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Probing ionizing radiation of $L \lesssim 0.1L^*$ star-forming galaxies at $z \gtrsim 3$ with strong lensing

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ABSTRACT

We show the effectiveness of strong lensing in the characterization of Lyman continuum emission from faint $L \lesssim 0.1L^*$ star-forming galaxies at redshift $\gtrsim$3. Past observations of $L \gtrsim L^*$ galaxies at redshift $\gtrsim$3 have provided upper limits of the average escape fraction of ionizing radiation of $f_{\rm esc} \sim 5$ per cent. Galaxies with relatively high $f_{\rm esc}$ (>10 per cent) seem to be particularly rare at these luminosities; there is therefore the need to explore fainter limits. Before the advent of giant ground-based telescopes, one viable way to probe $f_{\rm esc}$ down to 0.05–0.15L^* was to exploit strong lensing magnification. This is investigated with Monte Carlo simulations that take into account the current observational capabilities. Adopting a lensing cross-section of 10 arcmin^2 within which the magnification is higher than 1 (achievable with about four to five galaxy clusters), with a U-band survey depth of 30 (30.5) (AB, 1σ), it is possible to constrain $f_{\rm esc}$ for $z \simeq 3$ star-forming galaxies down to 15 (10) per cent at 3σ for $L < 0.15L^*$ luminosities. This is particularly interesting if $f_{\rm esc}$ increases at fainter luminosities, as predicted from various H I reionization scenarios and radiation transfer modelling. Ongoing observational programmes on galaxy clusters are discussed and positive prospects for the future are offered, even though from space the *Hubble Space Telescope* (*HST*)/Wide Field Camera 3 (WFC3) instrument represents the only option we have to investigate details of the spatial distribution of the Lyman continuum emission arising from $z \sim$ 2–4 galaxies.

Key words: gravitational lensing: strong – galaxies: distances and redshifts – galaxies: high-redshift.

1 INTRODUCTION

Recent works suggest that at $z > 3$ star-forming galaxies are the leading candidates for the production of ionizing photons (e.g. Haardt & Madau 2011; Ciardi et al. 2012; Kuhlen & Faucher-Giguère 2012). However, the mechanisms regulating the escape fraction of ionizing radiation ($f_{\rm esc}$) from galaxies are still unknown. In particular, it is not clear whether $f_{\rm esc}$ evolves with cosmic time or whether it is luminosity-dependent at fixed redshift. The complexity in modelling of galaxy evolution and the inclusion of radiative transfer prescriptions make the predictions on $f_{\rm esc}$ very uncertain, and opposite results are often obtained from simulations. Moreover, the predictions on $f_{\rm esc}$ show a large variation from galaxy to galaxy, between 0.01 and nearly 1, as a result of differences in the hydrogen distribution (e.g. Gnedin, Kravtsov & Chen 2008; Fernandez & Shull 2011; Yajima, Choi & Nagamine 2011, and references therein). From an observational point of view, the current situation is also far from clear. Various observations have provided significant upper limits on Lyman continuum (LyC) emission in the redshift range 1–4, i.e. $f_{\rm esc}$ smaller than 5–10 per cent (Vanzella et al. 2012, hereafter V12, and references therein). In particular, Vanzella et al.

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(2010b, hereafter V10b) and Boutsia et al. (2011) reported upper limits on $f_{\rm esc}$ of 5 per cent for $L \gtrsim L^{*}$ LBGs at redshift of 3–4. Very few galaxies with possible LyC detection have been reported in the literature (Shapley et al. 2006; Iwata et al. 2009; Nestor et al. 2011). The fact that bright sources with high $f_{\rm esc}$ (>10 per cent) are rare could support the interpretation that $f_{\rm esc}$ increases at lower luminosities. Indeed, recent radiative transfer calculations coupled with cosmological simulations show that low-luminosity and dwarf galaxies have high $f_{\rm esc}$ (>20–40 per cent) and are the major contributors to the ionizing background at redshift $3 < z < 6$ (e.g. Wise & Cen 2009; Razoumov & Sommer-Larsen 2010; Fernandez & Shull 2011; Yajima et al. 2011; but see Gnedin et al. 2008, for different results). The investigation of faint (and/or low-mass) star-forming galaxies at moderate redshift ($z \sim 3$–4) is therefore crucial to probe the ionization regimes and conditions that would be in place during the reionization epoch ($z > 7$). It is worth noting that the reionization at $z = 7$–10 requires an average $f_{\rm esc}$ much higher than what is observed for relatively bright and lower redshift galaxies ($z < 4$) (Bouwens et al. 2010; Robertson et al. 2010; Fernandez & Shull 2011).

While the direct measurements of escaping LyC photons are prohibitive during the epoch of reionization, they are still accessible at $z \lesssim 4$. The investigation of sub-L^{*} galaxies requires extremely deep U-band surveys ($U > 30$). However, even if they were available, spectroscopic redshift measurements for $L \ll L^{*}$ galaxies (e.g. r band > 27) would be very challenging with current facilities. In this respect, before the advent of the ELT and JWST telescopes, strong lensing magnification offered a viable way to explore faint limits in luminosity (and mass).

2 THE $f_{\rm esc}$ AND STRONG LENSING

The *relative* fraction of escaping LyC photons (at $\lambda < 912$ Å) relative to the fraction of escaping non-ionizing ultraviolet (1500 Å) photons is defined as (Steidel, Pettini & Adelberger 2001)

$$f_{\rm esc,rel} \equiv \frac{(L_{1500}/L_{\rm LyC})_{\rm int}}{\left(\frac{\mu\, F_{1500}}{\mu\, F_{\rm LyC}}\right)_{\rm obs}} \exp\left(\tau_{\rm LyC}^{\rm IGM}\right), \qquad (1)$$

where $(F_{1500}/F_{\rm LyC})_{\rm obs}$, $(L_{1500}/L_{\rm LyC})_{\rm int}$ and $\tau_{\rm LyC}^{\rm IGM}$ represent the observed 1500 Å/LyC flux density ratio, the intrinsic 1500 Å/LyC luminosity density ratio and the line-of-sight opacity of the intergalactic medium (IGM) for LyC photons, respectively. It is worth noting that the two quantities $(F_{1500})_{\rm obs}$ and $(F_{\rm LyC})_{\rm obs}$ are measured in the same spatial (i.e. physical) region, where the ionizing and non-ionizing radiations arise (V12). If the dust attenuation A_{1500} is known, $f_{\rm esc,rel}$ can be converted to the absolute $f_{\rm esc}$ as $f_{\rm esc} = 10^{-0.4A_{1500}} f_{\rm esc,rel}$ (e.g. Siana et al. 2007). The term μ is the magnification factor provided by a lens (e.g. a cluster of galaxies) and applies to both flux densities observed at two wavelengths (we leave the parameter explicitly in the expression). We assume for simplicity that it does not vary substantially within the isophote of the sources. Therefore, given the achromatic nature of lensing, $f_{\rm esc}$ is independent from μ. The two quantities $f_{\rm esc}$ and $f_{\rm esc,rel}$ are equal if $A_{1500} = 0$. Conservatively, in the following we perform calculations assuming $A_{1500} = 0$; the limits probed on $f_{\rm esc}$ are deeper if $A_{1500} > 0$, e.g. they are halved if $A_{1500} = 0.6$ (V10b). If not specified, we assume an intrinsic luminosity density ratio $(L_{1500}/L_{\rm LyC})_{\rm int} = 7$ (Siana et al. 2007; V10b). In Section 3.2, the IGM transmission of Inoue et al. (2011) is convolved with the adopted U-band filter. We perform calculations for three U-band filters: *F336W*, *u*-band Strömgren (*U-strom*) and U-special available at the Large Binocular Telescope (*LBC-U*) (in general the results do not change if other filters with similar widths and wavelength coverages are considered). It is clear from equation (1) that high magnitude contrasts between LyC and the 1500 Å rest frame provide strong constraints on $f_{\rm esc}$. We can rearrange equation (1) to give an estimate of the expected magnified flux at wavelengths smaller than the Lyman limit as a function of $f_{\rm esc}$ and magnification factor μ (i.e. $F_{\rm LyC}^{\rm Lens} = \mu F_{\rm LyC}$):

$$F_{\rm LyC}^{\rm Lens} = \left(\frac{L\lambda_{\rm rest}}{L_{1500}}\right)_{\rm int} \frac{f_{\rm esc} \times (F_{1500} \times \mu)_{\rm obs}}{{\rm e}^{\tau_{\lambda}^{\rm IGM}}} \times 10^{0.4 \times A1500}. \qquad (2)$$

As discussed in Inoue & Iwata (2008) and V10b, the stochastic nature of the IGM absorption introduces large uncertainties in the estimate of $f_{\rm esc}$ for a single line of sight. Stacking many galaxies among different lines of sight provides strong limits and reduces the variance due to IGM attenuation. Indeed, a deep U-band survey can provide firm constraints for $L \gtrsim L^{*}$ galaxies down to few per cent of $f_{\rm esc}$ by stacking tens of objects. This has been performed by V10b with deep Very Large Telescope/VIMOS U-band imaging ($\approx$30*AB* at 1σ) of $z \gtrsim 3.4$ LBGs (see also Boutsia et al. 2011).

For $L \ll L^{*}$ galaxies the situation becomes challenging. One reason is that the knowledge of the redshift is necessary to fix the observed wavelength position of the Lyman limit. Even though a deep U-band survey (e.g. mag-$U \simeq 30$ at 1σ) can still probe $f_{\rm esc}$ down to 20 per cent by stacking about thirty $0.1L^{*}$ galaxies, the redshift confirmation is not practicable with current facilities, or it is feasible only for a subclass of sources like the Lyα emitters. The lensing magnification greatly facilitates the redshift measurement also for faint galaxies. Additionally, it allows the investigation of $f_{\rm esc}$ down to stronger limits by U-band stacking and/or individual LyC detections. In the following we perform Monte Carlo (MC) simulations to derive predictions for $f_{\rm esc}$ as a function of the U-band depth, lensing magnification and lensing cross-section. In what follows, we adopt r and R to indicate the r-band magnitude (∼1500 Å rest frame) for non-magnified and magnified sources, respectively.

3 MAGNIFIED GALAXIES: MC SIMULATIONS

We now want to estimate the feasibility of probing $f_{\rm esc}$ down to <20 per cent for $L \lesssim 0.1L^{*}$ LBGs. To this aim, from equation (2) it is possible to calculate as a function of $f_{\rm esc}$ and U-band depth the number of sources detectable in the LyC above a certain threshold and the signal-to-noise ratio (S/N) in their LyC stack. We therefore perform MC simulations similar to those described in V10b by assuming reasonable distributions for the quantities involved in equation (2).

3.1 The expected number of magnified LBGs

The probability that a source galaxy is magnified by more than μ can be expressed in terms of the probability density $P(\mu)$: $P(>\mu) = \int_{\mu}^{\infty} P(\mu){\rm d}\mu$, where $P(\mu) = -{\rm d}P(>\mu)/{\rm d}\mu$. An interesting property of the lensing probability in the source plane is that $P(>\mu) \propto \mu^{-2}$ and therefore $P(\mu) \propto \mu^{-3}$ for $\mu \gg 1$, as can be shown in particular cases and argued to be true in general (see fig. 9 of Lima, Jain & Devlin 2010; Schneider, Ehlers & Falco 1992). A maximum magnification ($\mu_{\rm max}$) is imposed by the size of the source galaxies that we assume to have an intrinsic half-light radius not smaller than 0.2 kpc (assuming circular shape), i.e. $\mu_{\rm max} = 400$.

Each galaxy cluster produces a region within which the magnification in the source plane is larger than $\mu_{\rm min}$. This area is an effective cross-section for lensing statistics. For our purposes, it is enough to perform a simple calculation for the cross-section $\sigma_{\rm lens}$:

$$\sigma_{\rm lens} \simeq \frac{1}{\mu^2_{\rm min}} \sum_{i=1}^{N_{\rm clust}} \pi\theta^2_{{\rm E},i} \quad ({\rm arcmin}^2), \tag{3}$$

where $\theta_{{\rm E},i}$ is the Einstein radius of a given cluster. Lenses with the largest $\theta_{\rm E}$ are the best 'cosmic telescopes'; in particular, we consider in our simulations the case with $\sigma_{\rm lens} = 10\,{\rm arcmin}^2$ and $\mu_{\rm min} = 1$, corresponding approximately to four to five massive galaxy clusters (see Section 4), and the results can be linearly rescaled to other areas.

Adopting the $z \sim 3$ luminosity function (LF) parameters of Reddy & Steidel (2009) ($\alpha = -1.73$, $M^*_{AB} = -20.97$ and $\phi* = 1.71 \times 10^{-3}\,{\rm Mpc}^{-3}$), we can calculate the expected number of star-forming galaxies within the chosen area and redshift interval dz. A further important constraint is that the magnification must produce an apparent magnitude R brighter than the spectroscopic limit for redshift measurements ($R < m_{\rm spec}$) necessary to fix exactly the wavelength position of the Lyman limit. We adopt $m_{\rm spec} = 26$ that corresponds to a relatively deep spectroscopic survey (e.g. Vanzella et al. 2009). Together with the limit on μ (<400) defined above, the chosen $m_{\rm spec}$ implies a limit on the integration of the LF, i.e. $r = 32.5$ (i.e. sources with $r > 32.5$ would require $\mu > 400$ to have $R < 26$). It turns out that within an area $\sigma_{\rm lens} = 10\,{\rm arcmin}^2$ and redshift interval 3.0–3.5, ~2300 LBGs are expected in the magnitude range $26.5 < r < 32.5$, 30 of which have $R < m_{\rm spec} = 26$ (we refer to this sample as $N_{\rm spec} = 30$). Clearly, the intrinsically faint galaxies are the rarer cases accessible from ground-based spectroscopy, the galaxies being sources that need large magnification μ. We anticipate here that the constraints we discuss below on $f_{\rm esc}$ are mainly dictated by sources belonging to the magnitude bin $26.5 < r < 28$ (i.e. $L = 0.05$–$0.16L^*$, on average 24 of the 30 galaxies).

3.2 MC simulations of $L \lesssim 0.1L^*$ LBGs

We run MC simulations on the area $\sigma_{\rm lens} = 10\,{\rm arcmin}^2$ by varying for each galaxy the parameters involved in equation (2) and derive the ionized flux $F^{\rm Lens}_{\rm LyC}$ as a function of $f_{\rm esc}$. The flux is then compared with the depth of the U-band survey under study. The procedure is described in detail in V10b. Briefly, a redshift is randomly extracted from the interval dz (uniformly) and associated with a galaxy with a given r magnitude extracted randomly from the magnitude range 26.5–32.5 (accordingly with the magnitude distribution provided by the LF). The intergalactic transmission $T^{\rm IGM}_{\rm LyC} = {\rm e}^{-\tau^{\rm IGM}_{\lambda}}$ has been derived from thousands of random realizations at the extracted redshift value and convolved with the adopted U-band filter. The lower limit $z_{\rm min}$ of the redshift range dz is dictated by the adopted filter shape that probes LyC at $z > 3$, 3.2 and 3.3 for the three filters *F336W*, *U-strom* and *LBC-U*, respectively. The ideal upper limit would be $z_{\rm min} + 0.1$ such that the closest region bluewards of the Lyman limit is probed. However, we relax to $z_{\rm min} + 0.5$ by allowing more sources to be included (in order to reach $N_{\rm spec} \simeq 30$ in the three cases). The IGM prescription adopted here includes all the intervening absorption systems and modulates properly the $F^{\rm Lens}_{\rm LyC}$ signal for increasing redshift. This is also supported by the recent direct detection of LyC at $\lambda_{\rm rest} < 830$ Å (V10b).

The magnification factor (μ) is associated with each galaxy by extracting it randomly from the distribution $P(\mu) \sim \mu^{-3}$, as explained earlier in the text (we assume that galaxies are distributed uniformly over the sky). The $f_{\rm esc}$ is explored in two different regimes of variability: (1) it is fixed to a constant value for all $N_{\rm spec}$ sources spanning the range 0.01–1.00, with steps of 0.01 (i.e. the average $\langle f_{\rm esc}\rangle = f_{\rm esc}$ of each galaxy) and (2) it is fixed to values 0 or 1, assigned randomly such that 80 per cent of the $N_{\rm spec}$ sample have $f_{\rm esc} = 0$ and 1 for the remaining sources, i.e. $\langle f_{\rm esc}\rangle = 0.2$ with large variance (the 'on/off case').

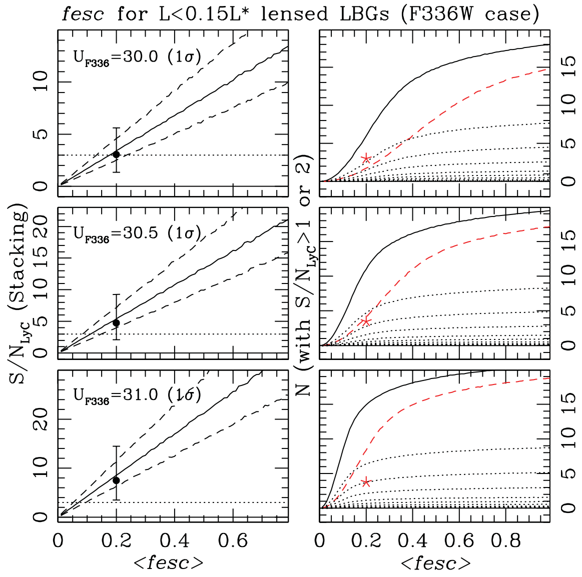

Figure 1. MC simulations for magnified LBGs at $3 < z < 3.5$ with intrinsic $L < 0.14L^*$ ($r > 26.5$) and adopting a lensing cross-section of $10\,{\rm arcmin}^2$ (see text for details). Top, middle and bottom panels show the results of our MC simulations for U-band depths of 29, 30 and 31 (1σ), respectively. Left-hand panels: the expected S/N in the LyC of the stacked fluxes (median and central 68 per cent interval, solid and dashed lines, respectively). Filled circles are the S/N (median and central 68 per cent interval) in the 'on/off case' with 20 per cent of the galaxies with $f_{\rm esc} = 1$ and 80 per cent with $f_{\rm esc} = 0$. Horizontal dotted lines mark S/N = 3. Right-hand panels: number of direct detections in the LyC at S/N > 1 (black solid line) and S/N > 2 (red dashed line). The dotted black lines report the number of galaxies in the faint magnitude bins from which they migrate to brighter apparent magnitudes ($R < 26$). The black solid line is the sum of the dotted lines. From top to bottom, the dotted lines refer to the magnitude bins $26.5 < r < 27.0$, $27.0 < r < 27.5$, etc. The red stars mark the expected number of direct detections at S/N > 2 in the 'on/off case'.

In summary, the sample of galaxies derived from the LF in the considered volume (area of $10\,{\rm arcmin}^2$ and d$z = 0.5$) and magnitude interval $26.5 < r < 32.5$ has been extracted 10 000 times by varying $f_{\rm esc}$, ${\rm e}^{-\tau^{\rm IGM}_{\lambda}}$, $(L_{1500}/L_{\rm LyC})_{\rm int}$, $(F_{1500})_{\rm obs}$ and μ (no dust has been considered). Fig. 1 shows the results for the *F336W* case. The resulting median S/N of the stacked LyC fluxes of the galaxies with $R < 26$ is shown as a function of $f_{\rm esc}$ and U-band depth (left-hand panels). The signal-to-noise ratio ${\rm S/N}^{\rm stack}_{\rm LyC}$ is calculated as $[\sum_{i=1}^{N_{\rm spec}} F^{i,{\rm Lens}}_{\rm LyC}/N_{\rm spec}]/[1\sigma_U/\sqrt{N_{\rm spec}}]$, where $1\sigma_U$ is the depth of the U-band survey and $N_{\rm spec} \simeq 30$, i.e. the number of surviving LBGs with $R < 26$. The number of direct LyC detections above the 2σ limit ($F^{\rm Lens}_{\rm LyC} > 2\sigma_U$) is also reported in the same Fig. 1 (right-hand panels). While the median ${\rm S/N}^{\rm stack}_{\rm LyC}$ of the two $f_{\rm esc}$ distributions, constant and 'on/off', are compatible if $\langle f_{\rm esc}\rangle = 0.2$ (as expected from the ${\rm S/N}^{\rm stack}_{\rm LyC}$ calculation), the variance is larger in the 'on/off' case. Also, the number of direct detections are different between the two, because by definition we fix a maximum fraction of detectable sources. It turns out that with a U-band depth $\gtrsim 30\,(1\sigma)$, the S/N of the stacking is >1(3) for $f_{\rm esc} > 0.05(0.18)$. The average number of individual detections (>2σ) is >3 for $f_{\rm esc} > 0.10(0.30)$ if the U-band depth is 31(30). These detections are originated from the magnification of sources with $r > 26.5$ that migrate from their

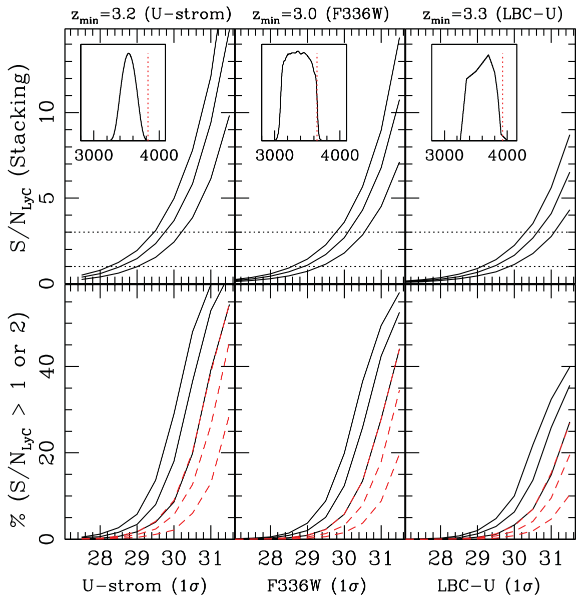

Figure 2. S/N in the LyC of the stacking (top panels) and the fraction (per cent) of LyC detections with S/N higher than 1 and 2 (bottom panels) are shown as a function of the *U*-band depth. Three different *U*-band filters have been used. In the three cases, $\sigma_{\rm lens} = 10\,{\rm arcmin}^2$ and $N_{\rm spec} \simeq 30$. In all panels the three curves have been calculated for $f_{\rm esc} = 0.2$, 0.15 and 0.10 from top to bottom, respectively. Horizontal dotted lines mark the one and 3σ levels. In the bottom panels solid and dashed lines refer to S/N > 1 and S/N > 2, respectively. The insets in the top panels show the adopted filter, with the dotted vertical line marking the position of the Lyman limit at the $z_{\rm min}$.

original magnitude bins to the brighter lensed regime ($R < 26$). The contribution of each bin to the $N_{\rm spec}$ sample is shown as dotted lines in Fig. 1. As a consistency check, and as expected, their number per magnitude bin flattens if the faint end slope of the LF is $\alpha = -3$ (i.e. the growth of the number counts and the dimming of the lensing cross-section compensate each other). The flattening of the number of direct detections as $f_{\rm esc}$ increases (in the fixed $f_{\rm esc}$ case, Fig. 1) is due to IGM attenuation, i.e. the interception of Lyman limit systems (LLSs) or damped Lyα systems (DLAs) along the line of sight suppresses the ionizing flux even for high $f_{\rm esc}$ values.

Fig. 2 shows the same quantities as a function of the *U*-band depth by fixing $f_{\rm esc}$ to 10, 15 and 20 per cent for all sources. It has been performed for three filters: *F336W*, *U-strom* and *LBC-U*. Clearly, the deeper *U*-band surveys give the best constraints to the faint galaxies; in particular, those with mag-$U > 30$ are the more effective and increase rapidly as the mag-$U = 31$ limit is approached. The intermediate band filter like the *U-strom* is an optimal solution. It is worth noting that observing a massive cluster with $\theta_{\rm E} \simeq 1$ arcmin (such us MACS 0717.5+3745, see below), we expect ∼10 galaxies with $R < 26$ and $r > 26.5$. If all of them have $f_{\rm esc} = 15$ per cent, then with a *U*-band (*U-strom*-like) depth of 30.5 we expect to detect three of them at S/N > 1 and S/N$_{\rm LyC} \simeq 3.0$ for the stacking. Therefore, we expect to observe signal already with a single deep pointing (of ∼60 h) with a 8–10 m class telescope.

4 THE CURRENT OBSERVATIONS

As mentioned above, the interception of LLSs or DLAs makes IGM attenuation quite stochastic and severe for ionizing radiation at $z \gtrsim 3$; therefore, the observations of magnified galaxies along different lines of sight are necessary to attenuate its effect. Assuming these absorbers are associated with individual structures with physical size of $\lesssim$50 kpc (e.g. Yajima, Choi & Nagamine 2012), different lines of sight separated by more than ∼10 arcsec will have a relatively small transverse correlation among high column density absorbers, even along a single cluster.

Currently, there are in the literature several massive clusters of galaxies characterized by relatively large lensing cross-sections, e.g. $\theta_{\rm E} \sim 0.7$–0.9 arcmin, like MACS 0717.5+3745 (Zitrin et al. 2009), 1E 0657−56 (‘bullet cluster’; Bradac et al. 2009) and A1689 (Broadhurst et al. 2005). Zitrin et al. (2012) recently measured the Einstein radius of 10 000 galaxy clusters from the Sloan Digital Sky Survey. In particular, they identified ≃40 candidates with $\theta_{\rm E} >$ 0.7 arcmin. The largest Einstein radius was $\theta_{\rm E} \simeq 1.1$ arcmin for the most massive cluster (for a source at $z_{\rm s} = 2$). The MAssive Cluster Survey (MACS) also provides a statistically complete sample of very X-ray luminous distant clusters of galaxies ($0.3 < z < 0.7$; Ebeling et al. 2010). Therefore, given the existing observations, the area of $\sigma_{\rm lens} = 10\,{\rm arcmin}^2$ considered in this Letter can be easily achieved with five clusters.

It is worth mentioning the ongoing Cluster Lensing And Supernova survey with Hubble (CLASH), a multitreasury programme that, in addition to other available ground-based observations, is observing (524 *HST* orbits) 25 X-ray selected massive galaxy clusters with new *HST* panchromatic imaging capabilities (16 filters): the ACS and both the ultraviolet and infrared channels of the WFC3. While 20 clusters were chosen to be X-ray selected, relatively relaxed clusters with no lensing-selection bias, the five additional clusters were chosen to be high-magnification clusters with $\theta_{\rm E} > 0.6$ arcmin (Postman et al. 2012). Even though the survey was not designed to provide deep limits on LyC for faint galaxies, the homogeneous panchromatic photometry on a statistically significant sample of massive clusters, together with magnification maps and high S/N spectroscopy on a number of highly magnified galaxies at $z \gtrsim 3$, will yield a very valuable test bed for probing LyC emission at the faint end of the galaxy LF.

5 CONCLUSIONS

We have explored the possibilities offered by gravitational lensing in constraining the ionizing emission from faint galaxies at $z > 3$, which has a great impact on studies of the reionization even at significantly higher redshifts ($z > 6$). We have shown that with current ground-based facilities and the magnification provided by known clusters of galaxies, it is possible to constrain the $f_{\rm esc}$ quantity down to 10–15 per cent for faint luminosities ($L \lesssim 0.1L^*$). In particular, strong lensing provides the opportunity to make a significant step forward in this field in the pre-ELT era. (1) The magnification allows us to measure redshifts for very faint galaxies, i.e. to fix the wavelength position of the Lyman limit and put strong constraints on the LyC with *U*-band imaging for galaxies down to $L \sim 0.05$–$0.1L^*$. (2) The magnification allows us to perform accurate spatial analysis of the LyC emission (if detected), down to hundreds of parsecs. If, on the one hand, the magnified area increases the probability of intercepting a foreground lower-z source that might mimic LyC emission (Vanzella et al. 2010a), on the other hand the possible presence of multiple images of the same background source will help solve the problem, since a real LyC detection will be present in all the counterparts (if μ are similar). The transverse separation of the light paths decreases rapidly as the source redshift is approached. Therefore, the IGM attenuation is practically the same for all the multiple images. (3) It has been suggested that the $f_{\rm esc}$

increases with decreasing luminosity (e.g. Yajima et al. 2011) and that the ionizing background is mainly produced by a large number of sub-L^* galaxies. A nice feature of the present approach is to put a limit to the process of attributing the ionizing contribution to lower and lower luminosities with the increasing observational depth of null results. This in fact would imply a steepening of the faint end of the LF that in principle can be excluded by the increasing number of highly magnified sources expected to be detected through lensing.

We have shown that deep U-band observations (as in V10b) of five massive galaxy clusters provide a sample of intrinsically faint ($L \lesssim 0.1L^*$) and magnified $z \sim 3$ galaxies (about 30) useful to investigate $f_{\rm esc}$ down to 10–20 per cent. An increasing number of well-studied clusters for this study, with multiband *HST* photometry, spectroscopy and lens modelling, are becoming available as part of the CLASH project.

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