The Redshift Distribution of the TOUGH Survey

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Introduction

Long-duration gamma-ray bursts (GRBs) are powerful tracers of star-forming galaxies at a very wide range of redshifts. We have defined a homogeneous subsample of 69 *Swift* GRB-selected galaxies in the redshift range $0.03 < z < 6.30$. Special attention has been devoted to making the sample optically unbiased through simple and well-determined selection criteria based on the high-energy properties of the bursts and their positions on the sky.

Thanks to our extensive VLT follow-up observations, The Optically Unbiased GRB Host (TOUGH) sample has now achieved a comparatively high degree of redshift completeness, and thus provides a legacy sample, useful for statistical studies of GRBs and their host galaxies. We detect the host galaxies for 55 of the 69 GRBs in the sample (80%). The majority of the detected host galaxies are sub-luminous with an average magnitude of R = 24.7. The TOUGH galaxies are generally blue, with an average color of R - K = 3.1. The sample is not uniformly blue, however, with two extremely red objects (EROs) detected. The survey design along the most basic properties of galaxies in this sample will be presented in a talk by Jens Hjorth on Friday. Here we focus on the redshift distribution.

Selection Criteria

The sample of GRB-selected galaxies has been defined such that selection effects are minimized and well understood. A statistically meaningful and optically unbiased sample is essential in addressing issues such as the GRB redshift distribution and the importance of dust obscuration. We have applied the following selection criteria to provide a large and homogeneous sample of targets:

1. *Swift*-detected GRBs. We pick only events triggered onboard by the BAT and disregard those (very few) discovered during ground analysis.

2. We limit ourselves to long GRBs, and discard all events with $T_{90} < 2$ s (Kouveliotou et al. 1993), based on the catalog of Sakamoto et al. (2008).

3. The bursts must have a detected X-ray afterglow, the location of which is made available less than 12 h after the trigger.

Looking for the hosts of all these GRBs would be very demanding. We therefore apply further cuts, with the purpose of reducing the sample size in an unbiased way:

4. The Galactic foreground optical extinction must be $A_V < 0.5$ mag.

5. As another visibility constraint, we require that the distance on the sky between the GRB and the Sun at the time of explosion is more than 55°.

6. We require that there is no nearby star or bright contaminating object that would render host galaxy identification and spectroscopy difficult.

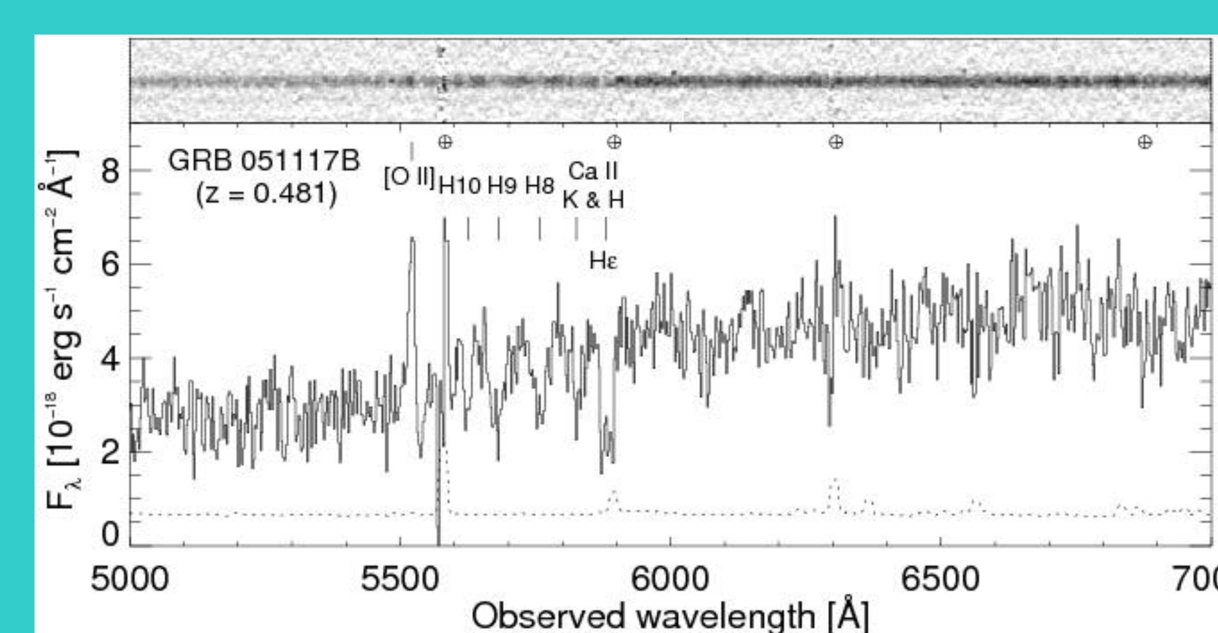
7. Bursts triggered between 2005 March 1 and 2007 August 10. During this period *Swift* was fully operational and automatic slews were routinely enabled.

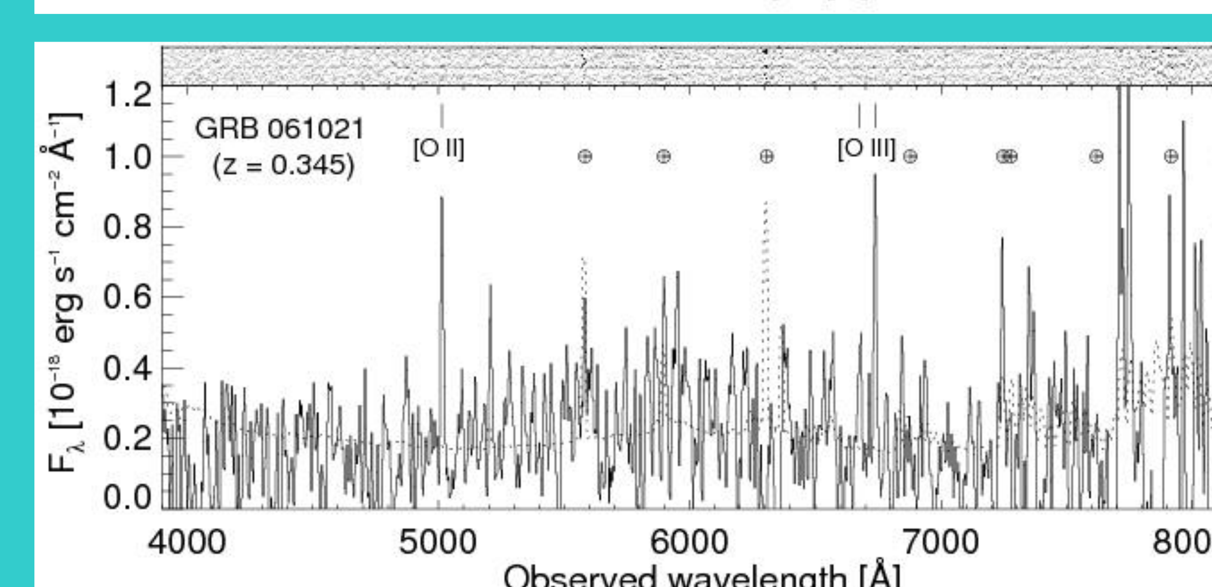
8. In order to be well placed for observation with the VLT we limit the declination range to be $-70° < \delta < +27°$ (J2000.0).

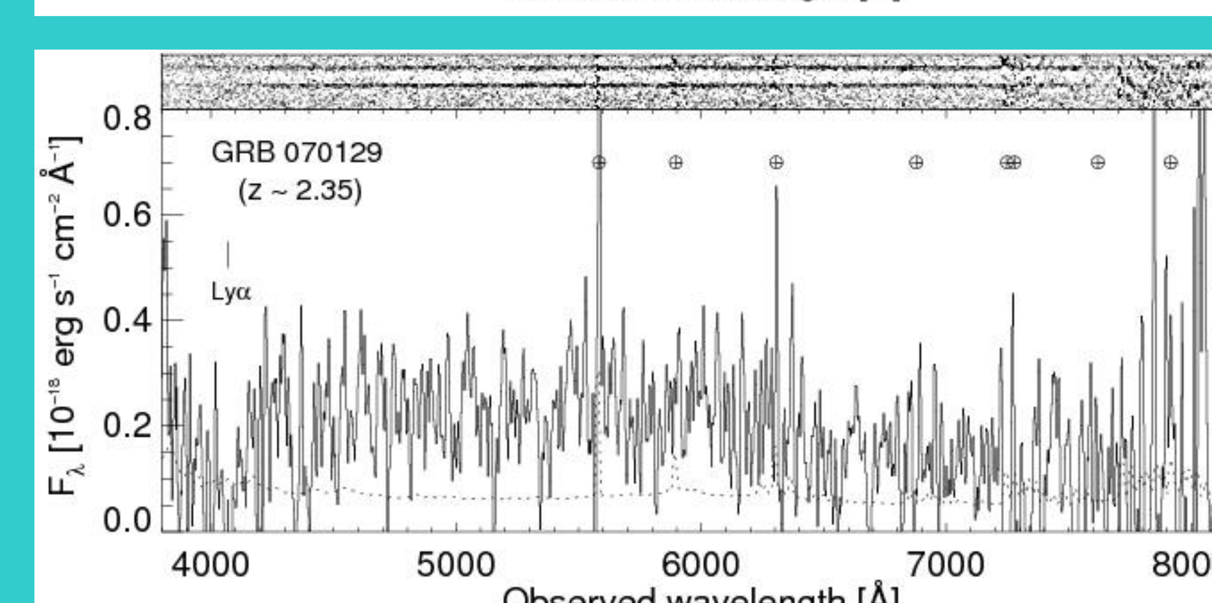
Our final criterion concerns the localization accuracy of the GRBs:

9. The X-ray localization uncertainty must be better than or equal to 2 arcsec (90% error radius). This constraint is dictated by the necessity to perform meaningful host searches. Larger error boxes would lead to too many ambiguous detections.

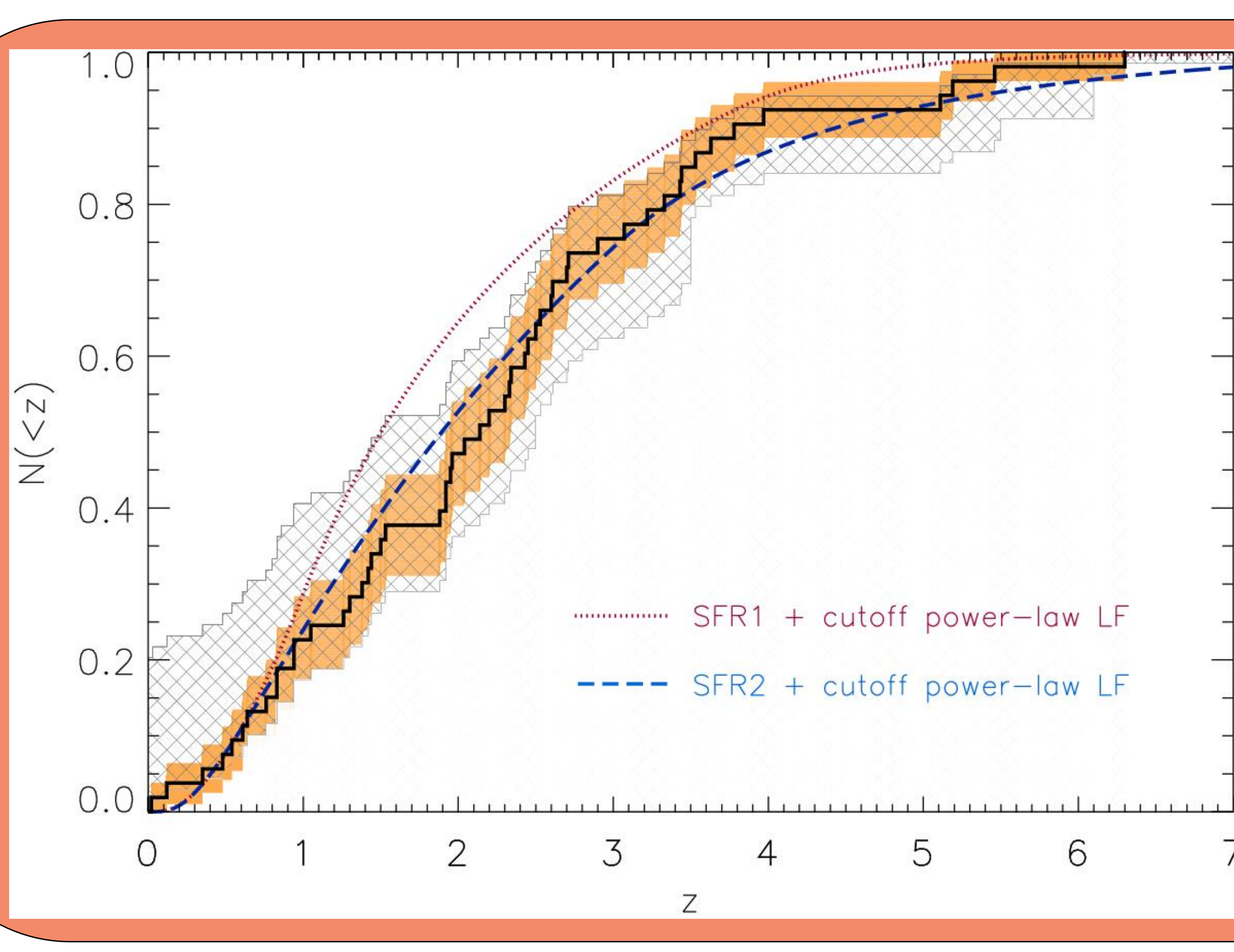
15 New Redshifts







In the TOUGH survey we have secured 15 new host redshifts (9 with FORS and 6 with X-shooter). The figures above show 3 of the spectra obtained with FORS. Three of our measurements revise incorrect values from the literature (GRBs 060306, 060814, and 060908). The homogeneous host sample researched here consists of 69 hosts that originally had a redshift completeness of 55% (with 38 out of 69 hosts having redshifts considered secure). Our project increases this fraction to 77% (53/69), making the survey the most comprehensive in terms of redshift completeness of any sample to the full *Swift* depth, analyzed to date.



The Redshift Distribution

On the left is the cumulative fraction of GRBs as a function of redshift for the 53 *Swift* bursts in the TOUGH sample with a measured redshift (thick solid curve with $\langle z \rangle = 2.23$). A conservative, yet small, associated uncertainty is also shown (hatched region: systematic errors; shaded orange region: 1σ sampling error). We constrain the fraction of *Swift* GRBs at high redshift to a maximum of 14% (5%) for $z > 6$ ($z > 7$).

Using this more complete sample we confirm previous findings that the GRB rate at high redshift ($z \geq 3$) appears to be in excess of predictions based on assumptions that it should follow conventional determinations of the star formation history of the Universe, combined with an estimate of its likely metallicity dependence (red dotted curve). This suggests that either star formation at high redshift has been significantly underestimated, for example due to a dominant contribution from faint, undetected galaxies, or that GRB production is enhanced in the conditions of early star formation, beyond that usually ascribed to lower metallicity (blue dashed curve).