

A set of distinctive properties ruling the prompt emission of GRB 230307A and other long γ -ray bursts from compact object mergers

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ABSTRACT

Short gamma-ray bursts (SGRBs), occasionally followed by a long and spectrally soft extended emission, are associated with compact object mergers (COMs). Yet, a few recent long GRBs (LGRBs) show compelling evidence for a COM origin, in contrast with the massive-star core-collapse origin of most LGRBs. While possible COM indicators were found, such as the minimum variability timescale (MVT), a detailed and unique characterisation of their γ -ray prompt emission that may help identify and explain their deceptively long profile is yet to be found. Here we report the discovery of a set of distinctive properties that rule the temporal and spectral evolution of GRB 230307A, a LGRB with evidence for a COM origin. Specifically, the sequence of pulses that make up its profile is characterised by an exponential evolution of (i) flux intensities, (ii) waiting times between adjacent pulses, (iii) pulse durations, and (iv) spectral peak energy. Analogous patterns are observed in the prompt emission of other long COM candidates. The observed evolution of gamma-ray pulses would imply that a relativistic jet is colliding with more slowly expanding material. This contrasts with the standard internal shock model for typical LGRBs, in which dissipation occurs at random locations within the jet itself. We tentatively propose a few simple toy models that may explain these properties and are able to reproduce the overall time profile.

1. Introduction

At least two kinds of progenitors of gamma-ray bursts (GRBs) are known: (i) the core-collapse of some kind of massive stars (a collapse; Woosley 1993; Paczyński 1998; MacFadyen and Woosley 1999); (ii) compact object mergers (COMs), in particular the coalescence of two neutron stars (NS; Eichler et al. 1989; Paczynski 1991; Narayan et al. 1992), or a NS with a black hole (BH). While the former class usually leads to a long ($\gtrsim 2$ s) GRB, the latter typically results in a short and hard GRB and, in the optical band, is expected to be associated with a kilonova (KN), radiation powered by the radioactive decay of r -process elements created in the aftermath of the merger (see Metzger 2020 for a review).

Although GRB duration was initially considered as an irrefutable property revealing the progenitor's nature, a number of baffling cases have recently been discovered: the apparently short GRB 200826A (Ahumada et al., 2021; Zhang et al., 2021; Rossi et al., 2022), which is instead associated with a core-collapse supernova (SN), or long GRBs (LGRBs) GRB 060614 (Della Valle et al., 2006; Fynbo et al., 2006; Jin et al., 2015), GRB 211211A (Rastinejad et al., 2022; Yang et al., 2022; Troja et al., 2022; Xiao et al., 2022), GRB 191019A (Levan et al., 2023; Stratta et al., 2025), for which a COM origin is strongly favoured. Furthermore, a subclass of events emerged—known as short GRBs with extended emission (SEE-GRBs)—which are characterised by an initial narrow, hard spike followed by a longer, softer tail (Norris and Bonnell, 2006). These events, possibly originating from mergers, further challenged the

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reliability of GRB duration as a robust classification criterion. To avoid confusion, Zhang et al. (2009) referred to GRBs with a merger origin as Type I GRBs, and to collapsars as Type II GRBs.

Recent GRB 230307A was thrust into the spotlight thanks to its exceptional brightness along with its peculiar properties. On March 7, 2023, at 15:44:06.650 UTC, GRB 230307A triggered the Gravitational wave high-energy Electromagnetic Counterpart All-sky Monitor (GECAM; Li et al. 2020), which observed it without saturation effects (Xiong et al., 2023). Despite its long duration ($T_{90} \sim 30$ s), this burst shows several pieces of evidence for a COM origin. Indeed, its locations in the Amati (Amati et al., 2002; Amati, 2006) and Yonetoku planes (Yonetoku et al., 2004) fall outside the 90% confidence predictions for Type II GRBs (Svinkin et al., 2023), and a short minimum variability timescale (MVT) of around 30 ms—typical of Type I GRBs—is observed (Camisasca et al., 2023b). Moreover, the X-ray afterglow flux, rescaled by the early γ -ray emission fluence, is comparably faint to those of other long Type I GRBs. Most importantly, the optical transient associated with it and with a projected offset of 30 kpc from its host galaxy, showed photometric and spectroscopic evidence for the presence of a KN (Levan et al., 2024; Gillanders and Smartt, 2025), which tipped the balance towards a COM origin.

GRB 230307A exhibits a well-structured γ -ray light curve (LC), made of three distinct episodes: a short initial soft spike, identified as a precursor (Dichiara et al., 2023), shortly followed by a long and hard main emission preceding a softer extended emission, the main and the extended emission being separated by a dip-like feature. This three-phase structure has been claimed to be shared by some similar long Type I GRBs, possibly forming a sub-class of the Type I GRBs, referred to as Type IL GRBs (e.g. Wang et al. 2025; Tan et al. 2025). GRB 230307A shares many properties with GRB 211211A: both exploded at close distances ($z = 0.076$ for GRB 211211A and $z = 0.065$ for GRB 230307A), have short MVTs of a few ten ms, and are clear outliers of the Amati relation for Type II GRBs (Peng et al., 2024).

NS-NS and NS-BH mergers might struggle to produce GRBs as long as GRB 230307A, owing to their short accretion timescale. A white dwarf (WD) disrupted by a NS companion, producing a less compact remnant, might be able to last long enough to explain the GRB duration. Wang et al. (2024) argues that a WD-NS merger could lead to a magnetar that could power a long GRB and a KN. The soft X-ray light curve measured by the Lobster Eye Imager for Astronomy (LEIA; Zhang et al. 2022) presents a plateau followed by a steeper decay compatible with a magnetar spin-down model. Sun et al. (2025) shows that broad-band (soft X to γ -rays) observations of GRB 230307A revealed a distinct X-ray component, possibly due to a newly born magnetar. A magnetar as a GRB central engine would lead to a Poynting-flux dominated outflow, which is confirmed by the non-detection of a thermal component, implying a high magnetisation parameter ($\sigma > 7$ at radius $R_0 = 10^{10}$ cm) to suppress the expected photospheric emission (Du et al., 2024).

The emission mechanism powering GRB 230307A is uncertain. Moradi et al. (2024) carried out a systematic spectral and temporal analysis of *Fermi*/GBM and GECAM data and showed that the energy flux and the peak energy temporal evolution in the late prompt emission are not fully compatible with the predictions of the internal shock (IS) model (Rees and Meszaros, 1994; Kobayashi et al., 1997; Daigne and Mochkovitch, 1998), although uncertainties in the micro-physics of the shock region might be responsible for the observed discrepancies (Bošnjak and Daigne, 2014). Yi et al. (2025a) shows that the long broad pulse shaping the overall GRB 230307A time profile could be the result of many superimposed narrow pulses produced by local magnetic reconnection events, as foreseen by the Internal-Collision-Induced Magnetic Reconnection and Turbulence (ICMART; Zhang and Yan 2011) model. Yi et al. (2025b) proposed a model in which a brief energy injection from the central engine triggers turbulence in a small localised region. Turbulence then propagates radially as the jet expands forward, moving away from the central engine. This model predicts a single broad pulse

that widens with decreasing energy ranges and progressively softens throughout the burst.

A progressive increase of the pulse width over time is a natural outcome of external shocks (ES). An intense debate emerged among the GRB community in the late 90s as to whether the dissipation mechanism into γ -rays was due to internal or external shocks (Fenimore et al., 1996; Dermer et al., 1999; Dermer, 2008). The absence of any timescale evolution along the profile of GRB 990123 (Fenimore et al., 1999) and of other long and multi-peaked GRBs tipped the balance towards ISs. In this respect, the temporal evolution of GRB 230307A, as well as of other similar events, might suggest a new distinctive hallmark of the elusive class of LGRBs that are COM candidates.

In this work, we focus on the GECAM LC in the 30–6000 keV pass-band: owing to the exquisite quality of the data, we could identify about one hundred peaks, thus enabling a statistical analysis, which is usually impossible for a single GRB. As a result, the prompt emission of GRB 230307A displays a set of distinctive properties, which suggest a different origin from the canonical LGRBs associated with the core-collapse of massive stars. Some of these properties are also observed in similar long-duration COM candidates mentioned above, as revealed by a preliminary analysis.

The identification and characterisation of this rare set of observed properties, which appear to distinguish COM candidates from most long GRBs, and particularly from collapsars, form the core of the present work. As a secondary objective, we tentatively propose a few possible toy models and interpretations that aim to account for these properties in a self-consistent way, discussing the advantages and limitations of each, without necessarily excluding alternative scenarios. Data analysis is reported in Section 2, results are presented in Section 3 and discussed in Section 4. Conclusions are drawn in Section 5. We adopted the cosmological parameter values from Planck Collaboration et al. (2020).

2. Data analysis

We obtained the GECAM background-subtracted LCs with 5 ms bin time in the following energy passbands: 30–70, 70–100, 100–150, 150–200, 200–300, 300–500, 500–1000, 1000–6000 keV, respectively. Background interpolation and subtraction were obtained as described in Zhang et al. (2025). In each of these profiles, peaks were identified by means of MEPSA, a flexible code that was specifically designed to identify peaks in GRB LCs across different timescales (Guidorzi, 2015). In this present study, we used both MEPSA and a faster version of it, which significantly reduces the computing time.¹

Peaks were selected imposing a threshold of $S/N \geq 5$ on the signal-to-noise ratio calculated by MEPSA. Each peak is automatically characterised by the following pieces of information: peak time t_p and its uncertainty, which corresponds to the MEPSA detection timescale δt_p ; peak amplitude A and its uncertainty; estimate of the full width at half maximum (FWHM) of the peak; S/N of the total net counts ascribed to the peak. The FWHM is estimated from the combination of MEPSA parameters as prescribed in eq. (A.3) of Camisasca et al. (2023a). We studied the evolution with time of peak times, FWHM, and of the waiting times (WT) Δt , defined as the time intervals between adjacent peaks. We also examined the evolution of E_p , which is the peak of the νF_ν energy spectrum: its values were taken from Moradi et al. (2024).

Hereafter, we focus on the 100–150 keV band LC, which displays the largest number of peaks (103).

3. Results and interpretations

The analysis of the 100–150 keV profile revealed the following properties:

¹ It is ~ 100 times faster than classical MEPSA at the cost of losing $\sim 5\%$ of all the detected peaks. This is made possible by a sparser sampling of the rebinning factors and related phases. See Maistrello et al. (in prep.) for details.

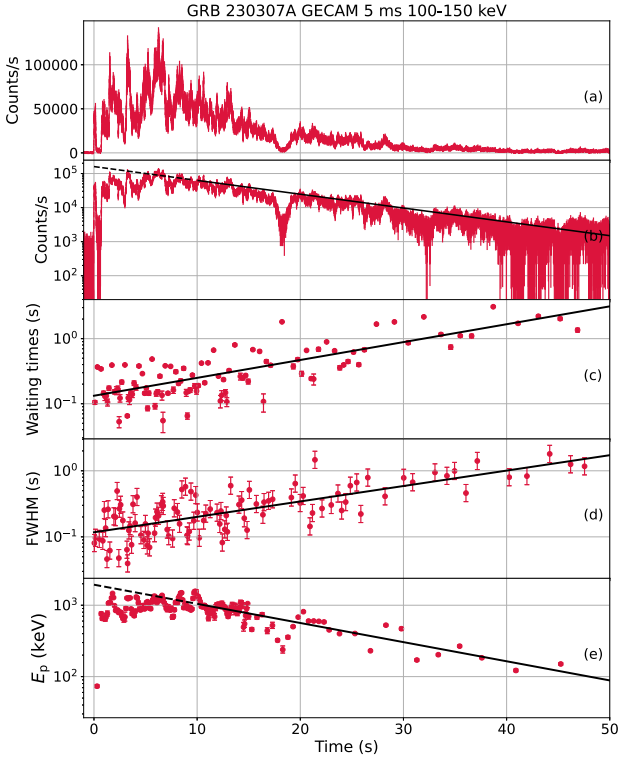


Fig. 1. Properties of GRB 230307A. (a) LC in the 100-150 keV band with 5-ms bin time. (b) same as (a), but in semi-logarithmic scale; (c) WTs of the peaks detected with MEPSA as a function of time; (d) FWHMs of the same peaks of (c) as a function of time; (e) time-resolved evolution of spectral peak energy. In panel (b), the solid line represents the exponential fit of the peak rates of the pulses. In panels (c), (d), and (e), solid lines show the exponential models obtained within the corresponding temporal window, whereas the dashed line, if present, shows the extrapolated fit to the time interval that was ignored by the fitting procedure.

1. the overall envelope of the LC looks like a so-called FRED. In particular, from $t > 10$ s the count rate decays exponentially, covering two decades, as shown in panels (a) and (b) of Fig. 1. Similarly, the peak rates of the pulses detected with MEPSA also evolve exponentially with time. Their evolution is described by Eq. (1):

$$P(t) \simeq P_0 e^{-t/\tau_p}, \quad (1)$$

with $P_0 = (1.64 \pm 0.12) \times 10^5$ cts s⁻¹ and $\tau_p = 10.7 \pm 0.4$ s. This model is shown in panel (b) of Fig. 1 along with the LC.

2. WTs evolve exponentially with time, spanning two decades, from ~ 0.1 to ~ 10 s, during the first 50 seconds, as described by Eq. (2),

$$\Delta t \simeq \Delta t_0 e^{t/\tau_{\Delta t}}, \quad (2)$$

with $\Delta t_0 = 0.14 \pm 0.02$ s and $\tau_{\Delta t} \simeq 15.8$ s (panel (c) of Fig. 1).

3. The FWHM of the pulses detected by MEPSA also increases with time: it could be either exponential or linear, spanning more than one decade, from 0.1 s. If modelled with an exponential, this is described by Eq. (3),

$$\text{FWHM}(t) \simeq \text{FWHM}_0 e^{t/\tau_F}, \quad (3)$$

with $\text{FWHM}_0 = 0.12 \pm 0.01$ s and $\tau_F = 18.6 \pm 1.7$ s. Panel (d) of Fig. 1 shows the FWHM values as a function of time.

We also performed a linear fit $\text{FWHM} = \text{FWHM}'_0 + \alpha t$ (see Fig. 2) and obtained $\text{FWHM}'_0 = 0.05 \pm 0.01$ s and $\alpha = 0.010 \pm 0.001$, but the result appears to be worse than the exponential model. We fitted both linear and exponential models, $y = mx + q$, modelling the dispersion as a further parameter, by adopting the D'Agos-

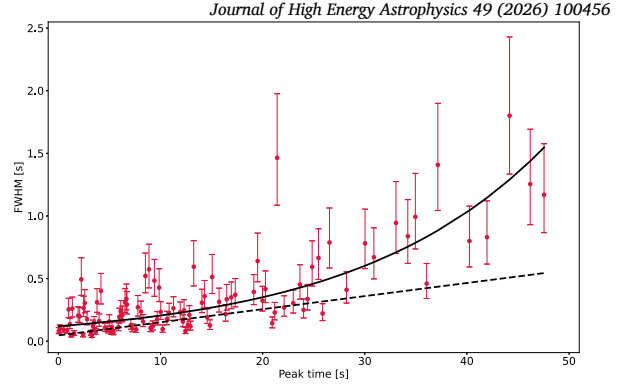


Fig. 2. FWHM evolution over time. Solid (dashed) line represents the exponential (linear) model.

tini likelihood (D'Agostini, 2005). When we used $y = \text{FWHM}$, the best-fit parameters are $m = 0.012 \pm 0.002$, $q = 0.077^{+0.026}_{-0.024}$ s, and $\sigma = 0.068^{+0.020}_{-0.017}$ s. Instead, when we use $y = \ln(\text{FWHM}/\text{s})$, we find $m = 0.054 \pm 0.008$, $q = -2.14 \pm 0.14$, and $\sigma = 0.48^{+0.08}_{-0.07}$. The corresponding goodness of the fit was evaluated as $\chi^2 = \sum (y_i - y_{\text{model},i})^2 / \sigma_{\text{tot},i}^2$, where $\sigma_{\text{tot},i}^2 = \sigma^2 + \sigma_{y,i}^2 + m^2 \sigma_{x,i}^2$, with $\sigma_{y,i}$ and $\sigma_{x,i}$ being the measurement uncertainties of the generic i -th point. We obtained $\chi^2_{\text{lin}} = 134$ and $\chi^2_{\text{exp}} = 99.6$ (100 degrees of freedom).

4. The evolution of the peak energy, E_p , from $t > 10$ s can also be described as a negative exponential,

$$E_p(t) \simeq (1940 \pm 150 \text{ keV}) e^{-t/\tau_E}, \quad (4)$$

with $\tau_E = 16.2 \pm 0.9$ s (see panel (e) of Fig. 1).

Equations (1)–(4) were fitted using a nonlinear least squares algorithm (applied on the logarithmic quantities), accounting for y-axis errors. Parameter uncertainties were estimated as the square root of the covariance matrix diagonal.

3.1. A simple toy model

Typically, long and multi-peaked GRB LCs do not show any specific evolution of WTs: moreover, this lack of systematic evolution represents one of the pillars of the IS model as opposed to the ES model as a possible explanation of GRB prompt emission (Fenimore et al., 1999). In this respect, the exponential evolution of WTs exhibited by GRB 230307A is enough to make it stand out from the population of long and multi-peaked GRBs. Hence, inspired by the unusual WT evolution, we conceived a toy model that can naturally account for it, along with the other observed properties described in Section 3.

The sequence of peak times $t_{p,i}$ ($i = 1, \dots, N_p$), where N_p is the total number of peaks, can be described in terms of a stochastic point process: each peak time marks the occurrence of an event. In this toy model, there are initially N_0 elementary bunches of energy, which share the same probability of “decaying” (=releasing their amount of energy within a single shot that manifests itself as a pulse) as well as the same amount of (bolometric) energy. They “decay” or release their energy independently of one another. From these simple assumptions, which are the same that rule the radioactive decay of a bunch of N_0 atoms of a given element, the exponential distribution of the peak (or release) times $\{t_{p,i}\}$ follows as a consequence. In particular, the mean number of energy bunches still available at time t , $N(t)$, is simply given by:

$$N(t) = N_0 e^{-t/\tau}, \quad (5)$$

where τ is the mean lifetime of each bunch. This model predicts the temporal evolution of the expected (or mean) WT, as

$$\langle \Delta t \rangle = -\frac{1}{\dot{N}(t)} = \frac{\tau}{N_0} e^{t/\tau}, \quad (6)$$

which accounts for the observed property modelled in Eq. (2).

The toy model aims to reproduce a surrogate version of the LC to be compared with that of GRB 230307A. The key idea is that the LC is the result of the superposition of elementary pulses, whose properties are governed by a few assumptions, which are hereafter defined along with the corresponding model parameters:

- N_0 peak times are sampled from an exponential distribution with e-folding time τ , in agreement with Eq. (5);
- pulse FWHMs are calculated assuming Eq. (3), where FWHM_0 and τ_F are treated as free parameters;
- the counts of each pulse is constant and is parametrised by N_{cts} ;
- the peak rate P of a given pulse is calculated by dividing the counts by the corresponding FWHM: this choice is corroborated by the fact that τ_p of Eq. (1) is not wildly different from τ_F of Eq. (3). By doing so, we are implicitly assuming that the peak rate decay and the FWHM rise evolve on a common timescale, τ_F . This assumption is not driven by any specific theoretical interpretation but rather stems from the observation of the data and adopting Occam's razor. To model the fact that the overall LC shows a finite rise time, we added an extra term that accounts for the suppressed flux of the initial pulses over a timescale described by the parameter τ_r , which acts as the rise time. As a result, peak rates are calculated as a function of the corresponding peak times t_p as

$$P(t_p) = \frac{N_{\text{cts}}}{\text{FWHM}_0} e^{-t_p/\tau_F} (1 - e^{-t_p/\tau_r}). \quad (7)$$

The corresponding additional free parameter is τ_r .

- Concerning the pulse shape, with reference to the Norris et al. (1996) model, the peakedness is fixed to $\nu = 2$, while the decay-to-rise time ratio r to 3 for all pulses. Since the FWHM is calculated for each pulse, rise and decay times are consequently computed as $t_r = \text{FWHM}/((1+r)(\ln 2)^{1/\nu}) \simeq \text{FWHM}/3.33$ and $t_d = r t_r$, respectively.

3.2. Physical model 1: multiple shells emitted with equal Lorentz factors

In the toy model of Section 3.1, the FWHM is assumed to evolve exponentially. Here, we adopted another FWHM evolution, derived from shock kinematics. In this model, the central engine is working in the same way as in Section 3.1, but, in addition, the train of shells emitted by the central engine is colliding with a so-called target shell. The target shell is expanding, so successive shocks occur at increasing radii. The target shell could have been expelled some time before the train of shells or right at the beginning of the merger. Alternatively to the target shell, the various shells might be refreshing the external blast wave, as it was suggested in the refreshed shock scenario to explain long-lived afterglows (Rees and Meszaros, 1998). The origin of the target shell is further discussed in Section 4.

To be more quantitative, we let $t_{e,i}$ be the emission time (lab frame) of the i -th shell. All shells are emitted with the same velocity $\beta = v/c$, whereas the target shell is moving with $\beta_s = v_s/c < \beta$. We let R_0 be the initial radius of the target shell at $t = 0$, when the first shell is emitted. We define $t_{c,i}$ the collision time (lab frame) of the i -th shell, which takes place at radius $R_{c,i}$. Since different collisions take place at different radii, the WTs measured by the observer will appear shorter than the corresponding WTs in the lab frame: to avoid confusion, the observed collision times are denoted as $t_{c,i}^{(\text{obs})}$ and are measured by the observer since the arrival of the first pulse. The kinematic solution for these quantities is

$$t_{c,i} = \frac{R_0}{v - v_s} + \left(\frac{v}{v - v_s} \right) t_{e,i}, \quad (8)$$

$$t_{c,i}^{(\text{obs})} = \left(\frac{\beta}{\beta - \beta_s} \right) (1 - \beta_s) t_{e,i}, \quad (9)$$

$$R_{c,i} = \left(\frac{\beta}{\beta - \beta_s} \right) (R_0 + v_s t_{e,i}). \quad (10)$$

From Eq. (9) the observed WTs, $\Delta t_{c,i}^{(\text{obs})}$, inherit the same exponential temporal evolution of the lab-frame WTs, $\Delta t_{e,i}$. The duration of each pulse is given by the angular timescale: because of the progressive expansion of the target shell, durations are predicted to increase linearly with time,

$$\text{FWHM}_i = \frac{R_{c,i}}{2c\Gamma^2} = \frac{1}{2c\Gamma^2} \left(\frac{\beta}{\beta - \beta_s} \right) (R_0 + v_s t_{e,i}). \quad (11)$$

That the velocity of the target shell would change only negligibly could be explained by its being more massive than the faster shells. If both fast and target shells are relativistic, the term $\beta/(\beta - \beta_s)$ is approximately $2\Gamma^2/((\Gamma/\Gamma_s)^2 - 1)$. In particular, Eqs. (9) and (11) would become,

$$t_{c,i}^{(\text{obs})} \simeq \frac{1}{1 - (\Gamma_s/\Gamma)^2} t_{e,i}, \quad (12)$$

$$\text{FWHM}_i \simeq \frac{R_0/c + \beta_s t_{e,i}}{(\Gamma/\Gamma_s)^2 - 1}. \quad (13)$$

Within this interpretation, from Eq. (11), FWHM is expected to grow linearly with time, in possible agreement with observations. Hence, to simulate the model, we replaced Eq. (3) with Eq. (11), and modified Eq. (7) to take into account the linear evolution of the FWHM. Furthermore, the emission times $t_{e,i}$ are still generated from an exponential distribution, but need to be transformed into the observed collision times, using Eq. (9).

We initially assumed a non-relativistic target shell, $\beta_s < 1$. This led to an untenable physical solution, in particular because of the compactness problem² (see Sect. 3.5). We consequently adopted Γ_s instead of β_s as a more convenient parameter, implicitly assuming an ultra-relativistic motion for the target shell.

3.3. Physical model 2: multiple shells emitted with gradually decreasing Lorentz factors

This model is almost the same as the previous one described in Section 3.2, except for one assumption: the Lorentz factors of the different shells decrease with the emission times, so that later shells are slower. In this model, the previous equations Eqs. (8)–(11) are still valid, but since the Lorentz factor is changing from one emitted shell to another, Γ has to be replaced by $\Gamma_i \equiv \Gamma(t_{e,i})$. Prompted by the exponential evolution of FWHM and peak energy (Eqs. (3) and (4)), we parametrised the temporal evolution of $\Gamma(t)$ as

$$\Gamma(t) = \Gamma_0 e^{-t/\tau_\Gamma}. \quad (14)$$

Instead of Γ of the model of Sect. 3.2, this scenario requires a couple of new parameters, Γ_0 and τ_Γ , through which each Γ_i is calculated.

3.4. Genetic algorithm based parameter optimisation

We determined the free parameters of each model using a genetic algorithm (GA; see Bazzanini et al. 2024; Maistrello et al. 2025 for similar usages). The loss function to be minimised by the GA consists of four different contributions. Each term aims to ensure that the corresponding property of the real LC of GRB 230307A is correctly reproduced by the simulated LC. The four properties include:

1. similar envelopes (smoothed time profiles);

² In this case, we obtained $\beta_s \sim 0.4$, $R_0 = 3 \times 10^{10}$ cm, and $\Gamma \sim 6.5$, implying sub-photospheric shocks between 5×10^{10} and 10^{12} cm, with pair-production opacity $\tau_{\gamma\gamma}$ (computed in Sect. 3.5) remaining extremely high (from 10^9 initially to 10^7) throughout the burst.

Table 1

Parameters of the three GRB emission models used to reproduce the temporal evolution of GRB 230307A.

Parameter	Toy Model	Physical Model 1 (Constant Γ)	Physical Model 2 (Declining Γ)
N_0	862^{+1}_{-25}	1270^{+110}_{-90}	894^{+21}_{-101}
τ [s]	$10.9^{+0.1}_{-0.5}$	$10.9^{+1.0}_{-2.3}$	$10.1^{+1.4}_{-0.8}$
FWHM ₀ [s]	$0.05^{+0.01}_{-0.01}$	—	—
τ_F [s]	$14.0^{+0.2}_{-0.4}$	—	—
τ_r [s]	$2.5^{+0.1}_{-0.7}$	$2.9^{+0.3}_{-0.5}$	$3.4^{+0.7}_{-0.9}$
N_{cts}	1449^{+26}_{-5}	920^{+30}_{-20}	1431^{+49}_{-20}
Γ or Γ_0	—	94^{+8}_{-1}	339^{+18}_{-20}
Γ_s	—	$8.6^{+0.1}_{-0.4}$	$26.2^{+0.5}_{-0.5}$
τ_Γ [s]	—	—	96^{+30}_{-17}
R_0 [cm]	—	$9.1^{+3.8}_{-1.5} \times 10^{10}$	$1.4^{+0.4}_{-0.3} \times 10^{11}$

2. compatible distributions of peak times;
3. comparable numbers of peaks detected with MEPSA;
4. compatible distributions of FWHM values.

A detailed description of the GA-based optimisation procedure is reported in Appendix A.

3.4.1. Results for the toy model

The best model parameters that we have come up with for the toy model of Sect. 3.1 are shown in Table 1. We converted the pulse counts N_{cts} to fluence N_F in erg cm^{-2} . This was done by multiplying N_{cts} by the fluence-to-counts ratio R computed using the values of the time-resolved spectral modelling of Moradi et al. (2024). For a constant N_{cts} , N_F decreases with time; thus, we adopted an average value of $1.8 \times 10^{-7} \text{ erg cm}^{-2}$ in the 100–150 keV energy range. After applying the k -correction, the fluence of a single shot over the full energy band (6–8000 keV) is $3.9 \times 10^{-6} \text{ erg cm}^{-2}$, which, placed at a distance of 300 Mpc ($z = 0.065$), corresponds to an isotropic-equivalent energy of $\sim 4.1 \times 10^{49} \text{ erg}$. Given that the total time-integrated fluence is $4.8 \times 10^{-3} \text{ erg cm}^{-2}$, the fluence of a single elementary pulse, multiplied by the number of pulses, roughly matches the total GRB fluence. The central engine is emitting numerous energy bunches with an average energy of $4.1 \times 10^{49} \text{ erg}$. Earlier bunches are more energetic, ranging from 2.5×10^{50} all the way down to $1 \times 10^{48} \text{ erg}$.

Noticeably, the intrinsic number of bunches of energy, N_0 , which is also the number of intrinsic peaks that make up the overall profile, is about ten times higher than the number of MEPSA-detected peaks (1000 vs 100). This result suggests that the observed LC consists of a myriad of short overlapping peaks, which blend together and appear as fewer, broader peaks.

We generated a synthetic profile and compared it and its properties with the corresponding real ones: Fig. 3 shows the overall LC in both linear (a) and logarithmic scale (b). The temporal evolution of WTs and of FWHMs of the peaks detected with MEPSA are displayed in panels (c) and (d), respectively. All the temporal properties that are found in the real data are faithfully reproduced by the synthetic profile. A possible weakness of this model is that the broad dip observed at 20 s can hardly be reproduced in its depth.

3.4.2. Results for the physical models

The results for the constant- Γ scenario (Section 3.2) and for the declining- Γ factor scenario (Section 3.3) are shown in Table 1. Fig. 4 shows the corresponding results analogously to Fig. 3. In the last scenario considered, the results show that Γ decreases relatively slowly for the model to reproduce the observed GRB time profile. Assuming a constant fluid-comoving-frame peak energy—thus attributing all observed peak energy variation to a decreasing Γ —is ruled out. In fact, a decay timescale of $\tau_\Gamma \sim 100 \text{ s}$ is not short enough to explain the drop seen in Panel (e) of Fig. 1. The observed peak energy decline should be a

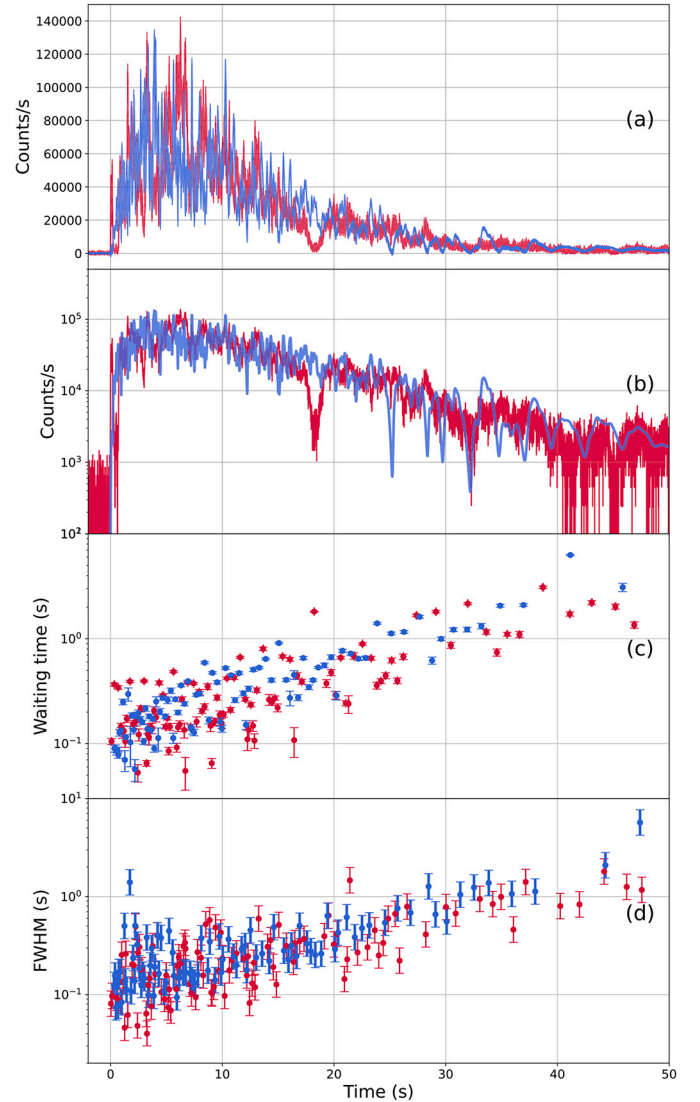


Fig. 3. Panels (a) and (b) illustrate the temporal evolution of count rates, (a) in linear and (b) in logarithmic scale. Panels (c) and (d) show the temporal evolution of the WTs and of the pulse FWHMs, respectively. Red points show real data, while blue points are simulated according to the toy model of Section 3.1.

consequence of the decreasing shock energy density resulting from the expansion of the emission radius.

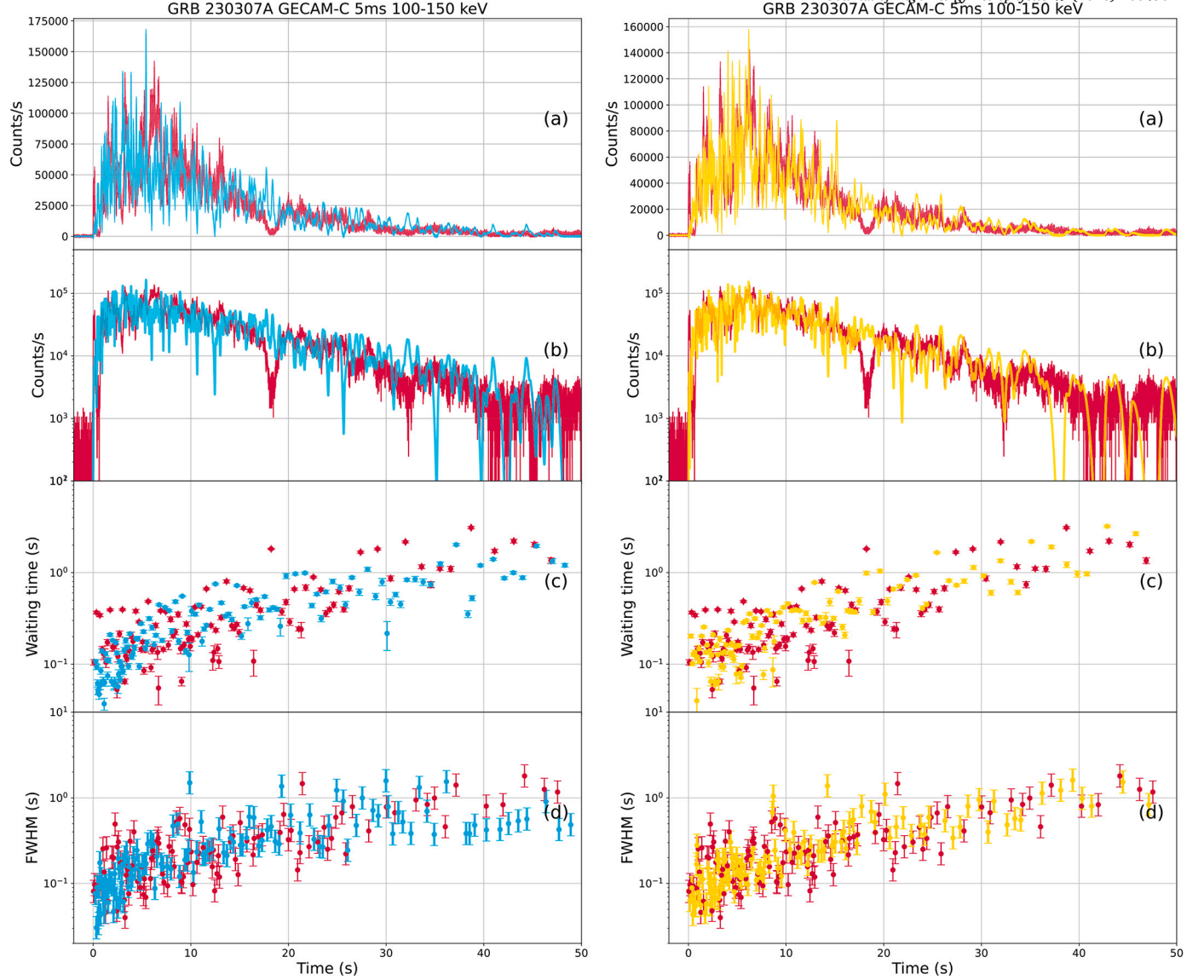


Fig. 4. Same as in Fig. 3, for the physical model with a wind of shells with constant Γ described in Section 3.2 (left panel) and the one with declining Γ 's described in Section 3.3 (right panel). Real data are shown in red, while simulated data from constant and declining Γ model are shown in cyan and yellow, respectively.

3.5. Testing the physical constraints: compactness problem, photosphere, and internal shock radii

We verified that the compactness problem is not an issue for our model. To this aim, we have computed the optical depth to pair production

$$\tau_{\gamma\gamma} = \frac{f_p \sigma_T \phi D_L^2}{\Gamma^3 R_e^2 m_e c^2}, \quad (15)$$

with f_p the fraction of photons making pairs, σ_T the Thomson scattering cross section, ϕ the fluence, D_L the luminosity distance, R_e the emission radius, m_e the electron mass, and c the speed of light (Piran, 2004). We evaluated $\tau_{\gamma\gamma}$ at early and late times, taking for R_e the radius of the first and last shocks, respectively. Given that the first pulses produced by the model have a width of about 25 ms, from Eq. (11) the initial shock radius is about 1.3×10^{13} cm and $\tau_{\gamma\gamma} \simeq 19 \times f_p$, while for the last wider pulses of about 1 s, the opacity drops to $\tau_{\gamma\gamma} = 1.2 \times 10^{-2} \times f_p$. The high initial opacity may account for the early rise in the observed flux, which in our model is modelled by the rise time τ_r . Consequently, the rising phase could reflect the transition from an initially optically thick to an optically thin regime as the emitting region expands.

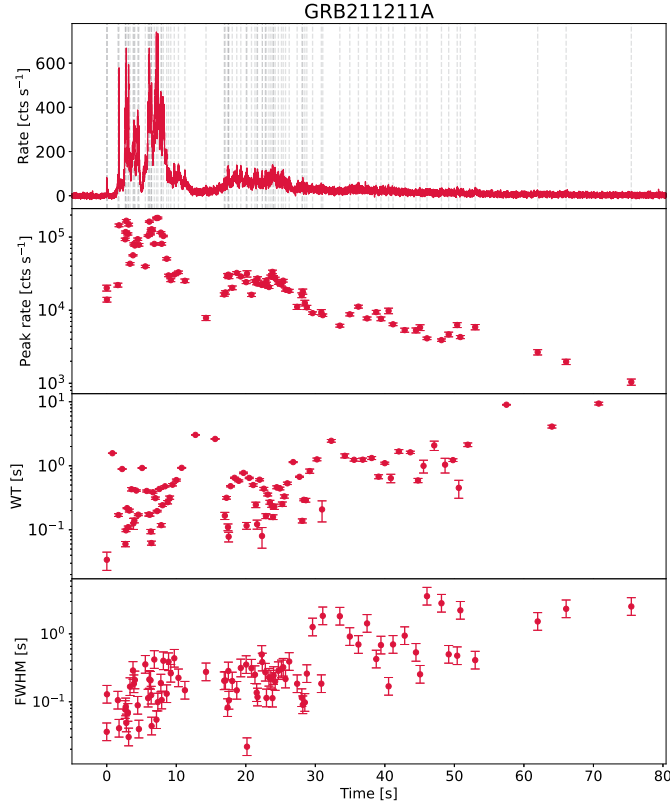
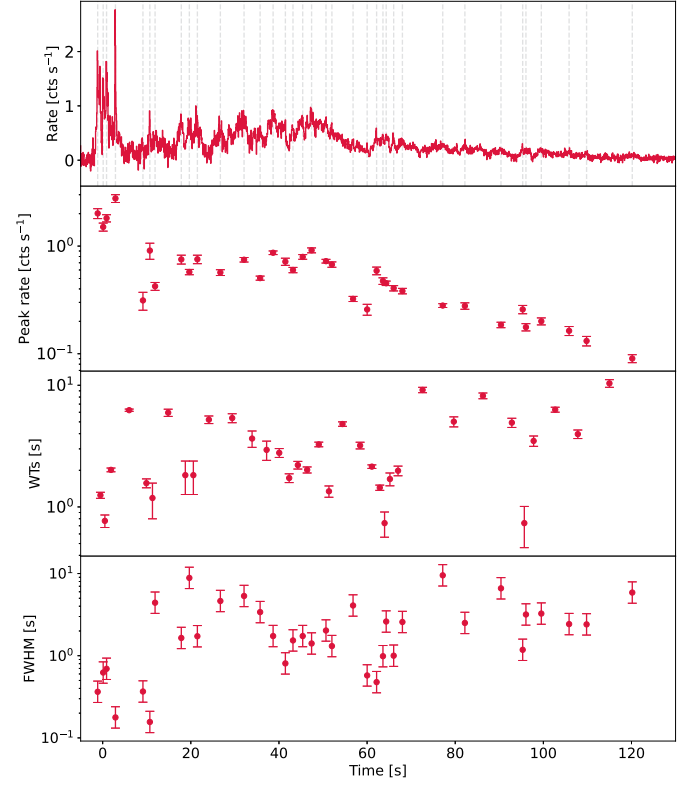
We also computed the photospheric radius, R_{ph} , to evaluate whether any emission in our model could originate below the photosphere, which would typically give rise to a thermal spectral component not observed in the data

$$R_{ph} = \frac{L \sigma_T}{8 \pi m_p c^3 \Gamma^3}, \quad (16)$$

here L is the isotropic luminosity, m_p the proton mass (Daigne and Mochkovitch, 2002). Using $L = 7.6 \times 10^{51}$ erg s⁻¹ (Svinkin et al., 2023), it is $R_{ph} = 5.5 \times 10^{12}$ cm, which is lower than the radius of the first shocks (1.3×10^{13} cm). Hence, all shocks in our model occur above the photosphere, consistent with the absence of a detectable thermal component in the prompt emission spectrum.

Finally, we verified that internal shocks between two fast shells do not occur before the collision with the target shell. While some variability in the ejection velocities is expected and may lead to internal shocks among the fast shells themselves, we computed the corresponding internal shock radius using

$$R_{IS} = \Gamma^2 c \Delta t, \quad (17)$$

Fig. 5. GRB 211211A *Fermi*/GBM 8-1000 keV LC binned at 4 ms.Fig. 6. GRB 060614 *Swift*/BAT 15-350 keV LC binned at 64 ms.

where Δt represents the time interval between the emission of two consecutive shells (Daigne and Mochkovitch, 1998). Assuming a typical value of $\Delta t = 0.1$ s for the early shells, we found $R_{IS} \approx 2.6 \times 10^{13}$ cm, which lies beyond the radius of the first shock with the target shell. Since the WTs increase more rapidly than the pulse widths, R_{IS} continues to grow and remains larger than the radius of the shocks between the fast and target shells. This confirms that the shell collisions between the fast shells and the slow target shell always occur before any possible internal shocks between fast shells.

3.6. Similar analysis of other known long COM candidates

We carried out a similar and preliminary analysis to other known LGRBs that are COM candidates with enough peaks: GRB 211211A and GRB 060614. Figs. 5 and 6 illustrate that these events exhibit similar trends as those observed in GRB 230307A, suggesting that such properties might be characteristic of this subclass of GRBs. A more detailed analysis of their temporal evolution is reported in Appendix B. To test whether these properties can be taken as indicators of a COM origin, we applied the same analysis to a LGRB with enough peaks and that is associated with a Ic broad-lined supernova and for which, therefore, a merger origin is excluded with confidence.

To this aim, the well-known naked-eye burst GRB 080319B (Racusin et al., 2008) represents an ideal test-bed: the exceptional quality of its *Swift*/BAT 15–150 keV spiky LC offers an excellent opportunity to detect possible temporal trends in WTs and FWHMs. However, as shown in Fig. 7, no such evolution of WTs or of FWHMs with time emerges, in full agreement with an IS interpretation. We extended the same test to the other known SN-associated GRBs having a LC with a suitable number of detected peaks for the same analysis to be applied. To this aim, we could identify six SN-GRBs, in addition to the extraordinary case of GRB 221009A: their analysis is reported in Appendix C. As a result, none of them exhibits the systematic exponential evolution of WT and of FWHM seen in GRB 230307A (see Fig. C.11). Further analysis involving a larger

sample of GRBs is planned for future work, but the current examples already suggest that such temporal characteristics can serve as valuable indicators to identify long COM candidates from their prompt emission profile.

4. Discussion

Contrary to the majority of multi-peaked LGRBs, GRB 230307A remarkably displays a number of properties that evolve with time exponentially. For other COM candidates, it was already found that both E_p and X-ray luminosity appear to decline exponentially with time (Gompertz et al., 2023): in this respect, our findings reinforce the role of an exponential evolution for the COM candidates and extend it to other properties, such as peak times, durations, WTs, and peak rates of the pulses that make up the GRB prompt emission.

The deterministic evolution of WTs and of FWHMs with time observed in GRB 230307A directly clashes with the key idea of the IS model, which was conceived at the time to explain the apparent lack of evolution of timescales within a number of BATSE bursts (Fenimore et al., 1999). Rather, the systematic increase of pulse durations with time, as pointed by the FWHM evolution, agrees with the expectations of a simple ES model: as the blast wave expands, the duration of pulses, supposedly caused by interactions with the medium inhomogeneities, increases with time (Fenimore et al., 1996; Dermer et al., 1999; Dermer, 2008).

4.1. Emission from multiple shells emitted by the central engine

Our model assumes that multiple shells (corresponding to the energy bunches described in Section 3.1) are emitted by the central engine and are colliding with either a previously emitted, more massive target shell that is expanding more slowly, or alternatively with the external blast wave as it was suggested to explain long-lived afterglows in the so-called refreshed shocks scenario (Rees and Meszaros, 1998). To ac-

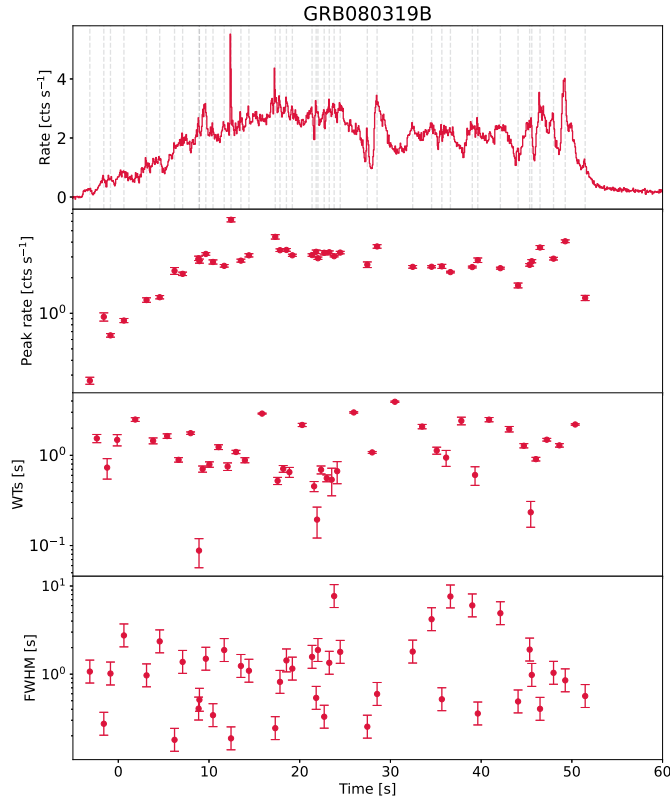


Fig. 7. Naked-eye burst GRB 080319B *Swift*/BAT 15–350 keV LC binned at 64 ms. Unlike COM candidates GRB 230307A, GRB 211211A, and GRB 060614, this collapsar event does not show the same monotonic evolution of the various observables.

count for the observed rapid variability and high-energy emission in the gamma-ray band – rather than in the optical – the collisions must occur at relatively small radii ($\sim 10^{13}$ cm), as discussed in Section 3.5. If the target shell corresponds to an external blast wave, the deceleration radius of the jet (or the radius at which a significant portion of jet begins to decelerate) must lie within the collision radius. This would imply that the merger occurred in an unusually high-density environment, and a bright afterglow would be expected. However, a low circumburst density of approximately 10^{-5} – 10^{-4} cm $^{-3}$ is required to explain both the non-detection of GeV emission and the multi-band afterglow data for this event (Dai et al., 2024). Therefore, the refreshed shock scenario – where the target shell is a blast wave – is disfavoured by these observations.

A plausible candidate for the slowly expanding target shell is the dynamical ejecta produced during the merger (e.g., neutron star–neutron star merger). Tidal interactions and shocks experienced by the neutron stars near the time of coalescence lead to the ejection of material on a dynamical timescale (e.g. Dietrich and Ujevic 2017; Radice et al. 2018; Shibata and Hotokezaka 2019; Rosswog et al. 2025). The tidal component of the dynamical ejecta is launched first, predominantly along the orbital plane, followed by a more isotropic, shock-driven ejecta component. Although the bulk of the merger ejecta is sub-relativistic, material along the rotational (jet) axis may be further accelerated by the leading edge or early-ejected component of the relativistic jet. Since the first interaction likely occurs well inside the photosphere, the associated shock radiation would be totally suppressed. Instead, the shock energy is efficiently converted into the bulk kinetic energy of the target shell (Kobayashi et al., 2002). Given the low baryon contamination along the jet axis, a significant boost in velocity may be achievable.

Another, more ad hoc possibility relates to the nature of the central engine. Since the jet acceleration process is still poorly understood, it is possible that the engine initially ejects a slower, more massive shell,

followed by faster, less massive ejecta. In our model, the initial radius of the target shell is 9×10^{10} cm. Given its relativistic velocity, this suggests that the massive, slow shell was expelled approximately 3 seconds prior to the rest of the ejecta in this scenario.

The central engine may be powered by a black hole accretion disc, into which fragmented material accretes independently. The accretion of each fragment leads to the ejection of a shell, which subsequently collides with the slower target shell at progressively larger radii. This simple toy model predicts a sequence of pulses that can be described as a piecewise Poisson process, whose shot rate gradually decreases with time (for further details, see Guidorzi et al. 2015). This mechanism explains the exponential distribution of the peak times as well as the exponential evolution with time of their WTs expressed by Eq. (6). In the so-called toy model, the FWHM evolution is phenomenological: to match the observed trend, an exponential evolution seems at first sight the best solution. However, the evolution of the FWHM could be directly inferred from shock kinematics, using Eq. (11).

We considered possible evolutions of the Lorentz factor Γ of the various shells: (i) approximately constant (Sect. 3.2); (ii) gradually decreasing with time (Sect. 3.3). In scenario (i), the FWHM is increasing linearly with time. Alternately to (i), scenario (ii) assumes a gradually decreasing Lorentz factor: this naturally explains both the evolution of FWHM, which can also be stronger than linear, as well as a decreasing Doppler boosting. In scenario (ii), the pulses’ broadening and the spectral softening share a common explanation. The decaying E_p could either indicate a gradually decreasing efficiency of the shocks in particle acceleration (i), or be due to a time decreasing Doppler boosting (ii). Fig. 8 illustrates both possibilities. The dip observed in the light curve is not neatly reproduced by our toy models. Yi et al. (2025a) interpreted the dip as a gap between two fast mini-jet pulses, implying that GRB 230307A’s time profile consists solely of short pulses without a slow variability component. Our model builds on the same assumption and also produces dips, most of which are less pronounced than the observed one, though. Alternative explanations include a temporary shutdown of the central engine or absorption/geometrical blocking along the line of sight. Given the rarity of this feature (possibly unique), stochasticity cannot be ruled out as its cause.

An alternative scenario invokes a central engine emitting a single shell, that is then expanding. In this scenario, the GRB emission could be due to: (a) an external shock between the expanding shell and inhomogeneities (clumps) present in the circumburst medium (Fenimore et al., 1996; Dermer et al., 1999; Dermer, 2008), or (b) magnetic reconnection events happening within the expanding shell, as proposed by Yi et al. (2025b). In both cases, the late, soft, and broad emission could be due to high-latitude photons arriving from large angles with respect to the line of sight. A major drawback of (a) is that the rate of shocked clumps, under the simple assumption of a spatially homogeneous distribution of clumps, should increase with time, whereas a decreasing rate of pulses is observed. The only way out would be assuming that the clumps are spatially clustered around the jet axis, which should roughly coincide with the line of sight, — a rather contrived assumption.

In (b) the emission arises from magnetic reconnection within a single expanding shell. A brief energy injection from the central engine triggers turbulence near the jet axis, which then spreads across the shell, producing delayed emission in expanding rings. This process leads to a broad pulse and naturally explains the observed spectral softening and the softer-wider/softer-later behaviour seen in GRBs like GRB 230307A. Table 2 summarises the different theoretical interpretations of the temporal and spectral properties observed in GRB 230307A.

5. Summary and conclusions

We discovered new features in the GRB 230307A time profile using exquisite data from GECAM. In particular, the waiting times, peak rate, pulse FWHM, and peak energy follow a characteristic exponential evolution over time. We show that these properties are also present in other

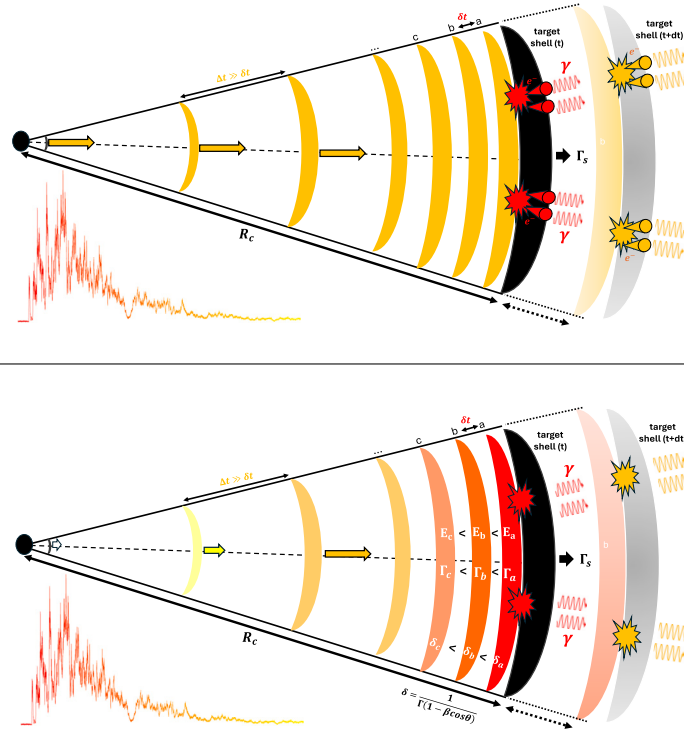


Fig. 8. Sketch of the emission from multiple shells in the (i) constant Lorentz factor (Sect. 3.2) model (top panel) and in the (ii) decreasing Lorentz factor (Sect. 3.3) model (bottom panel). Energy bunches emitted from the central engine collide with a slower target shell (shown in black) that was emitted earlier by the central engine. In (i), all shells nearly have the same Lorentz factor, while in (ii) the later-emitted shells (in yellow or light orange) are slower and carry less energy than the earlier ones (in deep orange and red). The first shocks correspond to the intense and narrow peaks observed in the early prompt emission of GRB 230307A, while the later shocks are associated with the dim and broad pulses seen in the extended emission phase.

Table 2

Summary of the different theoretical interpretations of the observed temporal and spectral properties of GRB 230307A.

Observed properties	Single shell model	Multiple shells model
Evolution of the peak rates	FRED shape expected	FRED envelope formed as a superposition of the shots
Evolution of the peak times/waiting times	constrained spatial distribution of the clumps	fading central engine activity
Evolution of the FWHM	high latitude emission and increasing emission radius	slower late emitted shells
Evolution of the peak energy	high latitude emission and increasing emission radius	slower late emitted shells

long GRBs, that are merger candidates, suggesting the existence of a new subclass of long GRBs—so-called type IL—as proposed in the literature (Wang et al., 2025; Tan et al., 2025). These would originate from compact object mergers rather than from collapsars, as is typical for classical long GRBs. We built a toy model that is able to accurately reproduce GRB 230307A light curve, which we optimised using a genetic algorithm. We proposed different theoretical scenarios to explain the observed trends, assuming either a central engine emitting multiple shells that collide with previously ejected material, or a single shell that expands and dissipates its energy progressively at larger radii. We also revisit the idea that external/refreshed shocks could explain prompt emission variability. While this scenario was previously disfavoured due to the apparent lack of timescale evolution within a sample of BATSE bursts, we show that the main criticisms that were historically used to support internal shocks as opposed to an external shocks interpretation of the GRB prompt emission, do not apply to GRB 230307A, whose FWHMs clearly increase over time.

In summary, while our toy and physical models are attempts to account for the unprecedented observed phenomenology within self-consistent pictures, alternative interpretations cannot be excluded in principle. Yet the fact remains that GRB 230307A, along with other long compact object mergers candidates, exhibits a set of properties that is rarely seen in any other long GRBs, especially in GRBs with associated SNe that are currently known. Such a potentially distinctive signature

of this class of GRBs may help their identification and challenges our current understanding of how GRB central engines operate.

Identifying clear prompt γ -ray signatures of events coming from compact object mergers is particularly relevant in an era where new space missions such as the *Space-based multi-band astronomical Variable Objects Monitor* (SVOM; Atteia et al. 2022) and *Einstein Probe* (Yuan et al., 2022) are capable of performing prompt X-ray and optical follow-up of merger candidates, consequently enhancing the chances of coincident gravitational wave detection.

CRediT authorship contribution statement

R. Maccary: Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **C. Guidorzi:** Writing – review & editing, Validation, Supervision, Software, Methodology, Conceptualization. **M. Maistrello:** Writing – review & editing, Validation, Software. **S. Kobayashi:** Writing – review & editing, Validation. **M. Bulla:** Writing – review & editing, Validation. **R. Moradi:** Writing – review & editing, Resources. **S.-X. Yi:** Writing – review & editing, Resources. **C.W. Wang:** Writing – review & editing, Resources. **W.L. Zhang:** Writing – review & editing, Resources. **W.-J. Tan:** Writing – review & editing, Resources. **S.-L. Xiong:** Writing – review & editing, Resources. **S.-N. Zhang:** Writing – review & editing, Resources.

Table A.3

Loss function values from the genetic algorithm optimization for the three models.

Loss Component	Toy Model	Model 1 (Constant Γ)	Model 2 (Declining Γ)
L_{N_p} (number of peaks)	0.091	0.370	0.181
L_{peak} (peak times)	0.000	0.000	0.000
L_{FWHM} (FWHM dist.)	1.160	0.047	0.012
L_{avgd} (smoothed profile)	0.860	0.935	0.770
Total loss L_{tot}	0.527	0.340	0.241

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Optimisation of the model

To optimise our toy model, we employed a genetic algorithm (GA), whose principle is described in Bazzanini et al. (2024). We are using four losses to optimise the different models we considered:

- A loss L_{avgd} regarding the averaged time profile of GRB 230307A. To compute L_{avgd} , we applied a 5 s window moving averaged to the simulated and observed time profile and have computed

$$L_{\text{avgd}} = \sum_{i=1}^{N_{\text{bins}}} (y_{\text{sim},i} - y_{\text{obs},i})^2, \quad (\text{A.1})$$

where $y_{\text{sim},i}$ and $y_{\text{obs},i}$ are the averaged observed and simulated time, and N_{bins} is the number of bins of the 5 s binned time averaged profile.

- A loss L_{peak} regarding the peak times distribution. L_{peak} is computed by performing a two-population Kolmogorov-Smirnov (KS) test between the simulated and the observed peak time distributions. If p is the p -value of the KS test,

$$L_{\text{peak}} = \begin{cases} 1 - \log(p) & \text{if } p \leq 0.05, \\ 0 & \text{otherwise.} \end{cases} \quad (\text{A.2})$$

- A loss L_{N_p} regarding the number of peaks produced by the model.

$$L_{N_p} = 3 \left| \log \left(\frac{N_{\text{obs}}}{N_{\text{sim}}} \right) \right|. \quad (\text{A.3})$$

The number of peaks in the observed and simulated profiles were obtained by applying MEPSA to these light curves. We defined L_{N_p} so to have $L_{N_p} = 0$ when $N_{\text{obs}} = N_{\text{sim}}$ and growing when the ratio deviates from 1, the absolute value is chosen to equally penalise the solution with too few or too many simulated peaks. The factor 3 is here to ensure that L_{N_p} weights equally as the other losses.

- A loss L_{FWHM} regarding the FWHM distribution. The FWHMs of the pulses contained in the simulated and observed profiles were computed using MEPSA, and the method described in Camisasca et al. (2023a). L_{FWHM} is computed by performing a two-population KS test between the simulated and the observed FWHM distributions, and computed similarly to L_{peak} .

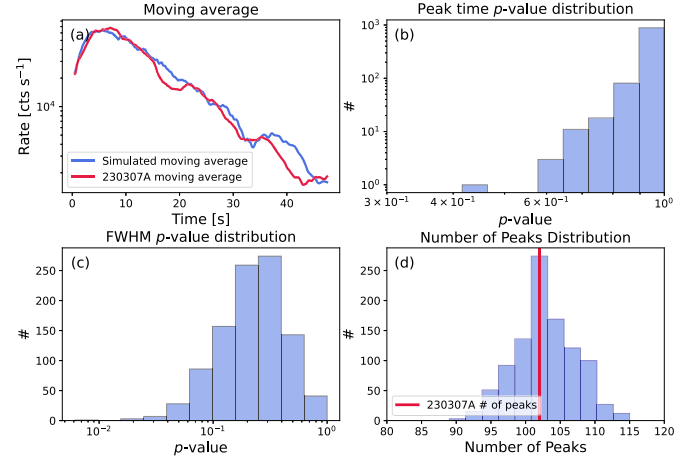


Fig. A.9. Four losses involved in the GA optimisation. Panel (a): Moving average time profile (5 s window) for the real (red) and simulated (blue) LCs. Panel (b): Distribution of p -values from the KS test comparing peak time distributions. Panel (c): Same as (b), but for FWHM distributions. Panel (d): Number of peaks detected in simulated LCs (blue histogram) compared with GRB 230307A (vertical red line).

We finally took the average of the four losses described above to compute the total loss L_{tot} . Each individual's set of parameters was initially sampled randomly from a uniform distribution in the logarithmic space of each quantity, within the following ranges:

- $N_0 \in [100, 2000]$.
- $\tau \in [5, 25]$ s.
- $\text{FWHM}_0 \in [0.01, 0.5]$ s.
- $\tau_F \in [10, 30]$ s.
- $\tau_{\text{rise}} \in [0.1 - 100]$ s.
- $N_F \in [500, 2000]$.

In addition, for the two physical models, Γ , Γ_s , and Γ_0 were sampled in $1 - 10^4$, R_0 in $10^{10} - 10^{17}$ cm and τ_{Γ} in $1 - 10^3$ s. These ranges were chosen to constrain the parameter space in a way that ensures coverage and diversity among potential solutions. For each individual, the loss was computed using 100 light curves generated from the same parameter set. We ran the genetic algorithm on at least 60 generations, using a population of 2000 individuals. From the total population, 300 individuals were selected for mating in each generation. The probability for a random mutation of the parameters was set to 10%.

A.1. Results of the toy models

The final optimised parameters are given by the median values of the individual parameter distributions in the final generation. The uncertainties are defined by the 16th and 84th quantiles of these distributions. We generated 1000 light curves to test the best-fit parameters, reported in Table 1, for the three models considered in this study and computed the loss on these profiles. The values of the individual losses and the total losses for the toy model (Sect. 3.1) and the physical model 1 (Sect. 3.2) and 2 (Sect. 3.3) are reported in Table A.3.

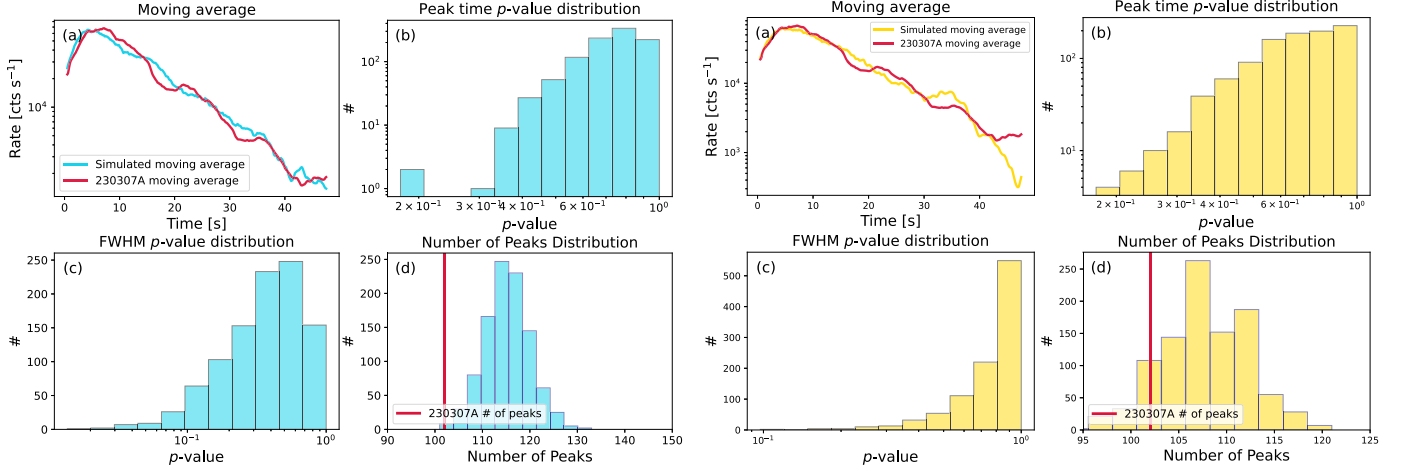


Fig. A.10. Same as in Fig. A.9, but for the constant (left panel) and decreasing (right panel) Γ -shell emission model.

Table B.4

Results and comparison of exponential temporal evolution modelling of WTs, FWHMs, and peak rates for GRB 211211A, GRB 230307A, and GRB 060614.

Property	GRB 211211A	GRB 230307A	GRB 060614
Waiting times	$\tau = 22.7^{+6.3}_{-4.0}$ s	$\tau = 15.8^{+2.2}_{-1.8}$ s	$\tau = 125^{+291}_{-56}$ s
	$N_0 = 136^{+23}_{-19}$	$N_0 = 124^{+12}_{-11}$	$N_0 = 68^{+106}_{-21}$
	$\sigma = 0.85^{+0.12}_{-0.10}$	$\sigma = 0.54^{+0.07}_{-0.06}$	$\sigma = 0.66^{+0.17}_{-0.12}$
	$\chi^2 = 86.5$ (dof = 86)	$\chi^2 = 100.1$ (dof = 99)	$\chi^2 = 32.4$ (dof = 32)
FWHM	$\tau_F = 21.6^{+4.4}_{-3.2}$ s	$\tau_F = 18.6^{+3.2}_{-2.5}$ s	$\tau_F = 74^{+97}_{-28}$ s
	$\text{FWHM}_0 = 0.09^{+0.02}_{-0.02}$ s	$\text{FWHM}_0 = 0.12 \pm 0.02$ s	$\text{FWHM}_0 = 0.85^{+0.50}_{-0.32}$ s
	$\sigma = 0.70^{+0.11}_{-0.10}$	$\sigma = 0.48^{+0.09}_{-0.07}$	$\sigma = 0.90^{+0.24}_{-0.18}$
	$\chi^2 = 86.6$ (dof = 87)	$\chi^2 = 99.9$ (dof = 100)	$\chi^2 = 32.4$ (dof = 33)
Peak rate	$\tau_p = 18.8^{+2.0}_{-1.6}$ s	$\tau_p = 10.9 \pm 0.6$ s	$\tau_p = 51.4^{+10.4}_{-7.4}$ s
	$P_0 = 6.5^{+1.2}_{-1.0} \times 10^4$ cts/s	$P_0 = 1.56^{+0.21}_{-0.18} \times 10^5$ cts/s	$P_0 = 1.33^{+0.30}_{-0.25}$ cts/s
	$\sigma = 0.32^{+0.06}_{-0.05}$	$\sigma = 0.22^{+0.05}_{-0.03}$	$\sigma = 0.39^{+0.10}_{-0.07}$
	$\chi^2 = 56.1$ (dof = 56)	$\chi^2 = 48.7$ (dof = 49)	$\chi^2 = 33.5$ (dof = 33)

Figs. A.9 and A.10 illustrate the outcome of the GA optimisation, showing how the synthetic light curves reproduce the main temporal features of GRB 230307A, including the overall smoothed time profile, the distributions of peak times and FWHMs, and the total number of detected peaks.

Appendix B. Analysis of other long merger candidates

As anticipated in Section 3.6, adopting the procedure of Section 3, we analysed the temporal behaviour of other long merger candidates, namely GRB 211211A and GRB 060614. Results are reported in Table B.4.

Overall, we found that the exponential model provides an accurate description of the data (see χ^2 values reported in Table B.4). In this respect, GRB 211211A behaves very similarly to GRB 230307A, consistent with previous claims (e.g. Peng et al. 2024). The WTs, the FWHMs, and the peak rates evolve with time as exponentials with timescales close to 20 s. In the case of GRB 060614, the different timescales are longer than in the case of GRBs 211211A/230307A, and are less tightly constrained. In this case, both WT and FWHM increase, and the PR decay does not seem to share a common timescale; although, given the parameters' uncertainties, we cannot exclude the possibility that they are equal.

Appendix C. Analysis of SN-GRBs

We investigated whether some Type-II GRBs could display behaviour similar to GRB 230307A by focusing on bursts associated with Type Ic-BL supernovae, a clear indicator of a collapsar origin. Table C.5 reports a list of known SN-GRB associations, along with the corresponding number of detected peaks. We searched for SN-GRBs with sufficiently complex light curves ($N_p \geq 10$), as detected by MEPSA using either *Swift*/BAT or *Fermi*/GBM data (same dataset as Guidorzi et al. 2024). Only six GRBs met this criterion, namely GRB 080319B, GRB 111228A, GRB 130427A, GRB 171010A, GRB 211023A, and GRB 190114C (in addition to the exceptional GRB 221009A, which is analysed separately). The LCs of these bursts, the corresponding WT and pulse FWHM evolution are displayed in Fig. C.11. None of these GRBs exhibits a similar joint temporal evolution of the observables to that of GRB 230307A.

The case of GRB 221009A was also considered. Its exceptional brightness makes it hard to obtain a complete time profile, unaffected by strong dead time and electronics saturation effects. We carried out a detailed analysis using both HXMT/HE and GECAM data (Zhang et al., 2025). HXMT/HE data cover $T_0 - 141$ to $T_0 + 1800$ s, with three saturation intervals (187–194 s, 216–290 s, 500–535 s). Data are binned at 1 s, and background estimated via 8th-order polynomial interpolation. GECAM data (180–550 s) cover the main and the last emission episodes, are unaffected by saturation and binned at 50 ms. MEPSA was applied to both data sets, excluding the HXMT/HE saturated intervals.

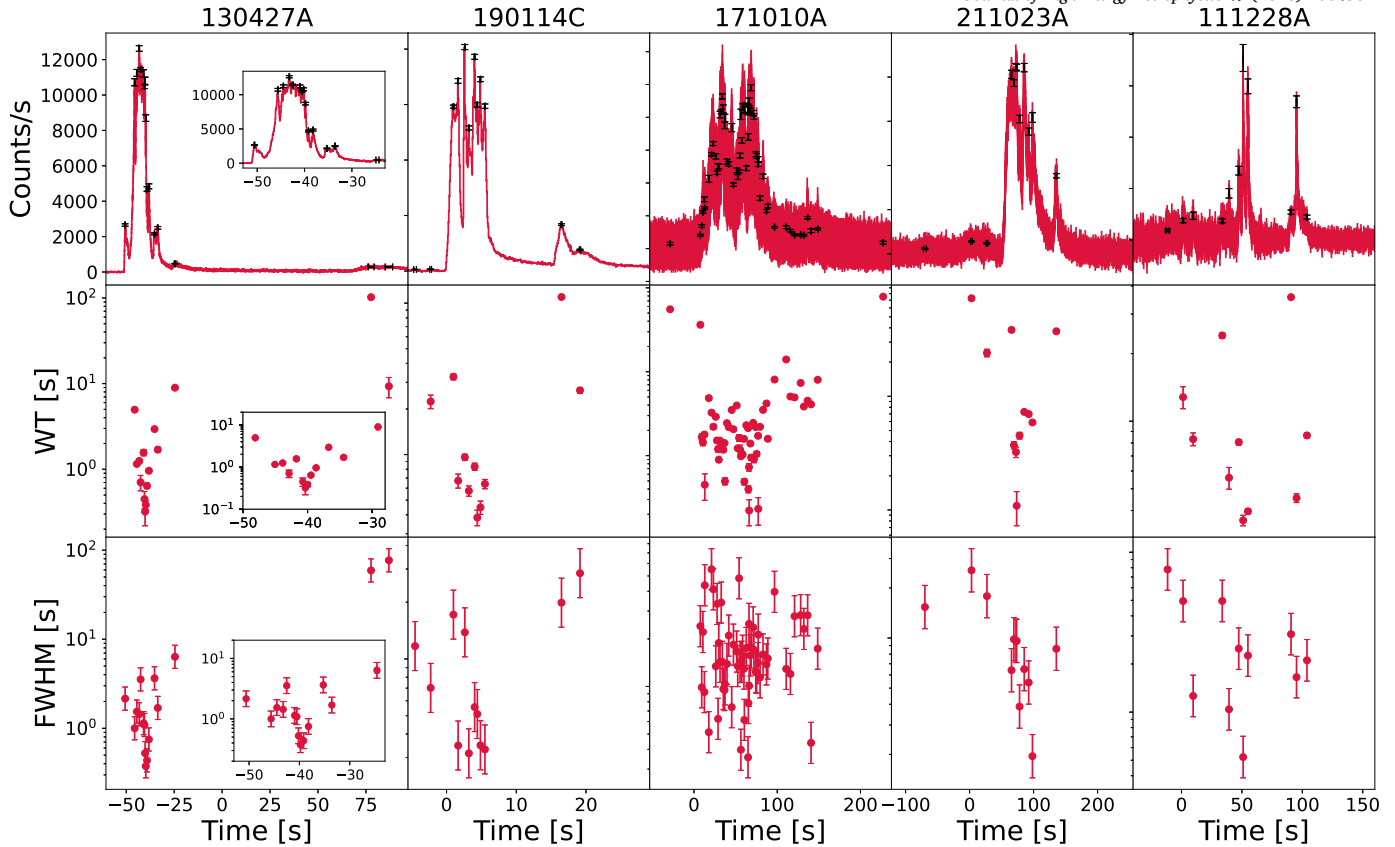


Fig. C.11. Five SN-GRBs having $N_p \geq 10$. Each top panel shows the γ -ray time profile (obtained with either *Fermi*/GBM or *Swift*/BAT). Black points represent the peaks detected by MEPSA. Middle and bottom panels respectively show the temporal evolution of WT and of FWHM throughout each burst. For GRB 130427A, two insets show a close-in view of the densely populated interval.

The combined HXMT/HE and GECAM light curves, along with the derived WTs, are shown in Fig. C.12. The complex profile consists of two long quiescent times: one between the precursor and the main emission, and the other between the main and late emission, separated by closely spaced pulses during each outburst. WTs in the main and late emission episodes were derived from GECAM data. Apart from noting that the WTs belonging to the late emission are somehow longer than those of the main episode, the overall evolution of WTs with time is very different from the monotonic WT rise seen in GRB 230307A.

Data availability

Data will be made available on request.

References

- Ahumada, T., Singer, L.P., Anand, S., Coughlin, M.W., Kasliwal, M.M., Ryan, G., Andreoni, I., Cenko, S.B., Fremling, C., Kumar, H., Pang, P.T.H., Burns, E., Cunningham, V., Dichiaro, S., Dietrich, T., Svinkin, D.S., Almualla, M., Castro-Tirado, A.J., De, K., Dunwoody, R., Gatkine, P., Hammerstein, E., Iyyani, S., Mangan, J., Perley, D., Purkayastha, S., Bellm, E., Bhalerao, V., Bolin, B., Bulla, M., Cannella, C., Chandra, P., Duev, D.A., Frederiks, D., Gal-Yam, A., Graham, M., Ho, A.Y.Q., Hurley, K., Karambelkar, V., Kool, E.C., Kulkarni, S.R., Mahabal, A., Masci, F., McBreen, S., Pandey, S.B., Reusch, S., Ridnaia, A., Rosnet, P., Rusholme, B., Carracedo, A.S., Smith, R., Soumagnac, M., Stein, R., Troja, E., Tsvetkova, A., Walters, R., Valeev, A.F., 2021. Discovery and confirmation of the shortest gamma-ray burst from a collapsar. *Nat. Astron.* 5, 917–927. <https://doi.org/10.1038/s41550-021-01428-7>.
- Amati, L., 2006. The $E_{p,d}-E_{iso}$ correlation in gamma-ray bursts: updated observational status, re-analysis and main implications. *Mon. Not. R. Astron. Soc.* 372, 233–245. <https://doi.org/10.1111/j.1365-2966.2006.10840.x>. arXiv:astro-ph/0601553.
- Amati, L., Frontera, F., Tavani, M., in't Zand, J.J.M., Antonelli, A., Costa, E., Feroci, M., Guidorzi, C., Heise, J., Masetti, N., Montanari, E., Nicastro, L., Palazzi, E., Pian, E., Piro, L., Soffitta, P., 2002. Intrinsic spectra and energetics of BeppoSAX Gamma-Ray Bursts with known redshifts. *Astron. Astrophys.* 390, 81–89. <https://doi.org/10.1051/0004-6361:20020722>. arXiv:astro-ph/0205230.
- Atteia, J.L., Cordier, B., Wei, J., 2022. The SVOM mission. *Int. J. Mod. Phys. D* 31, 2230008. <https://doi.org/10.1142/S0218271822300087>. arXiv:2203.10962.
- Bazzanini, L., Ferro, L., Guidorzi, C., Angora, G., Amati, L., Brescia, M., Bulla, M., Frontera, F., Maccary, R., Maistrello, M., Rosati, P., Tsvetkova, A., 2024. Long gamma-ray burst light curves as the result of a common stochastic pulse–avalanche process. *Astron. Astrophys.* 689, A266. <https://doi.org/10.1051/0004-6361/202450150>. arXiv:2403.18754.
- Bošnjak, Z., Daigne, F., 2014. Spectral evolution in gamma-ray bursts: predictions of the internal shock model and comparison to observations. *Astron. Astrophys.* 568, A45. <https://doi.org/10.1051/0004-6361/201322341>. arXiv:1404.4577.
- Camisasca, A.E., Guidorzi, C., Amati, L., Frontera, F., Song, X.Y., Xiao, S., Xiong, S.L., Zhang, S.N., Margutti, R., Kobayashi, S., Mundell, C.G., Ge, M.Y., Gomboc, A., Jia, S.M., Jordana-Mitjans, N., Li, C.K., Li, X.B., Maccary, R., Shrestha, M., Xue, W.C., Zhang, S., 2023a. GRB minimum variability timescale with Insight-HXMT and Swift. Implications for progenitor models, dissipation physics, and GRB classifications. *Astron. Astrophys.* 671, A112. <https://doi.org/10.1051/0004-6361/202245657>. arXiv:2301.01176.
- Camisasca, A.E., Guidorzi, C., Bulla, M., Amati, L., Rossi, A., Stratta, G., Singh, P., 2023b. GRB 230307A: short minimum variability timescale compatible with a merger origin. *GRB Coord. Netw.* 33577, 1.
- D'Agostini, G., 2005. Fits, and especially linear fits, with errors on both axes, extra variance of the data points and other complications. *ArXiv Physics e-prints arXiv: physics/0511182*.
- Dai, C.Y., Guo, C.L., Zhang, H.M., Liu, R.Y., Wang, X.Y., 2024. Evidence for a compact stellar merger origin for GRB 230307A from Fermi-LAT and multiwavelength afterglow observations. *Astrophys. J. Lett.* 962, L37. <https://doi.org/10.3847/2041-8213/ad2680>. arXiv:2312.01074.
- Daigne, F., Mochkovitch, R., 1998. Gamma-ray bursts from internal shocks in a relativistic wind: temporal and spectral properties. *Mon. Not. R. Astron. Soc.* 296, 275–286. <https://doi.org/10.1046/j.1365-8711.1998.01305.x>. arXiv:astro-ph/9801245.
- Daigne, F., Mochkovitch, R., 2002. The expected thermal precursors of gamma-ray bursts in the internal shock model. *Mon. Not. R. Astron. Soc.* 336, 1271–1280. <https://doi.org/10.1046/j.1365-8711.2002.05875.x>. arXiv:astro-ph/0207456.
- Della Valle, M., Chincarini, G., Panagia, N., Tagliaferri, G., Malesani, D., Testa, V., Fugazza, D., Campana, S., Covino, S., Mangano, V., Antonelli, L.A., D'Avanzo, P., Hurley, K., Mirabel, I.F., Pellizza, L.J., Piranomonte, S., Stella, L., 2006. An enigmatic long-lasting γ -ray burst not accompanied by a bright supernova. *Nature* 444, 1050–1052. <https://doi.org/10.1038/nature05374>. arXiv:astro-ph/0608322.

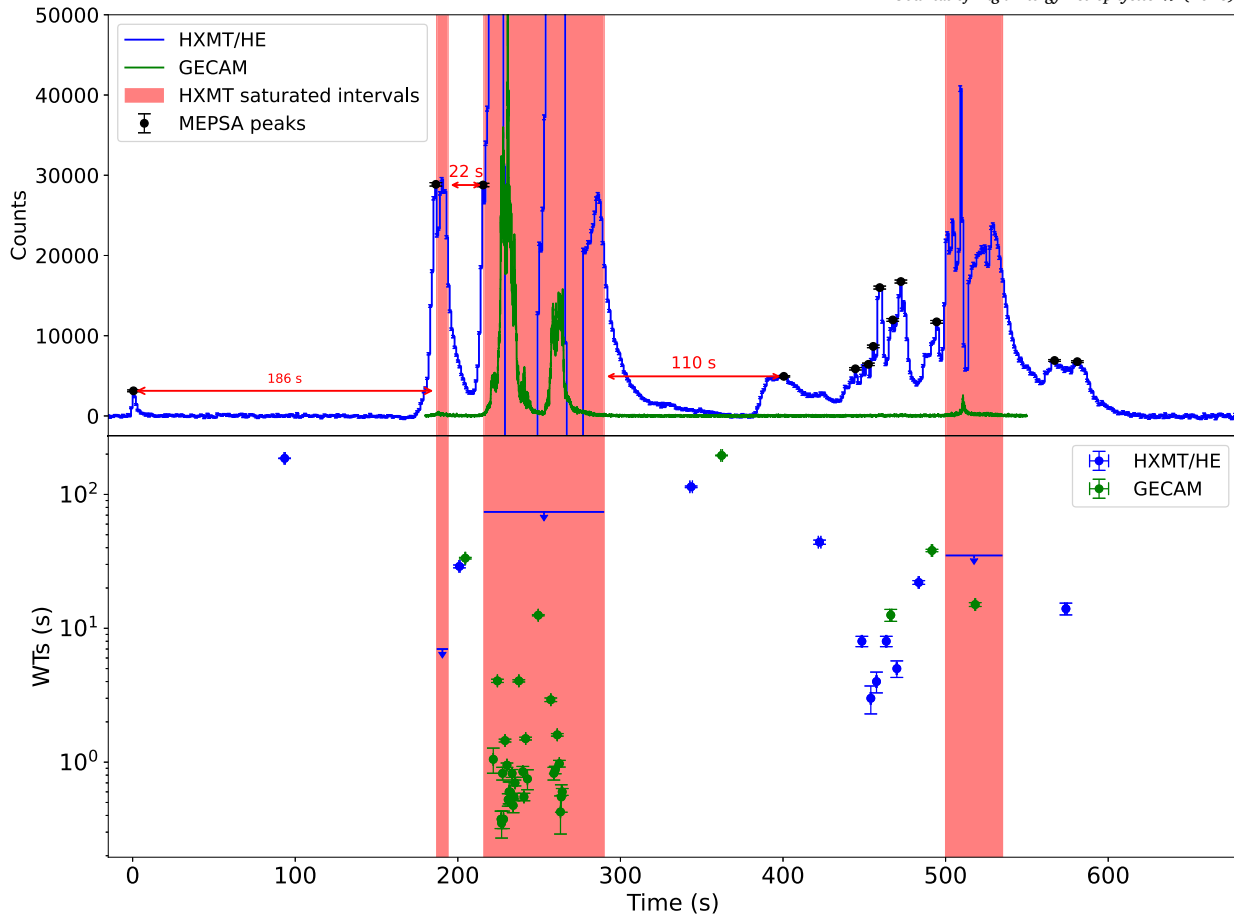


Fig. C.12. *Top panel:* Background-subtracted LCs of GRB 221009A from HXMT/HE (blue, 1 s binning) and GECAM (green, 50 ms binning). Red shaded areas mark intervals where HXMT/HE is affected by saturation. Peaks detected by MEPSA are shown as black markers. The two long quiescent intervals between the precursor and main emission (186 s) and between the main and late emission (110 s) are indicated. *Bottom panel:* WTs derived from MEPSA detections in HXMT/HE and GECAM data as a function of time. WTs inside HXMT/HE saturated intervals are computed from GECAM measurements.

- Dermer, C.D., 2008. Nonthermal synchrotron radiation from gamma-ray burst external shocks and the X-ray flares observed with Swift. *Astrophys. J.* 684, 430–448. <https://doi.org/10.1086/589730>. arXiv:astro-ph/0703223.
- Dermer, C.D., Böttcher, M., Chiang, J., 1999. The external shock model of gamma-ray bursts: three predictions and a paradox resolved. *Astrophys. J.* 515, L49–L52. <https://doi.org/10.1086/311972>. arXiv:astro-ph/9902306.
- Dichiara, S., Tsang, D., Troja, E., Neill, D., Norris, J.P., Yang, Y.H., 2023. A luminous precursor in the extremely bright GRB 230307A. *Astrophys. J. Lett.* 954, L29. <https://doi.org/10.1084/2041-8213/acf21d>. arXiv:2307.02996.
- Dietrich, T., Ujevic, M., 2017. Modeling dynamical ejecta from binary neutron star mergers and implications for electromagnetic counterparts. *Class. Quantum Gravity* 34, 105014. <https://doi.org/10.1088/1361-6382/aa6bb0>. arXiv:1612.03665.
- Du, Z.W., Lü, H., Liu, X., Liang, E., 2024. The jet composition of GRB 230307A: Poynting-flux-dominated outflow? *Mon. Not. R. Astron. Soc.* 529, L67–L72. <https://doi.org/10.1093/mnras/slad203>. arXiv:2401.05002.
- Eichler, D., Livio, M., Piran, T., Schramm, D.N., 1989. Nucleosynthesis, neutrino bursts and γ -rays from coalescing neutron stars. *Nature* 340, 126–128. <https://doi.org/10.1038/340126a0>.
- Fenimore, E.E., Madras, C.D., Nayakshin, S., 1996. Expanding relativistic shells and gamma-ray burst temporal structure. *Astrophys. J.* 473, 998. <https://doi.org/10.1086/178210>. arXiv:astro-ph/9607163.
- Fenimore, E.E., Ramirez-Ruiz, E., Wu, B., 1999. GRB 990123: evidence that the gamma rays come from a central engine. *Astrophys. J.* 518, L73–L76. <https://doi.org/10.1086/312075>. arXiv:astro-ph/9902007.
- Fynbo, J.P.U., Watson, D., Thöne, C.C., Sollerman, J., Bloom, J.S., Davis, T.M., Hjorth, J., Jakobsson, P., Jørgensen, U.G., Graham, J.F., Fruchter, A.S., Bersier, D., Kewley, L., Cassan, A., Castro Cerón, J.M., Foley, S., Gorosabel, J., Hinse, T.C., Horne, K.D., Jensen, B.L., Klose, S., Kocevski, D., Marquette, J.B., Perley, D., Ramirez-Ruiz, E., Stritzinger, M.D., Vreeswijk, P.M., Wijers, R.A.M., Woller, K.G., Xu, D., Zub, M., 2006. No supernovae associated with the long-short duration γ -ray bursts. *Nature* 444, 1047–1049. <https://doi.org/10.1038/nature05375>. arXiv:astro-ph/0608313.
- Gillanders, J.H., Smartt, S.J., 2025. Analysis of the JWST spectra of the kilonova AT 2023vfi accompanying GRB 230307A. *Mon. Not. R. Astron. Soc.* 538, 1663–1689. <https://doi.org/10.1093/mnras/staf287>. arXiv:2408.11093.
- Gompertz, B.P., Ravasio, M.E., Nicholl, M., Levan, A.J., Metzger, B.D., Oates, S.R., Lamb, G.P., Fong, W.f., Malesani, D.B., Rastinejad, J.C., Tanvir, N.R., Evans, P.A., Jonker, P.G., Page, K.L., Pe'er, A., 2023. The case for a minute-long merger-driven gamma-ray burst from fast-cooling synchrotron emission. *Nat. Astron.* 7, 67–79. <https://doi.org/10.1038/s41550-022-01819-4>. arXiv:2205.05008.
- Guidorzi, C., 2015. MEPSA: a flexible peak search algorithm designed for uniformly spaced time series. *Astron. Comput.* 10, 54–60. <https://doi.org/10.1016/j.ascom.2015.01.001>. <http://www.sciencedirect.com/science/article/pii/S2213133715000025>.
- Guidorzi, C., Dichiara, S., Frontera, F., Margutti, R., Baldeschi, A., Amati, L., 2015. A common stochastic process rules gamma-ray burst prompt emission and X-ray flares. *Astrophys. J.* 801, 57. <https://doi.org/10.1088/0004-637X/801/1/57>. arXiv:1501.02706.
- Guidorzi, C., Sartori, M., Maccary, R., Tsvetkova, A., Amati, L., Bazzanini, L., Bulla, M., Camisasca, A.E., Ferro, L., Frontera, F., Li, C.K., Xiong, S.L., Zhang, S.N., 2024. Distribution of the number of peaks within a long gamma-ray burst. *Astron. Astrophys.* 685, A34. <https://doi.org/10.1051/0004-6361/202449200>. arXiv:2402.17282.
- Jin, Z.P., Li, X., Cano, Z., Covino, S., Fan, Y.Z., Wei, D.M., 2015. The light curve of the macronova associated with the long-short burst GRB 060614. *Astrophys. J.* 811, L22. <https://doi.org/10.1088/2041-8205/811/2/L22>. arXiv:1507.07206.
- Kobayashi, S., Piran, T., Sari, R., 1997. Can internal shocks produce the variability in gamma-ray bursts? *Astrophys. J.* 490, 92. <https://doi.org/10.1086/512791>. arXiv:astro-ph/9705013.
- Kobayashi, S., Ryde, F., MacFadyen, A., 2002. Luminosity and variability of collimated gamma-ray bursts. *Astrophys. J.* 577, 302–310. <https://doi.org/10.1086/342123>. arXiv:astro-ph/0110080.
- Levan, A.J., Gompertz, B.P., Salafia, O.S., Bulla, M., Burns, E., Hotokezaka, K., Izzo, L., Lamb, G.P., Malesani, D.B., Oates, S.R., Ravasio, M.E., Rouco Escorial, A., Schneider, B., Sarin, N., Schulze, S., Tanvir, N.R., Ackley, K., Anderson, G., Brammer, G.B., Christensen, L., Dhillon, V.S., Evans, P.A., Fausnaugh, M., Fong, f.W., Fruchter, A.S., Fryer, C., Fynbo, J.P.U., Gaspari, N., Heintz, K.E., Hjorth, J., Kennea, J.A., Kennedy, M.R., Laskar, T., Leloudas, G., Mandel, I., Martin-Carrillo, A., Metzger, B.D., Nicholl, M., Nugent, A., Palmerio, J.T., Pugliese, G., Rastinejad, J., Rhodes, L., Rossi, A., Saccardi, A., Smartt, S.J., Stevance, H.F., Tohuavohu, A., van der Horst, A., Vergani, S.D.,

Table C.5

SN-GRBs with number of peaks N_p detected by MEPSA, using LCs binned at 64 ms. The SN Spec column indicates whether the evidence for the SN was both photometric and spectroscopic (1) or just photometric (0).

GRB	SN	SN Spec	z	N_p
221009A	2022xiw	1	0.1505	-
171010A	2017htp	1	0.3285	49
080319B	—	0	0.937	43
130427A	2013cq	1	0.3399	16
211023A	—	1	0.39	12
111228A	—	0	0.71627	11
190114C	2019jrr	1	0.4245	11
090618	—	0	0.54	9
111228A	—	0	0.71627	6
140506A	—	0	0.889	5
091127	2009nz	1	0.49034	4
140506A	—	0	0.889	3
060729	—	0	0.54	3
091127	2009nz	1	0.49034	3
180728A	2018fip	1	0.117	2
190829A	2019oyw	1	0.0785	2
140606B	iPTF14bfu	1	0.384	2
130831A	2013fu	1	0.4791	2
100316D	2010bh	1	0.0592	1
101219B	2010ma	1	0.5519	1
130215A	2013ez	1	0.597	1
130702A	2013dx	1	0.145	1
101219B	2010ma	1	0.5519	1
120422A	2012bz	1	0.283	1
120714B	2012eb	1	0.3984	1
120729A	—	0	0.8	1
171205A	2017iuk	1	0.0368	1
141004A	—	0	0.573	1
161219B	2016jca	1	0.1475	1
200826A	—	0	0.7481	1
201015A	—	1	0.426	1
980425	1998bw	1	0.0085	1

Watson, D., Barclay, T., Bhirombhakdi, K., Breedt, E., Breeveld, A.A., Brown, A.J., Campana, S., Chrimes, A.A., D'Avanzo, P., D'Elia, V., De Pasquale, M., Dyer, M.J., Galloway, D.K., Garbutt, J.A., Green, M.J., Hartmann, D.H., Jakobsson, P., Kerry, P., Kouveliotou, C., Langeroodi, D., Le Floch, E., Leung, J.K., Littlefair, S.P., Munday, J., O'Brien, P., Parsons, S.G., Pelisoli, I., Sahman, D.I., Salvaterra, R., Sbarufatti, B., Steeghs, D., Tagliaferri, G., Thöne, C.C., de Ugarte Postigo, A., Kann, D.A., 2024. Heavy-element production in a compact object merger observed by JWST. *Nature* 626, 737–741. <https://doi.org/10.1038/s41586-023-06759-1>. arXiv:2307.02098.

Levan, A.J., Malesani, D.B., Gompertz, B.P., Nugent, A.E., Nicholl, M., Oates, S.R., Perley, D.A., Rastinejad, J., Metzger, B.D., Schulze, S., Stanway, E.R., Inkenhaag, A., Zafar, T., Agüí-Fernández, J.F., Chrimes, A.A., Bhirombhakdi, K., de Ugarte Postigo, A., Fong, f.W., Fruchter, A.S., Fragione, G., Fynbo, J.P.U., Gaspari, N., Heintz, K.E., Hjorth, J., Jakobsson, P., Jonker, P.G., Lamb, G.P., Mandel, I., Mandhai, S., Ravasio, M.E., Sollerman, J., Tanvir, N.R., 2023. A long-duration gamma-ray burst of dynamical origin from the nucleus of an ancient galaxy. *Nat. Astron.* 7, 976–985. <https://doi.org/10.1038/s41550-023-01998-8>. arXiv:2303.12912.

Li, L., Wang, X.G., Zheng, W., Pozanenko, A.S., Filippenko, A.V., Qin, S., Wang, S.Q., Jiang, L.Y., Li, J., Lin, D.B., Liang, E.W., Volnova, A.A., Elenin, L., Klunko, E., Inasaridze, R.Y., Kusakin, A., Lu, R.J., 2020. GRB 140423A: a case of stellar wind to interstellar medium transition in the afterglow. *Astrophys. J.* 900, 176. <https://doi.org/10.3847/1538-4357/aba757>. arXiv:2008.02445.

MacFadyen, A.I., Woosley, S.E., 1999. Collapsars: gamma-ray bursts and explosions in “failed supernovae”. *Astrophys. J.* 524, 262–289. <https://doi.org/10.1086/307790>. arXiv:astro-ph/9810274.

Maistrello, M., Ferro, L., Bazzanini, L., Maccary, R., Guidorzi, C., 2025. An advanced pulse-avalanche stochastic model of long gamma-ray burst light curves. *Astron. Astrophys.* 697, A76. <https://doi.org/10.1051/0004-6361/202553821>.

Metzger, B.D., 2020. Kilonovae. *Living Rev. Relativ.* 23, 1. <https://doi.org/10.1007/s41114-019-0024-0>.

Moradi, R., Wang, C.W., Zhang, B., Wang, Y., Xiong, S.L., Yi, S.X., Tan, W.J., Karlica, M., Zhang, S.N., 2024. Temporal and spectral analysis of the unique and second-brightest gamma-ray burst GRB 230307A: insights from GECAM and Fermi/GBM observations. *Astrophys. J.* 977, 155. <https://doi.org/10.3847/1538-4357/ad8a64>. arXiv:2410.17189.

Narayan, R., Paczynski, B., Piran, T., 1992. Gamma-ray bursts as the death throes of massive binary stars. *Astrophys. J.* 395, L83–L86. <https://doi.org/10.1086/186493>. arXiv:astro-ph/9204001.

Norris, J.P., Bonnell, J.T., 2006. Short gamma-ray bursts with extended emission. *Astrophys. J.* 643, 266–275. <https://doi.org/10.1086/502796>. arXiv:astro-ph/0601190.

Norris, J.P., Nemiroff, R.J., Bonnell, J.T., Scargle, J.D., Kouveliotou, C., Paciesas, W.S., Meegan, C.A., Fishman, G.J., 1996. Attributes of pulses in long bright gamma-ray bursts. *Astrophys. J.* 459, 393. <https://doi.org/10.1086/176902>.

Paczynski, B., 1991. Cosmological gamma-ray bursts. *Acta Astron.* 41, 257–267.

Paczynski, B., 1998. Are gamma-ray bursts in star-forming regions? *Astrophys. J. Lett.* 494, L45–L48. <https://doi.org/10.1086/311148>. arXiv:astro-ph/9710086.

Peng, Z.Y., Chen, J.M., Mao, J., 2024. A comparative analysis of two peculiar gamma-ray bursts: GRB 230307A and GRB 211211A. *Astrophys. J.* 969, 26. <https://doi.org/10.3847/1538-4357/ad45fc>. arXiv:2404.17913.

Piran, T., 2004. The physics of gamma-ray bursts. *Rev. Mod. Phys.* 76, 1143–1210. <https://doi.org/10.1103/RevModPhys.76.1143>. arXiv:astro-ph/0405503.

Planck Collaboration, Aghanim, N., Akrami, Y., Ashdown, M., Aumont, J., Baccigalupi, C., Ballardini, M., Banday, A.J., Barreiro, R.B., Bartolo, N., Basak, S., Battye, R., Benabed, K., Bernard, J.P., Bersanelli, M., Bielewicz, P., Bock, J.J., Bond, J.R., Borrill, J., Bouchet, F.R., Boulanger, F., Bucher, M., Burigana, C., Butler, R.C., Calabrese, E., Cardoso, J.F., Carron, J., Challinor, A., Chiang, H.C., Chluba, J., Colombo, L.P.L., Combet, C., Contreras, D., Crill, B.P., Cuttaia, F., de Bernardis, P., de Zotti, G., Delabrouille, J., Delouis, J.M., Di Valentino, E., Diego, J.M., Doré, O., Douspis, M., Ducout, A., Dupac, X., Dusini, S., Efstathiou, G., Elsner, F., Enßlin, T.A., Eriksen, H.K., Fantaye, Y., Farhang, M., Fergusson, J., Fernandez-Cobos, R., Finelli, F., Forastieri, F., Frailis, M., Fraisse, A.A., Franceschi, E., Frolov, A., Galeotta, S., Galli, S., Ganga, K., Génova-Santos, R.T., Gerbino, M., Ghosh, T., González-Nuevo, J., Górski, K.M., Gratton, S., Gruppiso, A., Gudmundsson, J.E., Hamann, J., Handley, W., Hansen, F.K., Herranz, D., Hildebrandt, S.R., Hivon, E., Huang, Z., Jaffe, A.H., Jones, W.C., Karacki, A., Keihänen, E., Keskitalo, R., Kiiveri, K., Kim, J., Kisner, T.S., Knox, L., Krachmalnicoff, N., Kunz, M., Kurki-Suonio, H., Lagache, G., Lamarre, J.M., Lasenby, A., Lattanzi, M., Lawrence, C.R., Le Jeune, M., Lemos, P., Lesgourgues, J., Levrier, F., Lewis, A., Liguori, M., Lilje, P.B., Lilley, M., Lindholm, V., López-Cañiego, M., Lubin, P.M., Ma, Y.Z., Macías-Pérez, J.F., Maggio, G., Maino, D., Mandolesi, N., Mangilli, A., Marcos-Caballero, A., Maris, M., Martin, P.G., Martinelli, M., Martínez-González, E., Matarrese, S., Mauri, N., McEwen, J.D., Meinhold, P.R., Melchiorri, A., Mennella, A., Migliaccio, M., Millea, M., Mitra, S., Miville-Deschênes, M.A., Molinari, D., Montier, L., Morgante, G., Moss, A., Natoli, P., Nørgaard-Nielsen, H.U., Pagano, L., Paoletti, D., Partridge, B., Patanchon, G., Peiris, H.V., Perrotta, F., Pettorino, V., Piacentini, F., Poilastri, L., Polenta, G., Puget, J.L., Rachen, J.P., Reinecke, M., Remazeilles, M., Renzi, A., Rocha, G., Rosset, C., Roudier, G., Rubiño-Martín, J.A., Ruiz-Granados, B., Salvati, L., Sandri, M., Savelainen, M., Scott, D., Shellard, E.P.S., Sirignano, C., Sirri, G., Spencer, L.D., Sunyaev, R., Suur-Uski, A.S., Tauber, J.A., Tavagnacco, D., Tenti, M., Toffolatti, L., Tomasi, M., Trombetti, T., Valenziano, L., Valiviita, J., Van Tent, B., Vibert, L., Vielva, P., Villa, F., Vittorio, N., Wandelt, B.D., Wehus, I.K., White, M., White, S.D.M., Zacchei, A., Zonca, A., 2020. Planck 2018 results. VI. Cosmological parameters. *Astron. Astrophys.* 641, A6. <https://doi.org/10.1051/0004-6361/201833910>. arXiv:1807.06209.

Racusin, J.L., Karpov, S.V., Sokolowski, M., Granot, J., Wu, X.F., Pal'Shin, V., Covino, S., van der Horst, A.J., Oates, S.R., Schady, P., Smith, R.J., Cummings, J., Starling, R.L.C., Piotrowski, L.W., Zhang, B., Evans, P.A., Holland, S.T., Malek, K., Page, M.T., Vetere, L., Margutti, R., Guidorzi, C., Kamble, A.P., Curran, P.A., Beardmore, A., Kouveliotou, C., Mankiewicz, L., Melandri, A., O'Brien, P.T., Page, K.L., Piran, T., Tanvir, N.R., Wrochna, G., Aptekar, R.L., Barthelmy, S., Bartolini, C., Beskin, G.M., Bondar, S., Bremer, M., Campana, S., Castro-Tirado, A., Cucchiara, A., Cwiok, M., D'Avanzo, P., D'Elia, V., Della Valle, M., de Ugarte Postigo, A., Dominik, W., Falcone, A., Fiore, F., Fox, D.B., Frederiks, D.D., Fruchter, A.S., Fugazza, D., Garrett, M.A., Gehrels, N., Golenetskii, S., Gomboc, A., Gorosabel, J., Greco, G., Guarnieri, A., Immler, S., Jelinek, M., Kasprzowicz, G., La Parola, V., Levan, A.J., Mangano, V., Mazets, E.P., Molinari, E., Moretti, A., Nawrocki, K., Oleynik, P.P., Osborne, J.P., Pagani, C., Pandey, S.B., Paragi, Z., Perri, M., Piccioni, A., Ramirez-Ruiz, E., Roming, P.W.A., Steele, I.A., Strom, R.G., Testa, V., Tosti, G., Ulanov, M.V., Wiersema, K., Wijers, R.A.M.J., Winters, J.M., Zarnecki, A.F., Zerbi, F., Mészáros, P., Chincarini, G., Burrows, D.N., 2008. Broad-band observations of the naked-eye γ -ray burst GRB080319B. *Nature* 455, 183–188. <https://doi.org/10.1038/nature07270>. arXiv:0805.1557.

Radice, D., Perego, A., Hotokezaka, K., Fromm, S.A., Bernuzzi, S., Roberts, L.F., 2018. Binary neutron star mergers: mass ejection, electromagnetic counterparts, and nucleosynthesis. *Astrophys. J.* 869, 130. <https://doi.org/10.3847/1538-4357/aaf054>. arXiv:1809.11161.

Rastinejad, J.C., Gompertz, B.P., Levan, A.J., Fong, f.W., Nicholl, M., Lamb, G.P., Malesani, D.B., Nugent, A.E., Oates, S.R., Tanvir, N.R., de Ugarte Postigo, A., Kilpatrick, C.D., Moore, C.J., Metzger, B.D., Ravasio, M.E., Rossi, A., Schroeder, G., Jenson, J., Sand, D.J., Smith, N., Agüí-Fernández, J.F., Berger, E., Blanchard, P.K., Chornock, R., Cobb, B.E., De Pasquale, M., Fynbo, J.P.U., Izzo, L., Kann, D.A., Laskar, T., Marini, E., Paterson, K., Escorial, A.R., Sears, H.M., Thöne, C.C., 2022. A kilonova following a long-duration gamma-ray burst at 350 Mpc. *Nature* 612, 223–227. <https://doi.org/10.1038/s41586-022-05390-w>. arXiv:2204.10864.

Rees, M.J., Meszaros, P., 1994. Unsteady outflow models for cosmological gamma-ray bursts. *Astrophys. J.* 430, L93–L96. <https://doi.org/10.1086/187446>. arXiv:astro-ph/9404038.

Rees, M.J., Meszaros, P., 1998. Refreshed shocks and afterglow longevity in gamma-ray bursts. *Astrophys. J.* 496, L1. <https://doi.org/10.1086/311244>. arXiv:astro-ph/9712252.

- Rossi, A., Rothberg, B., Palazzi, E., Kann, D.A., D'Avanzo, P., Amati, L., Klose, S., Perego, A., Pian, E., Guidorzi, C., Pozanenko, A.S., Savaglio, S., Stratta, G., Agapito, G., Covino, S., Cusano, F., D'Elia, V., Pasquale, M.D., Valle, M.D., Kuhn, O., Izzo, L., Lofredo, E., Masetti, N., Melandri, A., Minaev, P.Y., Guelbenzu, A.N., Paris, D., Paiano, S., Plantet, C., Rossi, F., Salvaterra, R., Schulze, S., Veillet, C., Volnova, A.A., 2022. The peculiar short-duration GRB 200826A and its supernova. *Astrophys. J.* 932, 1. <https://doi.org/10.3847/1538-4357/ac60a2>. arXiv:2105.03829.
- Rosswog, S., Sarin, N., Nakar, E., Diener, P., 2025. Fast dynamic ejecta in neutron star mergers. *Mon. Not. R. Astron. Soc.* 538, 907–924. <https://doi.org/10.1093/mnras/staf324>. arXiv:2411.18813.
- Shibata, M., Hotokezaka, K., 2019. Merger and mass ejection of neutron star binaries. *Annu. Rev. Nucl. Part. Sci.* 69, 41–64. <https://doi.org/10.1146/annurev-nucl-101918-023625>. arXiv:1908.02350.
- Stratta, G., Nicuesa Guelbenzu, A.M., Klose, S., Rossi, A., Singh, P., Palazzi, E., Guidorzi, C., Camisassa, A., Bernuzzi, S., Rau, A., Bulla, M., Ragosta, F., Maiorano, E., Paris, D., 2025. The puzzling long GRB 191019A: evidence for kilonova light. *Astrophys. J.* 979, 159. <https://doi.org/10.3847/1538-4357/ad9b7b>. arXiv:2412.04059.
- Sun, H., Wang, C.W., Yang, J., Zhang, B.B., Xiong, S.L., Yin, Y.H.I., Liu, Y., Li, Y., Xue, W.C., Yan, Z., Zhang, C., Tan, W.J., Pan, H.W., Liu, J.C., Cheng, H.Q., Zhang, Y.Q., Hu, J.W., Zheng, C., An, Z.H., Cai, C., Cai, Z.M., Hu, L., Jin, C., Li, D.Y., Li, X.Q., Liu, H.Y., Liu, M., Peng, W.X., Song, L.M., Sun, S.L., Sun, X.J., Wang, X.L., Wen, X.Y., Xiao, S., Yi, S.X., Zhang, F., Zhang, W.D., Zhang, X.F., Zhang, Y.H., Zhao, D.H., Zheng, S.J., Ling, Z.X., Zhang, S.N., Yuan, W., Zhang, B., 2025. Magnetar emergence in a peculiar gamma-ray burst from a compact star merger. *Natl. Sci. Rev.* 12, nwae401. <https://doi.org/10.1093/nsr/nwae401>.
- Svinkin, D., Frederiks, D., Ridnaia, A., Tsvetkova, A., Lysenko, A., Konus-Wind Team, 2023. GRB 230307A: further analysis of the Konus-Wind detection and rest-frame energetics. *GRB Coord. Netw.* 33579, 1.
- Tan, W.J., Wang, C.W., Zhang, P., Xiong, S.L., Wu, B.B., Liu, J.C., Wang, Y., Xie, S.L., Xue, W.C., Yu, Z.H., Zhang, J.P., Zhang, W.L., Zhang, Y.Q., Zheng, C., 2025. Search for Type II Gamma-ray Bursts: Criterion, Results, Verification and Physical Implication. *ArXiv e-prints* arXiv:2504.06616. <https://doi.org/10.48550/arXiv.2504.06616>, 2025.
- Troja, E., Fryer, C.L., O'Connor, B., Ryan, G., Dichiaro, S., Kumar, A., Ito, N., Gupta, R., Wollaeger, R., Norris, J.P., Kawai, N., Butler, N., Aryan, A., Misra, K., Hosokawa, R., Murata, K.L., Niwano, M., Pandey, S.B., Kuttyrev, A., van Eerten, H.J., Chase, E.A., Hu, Y.D., Caballero-Garcia, M.D., Castro-Tirado, A.J., 2022. A long gamma-ray burst from a merger of compact objects. *Nature* 612, 228–231. <https://doi.org/10.1038/s41586-022-05327-3>.
- Wang, C.W., Tan, W.J., Xiong, S.L., Yi, S.X., Moradi, R., Li, B., Zhang, Z., Wang, Y., Meng, Y.Z., Wu, B.B., Liu, J.C., Wang, Y., Xie, S.L., Xue, W.C., Yu, Z.H., Zhang, P., Zhang, W.L., Zhang, Y.Q., Zheng, C., 2025. A subclass of gamma-ray burst originating from compact binary merger. *Astrophys. J.* 979, 73. <https://doi.org/10.3847/1538-4357/ad98ec>. arXiv:2407.02376.
- Wang, X.I., Yu, Y.W., Ren, J., Yang, J., Zou, Z.C., Zhu, J.P., 2024. What powered the kilonova-like emission after GRB 230307A in the framework of a neutron star-white dwarf merger? *Astrophys. J. Lett.* 964, L9. <https://doi.org/10.3847/2041-8213/ad2df6>. arXiv:2402.11304.
- Woosley, S.E., 1993. Gamma-ray bursts from stellar mass accretion disks around black holes. *Astrophys. J.* 405, 273–277. <https://doi.org/10.1086/172359>.
- Xiao, S., Peng, W.X., Zhang, S.N., Xiong, S.L., Li, X.B., Tuo, Y.L., Gao, H., Wang, Y., Xue, W.C., Zheng, C., Zhang, Y.Q., Liu, J.C., Li, C.K., Yi, S.X., Wang, X.L., Zhang, Z., Cai, C., Dong, A.J., Xie, W., Feng, J.C., Ma, Q.B., Wang, D.H., Luo, X.H., Zhi, Q.J., Song, L.M., Li, T.P., 2022. Search for quasiperiodic oscillations in precursors of short and long gamma-ray bursts. *Astrophys. J.* 941, 166. <https://doi.org/10.3847/1538-4357/aca018>. arXiv:2210.08491.
- Xiong, S., Wang, C., Huang, Y., Gecam Team, 2023. GRB 230307A: GECAM detection of an extremely bright burst. *GRB Coord. Netw.* 33406, 1.
- Yang, J., Ai, S., Zhang, B.B., Zhang, B.K., Liu, Z.K., Wang, X.I., Yang, Y.H., Yin, Y.H., Li, Y., Lü, H.J., 2022. A long-duration gamma-ray burst with a peculiar origin. *Nature* 612, 232–235. <https://doi.org/10.1038/s41586-022-05403-8>.
- Yi, S.X., Wang, C.W., Shao, X., Moradi, R., Gao, H., Zhang, B., Xiong, S.L., Zhang, S.N., Tan, W.J., Liu, J.C., Xue, W.C., Zhang, Y.Q., Zheng, C., Wang, Y., Zhang, P., An, Z.H., Cai, C., Feng, P.Y., Gong, K., Guo, D.Y., Huang, Y., Li, B., Li, X.B., Li, X.Q., Liu, X.J., Liu, Y.Q., Ma, X., Peng, W.X., Qiao, R., Song, L.M., Wang, J., Wang, P., Wen, X.Y., Xiao, S., Xu, Y.B., Yang, S., Yi, Q.B., Zhang, D.L., Zhang, F., Zhang, H.M., Zhang, J.P., Zhang, Z., Zhao, X.Y., Zhao, Y., Zheng, S.J., 2025a. Evidence of minijet emission in a large emission zone from a magnetically dominated gamma-ray burst jet. *Astrophys. J.* 985, 239. <https://doi.org/10.3847/1538-4357/adc9f8>. arXiv:2310.07205.
- Yi, S.X., Yorgancıoğlu, E.S., Xiong, S.L., Zhang, S.N., 2025b. Long pulse by short central engine: prompt emission from expanding dissipation rings in the jet front of gamma-ray bursts. *J. High Energy Astrophys.* 47, 100359. <https://doi.org/10.1016/j.jheap.2025.100359>.
- Yonetoku, D., Murakami, T., Nakamura, T., Yamazaki, R., Inoue, A.K., Ioka, K., 2004. Gamma-ray burst formation rate inferred from the spectral peak energy-peak luminosity relation. *Astrophys. J.* 609, 935–951. <https://doi.org/10.1086/421285>. arXiv: astro-ph/0309217.
- Yuan, W., Zhang, C., Chen, Y., Ling, Z., 2022. The Einstein probe mission. In: Bambi, C., Sanganello, A. (Eds.), *Handbook of X-ray and Gamma-ray Astrophysics*, p. 86.
- Zhang, B., Yan, H., 2011. The internal-collision-induced magnetic reconnection and turbulence (ICMART) model of gamma-ray bursts. *Astrophys. J.* 726, 90. <https://doi.org/10.1088/0004-637X/726/2/90>. arXiv:1011.1197.
- Zhang, B., Zhang, B.B., Virgili, F.J., Liang, E.W., Kann, D.A., Wu, X.F., Proga, D., Lv, H.J., Toma, K., Mészáros, P., Burrows, D.N., Roming, P.W.A., Gehrels, N., 2009. Discerning the physical origins of cosmological gamma-ray bursts based on multiple observational criteria: the cases of $z = 6.7$ GRB 080913, $z = 8.2$ GRB 090423, and some short/hard GRBs. *Astrophys. J.* 703, 1696–1724. <https://doi.org/10.1088/0004-637X/703/2/1696>. arXiv:0902.2419.
- Zhang, B.B., Liu, Z.K., Peng, Z.K., Li, Y., Lü, H.J., Yang, J., Yang, Y.S., Yang, Y.H., Meng, Y.Z., Zou, J.H., Ye, H.Y., Wang, X.G., Mao, J.R., Zhao, X.H., Bai, J.M., Castro-Tirado, A.J., Hu, Y.D., Dai, Z.G., Liang, E.W., Zhang, B., 2021. A peculiar short-duration gamma-ray burst from massive star core collapse. *Nat. Astron.* 5, 911–916. <https://doi.org/10.1038/s41550-021-01395-z>. arXiv:2105.05021.
- Zhang, C., Ling, Z.X., Sun, X.J., Sun, S.L., Liu, Y., Li, Z.D., Xue, Y.L., Chen, Y.F., Dai, Y.F., Jia, Z.Q., Liu, H.Y., Zhang, X.F., Zhang, Y.H., Zhang, S.N., Chen, F.S., Cheng, Z.W., Fu, W., Han, Y.X., Li, H., Li, J.F., Li, Y., Liu, P.R., Ma, X.H., Tang, Y.J., Wang, C.B., Xie, R.J., Yan, A.L., Zhang, Q., Jiang, B.W., Jin, G., Li, L.H., Qiu, X.B., Su, D.T., Sun, J.N., Xu, Z., Zhang, S.K., Zhang, Z., Zhang, N., Bi, X.Z., Cai, Z.M., He, J.W., Liu, H.Q., Zhu, X.C., Cheng, H.Q., Cui, C.Z., Fan, D.W., Hu, H.B., Huang, M.H., Jin, C.C., Li, D.Y., Pan, H.W., Wang, W.X., Xu, Y.F., Yang, X., Zhang, B., Zhang, M., Zhang, W.D., Zhao, D.H., Bai, M., Ji, Z., Liu, Y.R., Ma, F.L., Su, J., Tong, J.Z., Wang, Y.S., Zhao, Z.J., Feldman, C., O'Brien, P., Osborne, J.P., Willingale, R., Burwitz, V., Hartner, G., Langmeier, A., Müller, T., Rukdee, S., Schmidt, T., Kuulkers, E., Yuan, W., 2022. First wide field-of-view X-ray observations by a lobster-eye focusing telescope in orbit. *Astrophys. J. Lett.* 941, L2. <https://doi.org/10.3847/2041-8213/aca32f>. arXiv:2211.10007.
- Zhang, W.L., Xue, W.C., Li, C.K., Xiong, S.L., Li, G., Chen, Y., Cui, W.W., Li, X.B., Liu, C.Z., Ge, M.Y., Tan, W.J., Liu, J.C., Wang, C.W., Zheng, C., Zhang, Y.Q., Wang, Y., Zhang, Z., Yi, S.X., Xiao, S., Cai, C., Yi, S.X., Song, L.M., Tao, L., Zhang, S., Zhang, S.N., 2025. Insight-HXMT observations of the extremely bright GRB 221009A. *Astrophys. J.* 986, 170. <https://doi.org/10.3847/1538-4357/add14f>. arXiv:2504.18952.