Constraints on the Lyman continuum escape fraction for faint star forming galaxies

J. Japelj¹†, E. Vanzella², F. Fontanot¹, S. Cristiani¹,³, G. B. Caminha⁴, P. Tozzi⁵, I. Balestra⁶, P. Rosati¹, M. Meneghetti²

¹ INAF - Osservatorio Astronomico di Trieste, via G. B. Tiepolo 11, 34131 Trieste, Italy
² INAF - Osservatorio Astronomico di Bologna, via Ranzani 1, 40127 Bologna, Italy
³ INFN - National Institute for Nuclear Physics, via Valerio 2, I-34127 Trieste, Italy
⁴ Dipartimento di Fisica e Scienze della Terra, Università degli Studi di Ferrara, Via Saragat 1, I-44122 Ferrara, Italy
⁵ INAF - Osservatorio Astrofisico di Arcetri, Largo E. Fermi, I-50125, Firenze, Italy
⁶ University Observatory Munich, Scheinerstrasse 1, 81679 Munich, Germany

ABSTRACT
Star forming galaxies have long been considered the dominant sources of the cosmic ultraviolet background radiation at early epochs. However, observing and characterizing the galaxy population with significant ionizing emission has proven to be challenging. In particular, the fraction of ionizing radiation that escapes the local environment to the intergalactic medium is poorly known. We investigate the relation between the escape fraction and galaxy luminosity. We combine deep ultraviolet observations of Hubble Ultra Deep Field (UVUDF) with deep Multi Unit Spectroscopic Explorer (MUSE) observations of the same field, collecting a sample of 165 faint star forming galaxies in the $3 < z < 4$ redshift range with deep rest-frame observations of the Lyman continuum. In our sample, we do not find any galaxy with significant emission of LyC radiation. We bin the galaxies in various redshift and brightness intervals and stack their images. From stacked images we estimate the relative escape fraction upper limits as a function of the luminosity. Thanks to the depth of the sample we measure meaningful $1\sigma$ upper limits of $f_{esc,rel} < 0.07, 0.2$ and $0.6$ at $L \sim L^*_{z=3,0.5L^*_{z=3}}$ and $0.1L^*_{z=3}$, respectively. We use our estimates and theoretical predictions from the literature to study a possible dependence of the escape fraction on galaxy luminosity by modelling the ionizing background with different prescriptions of $f_{esc}(M_{UV})$. We show that the understanding of the luminosity dependence hinges on the ability to constrain the escape fraction down to $M_{UV} \sim -18$ mag in the future.

Key words: galaxies:high-redshift - ultraviolet: galaxies - intergalactic medium

1 INTRODUCTION

The epoch of cosmic reionization represents an important evolutionary stage of the Universe marking the formation of the first cosmic structures (e.g. Robertson et al. 2010).

* Based on observations collected at the European Southern Observatory for Astronomical research in the Southern Hemisphere under ESO programme 094.A-0289(B).
† E-mail: japelj@oats.inaf.it

A number of evidence suggests that reionization began at $z \sim 10–15$ and was completed by $z \sim 6$ (e.g. Robertson et al. 2015). The details of the reionization process are however still poorly known. In particular, identifying the sources driving the ionization of neutral hydrogen during the reionization epoch remains a challenge. Our understanding of the physics of the intergalactic medium (IGM) and galaxy formation depends on the detailed knowledge of the cosmic background radiation, therefore it is important to characterize the nature of the ionizing sources.

© 2016 The Authors
According to the predominant view, star-forming galaxies are the main drivers of the reionization at high redshifts ($z > 4$; e.g. Fontanot et al. 2012, 2014; Robertson et al. 2013, 2015; Haardt & Salvaterra 2015; Cristiani et al. 2016), although an identification of a numerous population of (faint) active galactic nuclei (AGNs) at $4 < z < 6.5$ (Giallongo et al. 2015) indicates that the contribution of AGNs to the cosmic reionization at early epochs may be more important than previously assumed (Madau & Haardt 2015; Khaire et al. 2016). In order to understand the relative contribution of AGNs and star-forming galaxies to the cosmic ionization background through cosmic time we need to characterize the population of star-forming galaxies with considerable Lyman continuum (LyC) emission. Direct observations of galaxies are only viable up to redshifts $z \sim 3.5 - 4$, beyond which the rest-frame LyC emission becomes unobservable due to the increasing IGM opacity (e.g. Madau 1995). A viable strategy implies the search for high-redshift analogs, whose LyC cannot be directly observed (e.g. Zackrisson et al. 2013; Schaerer et al. 2016).

The search for Lyman continuum leakers has been conducted by many surveys both at low ($z < 1.5$; Siana et al. 2007, 2010; Cowie et al. 2009; Grimes et al. 2009; Bridge et al. 2010) and high redshifts ($z \sim 3 - 4$; Steidel et al. 2001; Shapley et al. 2006; Iwata et al. 2009; Vanzella et al. 2010, 2012, 2015; Nestor et al. 2013; Mostardi et al. 2013; Guaita et al. 2016; Grazian et al. 2016; Marchi et al. 2016). Only a handful of sources with significantly detected Lyman continuum emission have been identified among hundreds of inspected galaxies, after accounting for contamination of superimposed foreground sources, which becomes increasingly more important when moving towards higher redshifts and lower luminosities (Vanzella et al. 2010; Mostardi et al. 2015; Siana et al. 2015). Secure spectroscopically confirmed detections of the Lyman continuum from star-forming galaxies have been found in the local Universe (Bergvall et al. 2006; Leitet et al. 2013; Borthakur et al. 2014), at low redshifts ($z < 0.3$; Izotov et al. 2016a,b) and high redshifts ($z \sim 3.2$; de Barros et al. 2016; Vanzella et al. 2016b; Shapley et al. 2016). More photometric LyC candidates at $z \sim 2 - 3$ are awaiting confirmation (e.g. Mostardi et al. 2015; Naidu et al. 2016).

In order to assess the contribution of star-forming galaxies to the cosmic ionization background we need to know their number densities, their ionizing photon production efficiency (i.e. the number of LyC photons per UV luminosity; Bouwens et al. 2016) and the fraction of the LyC photons (i.e. escape fraction $f_{\text{esc}}$) that can actually escape the local environment and ionize the IGM (Robertson et al. 2013). The escape fraction is the least constrained among the three quantities. Values for the galaxies with detected LyC (see above) range from a few (Leitet et al. 2013) to $> 50\%$ (Vanzella et al. 2016b). Because the frequency of detection is low, the escape fraction is low on average: analysis of large galaxy samples shows that on average $f_{\text{esc}} < 0.05$ at $3 < z < 3.5$ (Vanzella et al. 2010; Grazian et al. 2016). Assuming that star-forming galaxies are the only contributors to the ionization at $z \gtrsim 5$, the globally averaged escape fraction required to keep the Universe ionized should be $\sim 20\%$ (Ouchi et al. 2009; Bouwens et al. 2012; Finkelstein et al. 2012; Haardt & Madau 2012; Khaire et al. 2016). This value is obtained by extrapolating the UV luminosity function to $M_{\text{UV}} \sim -17$ mag, while the galaxy samples being used to search for Lyman continuum are limited to relatively bright galaxies ($L \sim L_{*;3}$; Vanzella et al. 2010; Mostardi et al. 2015). The galaxies with significantly detected Lyman continuum are in the same brightness range (Vanzella et al. 2016b; Schaerer et al. 2016). It has been therefore suggested that the escape fraction (on average) may evolve with redshift and/or luminosity (e.g. Ciardi et al. 2012; Kuhlen & Faucher-Giguère 2012; Fontanot et al. 2014). Together with the contribution from AGNs, such prescription is successful in reproducing the observed properties of the background in the $3 < z < 5$ range (e.g. Becker & Bolton 2013).

In this work we combine the HST WFC3-UVIS/F336W deep ultraviolet observations of the Hubble Ultra Deep Field (UDF; Beckwith et al. 2006) with VLT/MUSE deep observations of the same field, collecting a sample of $\sim 165$ faint galaxies in the $3 < z < 4$ range with deep rest frame $< 912\, \AA$ observations. Our aim is to search for galaxies with possible Lyman continuum analogs and to provide upper limits on the $f_{\text{esc}}$ in the $L > 0.1 L_{*;3}$ luminosity range. The presentation of data and the selection of the sample are given in Section 2. Results are reported in Section 3. In Section 4 we investigate the possibility of a luminosity-dependent escape fraction by modelling the ionizing background using different $f_{\text{esc}}(M_{\text{UV}})$ prescriptions. All magnitudes are quoted in the AB photometric system. We use standard cosmology (Planck Collaboration et al. 2014).

## 2 DATA AND SAMPLE SELECTION

### 2.1 Ultra-violet Hubble Ultra Deep Field

To investigate the Lyman continuum emission of galaxies at $z \sim 3 - 4$, we need deep imaging with filters probing the rest-frame emission bluewards of the Lyman limit. We use observations of a subfield of the UDF, which has been recently acquired in the ultra-violet (UVUDF; Teplitz et al. 2013; Rafelski et al. 2015) with three WFC3-UVIS filters: F225W, F275W and F336W\(^\dagger\). For our purposes we use the observations obtained with the F336W filter, because it probes the $\lambda_{\text{rest}} < 912\, \AA$ spectral region for galaxies at $z \gtrsim 3$. We show this schematically in Fig. 1, where a synthetic spectrum of a young, low-metallicity galaxy with $f_{\text{esc}} = 1$ (see Vanzella et al. 2015 for details) is plotted together with the normalized F336W filter transmission curve. In addition to the deep ultra-violet observations, the advantage of using this field is the availability of the imaging at longer wavelengths and high spatial resolution (Beckwith et al. 2006), which is crucial to identify galaxies that are free of contamination from interlopers (Vanzella et al. 2010; Siana et al. 2015; Mostardi et al. 2015).

An important quantity used throughout the study is the depth of the F336W image. Rafelski et al. (2015) quote $5\sigma$ upper limit of 28.3 mag for an aperture of $0.2'$. This value was obtained by measuring a pixel-to-pixel noise and scaling it to the $0.2'$ aperture, assuming the noise is uncorrelated. While we reproduce this value following the steps of Rafelski

\(^{\dagger}\) [http://uvudf.ipac.caltech.edu/](http://uvudf.ipac.caltech.edu/)
et al. (2015), we also measure the flux variations in the image background – where no sources are detected – directly in apertures of different sizes. Flux within each aperture is measured at 1000 random positions in the image. RMS of the image is estimated as sigma-clipped standard deviation of the resulting distribution of fluxes. In this way, we measure a slightly lower 5σ upper limit of 27.8 mag. The measurement is illustrated in Fig. 2. In the following we adopt the latter as a more conservative value.

2.2 MUSE deep observations

The Multi-Unit Spectroscopic Explorer (MUSE Bacon et al. 2010) is a second-generation VLT panoramic integral-field spectrograph. It has a field of view of 1 arcmin², spatial resolution of 0.′2, spectral range of 4750-9350 Å and resolution of R \approx 3000, making it a very efficient instrument for simultaneous observation of a large number of faint galaxies. We used MUSE observations of the UDF field conducted between September and December 2015 under the GTO Program ID. 094.A-0289(B) (PI: R. Bacon). The data consist in a mosaic covering 3 × 3 arcmin² of 9 pointings, plus one deeper pointing (UDF-10) in the central region of the field (overlapping the mosaic). We have used the archival data that are publicly available to date, i.e. \approx 6 hours of exposure time for each pointing in the 3 × 3 mosaic, and the full 20 hours in the UDF-10 field of view. Each exposure is 25 minutes, totalling 180 pointings, rotated by 90°, with small offsets of a fraction of arcsecond to reduce observational systematics, such as residuals in the sky subtraction and instrumental effects. The overall observational conditions were good with a mean DIMM seeing of 0.′85 ± 0.28.

We used the MUSE reduction pipeline version 1.2.1 (Weilbacher et al. 2012, 2014) to process the raw data and create the final data-cubes. All the standard calibrations provided by the pipeline were applied in each exposure (bias and flat field corrections, wavelength and flux calibration,
et al.), following the same procedure detailed in our previous works (Caminha et al. 2016; Vanzella et al. 2016a). Subsequently, we combined the calibrated observations into the 10 data-cubes covering the UDF area. Each data-cube has a spatial pixel scale of 0.2'' and spectral coverage from 4750 to 9350 Å, with a spectral scale of 1.25Å/pixel and a fairly constant spectral resolution of ≈ 2.4Å. The final coordinate match were done matching the source positions detected with SExtractor (Bertin & Arnouts 1996) in the collapsed MUSE 2D images with the corresponding deep F606W HST observations (Illingworth et al. 2013), resulting in a residual rms smaller than the 0.2''. Finally we applied the Zurich Atmosphere Purge (ZAP; Soto et al. 2016) to reduce the remaining sky residuals, using SExtractor segmentation maps to mask the objects with detected emission in the field-of-view. The final dataset consists of 10 MUSE cubes with some spatial overlaps covering an area of 3 × 3 arcmin². We checked the spectra of sources with detection in more than one data-cube, finding excellent consistence of wavelength and flux calibration.

To search for the suitable galaxy candidates for our work we employ the following technique. As a parent sample we take the catalogue of Coe et al. (2006) who provide photometric redshifts of the objects in the UDF field. We select all the objects within the 3 arcmin² that have photometric redshifts, resulting in ~ 2000 candidate galaxies. Then we search for these objects in the MUSE data cubes and investigate their spectra in order to measure their redshifts. Our work is focused towards faint galaxies: with the used instrumental setup and the integration times, the spectra of R ≳ 25 mag do not have sufficient signal to noise to allow us to measure absorption-line-based redshifts. Instead we have to rely on detections of Lyα emission lines which means that our sample is largely selected of Lyα emitters: there are only two galaxies in the bright part of the sample with no significant Lyα emission for which we were able to securely measure their redshifts from absorption lines. Furthermore, the fainter the object we are observing, the more we are biased towards systems with strong Lyα emission. Given the current depth of the survey we estimate that only lines with the rest-frame EW(Lyα) > 60Å can be detected with 3-sigma significance for objects fainter than ~ 29 mag. We emphasize that, while in the following we report all the measurements in the 3 < z_{spec} < 4 range (in the following we use z_{spec} = z), we consider only objects brighter than 28.5 mag in the stacking analysis of Section 3.3. We measure the redshifts by fitting a simple Gaussian function to Lyα emission lines. In cases where Lyα emission is double-peaked, we fit a gaussian to each peak and measure the average redshift. We caution that, on average, Lyα emission is double-peaked, we fit a gaussian to each peak and measure the average redshift. We

2 A strong LyC candidate awaiting for a secure redshift measurement, the I01 galaxy found by Vanzella et al. (2012), has no Lyα emission detected.
Figure 4. Representative galaxies in the clean (top) and contaminated (bottom) samples. 3′′ × 3′′ colour images are stacked BVi images obtained with the HST ACS camera. Dashed circle is 0′′.5 radius aperture. One of the galaxies has been identified as an AGN. For each galaxy we report the position (i.e. the centre of the white aperture), measured redshift and i775 magnitude. The latter is taken from the catalogue of Rafelski et al. (2015).

the galaxies of the clean sample. In particular, Rafelski et al. (2015) report photometry obtained with several HST cameras in the ultra-violet to near infrared (i.e. ∼0.2 − 1.6 µm) spectral range. We complement this data set with photometry given by Guo et al. (2013), who extended the measurements to the near infrared where available. The catalogue of Guo et al. (2013) does not include sources as faint as the one of Rafelski et al. (2015), therefore the near infrared measurements are not available for the whole clean sample. For the bright part of the sample we also retrieve measurements of stellar masses from Santini et al. (2015). General properties of the galaxies in the sample are presented in Fig. 5. The sample is homogeneous in terms of redshift and brightness in the 3.0 < z < 3.8 interval. We note that the galaxies are fainter with ∆m ≃ 3 mag on average with respect to the sample of Vanzella et al. (2010) in the same redshift range.

3 METHODOLOGY AND RESULTS

Having defined the sample, we first measure fluxes in the F336W image at the positions of the galaxies. For compact galaxies we measure the flux within the 0′′.2 aperture, as in Section 2.1. However, many galaxies show a complicated substructure, a non-compact morphology, and are treated with the following approach. The stacked HST/ACS image is used to define an aperture encompassing all the pixels whose flux value is above 1.5 times the local RMS of the
background around the galaxy. The F336W flux of the non-compact galaxy is then measured adopting this aperture. This approach should suffice for our proposes in this work since we are only interested whether the flux at the galaxy position is significant/detectable, however we caution that this methodology might not be desirable/good if precise photometry is necessary.

The distribution of fluxes measured in the described way is shown in Fig. 6. The fluxes of the clean sample have sigma-clipped mean and standard deviation of $0.004 \pm 0.056 \times 10^{-7} \text{ Jy}$. This 1σ dispersion corresponds to the magnitude of 29.5 mag, which is consistent with the value derived in Section 2.1. As the mean IGM transmission rapidly decreases with redshift (see discussion below), we also check the distribution of fluxes from galaxies limited to the $3.0 < z < 3.6$ range. We find that the mean and standard deviation do not change. For two galaxies ($G1$ and $G2$) we find a potential detection with $\sim 3\sigma$ significance. Furthermore, we repeat the measurements for the 20 galaxies from the contaminated sample. Fluxes for this sample are similarly crowded around zero, but there are two notable detections ($GC1$ and $GC2$) with high ($\sim 4$ and $7.5\sigma$) significance.

In Fig. 7 we show the images in different wavelengths of the four galaxies with flux detected at $\gtrsim 3\sigma$. We also include their spectral energy distributions (SEDs) built over a wide spectral range. Galaxies $G1$ and $G2$ from the clean sample are moderately faint ($i(\tau_{75} \sim 27.3 \text{ mag}$), while $GC1$ and $GC2$ from the contaminated sample are relatively bright ($i(\tau_{75} \sim 24.7 \text{ mag}$). Stellar masses of $\log M_*/M_\odot \sim 8.6, 9.2, 9.4$ and 9.7 are obtained from the SED modelling (Santini et al. 2015) for $G1$, $G2$, $GC1$ and $GC2$, respectively. Galaxies $G2$ and $GC2$ show an excess in the K-band flux, suggesting that strong H$\beta + [\text{O} iii]/[\text{O} ii]$ emission lines enter the K-band at their respective redshifts. [O iii] lines are redshifted redwards of the K-band in the case of other two galaxies. A large K-band flux excess with respect to the flux measured in the H-band implies a possibly large $[\text{O} iii]/[\text{O} ii]$ ratio. The observed excess is interesting in view of the proposed connection between large $[\text{O} iii]/[\text{O} ii]$ and high escape fraction of Lyman continuum (e.g. Jaskot & Oey 2013; Nakajima & Ouchi 2014; Nakajima et al. 2016). We discuss this more thoroughly in Section 4.1.

All four galaxies were also detected in the F336W image by Rafelski et al. (2015) using proper aperture-matched PSF corrected photometry, though we note that detections are of low significance in all cases with the exception of $GC2$. Furthermore, the galaxies $G1$ and $G2$ are not detected in the VIMOS $U$ image. This image is deeper than the one obtained with the F336W and the $U$ filter covers slightly redder wavelengths (e.g. see Fig. 1 in Vanzella et al. 2010). The non-detection of these two galaxies in this image therefore makes their detection in the F336W image tentative at best. Object $GC1$ has been already discussed by Vanzella et al. (2012), who argue that the signal, believed to be LyC emission, is in fact emission from a $z \sim 1.6$ interloping galaxy. Finally, in Appendix A we present a longer discussion regarding the galaxy $GC2$. We conclude that this galaxy is contaminated. Among the galaxies in our sample we therefore cannot claim a significant detection of Lyman continuum.

### 3.1 Intergalactic medium

With increasing redshift the absorption due to IGM becomes a limiting factor in our ability to detect Lyman continuum emission. This is illustrated in Fig. 1 where we show how the average transmission decreases for a galaxy at $z = 3.5$ with respect to the one at $z = 3$. To measure the real Lyman continuum that is being emitted by a galaxy, one has to apply proper correction to the measured fluxes (or, in the case of a non detection, to its upper limits). The absorption of the Lyman continuum is caused mainly by systems with relatively high H i column densities $N_{\text{HI}} > 10^{17}$ cm$^{-2}$ (Inoue & Iwata 2008) and therefore the absorption is characteristically stochastic. Its effects have to be taken into account in a statistical manner by simulating a large number of lines of sight, based on the observed properties of the IGM absorbers. We calculate the transmission of the IGM by performing Monte Carlo (MC) simulation, following the prescription of Inoue & Iwata (2008), Inoue et al. (2014) and Vanzella et al. (2015). The empirical distribution functions of the redshift-dependent properties of intergalactic absorbers (e.g. H i column density, number density, Doppler parameter) are used to generate a large number of absorbers along 10000 lines of sight at the given redshift. In Fig. 8 we show the median and average (from now on $<T>$) transmission along 10000 simulated lines of sight in the $z = 2.3 - 4$ range, where the transmission is convolved with the shape of the F336W filter. The convolved average transmission drops below $<T> = 0.2, 0.1$ and 0.05 at $z = 3.2, 3.4$ and 3.6.

### 3.2 Expected number of detections

Relative escape fraction $f_{\text{esc},\text{int}}$, i.e. the fraction of escaping LyC photons relative to the fraction of escaping non-ionizing photons
Figure 7. Detailed look into the observational properties of the four galaxies with detected signal in F336W filter at $\gtrsim 3\sigma$ significance. Top two galaxies are from our clean sample, while the bottom two are from contaminated sample. $3'' \times 3''$ images show observations in HST WFC3/F336W and ACS colour images. We also include the deep ground based VLT VIMOS-U images (Nonino et al. 2009). White dashed circles show 0.5'' radius aperture. Plotted are also spectral energy distributions, using photometric measurements from Rafelski et al. (2015) (red points) and Guo et al. (2013) (blue points). Vertical red and orange dashed lines indicate rest-frame wavelengths of 912 and 5007 Å, respectively. We also quote the central positions and, where available, GOODS designations (Giavalisco et al. 2004).

UV photons, can be written as (Steidel et al. 2001; Siana et al. 2007):

$$f_{\text{esc,rel}} = \frac{(L_{\text{UV}}/L_{\text{LyC}})^{\text{int}}}{(F_{\text{UV}}/F_{\text{LyC}})^{\text{obs}}} \exp(\tau_{\text{LyC}}),$$

(1)

where $(L_{\text{UV}}/L_{\text{LyC}})^{\text{int}}$ is the intrinsic luminosity density ratio, $(F_{\text{UV}}/F_{\text{LyC}})^{\text{obs}}$ is the observed flux density ratio and $\exp(\tau_{\text{LyC}})$ represents the line-of-sight opacity of the IGM for the Lyman continuum photons. In this work we do not work with the absolute escape fraction, i.e. relative escape fraction corrected for dust extinction $A_{\text{UV}}$, $f_{\text{esc}} = f_{\text{esc,rel}}10^{-0.4A_{\text{UV}}}$, due to the uncertainties involved in the measurements of the extinction. Note that the relative escape fraction is the quantity used to calculate the contribution from the observed UV LFs of high-z galaxies to the ionizing background.

In the previous section we have shown that we do not find a clear case with Lyman continuum emission among the galaxies in our sample. Indeed, from Eq. 1 we see that, from purely observational perspective, both faintness of our sample and the high redshift range – and therefore low IGM transmission – work against us. Following Vanzella et al. (2010) we first simulate how many detections are expected (on average) for different values of assumed $f_{\text{esc,rel}}$, given the intrinsic properties of our clean sample. The simulation
is performed in the following way. We take the clean sample of 145 galaxies with known redshifts and $F_{\text{UV}}$. For each galaxy in the sample we simulate 10000 different lines of sight with different IGM properties (see Section 3.1), i.e we simulate 10000 galaxy samples. For each galaxy in each sample we calculate the expected $F_{\text{LyC}}$ by inverting Eq. 1. An error is assigned to the $F_{\text{LyC}}$ by considering the dependency between the measurement error as a function of brightness, which has been obtained from the analytical fit to the measurements reported in the Rafelski et al. (2015) catalogue. If the expected flux is greater than the RMS, measured on the F336W image, the galaxy is counted as detected. For the purposes of this study we assume the luminosity ratio to evolve in this range (e.g. Steidel et al. 2014; de Barros et al. 2014), but also the F336W filter probes bluer intrinsic spectral region with redshift, having an impact on the luminosity ratio that we should input into the simulation. Given the uncertainties in the estimated $\langle L_{\text{UV}}/L_{\text{LyC}} \rangle^{\text{int}}$, we do not consider these redshift-dependent effects.

- IGM transmission in different lines of sight as a function of redshift is simulated as described in Section 3.1.
- $\langle f_{\text{esc},\text{rel}} \rangle$. It is reasonable to assume that the relative escape fraction is not the same in all galaxies but instead occupies a range of values. Due to the lack of actual measurements we don’t know the shape of the actual distribution. Following Vanzella et al. (2010), we run the simulation for three different distributions of $\langle f_{\text{esc},\text{rel}} \rangle$: (a) constant value, (b) gaussian distribution, and (c) exponential distribution. Mean value for each distribution is varied between 0 and 1 in steps of 0.01. Note that from Eq. 1 it follows that $\langle f_{\text{esc},\text{rel}} \rangle < 1$ (Vanzella et al. 2012). A possible evolution of $\langle f_{\text{esc},\text{rel}} \rangle$ with redshift and/or luminosity is not taken into account.

The simulation is run separately for three different $\langle f_{\text{esc},\text{rel}} \rangle$ distributions. Median and the 68% confidence level of the resulting relative escape fraction distribution at each $\langle f_{\text{esc},\text{rel}} \rangle$ step is shown in Fig. 9. The results are shown only for the case where the Lyman continuum is detected at $2\sigma$ significance. The results, though dependent on the simulation parameters, show that relatively high values of $\langle f_{\text{esc},\text{rel}} \rangle$ at $3 < z < 4$ would be necessary in order to detect Lyman continuum in our sample of faint galaxies.

### 3.3 Stacking analysis and $f_{\text{esc},\text{rel}}$ upper limits

Finally, we stack the F336W images of the galaxies in our sample to check whether we can detect a signal on a stacked image as well as to provide useful upper limits to the $f_{\text{esc},\text{rel}}$. As already discussed, the depth of the constraint on the escape fraction depends on the brightness of the galaxies and their redshift (i.e. IGM transmission). For this reason stacking the full sample is not very useful. We only consider the bright part of our sample ($i_{775} < 28.5$). Furthermore, galaxies are grouped into brightness and narrow redshift intervals, to illustrate how the $f_{\text{esc},\text{rel}}$ limit depends on the two quantities.

First we apply a simple average stacking of the subsamples. The expected RMS of the stacked image is the $1\sigma$ upper limit of 29.5 mag of the original image divided by $\sqrt{N}$, where $N$ is the number of images used in the stacking. Flux at the centre of each stacked image is measured within 0′′2 aperture and compared to the expected RMS of the stacked image. We do not detect any signal with a significance greater than $1\sigma$ in any of the stacked images. The upper limit of the $f_{\text{esc},\text{rel}}$ is estimated using Eq. 1, where we assume $\langle L_{\text{UV}}/L_{\text{LyC}} \rangle^{\text{int}} = 1.3$, ($F_{\text{UV}}^{\text{obs}}$) is approximated with $i_{775}$, and the transmission is taken to be the average transmission in the corresponding redshift interval (see Figure 8).

To further check our results we also apply different stacking techniques to the images: median stacking, weighted average stacking and weighted median stacking. The weights are not

![Figure 8. Median (full circles) and average (empty squares) IGM transmission convolved with the HST WFC3-UVIS F336W filter as a function of redshift. Values were obtained by averaging 10000 lines of sight. Error bars indicate the 68% confidence level.](image-url)
applied on the pixel-to-pixel basis, but rather image-wise: background noise in a region around each galaxy position is measured and its RMS is used as a weight for that particular galaxy. No significant flux is detected on any of the stacked images, regardless of the method used for stacking. Therefore we only consider simple average stacking in the following. The resulting transmission in each redshift bin is reported in parentheses next to each redshift interval. Number of frames $N$ used in the stacking of each case is reported in parentheses in the table. Cases with $N < 4$ are not considered in the analysis.

| $i'_{775}$cut | Redshift range ($<T>$) | $i'_{775}$cut | Redshift range ($<T>$) |
|--------------|-------------------------|--------------|-------------------------|
| 3.0 - 3.2 (0.26) | 3.2 - 3.4 (0.15) | 3.4 - 3.6 (0.08) | 3.0 - 3.6 (0.16) | 3.0 - 4.0 (0.11) |
| 24.0-26.0 | 0.07 (6) | -9.0 (0) | 0.58 (4) | 0.11 (10) | 0.16 (13) |
| 26.0-27.5 | 0.34 (9) | 0.53 (7) | 1.29 (7) | 0.31 (24) | 0.37 (32) |
| 27.5-28.5 | 0.73 (14) | 2.39 (5) | 2.46 (13) | 0.78 (32) | 0.93 (44) |
| 24.0-27.0 | 0.1 (10) | 0.52 (6) | 0.59 (7) | 0.15 (24) | 0.19 (33) |
| 27.0-28.5 | 0.51 (19) | 1.92 (6) | 1.84 (17) | 0.57 (42) | 0.7 (56) |
| 24.0-28.5 | 0.21 (29) | 0.71 (12) | 0.98 (24) | 0.25 (66) | 0.31 (89) |

Table 1. 1-sigma (top) and 3-sigma (bottom) upper limits of relative escape fractions $f_{\text{esc,rel}}$ for different redshift and luminosity bins. Average transmission in each redshift bin is reported in parentheses next to each redshift interval. Number of frames $N$ used in the stacking of each case is reported in parentheses in the table. Cases with $N < 4$ are not considered in the analysis.

4 DISCUSSION

4.1 K-band excess and Lyman continuum emission

Jaskot & Oey (2013) and Nakajima & Ouchi (2014) pointed out that there could be a connection between high [O III]/[O II] and high $f_{\text{esc}}$. In their scenario, high escape fractions are expected to arise in the case of density-bounded H II regions with low H I column densities. In the density-bounded scenario, the outer nebular region in which [O II] is produced do not extend as far as in the case of ionization-bounded regions. At the same time the central nebular region, in which [O III] is produced, is expected to be of similar sizes in both cases. In such a situation one therefore expects higher [O III]/[O II] ratios being connected to higher $f_{\text{esc}}$.

The number of detected Lyman continuum leakers is still too small to allow a firm test of this relation. Still, galaxies with detected LyC show very strong [O III] lines both at low (Izotov et al. 2016b,a) and high redshifts (Vanzella et al. 2016b), corroborating this view (see also Nakajima et al. 2016). While we cannot claim a true detection of Lyman continuum in any of our galaxies, we nevertheless check the occurrence of objects with strong emission lines. From our clean and contaminated samples we look at the galaxies lying in the 3.0 < $z$ < 3.6 redshift range, for which the [O III]4959,5007 emission lines fall within the K-band. Then we measure the excess of the K-band flux with respect to the average flux of the adjacent photometric bands. At these redshifts the Balmer break falls within the H-band, therefore the ratio between the $H$ and $K$-band alone traces the strength of the Balmer break instead of the strength between oxygen lines. For this reason, in addition to the measured H-band flux, we require the Spitzer/IRAC CH1 (i.e. 3.5 μm) observations. The average of the fluxes in these two bands should therefore reveal a strong K-band excess.
more accurately than if the comparison was made only with the H-band flux. Furthermore, the Spitzer measurements are required to be detected with at least 1σ significance. For example, G2 and GC2 in Fig. 7 qualify as good candidates. Limiting the analysis to $i_{775} < 28.5$, the ratio can be measured for 31 galaxies. We show the ratio as a function of the flux measured in the F336W in Figure 11.

We find a large spread in the excess values. In all cases the excess is lower than the one found for Ion2. Our LyC candidate GC2 has a marginal excess of $\sim 1.5$. For comparison, the five $\sim 0.3$ LyC leakers found by Izotov et al. (2016a) would have an excess of $\sim 1.7 - 2.6$ if they were lying in our redshift range.

4.2 Escape fraction as a function of luminosity

Our analysis of the faint sample of star-forming galaxies enabled us to extend the study of escape fraction down to $M_{1800} \sim -19$ mag at $z \sim 3 - 3.5$. The disadvantage of studying faint galaxies is that a large number of them is required in order to reach significant upper limits on the escape fraction. Consequently, strong observational constraints at the faint end are hard to reach. On the other hand, the luminosity dependence of the escape fraction has been suggested as a possible workaround to increase the contribution of star-forming galaxies to the ionizing background at high redshifts (Kuhlen & Faucher-Giguère 2012; Bouwens et al. 2012; Finkelstein et al. 2012; Fontanot et al. 2012, 2014; Robertson et al. 2013; Faisst 2016). In the following we consider the luminosity-dependent escape fraction using both our measurements and a prediction by Duncan & Conselice (2015)
with a goal to better understand the faint star-forming population that could provide necessary emission for ionization at high redshifts.

Following the formalism of Fontanot et al. (2014) (see also Cristiani et al. 2016) we estimate the relative contribution of AGNs and star forming galaxies to the photon volume emissivity ($\dot{N}_{\text{ion}}$) and photoionization rate ($\Gamma$) and compare the values to those determined by observations. In this paper we focus on the possible dependence of $f_{\text{esc}}$ on $M_{\text{UV}}$ in a star forming population. The ionizing background associated with each population is modelled in the following way. The emission rate of hydrogen-ionizing photons per unit comoving volume is computed as

$$\dot{N}_{\text{ion}}(z) = \int_{\nu_{\text{HI}}}^{\nu_{\text{UV}}} \frac{\rho_{\nu}}{h$\nu$} d\nu,$$

(2)

$$\rho_{\nu} = \int_{L_{\text{min}}}^{\infty} f_{\text{esc}}(L)\Phi(L, z)L_{\nu}(L) dL,$$

(3)

where $\nu_{\text{HI}}$ corresponds to frequency at 912 Å, $\nu_{\text{UV}}$ = 4$\nu_{\text{H}}$ (e.g. we assume that photons with higher energies are mostly absorbed by HeII; Madau et al. 1999). $\rho_{\nu}$ is monochromatic comoving luminosity density for sources brighter than $L_{\text{min}}$, and $\Phi(L, z)$ is a redshift-dependent luminosity function. Note that for both populations we assume that the escape fraction does not vary with redshift. Photoionization rate is computed as (e.g. Haardt & Madau 2012)

$$\Gamma(z) = 4\pi \int_{\nu_{\text{HI}}}^{\nu_{\text{UV}}} J(\nu, z) \frac{\rho_{\nu}}{h$\nu$} d\nu,$$

(4)

where $\sigma_{\text{HI}}(\nu)$ is the absorption cross-section of neutral hydrogen. $J(\nu, z)$ is the background intensity:

$$J(\nu, z) = \frac{c}{4\pi} \int_{s_{\text{HI}}}^{s_{\text{UV}}} \varepsilon_{\nu z_{1}}(z_{1}) e^{-\tau_{\text{HI}}(\nu, z)} \frac{(1 + z_{1})^{3}}{(1 + z_{1})^{3}} dt \frac{dz_{1}}{dz},$$

(5)

where the emissivity $\varepsilon_{\nu z_{1}}$ is equivalent to $\rho_{\nu}$ in the comoving frame, $\nu_{1} = \nu_{\text{HI}}z_{1}$ and $\tau_{\text{eff}}(\nu, z_{1})$ is the effective optical depth for photons of frequency $\nu$ at $z$ that were emitted at $z_{1}$:

$$\tau_{\text{eff}}(\nu, z, z_{1}) = \int_{z_{1}}^{z} dz_{2} \int_{0}^{\infty} dN_{\text{HI}} f(N_{\text{HI}}, z_{2}) \left(1 - e^{-\tau_{\text{HI}}(\nu, z_{2})}\right).$$

(6)

Here $\tau_{\nu}$ represents the continuum optical depth through an individual absorber at frequency $\nu_{2}$ = $\nu_{\text{HI}}z_{2}$ and $f(N_{\text{HI}}, z)$ is the distribution of absorbers. For the latter we adopt the distribution from Becker & Bolton (2013).

To calculate the AGN contribution to ionizing background we use the same approach as in Cristiani et al. (2016). We approximate the AGN spectra with a power-law form, $f_{\nu} \propto \nu^{-\alpha}$, with $\alpha = 1.75$. For the AGN luminosity function we use the bolometric luminosity function prescription at $z < 4$ given by Hopkins et al. (2007) and extrapolate it to higher redshifts. AGNs as faint as $L_{\text{min}} = 0.1L_{\odot}$, are taken into account: as shown by Cristiani et al. (2016), objects fainter than that limit should provide a negligible contribution to the ionizing photon budget. Finally, we do not make the usual assumption of $f_{\text{esc}}^{\text{AGN}} = 1$ but rather adopt $f_{\text{esc}}^{\text{AGN}} = 0.75$, which is the average value measured for AGNs at $z \approx 3.6 - 4.0$ (Cristiani et al. 2016). We also assume that $f_{\text{esc}}^{\text{AGN}}$ does not depend on the luminosity in the considered luminosity range.

As for star forming galaxies, we use in Eq. (1) to (4) the evolution of Lyman Break Galaxy luminosity function (Bouwens et al. 2015, see also Finkelstein et al. 2015). Following Fontanot et al. (2014), we estimate $L_{\text{min}}(z)$ assuming that galaxy formation becomes inefficient in dark matter haloes smaller than the characteristic mass (Okamoto et al. 2008), i.e. that the contribution of fainter galaxies to the ionizing background is negligible. In detail, we use the characteristic mass estimate based on a blazar heating thermal history (see Fig 2. in Fontanot et al. 2014). Finally, we consider a redshift-dependent spectral emissivity as in Haardt & Madau (2012).

In order to estimate the contribution of star forming galaxies to $\dot{N}_{\text{ion}}$ and $\Gamma$ we consider different prescriptions for $f_{\text{esc}}(M_{\text{UV}})$\(^3\). As the first step we use our most constrained values (at each luminosity) to define an escape fraction upper limit envelope, which we represent with the following analytical function (see Fig. 12):

$$f_{\text{esc,rel}}(M) = \frac{a e^{b M_{\text{HI}}} + b e^{a M}}{e^{a M_{\text{HI}}} + e^{a M}},$$

(7)

where $a = 0.02$ and $b = 1$ are high- and low-luminosity upper limits\(^4\), $M_{\text{HI}} = -19.3$ mag is the transitional luminosity

\(^3\) Sharma et al. (2016) uses the galaxies from the EAGLE cosmological hydrodynamical simulation (Schaye et al. 2015) to estimate the redshift and luminosity dependence of the escape fraction by assuming that high average escape fractions are related to high star formation rate densities. Their prescription results in an escape fraction which increases with increasing UV luminosity. Their prediction at $z = 3$ (see Fig. 2. in Sharma et al. 2016) is at odds with the results presented in this paper as well as with the low upper limits found in previous works for the bright galaxies (e.g. Vanzella et al. 2010; Marchi et al. 2016). In the following we therefore only consider models in which escape fraction increases with decreasing UV luminosity.

\(^4\) The value of 0.02 is used as the faintest constraint measured at

**Figure 12.** Relative escape fraction upper limits as a function of absolute magnitude. Solid line represents an estimated upper limit envelope (Eq. 7). Dashed line shows the $f_{\text{esc}}(M_{\text{UV}})$ relation for which the modelling produces a background best matching with the data (see the text and Fig. 13, left panel, right column). Shown is also the escape fraction upper limit measured by Amorin et al. (2014) for a single faint galaxy (star).
for two different highest allowed escape fractions of the physical model arising in ionization-bounded nebula with holes (model A in Fig. 14; Duncan & Conselice 2015). The models are shown to be too high. By varying the transitional magnitude \( M \) at face value, the calculated ionizing background turns out to be largely insensitive to this value. Given the limiting integration luminosity \( N_{\text{ion}} \), we search for the best match between the calculated and observed \( N_{\text{ion}}(z) \) and \( \Gamma(z) \) and find that this is achieved with \( M_{\text{br}} \sim -16 \) (see left column in the left panel in Fig. 13). Given the limiting integration luminosity \( L_{\text{min}}(z) \) (Fontanot et al. 2014), the background at \( z \sim 4 \) is mainly contributed by faint galaxies with \( M_{UV} \sim M_{br} \) and is being dominated by progressively fainter population when moving towards higher redshifts. At \( z \gtrsim 5 \) we clearly start to overestimate the rate of emitted photons per unit volume. This is a combination of two effects: (i) the decrease in \( L_{\text{min}} \) with redshift which increases the contribution of faint galaxies with high escape fraction, and (ii) the progressively steeper galaxy luminosity functions at higher redshifts (Bouwens et al. 2015) which increases the fraction of faint galaxies that have the highest escape fraction (in our model).

The results of our calculation using different models (introduced in the following text) are presented in Fig. 13, where they are compared to the measurements of \( N_{\text{ion}} \) and \( \Gamma \) from the literature. For each model we plot the contribution to the background from AGNs (dashed blue line), star forming galaxies (solid red line) and the contribution from both (dot-dashed green line).

The functional form of \( f_{\text{esc}}(M_{UV}) \) assumed above is not physically motivated, i.e. it is based on our inability to make stringent measurements for the faint galaxy population. Nevertheless, we use it as a first crude approximation of the luminosity dependency. Taking this \( f_{\text{esc}}(M_{UV}) \) at face value, the calculated ionizing background turns out to be too high. By varying the transitional magnitude \( M_{\text{br}} \) we search for the best match between the calculated and observed \( N_{\text{ion}}(z) \) and \( \Gamma(z) \) and find that this is achieved with \( M_{\text{br}} \sim -16 \) (see left column in the left panel in Fig. 13). Given the limiting integration luminosity \( L_{\text{min}}(z) \) (Fontanot et al. 2014), the background at \( z \sim 4 \) is mainly contributed by faint galaxies with \( M_{UV} \sim M_{br} \) and is being dominated by progressively fainter population when moving towards higher redshifts. At \( z \gtrsim 5 \) we clearly start to overestimate the rate of emitted photons per unit volume. This is a combination of two effects: (i) the decrease in \( L_{\text{min}} \) with redshift which increases the contribution of faint galaxies with high escape fraction, and (ii) the progressively steeper galaxy luminosity functions at higher redshifts (Bouwens et al. 2015) which increases the fraction of faint galaxies that have the highest escape fraction (in our model).

While due to the lack of knowledge of the actual \( f_{\text{esc}}(M_{UV}) \) shape the hypothesis of a sharp transition in \( f_{\text{esc}} \) at some magnitude cannot be rejected, it is reasonable to assume that low-luminosity galaxies cannot have \( f_{\text{esc}} \sim 1 \) on average. It is interesting to see what happens when the highest escape fraction allowed is lowered. Amorín et al. (2014) estimated an upper limit of \( f_{\text{esc,gal}} = 23\% \) for a lensed, faint galaxy (\( M_{UV} = -17.4 \) mag). This is by far the faintest galaxy for which the escape fraction has been constrained, but we caution that the number is very uncertain due to the uncertainties in the IGM transmission, and the result cannot be assumed to be representative of the whole galaxy population (Cen & Kimm 2015). Still, we set \( f_{\text{esc, max}} = 0.2 \) based on that result and also to compare our results to other studies where the same value is often assumed. We find that the calculated ionizing photon production rate in this case is in better agreement with measurements at high redshifts (the right column of the left panel in Fig. 13). In this case the transitional magnitude for the model best matching the...
data is $\sim -20$ mag, which is significantly brighter than in the previous case. It is worth stressing that the strong drop in the observed UV background when approaching $z \sim 6$ is hard to reproduce within our current scheme.

Irrespective of the highest allowed escape fraction, the bright part of the galaxy population contributes a negligible amount of photons for reionization. In fact, the above results do not change appreciably if we change the high-luminosity upper limit parameter to $a = 0.05$ or $a = 0$. This means that even if observationally we could constrain the escape fraction of the bright population to very low upper limits (or low absolute values if in the future the stacking analysis of a large sample results in a significant signal), that alone would not help us to constrain the properties of the faint population that is the dominant contributor to the reionization.

### 4.3 Comparison with a physically motivated model of the escape fraction

Robust constraints at the faint end of $f_{esc}(M_{UV})$ are observationally hard to achieve and, as illustrated in the discussion so far, the study of the $f_{esc}(M_{UV})$ is limited to a qualitative analysis. Motivated to explore the issue further, we repeat the above analysis but this time using a physically motivated model for $f_{esc}(M_{UV})$. Duncan & Conselice (2015, hereafter DC15) looked into the properties of LyC escaping from two particular models of star-forming regions: (A) a ionization-bounded nebula with dust-free holes, through which the LyC can escape; and (B) a density-bounded nebula where LyC can escape due to the incomplete Strömgren sphere (see also Zackrisson et al. 2013). Under certain assumptions on stellar population age, star-formation history, metallicity and dust extinction (see DC15 for details), they used a stellar population synthesis analysis to get relations between "observed" UV slope $\beta$, absolute escape fraction and extinction $A_V$ for each of the two models. We use the results reported in their Figs. 5 and 6 to extract the $f_{esc}(\beta)$ relations for different $A_V$ values. DC15 compiled observational relations between UV spectral index $\beta$ and $M_{UV}$ at different redshifts. We use the relation at $z \sim 4$ to transform the $f_{esc}(\beta)$ to $f_{esc}(M_{UV})$, as the relation at this redshift is the most reliable over a wide luminosity range. The resulting relations for the two models are presented in Fig. 14 and compared with the empirical model. We then repeat the analysis as in the previous section using these relations as input. We note that there are a few caveats when using the extracted models. The analysis of DC15 specifically focused on $z > 6$ galaxies: this reflects in the choice of the assumed parameters in their spectral synthesis analysis. In addition, we do not take into account the variation in the $\beta(M_{UV})$ relation with redshift (DC15; Bouwens et al. 2014; Rogers et al. 2014). Nevertheless, as long as we carry these caveats in mind, the extracted $f_{esc}(M_{UV})$ models should provide some valuable information, given the number of uncertainties and assumptions involved in the modelling of the ionizing background on the one hand and in the stellar synthesis analysis of DC15 on the other.

We redo the calculation of the ionizing background for the two models of DC15. Each model is limited to $f_{esc,max} = 1$ at the faint end. Both models in principle give very similar results to the ones obtained by our starting model, provided that the $A_V$ is sufficiently low. Model B $f_{esc}(M_{UV})$ relations have a rather sharp transition from $f_{esc} = 0 - 1$, and the calculated ionizing background is qualitatively similar to the one we obtained from our initial modelling using Eq. 7.

![Figure 14. Absolute escape fraction as a function of luminosity as predicted by Duncan & Conselice (2015) for the case of ionization-bounded nebula with holes (model A) and density bounded nebula (model B). Different curves correspond to different assumed values of dust extinction $A_V$ of the dust screen enclosing a star-forming region. Black dashed curve is the upper-limit envelope of relative escape fraction constrained by our measurements.](image-url)

Therefore we only show the calculated background using the model A relations (right panel in Fig. 13). Again we obtain a similar overestimation of the background at high redshifts, which we attribute to the very high values of escape fraction at low luminosities. Fixing the highest allowed escape fraction to $f_{esc,max} = 0.2$ results in a flat evolution all the way to the highest redshifts (see second column of the right panel in Fig. 13).

It is interesting to see that our measured upper limits can put some constraints to the parameter space inspected by DC15. Dust effects are understandably much stronger in the density-bounded model (model B). High dust extinction favours a relevant contribution of bright galaxies to the ionizing photons, which is at odds with our observational limits. On the other hand, based on the high redshift measurements of $N_{ion}$ and $\Gamma$ it is clear that galaxies cannot have very high escape fraction on average, as that leads to an overprediction of the background. Our "sharp" transition model with $f_{esc,max} = 0.2$ shows that the transition is expected at $M_{UV} \sim -20$ mag, but could also be in the somewhat less luminous regime. Increasing the number of observed galaxies with $M_{UV} \in (-20, -18)$ mag is therefore
critical to assess the level of importance of faint galaxies in reionization, irrespective of the actual $f_{\text{esc}}(M_{\text{UV}})$ relation. Finally we emphasize that we did not include any evolution of the escape fraction with redshift in the modelling. As shown in the past (e.g. Kuhlen & Faucher-Giguère 2012; Fontanot et al. 2012), an escape fraction independent of luminosity, but increasing with redshift, could likewise provide enough photons for ionization. Unfortunately, the information of a possible $f_{\text{esc}}(z)$ evolution can only be inferred from secondary sources (e.g. change in other galaxy properties as the emission line strength) or simulations (e.g. Sharma et al. 2016).

5 CONCLUSIONS

As the average escape fraction of hydrogen ionizing photons in star forming galaxies at the bright end of luminosity function at $z \sim 3$ is found to be low and in contrast with expectations based on the observed properties of reionizing background, it has been often suggested that the escape fraction may increase with decreasing luminosity of galaxies. In this paper we have studied this hypothesis by analysing the escape fraction of relatively faint galaxies. We combined the deep ultraviolet observations of the Ultra Deep Field with deep spectroscopic MUSE observations of the same field in order to compile a sample of $0.02 \lesssim L/L_{\text{UV}}^* \lesssim 10$ galaxies at $z > 3$ with photometric observations of their $\lambda < 912$Å part of the spectrum. None of the 165 galaxies in our sample shows a significant Lyman continuum emission (Section 3 and Appendix A).

Limiting our analysis to the brighter half of the sample ($L \gtrsim 0.1L_{\text{UV}}^*$) we use stacking analysis to provide deep upper limits on the relative escape fraction down to $M_{\text{UV}} \sim -19$ mag (Section 3.3). Stacking is performed for several subsamples of galaxies lying at different redshift and brightness intervals. We do not detect any significant LyC signal in any of the stacked images but provide 1σ upper limits of $f_{\text{esc,rel}} < 0.07, 0.2$ and 0.6 at $L \sim L_{\text{UV}}^*, 0.5L_{\text{UV}}^*$ and $0.1L_{\text{UV}}^*$, respectively.

Our measurements allow us to constrain the $f_{\text{esc}}(M_{\text{UV}})$ relation for star forming galaxies. Under the assumption that AGNs and star forming galaxies are the only sources of reionizing background, and using various prescriptions for $f_{\text{esc}}(M_{\text{UV}})$, we estimate the relative contribution of AGNs and star forming galaxies to the photon volume emissivity and photoionization rate and compare the values to those determined by observations (Section 4.2). We find that the bright part of the galaxy luminosity function (e.g. $M_{\text{UV}} < -20$ mag), given the low upper limit constraints, provides a negligible amount of reionizing photons, irrespective of the shape of the $f_{\text{esc}}(M_{\text{UV}})$ relation in the faint part. We also show that measurements like ours can provide means to better understand the general properties of star forming regions (Section 4.3). For example, comparing our upper limits with predictions from physical models (Duncan & Conselice 2015), we show that density-bounded nebulae with $A_V > 0.3$ are disfavoured. Deeper escape fraction constraints down to $M_{\text{UV}} \sim -18$ mag are therefore required to better understand both the $f_{\text{esc}}(M_{\text{UV}})$ relation as well as star forming regions at high redshifts.

For a more quantitative analysis we need more stringent constraints on the fainter part of the luminosity function, which could be achieved by repeating our analysis using a larger sample of faint galaxies. With deeper MUSE observations on this field, to become available in the future, it will be possible to greatly expand the number of spectroscopically confirmed faint Lyα emitters. Moreover, expanding the UVUDF field to cover larger area coinciding with wider, but shallower, MUSE coverage of the UDF field (i.e. GTO program ID 095.A-0240(A), PI: L. Wisotzki) will be essential to better constrain the escape fraction dependency on the luminosity. Alternatively, the low-luminosity regime can be more effectively probed by taking advantage of the gravitational lensing amplification effect by massive galaxy clusters with multi-band HST coverage, such as the programs CLASH, Hubble Frontier Fields and RELICS 5. In any case, understanding the role of star forming galaxies in the process of reionization at high redshifts will require a joint effort of direct searches for Lyman continuum leakers and improving our detailed knowledge of star forming regions and their evolution with redshift.

ACKNOWLEDGEMENTS

We thank the anonymous referee for a helpful report which improved this manuscript. We acknowledge financial contribution from the grant PRIN-MIUR 2012 201278X4FL 002 The Intergalactic Medium as a probe of the growth of cosmic structures. We acknowledge financial contribution from the grant PRIN-INAF 2014 1.05.01.94.02.

REFERENCES

Amorín R., et al., 2014, ApJ, 788, L4

Bacon R., et al., 2010, in Ground-based and Airborne Instrumentation for Astronomy III. p. 775508, doi:10.1117/12.856027

Becker G. D., Bolton J. S., 2013, MNRAS, 436, 1023

Beckwith S. V. W., et al., 2006, AJ, 132, 1729

Behrens C., Dijkstra M., Niemeyer J. C., 2014, A&A, 563, A77

Bergvall N., Zackrisson E., Andersson B.-G., Arnberg D., Masegosa J., Östlin G., 2006, A&A, 448, 513

Bertin E., Arnouts S., 1996, A&AS, 117, 393

Borthakur S., Heckman T. M., Leitherer C., Overzier R. A., 2014, Science, 346, 216

Bouwens R. J., et al., 2012, ApJ, 752, L5

Bouwens R. J., et al., 2014, ApJ, 793, 115

Bouwens R. J., et al., 2015, ApJ, 803, 34

Bouwens R. J., Smit R., Labbé I., Franx M., Caruana J., Oesch P., Stefanon M., Raspagnuolo, 2016, ApJ, 831, 176

Bridge C. R., et al., 2010, ApJ, 720, 465

Bruzual G., Charlot S., 2003, MNRAS, 344, 1000

Calverley A. P., Becker G. D., Haehnelt M. G., Bolton J. S., 2011, MNRAS, 412, 2543

Caminha G. B., et al., 2016, preprint, (arXiv:1607.03462)

Cen R., Kimm T., 2015, ApJ, 801, L25

Ciardi B., Bolton J. S., Maselli A., Graziani L., 2012, MNRAS, 423, 558

Coe D., Benitez N., Sánchez S. F., Lee M., Bouwens R., Ford H., 2006, AJ, 132, 926

Cowie L. L., Barger A. J., Trouille L., 2009, ApJ, 692, 1476

5 https://archive.stsci.edu/prepds/relics/
The SED reveals a slight -band excess indicating strong radiation transfer. For z ≈ 3.045, approximately half of the convolved transmission through the F336W filter results in an average age, decreasing IGM transmission (see Fig. 1). For example, at the redshift of this galaxy (z = 3.45), the convolved IGM transmission with the F275W filter increases in average transmission of < T > ≈ 0.045, approximately half of the convolved transmission through the F336W filter. The SED reveals a slight K-band excess indicating strong radiation transfer.
calculations in the H II regions and showed that a peak separation of $< 300 \text{ km s}^{-1}$ is favoured in the case of galaxies with escaping LyC radiation. The value for GC2 is therefore much higher than predicted for the case of escaping LyC. We note that for a few galaxies among the confirmed LyC leakers the peak separations of a double-peaked Lyα line were actually significantly higher than the predicted limit of 300 km s$^{-1}$ (de Barros et al. 2016; Verhamme et al. 2016), even though not as large as in our present case. The rest-frame Lyα equivalent width (EW) is estimated to be $\text{EW} \approx 40 \AA$.

The optical image of the galaxy shows a structured morphology with a bright compact source and a faint tail. The UV emission comes exclusively from the fuzzy part of the object. This feature, together with detection in all three UV bands, may indicate that we are dealing with a low-redshift interloper. The MUSE spectrum is rather noisy and we cannot confidently identify any absorption lines that would correspond to an interloper. We also do not detect any emission lines (other than Lyα) in the spectrum. This indicates that there may be no interlopers at $z < 1.5$, though the nondetection could also be simply due to the faintness of the interloper. Indeed, unless the interlopers have very strong emission lines, their faint nature presents a great challenge for current telescopes (e.g. Vanzella et al. 2012). Observations in the optical and near-infrared with the future generation of extremely large telescopes will be necessary to provide consensus for many ambiguous sources found in this and previous studies.

Assuming that the faint tail is indeed another galaxy, we determine its brightness in the rest-frame UV band by modelling the GC2 source in the HST ACS/F775W image with two galaxy components using GALFIT (Peng et al. 2010) and following the same procedure described in Vanzella et al. (2015). The two, bright and faint, components are reasonably well modelled (as illustrated by the residual image in Figure A1). The bright component is found to be compact and marginally resolved (with an effective radius $\lesssim 200$ pc). The faint component, which is of the main interest here, is well reproduced with a two-dimensional nearly Gaussian shape with a total magnitude of $i_{775} = 27.1 \pm 0.1$ mag. On the other hand, the brightness in the F336W image is measured to be $27.5 \pm 0.2$ mag. Using these two measurements and Equation 1 it follows that $f_{\text{esc,rel}} > 1$ for practically any physically-plausible IGM LOS. As pointed out by Vanzella et al. (2012), the relative escape fraction from a particular part of the galaxy cannot be larger than 1. A value of $f_{\text{esc,rel}} > 1$ is therefore a strong argument in favour of contamination. Furthermore, the fuzzy part is also detected in the F275W: repeating the analysis for this band would result in an even larger values of $f_{\text{esc,rel}}$.

Based on the presented analysis we conclude that the GC2 source is contaminated. This case points to the importance of the high-resolution imaging in such studies, as already shown by previous works (Vanzella et al. 2010; Siana et al. 2015; Mostardi et al. 2015): the source would be classified as a Lyman continuum emitter if only the seeing-limited VIMOS-U image were available to us.

This paper has been typeset from a TeX/LaTeX file prepared by the author.