GAMMA-RAY BURST HOST GALAXY SURVEYS AT REDSHIFT z ≥ 4: PROBES OF STAR FORMATION RATE AND COSMIC REIONIZATION

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Abstract
Measuring the star formation rate (SFR) at high redshift is crucial for understanding cosmic reionization and galaxy formation. Two common complementary approaches are Lyman break galaxy (LBG) surveys for large samples and gamma-ray burst (GRB) observations for sensitivity to SFR in small galaxies. The z ≥ 4 GRB-inferred SFR is higher than the LBG rate, but this difference is difficult to understand, as both methods rely on several modeling assumptions. Using a physically motivated galaxy luminosity function model, with star formation in dark matter halos with virial temperature $T_{\text{vir}} \gtrsim 2 \times 10^4$ K ($M_{\text{DM}} \gtrsim 2 \times 10^8 M_\odot$), we show that GRB- and LBG-derived SFRs are consistent if GRBs extend to faint galaxies ($M_{AB} \lesssim -11$). To test star formation below the detection limit $L_{\text{lim}} \sim 0.05 L_{\text{vir}}^* f_{\text{det}}$ of LBG surveys, we propose to measure the fraction $f_{\text{det}}(L > L_{\text{lim}}, z)$ of GRB hosts with $L > L_{\text{lim}}$. This fraction quantifies the missing star formation fraction in LBG surveys, constraining the mass-suppression scale for galaxy formation, with weak dependence on modeling assumptions. Because $f_{\text{det}}(L > L_{\text{lim}}, z)$ corresponds to the ratio of SFRs derived from LBG and GRB surveys, if these estimators are unbiased, measuring $f_{\text{det}}(L > L_{\text{lim}}, z)$ also constrains the redshift evolution of the GRB production rate per unit mass of star formation. Our analysis predicts significant success for GRB host detections at z ~ 5 with $f_{\text{det}}(L > L_{\text{lim}}, z) \sim 0.4$, but rarer detections at z > 6. By analyzing the upper limits on host galaxy luminosities of six z > 5 GRBs from literature data, we infer that galaxies with $M_{AB} > -15$ were present at z > 5 at 95% confidence, demonstrating the key role played by very faint galaxies during reionization.

Key words: galaxies: general – galaxies: high-redshift – gamma-ray burst: general – stars: formation

Online-only material: color figures

1. INTRODUCTION

The early stages of star formation at redshift z ≥ 4 are being probed by a growing number of observations. Lyman break galaxy (LBG) surveys are taking advantage of the Wide-Field Camera 3 (WFC3) on the Hubble Space Telescope (HST), pushing the frontier of galaxy detection to z ∼ 10 (Bouwens et al. 2011a; Oesch et al. 2012). There are now samples of several thousand galaxies at z ≤ 6 (Bouwens et al. 2007), and more than 100 galaxies at z ~ 7–8 (Bouwens et al. 2011b; Bunker et al. 2010; Finkelstein et al. 2010; Trenti et al. 2011, 2012). Narrowband observations discovered large samples of Lyα emitter (LAE) galaxies at z ~ 5–7 (Shimasaku et al. 2006; Ouchi et al. 2010; Ota et al. 2010). Large-area, ground-based surveys are detecting QSOs at z ~ 6–7 (Fan et al. 2006; Mortlock et al. 2011), shedding light on the formation of the first supermassive black holes. Gamma-ray burst (GRB) observations with SWIFT have detected the object with the highest spectroscopically robust redshift (z = 8.2; Tanvir et al. 2009; Salvaterra et al. 2009) and a photometric candidate at z ~ 9.4 (Cucchiara et al. 2011), providing an independent probe of the star formation rate (SFR) during the epoch of hydrogen reionization (Kistler et al. 2009; Virgili et al. 2011; Robertson & Ellis 2012). At the same time, numerical simulations and theoretical modeling are addressing the formation of stars and galaxies within the first billion years with increasingly successful predictions (Trenti et al. 2009, 2010; Lacey et al. 2011; Dijkstra & Wyithe 2012; Finlator et al. 2011; Jaacks et al. 2012).

Despite this progress, many open questions on early star formation remain. In fact, we do not know with confidence when ionization was completed or sources responsible for it. The Wilkinson Microwave Anisotropy Probe (WMAP) inferred epoch of cosmic reionization (z ~ 10.6 ± 1.2; Komatsu et al. 2011) is somewhat in tension with galaxy observations that suggest that reionization extended to lower redshift (z ~ 6–7), based on evolution of the LAE luminosity function (LF; Ouchi et al. 2010; Ota et al. 2010). In addition, the photon budget from observed galaxies at z ~ 6–10 falls short of that required to produce the optical depth to reionization measured by WMAP (Bolton & Haehnelt 2007; Shull & Venkatesan 2008; Trenti et al. 2010; Shull et al. 2012). A possible solution is that there is significant star formation in small galaxies with luminosity below $M_{AB} \sim -18$, the current limit for deep LBG surveys at z ≥ 6. The faint-end slope of the galaxy LF is very steep, $\phi(L) \propto (L/L^*)^\alpha \exp(-L/L_*)$ in the Schechter (1976) form, with $\alpha \sim -2$. Because observed LBGs live in massive dark matter halos ($M_{\text{DM}} \gtrsim 10^{10} M_\odot$), most of the z ≥ 6 star formation could take place in smaller halos that host dwarf-like galaxies, with luminosity in the range $-18 \lesssim M_{AB} \lesssim -10$. This corresponds to the limit of Lyα-cooling halos (virial temperature $T_{\text{vir}} \gtrsim 2 \times 10^4$ K and $M_{\text{DM}} \gtrsim 2 \times 10^8 M_\odot$), in broad agreement with theoretical modeling (Trenti et al. 2010).

The prediction that faint dwarfs are the main agents of reionization is difficult to test observationally. Even the James Webb Space Telescope (JWST) will be unable to reach the required sensitivity, as it will only improve the sensitivity by $\Delta M_{AB} \sim 2$ compared to HST/WFC3 (Gardner et al. 2006). In this respect, GRB observations offer an independent probe of the total SFR, unlimited by the faintness of the host galaxy and
well suited to investigate star formation during the epoch of reionization. Indeed, GRB rates suggest that the total SFR at \( z \gtrsim 5 \) is larger than that inferred from LBG observations and the difference arises because most of the star formation happens in small galaxies (Kistler et al. 2009; Robertson & Ellis 2012). Still, deriving the SFR from GRB observations is challenging, both because of the small number (19) of \( z > 4 \) GRB events with spectroscopically confirmed redshifts and because detailed modeling is required to translate the GRB rates into an SFR. In this respect, both selection and follow-up biases might be important. For example, GRBs with dusty sight lines will be under-represented (Robertson & Ellis 2012), and possibly GRBs with faint afterglows as well, depending on the inhomogeneous follow-up data available.

Following Kistler et al. (2009), the typical modeling assumes that the comoving GRB rate is related to the SFR by

\[
\dot{n}_{\text{GRB}}(z) = \varepsilon(z) \times \dot{\rho}_*(z),
\]

where \( \varepsilon(z) \) is the efficiency of GRB production per unit stellar mass, with a redshift dependence that can be used to model biases in the relation between \( \dot{\rho}_* \) and \( \dot{n}_{\text{GRB}} \) (e.g., Robertson & Ellis 2012). This quantity is often modeled as

\[
\varepsilon(z) = \varepsilon_0 (1 + z)^\beta,
\]

with \( \beta \approx -1.2 \) derived empirically at \( z < 4 \) and extrapolated to higher redshift to infer \( \dot{\rho}_*(z) \) (Virgili et al. 2011; Robertson & Ellis 2012).

To complement existing studies, we propose a novel idea for testing the relation between SFRs from GRB and LBG surveys and for investigating whether \( \beta \) remains constant at \( z > 4 \). We suggest measuring the fraction of GRB hosts detected from observations reaching the same magnitude limit as the typical LBG galaxy search. In Section 2, we show that this fraction quantifies the amount of star formation missed in LBG surveys, elucidating the minimum luminosity (and halo masses) of galaxies in the epoch of reionization. Measuring GRB-host detection efficiency at different redshifts also constrains \( \beta \).

In Section 3, we consider the prospects for carrying out our proposed measure and show a preliminary application of our method to recent HST observations by Tanvir et al. (2012). Section 4 summarizes our conclusions.

2. THE GRB-HOST DETECTION FRACTION AS PROBE OF STAR FORMATION

Both LBG and GRB surveys provide estimates of the SFR: from the observed galaxy light in the first case and from the observed GRB rate in the second. Both approaches rely on modeling assumptions, such as completeness estimates, dust extinction/obscuration, initial mass function (IMF), age, and metallicity of the stellar populations. Therefore, a discrepancy between the two estimates can either have a physical or a systematic origin. In Figure 1, we report the latest determination of the LBG–SFR from Bouwens et al. (2011b) and the GRB-inferred SFR from Kistler et al. (2009) and Robertson & Ellis (2012). The dust-corrected LBG SFR has been derived for galaxies with \( L > 0.05L_{*,z=3}^* (M_{\text{AB}} < -17.7) \), the approximate limit of the Bouwens et al. (2011b) observations. It is immediately clear that the GRB SFR is systematically above the LBG SFR. A
possible explanation for the difference is that there is significant star formation in galaxies with $M_{\text{AB}} > -17.7$ (Kistler et al. 2009). To illustrate this, we plot in Figure 1 the SFR inferred from the LF model of Trenti et al. (2010), calibrated on the $z = 6$ LF with the latest dust correction applied by Bouwens et al. (2011b). This model is based on relating the evolution of the galaxy LF to that of the dark matter halo mass function via a modified abundance matching and results in LBG LFs that the galaxy LF to that of the dark matter halo mass function via a modified abundance matching and results in LBG LFs that are close to a Schechter form and match the observation well (see Trenti et al. 2010). We show two model predictions with different assumptions on the luminosity below which galaxy formation is suppressed: $M_{\text{supp}} = -17.7$ (solid black line) and $M_{\text{supp}} = -11$ (dashed green line). The higher limit corresponds to the limit of the Bouwens et al. (2011b) observations, demonstrating that the model successfully reproduces the evolution of the LBG LF from $z = 5$ to $z = 10$ (the model assumptions are not appropriate for $z \lesssim 5$). The lower limit assumes that star formation proceeds in DM halos with smaller mass compared to that of the Hubble UltraDeep Field galaxies, down to the limit of Lyα cooling ($T_{\text{vir}} \sim 2 \times 10^4$ K). In most models of galaxy formation, these small halos are capable of cooling and forming stars, which are included in the GRB-derived SFR. The model prediction (Figure 1) is in agreement with the data within their uncertainty.

Another explanation for the difference in the observed SFRs is the possibility of systematic errors. For example, the redshift evolution of the GRB production efficiency $\varepsilon(z)$ may differ from the $(1 + z)^\beta$ derived from $z < 4$ data. To investigate which of the two hypotheses is correct, we introduce the idea of using the information contained in the fraction of GRB hosts detected at a given redshift.

To present our framework, we assume for simplicity that the stellar mass-to-light ratio does not depend on galaxy luminosity, and that the GRB rate is proportional to the SFR, with no bias depending on host galaxy luminosity. We assume that galaxy properties such as metallicity, dust content, and IMF do not depend on $L$ at a given redshift, but Equation (1) includes redshift evolution of these properties for the relation GRB rate and the SFR. This framework is equivalent to that of previous GRB studies such as Kistler et al. (2009). Recent studies of the nearby ($z < 1$) GRB sample suggest that these events may be biased toward lower-mass galaxies (Levesque et al. 2010a; Svensson et al. 2010), possibly a result of either the standard mass–metallicity relation for star-forming galaxies (e.g., Tremonti et al. 2004) or the fundamental metallicity relation (Mannucci et al. 2010). The physical phenomenon driving this apparent bias is not yet well understood (e.g., Levesque et al. 2010a, 2010b; Kocevski & West 2011; Niino et al. 2011). However, if the bias is related to a metallicity dependence, it should become less important at high redshift (Fynbo et al. 2008). These unknown factors that relate $\dot{\rho}_* \, L_{\text{GRB}}$ to the SFR are metallicity-dependent efficiency.

For LBG, we start by defining the integrated light above a given luminosity $L$ as

$$\mathcal{L}(L, z) = \int_L^{\infty} \tilde{\Phi}(L, z) d\tilde{L}.$$  \hspace{1cm} (3)

From this, the relation with the SFR follows as

$$\mathcal{L}(0, z) = \eta_{\text{LBG}}(z) \dot{\rho}_*(z),$$  \hspace{1cm} (4)

where $\eta_{\text{LBG}}(z)$ is the conversion factor from observed luminosity density to SFR (e.g., Madau et al. 1996). The SFR in galaxies with $L > L_{\text{lim}}$ is thus given as

$$\dot{\rho}_*(L > L_{\text{lim}}, z) = \frac{\mathcal{L}(L_{\text{lim}}, z)}{\eta_{\text{LBG}}(z)}.$$  \hspace{1cm} (5)

SFR estimators from GRBs (probing all sites of star formation) and LBGs (with observations at $L > L_{\text{lim}}$) can be derived assuming models for $\varepsilon(z)$ and $\eta_{\text{LBG}}(z)$. We indicate these estimates as $\dot{\rho}_*^{\text{GRB}}(z)$ and $\dot{\rho}_*^{\text{LBG}}(L > L_{\text{lim}}, z)$.

The detected fraction of GRBs with hosts of luminosities $L > L_{\text{lim}}$ at redshift $z$ is

$$f_{\text{det}}(L > L_{\text{lim}}, z) = \frac{\dot{\rho}_*(L > L_{\text{lim}}, z)}{\dot{\rho}_*(z)} \equiv \frac{\mathcal{L}(L_{\text{lim}}, z)}{\mathcal{L}(0, z)}.$$  \hspace{1cm} (6)

Assuming that $\dot{\rho}_*^{\text{GRB}}(z)$ and $\dot{\rho}_*^{\text{LBG}}(L > L_{\text{lim}}, z)$ are unbiased estimators, we can rewrite Equation (6) as

$$f_{\text{det}}(L > L_{\text{lim}}, z) = \frac{\dot{\rho}_*^{\text{LBG}}(L > L_{\text{lim}}, z)}{\dot{\rho}_*^{\text{GRB}}(z)}.$$  \hspace{1cm} (7)

The fraction $f_{\text{det}}(L > L_{\text{lim}}, z)$ allows us to measure the relative amount of star formation in galaxies below the detection threshold of the observations (Equation (6)). In fact, under the assumption that there is no luminosity dependence on the efficiency, GRBs are unbiased tracers of star formation at a given redshift. Furthermore, the fraction of detected hosts gives the relative amount of star formation present below $L_{\text{lim}}$, independent of the specific value of $\varepsilon(z)$ and $\eta_{\text{LBG}}(z)$. From $f_{\text{det}}(L > L_{\text{lim}}, z)$, it is therefore immediate to derive the integrated LF at $L < L_{\text{lim}}$.

To illustrate typical expected detection fractions of high-$z$ GRB hosts as a function of redshift and survey depth, we show in Figure 2 the predictions derived from our LF model, assuming $M_{\text{supp}} = -11$. Observations at the HUDF depth ($M_{\text{lim}} = -18$) are expected to detect 40%–50% of the GRB host halos at $z \lesssim 6$, but this fraction should decrease rapidly at high redshift. Although we resorted to a specific LF model to illustrate expected results, the relation in Equation (6) is not model-dependent. Hence, the observational determination of $f_{\text{det}}$ represents a powerful test to determine the amount of star formation below the sensitivity of LBG surveys.

With a model LF, it is also possible to go beyond the determination of the integrated LF at $L < L_{\text{lim}}$ and use $f_{\text{det}}$ to constrain the luminosity scale at which galaxy formation is suppressed and provide a test of galaxy formation theories and simulations. Figure 3 shows our model predictions for a shallow ($M_{\text{lim}} = -20$) and deep ($M_{\text{lim}} = -18$) survey as a function of $M_{\text{supp}}$. Ideally, one would search for GRB host galaxies at $z > 6$, where $f_{\text{det}}$ is most sensitive to changes in $M_{\text{supp}}$. However, by using the larger sample of known GRBs at $z \sim 4–6$, it is also possible to constrain $M_{\text{supp}}$ immediately after the epoch of reionization, as discussed in Section 3.

In addition, $f_{\text{det}}(L > L_{\text{lim}}, z)$ provides a consistency check of the model assumptions that led to the determination of $\dot{\rho}_*^{\text{LBG}}(L > L_{\text{lim}}, z)$ and $\dot{\rho}_*^{\text{GRB}}(z)$. The GRB efficiency $\varepsilon(z)$ is commonly described by Equation (2). Therefore, Equation (7) can be used to derive $\dot{\rho}_*$. For example, if $M_{\text{supp}} \equiv M_{\text{lim}} = -17.7$ at $z_1 = 4$ (as suggested by the fact that $\dot{\rho}_*^{\text{GRB}}(L > L_{\text{lim}}, z_1) \approx \dot{\rho}_*^{\text{GRB}}(z_1)$), and assuming that we have $M_{\text{supp}}(z_1) = M_{\text{supp}}(z_2)$.
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Figure 2. Predicted fraction of GRB host galaxy detections $f_{\text{det}}(L > L_{\text{lim}}, z)$, as a function of the limiting magnitude of the survey [$M_{\text{lim}} = -2.5 \log_{10}(L_{\text{lim}})$] for a model with star formation in galaxies with absolute AB magnitude $M < M_{\text{suppr}} = -11$. We predict a significant detection fraction for deep surveys with $M_{\text{lim}} \sim -18$ [$f_{\text{det}}(L > L_{\text{lim}}, z) \gtrsim 0.4$] at $z \lesssim 6$, and a decrease at higher redshift.

(A color version of this figure is available in the online journal.)

Figure 3. Predicted fraction of GRB host galaxy detections $f_{\text{det}}(L > L_{\text{lim}}, z)$, as a function of suppression magnitude $M_{\text{suppr}}$ for a shallow survey ($M_{\text{lim}} = -20$, left panel) and for a deep survey ($M_{\text{lim}} = -18$, right panel). Measuring $f_{\text{det}}$ allows one to determine $M_{\text{suppr}}$.

(A color version of this figure is available in the online journal.)

3. PREDICTIONS FOR HIGH-$z$ SEARCHES OF GRB HOST GALAXIES

So far, studies of GRB-host galaxies have been primarily limited to $z < 4$ and are based on heterogeneous observations. Adopting a compiled sample of 18 GRB hosts at $z < 1$ from
Christensen et al. (2004) and Levesque et al. (2010a), we find that nearby detected hosts have \( \langle M_B \rangle = -19.3 \). Similarly, Svensson et al. (2010) find that GRB hosts at \( z < 1.2 \) occur preferentially in small, relatively low-mass galaxies. Savaglio et al. (2009) compile a larger sample of 45 GRBs at \( z < 3.5 \), with \( \langle M_B \rangle = -20.3 \pm 0.5 \), again for detected hosts, as their catalog does not include GRBs for which only upper photometric limits are available.

A systematic search of host galaxies at low redshift would help to calibrate \( \varepsilon(z) \) and construct the basis for comparison with future detections of \( z > 4 \) hosts at rest-frame UV and optical wavelengths. The main problem currently is the limited sample size: there are only 19 GRBs spectroscopically confirmed at \( z > 4 \) and only three at \( z > 6 \). While this Letter was under review, upper limits on host galaxy luminosities for a sample of six \( z > 5 \) GRBs observed with HST have been derived by Tanvir et al. (2012). Still, a comprehensive effort to detect these high-\( z \) hosts is missing.

As proven by the Tanvir et al. (2012) sample, a systematic search is now feasible for host galaxies in all known \( z > 4 \) GRBs to a magnitude limit \( M_{AB} \sim -18 \). Using the Hubble Exposure Time Calculator, we estimate that 6000 s of integration time with WFC3 in \( F125W \) will reach a 2\( \sigma \) limit of \( m_{AB} = 28.5 \) within a diameter \( d = 0.5' \), corresponding to \( M_{AB} \sim -18.0 \), with a weak dependence on the GRB redshift. Compared to LBG surveys, a GRB-host survey has the key advantage that the position of the source is known a priori. Therefore, detections at a lower signal-to-noise ratio (S/N \( \sim 2-3 \)) are still statistically significant. Based on the surface density of sources in the Hubble Ultradeep Field Survey (Bouwens et al. 2011b), the chance of line-of-sight superposition with a foreground faint source is low. However, data in a second band blueward of the expected Lyman break would be useful to confirm that detected hosts are at the GRB redshift. Ground-based observations using 10 m class telescopes with sensitivity comparable to HST in the \( V \) and \( i \) bands provide a suitable alternative to search for \( z \lesssim 6 \) hosts and/or for deep observations in the second band (e.g., Basa et al. 2012).

From our galaxy LF model, we expect \( 0.4 \lesssim f_{\text{det}} \lesssim 1 \) at \( z \sim 5 \) depending on \( M_{\text{suppr}} \). Therefore, a GRB host survey would be expected to detect \( \gtrsim 8 \) host galaxies at \( 4 \lesssim z \lesssim 6 \). This will measure \( f_{\text{det}} \) to \( \sim 10\% \) accuracy, which will be sufficient to determine whether \( M_{\text{suppr}} \) is above or below \( M_{AB} = -15 \) to high confidence level. To illustrate that this is a feasible goal, we analyze in our framework the set of upper limits \( L_{\text{lim},i} \) (with \( i = 1, 6 \)) on host galaxy luminosity derived for the \( z > 5 \) GRBs sample in Table 2 of Tanvir et al. (2012). With those limits we construct the probability of null detection in their sample as a function of the \( M_{\text{suppr}} \) deriving \( f_{\text{det}} \) from our LF model (see Section 2):

\[
p_{\text{null}}(M_{\text{suppr}}|\{L_{\text{lim},i}, z_i\}) = \Pi_i[1 - f_{\text{det}}(L > L_{\text{lim},i}, z_i|M_{\text{suppr}})].
\]

The results are shown in Figure 4 and demonstrate that the absence of detected hosts constrains \( M_{\text{suppr}} > -15 \) at 95% confidence (and \( M_{\text{suppr}} > -16.5 \) at 99% confidence). This result is already a significant improvement upon the limits inferred from current LBG surveys alone (e.g., Muñoz & Loeb 2011). This technique also outperforms limits that can be obtained in future LBG surveys with JWST, which will reach \( M_{AB} \sim -16 \) (however, JWST will dramatically improve the efficiency of the search for GRB hosts). In the future, additional detections of

![Null detection probability from Tanvir et al. (2012) data](image-url)
GRBs at $z \sim 8$ would best distinguish between models with different suppression magnitudes, because $f_{\text{det}}(z = 8)$ is very sensitive to this quantity (see Figure 3).

4. CONCLUSIONS

In this Letter, we discuss the relation between SFR estimates from GRB and LBG surveys. The GRB-inferred rate is higher than that of LBGs at $z > 4$ (see Figure 1), suggesting that significant star formation takes place in galaxies below the LBG detection limit. The difference between the two approaches can be qualitatively explained by the model of galaxy formation based on the dark matter halo evolution developed by Trenti et al. (2010), under the assumption that star formation proceeds down to the limit of H I cooling ($T_{\text{vir}} \gtrsim 2 \times 10^4$ K or $M_{\text{DM}} \gtrsim 2 \times 10^8 M_\odot$). In this model, the assembly of galaxies is linked to the growth of their dark matter halos. By construction, our model is consistent with the buildup of stellar mass density, unaffected by the overproduction of stellar mass at $z = 4$ inferred from the GRB–SFR by Robertson & Ellis (2012).

In this respect, it is interesting that our SFR predictions in Figure 1 are systematically $\sim 1\sigma$ lower than the data points from GRB observations. Our findings suggest a mild systematic overestimation of the SFR derived from GRBs at $z > 4$, as concluded by Robertson & Ellis (2012) and by Choi & Nagamine (2012).

To gain further insight into the relation between the SFR estimates from GRB and LBG surveys, we introduced the idea that the fraction $f_{\text{det}}(L > L_{\text{lim}}, z)$ of detected GRB hosts in a survey with $L > L_{\text{lim}}$ provides an unbiased estimator of star formation. The relative amount of star formation in undetected faint galaxies (Equation (6)) can quantify the role played by galaxies during hydrogen ionization. Starting from $f_{\text{det}}(L > L_{\text{lim}}, z)$ and using an LF model, it is possible to determine the scale at which galaxy formation is suppressed at low masses. Furthermore, $f_{\text{det}}(L > L_{\text{lim}}, z)$ can be used to measure variations with redshift in the evolution of the GRB efficiency per unit stellar mass (Equations (1) and (8)), a key quantity to understand the production of GRBs across cosmic time.

Based on our specific galaxy formation model, we made predictions of the expected detection fraction of GRB hosts at high $z$ (Figures 2 and 3). We expect that $\sim 50\%$ of the GRB hosts could be detected at $z \sim 5$, followed by a sharp drop at higher redshift because of a steep faint-end slope of the galaxy LF. In general, the more that star formation is dominated by low-mass, low-luminosity halos, the smaller the detected host fraction. Our modeling is consistent with the non-detection of GRB hosts for the six highest-redshift GRBs known to date (Tanvir et al. 2012). The analysis of their limits in our framework allows us to constrain $M_{\suppr} > -15$ at 95% confidence (and $M_{\suppr} > -16.5$ at 99% confidence), demonstrating that the majority of ionizing photons at $z > 6$ were produced in small, low-luminosity galaxies. A systematic search for GRB hosts down to faint luminosity limits ($M_{\text{AB}} \sim -18$) for all known $z > 4$ GRBs would improve the limits on $M_{\suppr}$ and could provide the definitive proof that the faintest galaxies are the agents of hydrogen reionization.

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