Gamma-ray bursts from the early Universe: predictions for present-day and future instruments

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ABSTRACT
Long gamma-ray bursts (GRBs) are important for the study of the Universe near and beyond the epoch of reionization. In this paper, we describe the characteristics of an ‘ideal’ instrument that can be used to search for GRBs at \(z \geq 6-10\). We find that the detection of these objects requires soft-band detectors with high sensitivity and a moderately large field of view. In light of these results, we compare available and planned GRB missions, deriving conservative predictions of the number of high-redshift GRBs detectable by these instruments along with the maximum accessible redshift. We show that the Swift satellite will be able to detect various GRBs at \(z \geq 6\), and likely at \(z \geq 10\) if the trigger threshold is decreased by a factor of \(\sim 2\). Furthermore, we find that INTEGRAL and GLAST are not the best tools to detect bursts at \(z \geq 6\), the former being limited by the small field of view, and the latter by its hard energy band and relatively low sensitivity. Finally, future missions (SVOM, EDGE and, in particular, EXIST) will provide a good sample of GRBs at \(z \geq 6\) within a few years of operation.

Key words: stars: formation – cosmology: observations – gamma-rays: bursts.

1 INTRODUCTION
One of the main goals of available and future space missions is the study of the Universe at the epoch of reionization. In the last few years, our knowledge of the early Universe has enormously increased, mainly as a result of the observation of quasars by the Sloan Digital Sky Survey (SDSS; Fan 2006). Long gamma-ray bursts (GRBs) may constitute a complementary way to study the cosmos and the early evolution of stars, avoiding proximity effects and possibly probing even larger redshifts up to \(z \sim 10\). The five GRBs detected at \(z \geq 5\), over a sample of about 200 objects observed with the Swift satellite (Gehrels et al. 2004), show that a large percentage of GRBs are detected at high-\(z\), the highest currently being \(z = 6.29\) (Tagliaferri et al. 2005; Kawai et al. 2006). The identification of a large number of GRBs at \(z \geq 6\) will open a new window on the study of the early Universe. Just to give some examples, GRBs can be used to constrain the reionization history (Totani et al. 2006; Gallarani et al. 2007), to study the metallicity and dust content of normal galaxies at high-\(z\) (Campana et al. 2007b), and to probe the small-scale power spectrum of density fluctuations (Mesinger, Perna & Haiman 2005). Moreover, available and future GRB missions might be the first observatories to detect individual Population III stars, provided that massive metal-free stars are able to trigger GRBs (see Bromm & Loeb 2007 for a review). Finally, the study of GRBs at high redshift is interesting in itself. In particular, thanks to cosmological time dilation, the study of the early phases of the afterglow is easier and can provide fundamental highlights of the central engine and burst physics.

In this paper, we describe the main characteristics of an ‘ideal’ instrument that can be used to search for GRBs at \(z \geq 6-10\). In particular, we explore different observational bands, deriving the best combination of sensitivity and field of view (FOV) in order to detect bursts at \(z \geq 10\). In light of these results, we compare available and planned X-ray and gamma-ray missions, deriving conservative predictions on the number of high-\(z\) GRBs detectable by these instruments, along with the maximum accessible redshift.

The paper is organized as follows. In Section 2, we briefly describe the different models adopted here. In Section 3, we derive the main characteristics of an ‘ideal’ instrument for exploring the high-\(z\) GRB population, and predictions for available and planned GRB missions are given in Sections 4 and 5, respectively. Finally, we summarize our results in Section 6.

2 MODEL DESCRIPTION
Salvaterra & Chincarini (2007, hereafter SC07) have computed the luminosity function (LF) and the formation rate of long GRBs by fitting the observed Burst and Transient Source Experiment (BATSE) differential peak flux number counts in three different scenarios: (i) GRBs follow the cosmic star formation and have a redshift-independent LF; (ii) the GRB LF varies with redshift; (iii) GRBs are associated with star formation in low-metallicity environments.
We report here briefly the main equations used in the calculation. The observed photon flux, $P$, in the energy band $E_{\text{min}} < E < E_{\text{max}}$, emitted by an isotropically radiating source at redshift $z$ is

$$P = \frac{(1+z)^{\frac{(1+z)E_{\text{max}}}{4\pi d_L(z)}} S(E) dE}{4 \pi d_L(z)},$$

(1)

where $S(E)$ is the differential rest-frame photon luminosity of the source, and $d_L(z)$ is the luminosity distance. To describe the typical burst spectrum we adopt the functional form proposed by Band et al. (1993), i.e. a broken power law with a low-energy spectral index $\alpha$, a high-energy spectral index $\beta$, and a break energy $E_\text{b}$, with $\alpha = -1$ and $\beta = -2.25$ (Preece et al. 2000), and $E_b = 511$ keV (Porciani & Madau 2001). Moreover, it is customary to define an isotropic equivalent intrinsic burst luminosity in the energy band 30–2000 keV as $L = \int^{2000\text{keV}}_0 E S(E) dE$. Given a normalized GRB LF, $\phi(L)$, the observed rate of bursts with peak flux between $P_1$ and $P_2$ is

$$\frac{dN}{dt} (P_1 < P < P_2) = \int_0^{\infty} dL \frac{dV(z)}{dz} \frac{\Delta \Omega}{4 \pi} L \phi(L),$$

(2)

where $dV(z)/dz = 4 \pi c d_L(z)^2 /[v_H(z)(1+z)^2]$ is the comoving volume element, and $H(z) = H_0 [\Omega_M(1+z)^3 + \Omega_\Lambda + (1 - \Omega_M - \Omega_\Lambda)] (1+z)^{1/2}$, $\Delta \Omega$ is the solid angle covered on the sky by the survey, and the factor $(1+z)^{-1}$ accounts for cosmological time dilation. Finally, $\Psi_{\text{GRB}}(z)$ is the comoving burst formation rate. In this work, we assume that the GRB LF is described by

$$\phi(L) \propto \left( \frac{L}{L_{\text{cut}}} \right)^{-\delta} \exp \left( - \frac{L_{\text{cut}}}{L} \right).$$

(3)

SC07 found that it is possible in all cases to obtain a good fit to the data by adjusting the model free parameters, i.e. the GRB formation rate, the cut-off luminosity at $z = 0$, and the power index of the LF. Moreover, the models reproduce both BATSE and Swift differential counts without the need for any change in the free parameters, showing that the two satellites are observing the same GRB population. Finally, SC07 have tested the burst redshift distribution obtained in the different scenarios against the number of Swift detections at $z \geq 2.5$ and $z \geq 3.5$. This procedure allows the model results to be constrained without any assumption on the redshift distribution of bursts that have no redshift and on the effect of selection biases (see Fiore et al. 2007 for a detailed discussion of this important issue). Models in which GRBs trace the star formation rate (SFR) and are described by a constant LF are robustly ruled out by available data. Swift detections can be explained by assuming that the LF is evoking in redshift. In particular, SC07 have found that the typical GRB luminosity should increase with $(1+z)^{\delta}$ where $\delta > 1.4$. Alternatively, the large number of $z \geq 2.5$ identifications may indicate that GRBs are biased tracers of the star formation, forming preferentially in a low-metallicity environment. Assuming that the LF does not evolve in redshift, available data imply a metallicity threshold for GRB formation lower than $0.3 Z_{\odot}$ (SC07), consistent with the predictions of collapsar models (MacFadyen & Woosley 1999; Izzard, Ramirez-Ruiz & Tout 2004).

Here, we consider two models to compute the expected number of GRBs at $z \geq 6$–10 for different instruments. In the first case, we assume that GRBs form in proportion to the global SFR and that their typical luminosity evolves with redshift as $(1+z)^{1.4}$. We use here the recent determination of the SFR obtained by Hopkins & Beacom (2006), slightly modified to match the observed decline of the SFR with $(1+z)^{-1.3}$ at $z \geq 5$ suggested by recent deep-field data (Stark et al. 2007). This model predicts many GRBs at $z \geq 2.5$, but is barely consistent with the number of bright GRBs at $z \geq 3.5$ in the Swift 2-yr data sample (SC07). Moreover, this model falls below the lower limits of probability to find GRBs at $z \geq 5$ imposed by the five Swift confirmed detections. Because the small number of objects does not allow us definitely to rule out this model, we consider it a very conservative case and we adopt the predictions of this model as strong lower limits on the expected number of detections at $z \geq 6$–10.

Larger, but still conservative, numbers are derived by considering models in which GRBs form preferentially in low-metallicity environments. The GRB formation rate is obtained here by convolving the observed SFR with the expression obtained by Langer & Norman (2006), which gives the fraction of galaxies at redshift $z$ with metallicity below a threshold metallicity $Z_{\odot}$. We consider here $Z_{\odot} = 0.1 Z_{\odot}$ and no luminosity evolution, but similar results can be obtained for $Z_{\odot} = 0.3 Z_{\odot}$ and a linear redshift evolution of the GRB LF (Salvaterra et al. 2007). These models are also found to be consistent with the lower limit on the probability to detect GRBs at $z \geq 5$ (Salvaterra et al. 2007). We refer to this as our reference model.

We refer the interested reader to SC07 for any details of the model computation and results.

3 AN IDEAL EXPERIMENT FOR THE SEARCH FOR GRBS AT HIGH REDSHIFT

In this section, we explore the characteristics of an ‘ideal’ instrument that can be used for the detection of GRBs at very high-$z$ (i.e. $z \sim 6$–10). Given the formation efficiency and LF parameters obtained by fitting the BATSE differential peak flux distribution, we compute the fraction of the sky, $\Delta \Omega / 4 \pi$, that needs to be observed in order to detect one GRB per year at $z \geq 10$ as a function of the peak photon flux limit of the instrument. We also consider different observational bands. The results obtained for our reference model are shown in Fig. 1, where the solid line refers to the 15–150-keV band (as for Swift), the dotted line refers to the 50–300-keV band [BATSE and the Gamma-Ray Large Area Space Telescope (GLAST) Burst Monitor (GBM)], the short-dashed line refers to the 10–600-keV band [Energetic X-ray Imaging Survey Telescope (EXIST)] and the long-dashed line refers to the 8–200-keV band [Explorer of Diffuse Emission and Gamma-ray Burst Explosions (EDGE)]. It is clear that a hard observational band requires a very low flux limit in order to detect GRBs at $z \geq 10$, as for high-$z$ sources this type of instrument samples the steep, high-energy tail of the GRB spectrum. So, the search for bursts at very high redshift requires extremely sensitive detectors able to detect GRBs as faint as 0.01–0.05 photon s$^{-1}$ cm$^{-2}$. Note that we do not expect there to be any $z = 10$ GRBs in the BATSE catalogue.

Detectors with softer bands are more suited for detecting GRBs from the early Universe. Provided that the lower bound is as low as 10–15 keV, GRBs at $z \geq 10$ should trigger instruments with peak photon flux limits of 0.1–0.3 photon s$^{-1}$ cm$^{-2}$. We find that given a FOV, the sensitivity needed to observe GRBs at $z = 10$ decreases by increasing the low-energy bound of the instrument band, whereas the detection of high-$z$ bursts depends only slightly on the bandwidth. We note here that a large spectral coverage is still very important.
detectors will detect GRBs at a sensitivity of the instrument rather than on its FOV. Soft gamma-ray band observations of a few steradian should observe in the 8–200-keV band (but the shift of reionization requires soft-band detectors with a high sensitivity as low as 0.1 photon s$^{-1}$ cm$^{-2}$). Obviously, a larger FOV implies a larger number of detections.

In conclusion, the observation of GRBs near or beyond the redshift of reionization requires soft-band detectors with a high sensitivity and moderately large FOV. An ideal instrument with a FOV of a few steradian should observe in the 8–200-keV band (but the Swift 15–150-keV band may be enough) with a sensitivity as low as 0.1 photon s$^{-1}$ cm$^{-2}$. Assuming a FOV of 3 sr, this ‘ideal’ instrument will be able to detect $\sim$40 (3) GRBs at $z \geq 6$ ($z \geq 10$) in just one year of observations.

## 4 Predictions for Available Instruments

In this section, we discuss the expected number of detections for Swift, INTEGRAL and GLAST/GBM at $z \geq 6$ and $z \geq 10$. The model results are given in Table 1, where we also report on the maximum redshift accessible with this instrument, $z_{\text{max}}$, corresponding to the redshift at which $\sim$1 GRB per year should be detected. Lower limits are obtained with the conservative model (i.e. assuming luminosity evolution of the GRB LF with $\delta = 1.4$), whereas larger numbers are found by adopting models in which GRBs form in low-metallicity environments. We stress here that the upper bounds are also still conservative, as the models are just consistent with the limits imposed by the five GRBs observed at $z \geq 5$ (Salvaterra et al. 2007).

### 4.1 Swift

We compute the expected number of high-$z$ detections per year of observations in the 15–150-keV band of Swift. We assume a FOV of 1.4 sr and a trigger photon flux threshold of 0.4 photon s$^{-1}$ cm$^{-2}$. At this threshold, Swift number counts are still consistent with model predictions (SC07), indicating that the instrument essentially observes all bursts above this photon flux. Below this limit, the model prediction overestimates the number of Swift detections, showing that many bursts are missed by Swift. For $P_{\text{lim}} = 0.4$ photon s$^{-1}$ cm$^{-2}$, we expect $\sim$4 GRB per year to be detected at $z \geq 6$ in our reference model. The highest accessible redshift in this case is $\sim$7.5, and essentially no burst is expected to be detected at $z \geq 10$ during the entire Swift mission. For our very conservative model, we expect just $\sim$1 GRB per year to be detected by Swift at $z \geq 6$. We note that, in this case, the detection of GRB 050904 at $z = 6.3$ represents an extremely rare event.

The compilation of a large GRB sample at $z \geq 6$ (as well as many close-by faint GRBs) would require a lower trigger threshold. Assuming decreases of the Swift threshold down to $P_{\text{lim}} = 0.1 (0.25)$ photon s$^{-1}$ cm$^{-2}$, we should be able to detect bursts up to $z_{\text{max}} \sim 10$ ($z_{\text{max}} \sim 8.3$) for our reference model. As a lower limit, we predict $z_{\text{max}} \sim 7.6$ ($z_{\text{max}} \sim 7$) for the LF evolution model. In both cases, the GRB sample at $z \geq 6$ doubles by lowering the trigger threshold from 0.4 to $\sim$0.2 photon s$^{-1}$ cm$^{-2}$. For the lowest photon flux limit considered here, we expect to detect 3–16 GRBs per year at $z \geq 6$.

### Table 1. Characteristics of present-day and future GRB missions and the predicted number of GRB detections per year at $z \geq 6$ and $z \geq 10$.

| Instrument | Band (keV) | Field of view (sr) | $P_{\text{lim}}$ (photon s$^{-1}$ cm$^{-2}$) | $z_{\text{max}}$ | GRBs per year at $z \geq 6$ | GRBs per year at $z \geq 10$ |
|------------|-----------|-------------------|------------------------------------------|------------------|--------------------------------|-------------------------------|
| Swift      | 15–150    | 1.4               | 0.1 (0.25)                               | 6.3–7.5          | 1.3–4                           | 0.09–0.1                      |
| INTEGRAL/IBIS | 20–200  | 0.1               | 0.2 (0.1)                               | 7.0–8.3          | 2–7                             | 0.16–0.25                    |
| GLAST/GBM (on-board) | 30–300  | 9                 | 0.7 (0.1)                               | 7.5–9.9          | 3–16                           | 0.3–0.9                      |
| GLAST/GBM (ground) | 4–50    | 2                 | 0.47                                   | 6.8–6.9          | 1.8–2.4                         | 0.05–0.12                    |
| SVOM       | 8–200     | 2.5               | 0.6 (0.2)                               | 6.7–7.4          | 2–4                            | 0.1–0.13                     |
| EDGE       | 10–600    | 5                 | 0.16                                   | 9.7–11.3         | 11–56                           | 0.9–2.8                      |

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and tens at $z \sim 5$. Probably, one GRB per year should be at $z = 10$. The expected redshift distribution of GRB detections in the redshift range $z = 5–10$ is shown in Fig. 2 for different values of the trigger threshold. From the plot it is clear that lowering the trigger threshold of Swift would largely increase the probability of detecting GRBs at high redshift, possibly allowing a significant sample of bursts to be collected at $z \gtrsim 6$.

Once detected, redshift measurements for GRBs at $z \gtrsim 5$ require rapid follow-up observations of optical afterglow with 8-m ground-based telescopes. Because of the considerable competition for time on these instruments, we need to preselect the best candidates soon after detection. This can be done on the basis of some promptly available information provided by Swift, such as burst duration, photon flux, the lack of detection in the Ultraviolet/Optical Telescope (UVOT) $V$ band and the low Galactic extinction (Campana et al. 2007b; Salvaterra et al. 2007a). Salvaterra et al. (2007a) have tested this procedure against Swift data from the last year, showing that this method allows reliable $z \gtrsim 5$ targets to be picked up with an efficiency larger than 66 per cent, and also avoids contamination by low-$z$ interlopers.

We note that, thanks to cosmological time dilation, spectroscopically follow-up of high-$z$ GRBs is easier than for low-$z$ GRBs. In fact, even a few days after the trigger, we are still observing the afterglow in an early phase, when it is more luminous.

### 4.2 INTEGRAL

**INTEGRAL** is a satellite of the European Space Agency, launched in 2002 October. In almost five years, **INTEGRAL** has detected 45 bursts, but only in a few cases has it been possible to measure the redshift (the current record is GRB 050502A at $z = 3.793$).

Estimates carried out for the **INTEGRAL** Burst Alert System sensitivity yield a trigger threshold of $\sim 0.14–0.22$ photon s$^{-1}$ cm$^{-2}$ for the Imager on Board the **INTEGRAL** Satellite (IBIS) in the 20–200-keV energy band (Mereghetti et al. 2003). We find that the probability of detecting GRBs at $z \gtrsim 6$ is comparable or even higher than that obtained for Swift, owing to the higher sensitivity of **INTEGRAL**/IBIS (see also Gorosabel et al. 2004). Unfortunately, the above sensitivity applies only to the central $9 \times 9$ deg$^2$ of the IBIS where the fully instrument effective area can be used. In the external part of the FOV, the so-called partially coded region, the sensitivity is worse. Even assuming $P_{\text{lim}} = 0.2$ photon s$^{-1}$ cm$^{-2}$ on a FOV of $\sim 0.1$ sr (Gorosabel et al. 2004), only 1–3 GRBs at $z \gtrsim 6$ should be present in the entire **INTEGRAL** catalogue, and none at $z \gtrsim 10$. The maximum accessible redshift, computed as the redshift at which we predict $\sim 1$ GRB per year, is $z \sim 5.2$ and $\sim 3.8$ in our reference and conservative models, respectively. In conclusion, in spite of the relatively good sensitivity and sufficiently soft observational band, we do not expect **INTEGRAL** to provide a large number of $z \gtrsim 5$ identifications, as it is essentially limited by its very small FOV.

### 4.3 GLAST

**GLAST**$^2$ is the next gamma-ray astrophysics mission by the National Aeronautics and Space Administration (NASA), scheduled to be launched in 2008 January and expected to be operational for 5–10 yr. It will carry two instruments: the Large Area Telescope (LAT) and the GBM. The GBM will detect and localize burst monitoring over $\gtrsim 8$ sr of the sky, including the LAT FOV. In order to derive the expected number of bursts detectable by **GLAST**/GBM at very high redshift, we consider the $50–300$-keV band and a FOV of $\sim 9$ sr. The expected on-board photon flux limit is $0.7$ photon s$^{-1}$ cm$^{-2}$, whereas with more accurate data analysis on the ground it would be possible to reach a sensitivity as low as $0.47$ photon s$^{-1}$ cm$^{-2}$. As is clear from Fig. 1, **GLAST**/GBM is not well suited to the search for bursts at $z \gtrsim 10$. Indeed, the hard band of the instrument, together with the low sensitivity (with respect to the other instruments considered here), limits the possibility of detecting GRBs at a redshift much larger than $z = 6$. We find that only $\sim 1$ GRB per year would be detected at $z \simeq 6.2–6.3$. No burst at $z = 10$ is expected during the entire **GLAST** mission. Considering the more accurate ground data analysis, just $\sim 2$ GRBs per year are predicted at $z \gtrsim 6$. Although optical or near-infrared afterglow detection is, in principle, easier for high-$z$ bursts as a result of cosmological time dilation, a rapid response is still necessary in order to provide information about the first stages of the afterglow and to increase the probability of detecting GRBs at $z \gtrsim 6$. Thus, information on the bursts identified in the **GLAST** ground-based data analysis may not be available in time for follow-up studies.

In conclusion, the **GLAST**/GBM does not appear to be the best instrument to search for GRBs at $z \gtrsim 6$.

### 5 PREDICTIONS FOR THE NEXT GENERATION OF INSTRUMENTS

The next generation of X-ray and gamma-ray instruments will improve our knowledge of burst physics and perhaps allow a systematic study of the early Universe through the detection of a large number

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$^2$ See http://glast.gsfc.nasa.gov/.
of GRBs. In this section, we explore this possibility, considering future missions that match the characteristics described in Section 2. Three planned satellites will search for GRBs in a soft band comparable to or lower than that of Swift: the Space-based multiband astronomical Variable Object Monitor (SVOM), EDGE and EXIST. The expected numbers of $z \geq 6$ and $z \geq 10$ GRB detections for one year of observations are given in Table 1, together with the maximum accessible redshift.

### 5.1 SVOM

The SVOM is a Sino-French mission dedicated to the detection, localization and study of GRBs and other high-energy transient phenomena. The satellite launch is scheduled in 2012. The SVOM consists of the ECLAIRs telescope (Gotz 2007), which includes the X-ray and gamma-ray camera (CGX, the trigger device) and a soft X-ray camera (ESXC), the Gamma-Ray Monitor (GRM), the Wide Angle Cameras (WACs) and the Visible Telescope (VT). The ECLAIRs telescope and the associated GRM permanently observe a large portion of the sky (2 sr). The ECLAIRs trigger system uses the CGX data to search for the appearance of a new transient source in the gamma-ray and determines its localization in the sky. The refined source position in the sky is obtained with the ESXC reaching a position accuracy of 1 arcmin. The source position is then rapidly sent to the ground and also transmitted to the VT and the WACs on board the SVOM, in order to perform visible follow-up observations of the source. In the 4–50-keV trigger band, the expected peak photon flux limit for the burst detection is $\sim 1$ photon s$^{-1}$ cm$^{-2}$. As discussed in Section 3, the soft observational band of the SVOM is very suitable for the search for high-$z$ GRBs. Indeed, we predict that the SVOM will detect $\sim 2$–$4$ GRBs per year at $z \geq 6$. The maximum accessible redshift is $z \sim 7.4$ and $\sim 6.7$ in our reference and conservative models, respectively. In spite of these good results, the identification of a GRB at $z \geq 10$ will be an extremely rare event: just one burst during the entire mission is expected. In order to detect one GRB per year at this limit, the SVOM trigger threshold should be lowered by a factor of 3.

Finally, we note that, similarly to the case of Swift, GRB candidates at $z > 5$ can be selected on the basis of a few burst data promptly provided by ECLAIRs and by the optical instruments on board the SVOM.

### 5.2 EDGE

EDGE$^3$ is an X-ray space satellite, proposed in response to the 2007 ESA Cosmic Vision call for new space mission, which carries two X-ray telescopes and has fast repointing capabilities (Piro et al. 2007). The possibility of detecting GRBs is provided by a wide field monitor covering 2.5 sr and operating in the 8–200-keV band. The expected sensitivity for burst detection is 0.6 photon s$^{-1}$ cm$^{-2}$ in the entire FOV considered here. At this limit, we expect that EDGE will detect as many as 3–7 GRBs per year at $z \geq 6$. EDGE should be able, at least for the most luminous bursts, to directly measure the GRB redshift based on intrinsic absorption in the circumburst material and/or host galaxy; for example, in the case of high column densities with metal absorption edges (and related curvature) imprinted in the X-ray spectrum, and in the case of low absorption as a result of resonant absorption lines.

The larger FOV and slightly softer observational band with respect to Swift compensate in some way for the higher photon flux limit expected for EDGE. Thus, this instrument is well suited for the search for GRBs at $z = 6$, with a few bursts expected to be detected at $z > 7.5$. In principle, for our reference model, EDGE will be able to access $z_{\text{max}} \sim 8$. At $z = 10$, we expect only one GRB to be detected during the three years of the EDGE mission. In order to increase the number of high-$z$ detections, the flux limit of the instrument should be decreased by a factor of 2. This will allow the detection of $\sim 20$ GRBs per year at $z \geq 6$ and also a few bursts at $z = 10$ (see the short-dashed line in Fig. 1).

### 5.3 EXIST

EXIST$^4$ is a proposed hard X-ray imaging all-sky deep survey NASA mission, recommended by the 2001 Report of the Decadal Survey. It is based on proven technology and could be launched by $\sim 2015$. One of the main goals of this instrument is to detect and study GRBs out to $z > 6$–10, thanks to the High Energy Telescope (HET). The HET consists of 19 wide-field hard X-ray telescopes. It covers the 10–600-keV band with 6-arcmin resolution (70-arcsec position accuracy) over a FOV of 5 sr, using 6 m$^2$ of CZT detectors. The expected sensitivity is as low as 0.16 photon s$^{-1}$ cm$^{-2}$ (Band 2006). The Low Energy Telescope (LET) complements the HET with energy coverage from 3 to 30 keV and finer spatial resolution (1 arcmin, with 10-arcsec position accuracy) using 1.3 m$^2$ of silicon detectors.

Because of the very low trigger threshold and large FOV, EXIST will be the best instrument for detecting high-$z$ GRBs. Almost 10–60 bursts per year are expected to be observed at $z \geq 6$, one to three of which will be $z \geq 10$. Even for the very conservative model, EXIST will be able to detect GRBs up to $z \sim 10$ and to collect a significant number of bursts at $z \geq 6$ during the entire mission.

### 6 CONCLUSIONS

We have explored the characteristics of an ideal mission to search for GRBs near and beyond the epoch of reionization, i.e. $z \geq 6$–10. In particular, we have considered different observational bands, deriving the best combination of sensitivity and FOV in order to detect bursts at $z \geq 10$. We have found that such an experiment requires soft-band detectors and high sensitivity, whereas large FOV or wide energy coverage are less important. Assuming a FOV of 3 sr, an observational band of 8–200 keV and a sensitivity as low as 0.1 photon s$^{-1}$ cm$^{-2}$, this instrument would be able to detect $\sim 40$ (3) GRBs at $z \geq 6$ ($z \geq 10$) in a mission of one year.

In light of these results, we have compared available and planned GRB missions, deriving conservative predictions on the observable number of GRBs at $z \geq 6$ and $z \geq 10$ along with the maximum accessible redshift. We have shown that Swift is a viable tool to detect GRBs at $z \sim 6$. At the actual trigger threshold, 1.3–4 GRBs per year should be identified above this redshift. We also discuss the possibility of increasing the number of high-$z$ detections by lowering the Swift trigger threshold. We found that the number of detectable GRBs doubles by lowering this by about 50 per cent. Assuming that the trigger threshold can be lowered further to 0.1 photon s$^{-1}$ cm$^{-2}$, Swift should detect $\sim 1$ GRB per year at $z \geq 10$.

The INTEGRAL and GLAST satellites do not appear to be the best tools to search for GRBs at very high redshift. The former is limited by the very small FOV, whereas the GLAST hard-energy

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3 See http://projects.iasf-roma.inaf.it/edge/.

4 See http://exist.gsfc.nasa.gov/.
observational band and relatively low sensitivity do not allow the detection of more than one GRB per year at $z \geq 6$. No GRB at $z \geq 10$ is expected during the entire mission of both instruments.

Finally, we show that future missions, such as SVOM, EDGE and, in particular, EXIST, will be able to collect a good number of GRBs at $z \geq 6$ in a few years of operation. This sample can be used to study the early Universe, possibly providing strong constraints on the reionization process (Gallerani et al. 2007), and deriving estimates of the star formation and metallicity/dust content in normal high-$z$ galaxies.

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