General properties of optical/NIR emission of long-duration GRBs and their host galaxies

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Outline

1. LGRB optical/nIR emission (prompt & afterglow)

- 1.1. Photometric properties (prompt / early afterglow / late afterglow)
- 1.2. Spectroscopy
- 1.3. Optical/NIR afterglow parameters

2. LGRBs host galaxies

- 2.1. Morphology
- 2.2. Photometric properties
- 2.3. Spectroscopy
- 2.4. Host galaxies parameters

Summary

1. LGRB opt/NIR emission (prompt+afterglow) General Properties

1. LGRB Opt/nIR emission General Properties

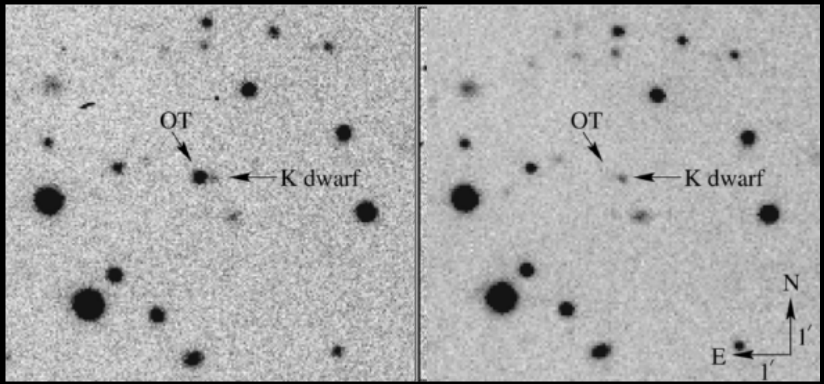
Early history

- The detection of the first GRBs by the *BeppoSAX*/WFC (3' error radius), and GRB 970111 (the first dark GRB) (Gorosabel et al. 1998).

- The detection of first X-ray afterglow (GRB 970228) by *BeppoSAX*/NFI (50" error radius) (Costa et al 1997) led to the detection of the first optical afterglow (van Paradijs et al. 1997).

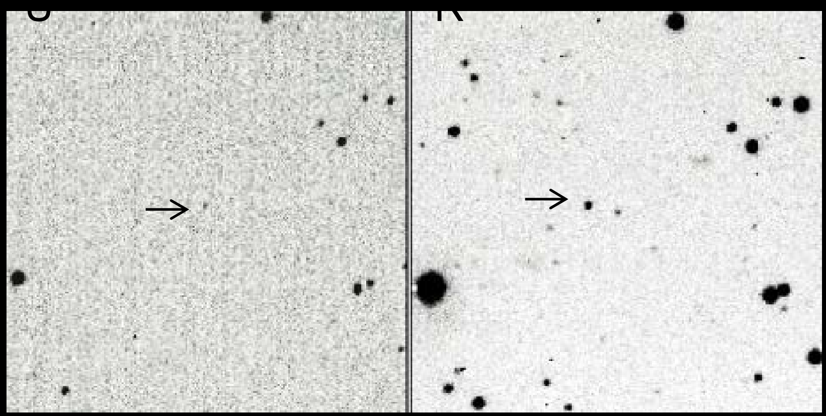
- The second optical afterglow (GRB 970508) revealed its extremely blue color and strong rebrightening few hours after (Castro-Tirado et al. 1998, Pedersen et al. 1998) .

GRB 970228



van Paradjis et al. (1998)

GRB 970508



Castro-Tirado et al. (1998)

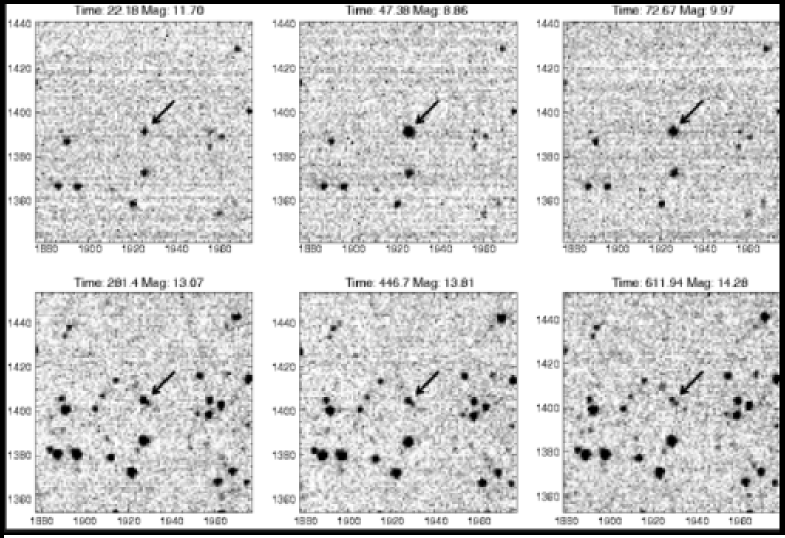
1. LGRB Opt/nIR emission General Properties

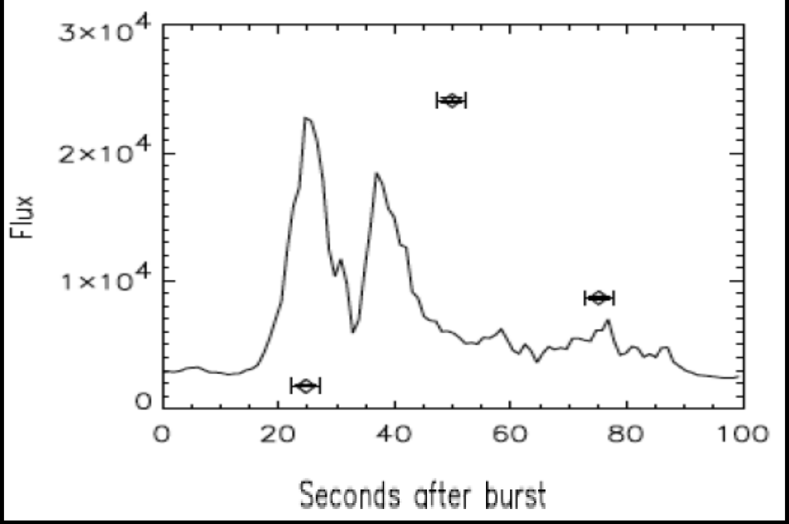
1.1. Photometric properties - Prompt emission (I)

GRB 990123: First detection of prompt optical emission simultaneously to the gamma-rays, with the optical emission peaking at V = 8.9 (Akerlof et al. 1999).

Only automated or robotic systems (such as ROTSE in this case) could promptly react to the incoming alerts.

GRB 990123





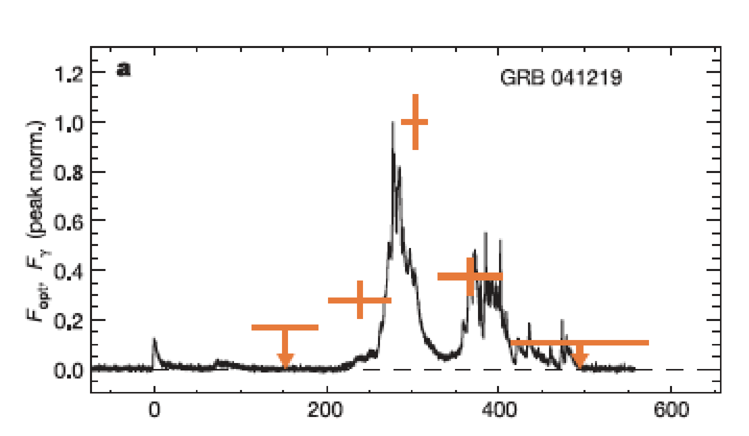
Akerlof et al. (1999)

1. LGRB Opt/nIR emission General Properties

1.1. Photometric properties - Prompt emission (II)

GRB 041219: 2nd detection of optical prompt emission (by RAPTOR-S) and first detection in the nIR (by the 1.3m PAIRITEL) related to a ~6 min *INTEGRAL* burst (Vestrand et al. 2005, Blake et al. 2005).

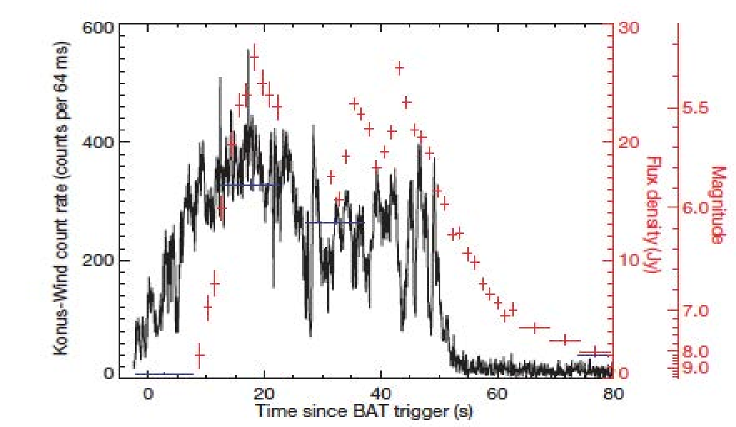
GRB 041219



Vestrand et al. (2005)

GRB 080319B: The brightest optical GRB counterpart detected so far (reaching V = 5.3), by TORTORA atop REM (Racusin et al. 2008).

GRB 080319B



Racusin et al. (2008)

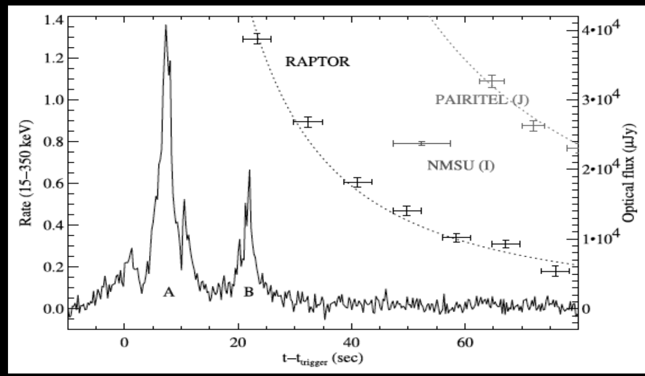
Explanation in both cases: Internal shocks.

1. LGRB Opt/nIR emission General Properties

1.1. Photometric properties - Prompt + Early time emission (I)

GRB 061126A: Color evolution of the optical flash. The optical/nIR photometric SED exhibited a moderate red-to-blue evolution in the spectral index at about 500s post burst (Perley et al. 2008).

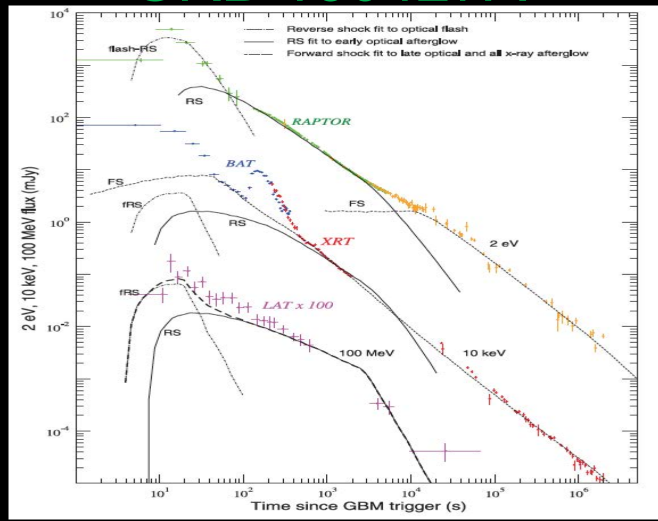
GRB 061126A



Perley et al. (2008)

GRB 130427A: The “monster” GRB prompt optical flash was detected by the RAPTOR full-sky monitors, reaching V = 7 (Laskar et al. 2013, Maselli et al. 2014). The optical measurements fell far from the values expected from the extrapolation of the keV-MeV SED.

GRB 130427A



Vestrand et al. (2008)

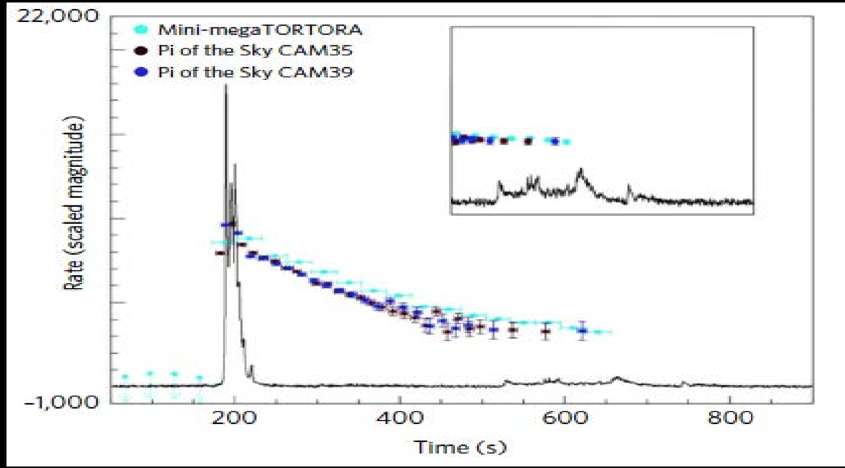
Explanation in both cases: synchrotron emission from a <u>reverse shock.</u>

1. LGRB Opt/nIR emission General Properties

1.1. Photometric properties - Prompt + Early time emission (II)

GRB 160625B

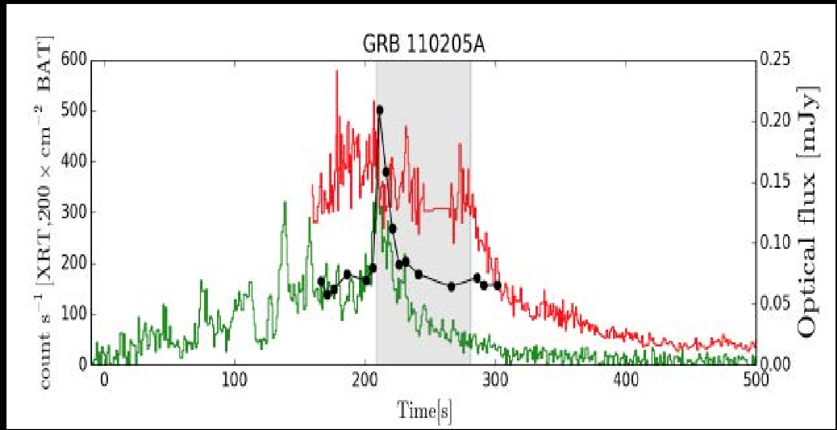
GRB 160625B: Detected by Pi-of-the-Sky (at the BOOTES-1 station in Spain) and Mini-Mega TORTORA. The prompt optical emission is explained as the forward shock. But it is above the extrapolation of the sub-MeV spectral component (Zhang et al. 2018). See also Ruffini et al. (2019).



Zhang et al. (2018)

GRB 110205A

Finally, internal shocks are proposed for a majority of GRBs in a sub-sample of 18 GRBs for which optical emission peaks during gamma-ray emission (Kopač et al. 2013). This is also supported by a larger LGRB sample (21) studied by Oganesyan et al. (2019).



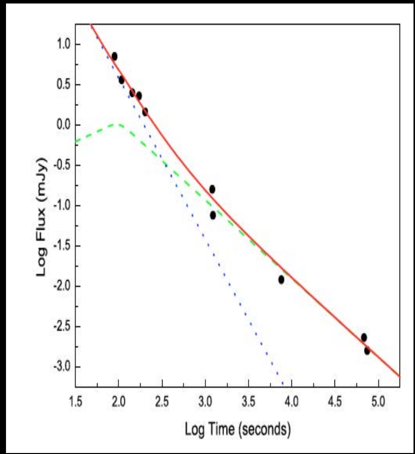
Oganesyan et al. (2019)

1. LGRB Opt/nIR emission General Properties

1.1. Photometric properties - Early time emission (I)

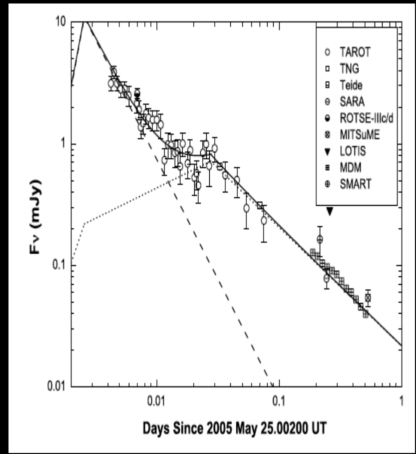
The early emission feature can be interpreted as RS emission superposed by FS emission in an ISM environment (Huang et al. 2016).

GRB 021211



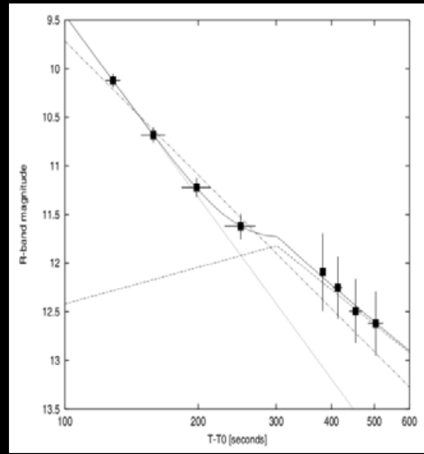
Wei (2003)

GRB 050525A



Shao & Dai (2005)

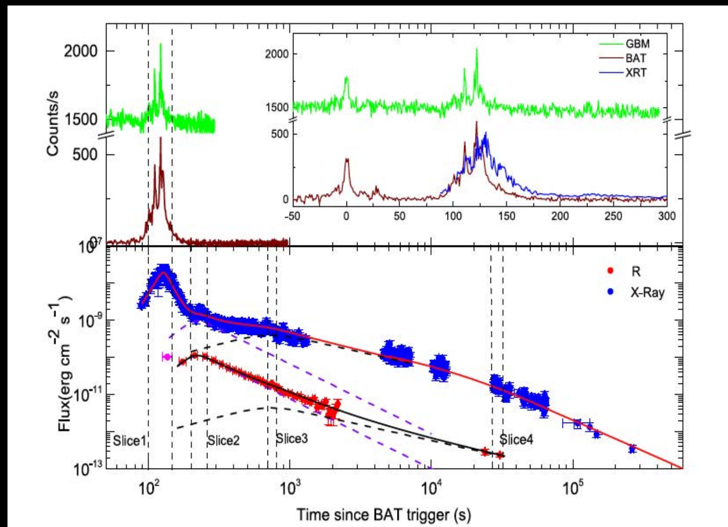
GRB 060117A



Jelínek et al. (2006)

By morphologically analyzing the early optical afterglow light curves of 63 GRBs, Gao et al. (2015) found 15 cases with early optical light curves dominated by RS emission. See also Japelj et al. (2014).

GRB 140512A

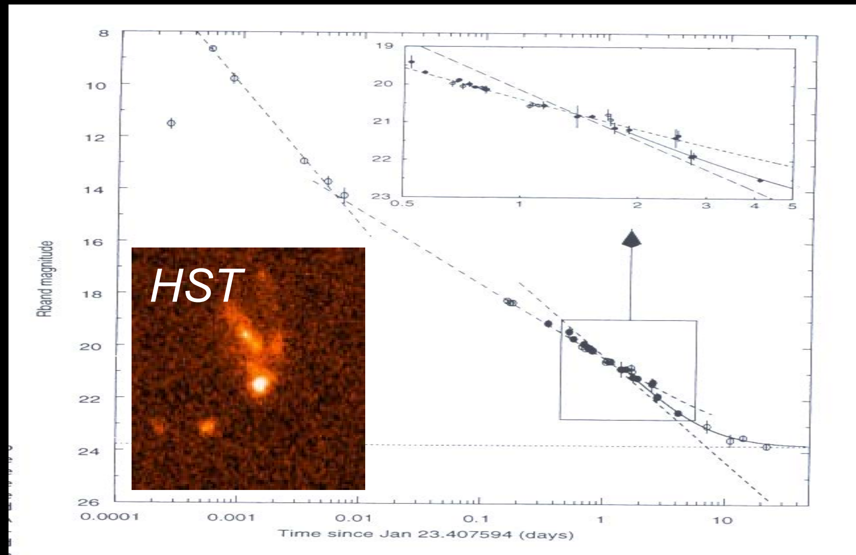


1. LGRB Opt/nIR emission General Properties

1.1. Photometric properties - Early time emission (II)

GRB 990123

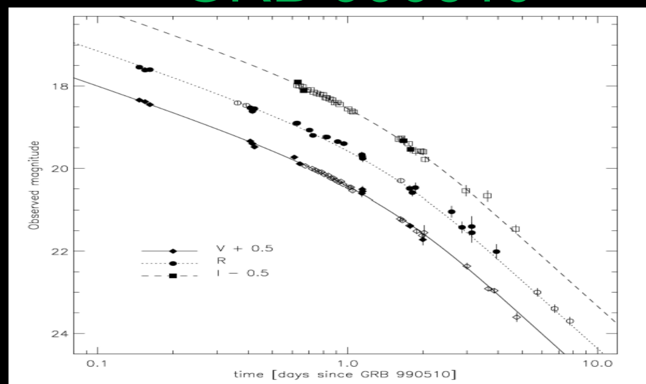
GRB 990123: 1st detection of <u>jet break</u> in a GRB (Castro-Tirado et al. 1999, Kulkarni et al. 1999). The jet was indicative of relativistic beaming, i.e. collimated (rather than isotropic) radiation, thereby reducing the total energy released by $f_b \sim \Theta_0^2/2$ (i.e. 10^{53} erg for $\Theta_0 = 0.3$), to a level where stellar-death models were still tenable.



C-T et al. (1999), Pian et al. (1999)

GRB 990510

GRB 990510: One of the best-sampled optical light curves and provided the clearest signature observed to date for jet collimation of the ejecta in GRB sources (Harrison et al. 1999).



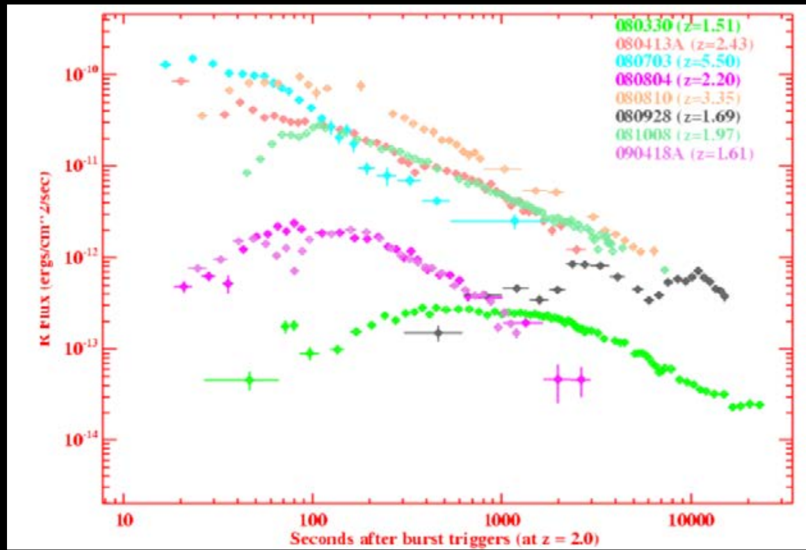
Harrison et al. (1999)

1. LGRB Opt/nIR emission General Properties

1.1. Photometric properties - Early time emission

The rising optical light curves help to constrain the jet geometry: off-axis vs structured jet models (Painatescu et al. 1998).

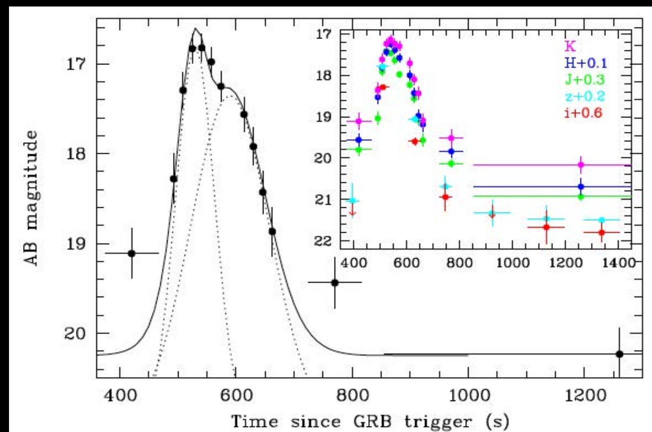
Moreover, the peak time of the rising lightcurves provides the initial Lorentz factor $\Gamma_0 = 2 \times \Gamma(t_{peak})$ (Molinari et al. 2007). For a sample of 8 LGRBs, Γ_0 ~10^2 to ~10^3 (Pandey et al. 2011)



Pandey et al. (2011)

Flaring at early time (< 10^4 s post-burst). Simultaneous broad-band observation of GRB 071031 provided evidence that inner engine activity may last (or be revived) over hours or days, due to internal shocks.

GRB 071031



Krühler et al. (2009)

1. LGRB Opt/nIR emission General Properties

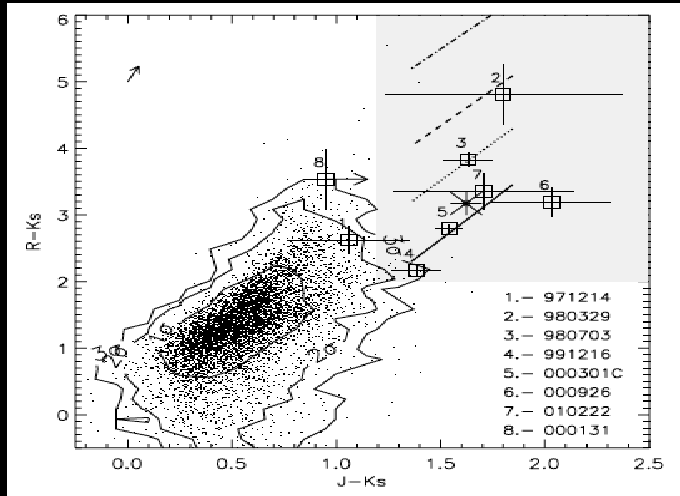
1.1. Photometric properties – Early & late time emission

- <u>Colors.</u> GRB afterglows have power-law spectral energy distributions $F_\nu \sim \nu^{-\beta}$, which can be distinguished from curved thermal stellar spectra in colour-colour plots.

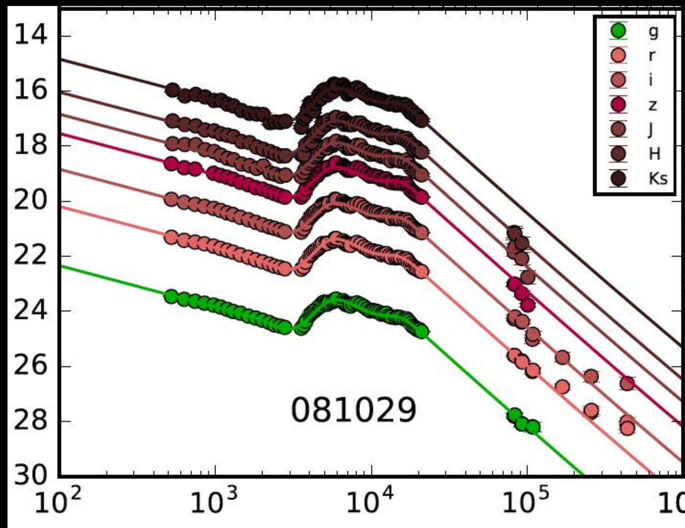
- For a sample of 8 LGRB Opt/nIR afterglows, the derredened colours verified $R\text{-}K_s > 2.0$ $J\text{-}K_s > 1.2$ (for $z < 3.7$)

- The GRB 001011 afterglow is the 1st discovered with the assistance of colour-colour diagram techniques (Gorosabel et al. 2002). See also Rhoads (2001), Simon et al. (2001).

- For a sample of 70 LGRBs, Li et al. (2018) found that color indexes do not vary with time (but only during short periods in most bursts).



Gorosabel et al. (2002)



Li et al. (2018)

1. LGRB Opt/nIR emission General Properties

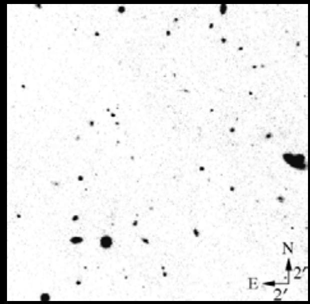
1.1. Photometric properties – Dark bursts

- In 1997 dark GRBs also showed up (e.g. GRB 970828) (Groot et al. 1998).

- The "dark burst" term was coined. Jakobsson et al. (2004) simply suggested that in dark bursts the optical-X-ray spectral index $\beta_{OX} < 0.5$.

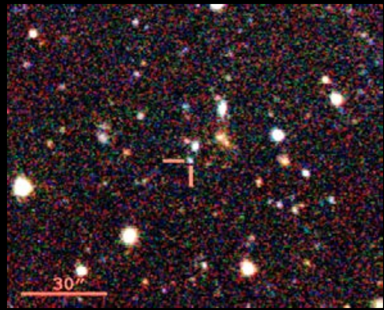
- Dark events: ~ 18+/- 8 % (and amongst them, 57 +/- 14% due to moderate dust extinction enhanced due to moderate z, and 28 +/- 14 % due to Lyman-α blanketing for high-z events) (Greiner et al. 2019).

GRB 970828



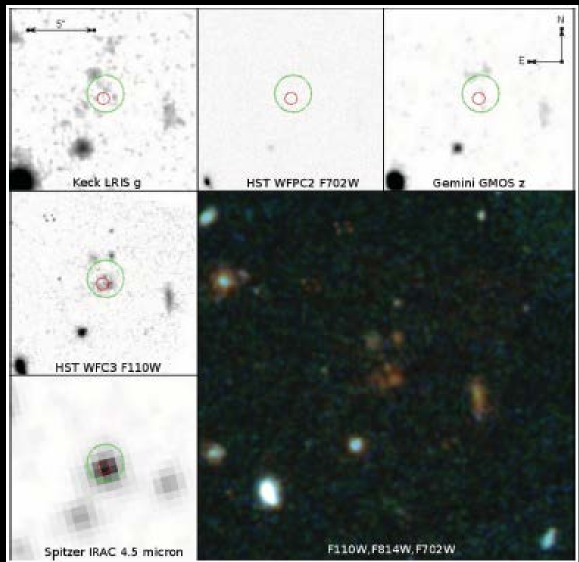
Groot et al. (1998)

GRB 051022A



C-T et al. (2005)

GRB 080207A



Svensson et al. (2012)

1. LGRB Opt/nIR emission General Properties

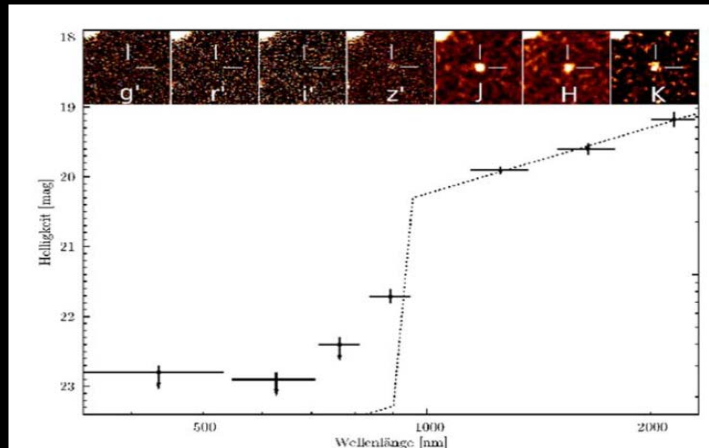
1.1. Photometric properties – High-z bursts

(see Tanvir and Le Floch's talks)

High-z events. There are ~18 GRBs at z > 5 reported so far. Amongst them: GRB 080913A (z~6.7, Greiner et al. 2009), GRB 090423A (z~8.2, Olivares et al. 2009, Tanvir et al. 2009) abd GRB 090429B (Cucchiara et al. 2011).

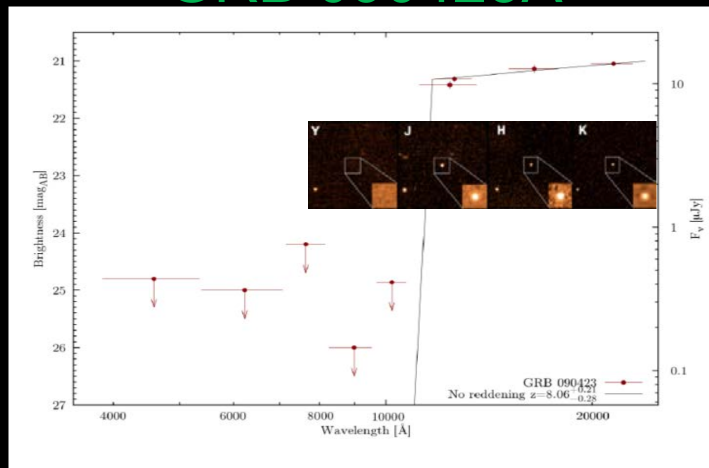
Among 273 GRB afterglows detected with GROND, no J-band drop-out GRB afterglows were detected. Unless z > 10 GRBs are systematically underluminous, the relative frequency of such z > 10 GRBs is < 0.4% (1σ). This is consistent with recent predictions of the redshift distribution of GRBs, similar to earlier estimates of ~5% (Greiner et al. 2019 and references therein).

GRB 080913A



Greiner et al. (2009)

GRB 090423A

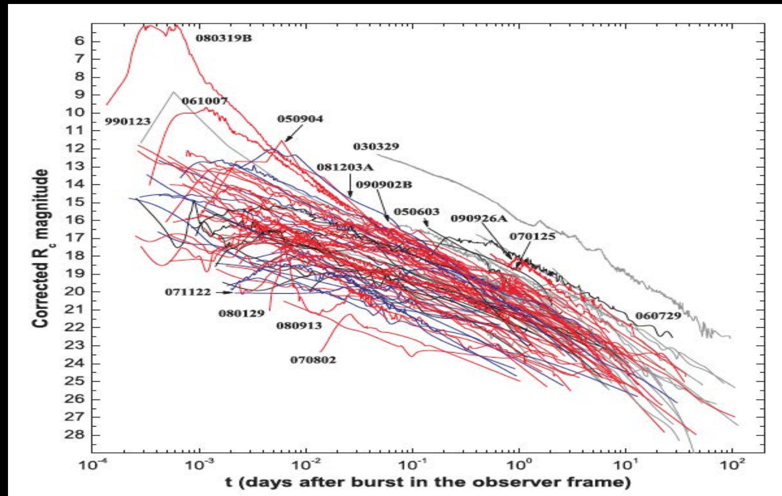


Tanvir et al. (2009)

1. LGRB Opt/nIR emission General Properties

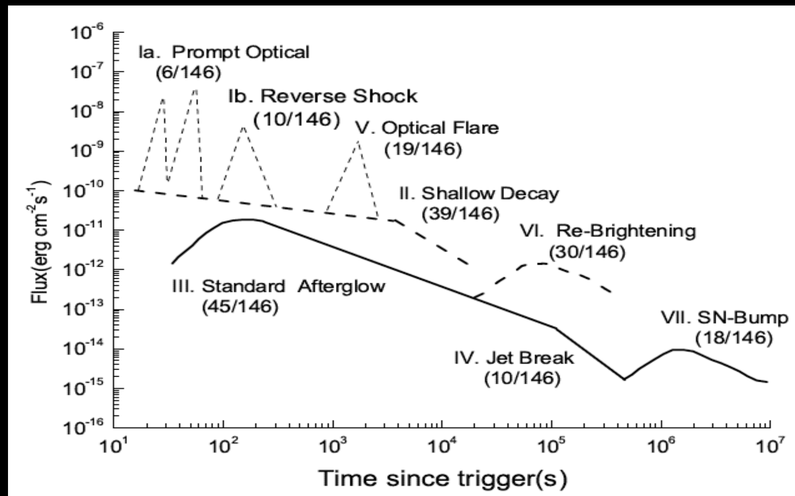
1.1. Photometric properties – Prompt, early & late time emission

•.A sample of 79 LGRB optical lightcurves up to 2009 was compiled by Kann et al. (2010).



Kann et al. (2010)

• A sample of 146 optical lightcurves was compiled by Li et al. (2012). By empirical fitting 8 possible emission components are identified and the results summarized in a "synthetic" lightcurve (Li et al. 2012). See also Li et al (2015).



Li et al. (2012)

1. LGRB Opt/nIR emission General Properties

1.2. Spectroscopy

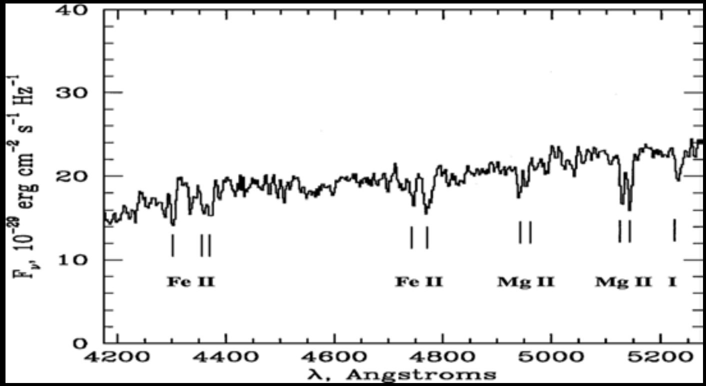
Since the first optical spectrum (Metzger et al. 1998), GRBs have become a powerful tool to probe the interstellar medium (ISM) of star-forming galaxies (Jakobsson et al. 2004, Prochaska et al. 2007, Fynbo et al. 2009, Krühler et al. 2013).

Spectral features in a sample of 69 GRB spectra are, on average, 2.5 times stronger than those seen in QSO DLA systems and slightly more ionised (de Ugarte Postigo et al. 2012).

Optical/nIR spectroscopy of the afterglows allows the measurement of a wide range of important properties of galaxies such as:

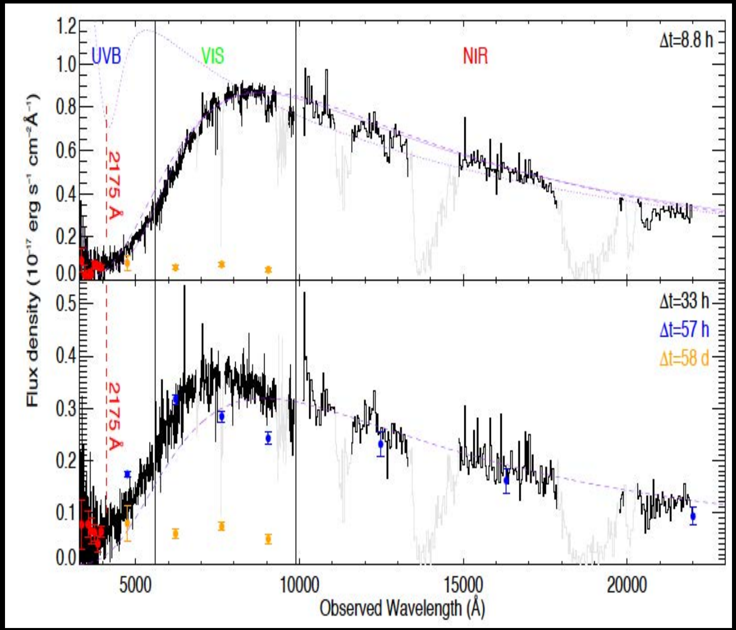
- chemical abundances (e.g. Savaglio 2006)
- molecular content (e.g. Fynbo et al. 2006)
- dust extinction (Watson et al. 2006).

GRB 970508



Metzger et al. (1998)

GRB 140506A



Fynbo et al. (2006)

1. LGRB Opt/nIR Emission General Properties

1.3. Opt/NIR afterglow parameters

[for a typical (non-obscured) LGRB afterglow]

1. R ~ 20-21 at 1 day postburst with a mean extinction A_V ~0.2
2. Colors R-K_s > 2.0   J-K_s > 1.2 (for z < 3.7)
3. *z* ~ 2
4. It may exhibit prompt emission, reverse shock and/or flaring in some cases if observations are conducted within the first hours post burst

- Parameters for a sample of 407 Type II (i.e. LGRB) optical afterglows (Li et al. 2016, 2020).

Parameter	Type II				
	N	mean $\mu(\gamma)$	σ	D_{KS}	P_{KS}
log T_{90}	371	1.68 ± 0.03	0.59 ± 0.03	0.05	0.41
log (1+z)	349	0.43 ± 0.01	0.18 ± 0.01	0.03	0.83
log E_{iso} (erg)	371	52.62 ± 0.05	1.01 ± 0.05	0.08	0.03
log L_{iso} (erg s^{-1})	368	52.00 ± 0.06	1.13 ± 0.07	0.08	0.03
α	197	-1.02 ± 0.03	0.34 ± 0.02	0.06	0.55

- Two interesting correlations:
  The Intrinsic Brightness-Average decay rate correlation (Oates et al. 2012)
  The Optical Luminosity-Time correlation (Dainotti et al. 2021).

2. LGRB Host galaxies general properties

2. Opt/nIR LGRB HGs General Properties

Early history

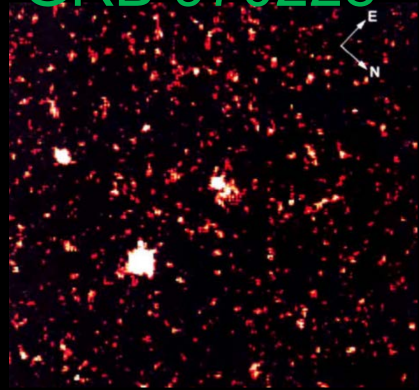
•The first opt/nIR HGs observations in 1997.

•They were typically faint, often compact, and required deep observations (even *HST*) to study their morphologies (Sahu et al. 1997, Pian et al. 1998).

•The detection of strong emission lines allowed to determine the HGs redshifts. z = 0.695 for GRB 970228 (the first one following this way) (Djorgovski et al. 1997).

•The galaxies were also typically blue and thus were clearly star forming systems, as seen with the first samples of HGs (Christensen et al. 2004).

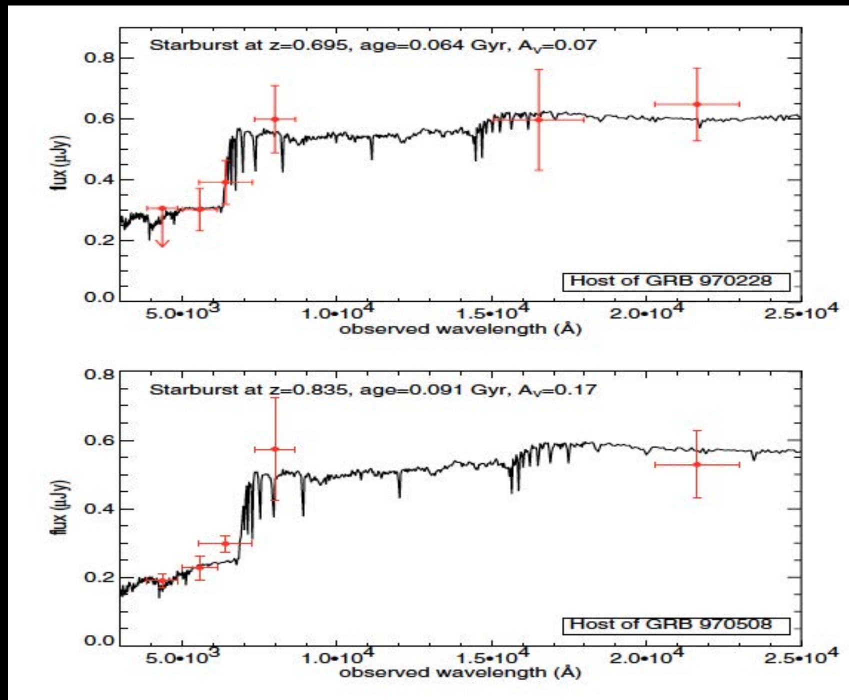
GRB 970228



Sahu et al. (1997)

GRB 970508

Pian et al. (1998)



Christensen et al. (1998)

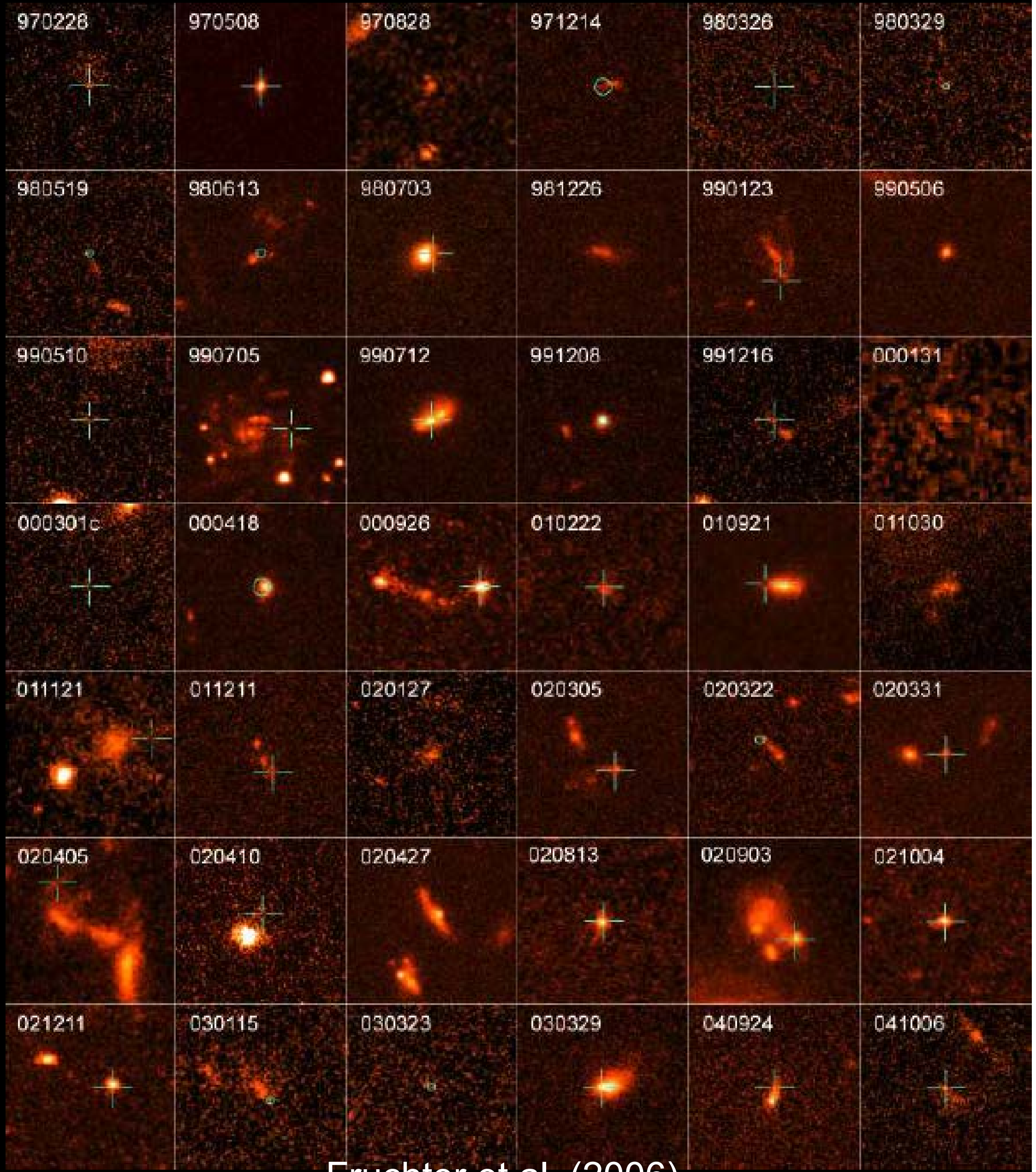
2. Opt/nIR LGRB HGs General Properties

2.1. Morphology (I)

Pre-*Swift* sample of 42 HGs (Fruchter et al. 2006).

•. The LGRB HGs are faint and can be seen in a wide range of galaxies, although there is a notable paucity of grand-design spirals.

•LGRBs are far more concentrated on the very brightest regions of their host galaxies than are the core-collapse SNe.



Fruchter et al. (2006)

2. Opt/nIR GRB HGs General Properties

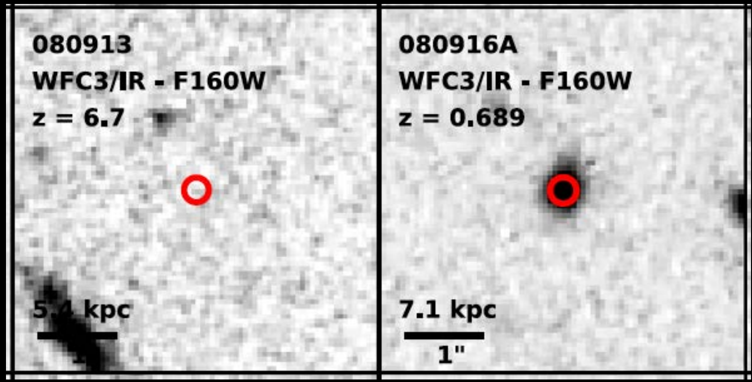
2.1. Morphology (II)

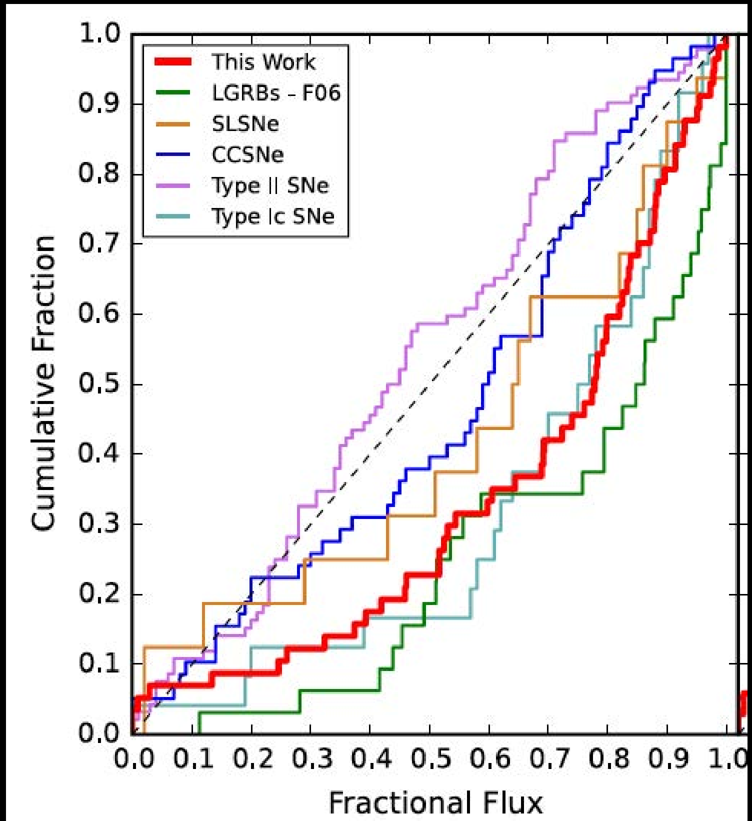
Post-*Swift* *HST* sample of 105 HGs (Blanchard et al. 2016).

- The spatial correlation of LGRBs with bright star-forming regions seen in the full sample is dominated by the contribution from bursts at small offset:

  -LGRBs in the outer parts of galaxies show no preference for unusually bright regions.

  -LGRBs strongly prefer the bright, inner regions of their hosts, indicating that the star formation taking place there is more favorable for LGRB progenitor production.

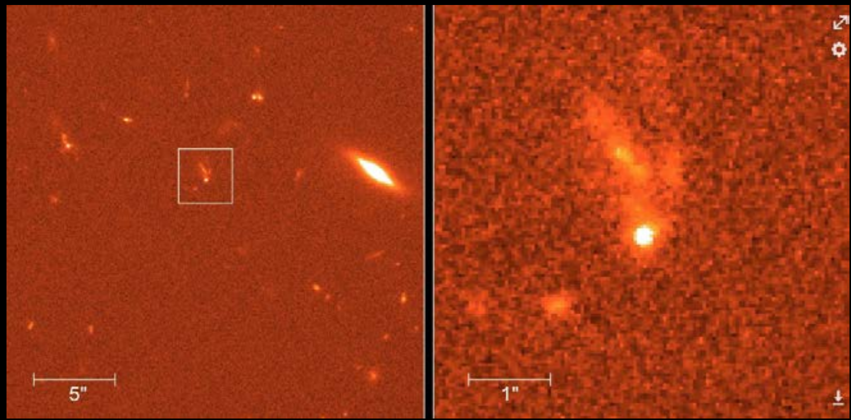




Blanchard et al. (2016)

2. Opt/nIR LGRB HGs General Properties

2.3. Morphology (III). Companions and interacting systems



GRB 990123 - Fruchter et al. (1999)

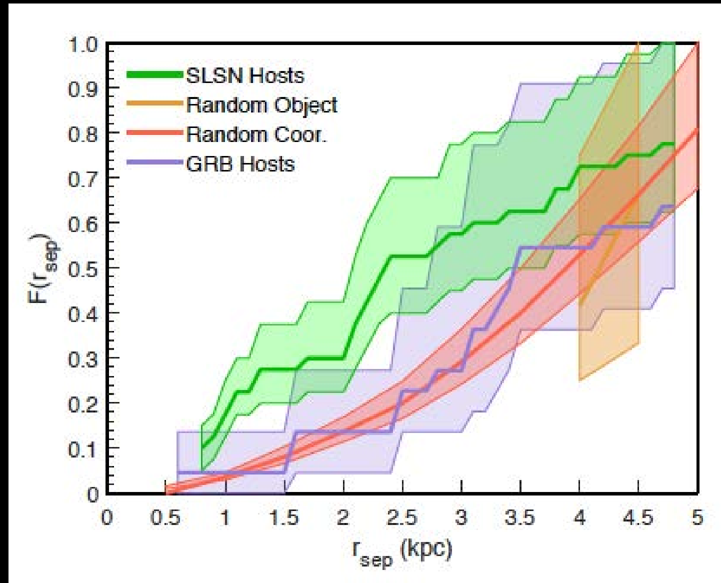
- 42 SLSN I hosts and 32 GRB HGs (all 74 observed by *HST*)

- GRB HGs have not many companion galaxies as SLSN I hosts (Vanggard Ørum et al. 2020).

- The differences between the SLSN and the GRB distributions are not statistically significant for the number of companions but they are marginally significant for the distance of the companions.

2. Average number of major companions within 5 kpc.

Sample	Number of companions
SLSN hosts	$0.70^{+0.19}_{-0.14}$
Random objects	$0.10^{+0.05}_{-0.05}$
Random coordinates	$0.06^{+0.02}_{-0.01}$
GRB hosts	$0.44^{+0.25}_{-0.13}$



Vanggaard Ørum et al. (2020)

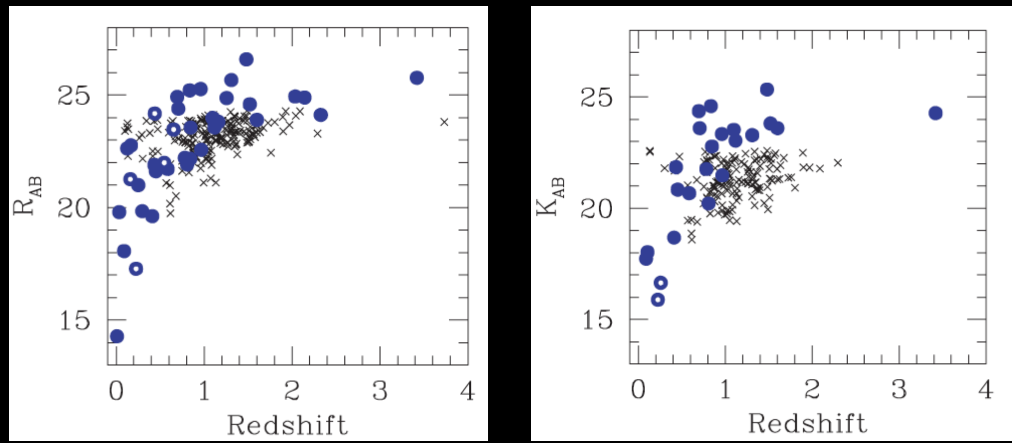
2. Opt/nIR LGRB HGs General Properties

2.2. Photometric properties (I)

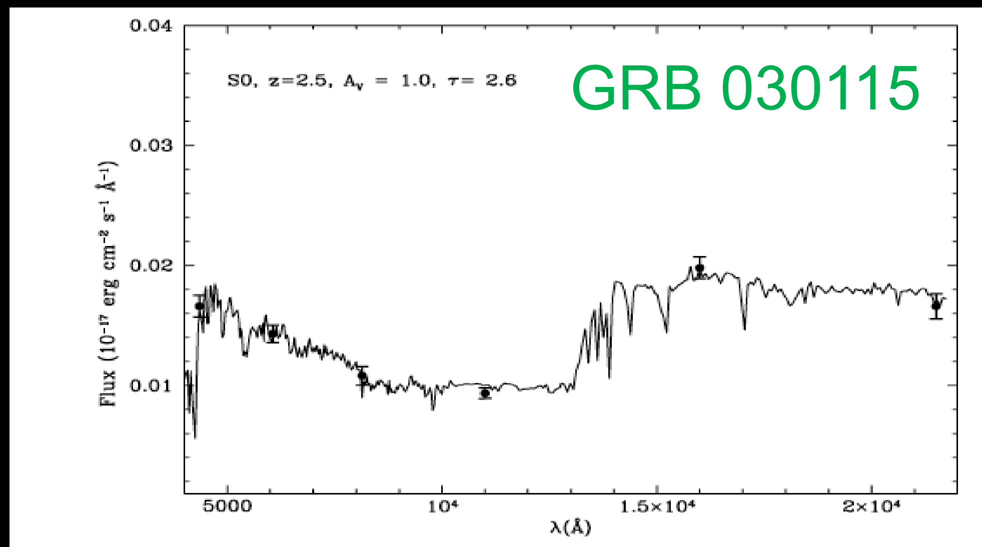
- On an initial sample of 46 GRB (32 Pre-*Swift*, 14 post-*Swift*), their HGs were found generally faint galaxies, with about half being fainter than R_{AB} = 23.5 and K_{AB} = 22.5 (Savaglio et al. 2009).

- Dust extinction in the visual band (for a subsample of 10 HGs) is A_V = 0.5 (Savaglio et al. 2009).

- Later studies revealed very few HGs showing a significant dust extinction, for example, by appearing as EROs (extremely red objects, R-K > 5) (e.g. Levan et al. 2006; Berger et al. 2007).



Savaglio et al. (2009)



Levan et al. (2006)

2. Opt/nIR LGRB HGs General Properties

2.2. Photometric properties (II)

• Using available multiband (opt/nIR) HG photometry, together with the redshift, allowed to determine galaxy parameters: stellar mass, metallicities, star forming-rate, first done by Savaglio et al. (2009).

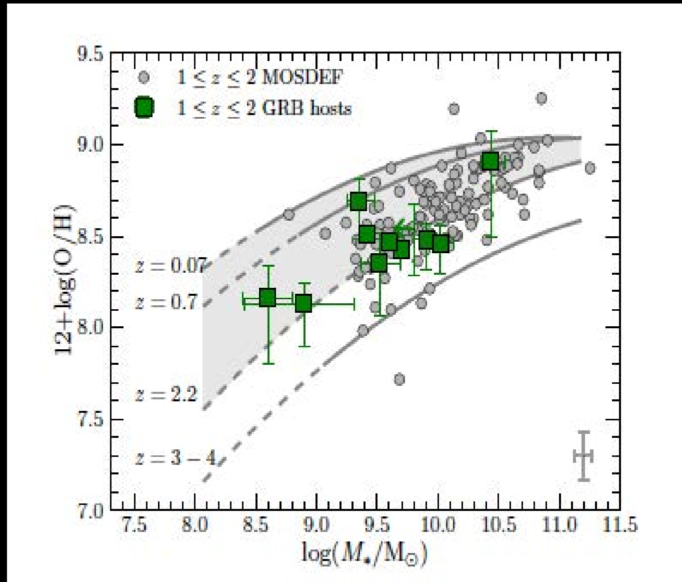
• This paved the way for the efforts in order to gather a carefully selected, unbiased and complete sample of LGRBs and their HGs such as: TOUGH (Hjorth et al. 2012), Swift/BAT6 (Salvaterra et al. 2012), SHOALS (Perley et al. 2016a) and e-SHOALS (Perley et al. 2021).

• Main results:

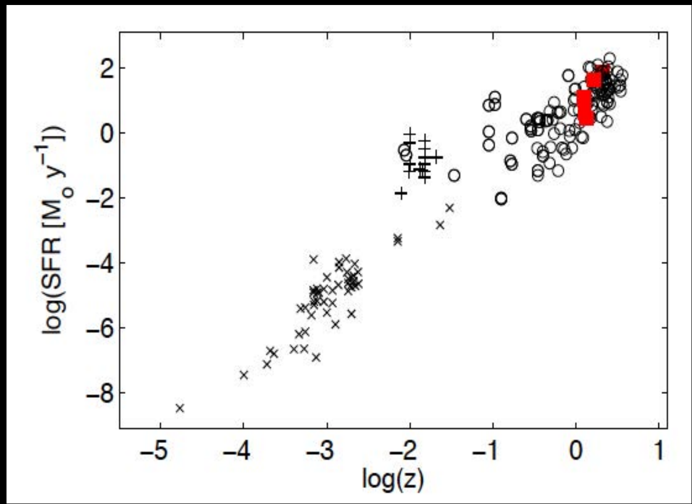
-The average HG stellar mass, log M_{*} ~ 9.5 $M_{\odot}$

-The average metallicity, Z ~1/5 $Z_{\odot}$ (Graham & Fruchter 2013, Leloudas et al. 2015, Palmerio et al. 2019) (Christensen's talk).

-The SFRs as a function of the redshift (Contini 2019) (Vergani's talk).



Palmerio et al. (2019)

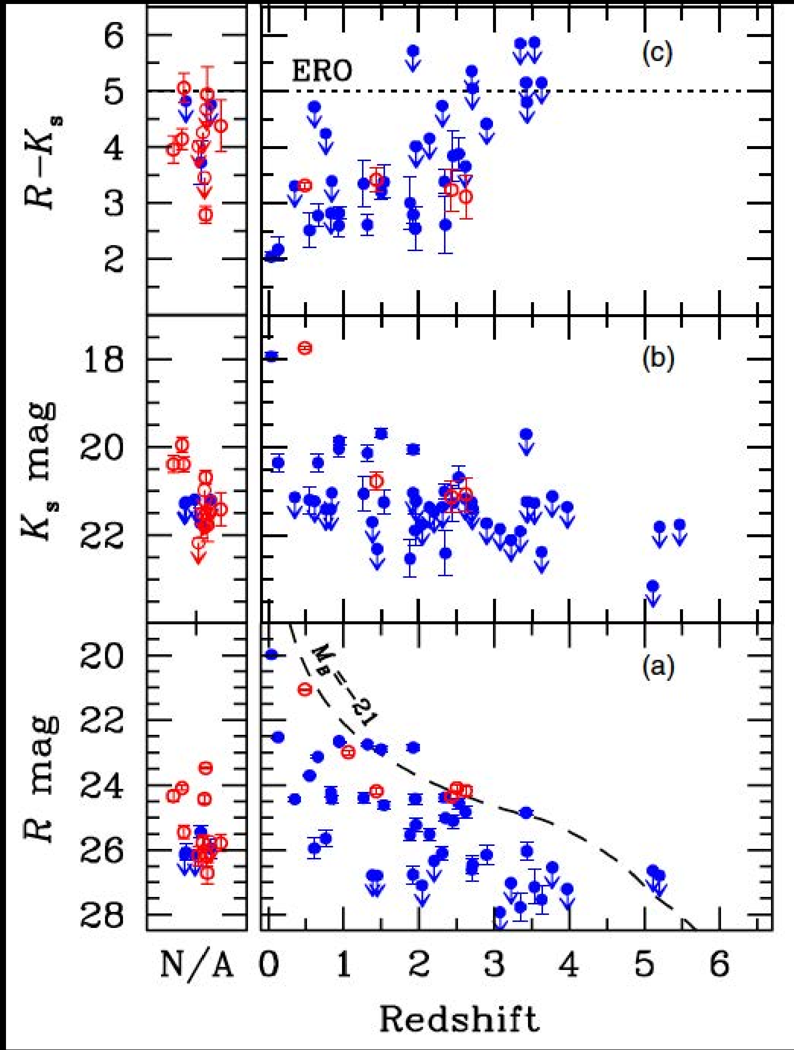


Contini (2019)

2. Opt/nIR LGRB HGs General Properties

2.2. Photometric Properties (III)

- For the TOUGH Survey – optically unbiased sample of 69 galaxies, <R> = 25.5 +/- 0.2 ; <K> > 22.5 (Hjorth et al. 2012)
- For Dark Hosts, <R> = 24.4 and <K> = 21.1 (in contrast to <R> = 25.8 and K > 22.5 for HGs with opt/nIR afterglows). HGs for Dark LGRBs are very different than the ones hosting opt/nIR afterglows! This shall be accounted for when performing statistical studies!
- 80% of the GRBs at z < 3 were detected, although only 42% have K_s–band detections, which confirms that GRB-selected host galaxies are generally blue. No detection of HGs at z > 3. And 77% had redshift measurements with <z> = 2. 14 +/- 0. 18.



Hjorth et al. (2012)

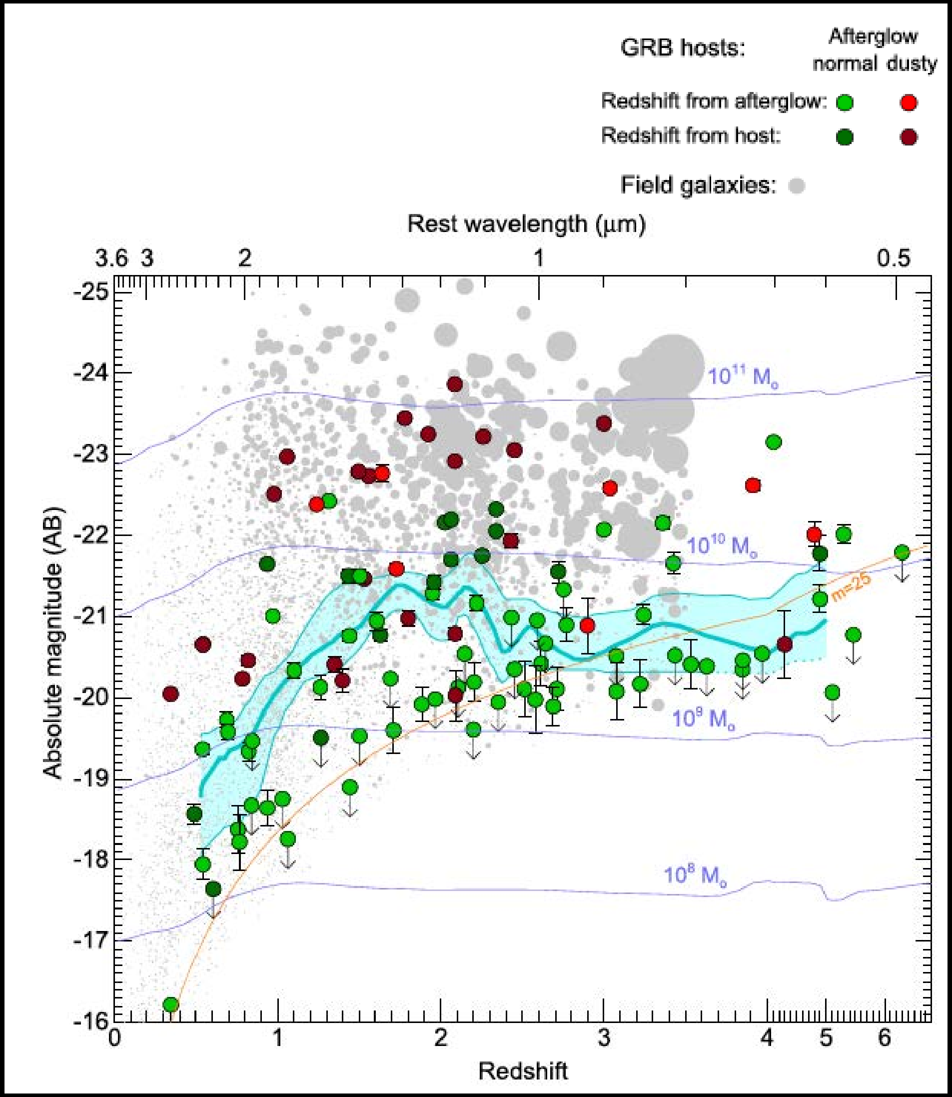
2. Opt/nIR LGRB HGs General Properties

2.2. Photometric Properties (IV)

•For the SHOALS survey, nIR luminosities and stellar masses were determined using deep *Spitzer* imaging of 119 targets from SHOALS, spanning 0.03 < z < 6.3 (Perley et al. 2016).

• A rapid increase in the characteristic nIR host luminosity in the range 0.5 < z < 1.5 was found, but little variation in the range 1.5 < z < 5. Dust-obscured GRBs dominate the massive HG population.

•. Dusty and extinguished GRBs are most likely related to a restriction on the metallicity of stars that can create GRBs (Vergani et al. 2015)



Perley et al. (2016)

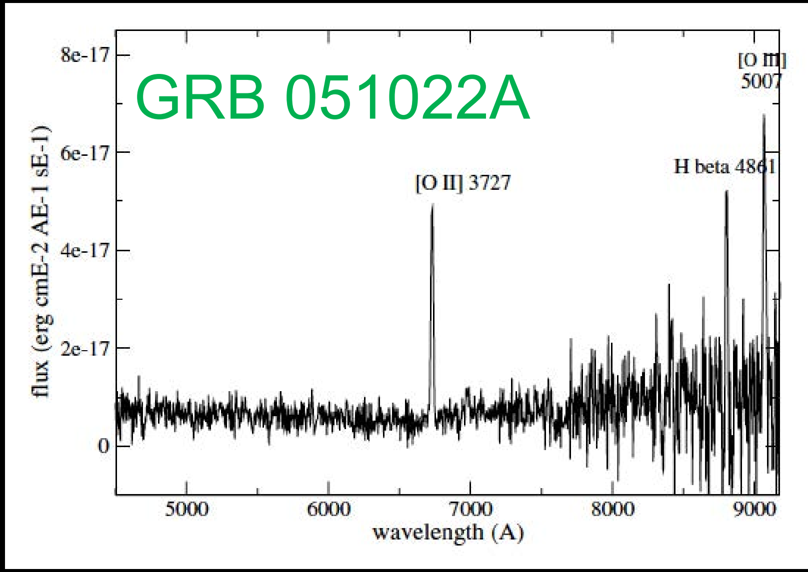
2. Opt/nIR LGRB HGs General Properties

2.3. Spectroscopy

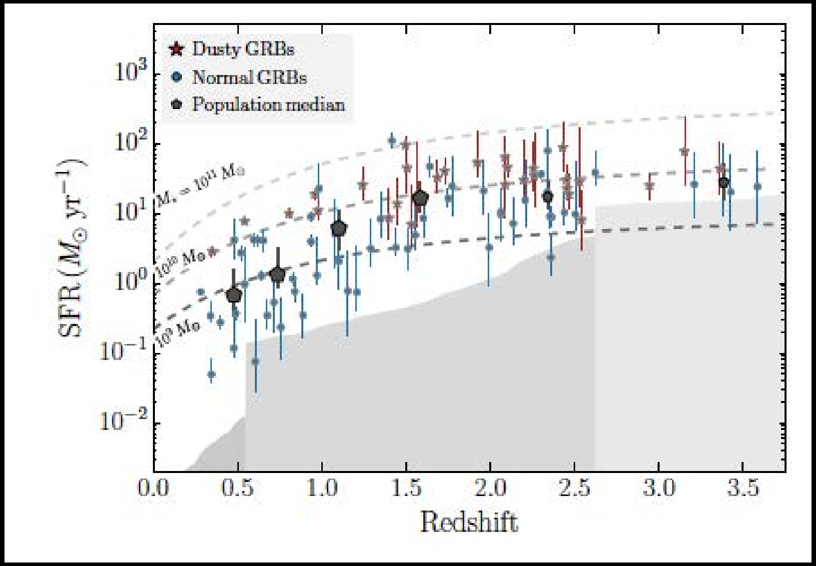
- Opt/nIR spectra of GRB HGs are also highly characteristic. The majority of the spectra exhibit strong emission lines excited by ongoing star formation in the hosts.

- These lines have a high equivalent width and can be seen in emission even when the galaxy host is too faint for the spectrum to be well measured in absorption. GRB host spectroscopy is plausible out to high redshift (z < 3) HGs (Krühler et al. 2015).

- The median SFR of GRB hosts increases from SFR ~0.6 $M_{\odot}$ yr^{-1} at z ~ 0.6 up to SFR ~15 $M_{\odot}$ yr^{-1} at z ~ 2.



Castro-Tirado et al. (2007)



Krühler et al. (2015)

2. Opt/nIR LGRB HGs General Properties

2.4. HG parameters

- Thus, a typical (non-obscured) LGRB host galaxy is:

1. Faint, with R ~ 26 and K > 22.5
2. Compact or irregular, with a half-light radii of a few kpc or less (we observe very few grand-design spiral host galaxies)
3. Blue, i.e. star-forming, with a relatively high specific star formation rate (star formation rate per unit mass)
4. Low metallicity, especially at the site of the burst.

- Parameters for a sample of 407 Type II (i.e. LGRB) HGs from Li et al. (2016).

Parameter	Type II				
	N	mean $\mu(\gamma)$	σ	D_{KS}	P_{KS}
log SFR ($M_\odot$ yr^{-1})	200	0.67 ± 0.05	0.82 ± 0.04	0.07	0.29
log sSFR (Gyr^{-1})	92	0.06 ± 0.08	0.72 ± 0.06	0.08	0.56
log M_* ($M_\odot$)	98	9.52 ± 0.08	0.81 ± 0.06	0.04	0.99
[X/H]	131	-0.70 ± 0.06	0.62 ± 0.03	0.11	0.09
log R_{50} (kpc)	126	0.26 ± 0.03	0.32 ± 0.02	0.07	0.50
log offset (kpc)	134	0.20 ± 0.05	0.55 ± 0.03	0.05	0.88
log offset (R_{50})	115	-0.12 ± 0.04	0.44 ± 0.03	0.06	0.75
F_{light}	97	1.37 ± 0.36[1]	-	0.09	0.45
F_{light}	97	1.33 ± 0.36[2]	-	0.09	0.39

Li et al. (2020)

Summary

Afterglow and host galaxy research continues today in the hopes of better constraining what type of massive star: in particular, its initial mass, the allowed range of metallicity, and the role of binarity.

Statistical studies (hundreds of hosts are now catalogued) on a systematic way (via a better understanding of selection effects, especially host-ISM dust extinction) are being conducted, both in redshift (the host population is well-constrained from z = 0 to z = 5) and in wavelength (legacy-scale samples now exist in the optical, nIR, and radio).

The collection of larger sample of high-z GRBs with future dedicated missions such as *THESEUS* will provide a viable way to probe the star formation history up to z = 10 and beyond.

Networks of Optical/nIR Robotic telescopes contemporaneous to *THESEUS* will still be very useful in order to study the early GRB phases (including prompt emission and the reverse shock) starting seconds after the triggers, thus completing the *THESEUS* dataset.

See you (hopefully) in Málaga for the next THESEUS Conference!