

On the Ultra-Long Gamma-Ray Transient GRB 250702B/EP250702a

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ABSTRACT

GRB 250702B/EP250702a is an interesting long-duration gamma-ray transient whose nature is in debate. To obtain a full picture in gamma-ray band, we implement a comprehensive targeted search of burst emission in a wide window of 30 days jointly with *Insight*-HXMT, GECAM and *Fermi*/GBM data within the ETJASMIN framework. In gamma-ray band, we find there is a 50-second precursor about 25 hours before the 4-hour main burst, which generally consists of 4 emission episodes. Remarkably, we find that the soft X-ray emission (after the main burst) decays as a power-law with start time aligning with the last episode of main emission and index of $-5/3$ perfectly consistent with the canonical prediction of fallback accretion. We conclude that the properties of precursor, main burst and the following soft X-ray emission strongly support the atypical collapsar Ultra-Long Gamma-Ray Burst (ULGRB) scenario rather than the Tidal Disruption Event (TDE), and all these gamma-ray and soft X-ray emission probably originate from relativistic jet whose luminosity is dominated by the fallback accretion rate during the death collapse of a supergiant star.

Keywords: Gamma-ray bursts (629) — X-ray transient sources (1852) — Tidal disruption (1696)

1. INTRODUCTION

As the most violent phenomenon in the universe, Gamma-Ray Bursts (GRBs) manifest themselves as bright gamma-ray emission from distant galaxies. GRBs can be traditionally classified into long GRB and short GRB based on the duration of gamma-ray emission (e.g. C. Kouveliotou et al. 1993). Long GRBs are usually resulted from the core collapse of massive star (Type II GRB) (S. E. Woosley 1993; B. Paczyński 1998; S. E. Woosley & J. S. Bloom 2006), while short GRBs are generally believed to originate from merger of compact

binaries (Type I GRB) (S. I. Blinnikov et al. 1984; B. Paczynski 1986; P. Meszaros & M. J. Rees 1992; L.-X. Li & B. Paczyński 1998; B. P. Abbott et al. 2017).

However, an increasing number of GRBs are reported to deviate the “long-collapsar, short-merger” classification pattern, including long duration GRBs with merger origin (e.g. GRB 060614, GRB 211211A, GRB 211227A, GRB 230307A) (N. Gehrels et al. 2006; J. Yang et al. 2022; H.-J. Lü et al. 2022; H. Sun et al. 2025) and short duration GRBs with collapsar origin (e.g. GRB 200826A, GRB 230812B, GRB 240825A) (B. B. Zhang et al. 2021; C.-Y. Wang et al. 2024; C.-W. Wang et al. 2025b). Furthermore, some merger GRBs (including GRB 211211A and GRB 230307A) feature an intrinsically long main burst and thus are suggested to form

a special sub-class of Type I GRB, i.e. Type II GRB (C.-W. Wang et al. 2025c; W.-J. Tan et al. 2025; S.-Y. Zhu et al. 2025). How the compact merger system can produce long duration burst is an open question.

Similar with the rare short-duration Type II GRBs, those with overwhelming long duration are also scarce: only a small fraction of Type II GRBs can last more than thousands of seconds, named as Ultra-Long GRB (ULGRB). The physical scenario of ULGRB remains an open question. Whether the ULGRBs remain a tail at the long-end of the distribution of Type II GRB, or distinguish themselves as a distinct new class with very different physical origin, is inconclusive yet. Indeed, there are suggestions that ULGRBs are produced by the collapse of a supergiant star (B. Gendre et al. 2013; D. Nakauchi et al. 2013).

Remarkably, some high-energy transients with extremely long duration initially considered to be GRB or ULGRB are finally identified as jetted Tidal Disruption Event (TDE), such as Swift J1644+57 (D. N. Burrows et al. 2011). In general consideration, TDEs are produced by the disruption of a star by a dormant supermassive black hole when the star passes too close to the black hole, or a White dwarf (WD) by an intermediate-mass black hole (J. H. Lacy et al. 1982; M. J. Rees 1988). In some cases, a relativistic jet could be launched, leading to jetted TDE. Recently, more jetted TDE candidates have been found, such as Swift J2058+05 (D. R. Pasham et al. 2015), and AT2022cmc (I. Andreoni et al. 2022). Determining whether a very long high energy transient is a jetted TDE or a ULGRB is helpful to probe the nature of the transient. Unfortunately, this is usually a very challenging task because of the rare occurrence and fast-fading nature of these astronomical transient events.

Recently, a peculiar long-duration high energy transient is discovered, denoted as GRB 250702B/EP2050702a, which is first reported by *Fermi*/GBM as a series of individual GRBs: GRB 250702B, GRB 250702D and GRB 250702E (*Fermi* GBM Team 2025a,b,c; E. Neights et al. 2025) on July 2nd, 2025. The gamma-ray¹¹ emission of this event is also detected by Konus-Wind (D. Frederiks et al. 2025), SVOM/GRM (C.-W. Wang et al. 2025a), Swift/BAT (J. DeLaunay et al. 2025), *Insight*-HXMT and GECAM-B. Prompt soft X-ray emission is detected by EP/WXT (H. Q. Cheng et al. 2025a) and MAXI (Y. Kawakubo

et al. 2025). Interestingly, stacking data of EP/WXT suggest that this transient has already emerged one day before the GBM gamma-ray trigger of GRB 250702B. X-ray follow-up of Swift/XRT (J. A. Kennea et al. 2025a), EP/FXT (H. Q. Cheng et al. 2025b) and hard X-ray of NuSTAR (B. O’Connor et al. 2025) reveal a fading X-ray source with a featureless absorbed power-law spectrum. Observations in optical, near-IR and radio are also performed. Especially, A. J. Levan et al. (2025a) reported an extremely red fast-fading counterpart located on the non-nuclear region of a disc-like galaxy with HST. A detailed summary of these observations could be found in A. J. Levan et al. (2025b). The EP location of this source is RA=284.6895 deg, Dec=-7.8738 deg (H. Q. Cheng et al. 2025a). As of this writing, accurate redshift (z) of GRB 250702B/EP2050702a is absent and is roughly estimated to be $0.1 < z < 1$ (A. J. Levan et al. 2025b).

Despite of many observations, the origin of GRB 250702B/EP2050702a is on hot debate. Especially, possibilities of ULGRB or jetted TDE have been proposed but cannot be decisively determined (e.g. A. J. Levan et al. 2025b). In this work, we primarily investigate the high energy emission (including gamma-ray and soft X-ray emission) of this source and obtain numerous interesting discoveries from several episodes of this transient — pre-burst, main burst gamma-ray activity, and post-burst X-ray emission.

This paper is organized as follows. Search for burst components and analyses covering the full burst episodes in gamma-ray band with *Insight*-HXMT/HE, GECAM-B and *Fermi*/GBM are described in Section 2. Temporal analysis of soft X-ray emission detected by Swift/XRT and Chandra are presented in Section 3, focusing on the power-law decay slope with different start time. Discussions on the plausible progenitor models and interpretation of the observations are depicted in Section 4. Summary and conclusion are given in section 5.

Please note that all parameter errors in this work are for 68% confidence level if not otherwise stated.

2. GAMMA-RAY EMISSION

2.1. Search for burst component

For this source, there are several triggers, initially named as GRB 250702B, GRB 250702D and GRB 250702E, reported by *Fermi*/GBM (*Fermi* GBM Team 2025a), SVOM/GRM (C.-W. Wang et al. 2025a), etc. We point out that the monitoring coverage to the source by individual instrument is usually incomplete due to the Earth blocking or instrument turn-off flying over the SAA region in orbit. Konus-Wind may have a complete

¹¹ In this work, gamma-ray means photons with energy greater than about 10 keV, which is also called soft gamma-ray or hard x-ray. On contrast, soft x-ray photons with energy below about 10 keV.

time coverage, but its reported light curve appears to be limited to about 5 hours (D. Frederiks et al. 2025). Whether there is other burst component outside these reported time windows, possibly separated by hours or even days, is unclear.

In attempt to provide a better view of this source with emphasis on both the wide time coverage and the high detection sensitivity, we performed a comprehensive targeted coherent search from about -10 days to +20 days relative to GRB 250702B, using the ETJASMIN pipeline (C. Cai et al. 2025; C. Cai et al. 2021) with *Insight*-HXMT/HE, GECAM-B and *Fermi*/GBM data. At each time interval, only those instruments that are visible to the source (not blocked by the Earth) and have available data are used for the burst search (see Fig 4). The search time scale is from 0.1 s to 4 s, thus, we note that our search focus on the fast variation emission; we may not be able to find the potential slow-varying emission component. More details about the search are depicted in Appendix A.

2.2. Burst episodes

According to our targeted search of this source, we find there is a relatively short emission around 2025-07-01 11:55 UTC and a series of much longer burst emissions from about 2025-07-02 12:50 to 16:30 UTC, as shown in Fig. 1. There is no other significant burst component found in gamma-ray band (20 keV to 3 MeV) from this source from -10 days to +20 days relative to GRB 250702B. Seeing from the morphology in the light curve and following the convention of GRBs, we indicate the burst emission at 2025-07-01 as precursor (denoted as P) and that at 2025-07-02 as main burst (denoted as M, including M1 to M4). Detailed light curves in higher temporal resolution of all these episodes (P, M1 to M4) are shown in Fig. 1b to 1f.

We notice that the joint light curve of *Insight*-HXMT/HE, GECAM-B and *Fermi*/GBM of the main burst is generally consistent with that of Konus-Wind (D. Frederiks et al. 2025). However, EP/WXT detected soft X-ray emission from 02:53:44 UTC to 22:32:44 UTC on July 2nd (H. Q. Cheng et al. 2025a) which is much longer and well embraces the main burst episode in gamma-ray band. In addition, EP/WXT also detected signal from this burst on July 1st with stacking analysis (H. Q. Cheng et al. 2025a), which lends additional support to our discovery of the precursor. We point out that this feature that soft X-ray emission spans wider in time than that of gamma-ray emission is often seen in GRBs (e.g. H.-X. Gao et al. 2025; Y.-Q. Zhang et al. 2025).

2.2.1. Main burst

We find that the main burst can be generally divided into 4 episodes (denoted as M1 to M4) as they are well separated by the (apparent) quiescent regions in the light curves (Fig. 1a).

Interestingly, we note that, for the first episode (M1), *Insight*-HXMT and GECAM-B detected the early burst emission starting from about 2025-07-02T12:52:52 UTC (denoted as T_0 in this work) which is well before the *Fermi*/GBM trigger time (13:09:02 UTC) of this event (literally GRB 250702D), as a large part of the emission in episode M1 is invisible to *Fermi*/GBM due to the Earth occultation, as shown in Fig. 1c. Three pulses are clearly visible in the *Insight*-HXMT/HE light curve from T_0 -50 to +100 s in Fig. 1c. *Insight*-HXMT/HE also detected many pulses in the time region where *Fermi*/GBM is occulted by the Earth. Some of the *Insight*-HXMT/HE pulses are also detected by GECAM-B, confirming these early emission.

Moreover, according to the background-subtracted and normalized light curves of *Insight*-HXMT/HE in higher energy range (200 keV–3 MeV) and *Fermi*/GBM and GECAM-B including a lower energy range (50 keV - 2 MeV), as shown in Fig. 1a, the first episode (M1) appears to be relatively harder in spectrum than the later three episodes (M2 to M4) of main burst. M1 also seems to have the longest duration among of all episodes. Besides, we find that there is no significant trend of monotonic increase or decrease in the fluence from episode M1 to M4.

2.2.2. Precursor

Surprisingly, we find that, owing to the sensitive targeted coherent search, there is a significant burst in GBM data which triggered our search program at 2025-07-01T11:55:17 UTC, which is about 25 hours before the start time of main burst. Localization of this burst with *Fermi*/GBM GDT package (A. Goldstein et al. 2024) shows that the direction of GRB 250702B/EP250702a falls within the $3\text{-}\sigma$ region of the skymap. No gamma-ray transient emission is found between this signal and the main burst, which is the reason we call it precursor, following the convention of GRB.

This precursor primarily consists of several pulses, with a total duration about 50 seconds. We note that the joint observation of *Insight*-HXMT and *Fermi*/GBM provides a complete monitoring of a much wider time window embracing this burst but found no other burst components (Fig. 1b). Therefore, we conclude that this precursor only lasts for about 50 seconds, much shorter than the episodes in the main burst. However, we notice that the precursor exhibits a min-

imum time variability timescale compatible to that of main burst.

Non-detection of this precursor by *Insight*-HXMT/HE indicates that its spectrum is relatively soft. Indeed, there is no signal above 150 keV in GBM data, well compatible with the non-detection. The spectral analysis of the GBM data shows that it can be adequately fit with power-law model with index of $1.65^{+0.10}_{-0.10}$ (see Appendix D for details). This precursor may be detectable by soft X-ray telescope (e.g. EP/WXT) if it lies in the field of view. If so, the accurate localization of this precursor could confirm the association with GRB 250702B/EP250702a.

According to our spectral analysis, the fluence of the precursor is $3.4^{+0.6}_{-0.5} \times 10^{-6} \text{ erg/cm}^2$, and the 1-second peak flux is $3.2^{+0.8}_{-0.7} \times 10^{-7} \text{ erg/cm}^2/\text{s}$, in an energy range of 8–1000 keV. The main burst has a total fluence of about 10^{-3} erg/cm^2 . The isotropic energy of the precursor and main burst is $4.1^{+0.7}_{-0.6} \times 10^{50} \text{ erg}$ ($1.86^{+0.31}_{-0.29} \times 10^{52} \text{ erg}$) and $\sim 10^{53} \text{ erg}$ ($\sim 10^{55} \text{ erg}$) assuming redshift of 0.2 (1), respectively. It should be noted that the energy of the main burst is approximately 300 times greater than that of the precursor.

The waiting time (T_{WT}) between precursor and main burst is about 25 hours, while the duration of the main burst (T_{90}) is about 4 hours. We compared this burst to all kinds of GRBs in the $T_{\text{WT}} - T_{90}$ diagram and find this burst is generally compatible to the trend of GRBs, as shown in Figure 2.

Note that there is reported emission by EP/WXT during the apparent quiescent time between precursor and main burst in gamma-ray band. The fact that there is ongoing emission during the so-called quiescent time is not unexpected but well consistent with the picture demonstrated in e.g. GRB 230307A (C.-W. Wang et al. 2025c).

2.3. Bulk Periodicity

The multi-episode emission separated by quiescent intervals implies a possible periodicity behavior. We note that A. J. Levan et al. (2025b) claimed a possible periodicity of $\sim 2800 \text{ s}$ based on the light curve of *Fermi*/GBM alone, however their analysis only considered a few specific pulses and ignored many other pulses in the burst. Thanks to the more complete coverage provided by joint observation of *Insight*-HXMT, GECAM-B and *Fermi*/GBM, we can investigate the periodicity considering the full course of the main burst episodes as well as the precursor discovered in this work.

Since there are numerous weak spikes and pulses which are difficult to accurately identify, here we mainly estimate the period cycle based on the time intervals be-

tween those 4 large episodes of main burst, also taking the durations and spiky structures into consideration (as marked in Fig. 1) for subsequent Monte-Carlo sampling method. When calculating the time intervals between different episodes, instead of applying the trigger time or pulse peak moments to represent each segment directly, we sample the time by taking the background-subtracted light curves as a probability distribution, obtaining a series of time points that represent the corresponding burst episodes. The obtained time differences between adjacent episodes are $4173^{+643}_{-622} \text{ s}$, $3862^{+2224}_{-1739} \text{ s}$, $3807^{+1707}_{-2191} \text{ s}$ with the mean value of 3962 s. This may also indicate a quasi-periodicity. Interestingly, we find that the precursor occurs about 23 cycles before the start time of episode M1. This period of $\sim 4000 \text{ s}$ is also consistent with the Konus-Wind light curve which only covers the main burst episodes (D. Frederiks et al. 2025). Nevertheless, it is worth noting that the existence of periodicity as well as the period of $\sim 4000 \text{ s}$ are not very robust yet, mainly due to the limited cycle number and the uncertainties of period duration.

3. SOFT X-RAY EMISSION

We collect and analyze the public available soft X-ray observation data by Swift/XRT (J. A. Kennea et al. 2025a) and the reported observation results from Chandra. Before the conclusion of its nature, we avoid to call it afterglow (with respect to the main burst). Since the soft X-ray emission follows the main burst in time, we call it “following emission” which is also denoted as episode F (see Fig. 1a) in this work.

To characterize the temporal evolution of these soft X-ray emission in episode F, we fit the X-ray flux data with the power-law model, $F \propto (t - T_0^{\text{PL}})^k$, where F is the flux in 0.3–10 keV, T_0^{PL} is the start time of the power-law decay, and k is the power-law index. We set the start time (T_0^{PL}) as free parameter and find the power-law fits the data well. Remarkably, the resulted power-law index is $-1.73^{+0.05}_{-0.04}$, which is almost perfectly consistent with the canonical $-5/3$ predicted for fallback in TDE or collapsar (F. C. Michel 1988; E. S. Phinney 1989). Also the start time of this power-law broadly aligns with the last episode of main burst (M4), which indicates a probable association between the gamma-ray emission in main burst (more specifically the episode M4) and soft X-ray emission in episode F.

We also tried to fix the start time of the power-law decay to the time of the precursor, GRB 250702D, GRB 250702B and GRB 250702E, resulting in power-law index of -2.54, -1.94, 1.91, and -1.82, respectively. Indeed, a broken power-law (BPL), rather than a single power-law, is required to fit the data if setting the precursor as

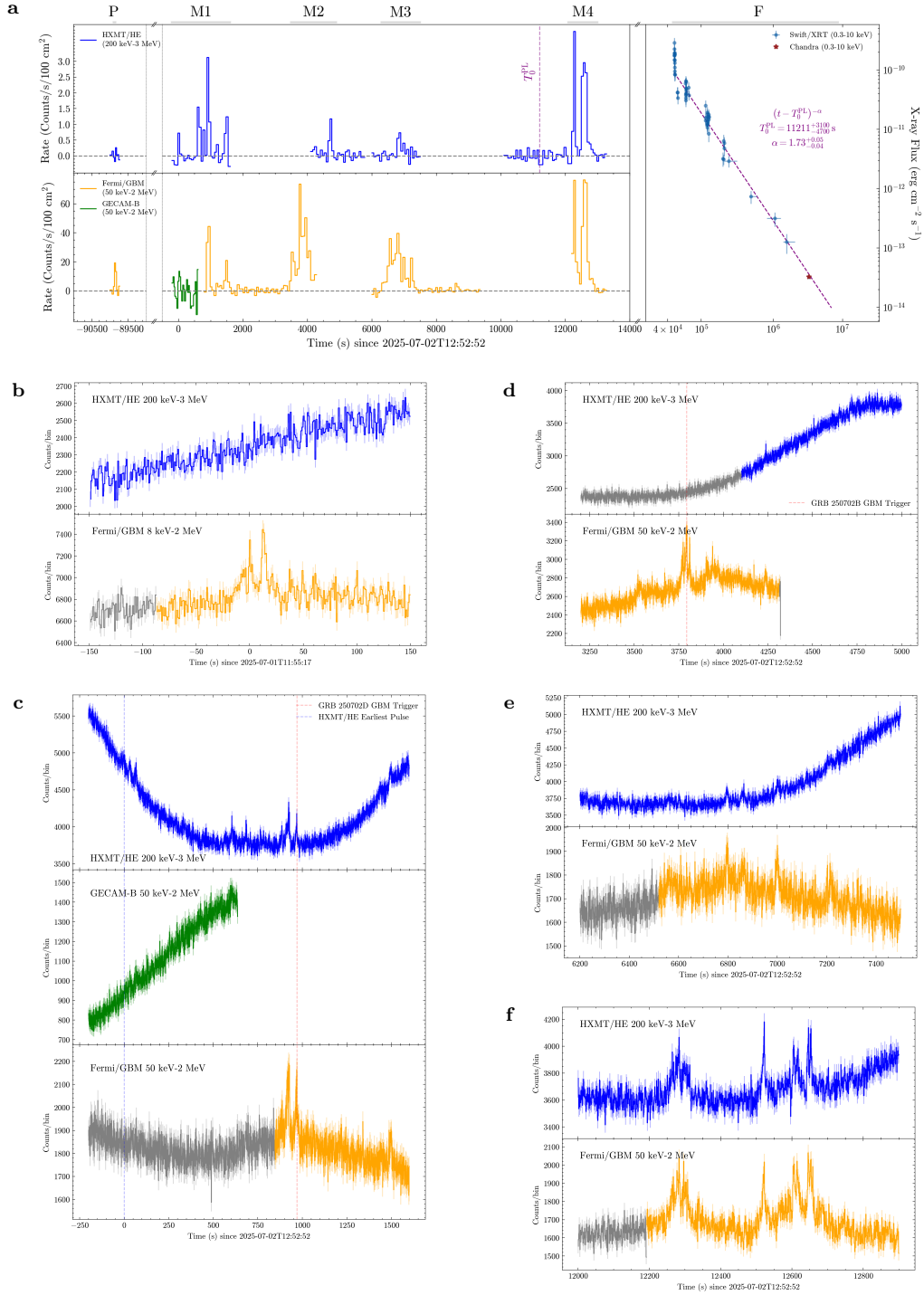


Figure 1. Panel (a): Gamma-ray and soft X-ray light curves of GRB 250702B/EP250702a in a wide time window of about 40 days. Gamma-ray light curves are background subtracted and normalized by receiving area of detectors, from *Insight*-HXMT/HE, GECAM-B and *Fermi*/GBM. Precursor light curves of *Insight*-HXMT/HE and *Fermi*/GBM, and main burst light curve of GECAM-B are binned in 30 seconds, while others in 60 seconds. Soft X-ray data are well fitted with a power-law with index of around -5/3. Details of data analyses could be found in text and appendix. **Panel (b) - (f):** Light curves of precursor (P) and four episodes (M1 to M4) of main burst, binned in 1 second.

the start time. The best fit result is shown in Fig. 1a. More details of these fittings can be found in Appendix B.

We stress that, among of these fittings, the one by setting the start time (T_0^{PL}) as free parameter and resulting the canonical $-5/3$ power-law decay gives the best fitting statistics (see Appendix B), thus is the most probable scenario in our discussions below. In addition, we note that it is usually desirable to fit the power-law evolution with a free start time rather than the trigger time of an instrument. An notable example is the discovery of the power-law evolution of the emission line from 37 MeV to 6 MeV in GRB 221009A (Y.-Q. Zhang et al. 2024), among which setting the initial time to the trigger time may also obtain a fit result but will lose the true physics.

We compare the soft X-ray emission of this burst with other GRBs, especially ULGRBs, as shown in Fig. 3. Here we consider two possible values to represent the redshift range of this source ($z = 0.2, 1$). One can see that both the luminosity and temporal evolution of soft X-ray emission are well consistent with known ULGRBs, which lie in the bright part of all GRBs. We suggest that this provides another evidence that this source is very likely a ULGRB.

4. DISCUSSION

4.1. Progenitor models

Firstly, we note that A. J. Levan et al. (2025b) has discussed several progenitor scenarios for this source: (1) tidal disruption of a main-sequence star (MS) by a supermassive black hole (SMBH); (2) TDE of an MS star by an intermediate-mass black hole (IMBH); (3) multiple partial tidal stripping of a white dwarf (WD) by an IMBH; (4) an atypical collapsar; (5) GRB dust echoes; and (6) a lensed GRB. The latter two are essentially ruled out due to direct conflicts with observations: dust echo models require non-usual dense-thin shells (P. Madau et al. 2000) and fail to match the observed spectrum evolution (C. D. Dermer & M. Böttcher 2000; L. Shao & Z. G. Dai 2007), while lensing is disfavored by mismatched temporal and spectral morphologies among episodes (as shown in Figure 1). For the MS-SMBH scenario, they used optical imaging of the counterpart to show it lies in a non-nuclear region of its host galaxy, thus disfavoring SMBH involvement. To distinguish between the MS-IMBH and WD-IMBH scenarios, they attributed the possible periodicity they found (i.e. ~ 2800 s) to the orbital period of the binary system, leading them to disfavor the MS-IMBH scenario. Consequently, they concluded that the most plausible progenitors are either the WD-IMBH multiple partial stripping scenario or the atypical collapsar scenario.

Here, based on our findings in this work, we discuss the following possible progenitor scenarios: ULGRB from collapsar, jetted TDE from MS-IMBH or WD-IMBH partial stripping, and peculiar Type II GRB from compact merger.

4.1.1. ULGRB: Self-regulated collapsar of supergiant star

Firstly, we find that the luminosity and temporal evolution of soft X-ray emission resembles other ULGRBs, as shown in in Fig. 3 and discussed in Section 3.

This burst is significantly longer than that of typical Type II GRBs – the latter are widely thought to originate from the collapse of massive stars. The duration of Type II GRB is generally believed to be determined by two key timescales: the energy dissipation timescale (on the order of seconds to tens of seconds) and the stellar collapse timescale (typically tens of seconds to minutes for free-fall collapse of a Wolf-Rayet star).

S. E. Woosley & A. Heger (2012) proposed that the collapse timescale of blue supergiant star could be extended to thousands of seconds, potentially explaining ULGRBs. If the progenitor is a more massive red supergiant star, the collapse of the inner layers can be in the time scale of hours, matching the duration of the observed gamma-ray emission of this burst.

Due to the high and fast variability of the observed X-ray emission in this burst, we suggest it originates from the prompt emission (on contrast to the smooth afterglow emission) of the jet which reflects the central engine activity. The $t^{-5/3}$ power-law decay of the X-ray flux perfectly matches the theoretical prediction of free fall collapse with a constant density profile (F. C. Michel 1988), thus the luminosity of the jet should be dominantly powered by the fallback accretion of the outer layers. The fallback time scale of the outer layers of the supergiant star can be in the time scale of ~ 100 days to years, which can account for the observation fact that $-5/3$ decay X-ray emission continues up to more than 30 days post burst. Besides, in this mass fallback scenario, the onset time of the $-5/3$ power-law corresponds to the time when the outer layer is expelled by the violent activity of the central engine. The fact that the last episode (M4) of main burst occurs around the onset time is very consistent with the aforementioned scenario.

Moreover, we suggest that the interplay of accretion feedback in this scenario may drive quasi-periodic accretion across multiple epochs, which could naturally explain the observed intermittent bursts and possible bulk periodicity of about 4000 s. This self-regulated collapse may also suppress the formation of a canonical core-collapse supernova (SN), providing an alternative

explanation for the lack of SN counterpart of this burst yet.

4.1.2. Jetted TDE: MS-IMBH or WD-IMBH

In the TDE scenario, a relativistic jet is required to explain the highly variable and non-thermal emission in the gamma-ray and soft X-ray band. However, the morphology of precursor and main burst are not very consistent with known jetted TDEs (e.g. Swift J1644+57), neither the luminosity and temporal evolution of the soft X-ray (as shown in Figure 4 in A. J. Levan et al. (2025b)).

Remarkably, we find that the best fit of the X-ray flux data reveals that it follows a power-law decay with index of $\sim -5/3$ (when the start time of power-law T_0^{PL} is set as a free parameter). In the TDE model, this $-5/3$ decay is a canonical trend typically associated with the evolution of matter fallback rates (e.g. M. J. Rees 1988). However, since the T_0^{PL} of the power-law decay corresponds to the moment of the tidal disruption of the star, the fact that the T_0^{PL} is about 28 hours after the precursor and about 3 hours after the emergence of the main burst in gamma-ray band raises a serious problem to interpret the precursor and main burst emission which precede the disruption of the star and mass fallback. If manually setting the T_0^{PL} to be precursor time or earlier time, the resulted power index will be steeper than ~ -2.5 , which is just marginally allowed in TDE (e.g. S. Gezari 2021). Yet, the waiting time between the start time T_0^{PL} of the power-law decay and the first data that follows the $-5/3$ decay is only about 10 hours, which is again very unusual for TDE events, as the fall-back timescales typically observed in TDEs are usually in the order of days to months (S. Sazonov et al. 2021).

Moreover, as noted in Section 2.3, although the limitations on the current data prevent us from drawing a robust conclusion on the periodicity, the burst light curves do show some sort of regular behavior with a bulk periodicity of about 4000 s. If this periodicity is real, one might invoke the repeated partial tidal stripping of a WD by an IMBH to account for such period. However, we argue that our results do not support such scenario. As a degenerate stellar object, a WD exhibits an inverse correlation between mass and radius (S. Chandrasekhar 1935): as a WD loses mass via partial stripping, the remaining core expands (increasing in radius) and becomes more vulnerable to tidal disruption in subsequent orbital passages. This would imply a progressive increase in the mass transferred to the IMBH with each orbit (J.-H. Chen et al. 2023) — a trend that should be reflected in rising fluence across successive burst epochs. However, no such monotonic

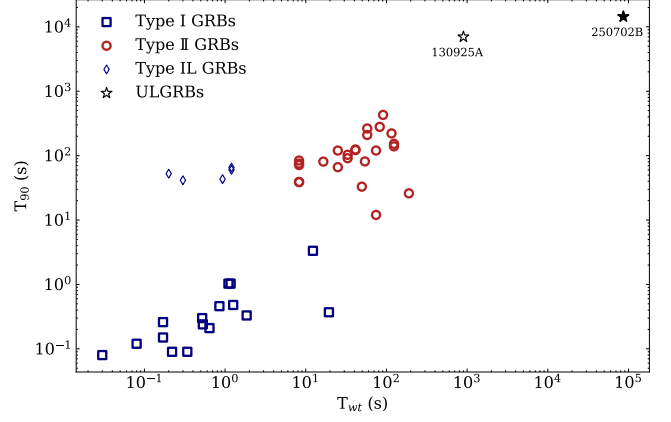


Figure 2. Relation between precursor waiting time and main burst duration.

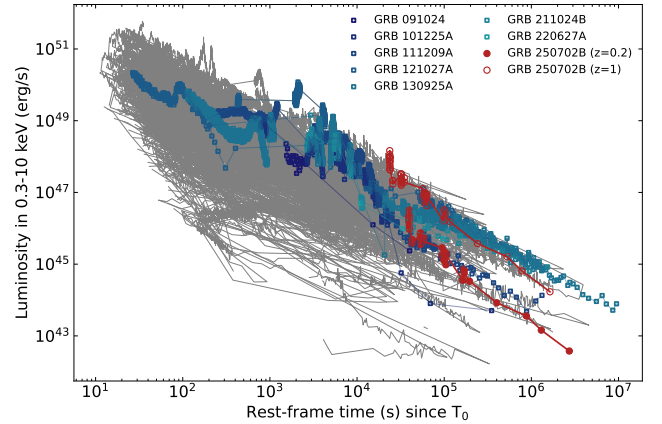


Figure 3. Soft X-ray emission of GRB 250702B/EP 250702a in comparison with GRBs including some ULGRBs.

increase is observed in our data (see Figure 1a and section 2.2.1). Additionally, this "stripped-easier-to-strip" behavior of a partially stripped WD would likely lead to a runaway stripping even during a single periastron passage. As a result, the binary system would be unlikely to survive more than ~ 4 periastron passages. This problem will be more severe if considering the precursor about 23 period cycles before the main burst. Consequently, we find that the observations presented in this work strongly disfavor the TDE scenario.

4.1.3. Type IL GRB: Compact Merger

Despite that the traditional theory of compact merger (e.g. NS-NS, BH-NS) can only lead to short duration GRB, it is worth to note that recent observations of some Type IL GRBs (e.g. GRB 230307A) indicate that the merger system can give rise to intrinsically long duration burst. Also Type IL GRBs are found to be composed of three stages of emission, i.e. precursor, main burst and extended emission (C.-W. Wang et al. 2025c; W.-J. Tan et al. 2025), which seems to be somewhat consis-

tent with the morphology of this burst. Indeed, how the compact merger of Type IL GRB can produce intrinsically long burst is not understood yet. Additionally, we note that this burst has an energy fluence less but compatible to GRB 230307A, the typical Type IL GRB. Therefore, the possibility of merger system to produce ultra-long burst thus can account for this burst is worth to explore. Moreover, synergy operation of this event by O4 of LIGO-Virgo-KAGRA (LVK) provided us a great opportunity to test this idea.

We checked the GW events reported by LVK during July 1st and 2nd, 2025. There are only two high-significance GW events, i.e. S250701bp and S250701bq, whose time and location do not conflict with this source. However, both of them are classified as BBH with more than 99% probability, making them very unlikely to be associated with this burst.

4.1.4. Conclusion of model

After the above discussions of possible models, we find that the ULGRB model can adequately interpret the gamma-ray and soft X-ray observation data. Especially, a self-regulated collapsar of a supergiant star can naturally unify the timescales and radiative properties: hour-scale inner collapse can sustain the ultra-long gamma-ray emission, days-to-year fallback of the outer layers can power the subsequent X-rays with a $t^{-5/3}$ power-law decline and accretion-feedback-driven intermittency. Such regulation may also suppress a canonical supernova, which is the case for some ULGRBs.

4.2. Interpretation of high energy emission

First, we summarize the key observational properties of high energy (gamma-ray and soft X-ray) emission we found in GRB 250702B/EP250702a: Temporally, the gamma-ray emission of main burst last for about 4 hours. It is longer than 1 day if taking the precursor into account. The main burst could be grouped into 4 episodes, segmented by quiescent periods. The waiting time between precursor and main burst is about 25 hours. The soft X-ray spans from -1 day to more than 30 days with respect to the main burst phase. The post-main burst soft X-ray flux follows a power-law decay of index $-5/3$ and the onset time of this power-law lies around the last episode of main burst. Not only the gamma-ray but also the following soft X-ray emission show high temporal variability. Spectrally, the precursor and the soft X-ray emission exhibit the same power-law index of about -1.6 , which also agrees with the β of Band spectrum for the main burst (E. Neights et al. 2025). Then, we discuss the possible interpretation of the observed gamma-ray and soft X-ray emission of GRB 250702B/EP250702a in the framework of ULGRB

scenario. Similar to other ULGRBs, the precursor and main burst could be readily interpreted by a relativistic jet launched during the collapse of a supergiant star. A two-step collapse (e.g. X.-Y. Song & S.-N. Zhang 2023) may be involved to account for the precursor and main burst: The first collapse may only launch a less energetic jet which produces a less luminous and shorter duration precursor than the main burst. The main burst emission are caused by a much more energetic jet launched during the second stage of collapse, which seems to last longer than the first stage. Interestingly, the energetic radiation in the last episode of main burst (M4) probably triggers a further collapse of outer layers of the supergiant star which gives rise to the post-main burst soft X-ray emission with $-5/3$ power-law decay. Moreover, the intermittent behavior and the possible periodicity of about 4000 s in the gamma-ray light curve may correspond to the complicated process and interactions between fallback, accretion, outflow and jet.

The $-5/3$ power-law decay of soft X-ray emission deviates the temporal evolution of typical GRB afterglow, which is dominated by the interaction between jet and interstellar medium or progenitor wind, but perfectly consistent with the prediction of the free fall accretion in collapsar (F. C. Michel 1988). Therefore, we conclude that the temporal evolution of soft X-ray emission is dominated by the fallback process of the collapsar and thus central engine activity. Moreover, the observation fact that the temporal variability in the soft X-ray (J. A. Kennea et al. 2025b) as well as the hard X-ray (B. O'Connor et al. 2025) during this power-law decay stage is much higher than the normal GRB afterglow also provides support to the above scenario.

Therefore, both the gamma-ray emission and the following soft X-ray emission (Fig. 1a) are produced by the jet and controlled by the fallback rate. In the following, we try to infer the Lorentz factor of the jet during the main burst and the following soft X-ray episode. First, we estimate the Lorentz factor of the main burst (denoted as Γ_M) using empirical relations. Based on the ‘‘Amati’’ relation (L. Amati et al. 2002) and $E_{\gamma,\text{iso}}-\Gamma_0$ relation (E.-W. Liang et al. 2010), we find

$$\Gamma_M \sim 133 \left(\frac{E_{\text{peak}}}{100 \text{ keV}} \right)^{\frac{5}{8}} (1+z)^{\frac{5}{8}}. \quad (1)$$

Using E_{peak} of about $400 \pm 100 \text{ keV}$ of the main burst (E. Neights et al. 2025) and the estimated redshift (z) of $0.2 \sim 1$ (A. J. Levan et al. 2025b), we estimate the Γ_M of $300 \sim 480$. This estimation has a large uncertainty due to the dispersion of the relations and uncertainties on the E_{peak} and z . It should be noted that the high energy photon index (β) of Band spectrum is about -1.6

(E. Neights et al. 2025), indicating that there is a break in higher energy range. If so, the Γ_M should be larger. Next, we roughly estimate the Lorentz factor during the following soft X-ray episode with $-5/3$ power-law decay (episode F, about 1 to 30 days post main burst, denoted as Γ_F). Given that the main burst and the following soft X-ray emission share the same power index of -1.6 , we assume that the spectrum in the jet co-moving frame maintains the same shape among these stages and the difference of observed spectrum is caused by the different Lorentz factor of the jet among these episodes, therefore we can roughly estimate the ratio of Lorentz factor between these two stages based on the lower energy boundaries of the energy band with spectral index of -1.6 , $\frac{\Gamma_M}{\Gamma_F} \sim 100$. Thus, we can infer that Γ_F is about several (order of magnitude estimation), which corresponds to relatively mild accretion rate (but not stable, considering the highly variable flux) and thus late time fallback rate.

5. SUMMARY AND CONCLUSION

In this work, we characterize the properties and investigate the nature of the peculiar ultra-long transient source GRB 250702B/EP250702a. We focus ourselves on the high energy emission, including gamma-ray and soft X-ray. Especially, we performed a comprehensive multiple-instrument burst search and implemented analyses jointly with Insight-HXMT/HE, GECAM-B and Fermi/GBM data. We also analyzed the temporal evolution of soft X-ray emission from Swift/XRT and Chandra observations. Our findings are summarized as following:

1. In gamma-ray band, the Insight-HXMT and GECAM-B observation shows that the main burst starts much earlier than the Fermi/GBM trigger time. The main burst could be generally divided into four episodes (denoted M1 to M4), with a total duration of about 4 hours. Each episode consists of a bulk of numerous spiky pulses. These episodes are separated by quiescent periods. There is no monotonic increase or decrease in the fluence of these episodes, however there may be a possible (quasi-)periodicity of about 4000 s.

2. There is a gamma-ray precursor (denoted as P) at 2025-07-01T11:55:17 UTC with a duration of about 50 s, which is about 25 hours before the main burst. Discovery of this precursor is broadly consistent with the EP/WXT detection of this burst a day before the gamma-ray trigger of the main burst. The relation between the precursor-main burst waiting time and the duration of main burst is generally compatible to the trend of GRBs and favors a ULGRB.

3. The luminosity and temporal evolution of the soft X-ray emission resemble other ULGRBs very well, but apparently differs from the known jetted TDEs at the same stage.

4. The soft X-ray flux exhibits a striking feature of $t^{-5/3}$ power-law decay, which perfectly matches the canonical expectation of fallback accretion to a black hole which could exhibit in collapsar and TDE scenarios. However, the fact that the initial time of the $t^{-5/3}$ power-law decay goes after the precursor and the onset of main burst in principle rejects the normal TDE scenario where all emission should be produced after the disruption of the star. Moreover, the emergence of the $-5/3$ decay in the soft X-ray is only about 10 hours after the initial time of this power-law decay, which is also unusually short for normal TDEs.

5. These gamma-ray and soft X-ray emission share similarities of highly variable in flux and non-thermal spectrum with the similar spectral shape. They are probably produced by a relativistic jet launched by a collapsar, whose luminosity and temporal evolution are dominated by the fallback process. Differences on the temporal and spectral behaviors of emission in different episode (P, M1 to M4, F) are likely primarily produced by the different Lorentz factor of the jet. The ultra-long duration of the fallback process requires a supergiant star as progenitor.

In conclusion, all these observation features of GRB 250702B/EP250702a found in this work strongly support the ULGRB collapsar scenario. Almost all properties of precursor and main burst, as well as the luminosity and temporal evolution of soft X-ray emission, can be interpreted by a relativistic jet (with Lorentz factor varying from hundreds to several) launched during the collapse of a supergiant star.

Finally, we note that GRB 250702B/EP250702a represents the longest ULGRB ever detected, with a total gamma-ray duration of about 29 hours considering the precursor. In this event, we reveal a classic fallback process in the late stage of the collapse of a supergiant star which exhibits the $t^{-5/3}$ decay on the fallback rate. Further multi-wavelength/multi-messenger observations and multi-instrument analyses are expected to uncover more mysteries of this peculiar transient.

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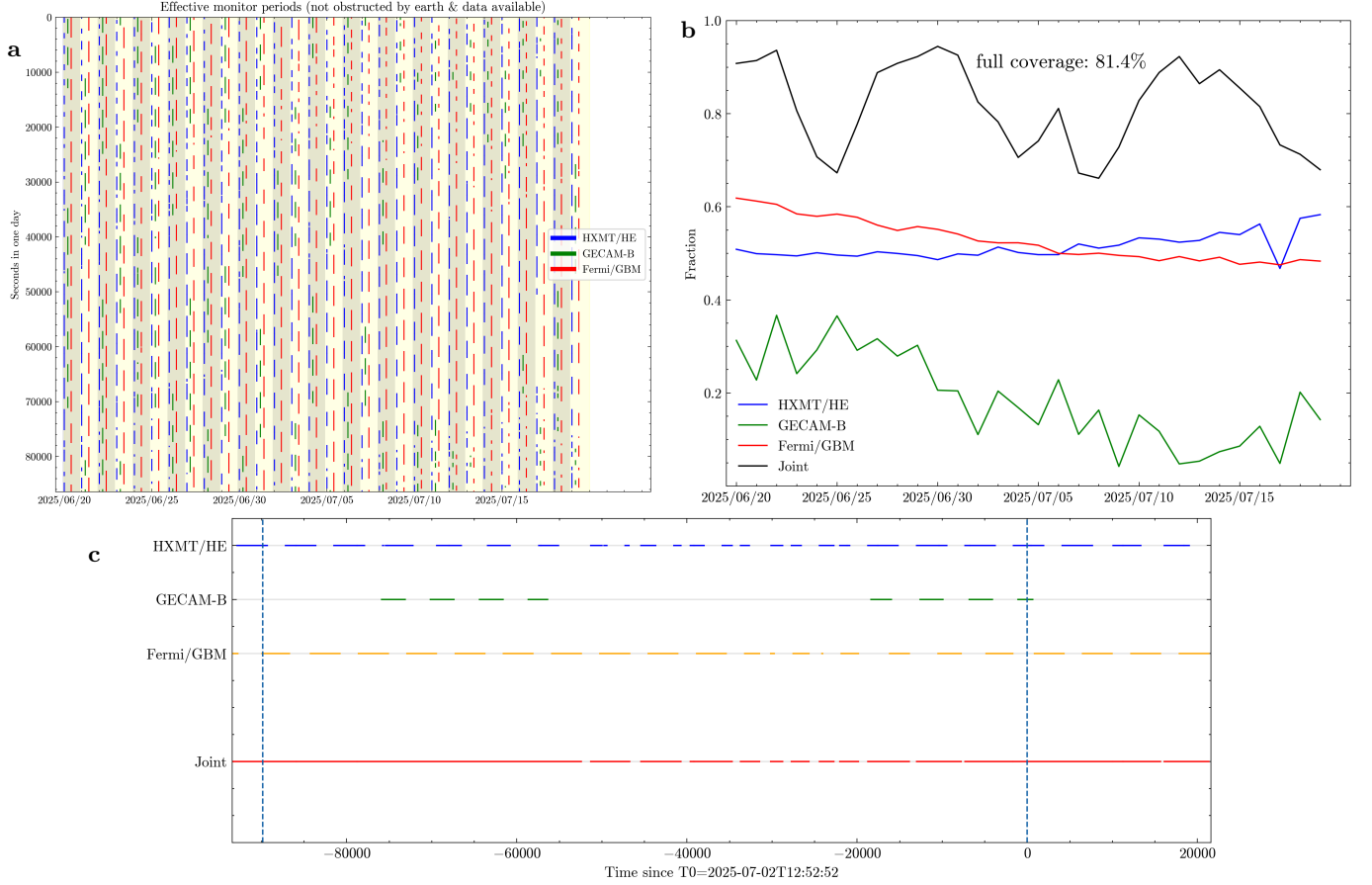


Figure 4. (a), cover periods for each satellite. (b), cover percentage for each satellite and joint observation. The joint monitored time intervals cover 81.4% of the 30-day search. (c), visible intervals from precursor to end of main burst stage for each satellite and joint observation.

APPENDIX

A. MULTI-INSTRUMENT GAMMA-RAY OBSERVATION

The high sensitivity joint targeted coherent search was performed on event-by-event data of *Insight*-HXMT/HE, GECAM-B and *Fermi*/GBM by the dedicated designed algorithm ETJASMIN (C. Cai et al. 2021; C. Cai et al. 2025) since June 20th to July 20th, with the coverage shown in Fig. 4. Compared to previous algorithms, finer energy bins are configured to reach higher sensitivity while maintaining the effectiveness of Gaussian approximation. The background is fitted with a 4th-order polynomial on 1s binned light curve, judging and adjusting recursively based on goodness-of-fit. This simple improvement makes background estimation more robust, preventing numerous false triggers caused by in-and-out-of-SAA background variation or cosmic X-ray source occultation. The search time scale spans from 0.1 to 4s. The significance calculation method in L. Blackburn et al. (2015) is adopted in this search.

B. EVOLUTION OF SOFT X-RAY EMISSION

It is known that the different time zero will affect the slope of power-law evolution. To investigate this effect, as well as exploring genuine initial start time of decaying, we fit the soft X-ray emission, including observation from Swift/XRT and Chandra, by power-law model with different T_0^{PL} . The fitting results are summarized in Table 1, and the corresponding plots are shown in Fig. 5.

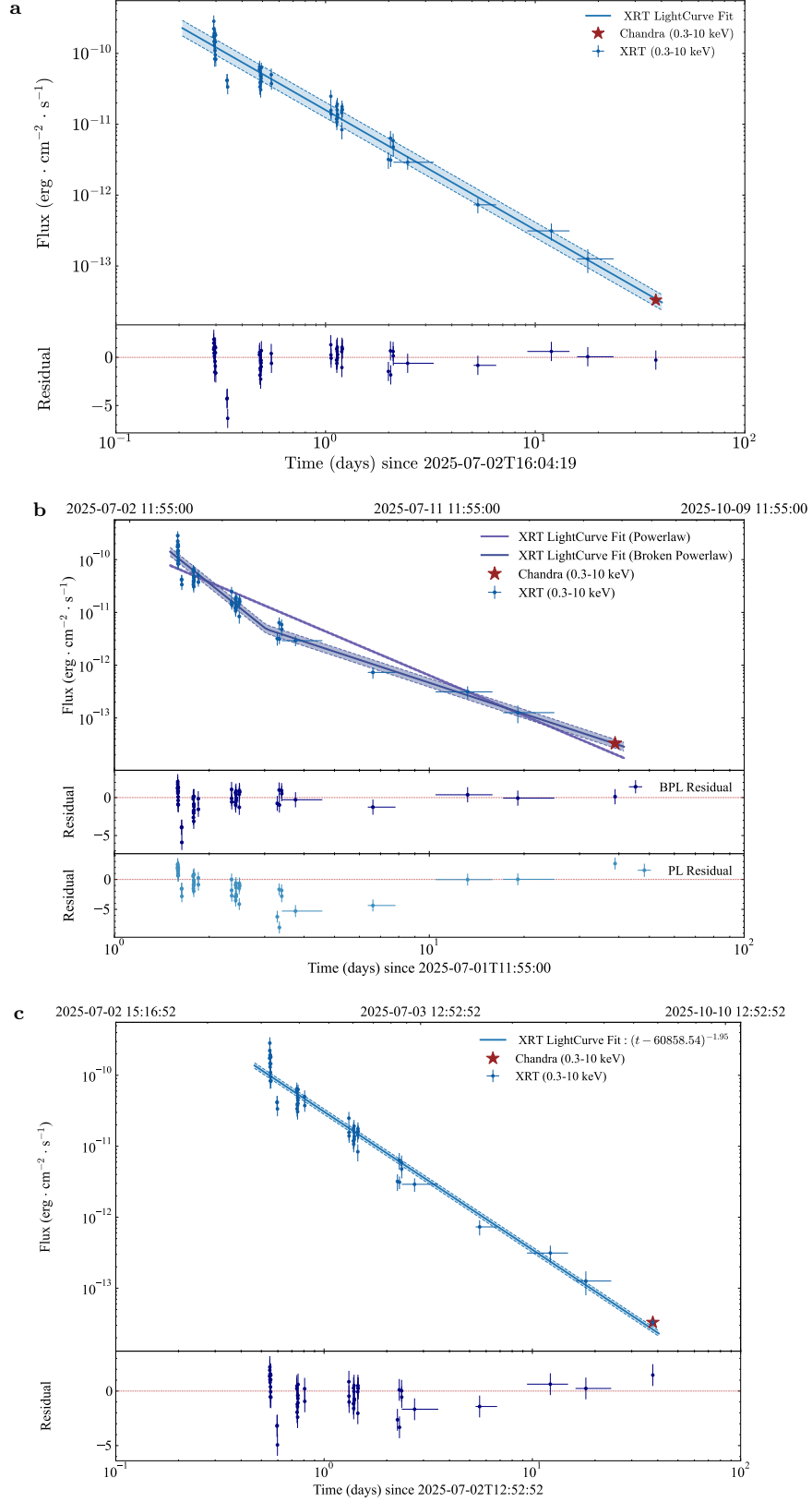


Figure 5. (a), the power-law model fitting curves and residual plots, whose T_0^{PL} is set as a free parameters during the fitting. (b), setting the trigger time of precursor as T_0^{PL} , the fitted curves and residual for the BPL model and the power-law model. (c), the power-law model fitting results with T_0^{PL} , and the start time of the HXMT observation (i.e. 2025-07-02T12:52:52) is set as T_0^{PL} .

Specifically, we note that, when setting the trigger time of precursor, which was detected about one day before the trigger of GRB 250702D, as the T_0^{PL} , the power-law model provides a poor fit, and the trend in residuals suggests a possible BPL behavior, whose mathematical expression is expressed as Eq. B1. By comparing the Bayesian Information Criterion (BIC, defined as $\text{BIC} = -2 \ln L + k \ln N$, where L represents the maximum likelihood value, k denotes the number of free parameters in the model, and N signifies the number of data points) and Akaike Information Criterion (AIC, defined as $-2 \ln L + 2k$) (H. Akaike 1974) values obtained from fitting the power-law model and the BPL model, we find that both $\text{BIC}_{\text{PL}} \gg \text{BIC}_{\text{BPL}}$ and $\text{AIC}_{\text{PL}} \gg \text{AIC}_{\text{BPL}}$, indicating that the BPL model provides a much better fit than power-law model when the start time of the precursor is set as T_0^{PL} , as shown in the Figure 5(b). Additionally, the two slopes of the BPL model are ~ -4.87 and ~ -1.96 , which are consistent with typical values of the steep decay phase and the decay phase after the jet break respectively, suggesting the soft X-ray emission can be explained as the afterglow is considered to have started from the precursor.

$$F(t) = \begin{cases} F_0[(t - T_0^{\text{PL}})/(t_j - T_0^{\text{PL}})]^{-\alpha_1}, & t < t_j \\ F_0[(t - T_0^{\text{PL}})/(t_j - T_0^{\text{PL}})]^{-\alpha_2}, & t > t_j \end{cases} \quad (\text{B1})$$

Additionally, we calculated the BIC and AIC for the power-law model with different T_0^{PL} . The results show that as the T_0^{PL} approaches the value derived from the free-fit, the BIC and AIC values of the power-law model decrease, and the free-fit T_0^{PL} is the most favored value.

Note	$T_0^{\text{PL}}(\text{UTC})$	power-law			Broken power-law				
		k	BIC_{PL}	AIC_{PL}	α_1	α_2	Δt_j^{a} (day)	BIC_{BPL}	AIC_{BPL}
Precursor	2025-07-01T11:55:00	-2.54 ± 0.03	330.46	326.37	4.87 ± 1.33	1.96 ± 0.13	3.00 ± 0.41	45.36	37.19
T_0	2025-07-02T12:52:52	-1.95 ± 0.02	54.11	50.03	—	—	—	—	—
GRB 250702D	2025-07-02T13:09:02	-1.94 ± 0.02	50.97	46.88	—	—	—	—	—
GRB 250702B	2025-07-02T13:56:06	-1.91 ± 0.02	42.03	37.95	—	—	—	—	—
GRB 250702E	2025-07-02T16:21:33	-1.82 ± 0.02	17.99	13.91	—	—	—	—	—
Free Fit	2025-07-02T16:04:19 ^b	-1.73 ± 0.05	8.87	2.74	—	—	—	—	—

NOTE—Parameter errors in this table are for 1σ (68% confidence level). **a:** $\Delta t_j = t_j - t_0$. The unit of the Δt_j is the “day”. **b:** The 1σ error of T_0^{PL} is +3100 s, -4700 s for free-fit.

Table 1. Fitting results for the soft X-ray data

C. LIGHT CURVE AND BACKGROUND ANALYSES

In order to reveal a complete day-long light curve, *Insight*-HXMT/HE, GECAM-B and *Fermi*/GBM are used to cover nearly full duration. The background of each instrument can change greatly in less than one hour, making the light curve from the source hard to recognize. Thus, background subtraction is necessary.

For *Insight*-HXMT/HE, the background varies slowly when the satellite enters or quits the high-latitude area. Although most of the pulses of this burst detected by *Insight*-HXMT/HE last for less than dozens of seconds, these pulses can be squished in a time interval of over a hundred seconds. In that case, 4th-order polynomial becomes less reliable for background fit.

We estimate the background of 400s to 1300s (part of M1) and 12100s to 12800s (part of M4) with revisited orbital data. For other time intervals, we use slide-window 4th-order polynomial to fit *Insight*-HXMT/HE background.

Revisited orbital data background subtraction method utilized for *Insight*-HXMT/HE is performed as follows:

First, we check satellite position and determine a 85500s raw shift period. We select number of shifted periods from -10 to 10 (except 0, which is the target lightcurve for background subtraction) and remove those with inconsistent satellite attitude. At least 3 effective orbits are selected at this stage. We find the lightcurves of these orbits with energy ranging from 200 keV to 3 MeV. Then, cross-correlation function (CCF) value between each pair of lightcurves is calculated for different refined shift period selection, ranging from 85480 to 85520 s. We use 85510 s as the best refined shift period, which maximizes the summed CCF value. The lightcurves at these revisited orbits are shifted

according to refined shift period and the shift period number. The stacked lightcurve then can provide a better shape reference than 4-th order polynomial for the target lightcurve. Finally, we fit the background with the only one remained free parameter, the amplitude multiplier between the target lightcurve background and the stacked revisited lightcurve.

The background of GBM varies greatly and in many time intervals of this burst hard to fit with 4-th order polynomial. For the background estimation of *Fermi*/GBM, we employ the method using revisited orbital data, which has been adopted by C. Zheng et al. (2024) and B. Biltzinger et al. (2020). After approximately 30 orbits, the *Fermi*/GBM returns to a nearby spatial location with a closely matched attitude, resulting in a nearly identical background environment for the GBM. The average background count rate from the ± 30 orbit data ($T \pm 85060$ s) of *Fermi*/GBM is used as an estimate of the background for the current orbit. This method remains applicable across different energy ranges, although some revisited orbits may exhibit particle contamination in the low-energy range. This contamination can significantly affect the background estimation. For instance, during the M2 period, the *Fermi*/GBM background remains relatively stable, whereas particle event contamination has been observed in the revisited orbits immediately preceding and following this period. Fortunately, the background in the high-energy range remains relatively stable, and we assume that the spectral shape of the background remains constant during this interval. Thus, the variation of the background in the low-energy range can be extrapolated from its variation in the high-energy range. This procedure yields a background estimate that subsequently undergoes a straightforward angular correction, ultimately producing the net light curve for the GBM.

For HXMT/HE, all 18 HED are selected. For GECAM-B, 3 detectors with incident angle smaller than 70 deg are selected, namely GRD 12, 13, and 21. For *Fermi*/GBM, to maintain favorable incident angles throughout all observational periods, the n8, na and nb detectors were selected for revisited orbital background subtraction.

Detailed light curves can be found in Fig. 1.

D. SPECTRAL FIT FOR PRECURSOR CANDIDATE

Fermi/GBM detected a precursor candidate at 2025-07-01T11:55:17 UTC (denoted as T_0^{pre} , we adopt it as reference time in this section). We use two most significant detectors, n8 and nb, to perform spectral fit.

To estimate the background count rate at each PHA channel, we use 4-th order polynomial to fit the 10 s binned light curve for each channel in certain time intervals (-130 to -30 s, and 50 to 150 s). Total spectrum, in 127 channels (among all 128 channels, the last channel is overflow channel and thus is excluded), is calculated from -10 to +20 s and subtracted by background spectrum to get the net spectrum. All errors are estimated under Gaussian approximation. We use Elisa¹² to perform Bayesian posterior estimation and limit the energy range to 8 keV–1000 keV. The spectrum is well fitted by a power-law with an index of $1.65^{+0.10}_{-0.10}$, as shown in Fig. 6.

¹² <https://github.com/wcxve/elisa>

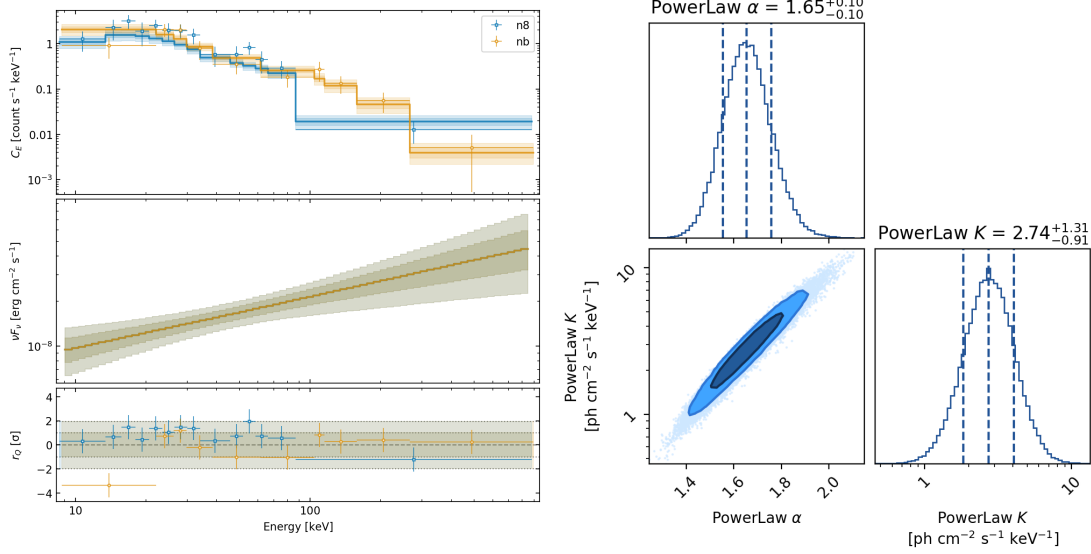


Figure 6. The spectral fit result of the precursor candidate with power-law model.

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