

LETTER TO THE EDITOR

The hidden population of long gamma-ray bursts from compact object mergers

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ABSTRACT

Context. The prompt-emission time profiles of GRB 230307A and other long-duration compact object merger (COM) candidates exhibit a unique set of temporal properties, characterised by a deterministic evolution of waiting times and pulse widths.

Aims. We searched the *Fermi*/GBM catalogue for other unidentified long COM candidates exhibiting temporal properties similar to those observed in GRB 230307A.

Methods. We examined the temporal and spectral prompt-emission properties of GRBs featuring at least eight light-curve peaks. For candidates, all with unknown redshifts, that exhibited properties similar to GRB 230307A, we analysed their trajectories in the $E_{p,i} - E_{iso}$ plane as a function of redshift. We then evaluated the joint likelihood of their compatibility with the $E_{p,i} - E_{iso}$ relation satisfied by the bulk of long GRBs. Furthermore, we calculated their minimum variability timescales (MVTs) for comparison against known COM and collapsar populations.

Results. We identified nine COM candidates with unknown redshifts and demonstrated that there are at least two outliers of the $E_{p,i} - E_{iso}$ relation with 3.1σ (Gaussian) confidence level. Furthermore, their MVTs are more consistent with those of COM than with collapsar GRBs.

Conclusions. These results indicate that this specific set of temporal properties can serve as a diagnostic tool to distinguish long-duration COMs from the broader collapsar population. Furthermore, our findings suggest that the fraction of unidentified COMs among long GRBs might be larger than previously assumed.

Key words. gamma-ray burst: general – gamma-ray burst: individual: GRB230307A

1. Introduction

Compact object mergers (COMs), typically associated with short γ -ray bursts (SGRBs), are also occasionally found to be associated with long-duration GRBs (LGRBs). This association is exemplified by the case of GRB 230307A, a long burst accompanied by kilonova emission characteristic of COMs (e.g., Dai et al. 2024; Zhong et al. 2024; Levan et al. 2024; Yang et al. 2024; Dalessi et al. 2025; Gillanders & Smartt 2025). For this reason, GRBs are now often classified according to their progenitor and referred to as type-I and type-II GRBs, corresponding to COMs and massive star collapse, respectively, rather than being classified solely by their duration (e.g., Zhang 2006).

Maccary et al. (2026, hereafter M26) identified a set of four distinctive properties characterising the evolution of the time profile of GRB 230307A and those of other COM candidates such as GRB 211211A and GRB 060614. By contrast, the same properties are not seen in any typical long GRB associated with a type Ic-BL supernova (SN). The $E_{p,i} - E_{iso}$ relation (e.g.,

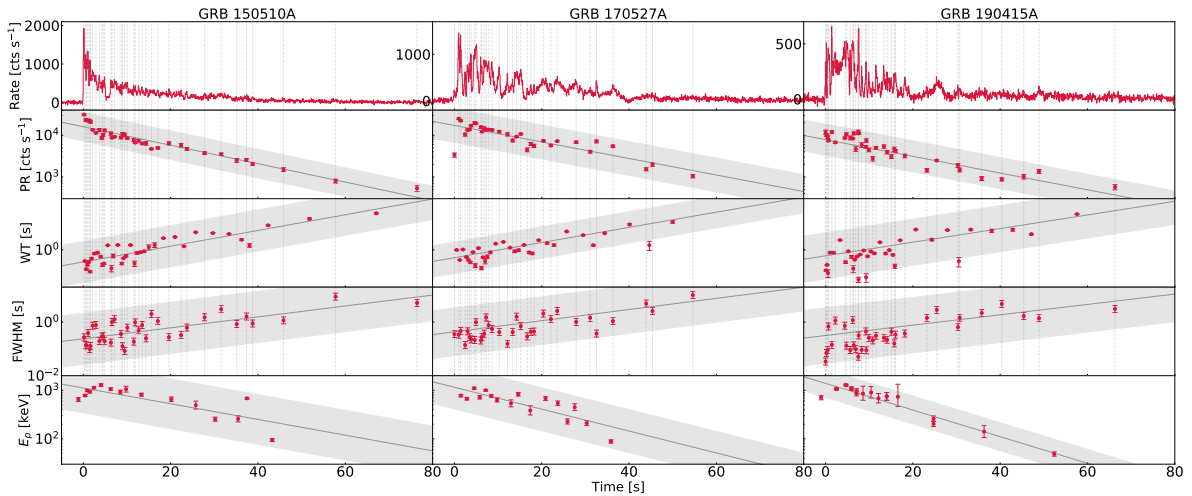
Amati et al. 2002; Amati 2006) holds for type-II GRBs, while type-I lie above them in this plane and form a distinct cluster of points, thus offering a way to distinguish GRB progenitors. Moreover, a short ($\lesssim 100$ ms) minimum variability timescale (MVT) characterises the time profiles of type-I GRBs, both short and long (MacLachlan et al. 2012, 2013; Golkhou et al. 2015; Camisasca et al. 2023; Veres et al. 2023; Maccary et al. 2025; Stratta et al. 2025).

The goal of this paper is to identify additional COM candidates within the *Fermi*/GBM catalogue and to use the $E_{p,i} - E_{iso}$ relation to further investigate their origin along with the clues given by the MVT. In Sect. 2, we describe our selection of a sample of long type-I GRB candidates that display similar properties to those identified in M26. Given these GRBs are not associated with a redshift measurement, we study their tracks in the $E_{p,i} - E_{iso}$ plane as a function of the (unknown) redshift, performing statistical tests to assess their compatibility with the $E_{p,i} - E_{iso}$ of type-II GRBs. In Sect. 3, we discuss our results and present our conclusions. Throughout this work, we use the flat- Λ CDM cosmology model with the latest

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Table 1. Type-I GRB candidates identified in this work (referred to as sample S_0).

GRB	Fermi ID	T_{90} (s)	FWHM _{min} (ms)	Fluence (10^{-6} erg/cm ²)	E_p (keV)	\mathcal{L}_*
GRB 090831	bn090831317	39.4 ± 0.6	69^{+24}_{-18}	9.44 ± 0.07	256 ± 137	0.08
GRB 140306A	bn140306146	51.7 ± 0.8	78^{+27}_{-20}	57.80 ± 0.09	1937 ± 209	4.84
GRB 150510A	bn150510139	51.9 ± 0.5	84^{+29}_{-22}	98.62 ± 0.09	1270 ± 50	2.29
GRB 170527A	bn170527480	49.2 ± 1.6	140^{+48}_{-36}	84.30 ± 0.03	1095 ± 47	1.94
GRB 190415A	bn190415173	52.5 ± 0.8	15^{+5}_{-4}	60.13 ± 0.03	1834 ± 126	4.60
GRB 211019A	bn211019250	47.4 ± 0.6	86^{+30}_{-22}	107.06 ± 0.05	1169 ± 40	1.90
GRB 220408B	bn220408311	32.5 ± 1.1	110^{+38}_{-28}	34.60 ± 0.07	225 ± 5	-0.38
GRB 221121A	bn221121274	40.7 ± 1.6	110^{+27}_{-37}	14.93 ± 0.03	889 ± 57	3.41
GRB 230304B	bn230304608	34.8 ± 0.6	93^{+32}_{-24}	37.62 ± 0.03	301 ± 11	-0.25

**Fig. 1.** Temporal evolution of the PR, WT, FWHM, and E_p for three GRBs selected from the sample S_0 . The grey solid lines represent the best-fitting exponential evolution and the shaded areas show the 3σ confidence intervals.

cosmological parameter values, $H_0 = 67.66$ km Mpc⁻¹ s⁻¹ and $\Omega_0 = 0.31$ (Planck Collaboration VI 2020).

2. Data analysis

2.1. Sample selection

We inspected the bursts detected by *Fermi*/GBM, from launch to June 2024, looking for a behaviour similar to that observed in GRB 230307A (M26). The background subtraction was carried out following the procedure in Maccary et al. (2025), resulting in the GRBs drawn for the present analysis. The peaks present in the light curve (LC) were identified with MEPSA (Guidorzi 2015). We selected the bursts exhibiting at least eight statistically significant peaks in their LCs to ensure an adequate sampling of the temporal profile, enabling a statistically meaningful characterisation of the temporal evolution of the properties identified in M26. We ended up with 263 bursts. We identified nine type-I candidates (hereafter called sample S_0) featuring pulses, whose peak rates (PRs), waiting times (WTs), and full widths at half maximum (FWHMs) clearly show a deterministic evolution over time, in line with what was observed for GRB 230307A. These data are reported in Table 1. Three cases are showcased in Fig. 1, while the other six are reported in Fig. A.1 of the Appendix. Table A.1 reports the parameters obtained for the exponential models, defined in Appendix A, which describe the temporal evolution of the properties listed above. In Appendix C,

we performed a Pearson correlation test (reported in Fig. C) to further assess the observed correlations between the aforementioned four properties and the peak times of the pulses observed in the time profile of these bursts.

2.2. Time-resolved spectral analysis

Using the *Fermi*/GBM data tools, we modelled the time-resolved energy spectra, adopting the Band function (Band et al. 1993), and we derived the temporal evolution of the peak energy, E_p , of the νF_ν spectrum throughout the burst. The high-energy power-law index β was fixed to $\beta = -2.3$ whenever it could not be constrained (e.g., Tsvetkova et al. 2017).

Time-resolved intervals were determined via Bayesian blocks (Scargle et al. 2013), merging adjacent blocks to ensure ≥ 1000 counts per interval (Maistrello et al. 2024). The criterion on the minimum number of counts was added to ensure that each block provides a statistically meaningful fit of the spectrum.

For at least seven GRBs, we observed an exponential evolution of E_p with time, sometimes following an initial rise before the peak. For GRB 140306A and GRB 230304B, we observed a significant tracking throughout the burst, in addition to the hard-to-soft exponential behaviour. For two cases, GRB 090831 and GRB 221121A, we were unable to obtain the time-integrated spectrum, owing to the faintness of the signal. The results of the modelling are reported in Table A.2 and the evolution of E_p with time is shown in Figs. 1 and A.1.

2.3. Study in the $E_{p,i} - E_{\text{iso}}$ plane

We retrieved the intrinsic spectral peak energy, $E_{p,i} = E_p (1 + z)$, and isotropic-equivalent energy E_{iso} values for 344 type-II GRBs with known redshift, z , using all available data from February 1997 to September 2025, mainly from the *Konus*/Wind catalogues (Tsvetkova et al. 2017, 2021). Hereafter, this sample is referred to as S_{II} .

We modelled the $E_{p,i} - E_{\text{iso}}$ correlation with a power-law following standard procedures, using the D’Agostini likelihood (D’Agostini 2005), which accounts for errors on both x - and y -axis and models the intrinsic dispersion, σ_{int} , of the relation. The likelihood maximisation was carried out within a Bayesian framework, performing a Markov chain Monte Carlo analysis (MCMC), using the Python package *emcee* (Foreman-Mackey et al. 2013). We modelled the relation as

$$\log\left(\frac{E_{p,i}}{\text{keV}}\right) = m \log\left(\frac{E_{\text{iso}}}{\text{erg}}\right) + q, \quad (1)$$

obtaining $q = -15.3 \pm 1.5$, $m = 0.34 \pm 0.03$, and $\sigma_{\text{int}} = 0.27 \pm 0.02$. In parallel, we considered a sample of 47 type-I GRBs (15 of which being classified as short with extended emission), which is hereafter referred to as S_{I} . Data were taken from the different *Konus*/Wind catalogues (Svinkin et al. 2016; Tsvetkova et al. 2017, 2021; Lysenko et al. 2025) and complemented with the data from the *Fermi*/GBM online catalogue¹.

All S_0 candidates have unknown redshifts. One can track their paths in the $E_{p,i} - E_{\text{iso}}$ plane as a function of the unknown redshift, z , treated as a variable in the 0.01–5 range. To this aim, we used the fluence, f , and the observed peak energy, E_p , from the *Fermi*/GBM catalogue. The isotropic-equivalent energy, $E_{\text{iso}}(z)$, was calculated as $E_{\text{iso}}(z) = 4\pi d_L^2(z) f / (1 + z)$, where $d_L(z)$ is the luminosity distance, while the intrinsic peak energy is $E_{p,i}(z) = E_p (1 + z)$. Figure 2 shows the results. Overall, one cannot help but notice that the S_0 candidates preferentially populate the region above the $E_{p,i} - E_{\text{iso}}$ relation, where most type-I GRBs lie.

To evaluate the joint probability that the location of the S_0 sample in the $E_{\text{iso}} - E_{p,i}$ plane is incidental and that they are type-II GRBs, compatibly with the relation dispersion σ_{int} and with the individual measurement uncertainties, we conceived the following test. We collected all long ($T_{90} > 2$ s) GRBs without redshift in the online *Fermi*/GBM catalogue (excluding the S_0 candidates) into the sample called S_{Inz} . Under the assumption that all these GRBs are consistent with the $E_{p,i} - E_{\text{iso}}$ relation, for each of them we derived the path in the $E_{\text{iso}} - E_{p,i}$ plane and calculated the D’Agostini negative log-likelihood that best models the $E_{p,i} - E_{\text{iso}}$ of S_{II} , whose parameters ($m, q, \sigma_{\text{int}}$) are reported above

$$\mathcal{L}(z) = \frac{1}{2} \log \left[2\pi(\sigma_{\text{int}}^2 + \sigma_y^2 + m^2 \sigma_x^2) \right] + \frac{[y(z) - m x(z) - q]^2}{2(\sigma_{\text{int}}^2 + \sigma_y^2 + m^2 \sigma_x^2)}, \quad (2)$$

where $x(z) = \log E_{\text{iso}}(z)$ and $y(z) = \log E_{p,i}(z)$, where σ_x and σ_y are the corresponding uncertainties, which do not depend on z , but just on the relative uncertainties on f and on E_p .

For each GRB of S_{Inz} , we determined z_* , which is the value of z when minimising $\mathcal{L}(z)$: $\mathcal{L}_* = \mathcal{L}(z_*) = \min_z (\mathcal{L}(z))$. The same procedure was applied to the S_0 sample, whose \mathcal{L}_* values are reported in Table 1. The sum of the values obtained for the S_0 sample is a measure of the un-normalised joint likelihood, being

¹ <https://heasarc.gsfc.nasa.gov/w3browse/fermi/fermigbrst.html>

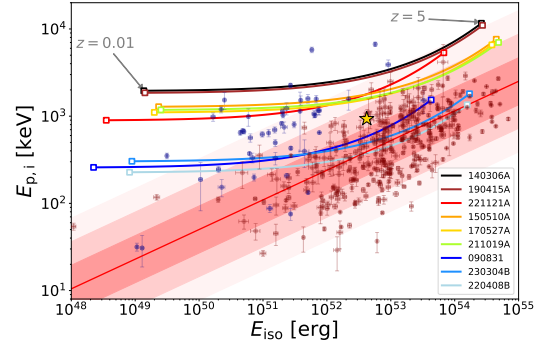


Fig. 2. Tracks of type-I candidates (sample S_0) in the $E_{p,i} - E_{\text{iso}}$ plane as a function of z . The tracks are colour-coded according to their \mathcal{L}_* values, with darker (lighter) colours corresponding to higher (lower) \mathcal{L}_* . Blue and brown points represent GRBs from sample S_{I} and S_{II} , respectively. The red line shows the $E_{p,i} - E_{\text{iso}}$ relation and the shaded areas are the 1-, 2-, and 3- σ_{int} regions. The gold star is GRB 230307A.

the logarithm of the product of all individual likelihood values: $\mathcal{L}_{*,S_0}^{(\text{tot})} = \sum_{i=1}^9 \mathcal{L}_*^{(i)}$, where $\mathcal{L}_*^{(i)}$ is the value for the i -th GRB of S_0 .

To determine the p -value, which is the probability of obtaining a value of $\geq \mathcal{L}_{*,S_0}^{(\text{tot})}$ under the assumption that they are all type-II GRBs, we built the reference distribution for $\mathcal{L}_{*,S_0}^{(\text{tot})}$, according to the following process. We randomly drew $N_{\text{sim}} = 10^6$ samples of $N = 9$ GRBs from S_{Inz} and for each of them we calculated the same metric, $\mathcal{L}_*^{(\text{tot})}$. The corresponding distribution of $\mathcal{L}_*^{(\text{tot})}$ values was then used as a reference. As a result, only 124 cases had $\mathcal{L}_*^{(\text{tot})} \geq \mathcal{L}_{*,S_0}^{(\text{tot})}$. We conclude that the assumption that our S_0 sample of nine long merger candidates are all type-II GRBs following the $E_{p,i} - E_{\text{iso}}$ relation has a p -value equal to 1.24×10^{-4} , equivalent to 3.7σ (Gaussian). We also tried to reject the following more general H_0 hypothesis: S_0 includes at most N_{out} outliers of the $E_{p,i} - E_{\text{iso}}$ relation. To test this H_0 , we have to reject from each sample a number, N_{out} , of GRBs with the largest \mathcal{L}_* values out of nine and calculate the total value over the remaining ones, $\mathcal{L}_*^{(\text{tot})} = \sum_{i=1}^{9-N_{\text{out}}} \mathcal{L}_*^{(i)}$. This must be done for the real and the simulated samples. The $N_{\text{out}} = 0$ case is already described above. Table B.1 reports the p -values obtained for a range of N_{out} values. In particular, for $N_{\text{out}} = 1$, the p -value is 8.21×10^{-4} , which is equivalent to 3.1σ (Gaussian). Thus, we conclude, with $> 3\sigma$ confidence, that at least 2/9 of our S_0 candidates do not satisfy the $E_{p,i} - E_{\text{iso}}$ relation.

2.4. Analysis in the MVT- T_{90} plane

Figure 3 shows the S_0 candidates in the MVT- T_{90} plane. The data set of Maccary et al. (2025) was used as a reference. We adopt the MVT definition based on FWHM_{min} , which is the FWHM of the shortest pulse, following Camisasca et al. (2023), although similar conclusions can be drawn using alternative definitions². In Appendix E, we studied the impact of using different MVT metrics. Both quantities were not divided by $(1 + z)$ for the reasons explained in Camisasca et al. (2023). All S_0 candidates lie at similar locations in the upper left of the plot, with $T_{90} \sim 30\text{--}50$ s and $\text{MVT} \lesssim 0.1$ s. Notably, some

² FWHM_{min} correlates with other MVT metrics (Golkhou et al. 2015; MacLachlan et al. 2013), with values that are on average $\sim 5\text{--}6$ larger (Maccary et al. 2025). This difference does not affect the results presented here, since the relative position of the bursts in the MVT- T_{90} plane remains essentially unchanged.

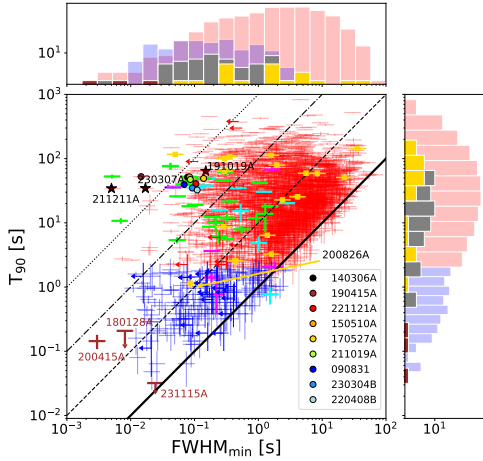


Fig. 3. MVT- T_{90} plane, with MVT defined as FWHM_{\min} (adapted from Maccary et al. 2025). The filled circles represent the type-I GRB candidates (sample S_0) identified in the present analysis. The blue and red crosses indicate short ($T_{90} < 2$ s) and long ($T_{90} > 2$ s) GRBs, respectively. Gold points represent SN-associated GRBs. Magenta, lime, and cyan points represent SEE-GRBs from Lien et al. (2016), Lan et al. (2020), Kaneko et al. (2015), respectively. Three extragalactic magnetar giant flare candidates, 180128A, 200415A, and 231115A are shown in brown. The solid black line represents the equality line, while the dashed, dashed-dotted, and dotted lines represent a factor of 10, 100, and 1000 respectively, deviation from equality.

previously identified long type-I GRBs, such as GRB 191019A, GRB 211211A, and GRB 230307A, lie in the same region. In particular, GRB 190415A and GRB 230307A lie very close to each other. Only 0.2% of long bursts exhibit smaller MVT values than GRB 190415A. The MVT and T_{90} values of GRBs from the S_0 set are reported in Table 1.

3. Discussion and conclusion

We identified nine type-I candidates sharing properties similar to those noted in M26 and analysed their positions in the $E_{p,i} - E_{\text{iso}}$ plane as a function of (unknown) redshift. Out of 263 bursts selected from the full *Fermi*/GBM catalogue, the fraction of long, multi-peaked type-I candidates identified via this method is around 3%. We demonstrated, with a confidence level exceeding 3σ , that at least two of these candidates are incompatible with the population of long GRBs lacking measured redshifts.

This suggests that the distinctive properties identified in M26 serve as a promising indicator of a compact object merger (COM) origin. Such findings have practical applications for identifying COM-associated GRBs, as these characteristics can be extracted directly from the prompt-emission light curve. This provides early, direct clues of a COM origin, which can help guide and prioritise the search for multi-wavelength counterparts. Unfortunately, owing to the poor localisations of these events, no afterglow searches were conducted for any of these candidates. Consequently, their redshifts remain unknown. In Appendix D, based on the possible incompatibility of these bursts with the Amati relation, we propose some limiting values for their redshifts. A preliminary search for the best-localised candidate, GRB 230304B³, identifies potential hosts at $z \lesssim 0.04$. This would render the event consistent with other known long mergers in terms of energetics and luminosity, although the

³ It was localised by the InterPlanetary Network within an error box of about 100 arcmin square (Kozyrev et al. 2023).

precise identification of the host remains unfeasible at this stage. Prospectively, promptly identifying these distinctive properties in future GRBs could help the community to quickly select promising COM candidates and plan dedicated multi-wavelength campaigns aimed at detecting the afterglow, assessing and characterising the progenitor. These distinctive properties are not only observationally significant, but also challenge the stochastic nature predicted by most theoretical models of GRB prompt emission. Specifically, the observed increase in pulse width throughout the burst profile is difficult to reconcile with the internal shock model; previously, the lack of such evolution in various multi-peaked GRBs was used to favour internal shocks over external ones (e.g. Fenimore et al. 1999). However, this reasoning applies neither to GRB 230307A nor to the other GRBs identified in this study. Thus, the observation of these properties opens the door for alternative scenarios, such as the target-shell model introduced in M26, which posits the existence of a primitive shell emitted before the main train of shells from the central engine. Alternatively, we could look to refined versions of the ICMART framework (Zhang & Yan 2011), where an expanding emission region with mini-emitters radiating through magnetic reconnection accounts for the properties of long merger events resembling that of GRB 230307A (Yi et al. 2025).

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References

- Amati, L. 2006, *MNRAS*, **372**, 233
Amati, L., Frontera, F., Tavani, M., et al. 2002, *A&A*, **390**, 81
Band, D., Matteson, J., Ford, L., et al. 1993, *ApJ*, **413**, 281
Camisasca, A. E., Guidorzi, C., Amati, L., et al. 2023, *A&A*, **671**, A112
D’Agostini, G. 2005, arXiv e-prints [arXiv:physics/0511182]
Dai, C.-Y., Guo, C.-L., Zhang, H.-M., Liu, R.-Y., & Wang, X.-Y. 2024, *ApJ*, **962**, L37
Dalessi, S., Veres, P., Hui, C. M., et al. 2025, *ApJ*, **994**, 17
Fenimore, E. E., Ramirez-Ruiz, E., & Wu, B. 1999, *ApJ*, **518**, L73
Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, *PASP*, **125**, 306
Gillanders, J. H., & Smartt, S. J. 2025, *MNRAS*, **538**, 1663
Golkhou, V. Z., & Butler, N. R. 2014, *ApJ*, **787**, 90
Golkhou, V. Z., Butler, N. R., & Littlejohns, O. M. 2015, *ApJ*, **811**, 93
Guidorzi, C. 2015, *Astron. Comput.*, **10**, 54
Kaneko, Y., Bostanci, Z. F., Göğüş, E., & Lin, L. 2015, *MNRAS*, **452**, 824
Kozyrev, A. S., Golovin, D. V., Litvak, M. L., et al. 2023, *GRB Coordinates Network*, **33480**, 1
Lan, L., Lu, R.-J., Lü, H.-J., et al. 2020, *MNRAS*, **492**, 3622
Levan, A. J., Gompertz, B. P., Salafia, O. S., et al. 2024, *Nature*, **626**, 737
Lien, A., Sakamoto, T., Barthelmy, S. D., et al. 2016, *ApJ*, **829**, 7
Lysenko, A. L., Svinkin, D. S., Frederiks, D. D., et al. 2025, *PASA*, **42**
Maccary, R., Guidorzi, C., Camisasca, A. E., et al. 2025, *A&A*, **702**, A95
Maccary, R., Guidorzi, C., Maistrello, M., et al. 2026, *J. High Energy Astrophys.*, **49**, 100456
MacLachlan, G. A., Shenoy, A., Sonbas, E., et al. 2012, *MNRAS*, **425**, L32
MacLachlan, G. A., Shenoy, A., Sonbas, E., et al. 2013, *MNRAS*, **432**, 857
Maistrello, M., Maccary, R., Guidorzi, C., & Amati, L. 2024, *A&A*, **684**, L10
Planck Collaboration VI. 2020, *A&A*, **641**, A6
Scargle, J. D., Norris, J. P., Jackson, B., & Chiang, J. 2013, *ApJ*, **764**, 167
Stratta, G., Nicuesa Guelbenzu, A. M., Klose, S., et al. 2025, *ApJ*, **979**, 159
Svinkin, D. S., Frederiks, D. D., Aptekar, R. L., et al. 2016, *ApJS*, **224**, 10
Tsvetkova, A., Frederiks, D., Golenetskii, S., et al. 2017, *ApJ*, **850**, 161
Tsvetkova, A., Frederiks, D., Svinkin, D., et al. 2021, *ApJ*, **908**, 83
Veres, P., Bhat, P. N., Burns, E., et al. 2023, *ApJ*, **954**, L5
Yang, Y.-H., Troja, E., O’Connor, B., et al. 2024, *Nature*, **626**, 742
Yi, S.-X., Yorgancıoğlu, E. S., Xiong, S. L., & Zhang, S. N. 2025, *J. High Energy Astrophys.*, **47**, 100359
Zhang, B. 2006, *Nature*, **444**, 1010
Zhang, B., & Yan, H. 2011, *ApJ*, **726**, 90
Zhong, S.-Q., Li, L., Xiao, D., et al. 2024, *ApJ*, **963**, L26

Appendix A: Exponential fit of the four temporal properties

We used the following exponential models to describe the temporal behaviour of the PR, WTs, FWHMs, and peak energy.

$$PR(t) = PR_0 \exp(-t/\tau_R), \quad (\text{A.1})$$

$$WT(t) = \frac{\tau_{WT}}{N_0} \exp(t/\tau_{WT}), \quad (\text{A.2})$$

$$FWHM(t) = FWHM_0 \exp(t/\tau_{FWHM}), \quad (\text{A.3})$$

$$E_p(t) = E_{p,0} \exp(-t/\tau_{E_p}). \quad (\text{A.4})$$

PR_0 , $FWHM_0$, and $E_{p,0}$ are the initial values at $t = 0$, and τ_R , τ_{WT} , τ_{FWHM} , τ_{E_p} the characteristic evolution timescales. N_0 is the number of elementary bunches of energy in the toy model defined in M26 used to model the WTs evolution.

These relations were modelled using the D'Agostini likelihood, in a similar way as for the modelling of the $E_{p,i} - E_{iso}$ previously described, and the dispersion of these relations are described by σ_R , σ_{WT} , σ_{FWHM} , and σ_{E_p} , respectively. The evolution of these four properties are displayed in Fig. 1 and Fig. A.1. The parameters of the fit are given in Table A.1, and Table A.2 for the fit of the peak energy.

Appendix B: Statistical tests

Figure B.1 represents the likelihood values of the S_0 sample testing the compatibility of these GRBs to the $E_{p,i} - E_{iso}$ relation for type-II GRBs. Table B.1 reports the results of the statistical tests.

Appendix C: Correlation tests

To further assess whether the temporal and spectral properties of the prompt emission evolve during the burst, we tested for correlations between time, described by the peak time of the pulses detected by MEPSA, and the four properties studied in M26, i.e. PR, WTs, pulse FWHM, and, when available, spectral peak energy E_p . For each observable, we evaluated the presence of a linear trend with time using a standard correlation test. Since all four properties show an exponential evolution, the analysis was performed in logarithmic space for the dependent variables. A Pearson test, testing for linear correlation, was performed. We computed the corresponding correlation coefficient and associated p -value, which quantifies the probability of obtaining the observed correlation by chance under the null hypothesis of no temporal trend. The result of this analysis is shown in Figure C.1. Several GRBs (GRB 140306A, GRB 150510A, GRB 170527A, GRB 190415A, GRB 230304B) have all four properties correlated with time (or at least three when the time-integrated spectrum is not available, as for GRB 221121A). In some cases (GRB 211019A, GRB 220408B), for one or two properties the correlation cannot be established. Only for GRB 090831, the faintest GRB considered in sample S_0 , no correlation can be firmly established.

Appendix D: Redshift limiting values from the violation of the Amati relation of type-II GRBs

The $E_{p,i} - E_{iso}$ plane can be used to estimate the redshift below which a given GRB in the sample S_0 becomes incompatible (at 3 or 2 σ confidence level) with the $E_{p,i} - E_{iso}$ followed by the bulk of collapsar GRBs. This value is obtained by computing the redshift at which the track formed by a given GRB intersects

the 3 σ_{int} line (resp. 2 σ_{int} line) of the $E_{p,i} - E_{iso}$ relation. The results are reported in Table D.1. Although this quantity does not directly provide an upper limit on the GRB redshift (as several type-I GRBs are very close to the Amati relation of type-II GRBs) GRBs, this information could be used to ease the research of an associated host galaxy. In particular, for GRB 090831, GRB 220408B, GRB 230304B, the obtained limits would place these GRBs at very close distances. However, we emphasise that these values should not be taken as direct estimates of the burst redshift. Indeed, as for instance is the case for GRB 230307A, a type-I GRB can perfectly lie within the 3 σ relation of type-II GRBs.

Appendix E: The impact of using different MVT metrics

Various studies have focused on computing the MVT. Notably, MacLachlan et al. (2012, 2013), and Golkhou & Butler (2014), Golkhou et al. (2015) developed non-parametric, wavelet-based measures of intrinsic variability. These methods are designed to study the temporal power as a function of timescale in a robust and unbiased manner, without relying on pulse fitting procedures or specific assumptions regarding pulse shape. The resulting MVT values are found to be closely related to the shortest rise times in GRB light curves. In contrast, the MVT defined in Camisasca et al. (2023) and in Maccary et al. (2025), computed as the FWHM of the shortest pulse in the light curve, is found to be about 5 – 6 times longer than the MVT derived from the aforementioned studies. However, this discrepancy does not impact the conclusions drawn from Figure 3. In fact, adopting alternative MVT definitions would essentially result into a leftward, roughly uniform, shift of all data points. Consequently, the relative positioning of the 9 candidates against the bulk population remains fundamentally unchanged. This consistency is illustrated in Figure E.1, which compares the MVT- T_{90} plane using the GRB sample from MacLachlan et al. (2013) (left panel) with values sourced from both that catalogue and Maccary et al. (2025) (right panel).

In spite of subtle differences between the two sets and a significant overlap between the two populations of long and short GRBs, the latter consistently exhibit lower MVT values than the former. Notably, the MVT values of the two populations from MacLachlan et al. (2013) (left panel) appear to be slightly better separated than the corresponding $FWHM_{min}$ values (right panel). Ultimately, for the scope of this study, both MVT definitions lend support to the same conclusions.

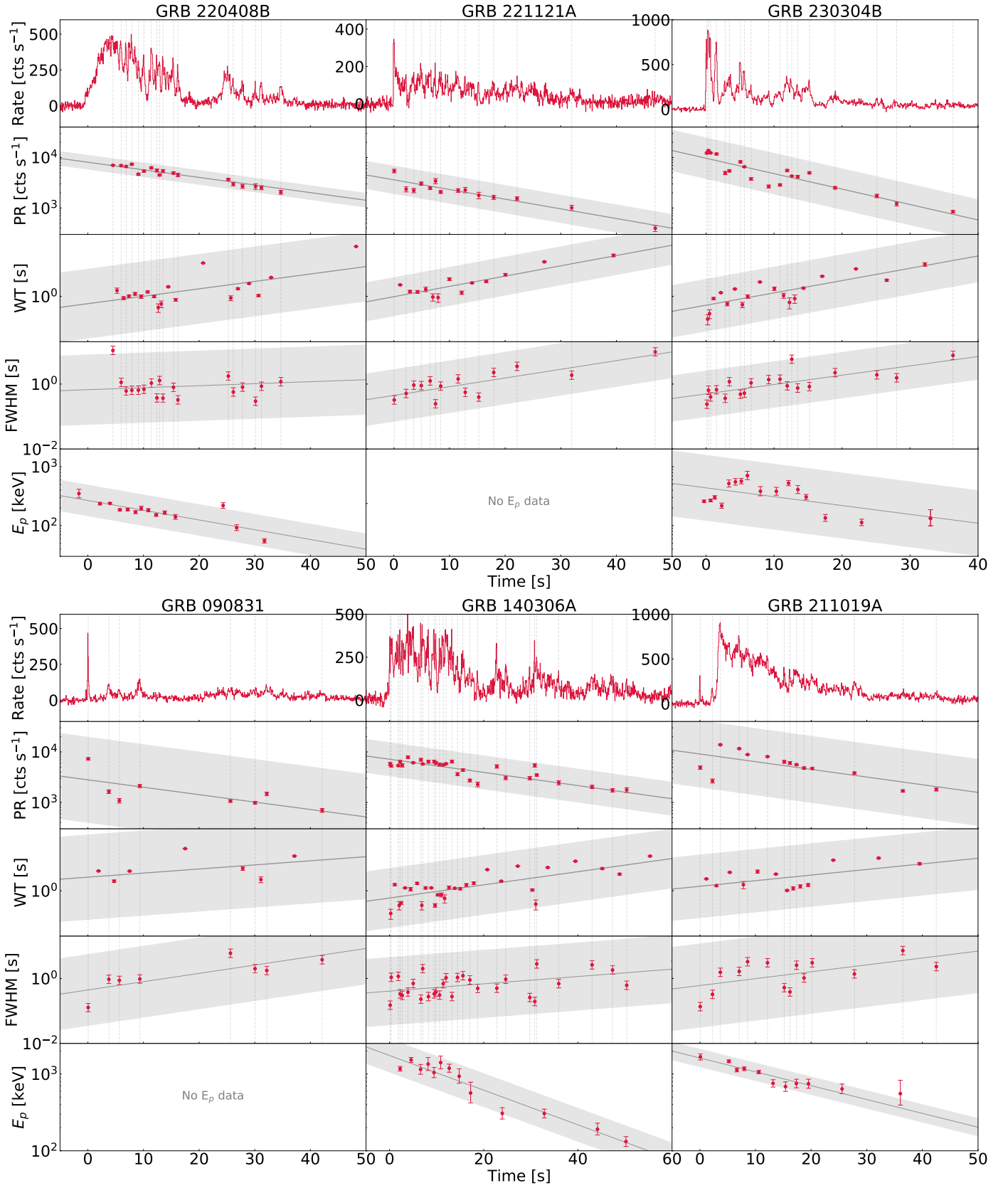


Fig. A.1. Temporal evolution of the PR, WTs, FWHM, and E_p for the six remaining GRBs of the sample S_0 . The grey solid lines represent the best fits of the linear relation and the shaded grey regions represent the 3 σ confidence intervals of the fits.

Table A.1. Best-fit parameters for each GRB of the S_0 sample for the three different fits (WTs, FWHM, and PR).

GRB	τ_{WT} (s)	N_0	σ_{WT}	τ_{FWHM} (s)	$FWHM_0$ (s)	σ_{FWHM}	τ_R (s)	PR_0 ($\times 10^3$ cts/s)	σ_R
GRB 090831	37^{+270}_{-24}	15^{+64}_{-8}	$0.93^{+0.74}_{-0.36}$	17^{+28}_{-7}	$0.44^{+0.67}_{-0.27}$	$0.84^{+0.73}_{-0.36}$	30^{+75}_{-17}	$2.8^{+2.7}_{-1.4}$	$0.65^{+0.59}_{-0.25}$
GRB 140306A	$23.0^{+7.0}_{-4.0}$	37^{+9}_{-7}	$0.65^{+0.19}_{-0.13}$	39^{+30}_{-12}	$0.41^{+0.17}_{-0.12}$	$0.79^{+0.24}_{-0.17}$	33^{+5}_{-4}	$7.2^{+0.9}_{-0.8}$	$0.25^{+0.07}_{-0.05}$
GRB 150510A	$14.7^{+3.3}_{-3.0}$	25^{+7}_{-5}	$0.59^{+0.23}_{-0.14}$	21^{+8}_{-5}	$0.24^{+0.08}_{-0.06}$	$0.73^{+0.21}_{-0.15}$	20^{+2}_{-2}	16^{+2}_{-2}	$0.26^{+0.07}_{-0.05}$
GRB 170527A	$16.4^{+3.9}_{-2.6}$	31^{+5}_{-4}	$0.42^{+0.13}_{-0.09}$	21^{+12}_{-6}	$0.43^{+0.20}_{-0.14}$	$0.68^{+0.24}_{-0.17}$	22^{+3}_{-2}	$17.2^{+3.0}_{-2.6}$	$0.31^{+0.09}_{-0.07}$
GRB 190415A	$18.3^{+6.3}_{-3.7}$	30^{+8}_{-6}	$0.62^{+0.21}_{-0.14}$	23^{+14}_{-6}	$0.32^{+0.16}_{-0.10}$	$0.79^{+0.27}_{-0.19}$	22^{+3}_{-2}	$7.9^{+1.1}_{-1.1}$	$0.29^{+0.10}_{-0.07}$
GRB 211019A	27^{+68}_{-12}	20^{+28}_{-7}	$0.69^{+0.36}_{-0.20}$	21^{+54}_{-10}	$0.61^{+0.73}_{-0.33}$	$0.98^{+0.52}_{-0.30}$	29^{+36}_{-11}	9^{+4}_{-3}	$0.50^{+0.25}_{-0.14}$
GRB 220408B	$20.4^{+14.6}_{-5.7}$	33^{+13}_{-9}	$0.76^{+0.30}_{-0.18}$	71^{+391}_{-40}	$0.67^{+0.33}_{-0.27}$	$0.82^{+0.33}_{-0.22}$	29^{+3}_{-2}	$8.1^{+0.6}_{-0.6}$	$0.11^{+0.04}_{-0.03}$
GRB 221121A	$14.7^{+6.0}_{-3.4}$	15^{+4}_{-3}	$0.42^{+0.24}_{-0.13}$	16^{+12}_{-5}	$0.45^{+0.28}_{-0.17}$	$0.61^{+0.36}_{-0.23}$	23^{+6}_{-4}	$3.6^{+0.6}_{-0.5}$	$0.21^{+0.12}_{-0.07}$
GRB 230304B	$12.3^{+3.9}_{-3.0}$	22^{+7}_{-5}	$0.56^{+0.26}_{-0.15}$	15^{+9}_{-4}	$0.50^{+0.22}_{-0.15}$	$0.54^{+0.23}_{-0.18}$	14^{+4}_{-2}	$9.7^{+2.1}_{-1.8}$	$0.34^{+0.14}_{-0.08}$

Table A.2. Best-fit results of the exponential evolution of E_p with time for each GRB of the S_0 sample.

GRB	τ_{E_p} (s)	$E_{p,0}$ (keV)	σ_{E_p}	$\chi^2/\text{d.o.f.}$
GRB 140306A	$19.2^{+3.5}_{-2.9}$	1749^{+393}_{-209}	$0.21^{+0.15}_{-0.09}$	9.2/10
GRB 150510A	$16.3^{+2.9}_{-2.0}$	1759^{+419}_{-329}	$0.18^{+0.17}_{-0.09}$	6.9/7
GRB 170527A	$19.2^{+9.4}_{-4.7}$	1150^{+442}_{-313}	$0.39^{+0.18}_{-0.13}$	17/18
GRB 190415A	$15.2^{+1.7}_{-1.4}$	1526^{+254}_{-198}	$0.15^{+0.13}_{-0.06}$	4.6/9
GRB 211019A	$24.1^{+9.3}_{-4.5}$	1619^{+202}_{-232}	$0.09^{+0.11}_{-0.06}$	8.2/8
GRB 220408B	$26.2^{+13.2}_{-6.7}$	268^{+59}_{-48}	$0.24^{+0.14}_{-0.08}$	11.4/11
GRB 230304B	29^{+44}_{-12}	436^{+162}_{-112}	$0.48^{+0.22}_{-0.13}$	12.9/14

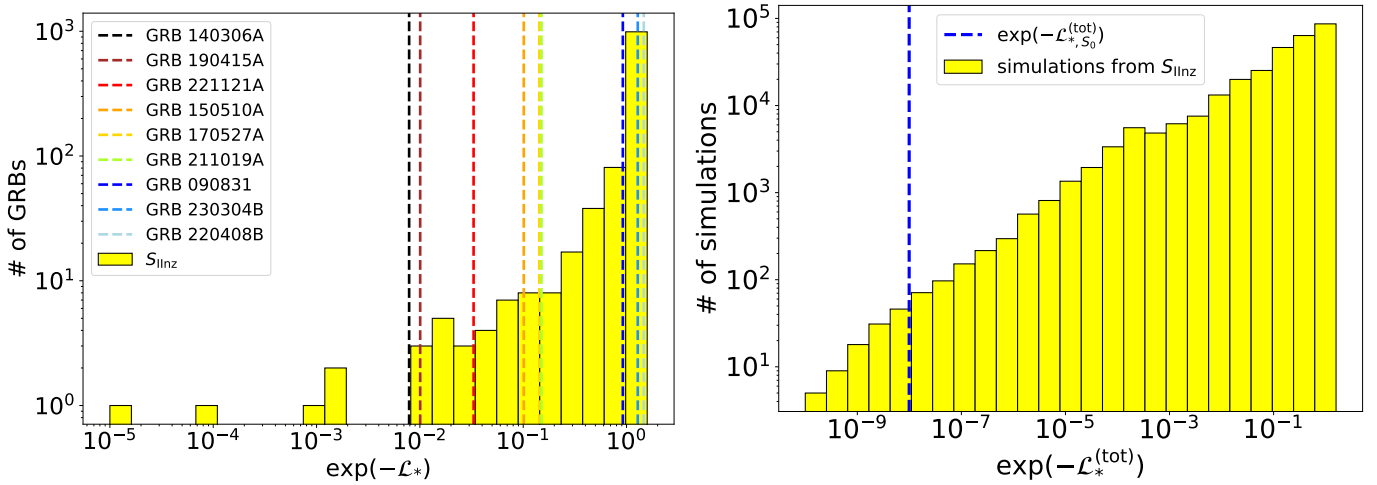


Fig. B.1. *Left:* distribution of likelihoods (given by $\exp(-\mathcal{L}_*)$, \mathcal{L}_* being the negative log-likelihood) for GRBs from sample S_{Inz} . Vertical lines show the values of S_0 candidates. *Right:* histogram of $\exp(-\mathcal{L}_*^{(\text{tot})})$, where $\mathcal{L}_*^{(\text{tot})} = \sum_{i=1}^9 \mathcal{L}_*^{(i)}$ obtained from 10^6 realisations of random selection of 9 GRBs from S_{Inz} (Sec. 2.3). The vertical blue line shows the value obtained from the sample S_0 , $\exp(-\mathcal{L}_*^{(\text{tot})})$. The fraction of simulations for which is it $\mathcal{L}_*^{(\text{tot})} \geq \mathcal{L}_*^{(\text{tot})}$ is the joint probability that all 9 GRBs from S_0 are consistent with the $E_{p,i} - E_{\text{iso}}$ for type-II GRBs. This fraction turns out to be 1.2×10^{-4} , equivalent to 3.7σ (Gaussian).

Table B.1. Probabilities for a set of H_0 hypotheses, each of which assumes a maximum value of the number of outliers of the $E_{p,i} - E_{\text{iso}}$ relation in the S_0 sample (Sect. 2.3).

N_{out}	p -value	σ Gaussian
0	1.24×10^{-4}	3.7
1	8.21×10^{-4}	3.1
2	8.46×10^{-3}	2.4
3	2.10×10^{-2}	2.0
4	4.40×10^{-2}	1.7

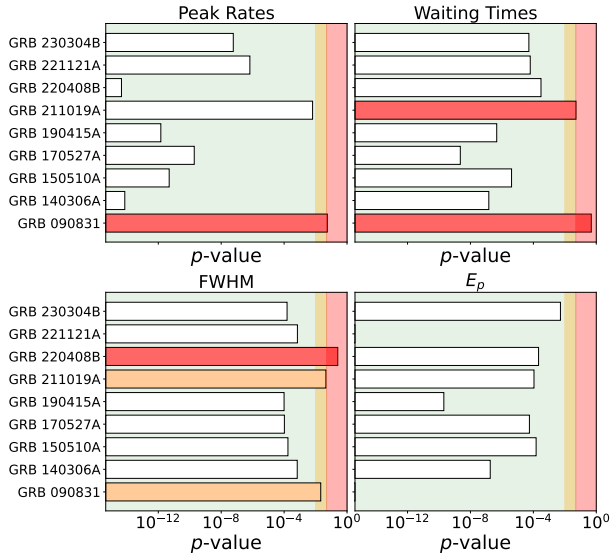


Fig. C.1. From top to bottom panels, left to right: p -values from Pearson correlation tests for the PR, WTs, pulse FWHM, and, when available, the spectral peak energy E_p . Horizontal bars indicate the p -values associated with each correlation test. Green-shaded regions (corresponding to white bars) denote p -values below 0.01, for which the null hypothesis of no temporal trend is rejected. Orange bars correspond to p -values between 0.01 and 0.05, indicating marginal detections of temporal trends. Red bars indicate p -values greater than 0.05, for which the null hypothesis of no temporal evolution cannot be rejected.

Table D.1. Redshift values below which each GRB becomes incompatible with the Amati relation for type-II GRBs at 2 and 3σ confidence levels.

GRB	$z_{3\sigma}$	$z_{2\sigma}$
GRB 090831	0.050	0.14
GRB 140306A	0.88	–
GRB 150510A	0.19	0.97
GRB 170527A	0.16	0.65
GRB 190415A	0.67	–
GRB 211019A	0.16	0.62
GRB 220408B	0.021	0.054
GRB 221121A	0.34	–
GRB 230304B	0.031	0.083

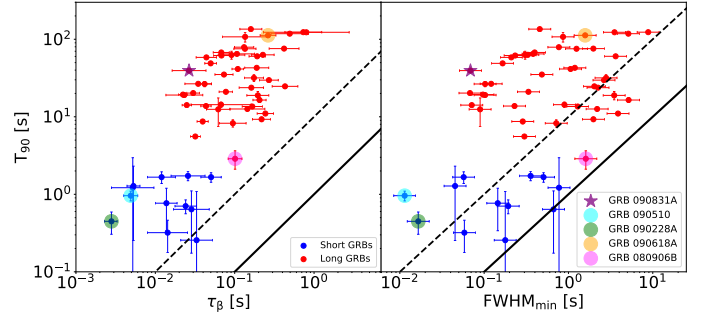


Fig. E.1. *Left:* MVT- T_{90} plane, with the MVT (denoted as τ_β) values taken from MacLachlan et al. (2013), using their GRB sample. *Right:* MVT- T_{90} plane for the same bursts using the MVT values (denoted as FWHM_{min}) from Maccary et al. (2025). Solid and dashed lines show equality and $T_{90} = 10 \times \text{MVT}$. Some bursts are shown with coloured filled circles with the only purpose of highlighting the corresponding location in each plot. GRB 090831A, which belongs to the S_0 sample, is identified with a purple star. Evidently, the relative positioning of these bursts remains essentially invariant, regardless of the MVT metric employed.