The production of ionizing photons in UV-faint $z$ similar to 3-7 galaxies

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The production of ionizing photons in UV-faint z \sim 3–7 galaxies

Gonzalo Prieto-Lyon1,2, Victoria Strait1,2, Charlotte A. Mason1,2, Gabriel Brummer1,2, Gabriel B. Caminha3,4, Amata Mercurio5,6, Ana Acebron7,8, Pietro Bergamin7,9, Claudio Grillo7,8, Piero Rosati9,10, Eros Vanzella10, Marco Castellano11, Emiliano Merlin11, Diego Paris11, Kristan Boyett12,13, Antonello Calabrò11, Takahiro Morishita14, Sara Mascia11, Laura Pentericci11, Guido Roberts-Borsani15, Namrata Roy16, Tommaso Treu13, and Benedetta Vulcanti17

1 Cosmic Dawn Center (DAWN), Copenhagen, Denmark
2 Niels Bohr Institute, University of Copenhagen, Jagtvej 128, 2200 Copenhagen N, Denmark
e-mail: gonzalo.prieto@nbi.ku.dk
3 Technische Universität München, Physik-Department, James-Franck Str. 1, 85748 Garching, Germany
4 Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85748 Garching, Germany
5 Dipartimento di Fisica “E.R. Caianiello”, Università degli Studi di Salerno, Via Giovanni Paolo II, 84084 Fisciano, (SA), Italy
6 INAF – Osservatorio Astronomico di Capodimonte, Via Moutiello 16, 80131 Napoli, Italy
7 Dipartimento di Fisica, Università degli Studi di Milano, Via Celoria 16, 20133 Milano, Italy
8 INAF – IASF Milano, Via A. Corti 12, 20133 Milano, Italy
9 INAF – OAS, Osservatorio di Astrofisica e Scienza dello Spazio di Bologna, Via Gobetti 93/3, 40129 Bologna, Italy
10 Dipartimento di Fisica e Scienze della Terra, Università di Ferrara, Via Saragat 1, 44122 Ferrara, Italy
11 INAF – Osservatorio Astronomico di Roma, Via Frascati 33, 00078 Monteporzio Catone, Rome, Italy
12 School of Physics, University of Melbourne, Parkville 3010, VIC, Australia
13 ARC Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D), Mount Stromlo Rd, Australia
14 IPAC, California Institute of Technology, MC 314-6, 1200 E. California Boulevard, Pasadena, CA 91125, USA
15 Department of Physics and Astronomy, University of California, Los Angeles, 430 Portola Plaza, Los Angeles, CA 90095, USA
16 Center for Astrophysical Sciences, Department of Physics & Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA
17 INAF – Osservatorio Astronomico di Padova, vicolo dell’Osservatorio 5, 35122 Padova, Italy

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ABSTRACT

Aims. The demographics of the production and escape of ionizing photons from UV-faint early galaxies is a key unknown that has hindered attempts to discover the primary drivers of reionization. With the advent of JWST, it is finally possible to observe the rest-frame optical nebular emission from individual sub-L* z > 3 galaxies to measure the production rate of ionizing photons, \( \xi_{\text{ion}} \).

Methods. Here we study a sample of 370 z \sim 3–7 galaxies spanning \( 23 < M_{\text{UV}} < 15.5 \) (median \( M_{\text{UV}} = -18 \)) with deep multiband HST and JWST/NIRCam photometry that covers the rest-UV to the optical from the GLASS and UNCOVER JWST surveys. Our sample includes 102 galaxies with Lyman-alpha emission detected in MUSE spectroscopy. We used H\( \alpha \) fluxes inferred from NIRCam photometry to estimate the production rate of ionizing photons that do not escape these galaxies, \( \xi_{\text{ion}}(1 - f_{\text{esc}}) \).

Results. We find median log\( \log_{10}(\xi_{\text{ion}}(1 - f_{\text{esc}})) = 25.33 \pm 0.47 \), with a broad intrinsic scatter of 0.42 dex, which implies a broad range of galaxy properties and ages in our UV-faint sample. Galaxies detected with Lyman-alpha have \( \sim 0.1 \) dex higher \( \xi_{\text{ion}}(1 - f_{\text{esc}}) \), which is explained by their higher H\( \alpha \) equivalent width distribution; this implies younger ages and higher specific star formation rates and, thus, more O/B stars. We find significant trends of increasing \( \xi_{\text{ion}}(1 - f_{\text{esc}}) \) with increasing H\( \alpha \) equivalent width, decreasing UV luminosity, and decreasing UV slope; this implies that the production of ionizing photons is enhanced in young galaxies with assumed low metallicities. We find no significant evidence for sources with very high ionizing escape fractions (\( f_{\text{esc}} > 0.5 \)) in our sample based on their photometric properties, even amongst the Lyman-alpha-selected galaxies.

Conclusions. This work demonstrates that considering the full distribution of \( \xi_{\text{ion}} \) across galaxy properties is important for assessing the primary drivers of reionization.

Key words. quasars: emission lines – galaxies: high-redshift – galaxies: evolution

1. Introduction

In recent years, we have obtained increasing evidence that the reionization of hydrogen happened fairly late, approximately one billion years after the Big Bang (z \sim 5.5–10), with a midpoint around z \sim 7–8 (e.g., Fan et al. 2006; Stark et al. 2010; McGreer et al. 2015; Mason et al. 2018; Davies et al. 2018; Qin et al. 2021; Planck Collaboration VI 2020; Bolan et al. 2022). However, there is evidence for significant star formation before this time (e.g., Oesch et al. 2018; Hashimoto et al. 2018; McLeod et al. 2021), and thus it appears that reionization lags behind galaxy formation. The reason for this lag is unknown: we are still lacking a full physical understanding of the reionization process. In particular, we still do not know which types of galaxies drive the process, that is to say, which physical mechanisms mediate the production and escape of ionizing photons from galaxies. In order to produce such a late and...
fairly rapid reionization, the ionizing population could have been dominated by low mass, UV-faint galaxies with a low average escape fraction (≈5%; e.g., Mason et al. 2019; Qin et al. 2021). Alternatively, rarer, more massive galaxies with higher escape fractions could have been responsible (e.g., Sharma et al. 2017; Naidu et al. 2020). With only measurements of the timing of reionization, these scenarios are degenerate, and thus physical priors on the ionizing properties of galaxies across cosmic time are necessary to pinpoint the sources of reionization. The total ionizing output of galaxies can be simply parameterized (e.g., Madau et al. 1999; Robertson et al. 2010) as the product of the production rate of ionizing photons relative to non-ionizing UV photons, $\xi_{\text{ion}}$ (determined by the stellar populations; e.g., Stanway et al. 2016) and the fraction of ionizing photons that escape the interstellar medium (ISM) into the intergalactic medium, $f_{\text{esc}}$ (determined by the structure and ionization state of the ISM, which is likely shaped by star formation and feedback; e.g., Trebitsch et al. 2017; Ma et al. 2020). Both of these quantities are also expected to vary with time in an individual galaxy, for example due to the lifetime and properties of young stellar populations, and depending on the effects of feedback and bursty star formation on the ISM.

While we can easily observe the non-ionizing UV photons from galaxies, the high optical depth of the intergalactic medium to ionizing photons makes direct measurements of the escaping ionizing spectrum statistically unlikely at $z \gtrsim 3$ (Inoue et al. 2014; Becker et al. 2021; Vanzella et al. 2018). Alternatively, fluxes of nonresonant recombination lines, emitted by gas that was ionized in HII regions around massive stars, can crucially measure the flux of ionizing photons that do not escape galaxies. In particular, $\text{H}\alpha$ emission can be used to directly estimate $(1 - f_{\text{esc}})\xi_{\text{ion}}$ (e.g., Leitherer & Heckman 1995; Bouwens et al. 2016; Shivaei et al. 2018; Emami et al. 2020). As $f_{\text{esc}}$ is inferred to be low (≤10%) on average for Lyman-break galaxies at $z \approx 2-4$ (Steidel et al. 2018; Begley et al. 2022; Pahl et al. 2023), measurements of $\text{H}\alpha$ should track the intrinsic production of ionizing photons reasonably well. The value of $\xi_{\text{ion}}$ can also be inferred from the strength of $\text{[OIII]} + \text{H}\beta$ emission; however, due to the dependence of $\text{[OIII]}$ emission on metallicity and the ionization parameter, the correlation is not as tight as with $\text{H}\alpha$ (e.g., Chevallard et al. 2018).

Previous work at $z \lesssim 2.5$, where direct $\text{H}\alpha$ spectroscopy has been possible from the ground, has found a mean log $E_{10} \xi_{\text{ion}}$ erg Hz$^{-1}$ s$^{-1}$ ≈ 25.3, with a scatter of ∼0.3 dex, likely dominated by variations in stellar populations between galaxies (e.g., Shivaei et al. 2018; Tang et al. 2019). At higher redshifts, where $\text{H}\alpha$ redshifts into the infrared, broadband photometry with Spitzer has been used extensively to estimate $\text{H}\alpha$ line fluxes (e.g., Schaerer & de Barros 2009; Shim et al. 2011; Stark et al. 2013; Smit et al. 2015; Bouwens et al. 2016; Lam et al. 2019; Maseda et al. 2020; Stefanon et al. 2022). However, due to the limited spatial resolution and sensitivity of Spitzer, previous works were limited to studying $\xi_{\text{ion}}$ in isolated, bright ($L^*$) galaxies, where de-blending Infrared Array Camera (IRAC) photometry was possible (e.g., Bouwens et al. 2016), and using stacks for fainter galaxies (e.g., Lam et al. 2019; Maseda et al. 2020). With James Webb Space Telescope (JWST) it is finally possible to extend these studies to individual UV-faint galaxies (Endsley et al. 2022) and obtain rest-frame optical spectroscopy at $z > 3$ (e.g., Sun et al. 2022; Williams et al. 2022).

Results from previous analyses have been intriguing but require further investigation. Using stacked IRAC photometry, Lam et al. (2019) find no significant evidence for a strong correlation of $\xi_{\text{ion}}$ with $M_{\text{UV}}$. However, Maseda et al. (2020) find a population of extremely UV-faint galaxies ($M_{\text{UV}} > -16$) selected as Ly$\alpha$ emitters in deep Multi Unit Spectroscopic Explorer (MUSE) observations, which have very elevated $\xi_{\text{ion}}$ compared to higher luminosity galaxies and at fixed $\text{H}\alpha$ equivalent widths (EWs), which implies that these efficient ionizing galaxies are particularly young and of low metallicity. It is thus important to examine the distribution of $\xi_{\text{ion}}$ at low UV luminosities, and to compare galaxies with and without Ly$\alpha$ emission to better understand the demographics of the ionizing population.

Furthermore, using early JWST NIRCam data, Endsley et al. (2022) discovered a population of UV-faint galaxies ($M_{\text{UV}} \sim -19$) at $z \sim 6.5-8$ with high specific star formation rates (sSFRs) but low EW $\text{[OIII]} + \text{H}\beta$ inferred from photometry. The high sSFR would imply high $\xi_{\text{ion}}$ due to the increased abundance of O and B stars. To explain the low $\text{[OIII]} + \text{H}\beta$ EW, Endsley et al. (2022) suggest that either these galaxies have extremely low metallicities (reducing oxygen abundance) or, alternatively, that all nebular lines are reduced. A reduction in all nebular lines could be due to either them being produced in density-bounded HII regions with a very high ionizing escape fraction (e.g. Zackrisson et al. 2013; Marques-Chaves & Schaerer 2022) or a recent cessation of star formation. At $z \sim 3-7$, both $\text{[OIII]} + \text{H}\beta$ and $\text{H}\alpha$ are visible in NIRCam photometry, enabling us to test these scenarios.

In this paper we make use of deep multiband Hubble Space Telescope (HST)/ACS, WFC3, and JWST/NIRCam imaging with overlapping MUSE observations, which enables us to blindly detect a spectroscopic sample with precision rest-frame UV-to-optical photometry. We measure the distribution of $\xi_{\text{ion}}$ over a broader luminosity range ($z \sim 2 < M_{\text{UV}} < 15.5$) than previously possible in individual galaxies thanks to the excellent resolution and sensitivity of NIRCam at rest-optical wavelengths compared to Spitzer/IRAC as well as the power of gravitational lensing. We explore correlations of $\xi_{\text{ion}}$ with empirical galaxy properties. We find significant trends of increasing $\xi_{\text{ion}}$ with decreasing UV luminosity, decreasing UV $\beta$ slope, and increasing $\text{H}\alpha$ EW, all of which implies that the strongest ionizers are young sources with expected low metallicities. We also explore whether our sample shows evidence for very low metallicities or an extremely high escape fraction.

The paper is structured as follows. In Sect. 2 we describe the photometric and spectroscopic data for our study. In Sect. 3 we describe how we infer the ionizing production rate, $\xi_{\text{ion}}$, and in Sect. 4 we describe the correlations we find between $\xi_{\text{ion}}$ and other galaxy properties and present a comparison to the literature. We discuss our results and state our conclusions in Sect. 6.

We assume a flat cold dark matter cosmology with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$ and $h = 0.7$. All magnitudes are in the AB system.

2. Data

For this work we selected fields with multiband HST/ACS and JWST/NIRCam imaging and overlapping MUSE spectroscopy. We selected sources detected with Ly$\alpha$ emission ($z \sim 2.9-6.7$ in MUSE) and sources with a high probability of being in the same redshift range based on photometric redshift, and we used the HST + JWST photometry to extract optical emission line fluxes. Below we describe the data sets and the selection of our sample.

2.1. Imaging

We used JWST NIRCam imaging in parallel to and of the cluster Abell 2744 from the GLASS-JWST program ERS-1324 (PI
Treu; Treu et al. 2022) and the UNCOVER\footnote{1} program GO-2561 (co-PIs Labbé and Bezanson).

The GLASS-JWST NIRCam observations discussed in this paper were taken in parallel to NIRISS observations of the cluster Abell 2744 on June 28–29, 2022. They are centered at RA = 3.5017025 deg and Dec = −30.375436 deg and consist of imaging in seven bands: F090W (total exposure time: 11 520 s), F115W (11520 s), F150W (6120 s), F200W (5400 s), F277W (5400 s), F336W (6120 s), and F444W (23400 s). The UNCOVER NIRCam observations of the Abell 2744 cluster were taken on November 2–15, 2022. They are centered at RA = 3.5760475 deg and Dec = −30.37946 deg and consist of imaging in seven bands: F115W (10823 s), F150W (10823 s), F200W (6700 s), F277W (6700 s), F336W (6700 s), F410M (6700 s), and F444W (8246 s).

In our analysis, we also included new and archival HST imaging; the ACS imaging is particularly important for constraining photometric redshifts. This includes new HST/ACS data in F606W (59 530 s), F775W (23 550 s), and F814W (123 920 s) from HST-GO-DD program 17231 (PI Treu), as well as archival data acquired under the Hubble Frontier Fields program (HST-GO-DD-13495, PI Lotz; Lotz et al. 2017), BUKALO (HST-GO-15117 PI Steinhardt; Steinhardt et al. 2020), and programs HST-GO-11689 (PI Dupke), HST-GO-11386 (PI Rodney), HST-GO-13389 (PI Siana), HST-GO-15940 (PI Ribeiro), and HST-SNAP-16729 (PI Kelly). Not all HST bands cover every object in our sample, and we only kept objects in our sample that have a well-constrained photometric redshift, usually meaning that there is ACS coverage (see Sect. 2.4). We also included HST/WFC3 imaging for completeness, but it is generally not as constraining as the NIRCam fluxes.

The image reduction and calibration, and the methods used to detect sources and measure multiband photometry in both fields, closely follow that of Brammer et al. (in prep.). Briefly, we pulled calibrated images from the Mikulski Archive for Space Telescopes (MAST)\footnote{2} and processed them with the grizli pipeline (Brammer et al. 2022). The pipeline first aligns the exposures to external catalogs and to one another and corrects for any distortion within the image. Following this, we subtracted a sky-level background, divided out flat-field structure using custom drifts within the image. Following this, we subtracted any remaining cosmic rays, and “snowballs” (see Rigby et al. 2023). Finally, we applied zero-point corrections calculated by G. Brammer\footnote{3} and drizzled all exposures to a common pixel grid.

For source detection, we used SEP, Source Extraction and Photometry (Barbary 2018), to perform aperture photometry on the F444W detection image in each field.

2.2. VLT MUSE spectroscopy

MUSE spectroscopy of the Abell 2744 cluster was obtained through ESO program 094.A-0115 (PI Richard) and is described by Mahler et al. (2018) and Richard et al. (2021). We used their publicly available catalog to select Lyα-emitting galaxies. The data comprise a 4 sq. arcmin mosaic centered on the cluster core. Four 1 sq. arcmin quadrants were observed for a total of 3.5, 4, and 5 h, respectively, and the center of the cluster was observed for an additional 2 h. The median line flux 1σ uncertainty in the MUSE data is 3.6 × 10⁻¹⁹ erg s⁻¹ cm⁻². This corresponds to a 5σ EW limit of ~4–30 Å over z ~ 3–7 for a galaxy with M_{Ly} = −19 (the median for our sample before accounting for magnification as EW is invariant under magnification).

Very Large Telescope (VLT)/MUSE spectroscopy in the GLASS-JWST NIRCam fields were obtained through a new ESO Director’s Discretionary Time program, 109.24EZ-001 (co-PIs Mason, Vanziella), on the nights of July 28 and August 20, 2022. The data comprise five pointings (four of which are over 4 sq. arcmin and overlap with NIRCam imaging), each with 1 h of exposure time. The raw data are publicly available on the ESO archive\footnote{4}. The reduction, calibration, and source detection methods used for this work are identical to techniques described in Caminha et al. (2017, 2019). A full assessment of the depth is ongoing, but, based on the ~4 h depth of the Mahler et al. (2018) observations described above, we estimate a 5σ EW limit of ~8–60 Å in these shallower data.

In this work we used 102 spectroscopic confirmations at z ~ 2.9–6.7: 42 from the GLASS-JWST NIRCam fields and 60 from the Abell 2744 cluster field.

2.3. Gravitational lensing magnification

For the galaxies detected in the core of the Abell 2744 cluster, we corrected for gravitational lensing magnification using the model of Bergamini et al. (2023). The median magnification of the sample is μ = 3.54, and 90% of the galaxies have μ = 2–20. We removed sources with a magnification with μ > 50 (12 sources) due to high uncertainties in the model near the critical curves. The galaxies in the parallel fields are ~3–10′ away from the cluster core, where the magnification is expected to be modest (μ ≈ 1). We do not account for the magnification of these sources.

2.4. Sample selection

For this work we focused on selecting a sample of galaxies at z ~ 3–7 with high purity. We selected 102 MUSE Lyα-detected galaxies with overlapping HST/ACS and JWST/NIRCam data as described above. We also selected a comparison sample of galaxies based on peak photometric redshift, within the same footprint as the MUSE observations, which we expect to have slightly lower Hα EWs than the Lyα-selected sample.

We found the photometric redshift distribution of all sources detected as described in Sect. 2.1 using EAZY (Brammer et al. 2008) and using all available photometric bands. To build a photometric sample with high purity, following Bouwens et al. (2016), we selected sources with the peak of their photometric redshift between 2.9 < z < 6.7 and kept only sources that have 90% of the redshift probability density between Δz = 1 of the peak of their distribution. The resulting high purity photometric sample consists of 268 galaxies.

The redshift and UV magnitude distribution of our sample is shown in Fig. 1. The median redshift of the full sample is 4.02, and the Lyα-selected sample has a median redshift of 3.95. The median M_{UV} is ~18.1, with a Kolmogorov-Smirnov (KS) test showing no significant difference between the Lyα- and photometrically selected samples.

\footnotesize

1 \url{https://www.stsci.edu/jwst/science-execution\_program\_information.html?id=2561}
2 \url{https://www.stsci.edu/cgi-bin/get-proposal-info?ido=17231\&observatory=HST}
3 \url{https://archive.stsci.edu}
4 \url{https://github.com/gbrammer/grizli/pull/107}

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any broadbands where H$\alpha$ We adopted BC03 (Bruzual & Charlot 2003) templates and line flux. that we could subtract from the observed photometry to infer the Mármol-Queraltó et al. 2016; Bouwens et al. 2016). This pro-
tetry, excluding bands we expected to contain strong nebu-
lar emission lines for each galaxy. We compared our measure-
ments with a sample of six galaxies with [OIII] + H$\beta$ EW me-
asurements from the GLASS-ERS program using JWST/NIRISS
(Boyett et al. 2022a), finding that our method recovers the EW
of these sources to within $\sim$20–40%. A full comparison of these
photometric inference methods is left to future work.

There are some limitations to our method for obtaining line
fluxes, such as contamination from the 4000 Å break in the
broadband that contains [OIII] + H$\beta$, the chance that the line
falls outside the effective width of any of our broadband filters,
or H$\alpha$ and [OIII] + H$\beta$ falling on the same band. We consid-
ered a contribution of 6.8% from [NII] to the calculated H$\alpha$
flux, and 9.5% from [SII] according to Anders (2003). We removed
galaxies with a poor $\chi^2$ score ($>$50) on their SED fit; we chose
this value by ignoring all galaxies on the high end of the $\chi^2$
distribution.

The advantage of this approach, unlike estimating line fluxes
directly from the SED fitting, is that it does not depend strongly
on star formation history assumptions and allows us to make a
mostly empirical measurement of the line fluxes. We obtain com-
parable results using the flux in the band redward of H$\alpha$ as the
continuum flux, assuming a flat optical continuum (see also, e.g.,
Maseda et al. 2020). Estimating other physical parameters, such as
the star formation rate and stellar mass, from the SED fit-
ing did not give reliable results. This is because the fitting was
too dependent on the initial assumptions and needed extremely
young ages ($<$10 Myrs) and an instantaneous burst of star forma-
tion to recreate the observed nebular emissions.

The following results consist of 83 and 64 Ly$\alpha$-emitting
galaxies with H$\alpha$ and [OIII] + H$\beta$ emission line measure-
ments, respectively, and a photometric sample of 220 and 203 galaxies
with H$\alpha$ and [OIII] + H$\beta$ emission line measurements, respec-
tively. We see both lines in 62 Ly$\alpha$ galaxies and 177 photomet-
rically selected galaxies. We see no apparent biases in our $M_{uv}$
distribution after narrowing down the sample. Nebular emission
flux errors are derived from the 68% confidence interval of the
resulting distributions.

3.2. Measuring UV absolute magnitude and slope

To infer the UV absolute magnitude, $M_{uv}$ (magnitude at
1500 Å), and $\beta$ slope, we fit the power law (e.g., Rogers et al.
2013) $f_\lambda \propto \lambda^{-\beta}$ to the fluxes from the HST and JWST bands. We performed the fit using a Markov chain Monte Carlo sampling
and the python module emcee (Foreman-Mackey et al. 2013).
In the following, uncertainties on \( f_{\text{esc}} \) are at the 68% confidence intervals and were obtained from propagating the uncertainty in the H\( \alpha \) flux from its resulting distribution, as described in Sect. 3.1. The posterior distributions for \( \beta \) and \( M_{\text{UV}} \) were obtained as described in Sect. 3.2.

### 3.4. Correlation analysis

For the purpose of studying the correlations between galaxy properties, we used the python package \textsc{linmix}\(^6\) to perform Bayesian linear regression, including intrinsic scatter and accounting for two-dimensional errors (Kelly 2007). We fit for \( \log_{10}[(1 - f_{\text{esc}})\xi_{\text{ion}}] = \alpha + \beta X + \varepsilon \), where \( \varepsilon \) is the intrinsic scatter and is assumed to be normally distributed with variance \( \sigma_{\varepsilon}^2 \).

### 4. Results

In this section we present our results. In Sect. 4.1 we study the trends between \( \xi_{\text{ion}}, H\alpha\) EW, \( M_{\text{UV}} \), and the \( \beta \) slope, and in Sect. 4.2 we investigate whether our sample shows evidence for galaxies with very high ionizing photon escape fractions and/or very low metallicities.

#### 4.1. Behavior of \( \xi_{\text{ion}} \)

Figure 2 shows the distribution of \( (1 - f_{\text{esc}})\xi_{\text{ion}} \) for our Ly\( \alpha \)-selected and photometric samples. We find median values of \( \log_{10} (1 - f_{\text{esc}})\xi_{\text{ion}} \equiv 25.39 \pm 0.64 \) and \( 25.31 \pm 0.43 \), respectively, and 25.33 \( \pm \) 0.47 [Hz erg\(^{-1}\)] for the complete data set. We find an intrinsic scatter of 0.42 dex, obtained by subtracting in quadrature the average uncertainty in \( \log_{10} \xi_{\text{ion}} \) (= 0.21 dex) from the standard deviation of the observed distribution. The recovered intrinsic scatter is broader by ~0.1 dex than that found by Bouwens et al. (2016) and Shivaei et al. (2018) in \( M_{\text{UV}} \leq -20 \) galaxies. The broad distribution of \( \xi_{\text{ion}} \) is likely an outcome of the broad range of stellar populations in these galaxies, that is to say, due to a range of star formation histories (and thus ages) and stellar metallicities (see e.g., Shivaei et al. 2018).

We performed a two-sample KS test to determine whether the Ly\( \alpha \)-selected and photometric samples are drawn from the same distribution. We recover a \( p \)-value of 0.03, meaning it is likely that the underlying distributions are different; this is consistent with the results from Saldana-Lopez et al. (2022), where a statistically significant difference is found between the \( \xi_{\text{ion}} \) distributions of Ly\( \alpha \) emitters and non-Ly\( \alpha \) emitters at \( z \sim 3-5 \).

The broad distribution of \( \xi_{\text{ion}} \) can also be linked to very high ionizing photon escape fractions (e.g., Verhamme et al. 2015; Dijkstra et al. 2016), which is likely the intrinsic

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\( \xi_{\text{ion}} \) is the intrinsic UV luminosity density at 1500 Å. The intercept, \( \beta < 23 \)

6 https://github.com/jmeyers314/linmix

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Slope, ( \alpha )</th>
<th>Intercept, ( \beta )</th>
<th>Scatter variance, ( \sigma_{\varepsilon}^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_{\text{UV}} + 20 )</td>
<td>0.03 ± 0.02</td>
<td>25.33 ± 0.03</td>
<td>0.027 ± 0.006</td>
</tr>
<tr>
<td>( \log_{10} \text{EW}_{\text{H} \alpha} - 2.5 )</td>
<td>0.73 ± 0.04</td>
<td>25.14 ± 0.02</td>
<td>0.003 ± 0.001</td>
</tr>
<tr>
<td>( \beta + 2 )</td>
<td>−0.20 ± 0.04</td>
<td>25.38 ± 0.01</td>
<td>0.032 ± 0.005</td>
</tr>
</tbody>
</table>

Notes. We fit for \( \log_{10}[(1 - f_{\text{esc}})\xi_{\text{ion}}] = \alpha + \beta X + \varepsilon \), where \( \varepsilon \) is the intrinsic scatter and is assumed to be normally distributed with variance \( \sigma_{\varepsilon}^2 \).
ionizing photon production efficiency of these galaxies is even higher than what we can infer based on H_\alpha.

Figure 3 shows \((1 - f_{\text{esc}})\xi_{\alpha}\). Ly\(\alpha\)-detected galaxies are shown with purple stars and photometrically selected sample with no Ly\(\alpha\)-detected with gray circles. We show data from Maseda et al. (2020), Harikane et al. (2018), Lam et al. (2019), and Bouwens et al. (2016) as colored boxes for comparison. We find evidence for an increase in \(\log_{10}(1 - f_{\text{esc}})\xi_{\alpha}\) toward fainter UV magnitudes, with a slope of 0.03 ± 0.02, but only when considering the range where our sample is \(M_{\text{UV}}\) complete (\(M_{\text{UV}} < -18.1\)). We show literature constraints at similar redshifts as colored shapes (Bouwens et al. 2016; Harikane et al. 2018; Lam et al. 2019; Maseda et al. 2020), noting that all constraints fainter than \(M_{\text{UV}} < -20\) were obtained by stacking IRAC photometry.

As described in Sect. 3.4, we performed a linear regression to assess correlations in our data. In contrast to Lam et al. (2019), we find significant evidence for a weak trend between \(\xi_{\alpha}\) and \(M_{\text{UV}}\), where the highest \(\xi_{\alpha}\) tends to come from the faintest galaxies. Since our sample is not \(M_{\text{UV}}\) complete, we only study the correlation up to the peak of our \(M_{\text{UV}}\) distribution (~18.14) in Fig. 1. We find \(\log_{10}(1 - f_{\text{esc}})\xi_{\alpha}\) = \((0.03 ± 0.02)\Delta M_{\text{UV}} + 20\) + 25.36 ± 0.03, but with a large scatter (see Table 1).

Figure 4 shows that \(\xi_{\alpha}\) follows a strong trend with H\(\alpha\) EW, as found in previous work (Harikane et al. 2018; Lam et al. 2019; Tang et al. 2019). Such works were limited to the highest H\(\alpha\) EW values, while we reach ~0.75 dex lower due to the sensitivity of NIRCam. This trend is consistent with a picture where \(\xi_{\alpha}\) is elevated in the youngest, most highly star-forming galaxies (e.g., Tang et al. 2019). We find \(\log_{10}(1 - f_{\text{esc}})\xi_{\alpha}\) = \((0.73 ± 0.04)\log_{10} \text{EW}_{\text{H}\alpha} - 2.5\) + 25.15 ± 0.02. The measurement by Maseda et al. (2020), obtained from a stack of extremely UV-faint galaxies with high L\(\alpha\) EWs, lies significantly above our sample and values from the rest of the literature, with higher \((1 - f_{\text{esc}})\xi_{\alpha}\) at fixed H\(\alpha\) EWs. As discussed by Maseda et al. (2020), this likely implies their sources have a much lower gas-phase metallicity than other samples.

We also find that Ly\(\alpha\)-selected galaxies have a higher H\(\alpha\) EW than the photometrically selected sample (median EW = 732 ± 187 Å compared to 457 ± 161 Å for the photometric sample). A two-sample KS test establishes that the EW distributions of the two samples are different (p-value < 0.01). This is likely the primary driver of the increased \(\xi_{\alpha}\) distribution for the Ly\(\alpha\)-selected sample (Fig. 2).

At a fixed H\(\alpha\) EW, we see a clear tendency for galaxies with very blue \(\beta\) UV slopes to have elevated \(\xi_{\alpha}\) (Fig. 4). This trend is also seen in the full sample (Fig. 5), where we find high \(\xi_{\alpha}\) is weakly correlated to a blue \(\beta\) slope, but with a large scatter. We find \(\log_{10}(1 - f_{\text{esc}})\xi_{\alpha}\) = \((-0.20 ± 0.04)(\beta - 2) + 25.41 ± 0.01\) (see Table 1). Similar correlations have been seen at z < 6 (e.g., Ning et al. 2023). Using a KS test, we find no significant difference in the \(\beta\) distributions for the Ly\(\alpha\) and photometric samples. Our sample has a median \(\beta = -2.1\).

4.2. A search for high-escape-fraction and extremely low-metallicity galaxies

As well as being a tracer of the ionizing photon production of galaxies, nebular emission lines are also sensitive to the escape fraction. Zackrisson et al. (2013) proposed that in galaxies with a very high ionizing escape fraction, one would expect a reduction in nebular emission line strength (H\(\beta\) EW ≤ 30 Å) and extremely blue UV slopes (\(\beta < -2.5\)) due to the lack of nebular continuum. Early JWST observations have discovered potentially very blue galaxies (Topping et al. 2022, though cf. Cullen et al. 2023) and galaxies with weak nebular line emission yet high sSFRs (via [OIII] + H\(\beta\); Endsley et al. 2022), potentially indicating a

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In Fig. 4 we show the distribution of \( \text{H}\alpha \) EW for our sample (where we correct for dust attenuation as described in Sect. 3.1). We compare our sample to the values found by Zackrisson et al. (2017) to show the region predicted by Zackrisson et al. (2017) to show a lower limit of the \( f_{\text{esc}} \) for galaxies with detected Ly\( \alpha \) emission have an \( \text{H}\alpha \) EW distribution with higher values, median 732 \( \pm \) 187 Å compared to 457 \( \pm \) 161 with a Kolmogorov-Smirnov test \( p \)-value \( < \) 0.01. The sources with the reddest UV slopes systematically lie below the best-fit relation at fixed \( \text{H}\alpha \) EW.

![Fig. 4](image)

**Fig. 4.** Comparison between the intrinsic (unattenuated) EW of \( \text{H}\alpha \) and the UV \( \beta \) slope, color-coded by [OIII] + H\( \beta \) EW. Ly\( \alpha \) galaxies are shown with star-shaped markers, and the photometric sample as circles. Galaxies shown in gray do not have [OIII] + H\( \beta \) EW measurements. We rescale from \( \text{H}\alpha \) EW to intrinsic \( \text{H}\alpha \) EW. Ly\( \alpha \)-detected galaxies are shown as stars.

In Fig. 5 we show UV \( \beta \) slope vs. \( \xi_{\text{ion}}(1 - f_{\text{esc}}) \). Ly\( \alpha \)-detected galaxies are shown in purple and the photometrically selected sample with no Ly\( \alpha \)-detected in gray. As above, error bars are only shown for 30% of the sources for clarity. We add the stacked measurements from Lam et al. (2019) for comparison. We find a very weak trend of increasing \( \xi_{\text{ion}} \) with decreasing \( \beta \), with a linear slope of \( -0.10 \pm 0.06 \).

![Fig. 5](image)

**Fig. 5.** UV \( \beta \) slope vs. \( \xi_{\text{ion}}(1 - f_{\text{esc}}) \). Ly\( \alpha \)-detected galaxies are shown in purple and the photometrically selected sample with no Ly\( \alpha \)-detected in gray. As above, error bars are only shown for 30% of the sources for clarity. We add the stacked measurements from Lam et al. (2019) for comparison. We find a very weak trend of increasing \( \xi_{\text{ion}} \) with decreasing \( \beta \), with a linear slope of \( -0.10 \pm 0.06 \).

In Fig. 6 we show UV \( \beta \) slopes as a function of intrinsic \( \text{H}\alpha \) EW for our sample (where we correct for dust attenuation as described in Sect. 3.1). We compare our sample to the region proposed by Zackrisson et al. (2017) to show \( f_{\text{esc}} > 0.5 \). We rescale from H\( \beta \) EW to intrinsic \( \text{H}\alpha \) with a case B recombination scenario of factor 2.89, assuming a flat optical continuum in \( f_{\lambda} \), which we confirm from the SED fitting done in Sect. 3.1.

![Fig. 6](image)

**Fig. 6.** Comparison between the intrinsic (unattenuated) EW of \( \text{H}\alpha \) and the UV \( \beta \) slope, color-coded by [OIII] + H\( \beta \) EW. Ly\( \alpha \) galaxies are shown with star-shaped markers, and the photometric sample as circles. Galaxies shown in gray do not have [OIII] + H\( \beta \) EW measurements. We show the region predicted by Zackrisson et al. (2017) to show \( f_{\text{esc}} > 0.5 \).
0.5. While several sources fall into this region, and also have low [OIII] + Hβ EWs ($\lesssim$100 Å), the uncertainties are too large to make them robust candidates. We discuss this further in Sect. 5.2.

Figure 7 shows the Hα EW as a function of [OIII] + Hβ for our sample. We see the expected positive correlation between both nebular emission lines, as these lines are all generated by the effects of stellar ionizing radiation. We see a very large scatter (with a range of $\sim$1.5 dex) as expected due to variations in metallicity, temperature, and the ionization parameter, all of which affect the strength of individual [OIII] galaxies (e.g., Maiolino et al. 2008; Steidel et al. 2014; Sanders et al. 2021). We find $\log_{10} \text{EW}(\text{H}\alpha) = 0.97 \pm 0.06(\log_{10} \text{EW}(\text{[OIII]} + \text{H}\beta) - 2.5) + 2.52 \pm 0.03$.

Galaxies with detected Lyα emission tend to occupy the top right of the plot, with strong nebular emission lines, suggesting they are young star-forming galaxies with low metallicities and large ionization parameters that produce the copious amounts of ionizing photons needed to power these emission lines (see e.g., Yang et al. 2017; Du et al. 2020; Tang et al. 2021, for more detailed studies). We find the Lyα-detected galaxies have stronger [OIII] + Hβ EWs compared to the photometric population, following the trend with Hα EW in Fig. 4. However, as discussed by Tang et al. (2021), not all galaxies with strong nebular emission are detected in Lyα, indicating that Lyα transmission is reduced due to a high column density of neutral gas in these systems and/or inclination effects. We compare our data to a $z \sim 2$ sample by Tang et al. (2019), which was selected based on strong [OIII] emission. We find a similar correlation, but overall our ratio of Hα EW/[OIII] + Hβ EW is higher by $\sim$0.1 dex. Given that the Tang et al. (2019) sample has a significantly subsolar gas-phase metallicity, $Z < 0.3Z_\odot$ (Tang et al. 2021), the decrease we observe in [OIII] at fixed Hα EW would likely imply an overall lower metallicity due to a lower number of metal atoms in our sample.

5. Discussion

5.1. The profile of a strong ionizer

Thanks to the depth of JWST/NIRCam, we have been able to assess trends of $\xi_{\text{ion}}$ at $z > 3$ across the broadest range of galaxy properties to date. From these results, we corroborate previous work at lower redshifts and high luminosities and push the measurement of $\xi_{\text{ion}}$ to a large sample of individual UV-faint galaxies for the first time.

We find that galaxies with strong ionizing photon emission tend to have high Hα EWs, low UV luminosities, blue UV β slopes, and Lyα emission – all implying that these galaxies are young and likely have a low dust content, low metallicity, and a high O/B star population that is capable of producing hard ionizing photons (e.g., Tang et al. 2019; Boyett et al. 2022b). This picture of the integrated emission from galaxies is complemented by high spatial resolution observations of highly magnified arcs with JWST. They have revealed extremely young star clusters ($\lesssim$10 Myr) with [OIII] + Hβ EW > 1000 Å. They dominate the ionizing photon production in their galaxy (Vanzella et al. 2022, 2023), indicating that there can be large variations in $\xi_{\text{ion}}$ in individual galaxies if they contain multiple stellar populations, but also that the variation is primarily driven by the age of the stellar populations. We also find that, overall, our Lyα galaxy sample has higher $\xi_{\text{ion}}$ than the photometrically selected one; the primary reason for this difference is that the former has higher Hα EWs (Fig. 4). The enhanced prevalence of Lyα emission in strong Hα emitters is likely a combination of an increased production of Lyα photons due to the young stellar population implied by the strong Hα and (potentially) an increase in the Lyα escape fraction in the ISM (Tang et al. 2021; Naidu et al. 2022). In these rapidly star-forming galaxies, the hard ionizing radiation may be ionizing the ISM and/or feedback may disrupt the ISM gas, leading to a reduced HI column density and dust cover. We note that the galaxies with the
highest \((1 - f_{\text{esc}}) \xi_{\text{ion}}\) are not necessarily all Ly\(\alpha\) emitters, likely due to variance in the geometry and column density of neutral gas and dust in these sources. Ning et al. (2023) show this same correlation between \(\xi_{\text{ion}}\) and Ly\(\alpha\) for a broad range of luminosities and EWS.

5.2. The ionizing photon escape fraction

In Sect. 4.2 we explore whether our sample shows signs of high ionizing photon escape fraction, \(f_{\text{esc}}\), using the low H\(\beta\)–blue UV \(\beta\) slope region defined by Zackrisson et al. (2017) for \(f_{\text{esc}} > 0.5\). While several sources fell into this region, with both low H\(\alpha\) EW and [OIII] + H\(\beta\) EW (\(<100\ \text{Å}\)), the uncertainties on the line flux measurements are too large for them to be robust candidates. More precise emission line measurements with JWST spectroscopy will be vital for identifying such candidates and their relative abundance in the galaxy population.

The lack of high \(f_{\text{esc}}\) candidates amongst the Ly\(\alpha\)-selected galaxies is also surprising. As the same conditions (a low neutral gas covering fraction) facilitate both Ly\(\alpha\) escape and Lyman continuum escape, a correlation between the two is expected (e.g., Verhamme et al. 2015; Dijkstra et al. 2016; Reddy et al. 2016). As discussed by Topping et al. (2022), however, it is possible for galaxies with high \(f_{\text{esc}}\) but very young ages to still have high nebular emission due to high ionizing photon production. It is likely that the criteria proposed by Zackrisson et al. (2017) can only find high \(f_{\text{esc}}\) systems within the bounds of the assumptions made for their model, such as galaxy star formation histories, ages, metallicities, and dust levels, but also the stellar populations made for their model, such as galaxy star formation his-

4. We examine our sample for signs of very high \(f_{\text{esc}}\) by comparing the inferred strengths of nebular emission lines ([OIII] + H\(\beta\) and H\(\alpha\)) and the strength of the nebular continuum via the UV \(\beta\) slope. We find no significant evidence for sources with high-escape-fraction galaxies with low nebular emission line strengths and very blue UV \(\beta\) slopes. The reduced strength of the [OIII] + H\(\beta\) EWs in our \(z > 3\) sample compared to a sample at \(z \sim 2\) from Tang et al. (2019) implies our sample likely has a lower gas-phase metallicity and/or ionization parameter.

We have demonstrated the power of JWST/NIRCam photometry to more precisely constrain the rest-frame optical emission of UV-faint high redshift galaxies than previously possible with Spitzer/IRAC. These observations allow us to constrain the production rate of ionizing photons from early galaxies, corroborating the picture obtained from previous stacking analyses, that \(\xi_{\text{ion}}\) is elevated in young, highly star-forming galaxies but that there is a broad distribution of \(\xi_{\text{ion}}\), likely driven by variations in galaxy properties and ages.

With JWST spectroscopy it is becoming possible to obtain direct measurements of optical emission lines in large samples (e.g., Sun et al. 2022; Williams et al. 2022; Matthee et al. 2022). Deriving a census of the ionizing photon production rate across the full galaxy population will be necessary to fully understand reionization. Here we have shown that \(\xi_{\text{ion}}\) is elevated in UV-faint galaxies with strong nebular emission lines, likely due to young ages. While a thorough analysis of the implications of our results for reionization is beyond the scope of this work, it becomes more prominent at high redshift (e.g., Boyett et al. 2022b; Endsley et al. 2022), implying that it would be possible to complete reionization with modest \(f_{\text{esc}}\). Considering the full distributions of \(\xi_{\text{ion}}\) and \(f_{\text{esc}}\) across galaxy properties will be required to assess the primary drivers of reionization.

References


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