Uncovering the Population of Short Gamma-Ray Bursts at $z > 1.5$

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Short-duration gamma-ray bursts (SGRBs) are highly energetic, relativistic explosions with durations $T_{90} < 2$ s. Much work has been done to investigate the origin of these bursts. However, until a few years ago, there was only indirect evidence linking them to the mergers of binary neutron stars (BNS) or neutron star–black hole (NSBH) mergers (e.g., the lack of associated supernovae, host galaxy demographics, explosion environments, offsets from their host galaxies, and excess emission consistent with r-process kilonovae; see [1], [2], [3], and [4] for examples).

The 2017 discovery of the BNS merger GW170817 by LIGO/Virgo [5] and the associated short-duration GRB 170817A provided direct evidence that at least some SGRBs originate from BNS mergers. Although gravitational wave (GW) facilities continue to make ground-breaking discoveries of new BNS and NSBH mergers, the detection of these events in GWs is limited to the nearby Universe ($z < 0.05$). However, SGRBs themselves can be detected at cosmological distances, providing powerful probes of the BNS progenitor population, rates, and evolution to redshift $z \sim 2$. Thus, the combination of GWs and SGRBs allows the study of BNS mergers over the full history of the Universe.

Since 2004, the Neil Gehrels Swift Observatory [6] has discovered over 130 SGRBs [7]. Key to Swift's capabilities is its capacity to localize SGRBs to arcsecond precision, enabling multi-wavelength follow-up to catch their fading afterglow signals and identify the host galaxies. Although dedicated campaigns to characterize their host galaxies have led to secure redshift determinations for about a third of the detections, only ~ 5% of these bursts have confirmed redshifts of $z > 1$. These are particularly challenging to characterize. First, their afterglows are apparently fainter, typically $r > 24$ mag within hours of the burst, and often elude detection if not followed up with extremely sensitive facilities. Second, Swift is less sensitive to SGRBs at $z > 1$ owing to its detector characteristics. Finally, the redshift range of $1.3 < z < 2.5$ comprises the so-called redshift desert, in which it is challenging to determine redshifts for host galaxies because of their featureless optical spectra. Studies must resort to near-infrared wavelengths, but the available facilities having the required capabilities are very limited.

Using the rapid-response capabilities of Gemini North, we initiated imaging observations of the field of GRB 181123B a mere ~ 9 hrs after its detection by Swift. Combined with template observations at ~ 2.4 days, these images revealed a faint optical afterglow with $i \sim 25.1$ mag (Figure 1). This faint afterglow provided the necessary sub-arcsecond localization to identify the host galaxy of GRB 181123B. Using data from multiple large facilities including Gemini, Keck, and the MMT, we endeavored to determine the redshift of GRB181123B and study its host galaxy properties. Unlike most SGRB host galaxies discovered to date, the optical spectrum appeared featureless, suggesting a location in the redshift desert at $z > 1.3$. We therefore obtained a near-infrared spectrum with FLAMINGOS-2 mounted on Gemini South in Chile and identified a single emission line at 1.339 μm. Inferred to be Hβ, the detection gives a redshift of $z = 1.754 \pm 0.001$, in perfect agreement with the galaxy photometric redshift calculated using *grizYJHK* observations, as well as the absence of other emission lines in the observed spectra.

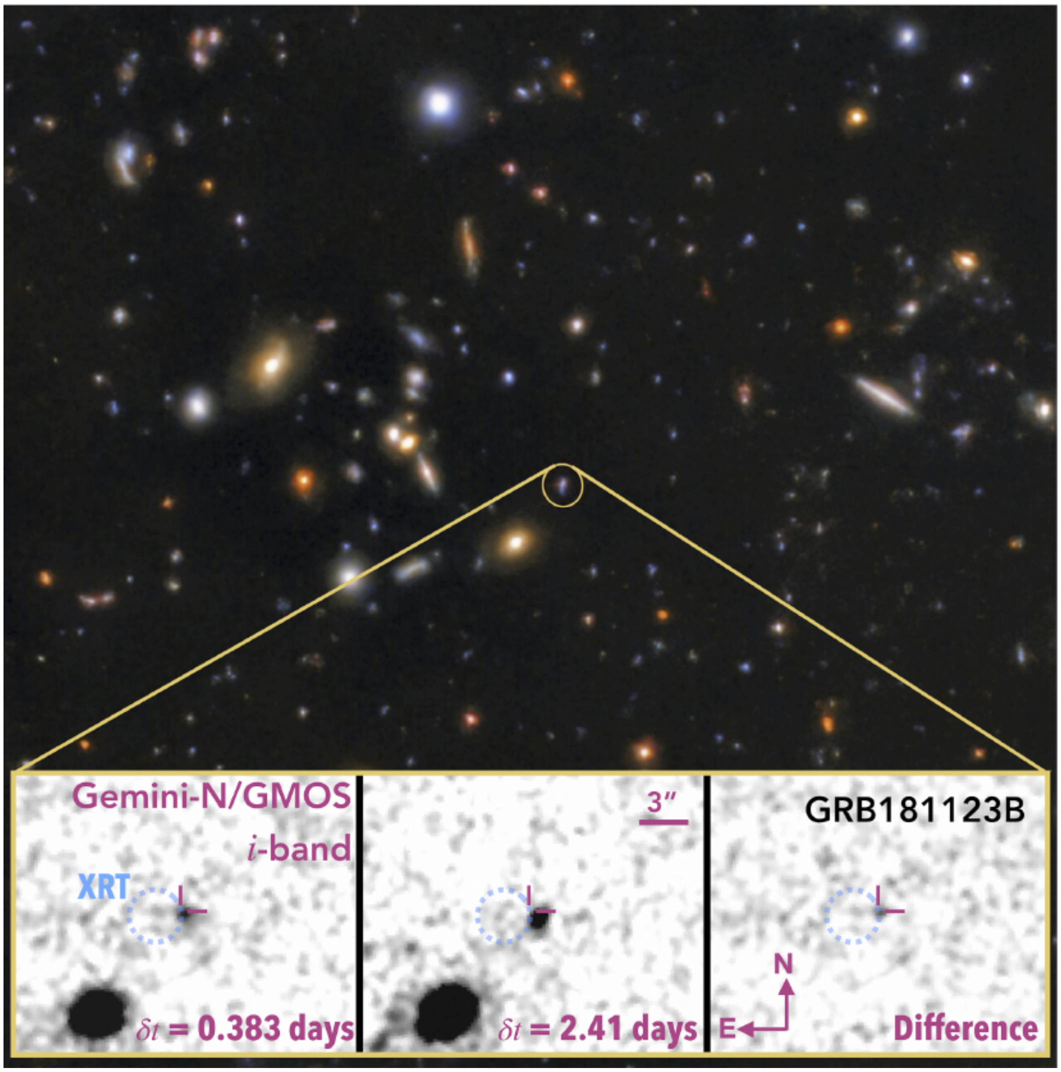

Figure 1. *Top*: Color-composite image of the field containing GRB181123B, with the host galaxy enclosed in the yellow circle. Inset: Detection of the optical afterglow using Gemini North/GMOS. In each image, the blue circle shows the X-ray position from Swift/XRT, while the pink crosshairs show the position of the afterglow. *Left*: Epoch 1 image taken ~ 9 hours after the initial burst. *Middle*: Epoch 2 image taken ~ 2 days later. *Right*: Difference image (epoch 1 minus epoch 2) showing the detection of the afterglow at the position of the cross hairs. (Adapted from [8], with permission)

The discovery of GRB 181123B at $z = 1.75$ adds to the very small, but growing, population of SGRBs with $z > 1$. GRB181123B is the second most distant SGRB with a secure redshift discovered by Swift to date and the most distant with an optical afterglow detection. Finding an SGRB at this redshift offers a unique opportunity to study these systems at a time when the Universe was only 3.8 billion years old (< 30% of its current age) and more rapidly forming stars than it is today. Modeling of the host galaxy revealed properties that are typical of other SGRB hosts, with an inferred stellar mass of ~ 9×10^9 $M_\odot$, age ~ 0.9 Gyr, and optical luminosity ~ 0.9 L^* (Figure 2). However, with a star formation rate just below the main sequence for galaxies at similar redshifts, we found that the host of GRB181123B is producing stars at a lower rate than its cosmic neighbors, perhaps transitioning to a quieter and less active phase in its life.

Motivated by the growing number of high-redshift SGRBs like our recent discovery, we explored the effects of incompleteness in the $z > 1.5$ SGRB population among the current Swift sample. We focused particularly on the effect on delay time distribution models (the delay time is the time it takes for binary stars to evolve to the BNS stage and then merge). The delay time distribution provides important clues on the formation channel of these BNS mergers (dynamical formation in globular clusters versus primordial binaries that were born and evolve as a pair), as well as their merger timescales, which are highly unconstrained by observations at present.

Our study found that SGRBs at $z > 1.5$ have comparatively large discriminating power between the models allowed (Figure 3). Specifically, the addition of a few bursts at

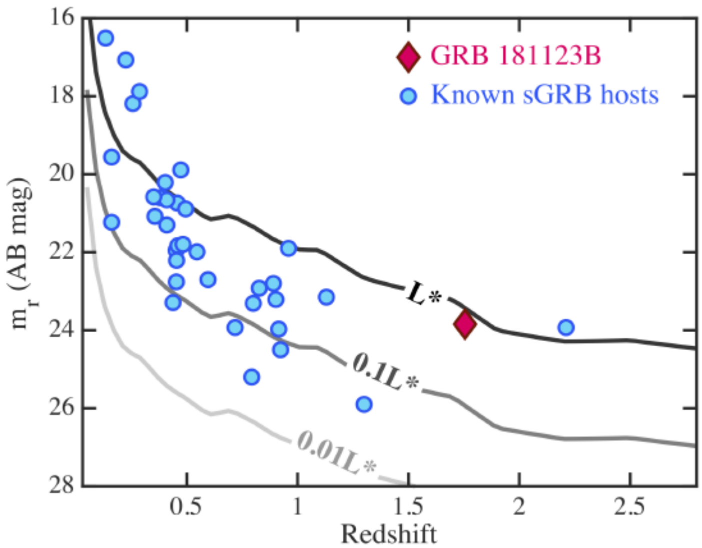

Figure 2. Apparent *r*-band magnitudes of the host galaxies of 34 SGRBs with known redshifts and optical measurements (blue circles). The high-redshift burst GRB181123B, discovered in our recent work, is indicated by the red diamond. The solid lines, corresponding to L^*, 0.1 L^*, and 0.01 L^*, show the effect of the evolving galaxy luminosity function. GRB181123B resides in a galaxy similar to others at the same redshift and in relatively uncharted territory for SGRBs. (Adapted from [8], with permission)

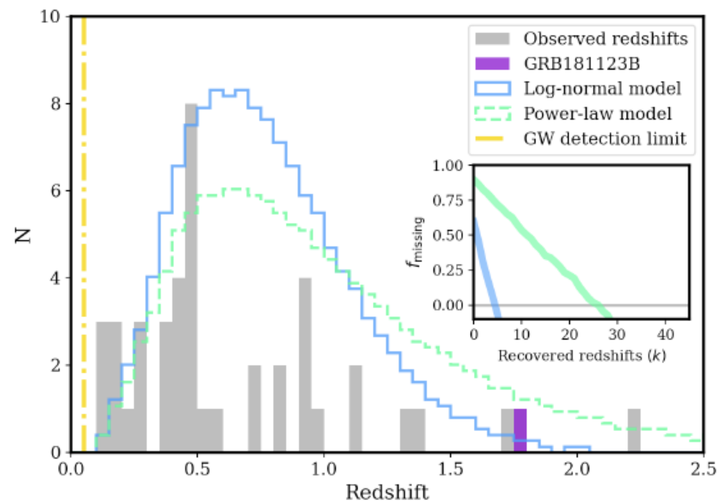

Figure 3. Observed SGRB distribution in redshift (solid histogram, with GRB181123B highlighted by the magenta bar) overlaid with predictions from two delay time distribution models from [9], one representing an example of a log-normal distribution (blue solid line) and the other an example of a power-law distribution (green dashed line). From the models we see the log-normal distribution peaks at lower redshifts, with very few SGRBs predicted at $z > 1.5$, while the power-law model predicts a larger number of SGRBs at higher redshifts. The inset shows the number of recovered (from the current Swift population) high-redshifts bursts ($z > 1.5$) it would take to rule out each model to 95% confidence (the horizontal gray line). With the current observed distribution, we see that the log-normal model is ruled out very quickly with the addition of a few recovered redshifts, while the power-law model is able to accommodate many more of the high-redshift bursts. (Adapted from [8], with permission)

$z > 1.5$ to the current Swift population could rule out log-normal delay time distribution models of BNS mergers to 95% confidence. In contrast, power-law delay time distribution models could accommodate 30 additional SGRBs at $z > 1.5$, in support of primordial formation channels. We also showed that about a third of the current Swift population could in fact originate at high redshifts ($z > 1$). Our findings are supported by complementary studies of GW170817 and observations of BNS systems in our own Galaxy. This motivates further efforts to uncover the full population of SGRBs at these high redshifts in order to properly constrain the underlying redshift distribution and probe the fundamental properties of BNS mergers. Our team will continue to use state-of-the-art facilities like Gemini to quantify the true fraction of SGRBs at these redshifts.

References

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