On the relative Contribution of high-redshift Galaxies and Active Galactic Nuclei to Reionization.

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ABSTRACT

In this paper we discuss the contribution of different astrophysical sources to the ionization of neutral hydrogen at different redshifts. We critically revise the arguments in favor/against a substantial contribution of Active Galactic Nuclei (AGNs) and/or Lyman Break Galaxies (LBGs) to the reionization of the Universe at $z > 5$. We consider extrapolations of the high-$z$ QSO and LBG luminosity functions and their redshift evolution as well as indirect constraints on the space density of lower luminosity Active Galactic Nuclei based on the galaxy stellar mass function. Since the hypothesis of a reionization due to LBGs alone requires a significant contribution of faint dwarf galaxies and a LyC photon escape fraction ($f_{\text{esc}}$) of the order of $\sim 20\%$, in tension with present observational constraints, we examine under which hypothesis AGNs and LBGs may provide a combined relevant contribution to the reionization. We show that a relatively steep faint-end of the AGN luminosity function, consistent with present constraints, provides a relevant (although sub-dominant) contribution, thus allowing us to recover the required ionizing photon rates with $f_{\text{esc}} \sim 5\%$ up to $z \sim 7$. At higher redshifts, we test the case for a luminosity-dependent $f_{\text{esc}}$ scenario and we conclude that, if the observed LBGs are indeed characterized by very low $f_{\text{esc}}$, values of the order of $f_{\text{esc}} \sim 70\%$ are needed for objects below our detection threshold, for this galaxy population to provide a substantial contribution to reionization. Clearly, the study of the properties of faint sources (both AGNs and LBGs) is crucial.

Key words: cosmology: observation - early Universe - quasars: general - galaxies: active - galaxies: evolution

1 INTRODUCTION

Cosmic reionization is a major focus in present Cosmology, since it represents a crucial cosmic epoch for the formation of the first structures and the production of the photons responsible for the end of the Dark post-recombination Ages. Moreover, these energetic photons affect, in a critical interplay, the species available for gas cooling (and consequently the star formation) and the collapse of (small) dark matter halos.

An important constraint on the epoch when this phase transition occurs is set by the measurement of the Thomson optical depth of the intergalactic medium (IGM) via the large scale polarization of the Cosmic Microwave Background (CMB, Komatsu et al. 2011), which provides - with the rough assumption of instantaneous reionization - $z_{\text{reion}} = 10.6 \pm 1.2$. Additional evidence comes from the Gunn-Peterson test applied at the Lyman-$\alpha$ forest, characterized by a low neutral hydrogen fraction at redshifts below 6 (Fan et al. 2006, but see also McGreer et al. 2011). Recent evidence for a damping wing around the systemic redshift of a $z=7.085$ quasar (Bolton et al. 2011) and for a sudden decrease in the fraction of Lyman-$\alpha$ emitters among $z \sim 7$ Lyman-break galaxies (LBGs, see e.g., Pentericci et al. 2011, Schenker et al. 2012, Ono et al. 2012) also suggests a rapid increase of the neutral fraction of hydrogen in the Universe at these epochs. All these evidences broadly constrain the epoch of hydrogen reionization in the redshift range $6 < z < 12$.

At the same time, many studies have addressed the nature of the ionizing sources. Pop III stars (e.g., Ciardi et al. 2000), star-forming galaxies (e.g., Robertson et al. 2010), and Active Galactic Nuclei (AGNs, e.g., Haiman & Loeb 1998) have found to be prime candidates, with more exotic possibilities explored in the form of primordial black-holes and mini-quasars (e.g., Madau et al. 2004), and decaying particles (dark matter and neutrinos, e.g., Scott et al. 1991, Pierpaoli 2004). It is commonplace that by $z \sim 6$ the ionizing radiation emitted by quasars alone is insufficient to reionize the IGM (e.g., Schirber & Bullock 2003, Cowie et al. 2009); on the other hand high-redshift galaxies are in principle able to produce the bulk of the cosmic emissivity ionizing the IGM (see...
The structure of this paper is as follows: in sec. 2 we discuss the implication of our finding and in sec. 3 we present our conclusions. Throughout this paper we assume that QSOs represent the luminous sub-population of the homogeneous AGN population, and that Lyman Break Galaxies are a good tracer of the overall galactic population.
between SMBH mass and the spheroidal host component mass, and on the AGN fraction/duty cycle (see e.g. Shankar 2009; Fiore et al. 2012 and discussion herein). The bright-end of the AGN-LF is steeper than any QSO-LF, while its faint-end is steeper than both the Fiore et al. (2012) and Fontanot et al. (2009) estimates, but still in the range allowed by the Shankar & Mathur (2007) analysis.

In order to compute the QSO contribution to reionization, we compute the rate of emitted ionizing photons per unit comoving volume $\Gamma_{\text{AGN}}$ as a function of redshift, following the same formalism as in Shankar & Mathur (2007) see also Madda et al. (1999):

$$\Gamma_{\text{AGN}}(z) = \int_{V_H}^{V_\text{up}} \frac{\rho_c(z)}{h_p} dL$$

The above equations, $L_{\nu}$ is in erg s$^{-1}$ Hz$^{-1}$, $h_p$ represents the Planck’s constant, $\nu_H = 3.2 \times 10^{15}$ Hz is the frequency at the Lyman limit (i.e. 912 Å); $\nu_{up}$ is $12.8 \times 10^{15}$ Hz is the usual upper limit to the integration, since photons more energetic are preferentially absorbed by He atoms. In practice, we assume that the absorbing cross section gives us a good grasp of the maximum contribution of QSO to the reionization background. We also assume that all the ionizing photons associated with the AGN spectra contribute to the ionizing background (i.e. $f_{\text{esc}} = 1$). In the calculations, we assume a QSO spectral continuum of the form $f_{\nu} = \nu^p$ and we assume a slope $\gamma = -1.76$ blueward of the Ly$\alpha$ line (Telfer et al. 2002). In the following, we will compare $\Gamma_{\text{AGN}}$ with the required total ionizing photon rate per unit comoving volume $\Gamma_{\text{ion}}$, using the formalism proposed in Madda et al. (1999), rescaled to WMAP7 cosmology as in Pawlik et al. (2009):

$$\Gamma_{\text{ion}}(z) = 0.027 \kappa \left( \frac{C}{30} \right)^3 \left( \frac{1+z}{7} \right)^3 \left( \Omega_{\text{C}} \right)^{3/2}$$

where we convert the critical star formation rate into a photon rate, by assuming that $\kappa = 10^{23.1}$ s$^{-1}$ LyC photons per M$_{\odot}$ yr$^{-1}$ are produced (see e.g. Shull et al. 2013, see also eq. 3 below) and $C$ is the clumping factor of the ionizing hydrogen medium. Early work (see e.g. Madda et al. 1999, Shankar & Mathur 2007) assumed a high value $C = 30$ for the clumping factor, following the results of numerical simulations by Gnedin & Ostriker (1997), and concluding that the space density of ionizing photons deducted by observations was in most cases insufficient to reionize the Universe and/or keep it ionized. More recent theoretical estimates (see e.g. Bolton & Haehnelt 2007, Pawlik et al. 2009, Haardt & Madda 2012) revised the value of the clumping factor towards lower values. In particular, Pawlik et al. (2009) estimates $C = 6$ as adequate for gas with densities of the order of the critical density of the onset of star formation, while finding an even lower $C = 3$ value for gas with overdensities $\sim 100$. It is also worth stressing that $C$ is expected to be a decreasing function of redshift. For example Haardt & Madda (2012) propose the following fitting formula:

$$C(z) = 1 + 43 \times z^{-1.71}$$

derived for gas with overdensities $\sim 100$. Eq. 4 is fully consistent with the Pawlik et al. (2009) estimate on the same overdensity scale. Lower values for the clumping factor reduce considerably the number of ionizing photons required to keep the Universe ionized at $z > 6$, mitigating the requests on the observed astrophys-
2.2 High-z LBGs Luminosity Functions

In order to estimate the number of ionizing photons produced by the galaxy population, we consider the high-z luminosity function of Lyman Break Galaxies (LBGs hereafter) as estimated by Bouwens et al. (2011). Following these authors we describe the LBG-LF in the redshift range 3.5 \( \lesssim z \lesssim 8 \) as an evolving Schechter function (i.e. whose parameters are evolving with cosmic time, see table 1 in Bouwens et al 2011). We then compute the luminosity density \( \rho_{UV} \) using eq. 2 and we convert it to an estimate of the star formation rate density \( \rho_{SFR} \) using the Haardt & Madau (2012) conversion factor:

\[
\rho_{SFR}(z)[M_{\odot}yr^{-1}Mpc^{-3}] = \frac{\rho_{UV}(z)[erg s^{-1}Hz^{-1}Mpc^{-3}]}{1.05 \times 10^{28}}
\]

(5)

Major uncertainties affect the conversion between UV luminosity density and the \( \rho_{SFR} \). First of all, UV observations are severely affected by dust attenuation. Bouwens et al. (2007) estimated that \( z > 4 \) LBGs suffer lower attenuation levels that lower-z counterparts, and they suggest that the \( \rho_{SFR} \) obtained from eq. 5 may be underestimated by a factor \( \sim 1.5 \). Moreover, the conversion factor itself critically depends on the details of the Stellar Population Synthesis modeling; in particular the chosen Initial Stellar Mass Function play a relevant role, by determining the relative abundance of massive stars, the main contributors to UV fluxes. The value we use in eq. 5 has been computed assuming a Salpeter IMF. If we consider, i.e. a Kroupa IMF, its value is reduced by a factor \( \sim 1.5 \).

In the following, we take into account all these sources of uncertainties by assuming eq. 5 as a good representation of the mean conversion and by defining a “maximal” and a “minimal” model by increasing and decreasing the resulting \( \rho_{SFR} \) by a factor 1.5, respectively. We then estimate the rate of ionizing photon production using the conversion factor proposed for a low-metallicity gas by Shull et al. (2012; see also Madau et al. 1999):

\[
\Gamma_{\text{LBG}}(z)[s^{-1}Mpc^{-3}] = \kappa f_{\text{esc}} \rho_{SFR}(z)
\]

(6)

where \( f_{\text{esc}} \) represents the escape fraction\(^2\), i.e. the fraction of produced ionizing photons which are able to escape the local environment and ionize the intergalactic medium. This parameter has a key importance in order to evaluate the contribution of LBGs to the ionizing background, but its very poor constrained. At \( z \sim 3 - 4 \), proposed values range from low \( (f_{\text{esc}} < 5\%) \), Vanzella et al. (2010b), to relatively high values \( (f_{\text{esc}} \gtrsim 20\%) \), Shankle et al. (2009).

3 DISCUSSION

3.1 The AGN contribution to the ionizing background

First of all we consider the AGN contribution to the ionizing background. At variance with previous analyses we don’t fix \( L_{\text{min}} \) in eq. 2 but we study how the ratio \( \Gamma_{\text{AGN}}/\Gamma_{\text{ion}} \) evolves as a function of redshift and limiting magnitude. We also compute the AGN contribution to the reionization by applying the same approach to our GSMF-derived AGN-LF (sec. 2.1), and include these results in Fig. 2 (red lines and red hatched area). Following the same (a) to (f) prescriptions described in sec. 2.1 we estimate that the putative AGN luminosity associated to a Jeans Mass of pristine gas is roughly \( M_{\text{UV}} \sim 10 \). The formation of the ancestors of SMBHs at very high redshifts has been discussed by a number of authors (see e.g. Petri et al. 2012 and references therein), showing that both heavy (> \( 10^5 M_{\odot} \)) and light SMBHs seeds are physically plausible at the same scales accessible for gas cooling and star formation.

We further assume that all ionizing photons associated with the AGN spectra are available for ionizing the IGM and we show our results in Fig. 2.

We find that the QSO contribution at the current observational limit \( (M_{\text{UV}} \sim -20.6) \), is not negligible at \( z \sim 6 \), but still insufficient to provide the required rate of ionizing photons. The difference with respect to analogous works in the literature (e.g. Shankar & Mathur 2007), is to be ascribed to the lower clumpiness adopted here.

At higher redshift the contribution of AGNs to the ionizing background decreases rapidly, becoming of the order of a few percent at \( z \sim 8 \) and negligible thereafter. To obtain a relevant AGN contribution (i.e. \( > 10\% \)) at these redshifts a steep faint end is re-
We confirm the result of Pawlik et al. (2009) that the LBG contribution to the ionizing background according to this analysis.

3.2 The LBG contribution to the ionizing background

In Fig. 3 we present the estimated contribution of LBGs to cosmic reionization for different $f_{esc}$ values. Also for this class of sources we integrate the contribution of sources down to $M_{UV} \sim -10$. We directly compare these results with the contribution from the AGN-LF, and in particular with the results of Fiore et al. (2012, grey shaded area). We integrate the contribution of LBGs for epochs. Yellow, blue and green lines and hatched regions refer to the integrated contribution of LBGs for different $f_{esc}$ values. It is apparent that high $f_{esc}$ values for fainter LBGs.

Despite the lack of constraints on the distribution of $f_{esc}$ in different galaxy population, this exercise allows us to provide a qualitative estimate for the typical magnitude of objects responsible for the bulk of reionization and their expected escape fractions, if $f_{esc}$ is indeed a decreasing function of luminosity. This simple toy model predicts that complete reionization at $z = 8$ by LBGs alone is achieved at typical magnitudes $M_{UV} \sim -13.5, -15, -15.5$ for $f_{esc} = 0.1, 0.2, 0.3$ respectively. The predicted corresponding escape fractions are $f_{esc} = 50, 60, 80\%$. A similar result is obtained at $z = 9$ (typical magnitudes $M_{UV} \sim -12.5, -14, -15$ and $f_{esc} \sim 55, 75, 90\%$), this results are compatible with the recent hydrodynamical simulations (see e.g. Ciardi et al. 2011), which require very high $f_{esc}$ values for fainter LBGs. It is also worth noting that, in general, lower $f_{esc}$ values are still compatible with an LBG-driven reionization if a redshift increasing efficiency of ionizing photons production and/or a top-heavy IMF are assumed (see e.g. Schneider et al. 2002).

3.3 Combined AGN-LBG contribution to ionizing background

Fig 4 shows the combined AGN+LBG contribution to the reionization of the Universe. For the sake of simplicity we only consider the maximum AGN contribution as estimated on the basis of the AGN-LF of Fiore et al. (2012, marked as a solid line in each panel): this is at the same time a conservative but representative choice among the various LF estimates that we consider in sec. 2.1. From a comparison with the results shown in Fig. 4 it is apparent that AGNs may significantly help reducing the gap between the LBG ionizing photon production rate and the required amount of ionizing photons up to $z \sim 7$. For a given $f_{esc}$ the minimum luminosity of the galaxies required to match the theoretically estimated ionization limit is significantly increased. Nonetheless, at the highest redshift considered, it is still not possible to reach the expected space density of ionizing photons for reionization if $f_{esc} \sim 5\%$. Again, in order to reionize the Universe with LBGs and AGNs combined at such high redshifts, either $f_{esc}$ has to be higher than the current estimates (at least for the faint LBG population, which is assumed to provide the largest contribution), and/or the evolution of the LF has to slow down with respect to the present estimates. In Fig. 5 we then show the $\Gamma_{AGN}/\Gamma_{LBG}$ ratio as a function of $M_{UV}$ and redshift. For the AGN population we consider as representative the observed LBGs may account for the total required ionizing photon budget at $z \sim 6$ if $f_{esc} \sim 20\%$; at higher redshifts, we have to integrate the LBG-LF to increasingly fainter limiting magnitudes (up to $M_{UV} \sim -10$ at $z \sim 9$), in order to produce enough ionizing photon to fully account for cosmic reionization. However, if $f_{esc} \sim 5\%$ for the whole LBG population, the LBG contribution is not enough to account for the whole required ionizing photon rate at $z \sim 7$, even if we extrapolate the LBG-LF up to the fainter magnitudes, and it becomes roughly compatible with that of AGNs for $z \sim 7$. In order to achieve high-$z$ reionization with LBGs only, a substantial contribution to the ionizing background of sources fainter than the actual observational limit is required and/or a very different (i.e. increasing) $f_{esc}$ with respect to their bright counterparts.

In order to test this hypothesis we impose a simple luminosity-dependent $f_{esc}$ scenario to our maximal model by defining $f_{esc} = 0$ for $M_{UV} < -18.00$ and a linearly increasing $f_{esc}$ with increasing magnitude:

$$f_{esc} = \min[1, \eta \times (M_{UV} + 18.00)]$$

Figure 5. Reionization Sources 5

We have also imposed that our analysis be consistent with present constraints on the HeII reionization (see e.g. Furlanetto & Oh 2008), i.e. areas of the parameter space predicted by Santini et al. (2012) and an integration to very low luminosity limits, under the hypothesis that very faint AGNs are characterized by the same properties of their bright counterparts. Another possibility is that the evolution of the low-luminosity AGN population becomes slower with respect to the $3 < z < 5$ estimates.

We briefly mention that, in general, faint AGNs may significantly help reducing the gap between the LBG ionizing photon production rate and the required amount of ionizing photons up to $z \sim 7$. For a given $f_{esc}$ the minimum luminosity of the galaxies required to match the theoretically estimated ionization limit is significantly increased. Nonetheless, at the highest redshift considered, it is still not possible to reach the expected space density of ionizing photons for reionization if $f_{esc} \sim 5\%$. Again, in order to reionize the Universe with LBGs and AGNs combined at such high redshifts, either $f_{esc}$ has to be higher than the current estimates (at least for the faint LBG population, which is assumed to provide the largest contribution), and/or the evolution of the LF has to slow down with respect to the present estimates. In Fig. 5 we then show the $\Gamma_{AGN}/\Gamma_{LBG}$ ratio as a function of $M_{UV}$ and redshift. For the AGN population we consider as representative the observed LBGs may account for the total required ionizing photon budget at $z \sim 6$ if $f_{esc} \sim 20\%$; at higher redshifts, we have to integrate the LBG-LF to increasingly fainter limiting magnitudes (up to $M_{UV} \sim -10$ at $z \sim 9$), in order to produce enough ionizing photon to fully account for cosmic reionization. However, if $f_{esc} \sim 5\%$ for the whole LBG population, the LBG contribution is not enough to account for the whole required ionizing photon rate at $z \sim 7$, even if we extrapolate the LBG-LF up to the fainter magnitudes, and it becomes roughly compatible with that of AGNs for $z \sim 7$. In order to achieve high-$z$ reionization with LBGs only, a substantial contribution to the ionizing background of sources fainter than the actual observational limit is required and/or a very different (i.e. increasing) $f_{esc}$ with respect to their bright counterparts.

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Figure 4. Combined LBG and AGN contributions to reionization. Colours and lines as in Fig. 3. In each panel we consider the maximal AGN contribution from the high-z AGN-LF from Fiore et al. (2012, marked by the solid line in each panel, see text for more details).

Figure 5. Logarithmic ratio between the AGN and LBG contributions to the reionization. As a reference for AGNs, the Fiore et al. (2012) AGN-LF has been considered. Colours and lines as in Fig. 3. The red filled triangle marks the position of our measurement at $3.4 < z < 4$.0 carried out in the GOODS fields (see text for more details).

Figure 6. Distribution of U-band fluxes (probing the rest-frame LyC) for 67 LBGs (upper panel) and 7 AGNs (lower panel) in the GOODS South field (selected with $3.4 < z < 4.0$ and $23.4 < i_i < 26$). Fluxes have been measured in both cases within an aperture of 1.2" diameter. The red dashed Gaussian distributions show the expected distribution of null detections normalized to the total number of measurements in each panel. For comparison, the dot-dashed blue histogram shows the expected distribution of fluxes for galaxies with an $f_{esc} = 10\%$ (the IGM absorption being simulated as in Vanzella et al. 2010b). The vertical dashed line marks the $3\sigma$ confidence limit.

An interesting reference point can be obtained by studying the LBGs and AGNs in the GOODS South field, selected in equal redshift and magnitude intervals, $3.4 < z < 4.0$ and $23.5 < i_i < 26$. Following the procedure described in Vanzella et al. (2010b), we have measured the flux of 67 LBGs and 7 AGN in the U-band (probing the rest-frame LyC) using a circular aperture of 1.2" diameter. As shown in Fig. 6, one galaxy (dubbed Ion1 in Vanzella et al. (2012)) and two AGNs are detected above the $3\sigma$ confidence level. The average flux from AGN turns out to be $(0.041 \pm 0.08) \times 10^{-30}$ erg$^{-1}$ cm$^{-2}$ Hz$^{-1}$. In order to compute the corresponding quantity for galaxies we have considered that the distribution of their UV fluxes is characterized by 66 non-detections and one outlier. We have therefore assumed as an average UV flux of galaxies the flux of the outlier divided by 66 (we would obtain a similar value by averaging over the whole distribution) and as $1\sigma$ confidence levels those computed by Gehrels (1986) for small numbers of events (in this case one), obtaining $(0.0024^{+0.0053}_{-0.0020}) \times 10^{-30}$ erg$^{-1}$ cm$^{-2}$ Hz$^{-1}$. The statistics are poor but allow us to roughly estimate a ratio between the AGN and LBG contribution to the UV ionizing background (shown in Fig. 5 with a red triangle) of $17^{+105}_{-13}$. This value is conveniently independent of the IGM transmission and is

Fiore et al. (2012) LF, while for the LBG population we show results for $f_{esc} = 1\%, 5\%$ and $20\%$. From Fig. 5 it is clear that $\Gamma_{AGN}$ is decreasing at increasing redshifts at a faster pace relative to $\Gamma_{LBG}$ independently on $f_{esc}$. The latter contribution becomes dominant for faint sources at $z > 5$ for $f_{esc} \gtrsim 5\%$.

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consistent with the $\lesssim 5\%$ estimate of the $f_{\text{esc}}$ from galaxies discussed in Vanzella et al. (2010).

It is worth noting that a similar measurement and result has been obtained at lower redshift by Cowie et al. (2009). These authors study the ionizing fluxes associated with the AGN and galaxy populations at $z \sim 1.15$ in the GOODS-North field by means of observations with the Galaxy Evolution Explorer (GALEX). Their results show the presence of a detectable signal corresponding to known AGNs/QSOs, while stacking analysis of galaxy images provides no evidence for a significant ionizing flux (compatible with $f_{\text{esc}} \gtrsim 1\%$).

4 CONCLUSIONS

We have critically discussed in view of recent results the contribution to cosmic reionization at $z > 5$ of both high-z QSOs (Fontanot et al. 2007; Shankar & Mathur 2007; Fiore et al. 2012) and LBGs (Bouwens et al. 2011). In order to take into account the contribution from AGN fainter than the current observational depths we have also used a derivation of the AGN LF based on the evolution of the galaxy stellar mass function (Santini et al. 2012).

In the following we assume $z \sim 7$ (e.g. Mitra et al. 2012) as the fiducial redshift for a rapid transition of the hydrogen from a significantly neutral condition to a neutral fraction $x_{\text{HI}} \ll 10^{-3}$.

Our results show that

(i) In order to achieve the HI reionization at $z \sim 7$ the properties of the AGN population have to be pushed to rather extreme values in terms of steepness of the faint end of the LF ($\alpha \gtrsim -2$) and contribution of very faint (up to $M_{UV} \sim -10$) objects. But in the case such conditions were met we would expect the reionization of HeII to take place, owing to the typical AGN SED, above redshift $z \sim 5$, which is in contrast with present observations (e.g. Fechner et al. 2009, 2011). In order to take into account the contribution from AGN fainter than the current observational depths we have also used a derivation of the AGN LF based on the evolution of the galaxy stellar mass function (Santini et al. 2012).

(ii) The LBG population may account for the whole photon budget needed for reionization, but only if the mean escape fraction of this population is of the order of $\sim 5\%$ of both high-z QSOs (Fontanot et al. 2007; Shankar & Mathur 2007; Fiore et al. 2012) and LBGs (Bouwens et al. 2011). AGN alone, at least in their standard manifestation, cannot be responsible for the reionization of HI. In the following we assume $z \sim 7$ (e.g. Mitra et al. 2012) as the fiducial redshift for a rapid transition of the hydrogen from a significantly neutral condition to a neutral fraction $x_{\text{HI}} \ll 10^{-3}$.

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(ii) The LBG population may account for the whole photon budget needed for reionization, but only if the mean escape fraction of this population is of the order of $\sim 5\%$ of both high-z QSOs (Fontanot et al. 2007; Shankar & Mathur 2007; Fiore et al. 2012) and LBGs (Bouwens et al. 2011). AGN alone, at least in their standard manifestation, cannot be responsible for the reionization of HI. In the following we assume $z \sim 7$ (e.g. Mitra et al. 2012) as the fiducial redshift for a rapid transition of the hydrogen from a significantly neutral condition to a neutral fraction $x_{\text{HI}} \ll 10^{-3}$.
responsible for reionization at $z < 7$. In this way, if the sources significant contribution to reionization at $z > 7$; LBGs show a milder density evolution for faint $M_{\text{lim}}$ values, steepening as $f_{\text{esc}}$ increases (and $M_{\text{lim}}$ brightens), the steepening being due to the redshift-dependent evolution of the LF shape (Bouwens et al. 2011).

In both cases our empirical models do not predict enough ionizing photons at $z > 7$, if we force them to obey the constraints on $\Gamma_{\text{BKG}}$ and $f_{\text{esc}}$ is kept constant. Also in this case, the most likely solution for an LBG-driven early reionization requires an increase of $f_{\text{esc}}$ either with decreasing luminosity (or with increasing redshift); this is clearly shown by the red line in fig. 7, which represents the contribution to the ionizing background in the luminosity-dependent $f_{\text{esc}}$ scenario (eq. 2, $\eta = 0.1$).

The exact relative contributions from AGNs and LBGs critically depends on the details of the slopes of the corresponding faint-end LFs, on the faintest luminosity limits of these populations and on $f_{\text{esc}}$. Given the present uncertainties in its determination, better constraints on the high-$z$ AGN-LF faint-end slope would be of fundamental importance to understand the maximal contribution of the AGN population to the ionizing background. In general, our analysis suggests that pushing the actual observational limits at least one magnitude fainter, despite very demanding from the observational side, would be quite rewarding to clearly understand the relative importance of different astrophysical sources in determining the ionization state of the early Universe.

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