Supplementary Notes:

1. The association of GRB 060614 with the proposed z=0.125 host galaxy:

In this section we test the possibility that GRB 060614 is a typical long GRB that occurred at high redshift and its association with the z=0.125 host we identified is due to a random projection. We find direct observational evidence that rule out this scenario at an estimated 99.85% confidence level, without taking into account the a posteriori probability for a random background GRB to be projected on top of the putative host. When the likelihood for a chance projection is evaluated conservatively, the combined probability that this specific GRB is a background event is found to be 6×10^{-6}. We comment on the validity of treatments of this question that have recently appeared.[1,2]

Direct evidence against GRB 060614 as a background event:

Let us assume that GRB 060614 is a typical long GRB that indeed occurred at high redshift, behind the proposed z=0.125 host galaxy, and test whether the observational data are consistent with this hypothesis. If GRB 060614 has occurred at high redshift, its host galaxy might itself be visible in our high-resolution, sensitive *HST* imaging.[2] To test this possibility we subtracted a galaxy model (SI § 2) from our V- and I-band *HST* images. As often seen in such galaxies, the model is not perfect, and residuals due to galactic substructure (the brightest of which having peak flux which is < 10% of that of the galaxy) remain. However, none of these residuals is close to the afterglow location. Close inspection of this area rules out the existence of a bright background source at this location.

To quantify our limit, we have added artificial galaxies with decreasing luminosity at the location of the optical afterglow. These were modeled as exponential disks (SI § 2) and are similar to real nearby galaxies seen in our images (e.g., Fig. 1, top right). We assumed a redshift of $z = 1$, at the top of the allowed redshift range,[3] for such a postulated host, to relate the intrinsic luminosity to artificial V magnitudes via the luminosity distance for the standard WMAP cosmology (SI § 2). We then examined the artificial images by eye, and repeated the galactic-model subtraction procedure. We find that galaxies brighter than $M_V = -17.5$ are easily seen as local "bumps" above the smooth profile of the z=0.125 galaxy, and would have therefore been easily detected. Galaxies as faint as $M_V = -16$ produce prominent residuals after the galactic model is subtracted, and are therefore ruled out as well. We thus conclude that any background host galaxy cannot be brighter than $M_V = -16$. Using a recent compilation of GRB host galaxy luminosities[4] we find that only a single host galaxy (of the 36 galaxies listed there; 2.8%) would have escaped detection in our images. We adopt this as an estimate for the probability for GRB 060614 to have occurred in a galaxy below our detection limit.

An additional consequence of the assumption that GRB 060614 occurred at high redshift and is projected behind the $z = 0.125$ galaxy is that, since our line of sight goes through the body of an intervening galaxy, we expect to see signatures of absorption by gas and dust in this galaxy. To derive quantitative estimates, we model the properties of the putative dwarf host galaxy of GRB 060614 using our knowledge of the nearest and best studied local dwarf galaxies - the Magellanic clouds. Following studies of background objects behind the Magellanic clouds[5] we estimate the average extinction inflicted by the clouds on background sources as twice the mean value for Magellanic cloud stars, to obtain an average extinction of $E_{B-V} = 0.26$ mag[6] for the large Magellanic cloud (LMC) and $E_{B-V} = 0.18$ mag[7] for the small Magellanic cloud (SMC). For the SMC (which is more similar to our putative host) we further estimate a range of $0.12 < E_{B-V} < 0.5$.[8]

Modeling of the combined afterglow X-ray and UV-optical spectral energy distribution[9] indicates an extinction value ($A_V < 0.2$; $E_{B-V} < 0.057$) well below the average values given above, and significantly below even our conservative range $0.12 < E_{B-V} < 0.5$. We thus find that the data appear to exclude the amount of dust extinction expected in a line of sight through a dwarf galaxy similar to the putative host.

A similar line of argument can be made using the X-ray data. From the correlation between the amount of dust extinction and gas column density $N_H = 5.3 \times 10^{21} cm^{-2} \times E_{B-V}$[10] we estimate a hydrogen column density of $N_H > 6.4 \times 10^{20}\mathrm{cm}^{-2}$ in a line of sight going through the SMC. This is above the measured amount from X-ray observations of the afterglow of GRB 060614 ($N_H = 0.42^{+1.8}_{-0.32} \times 10^{20}$).[3] So, our observations show that the amounts of both dust and gas along the line of sight toward GRB 060614 are well below the lower limits estimated from studies of the Magellanic clouds. The absorption limits can only be avoided by assuming that our line of sight through the host of GRB 060614 happens to penetrate the galaxy through a low-extinction "hole". While an exact estimate of the likelihood of this happening is impossible for a poorly-studied, remote galaxy, based on the frequency of such "holes" in our galaxy, as well as the observations in the SMC[8] we conservatively estimate it to lie below 5%.

The above analysis indicates that the observational data directly argue against the hypothesis that GRB 060614 lies at high redshift, behind the z=0.125 galaxy we proposed as its host. The combination of the requirements that such a host would be intrinsically faint, and the GRB be seen through a "hole" in the z=0.125 foreground galaxy, suggest a probability below 1.5×10^{-3} for our null hypothesis to be true. Note that this result is based purely on observational constraints, and so far does not involve a posteriori statistics.

Statistical analysis:

In order for the hypothesis discussed above (that GRB 060614 occurred at high redshift, behind the z=0.125 galaxy we describe) to materialize, one has to assume that this projection occurred by chance. To estimate the probability for this we follow previous analysis[2] and calculate the sky density of galaxies as bright or brighter than our putative host. Previous calculations[2] were based on ground-based imaging. In such images, the size of objects that are intrinsically smaller than the atmospheric seeing disk is inflated by the effect of seeing, leading to an over-estimate of the fraction of sky covered by faint galaxies. We repeat this analysis using our superior high-resolution *HST* data and find a smaller fraction, 0.004 of the sky, is covered by galaxies, both in V- and I- band images. The fraction is calculated as the ratio of the number of *HST* pixels assigned by *Sexstractor* to galaxies that are detected above 10σ to the total number of pixels in our images. Our galaxy catalogs includes galaxies that are as much as 10 times fainter than the z=0.125 galaxy we discuss (which is itself detected at 55σ; these faint objects comprise $\sim 2/3$ of our catalogs) so our analysis is conservative when compared to previous work.[2] Note, that since we do not know the redshift off all the galaxies in our image we do not impose a redshift cut on our galaxy population, as would indeed be appropriate,[1] since most of the galaxies dominating our reported sky-coverage are at high redshifts, and therefore cannot lead to a false claim about the absence of a SN. Therefore, our estimate of the chance coincidence is very conservative (taking a redshift cut into account is likely to reduce the probability by another factor of order 10-100[1,2]).

To conclude, we find that the hypothesis that GRB 060614 is by chance projected through an unrelated, foreground galaxy at z=0.125 requires the following unlikely sequence of events. First, the event should be projected by chance on such galaxy (0.4%). Next, its real host should be exceedingly faint, even compared to the relatively faint host galaxies of long GRBs (2.8%). And finally, it should happen to penetrate the foreground galaxy in a low-extinction "hole" to avoid our limits on dust and gas absorption set by the excellent observational data collected for this burst ($\sim 5\%$). Conservatively, the probability for this to happen is **smaller than** 6×10^{-6}, so we can safely argue that the above assumption is ruled out at high significance.

Notes on previous works:

A treatment of the a posteriori probability of this event to have been a chance projection, including a reasonable redshift cut ($z = 0.2$), was recently carried out.[1] However, this analysis assumed that an association of GRB 060614 with the foreground z=0.125 host galaxy would be accepted given an unrealistically large offset of $4.3''$. As can be seen in Fig. 1, at *HST* resolution, an event at such a large offset would not have been associated with this host. In fact, events falling on most of the circumference of a circle with a radius of $4.3''$ around the putative host, are more likely to have been associated with other (probably higher redshift) galaxies seen in the *HST* images. For example, an event at the position we marked by 'X', is much more likely to be associated with the nearby large z=0.45 spiral galaxy. The association scale for an event with a proposed host depends on the properties of the host, and for the z=0.125 dwarf galaxy we discuss, an area with approximate radius of $1''$ (thin ellipse) would be a conservative association range. Repeating recent calculations[1] with this radius yields a probability of 4.3×10^{-4} for a chance projection, showing that our above estimate (0.004), without a redshift cut, is indeed conservative. Considering also the small probabilities for missing a high-redshift host galaxy behind the $z = 0.125$ galaxy (2.8%) and of avoiding extinction in that galaxy ($\sim$ 5%), the probability for chance coincidence following this line of argument would fall below 10^{-6}, leading to the conclusion that such chance projection is, in fact, highly unlikely, and not as previously claimed.[1]

It is interesting to note that the high redshift claimed for this event based on gamma-ray luminosity indicators ($1.4 < z < 1.71$)[1] is ruled out by the analysis of the combined optical-UV-X-ray data.[3] If one accepts the validity of gamma-ray luminosity indicators for long GRBs, the fact that GRB 060614 is a significant outlier (reduced $\chi^2 = 315$[1]) from these correlations indicates that it does not belong to the same parent population of bursts, and indeed, likely requires a novel explosion mechanism, supporting our main conclusion.

Finally, we stress that our analysis rejects the superposition hypothesis based on direct observational evidence at high confidence, without resorting to an a posteriori statistical analysis, as previously done.[1,2] However should such an analysis be carried out in similar future cases, it is important to adopt a realistic association radius (c.f.[1]) and to take into account an appropriate redshift cut.

2. Host properties and GRB environment:

We photometered the host galaxy of GRB 060614 relative to a grid of nearby calibrated compact sources[11] using a large ($1.5''$) aperture, and derived its standard magnitudes ($V = 22.70$; $I = 21.92$) from our *HST*/ACS images. As the galaxy spectral energy distribution is well-described by an Sc galaxy template[12] (Fig 2) we apply synthetic photometry to the template, scaled to match the measured V and I magnitudes, and derive the host galaxy magnitudes to be $[UBVRI]$ = [22.29 22.94 22.71 22.52 21.92] mag. These are in excellent agreement with independent ground-based measurements.[9,2] Note that the U-band host magnitude is brighter than reported late UVOT U-band photometry[13] indicating that the proposed possible late-time brightening is probably not real. Assuming the currently favored WMAP cosmology ($\Omega_m = 0.27, \Omega_\Lambda = 0.73, H_0 = 71$ km s^{-1} Mpc^{-1}) we find a luminosity distance $d_L = 578.3$ Mpc to the galaxy at z=0.125, and a distance modulus $m-M$=-38.81 mag. We thus calculate absolute magnitudes for the galaxy of $[M_B\ M_V\ M_R] = [-15.9\ -16.1\ -16.3]$ mag, indicating this is a low luminosity dwarf galaxy. To relate these numbers to typical galactic luminosities, we use $M_{B*} = -21$, in order to retain backward compatability with previous works.[14–17] We note, though, that recent determinations of that parameter based on SDSS[18] and 2dF[19] galaxy redshift surveys indicate lower values (by $\sim$ 1 mag) should be used. We find that, using this value of M_*, the luminosity of the host of GRB 060614 is $L_B = 0.0092\ L_*$. Using our spectroscopically measured star formation rate $SFR = 0.0084$ M$_\odot$y^{-1} (Fig 2) we can now calculate the specific star formation rate, $SSFR \equiv SFR/L[L_*]$ and find $SSFR = 0.91$ M$_\odot$ y^{-1} $(L/L_*)^{-1}$.

Inspecting the sample of long GRBs[14] we find these have a mean SSFR value of $< SSFR >= 9.7 \pm 2.1$, indicating that the galaxy has a remarkably low SSFR in comparison, more than 4 standard deviations below the mean (and > 5 times below the lowest value in the sample, SSFR=5.45 for the host of GRB 990123). Considering only long GRBs at low redshifts, we find 4 available data points: GRB 980425 ($z = 0.0084, SSFR \sim 6$[16]), XRF 060218 ($z = 0.03, SSFR \sim 7$[17]), GRB 031203 ($z = 0.103, SSFR = 52.6$[20]) and GRB 030329 ($z = 0.168, SSFR = 34$[15]). While the sample is obviously too small for a robust statistical analysis, its mean SSFR is actually higher than the mean SSFR for the high-z sample, and the SSFR value for the GRB 060614 host lies > 20 times below the mean value and > 6 times below the lowest SSFR value among the low-z long GRB sample. We conclude that the host of GRB 060614 appears to have an atypically low SSFR.

Recently,[4] it has been shown that long GRBs explode in unique locations within their hosts - in proximity to the brightest star-forming knots. This effect is stronger than expected had the GRB distribution followed the UV light (a tracer of massive star population) as do core-collapse SNe. This may suggest that long GRBs originate from the most massive, short-lived stars, preferentially formed in, and exploding in the vicinity of, areas of intense star formation.[4] We have repeated this analysis on *HST*/ACS *B*-band images of the host of GRB 060614. We find that GRB 060614 resides in a markedly faint pixel, offset from the rest-UV brightest regions in the host. Only $1-2$ of known 32 long GRBs[4] reside in fainter pixels (Fig. 3), indicating an atypical location of GRB 060614 within its galaxy, when compared to the census of long GRBs.

Finally, we applied galaxy modelling to our high-resolution *HST* data to determine the galaxy light distribution. We calculated a model of the galaxy using the *GALFIT* galaxy modelling package.[21] The galaxy is best fit by an exponential disk model, accounting for the majority of the galaxy light.

Supplementary Figures:

Supplementary Figure 1: *HST* imaging of the vicinity of GRB 060614 argues against a chance coincidence of a high redshift GRB behind the z=0.125 host galaxy. The afterglow of GRB 060614 (diamond) is spatially coincident with a dwarf, z=0.125 galaxy (upper left). No evidence of faint, background galaxies is seen at this location, and artificial galaxies (fainter versions of the galaxy marked on the upper right) are recovered even when their intrinsic luminosity, when placed at z=1, is as low as $M_V = -16$. The host of GRB 060614 is spatially small, and only events occurring within the thin ellipse (with major axis of $1''$) would be likely associated with it. Events offset from the galaxy by $4.3''$[1] would most likely be related to other galaxies in the field. Finally, note that the low surface density of bright galaxies in this area indicates a low probability (0.004) for a random line of sight to intersect a galaxy.

Supplementary Figure 2: The remarkable host galaxy of GRB 060614. A spectrum of the host galaxy of GRB 060614 (thin blue curve) obtained with the GMOS-S spectrograph mounted on the Gemini-South 8m telescope at Cerro Pachon, Chile, on July 15, 2006 UT. Four exposures of 1200s each were reduced and combined in the usual manner within IRAF, including wavelength- and flux-calibration using the smooth spectrum standard star EG131. The spectral continuum is similar to a template Sc galaxy spectrum (heavy green curve) shifted to $z = 0.125$ and scaled in flux. We note that the emission lines are much weaker, though. From the luminosity of the Hα line we derive an estimate of the star-formation rate in the galaxy, SFR = 0.0084 $M_\odot$ yr^{-1}. Correction for possible slit losses was performed by deriving synthetic photometry from the spectrum and scaling it to match our *HST*-based host galaxy magnitudes. The applied correction was small ($\approx 20\%$) as expected in view of the small spatial size of the galaxy (Fig. 1) and the use of a $1''$-wide slit under good atmospheric conditions ($0.7''$ seeing). The ratio of Hα to Hβ line strengths indicates that emission-line regions in this dwarf galaxy suffer negligible extinction.

Supplementary Figure 3: The position of GRB 060614 on the Fruchter diagram,[4] a measure of the distance of a GRB from bright areas in its host galaxy, is atypical for long GRBs. We conducted the analysis by exact replication of the published one[4] on our host galaxy *HST* B-band (restframe $3,900$ Å) image (red asterisk). Long GRBs have been shown[4] to be found in the rest-UV-brightest areas of their host. This is not the case for GRB 060614 – only two of the 32 GRBs in the sample reside in fainter pixels – indicating an atypical location. Moreover, due to the low redshift of GRB 060614 compared with those in the above sample, we suspect that our analysis underestimates how atypical the location of this GRB is. First, we note that due to the low redshift of this GRB an image in an even bluer band would be more appropriate for the analysis, to match the restframe-UV (typically $\sim 2,500$ Å) used in the analysis of the long GRB sample. As star-forming regions become more dominant in restframe UV and galaxies tend to become more clumpy around these areas, we estimate that the location of this GRB on a restframe-UV image would become even more remarkable (following the trend we see when performing the analysis on our BVI images). Second, at higher redshift, the lower signal to noise will cause the outskirts of galaxies to no longer be detected, decreasing the fraction of detected light in fainter pixels. To simulate this effect[4] we increase the galaxy detection threshold from 1σ to 2σ (to emulate higher noise levels) and find that indeed the fraction of host galaxy light in pixels fainter than the GRB location falls by $\sim 50\%$ (green asterisk). Only a single GRB in the entire sample[4] falls on a fainter pixel. We thus conclude that the location of GRB 060614 within its host is atypical, as it falls among the fainter $3-6\%$ (1-2 of 32) of known long GRB locations. While the location of this event (around the half-light radius of its host in V-band) would be exactly what you expect for events that follow the stellar light, it is surprising for long GRBs, which have been shown[4] to be significantly more concentrated around the bright star-forming regions in their hosts.

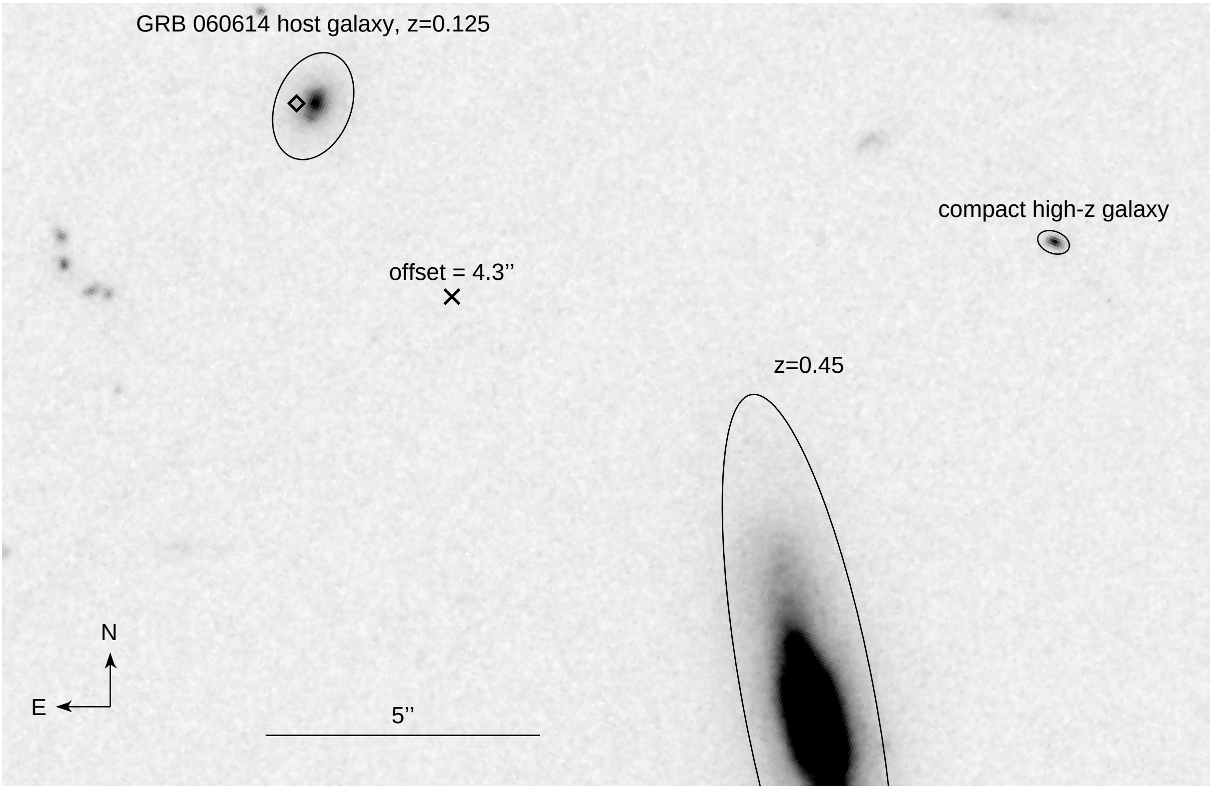
GRB 060614 host galaxy, z=0.125
compact high-z galaxy
offset = 4.3''
z=0.45
N
E
5''

Figure 1.

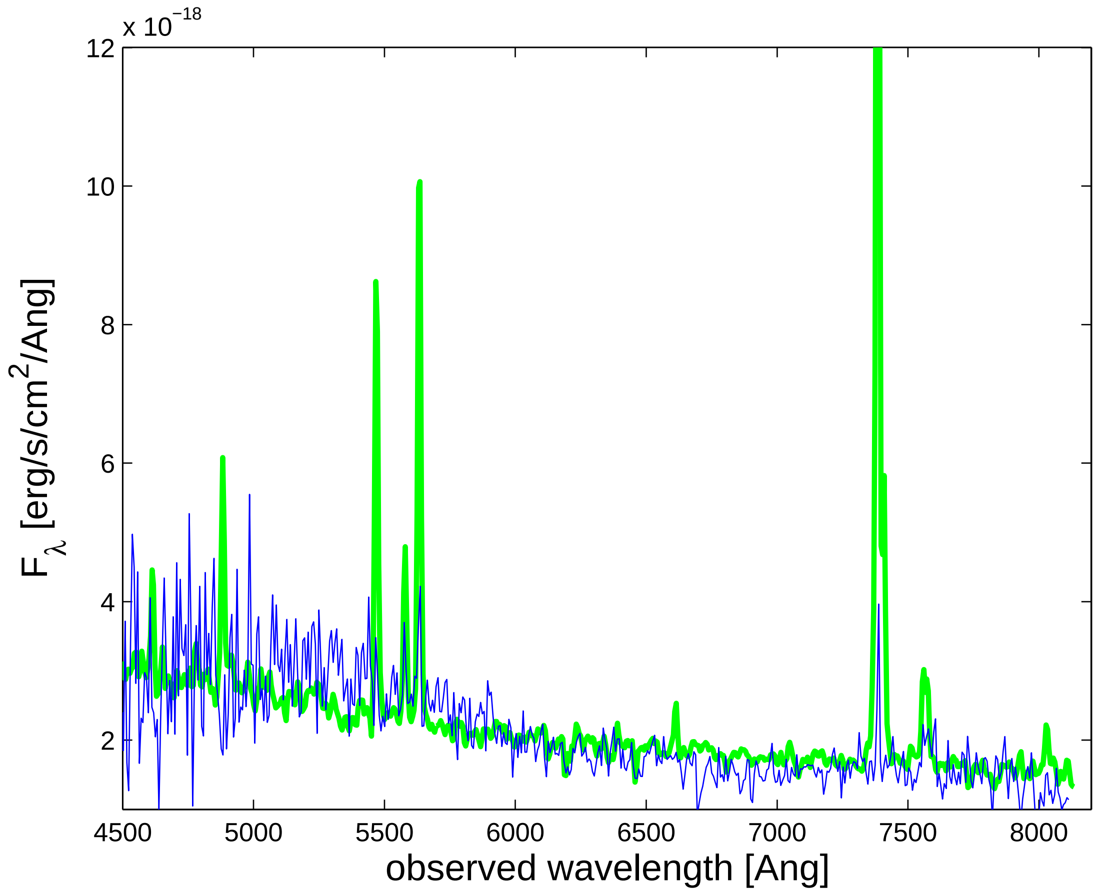
x 10^−18
12
10
8
6
4
2
F_λ [erg/s/cm²/Ang]
4500
5000
5500
6000
6500
7000
7500
8000
observed wavelength [Ang]

Figure 2.

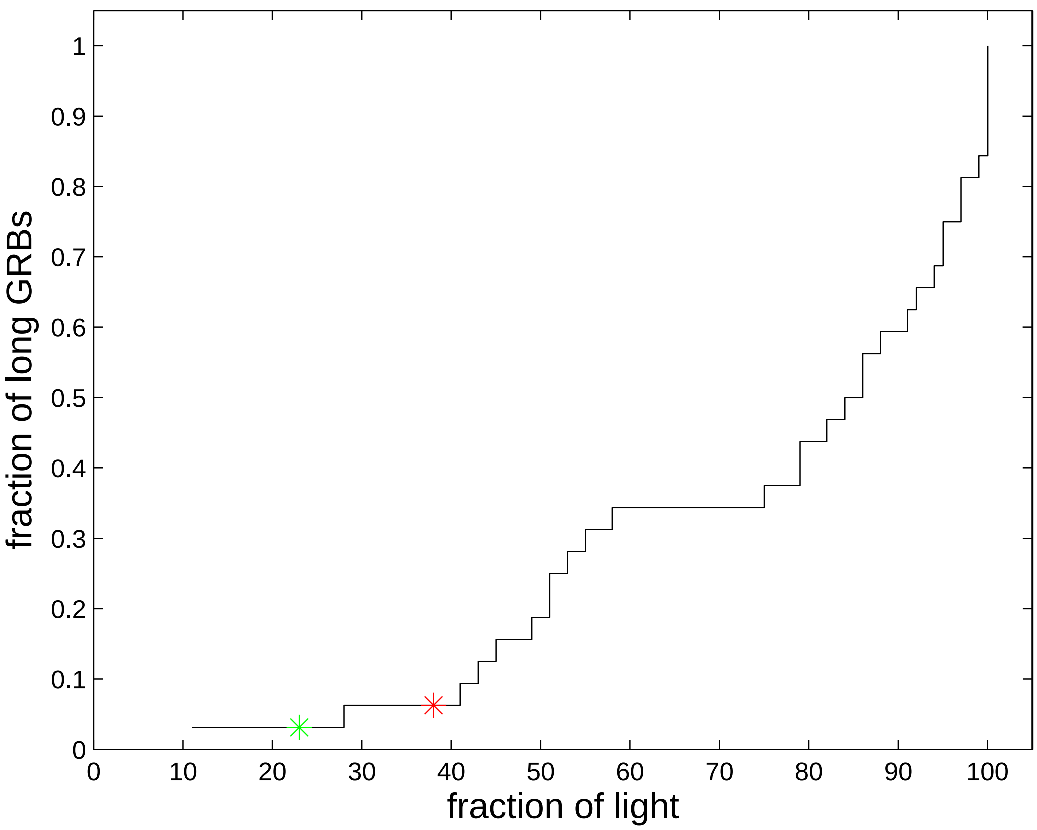
fraction of long GRBs
fraction of light
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
70
80
90
100

Figure 3.

Supplementary Data:

a. Observations reported here:

Band	Magnitude [mag]	error [mag]	Flux [erg s^{-1} cm^{-2} $Å^{-1}$]	Flux error	Time from GRB [day]	Instrument	Exposure time [s]
R	20.2	0.3	0.1552×10^{-16}	0.0985×10^{-16}	0.0179	SSO40+CCD	300
R	19.9	0.2	0.2112×10^{-16}	0.0859×10^{-16}	0.0221	SSO40+CCD	300
R	19.9	0.2	0.2112×10^{-16}	0.0859×10^{-16}	0.0262	SSO40+CCD	300
R	19.9	0.2	0.2112×10^{-16}	0.0859×10^{-16}	0.0303	SSO40+CCD	300
R	19.1	0.1	0.4638×10^{-16}	0.0894×10^{-16}	0.0713	SSO40+CCD	300
R	19.2	0.1	0.4212×10^{-16}	0.0815×10^{-16}	0.1188	SSO40+CCD	300
R	19.1	0.1	0.4638×10^{-16}	0.0894×10^{-16}	0.1608	SSO40+CCD	300
R	19.0	0.1	0.5106×10^{-16}	0.0980×10^{-16}	0.1968	SSO40+CCD	300
R	18.8	0.1	0.6180×10^{-16}	0.1178×10^{-16}	0.2427	SSO40+CCD	300
V	26.3	0.18	1.0631×10^{-19}	3.6302×10^{-20}	13.9672	*HST*+WFPC2	6000
V	>27.75	-	2.8221×10^{-20}	-	31.7609	*HST*+ACS	3600
I	24.9	0.1	1.2904×10^{-19}	1.9120×10^{-20}	13.5682	*HST*+WFPC2	6000
I	>27.5	-	1.2324×10^{-20}	-	31.9734	*HST*+ACS	3600

b. Swift data:

Band	Flux [erg s^{-1} cm^{-2} $Å^{-1}$]	Flux error	Time from GRB [day]	Instrument
V	4.26×10^{-17}	1.19×10^{-17}	0.0667	*Swift*+UVOT
V	4.35×10^{-17}	0.99×10^{-17}	0.1869	*Swift*+UVOT
V	6.60×10^{-17}	1.22×10^{-17}	0.1905	*Swift*+UVOT
V	4.26×10^{-17}	0.99×10^{-17}	0.1940	*Swift*+UVOT
V	3.36×10^{-17}	1.02×10^{-17}	0.5706	*Swift*+UVOT
V	2.43×10^{-17}	0.69×10^{-17}	1.1030	*Swift*+UVOT
V	0.8×10^{-17}	0.26×10^{-17}	2.4493	*Swift*+UVOT

c. Data from the literature:

Band	Magnitude [mag]	error [mag]	Flux [erg s^{-1} cm^{-2} $Å^{-1}$]	Flux error	Time from GRB [day]	Instrument	Exposure time [s]
R	19.0	0.3	0.5106×10^{-16}	0.2974×10^{-16}	0.3376	Watcher40[22]	1200
R	19.43	0.1	0.3368×10^{-16}	0.0660×10^{-16}	0.5832	D1.5+DFOSC[23]	300
R	19.56	0.1	0.2965×10^{-16}	0.0585×10^{-16}	0.6412	D1.5+DFOSC[23]	300
R	19.61	0.1	0.2822×10^{-16}	0.0559×10^{-16}	0.6865	D1.5+DFOSC[23]	300
R	19.70	0.1	0.2581×10^{-16}	0.0514×10^{-16}	0.7259	D1.5+DFOSC[23]	300
R	19.81	0.1	0.2312×10^{-16}	0.0465×10^{-16}	0.7789	D1.5+DFOSC[23]	300
R	19.83	0.1	0.2266×10^{-16}	0.0456×10^{-16}	0.7822	D1.5+DFOSC[23]	300
R	19.76	0.1	0.2431×10^{-16}	0.0487×10^{-16}	0.7854	D1.5+DFOSC[23]	300
R	19.87	0.1	0.2177×10^{-16}	0.0440×10^{-16}	0.7888	D1.5+DFOSC[23]	300
R	21.14	0.2	0.0533×10^{-16}	0.0274×10^{-16}	1.5149	D1.5+DFOSC[23]	2700

Notes:

The host galaxy flux has been subtracted from the flux data reported above. Magnitudes reported are not galaxy subtracted. The early evolution of the light curve of this event is illustrated using R-band data obtained by us and some of the observations reported in the literature. Additional multicolor data are reported elsewhere.[23,9]

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