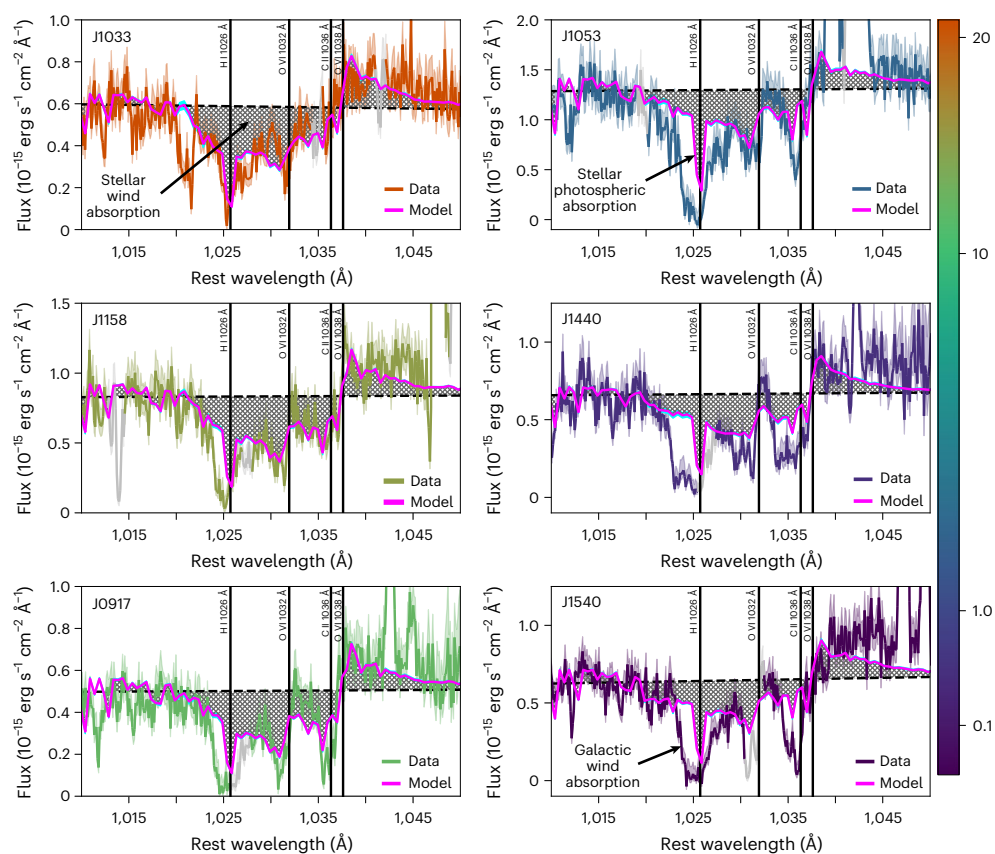


Fig. 2 | Evolution of stellar spectral absorption features with decreasing $f_{\text{esc}}^{\text{LyC}}$ in compact, highly star-forming galaxies. The spectra, with shaded bands indicating 1σ observational flux uncertainties, include the O VI $\lambda\lambda 1032, 1038$, C II $\lambda 1036$ and H I Ly β $\lambda 1026$ absorption lines. Galaxies are arranged in order of decreasing $f_{\text{esc}}^{\text{LyC}}$ from top to bottom, left to right, and are coloured according to their individual $f_{\text{esc}}^{\text{LyC}}$ values, as indicated by the colour bar. This sequence correlates with the light fraction of stars older than 3 Myr, suggesting that $f_{\text{esc}}^{\text{LyC}}$ decreases as galactic winds strengthen during the first ~ 10 Myr of star formation. Silver regions denote contamination by Milky Way absorption. Best-fit FICUS SEDs are shown in magenta; the cyan bands indicate the corresponding 1σ model uncertainties. Stellar absorption features, identified by the models, including

stellar wind and photospheric absorption, are further shaded in hatched dark grey; all remaining absorption is attributed to galactic winds. We note that the magenta line, which refers specifically to the SED model fits in this figure, is not used consistently across all figures and is therefore defined separately in each caption. Galaxies with higher $f_{\text{esc}}^{\text{LyC}}$ (for example, J103344+635317, orange) exhibit deep, large-scale stellar-wind absorption features that account for most of the total absorption, likely produced by massive O-type stars. In contrast, galaxies with lower $f_{\text{esc}}^{\text{LyC}}$ (for example, J154050+572442, purple) show more shallow stellar-wind absorption features and enhanced absorption in galactic winds. This trend likely reflects the death of the most massive O stars and the emergence of supernova-driven winds as the starbursts age.

absorption in J154050+572442 may reflect cooling of the outflow. Note that although this line suffers from Milky Way contamination (C II $\lambda 1334.5$), we can conclude that absorption does not reach velocities in excess of 500 km s^{-1} . Although EWs are generally weaker in the higher-ionization lines, the shapes of the N III and O VI profiles closely match the H I winds in the four strongest leakers. In the two weakest

leakers, J154050+572442 and J144010+461937, we instead observe multiple components or line splitting, possibly signalling the formation of superbubbles or cooling gas¹⁶.

In general, the anticorrelations between $\nu_{90,1026\text{\AA}}$ and $\text{EW}_{1026\text{\AA}}$ with $f_{\text{esc}}^{\text{LyC}}$ suggest an accelerating neutral wind whose growing column density increasingly suppresses LyC escape as the outflow develops

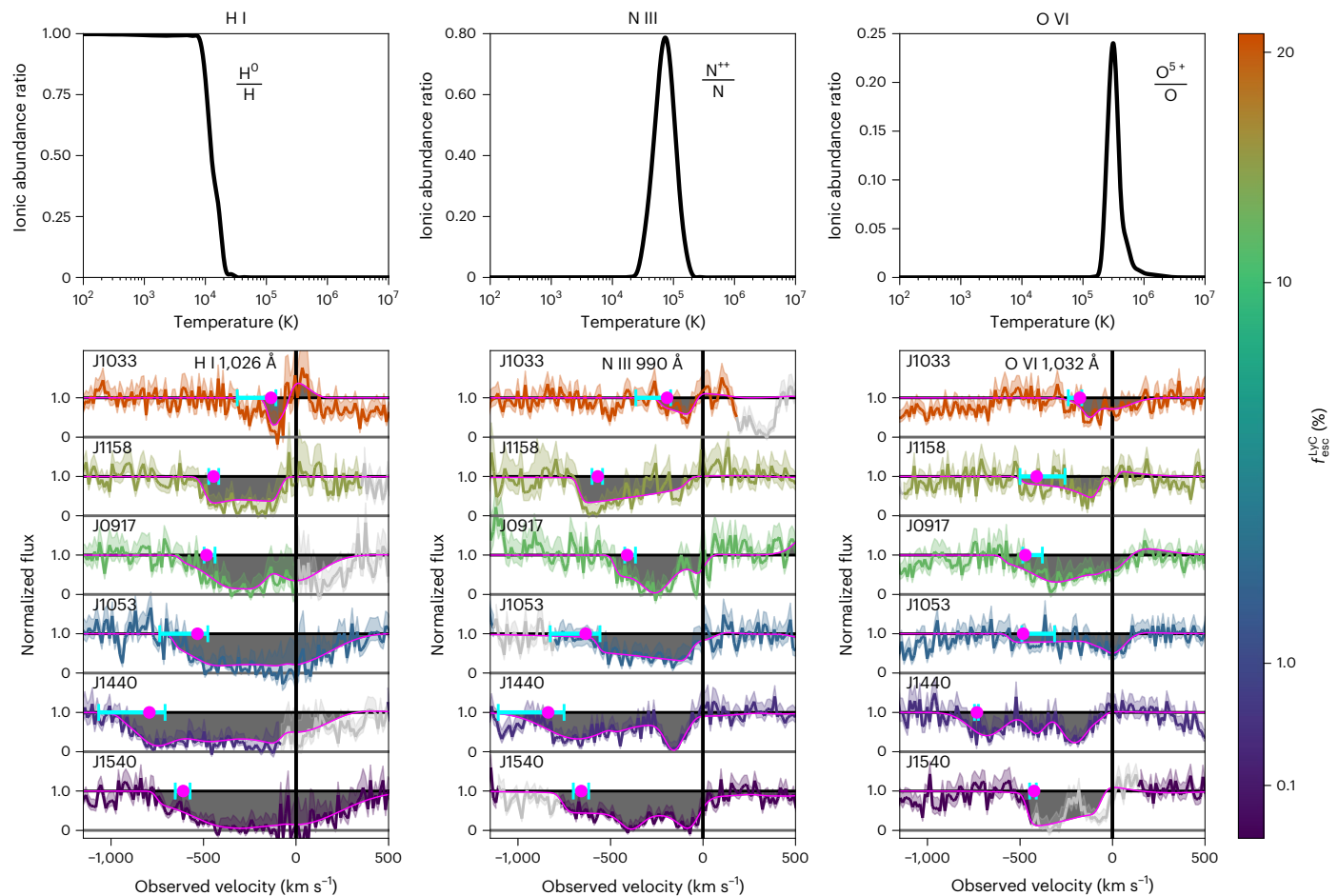


Fig. 3 | Evolution of galactic spectral absorption features with decreasing $f_{\text{LyC}}^{\text{esc}}$ in compact, highly star-forming galaxies. Top row: ionic abundances calculated at a metallicity of $0.4 Z_{\odot}$, redshift $z = 0.3$, hydrogen density $n_{\text{H}} = 1 \text{ cm}^{-3}$ and ionization equilibrium in the presence of inter and extragalactic ionizing radiation, as well as cosmic rays⁶². Each column shows a different transition: H I Ly β 1026 Å (left), N III 990 Å (middle) and O VI 1032 Å (right). The spectra are normalized by the best-fit FiCUS SEDs, with shaded bands indicating the 1σ observational flux uncertainties. Together, these lines trace the ionization structure of galactic winds over $\sim 10^2$ – 10^6 K. Galaxies are ordered from top to bottom in decreasing $f_{\text{LyC}}^{\text{esc}}$ and are coloured accordingly, as indicated by the colour bar. This sequence correlates with the light fraction of stars older than 3 Myr, suggesting that $f_{\text{LyC}}^{\text{esc}}$ decreases as stellar populations age and galactic

winds become more prominent over the first ~ 10 Myr of star formation. Silver regions denote contamination from Milky Way absorption. v_{90} values are shown in magenta, with uncertainties in cyan; the best-fit SALT model is also shown in solid dark grey. The H I profiles reach zero residual flux, consistent with a neutral gas covering fraction near unity. The transition from a P Cygni profile in J103344+635317 to a pure absorption profile with redshifted absorption in J154050+572442 suggests an increase in H I column density with decreasing $f_{\text{LyC}}^{\text{esc}}$. Except for J115855+312559 (N III, gold) and J154050+572442 (O VI, purple), the v_{90} values closely track one another across all lines, consistent with a multiphase outflow. These results suggest that $f_{\text{LyC}}^{\text{esc}}$ peaks prior to the onset of supernovae and declines as neutral gas and dust are incorporated into supernova-driven winds.

over time. Because we control for the galaxy properties governing the wind energy budget and metallicity, these anticorrelations are also consistent with an evolutionary sequence in the underlying star formation. Cosmological zoom-in simulations from FIRE-2 with comparable masses show that galactic winds accelerate and gain mass over the first ~ 50 Myr following the onset of star formation¹⁷. If these simulations capture the general dynamics of galactic winds, the production of a fast, high-column-density outflow—such as that observed in J1540—requires substantial time to develop. These and related correlations are shown in Extended Data Fig. 3, with additional discussion provided in Supplementary Note 2. We further examine the galaxies' surface-brightness profiles in Extended Data Fig. 4 and Supplementary Note 3, finding that the oldest systems in our sample are more spatially extended, consistent with accelerating winds propagating at several hundred kilometres per second over ~ 10 Myr.

Although we do not detect fast ionized winds in the strongest leakers of our sample^{5,18,19}, our analysis does not probe the hot ($\gtrsim 10^7$ K) wind phase, which requires X-ray observations. We have XMM-Newton

data only for J103344+635317 (Z.J. et al., manuscript in preparation). No X-rays were detected, with a 3σ upper limit on the 0.5–8 keV luminosity of $10^{40.8} \text{ erg s}^{-1}$. This limit is consistent with a young stellar population ($\lesssim 5$ – 10 Myr) lacking X-ray binaries and suggests that a dense, volume-filling hot phase associated with a supernova-driven wind has not yet developed.

Together, these results favour a scenario in which a volume-filling wind—driven by radiation and stellar winds and possibly aided by a few early supernovae from the most massive stars²⁰—expels the first material from the ISM in compact starbursts²¹. Early feedback and clumping open low-density pathways with little dust or neutral gas, creating optimal conditions for LyC escape^{1,22}. As more supernovae occur, they drive additional neutral mass into the outflow. These supernovae likely destroy dense clouds and carve out lower-density channels⁶, but the accompanying mass loading, dust creation and increased lateral volume filling of the wind reduce $f_{\text{LyC}}^{\text{esc}}$ on average^{5,19,23}. Over time, the rising gas- and dust-column densities suppress LyC escape entirely, with the neutral phase likely enhanced by cooling following the decline of ionizing

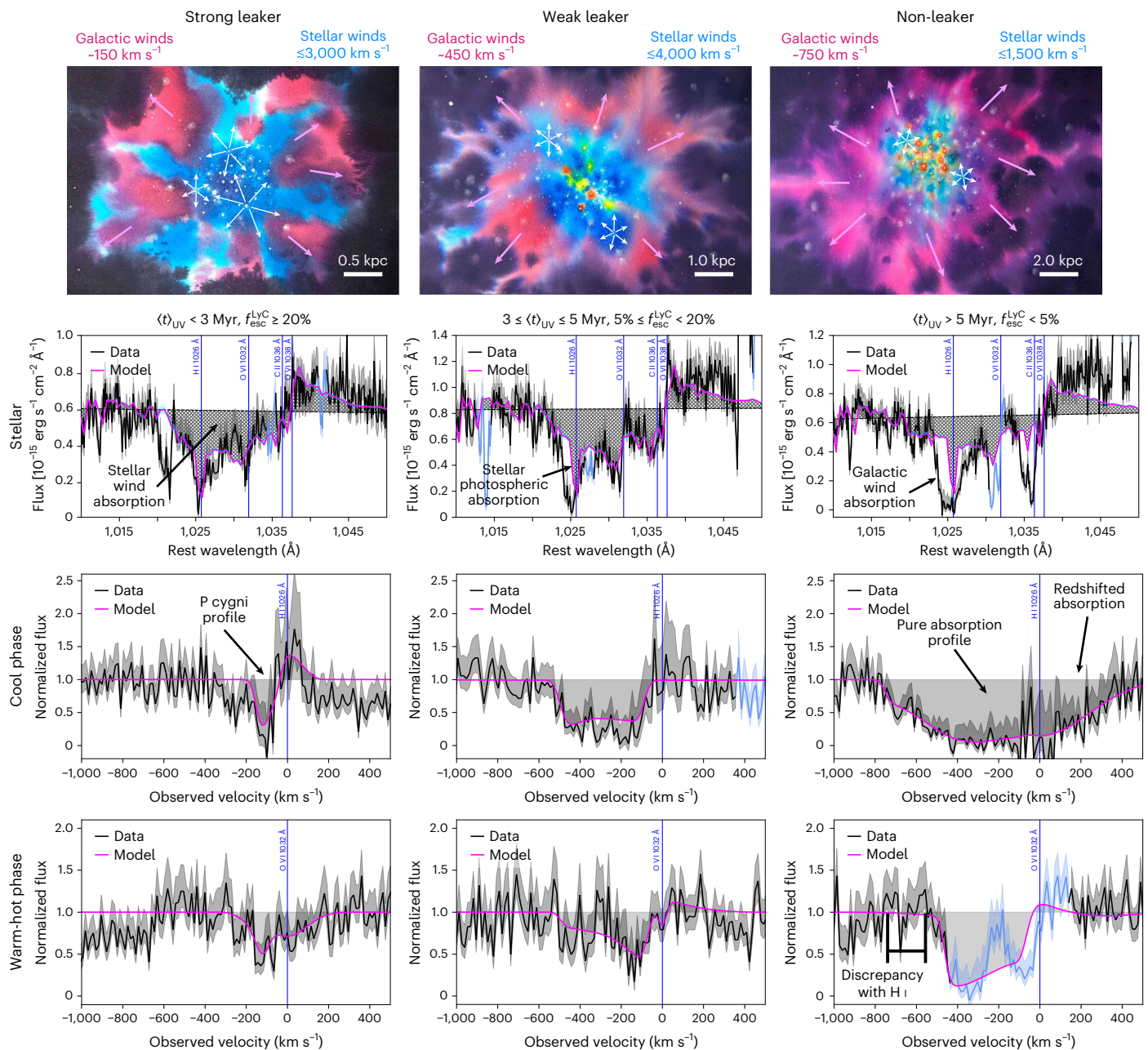


Fig. 4 | Illustration of the LyC escape sequence alongside the launch of a multiphase galactic wind in compact, star-forming galaxies, inferred from stellar and galactic absorption features. Example observations are shown in black with shaded bands indicating 1σ uncertainties; light blue regions indicate Milky Way contamination. Top row: an artist's rendering of the evolution of stellar feedback in compact, star-forming galaxies. Red regions represent the multiphase wind, and blue regions denote areas dominated by ionizing radiation; lighter shades indicate lower gas densities. Early on, intense radiation and fast stellar winds drive a slow galactic outflow, clearing dust and neutral gas. Strong ionizing feedback and potential gas clumping promote high $f_{\text{esc}}^{\text{LyC}}$. After the onset of supernovae, neutral mass and dust are expelled into the ISM, lowering $f_{\text{esc}}^{\text{LyC}}$ on average despite the possible creation of lower-density channels. At later times, supernovae drive large-scale winds that inhibit LyC escape, potentially enhanced by cooling and condensation from warmer gas. Second row: evolution of O VI

$\lambda 1032$, 1038 , C II $\lambda 1036$ and H I Ly β $\lambda 1026$ absorption lines. Best-fit FICUS SEDs are shown in magenta, with 1σ uncertainties in cyan. Stellar absorption features, identified by the models, are shaded in hatched grey; remaining absorption is attributed to galactic winds. The weakening of stellar absorption and emergence of galactic wind absorption trace the transition from radiation to SNe-driven outflows as the starbursts age. Third row: evolution of the normalized H I Ly β $\lambda 1026$ line. Best-fit SALT models are shown in magenta and shaded in solid grey. The transition from a P Cygni profile to a pure absorption profile with redshifted absorption suggests an increase in the neutral wind-column density as $f_{\text{esc}}^{\text{LyC}}$ declines. Bottom row: evolution of the normalized O VI $\lambda 1032$ line. Absorption initially traces cooler H I gas but does not extend to higher velocities at later times, indicating decreasing density and possible cooling of the outflowing gas. Credit: Artwork in a, Siyi Wang.

feedback from the deaths of the most massive stars. A schematic of this evolutionary sequence for compact starbursts is shown in Fig. 4.

We explore whether our proposed sequence extends to the broader population of compact, highly star-forming galaxies in LzLCS+ by constructing three spectral stacks from the median flux of galaxies

with sizes $R_{\text{UV}} < 1 \text{ kpc}$ and $\log \Sigma_{\text{SFR}} > 0.5 \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$. The stacks are grouped by $f_{\text{esc}}^{\text{LyC}}$ into strong leakers ($f_{\text{esc}}^{\text{LyC}} \geq 20\%$), weak leakers ($20\% > f_{\text{esc}}^{\text{LyC}} \geq 5\%$) and non-leakers ($f_{\text{esc}}^{\text{LyC}} < 5\%$) and are shown in Extended Data Fig. 5 over the wavelength range 1,010–1,050 Å.

The strong leakers exhibit narrower H I λ 1026 absorption profiles than the weak and non-leakers, although the latter two populations are indistinguishable within the uncertainties. In contrast, the C II absorption profiles are distinguishable among all three stacks, suggesting that the non-leakers host the fastest outflows, followed by the weak leakers. The lack of distinguishability between the weak and non-leakers in H I λ 1026 may result from the limited spectral resolution of the stacked data, insufficient signal-to-noise or variations in column density. We therefore emphasize the importance of obtaining high-resolution, high signal-to-noise observations of individual LyC-leaking galaxies to robustly assess wind kinematics while controlling for variation among galaxy properties. Overall, these stacked spectra are consistent with the trends identified in our individual-galaxy analysis, supporting the interpretation that the evolutionary sequence shown in Fig. 4 extends to the broader population of compact, highly star-forming galaxies in LzLCS+.

Establishing the LyC escape sequence and the role of galactic winds is essential for determining a galaxy's contribution to re-ionization, because this contribution depends on both the intrinsic production rate of ionizing photons and the fraction that escape—two quantities that may vary independently over time. Historically, LyC escape was expected to peak only after galactic winds had cleared low-density channels through the ISM, by which point the intrinsic LyC production would already be declining following the deaths of the most massive stars^{24–26}. However, early population studies of LyC emitters began to challenge this picture, revealing that many strong LyC emitters still host very young stellar populations^{4–6,27}. Despite this, the role of galactic winds in regulating LyC escape in such systems remains heavily debated. Several studies report correlations between $f_{\text{esc}}^{\text{LyC}}$ and wind-speed diagnostics^{21,28–30}, whereas others argue that winds instead suppress LyC escape by enhancing absorption in the neutral phase^{5,19,23}. Some even propose a confluence of both supernovae and radiation feedback working together in a two-stage burst scenario⁶. These conclusions frequently rely on indirect or model-dependent tracers of wind kinematics, leading to contradictory interpretations of the same galaxies (see also refs. 5,29). We compare our velocity measurements to other values from the literature in Extended Data Fig. 6 with further discussion in the Supplementary Note 4.

Our results clarify these discrepancies: although compact, high-SFR galaxies do launch fast multiphase winds, LyC escape peaks before the neutral component becomes optically thick during the early phases of star formation when radiation feedback dominates. This framework also naturally explains the detection of relatively strong leakers with moderate wind speeds ($\sim 400 \text{ km s}^{-1}$ (refs. 31,32)), as their neutral phases may not be fully developed, consistent with what we observe for J091703+315221 and J115855+312559.

It is important to note that we do not observe the full LyC escape sequence. After the most massive stars die, LyC production from binary products—such as blue stragglers and stripped stars—can dominate for 10–50 Myr (ref. 33). During this period, galactic winds may begin to clear the ISM and enable LyC escape rather than suppress it, particularly if mass loading is reduced. This may explain fast-wind, low-LyC galaxies that lack very young ($< 3 \text{ Myr}$) stellar populations²¹. Finally, we note that we do not consider how prior episodes of star formation may influence subsequent generations by altering the structure of the ISM²⁰.

Our results contrast with current cosmological hydrodynamical simulations, which typically predict LyC escape to peak following the onset of supernovae^{34–37}. The discrepancy may arise from insufficient resolution and missing subgrid physics. For example, high-mass-resolution ($1 M_{\odot}$) studies of dwarf galaxies have shown that radiation feedback can quickly disrupt molecular clouds and enhance mass loading in supernova-driven winds³⁸. Capturing the effect of supernova-driven winds may also require higher resolution in the circumgalactic medium, as targeted higher-resolution studies of the circumgalactic medium typically show higher H I covering fractions

at moderate column densities ($\log N < 18 \text{ cm}^{-2}$), which are capable of reducing $f_{\text{esc}}^{\text{LyC}}$ ³⁹. Converging in $f_{\text{esc}}^{\text{LyC}}$ in cosmological simulations remains notoriously challenging^{35,36,40}. Note that the timeline in Fig. 4 is based on mean light-weighted ages inferred from the UV spectra and may not correspond directly to a fixed evolutionary timescale as used in simulations. A more direct comparison between models and observations can be made by comparing mock spectra and associated $f_{\text{esc}}^{\text{LyC}}$ values to the observed spectra.

Finally, our results have important implications for cosmic re-ionization. We compare our galaxies to $z > 5$ systems in Fig. 1 in terms of stellar mass, metallicity, compactness and other properties. Although our galaxies occupy the higher-mass, lower-H β EW and higher-metallicity end of the distribution, they lie at the focus of high-redshift systems in terms of compactness and high SFR surface density: the two properties ubiquitous among LyC emitters in LzLCS+ and associated with efficient stellar feedback for clearing the ISM³. At lower masses and metallicities, radiation feedback is expected to become even more important, particularly in very compact, highly star-forming galaxies, some of which may be super-Eddington⁴¹. In low-metallicity environments, radiation-dominated phases may also be more efficient and prolonged, as massive stars are more likely to collapse directly into black holes, delaying the onset of supernova-driven winds^{5,6,22,42}. Additionally, stellar winds are expected to be intrinsically weaker at low metallicity^{21,22}, and rapid cooling and pressure confinement may further suppress supernova feedback in high-redshift galaxies^{19,43–46}. Whether compact, star-forming galaxies alone were sufficient to re-ionize the Universe remains an open question; however, identifying the physical processes that regulate LyC escape is a critical step towards answering it.

The deep spectroscopic dataset analysed in this study was obtainable only with HST, underscoring the importance of similar observations as the telescope approaches the end of its operational lifetime. Future observatories, such as the Habitable Worlds Observatory, will enable routine low-redshift observations at high spectral resolution, and 30-m-class ground-based telescopes will extend these studies to even higher redshifts. Together, this and other high-resolution spectroscopic studies will provide critical benchmarks for these next-generation instruments.

Methods

Data

Spectra were obtained with the G130M grating on HST/COS, using CENWAV = 1,222 for all targets except J103344+635317, which—due to its higher redshift—was observed with CENWAV = 1,291. G160M data were drawn from previously approved programmes (12928, principal investigator (PI) Henry; 14201, PI Malhotra; 17153, PI Leclercq) focused on Ly α emission line profiles. XMM-Newton data was obtained for J103344+635317 from programme 0934050101 (PI Ji). These spectra, along with photometric data from the LaCOS programme (17069, PI Hayes) and Sloan Digital Sky Survey spectra, were corrected for Milky Way foreground reddening with Galactic $E(B - V)$ estimates derived from dust maps⁴⁷ and extinction curves⁴⁸. Target galaxy properties including the redshift orbits, observed flux at 1,100 Å, LyC flux between 880 and 900 Å and Milky Way extinction are provided in Extended Data Table 1. Physical galaxy properties including stellar mass, UV half-light radius, SFR and metallicity are provided in Extended Data Table 2. The $f_{\text{esc}}^{\text{LyC}}$ is shown in all tables for reference.

SED modelling

We used the Fitting the stellar Continuum of UV Spectra (FiCUS)^{49–51} code to model the SEDs and measure the light fractions and UV properties. We followed the same procedure used for the low-resolution G140L data obtained through LzLCS+⁵⁰. In FiCUS, the UV stellar continuum modelling is achieved by fitting the observed spectra with a linear combination of theoretical, single-burst Starburst99⁵² models.

Specifically, we use the fully theoretical Starburst99 single-star models without stellar rotation^{52,53} using the Geneva evolution models⁵⁴ and computed with the WM-Basic method^{55,56}. The Starburst99 single-star models without stellar rotation models use a Kroupa initial mass function⁵⁷ with a high-(low-)mass exponent of 2.3 (1.3) and a high-mass cutoff at 100 $M_{\odot}$. We adopted a set of four stellar metallicities (0.05, 0.2, 0.4 and 1.0 $Z_{\odot}$) and ten stellar-age bins (0–10 Myr). A nebular continuum was added to every model by self-consistently processing the original Starburst99 models through CLOUDY v17.04⁵⁸, assuming similar gas-phase and stellar metallicities, an ionization parameter of $\log U = -2.5$ and a volume hydrogen density of $n_{\text{H}} = 100 \text{ cm}^{-3}$. We adopted the Reddy dust attenuation law⁵⁹ and a simple geometry where all the light is attenuated by a uniform foreground slab of dust.

By combining G130M and G160M spectra, we recovered a wavelength range similar to that probed by G140L, except for a gap of $\sim 50 \text{ \AA}$ that appears in all galaxies except J103344+635317. This wavelength coverage includes key stellar-wind features used to constrain stellar ages, such as the O VI $\lambda\lambda 1032, 1038$ and N V $\lambda\lambda 1238.8, 1242.8$ doublets and photospheric features (for example, S IV $\lambda 1065$, C III $\lambda 1175$), sensitive to metallicity. All recorded quantities (light fractions, $f_{\text{esc}}^{\text{LyC}}$, and so on) were obtained directly from the FiCUS outputs^{1,50}. Importantly, $f_{\text{esc}}^{\text{LyC}}$ values were obtained as the ratio between the ionizing flux measured over the new G130M observations and the intrinsic flux in the same LyC window predicted by the FiCUS SED fits.

We measure $f_{\text{esc}}^{\text{LyC}}$ values that differ from those reported for LzLCS+¹ with an average relative error of $\sim 45\%$. We attribute these differences primarily to the higher spectral resolution and S/N of the G130M and G160M data compared to the observations of LzLCS+ made with G140L, which allow us to resolve finer details in the spectral lines. Part of the discrepancy may also arise from differences in the masking procedure, specifically the removal of absorption features associated with the ISM or galactic winds. These features are more easily identified in the higher-resolution spectra. Finally, we note that our $f_{\text{esc}}^{\text{LyC}}$ measurements generally have smaller uncertainties. These errors were estimated by folding together the uncertainties in the FiCUS SED fits (using 200 iterations) and in the mean LyC flux of our data. Again, the higher resolution of our data returned both higher signal to noise in the measured LyC flux and lower uncertainties in the FiCUS best-fit models, which overall reduced the $f_{\text{esc}}^{\text{LyC}}$ error bars.

We require more data to fully assess how higher-spectral-resolution data impact estimates of $f_{\text{esc}}^{\text{LyC}}$ through SED modelling. However, we note that the overall trends involving $f_{\text{esc}}^{\text{LyC}}$ remain consistent across the LzLCS+ sample, regardless of the escape fraction measurement method (for example, the empirical-based flux ratio, $F_{900\text{\AA}}/F_{1100\text{\AA}}$ (refs. 1,4)). Moreover, with the exception of galaxies J115855+312559 and J091703+315221 swapping positions, the rank order in $f_{\text{esc}}^{\text{LyC}}$ remains consistent with the lower-resolution results in our sample, as does the general classification of strong leakers ($\geq 20\%$), weak leakers (5–20%) and non-leakers ($< 5\%$).

Stacks

To stack the HST/COS G140L spectra from LzLCS+¹, we followed the procedure of Flury et al.⁶. Each spectrum was normalized by the flux summed over a 1- $\text{\AA}$ bin centred at 1,100 $\text{\AA}$ in the rest frame. This wavelength region is sufficiently removed from strong telluric, interstellar and stellar spectral features. The normalized spectra were then rebinned into 0.5- $\text{\AA}$ rest-frame wavelength bins over the interval 800–1,450 $\text{\AA}$, corresponding to 1,125–1,850 $\text{\AA}$ in the observed frame. The stacked spectrum was constructed by taking the median flux of all spectra contributing to each wavelength bin. Uncertainties on the stacked flux were estimated via bootstrap resampling: for each wavelength bin, we repeatedly resampled the contributing flux measurements and recomputed the median 10^4 times. This procedure accounted for both the intrinsic scatter among the contributing spectra and the number of spectra contributing to each bin.

Spectral line fitting

To estimate the EWs and v_{90} values, or the observed velocity at 90% of the EW when integrating blueward of line centre, we first fit the normalized spectra using radiative transfer models and then extracted the desired quantities directly from the best-fitting models. This approach reduced the impact of noise and corrected for blue emission infilling in the absorption profiles. We used the semi-analytical line transfer radiative transport code¹⁵ with a Bayesian-based fitting procedure²³. Semi-analytical line transfer has been shown to accurately reproduce a wide range of galactic wind absorption line profiles in both observations^{5,23,60} and simulations^{15,17}. A more detailed modelling of these data will be presented in a future paper.

To account for multiple absorption components, we included additional Gaussian-shaped features⁶⁰. For example, to model the O VI $\lambda 1032$ line in J144010+461937, we included three components with variable amplitude, width and central velocity. All measured v_{90} and EW values for the H I $\lambda 1026$, N III $\lambda 990$ and O VI $\lambda 1032$ lines are listed in Extended Data Table 4. We note that the N III line may suffer from blending with the neighbouring O I $\lambda 988$ line. Given the subsolar metallicities of our sample and the low oscillator strength for this transition ($\sim 5 \times 10^{-2}$), we suspect the amount of absorption due to this transition to be small.

Data availability

The HST/COS observations used in this study are publicly available via the Mikulski Archive for Space Telescopes at <https://mast.stsci.edu> under HST programme IDs 12928, 14201, 17153 and 17443. The photometric observations from the LaCOS survey are available via the Mikulski Archive for Space Telescopes under HST programme ID 17069. The XMM-Newton observation of J103344+635317 is publicly available via the XMM-Newton Science Archive at <https://nxa.esac.esa.int/nxa-web/> under observation ID 0934050101. Source data are provided with this paper.

Code availability

The SALT radiative transport code used in our analysis is publicly available at <https://github.com/CodyCarr/SALT>. The FiCUS code is publicly available at <https://github.com/asalda/FiCUS>.

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Conceptualization: C.C., R.C., S.M. Data curation: C.C., S.M. Formal analysis: C.C., S.M., A.S.-L., J.F. Funding acquisition: C.C., R.C., S.M. Investigation: C.C., S.M. Methodology: C.C., R.C., S.M., A.S.-L., J.F. Project administration: R.C. Resources: R.C. Software: C.C., S.M., A.S.-L., J.F. Supervision: R.C., S.M. Validation: S.M., A.S.-L., J.F. Visualization: C.C., S.M. Writing—original draft: C.C., R.C., S.M. Writing—review and editing: A.S.-L., J.F., C.S., M.S.H., A.J., S.F., M.S.O., R.O.A., S.B., M.H., T.H., Z.J., L.K., A.L.R., F.L., R.M.-C., L.M.-D., G.O., S.R., M.J.R., D.S., T.T., E.V., B.W., X.X.

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Competing interests

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Extended Data Table 1 | Observational Galaxy Properties

Object	$f_{\text{esc}}^{\text{LyC}}$ (%)	z	F_{1100} ($10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$)	$E(B-V)_{\text{MW}}$ (mag)	Orbits	F_{LyC} ($10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$)
J103344+635317	$21.0^{+2.2}_{-2.0}$	0.347	50.1	0.016	5	$10.24^{+0.50}_{-0.22}$
J115855+312559	$14.7^{+3.7}_{-1.5}$	0.243	84.8	0.023	3	$23.55^{+5.70}_{-1.86}$
J091703+315221	$12.0^{+2.1}_{-1.5}$	0.300	43.1	0.020	5	$6.20^{+0.80}_{-0.29}$
J105331+523753	$2.2^{+2.4}_{-0.7}$	0.253	122.0	0.019	2	$3.96^{+4.41}_{-1.24}$
J144010+461937	$0.4^{+0.5}_{-0.1}$	0.301	70.5	0.018	4	$0.77^{+0.90}_{-0.25}$
J154050+572442	<0.4	0.294	72.3	0.019	4	<0.78

>The columns show the object name (1), Lyman continuum escape fraction (2), redshifts (3), FUV fluxes at 1100 Å (4), Milky Way dust extinction (5), number of HST orbits required for G130M spectroscopy (6), and mean background subtracted LyC flux measured between 880-900 Å, except for J103344+635317 which was measured in a 20 Å window below 1180 Å (observed frame) to avoid geocoronal contamination (7). Upper limits represent one sigma uncertainties. Fluxes are in units of $10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$.

Extended Data Table 2 | Physical Galaxy Properties

Object	$f_{\text{esc}}^{\text{LyC}}$	R_{UV}	$\log M_{\star}$	$\log \text{SFR}$	$\log \Sigma_{\text{SFR}}$	$12 + \log(\text{O}/\text{H})$
	(%)	(kpc)	($\log_{10} M_{\odot}$)	$\log_{10} (M_{\odot} \text{ yr}^{-1})$	$\log_{10} (M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2})$	(dex)
J103344+635317	$21.0^{+2.2}_{-2.0}$	0.544 ± 0.029	$9.13^{+0.44}_{-0.43}$	1.379 ± 0.025	1.211 ± 0.116	8.242 ± 0.039
J115855+312559	$14.7^{+3.7}_{-1.5}$	0.546 ± 0.029	$9.75^{+0.52}_{-0.36}$	1.328 ± 0.021	1.146 ± 0.092	8.386 ± 0.031
J091703+315221	$12.0^{+2.1}_{-1.5}$	0.407 ± 0.029	$9.31^{+0.44}_{-0.43}$	1.293 ± 0.020	1.337 ± 0.139	8.459 ± 0.035
J105331+523753	$2.2^{+2.4}_{-0.7}$	0.618 ± 0.030	$9.29^{+0.44}_{-0.43}$	1.438 ± 0.020	1.69 ± 0.085	8.251 ± 0.032
J144010+461937	$0.4^{+0.5}_{-0.1}$	0.641 ± 0.029	$9.55^{+0.44}_{-0.43}$	1.552 ± 0.020	1.147 ± 0.091	8.206 ± 0.033
J154050+572442	<0.4	0.946 ± 0.031	$9.62^{+0.44}_{-0.43}$	1.397 ± 0.025	0.649 ± 0.067	8.396 ± 0.043

The columns show the object name (1), Lyman continuum escape fraction (2), UV half-light radius (3), stellar mass (4), log of the H β -derived star formation rate (SFR) (5), log of the H β -derived star formation rate surface density (6), and gas-phase metallicity (7). Quoted uncertainties and upper limits reflect the 1σ errors. All values were obtained from¹, Flury2022_data_erratum, except for $f_{\text{esc}}^{\text{LyC}}$, which was measured in this study.

Extended Data Table 3 | Stellar Age Diagnostics

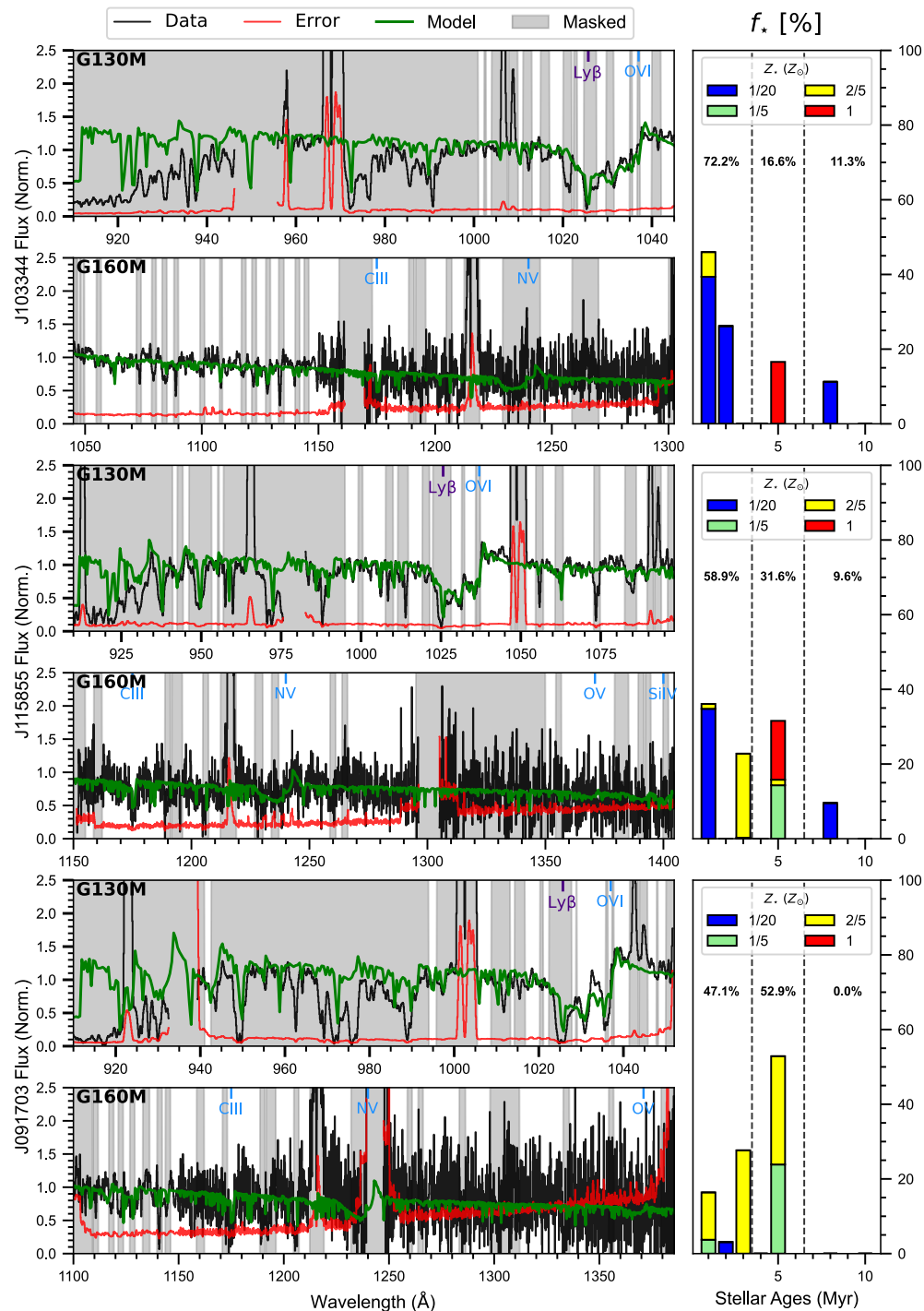
Object	$f_{\text{esc}}^{\text{LyC}}$ (%)	$E(B-V)_{\text{UV}}$	$\alpha_{3\text{ GHz} / 6\text{ GHz}}$	$\text{EW}(\text{H}\beta)$ (Å)	$\log(\text{O32})$ (dex)	$\beta_{1550\text{ Å}}$
J103344+635317	$21.0^{+2.2}_{-2.0}$	0.027 ± 0.011	0.129 ± 0.019	80.07 ± 1.505	0.662 ± 0.030	-2.642 ± 0.057
J115855+312559	$14.7^{+3.7}_{-1.5}$	0.118 ± 0.007	-0.907 ± 0.108	70.22 ± 1.451	0.374 ± 0.023	-1.957 ± 0.036
J091703+315221	$12.0^{+2.1}_{-1.5}$	0.068 ± 0.013	-0.227 ± 0.046	50.68 ± 0.798	0.422 ± 0.023	-2.167 ± 0.067
J105331+523753	$2.2^{+2.4}_{-0.7}$	0.130 ± 0.006	-0.992 ± 0.111	73.36 ± 0.863	0.531 ± 0.023	-1.893 ± 0.030
J144010+461937	$0.4^{+0.5}_{-0.1}$	0.161 ± 0.013	-0.717 ± 0.076	54.65 ± 0.698	0.382 ± 0.023	-1.767 ± 0.064
J154050+572442	<0.4	0.194 ± 0.011	—	40.44 ± 0.777	0.223 ± 0.029	-1.593 ± 0.062

Columns show the object name (1) Lyman continuum escape fraction (2), the dust extinction inferred from the stellar SED fitting (3), radio spectral index between 3 GHz and 6 GHz (4), the equivalent width of Hβ (5), [O III] λ5007 / [O II] λλ3726, 3729 = 0.662 ratio (6), and UV spectral index near 1550 Å (7). Radio information was obtained from²⁷ and the remaining information was obtained from¹, Flury2022_data_erratum.

Extended Data Table 4 | Velocity and Equivalent Width (EW) measurements

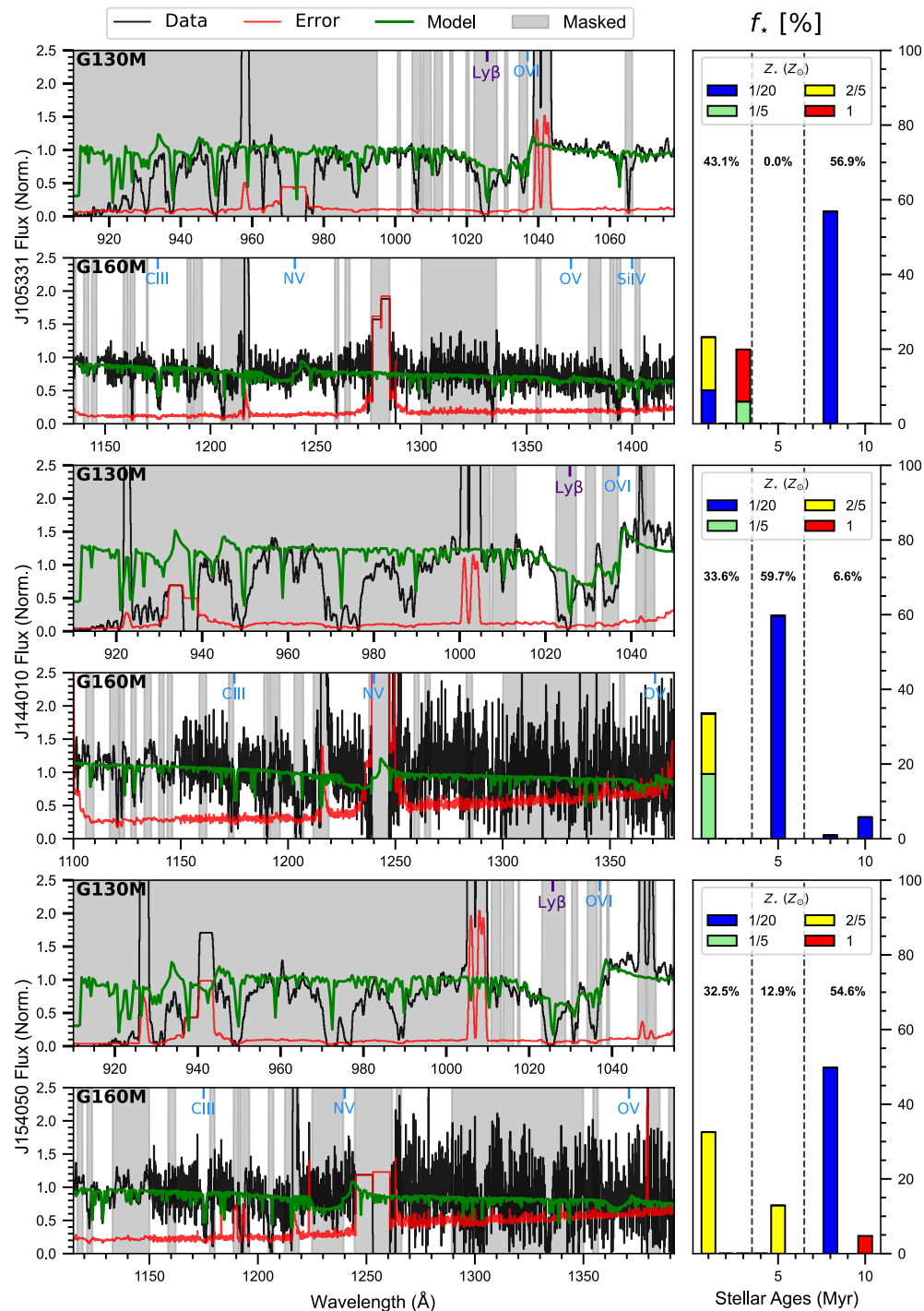
Galaxy	$f_{\text{esc}}^{\text{LyC}}$	EW_{1026}	$v_{90, 1026}$	EW_{990}	$v_{90, 990}$	EW_{1032}	$v_{90, 1032}$
	(%)	(Å)	(km s ⁻¹)	(Å)	(km s ⁻¹)	(Å)	(km s ⁻¹)
J103344+635317	21.0 ^{+2.2} _{-2.0}	0.31 ^{+0.14} _{-0.18}	135 ⁺¹⁸³ ₋₂₆	0.13 ^{+0.20} _{-0.03}	194 ⁺¹⁶⁹ ₋₁₉	0.37 ^{+0.10} _{-0.17}	176 ⁺⁶³ ₋₁₀
J115855+312559	14.7 ^{+3.7} _{-1.5}	1.10 ^{+0.23} _{-0.16}	446 ⁺²⁶ ₋₂₈	1.05 ^{+0.03} _{-0.17}	569 ⁺³¹ ₋₂₆	0.43 ^{+0.12} _{-0.17}	410 ⁺⁹⁰ ₋₁₅₃
J091703+315221	12.0 ^{+2.1} _{-1.5}	1.75 ^{+0.14} _{-0.18}	484 ⁺¹³ ₋₄₆	0.85 ^{+0.16} _{-0.19}	410 ⁺¹³ ₋₄₅	0.96 ^{+0.05} _{-0.17}	471 ⁺¹⁴ ₋₉₂
J105331+523753	2.2 ^{+2.4} _{-0.7}	2.58 ^{+0.23} _{-0.27}	533 ⁺²⁰⁴ ₋₅₆	1.23 ^{+0.03} _{-0.25}	634 ⁺¹⁹² ₋₇₇	0.58 ^{+0.01} _{-0.13}	483 ⁺⁷ ₋₁₇₀
J144010+461937	0.4 ^{+0.5} _{-0.1}	3.12 ^{+0.23} _{-1.01}	793 ⁺²⁷⁴ ₋₈₅	1.70 ^{+2.24} _{-0.01}	837 ⁺²⁷⁰ ₋₈₆	1.17 ^{+0.06} _{-0.02}	733 ⁺¹³ ₋₈
J154050+572442	<0.4	2.91 ^{+0.12} _{-0.09}	610 ⁺⁴³ ₋₃₇	2.08 ^{+0.11} _{-0.08}	658 ⁺⁴³ ₋₄₀	1.06 ^{+0.23} _{-0.38}	424 ⁺²⁴ ₋₁₂

Columns show the object name (1), Lyman continuum escape fraction (2) as well as the v_{90} and EW measurements for the H I 1026 Å (3), N III 990 Å (4), and O VI 1032 Å (5) lines. Uncertainties represent the median deviation from above and below the best fit.



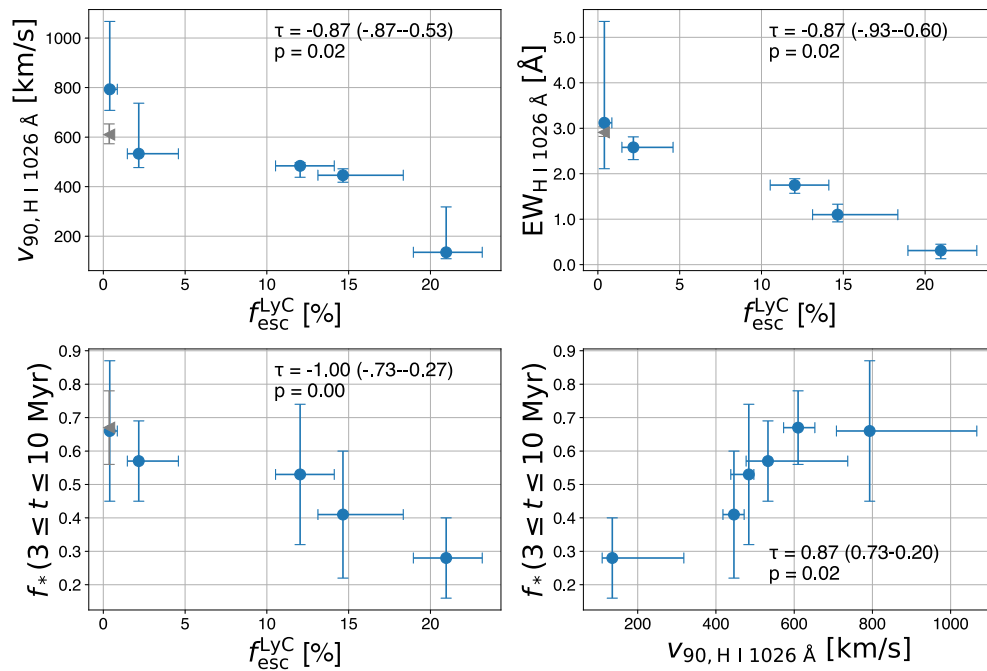
Extended Data Fig. 1 | Spectral energy distributions and best-fitting FICUS models for the three strongest leakers, J103344+635317, J11855+312559, and J091703+315221. Each row shows the observed spectrum (black), the best-fitting model (green), and the associated 1σ uncertainties (red) for the G130M (top) and G160M (bottom) gratings; masked spectral regions are shaded grey. Objects are ordered from top to bottom in decreasing $f_{\text{esc}}^{\text{LyC}}$. The stellar-wind doublets NV

$\lambda\lambda 1239, 1243$ and O VI $\lambda\lambda 1032, 1038$ are particularly sensitive to the ages of the youngest stellar populations, while photospheric features such as C III $\lambda 1175$ are sensitive to stellar metallicity. The panels on the right show the fractional light contribution as a function of stellar age for individual age bins, color-coded by metallicity. The contributions are additionally grouped into stellar populations with ages < 3 Myr, $3 - 5$ Myr, and > 5 Myr.



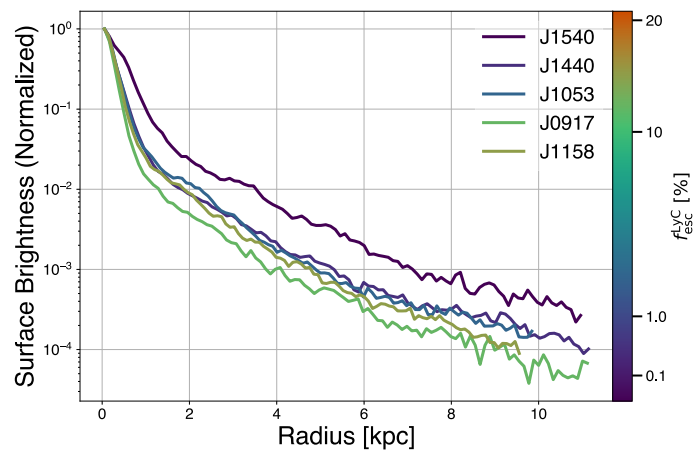
Extended Data Fig. 2 | Spectral energy distributions and best-fitting FICUS models for the three weakest leakers, J105331+523753, J144010+461937, and J154050+572442. Each row shows the observed spectrum (black), the best-fitting model (green), and the associated 1σ uncertainties (red) for the G130M (top) and G160M (bottom) gratings; masked spectral regions are shaded grey. Objects are ordered from top to bottom in decreasing $f_{\text{esc}}^{\text{LyC}}$. The stellar-wind

doublets NV $\lambda\lambda 1239, 1243$ and O VI $\lambda\lambda 1032, 1038$ are particularly sensitive to the ages of the youngest stellar populations, while photospheric features such as C III $\lambda 1175$ are sensitive to stellar metallicity. The panels on the right show the fractional light contribution as a function of stellar age for individual age bins, color-coded by metallicity. The contributions are additionally grouped into stellar populations with ages < 3 Myr, $3 - 5$ Myr, and > 5 Myr.

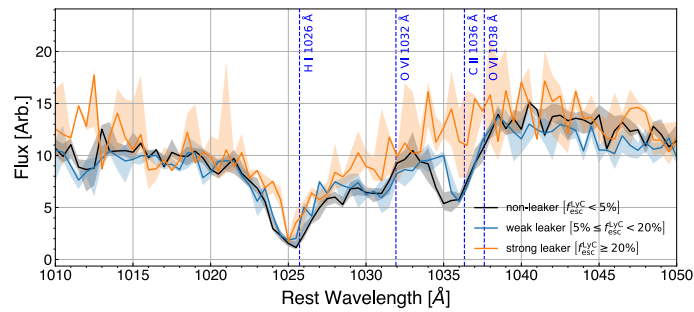


Extended Data Fig. 3 | Kendall rank correlations between galactic wind properties, stellar population age, and LyC escape. Upper left: v_{90} [km s⁻¹] versus $f_{\text{esc}}^{\text{LyC}}$ [%]. Upper right: $\text{EW}_{1026\text{\AA}}$ versus $f_{\text{esc}}^{\text{LyC}}$ [%]. Bottom left: the stellar light fraction $f(3 \leq t \leq 10 \text{ Myr})$ versus $f_{\text{esc}}^{\text{LyC}}$ [%]. Bottom right: $f(3 \leq t \leq 10 \text{ Myr})$ versus v_{90} [km s⁻¹]. Upper limits are shown as gray arrowheads. Both v_{90} and $\text{EW}_{1026\text{\AA}}$ exhibit strong anti-correlations with $f_{\text{esc}}^{\text{LyC}}$ ($\tau = -0.87$, $p = 0.02$). Monte Carlo resampling demonstrates that these relations remain robust to measurement uncertainties, yielding 16th–84th percentile ranges in τ of -0.87 to -0.53 and -0.93 to -0.60 , respectively. The stellar light fraction $f(3 \leq t \leq 10 \text{ Myr})$ exhibits a

near-perfect monotonic correlation with $f_{\text{esc}}^{\text{LyC}}$ ($\tau = 1.0$, $p = 0.00$); however, the broad resampled distribution in τ (-0.73 to -0.27) indicates that the strength of the correlation is less well constrained owing to uncertainties in the stellar population ages. A similarly strong anti-correlation is found between v_{90} and $f(3 \leq t \leq 10 \text{ Myr})$ ($\tau = -0.87$, $p = 0.02$), although the resampled distribution is likewise broad ($\tau = -0.73$ to -0.20), indicating that the correlation strength is less well constrained. Uncertainties in v_{90} and EW represent the median deviations above and below the best-fitting value. All other uncertainties correspond to 1σ deviations.

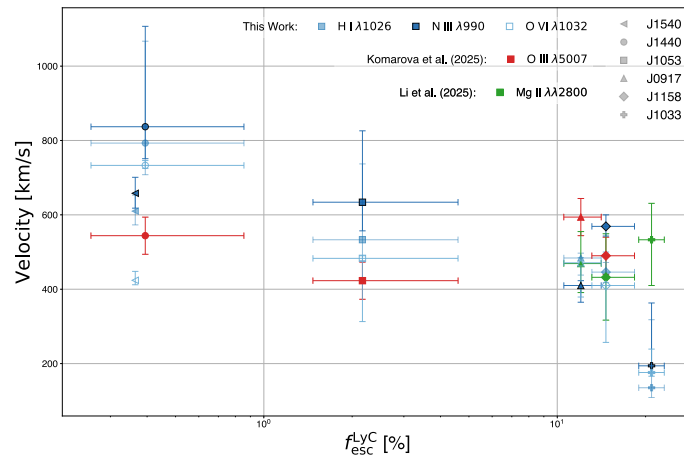


Extended Data Fig. 4 | Normalized surface brightness profiles. Obtained with the HST/ACS Solar Blind Channel (SBC) using the F150LP filter through LaCOS² for five of the six galaxies in our sample; no data are available for J103344 + 635317. Galaxies are color-coded by their individual $f_{\text{esc}}^{\text{LyC}}$ values, as indicated by the color bar. Systems with lower $f_{\text{esc}}^{\text{LyC}}$ generally exhibit more extended profiles.



Extended Data Fig. 5 | Median flux spectral stacks of compact ($R_{\text{UV}} < 1 \text{ kpc}$), highly star-forming ($\log \Sigma_{\text{SFR}} > 0.5 \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$) LzLCS+ galaxies. The stacks are composed of strong leakers ($f_{\text{esc}}^{\text{LyC}} \geq 20\%$, orange), weak leakers ($20\% > f_{\text{esc}}^{\text{LyC}} \geq 5\%$, light blue), and non-leakers ($f_{\text{esc}}^{\text{LyC}} < 5\%$, black). The spectra include the O VI $\lambda\lambda 1032, 1038$, C II $\lambda 1036$, and H I Ly β $\lambda 1026$ absorption lines. The shaded regions show the asymmetric bootstrap standard error of the median stacked flux. Strong leakers exhibit narrower H I $\lambda 1026$ absorption profiles than

weak and non-leakers, although the latter two populations are indistinguishable within the uncertainties. In contrast, the C II absorption profiles differ among all three stacks, suggesting that the non-leakers host the fastest outflows, followed by the weak leakers. These trends are consistent with our overall results and support a scenario in which supernova-driven winds suppress LyC escape on $\sim 10 \text{ Myr}$ timescales in compact starbursts.



Extended Data Fig. 6 | Comparing velocity versus $f_{\text{esc}}^{\text{LyC}}$ using different velocity estimates from the literature. H I $\lambda 1026$, N III $\lambda 990$, and O VI $\lambda 1032$ v_{90} values from this work are shown in shades of blue. V_{max} values derived from the [O III] $\lambda 5007$ line by Komarova et al.²¹ are shown in red, while V_{max} values derived from the Mg II $\lambda\lambda 2796,2803$ doublet by Li et al.²⁹ appear in green. Points corresponding to galaxy J154050+572442 represent upper limits in $f_{\text{esc}}^{\text{LyC}}$; data for this galaxy are available

only in this work. The Komarova et al.²¹ estimates generally agree with our measurements within the error bars, except for J144010+461937 and J105331+523753, where their values underestimate ours. The estimates of Li et al.²⁹ also generally agree with our values except in the case of J103344+635317—the strongest leaker—where their value overestimates our value. Uncertainties from this work reflect the median deviation above and below the best-fitting value.