Mon. Not. R. Astron. Soc. **000**, 1–9 (2022) Printed 19 October 2022 (MN LaTeX style file v2.2)

An alternative statistical interpretation for the first direct evidence of Collapsars

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ABSTRACT
The existence of a plateau in the short-duration tail of the observed distribution of cosmological Long-soft Gamma Ray Bursts (LGRBs) has been argued as the first direct evidence of Collapsars. A similar plateau in the short-duration tail of the observed duration distribution of Short-hard Gamma Ray Bursts (SGRBs) has been suggested as evidence of compact binary mergers. We present an equally plausible alternative interpretation for this evidence, which is purely statistical. Specifically, we show that the observed plateau in the short-duration tail of the duration distribution of LGRBs can naturally occur in the statistical distributions of strictly-positive physical quantities, exacerbated by the effects of mixing with the duration distribution of SGRBs, observational selection effects and data aggregation (e.g., binning) methodologies. The observed plateau in the short-duration tail of the observed distributions of SGRBs can similarly result from a combination of sample incompleteness and inhomogeneous binning of data.

Key words: Gamma-Rays: Bursts – Gamma-Rays: observations – Methods: statistical

1 INTRODUCTION

Gamma-ray bursts (GRBs) are primarily broken into two categories: Long-duration GRBs (LGRBs), with $T_{90} > 2$ s, and Short-duration GRBs (SGRBs), with $T_{90} < 2$ s. T_{90} is the duration in which 90% of the gamma-ray photon flux is detected. Significant observational evidence over the past two decades connect LGRBs to the death and the core-collapse of supermassive stars (Fruchter et al. 2006; Woosley & Bloom 2006). This *Collapsar model* of LGRBs is supported by evidence such as the association of half a dozen GRBs with spectroscopically confirmed broad-line Ic supernovae (SNe) as well as photometric evidence of underlying SNe in about two dozen more (Woosley & Heger 2006; Hjorth et al. 2011). In addition, there is indirect evidence for the connection of LGRBs with massive stars from the identification of LGRB host galaxies as intensively star-forming galaxies (Bloom et al. 2002; Le Floc'h et al. 2003; Christensen, Hjorth & Gorosabel 2004; Fruchter et al. 2006). The LGRBs are localized in the most active star-forming regions within those galaxies, increasing the probability that they originate from the death of supermassive stars. Physically, according to the Collapsar model, as the core collapses in a supernova explosion, a bipolar jet is launched from the center of the star that has to drill through the stellar envelope and break out in order to produce an observed GRB (MacFadyen & Woosley 1999; MacFadyen, Woosley & Heger 2001, e.g.,).

In their paper, Bromberg et al. (2012) develop a model of LGRBs that provides the first observational imprint of this jet-envelope interaction, and thus, direct confirmation of the Collapsar model. A distinct signature in the duration

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distribution is detected: the appearance of a plateau toward short durations. This occurs at times much shorter than the typical breakout time of the jet, i.e., the time it takes for the jet to drill through the stellar envelope. This action dissipates energy, so the engine driving these jets must be in operation for at least the breakout time. If it is not, a GRB is not produced. For breakout times that are very close to the engine time, the GRB is brief, and a characteristic plateau is seen in the duration distribution. The breakout time is set by the density and radius of the stellar envelope at radii $> 10^{10}$ cm, while the engine working time is determined by the stellar core properties at radii $< 10^{8}$ cm.

Unlike LGRBs, SGRBs are theorized to result from the merger of either two neutron stars (NS-NS) or of a neutron star and a black hole (NS-BH) (Eichler et al. 1989; Narayan, Piran & Kumar 2001; Metzger & Berger 2012; Berger 2014; D'Avanzo 2015). Recently, the first NS-NS merger was confirmed in an unprecedented joint gravitational and electromagnetic observation by *Advanced LIGO*, *Advanced Virgo*, and the *Fermi Gamma-ray Space Telescope*'s Gamma-ray Burst Monitor (GBM) (Abbott et al. 2017; Goldstein et al. 2017). Compact binary mergers of these types are accompanied by significant dynamical mass ejection. Models range on how much mass is ejected depending on the GRB, from 0.03 $M_\odot$ (GRB 130603B) to 0.13 $M_\odot$ (GRB 060614) (Berger, Fong & Chornock 2013; Yang et al. 2015). It is suggested based on observed breaks in SGRB afterglows that they involve jets as well (Soderberg et al. 2006; Fong et al. 2012). Therefore similar to the Collapsar model, the merger launches a relativistic jet that has to push through the expanding ejecta of significant mass (Murguia-Berthier et al. 2014; Nagakura et al. 2014). According to Moharana & Piran (2017) this again produces a plateau in the T_{90} distribution, only at shorter durations than the one seen with LGRBs, reflecting the typical time it takes for the jet to reach the outer edge of the ejecta and produce the prompt γ-ray emission.

In this manuscript, we argue that although the plateaus seen in the analysis of the T_{90} distributions of GRBs by Bromberg et al. (2012) and Moharana & Piran (2017) could be direct confirmation of theoretical models, they could, with equal plausibility, simply be statistical artifacts. This work is organized as follows: Section 2 reviews the theoretical arguments in favor of a Collapsar interpretation of the observed plateau of LGRBs duration distribution. Section 3 details our alternative statistical interpretation of the plateau and our attempt to reproduce the apparent plateaus seen in observational GRB durations from sample incompleteness. Section 4 is a discussion of our results, and Section 5 contains links to where our data and code can be found.

2 THE COLLAPSAR INTERPRETATION OF THE PLATEAU

The argument for the presence of a plateau in the observed duration distribution of LGRBs begins with the assumption that the intrinsic[1] prompt gamma-ray emission duration (t_γ) depends exclusively on the LGRB central engine activity time (t_e) and the jet breakout time (t_b) from the stellar envelope,

$$t_\gamma = \begin{cases} 0 & \text{if } \ t_\mathrm{e} \le t_\mathrm{b} \ , \\ t_\mathrm{e} - t_\mathrm{b} & \text{if } \ t_\mathrm{e} > t_\mathrm{b} \ . \end{cases} \tag{1}$$

Realistically, as Bromberg et al. (2012) state, the jet breakout, engine working times, and the gamma-ray emission duration might be correlated with each other and other properties of the LGRB progenitor. Nevertheless, assuming the validity of (1), one can write the probability density function (PDF) of t_γ (i.e., the probability distribution of the intrinsic LGRB duration) in terms of the PDF of the engine working time t_e,

$$\pi_\gamma(t_\gamma)\mathrm{d}t_\gamma = \begin{cases} 0 & \text{if } \ t_\mathrm{e} \le t_\mathrm{b} \ , \\ \pi_\mathrm{e}(t_\mathrm{e})\mathrm{d}t_\mathrm{e} = \pi_\mathrm{e}(t_\mathrm{b} + t_\gamma)\mathrm{d}t_\gamma & \text{if } \ t_\mathrm{e} > t_\mathrm{b} \ . \end{cases} \tag{2}$$

where π denotes the PDF. In other words, the duration distribution of LGRBs (for a given t_b) is simply the tail of the distribution of the engine work time beyond t_b. Under further assumption that π_e is *locally analytic* at $t_\mathrm{e} = t_\mathrm{b}$, the Taylor expansion of the right-hand side of (2) at $t_\mathrm{e} = t_\mathrm{b}$ yields,

$$\pi_\mathrm{e}(t_\mathrm{b} + t_\gamma) = \pi_\mathrm{e}(t_\mathrm{b}) + t_\gamma \frac{\mathrm{d}\pi_\mathrm{e}(t_\mathrm{e})}{\mathrm{d}t_\mathrm{e}}\bigg|_{t_\mathrm{e}=t_\mathrm{b}} + \mathcal{O}\left(t_\gamma^2\right) \ . \tag{3}$$

We note that π_γ has an *essential singularity* at $t_\gamma = 0$ where it cannot be *directly* expanded as a Taylor series, that is,

$$\pi_\gamma(t_\gamma = 0) = 0 \neq \pi_\mathrm{e}(t_\mathrm{e} = t_\mathrm{b}) \ . \tag{4}$$

Given (2), (3) implies a *nearly constant* PDF for the prompt emission duration of LGRBs as $t_\gamma \to 0$ *if and only if* the higher order terms in the Taylor expansion are negligible compared to the first (constant) term. This requires either $t_\gamma \ll t_\mathrm{b}$ or *all* derivatives of $\pi_\mathrm{e}(t_\mathrm{e})$ near t_b be nearly zero. Specifically, the second term in the right-hand-side of (3) containing the first derivative of $\pi_\mathrm{e}(t_\mathrm{e})$ must satisfy the condition,

$$\frac{\mathrm{d}\pi_\mathrm{e}(t_\mathrm{e})}{\mathrm{d}t_\mathrm{e}}\bigg|_{t_\mathrm{e}=t_\mathrm{b}} \ll \frac{\pi_\mathrm{e}(t_\mathrm{b})}{t_\gamma} \ . \tag{5}$$

Independent theoretical arguments (e.g., Bromberg,

[1] Note that Bromberg et al. (2012) use the keywords 'intrinsic' and 'observed' interchangeably to represent rest-frame LGRB duration. In this manuscript, 'intrinsic' and 'observed' exclusively refer to the GRB rest-frame and the observer-frame on Earth, respectively.

Nakar & Piran 2011) suggest a typical jet breakout time $\hat{t}_{\rm b} \simeq 50$ [s] which is of the same order as the starting point of the plateau behavior in the duration distribution of LGRBs at $\hat{t}_\gamma \simeq 20 - 30$ [s] (Bromberg et al. 2012). This similarity ($\hat{t}_\gamma \simeq \hat{t}_{\rm b}$) clearly violates the condition $t_\gamma \ll t_{\rm b}$ under which the Taylor expansion is valid. Bromberg, Nakar & Piran (2011); Bromberg et al. (2012) reconcile this by further "assuming that $\pi_{\rm e}(t_{\rm e})$ is a smooth function and *does not vary* on short timescales in the vicinity of $\hat{t}_{\rm b}$", that is, the first and higher-order *derivatives* in the Taylor expansion must be effectively zero relative to the first constant term in (3).

Such a strict additional constraint on the derivatives in the Taylor expansion (3) leads to a circular logic where the Collapsar *interpretation* of the observed nearly-flat plateau in t_γ requires the *assumption* of a nearly-flat plateau in engine working time distribution around $t_{\rm b}$. Recall that $\pi_\gamma(t_\gamma > 0) = \pi_{\rm e}(t_{\rm e} > t_{\rm b})$, by definition (2). In other words, the Collapsar interpretation of the plateau requires the implicit assumption of the existence of the plateau.

The above circular logic can be resolved in several ways: 1) The theoretical predictions of the typical breakout time $\hat{t} \sim 50$ [s] are imprecise. 2) The distribution of the engine activity time $\pi_{\rm e}(t_{\rm e})$ is indeed nearly flat around $\hat{t}_{\rm b}$. 3) The observed plateau in the duration distribution of LGRBs does not have a Collapsar interpretation but is due to the statistical nature of the distributions of strictly positive physical quantities combined with sample incompleteness, convolution effects, contamination with SGRBs, and visual effects.

In the following section, we argue the last resolution offers a natural plausible explanation for the apparent plateaus in the duration distributions of both LGRBs and SGRBs without invoking any physical theories.

3 THE STATISTICAL INTERPRETATION OF THE PLATEAU

Statistical distributions with strictly-positive support, for example: $\pi(t_\gamma), t_\gamma \in (0, +\infty)$, frequently and naturally exhibit plateaus in their short tails. Such plateaus can appear under different independent circumstances that are discussed in the following subsections.

3.1 All finite-valued statistical distributions with positive support have plateaus

Recall that the Taylor expansion of the PDF of an analytic statistical distribution at any point within its support guarantees the existence of a plateau near the point of expansion. Such a plateau, however, is mathematically infinitesimal, defined only asymptotically as one approaches the point of expansion. Therefore, these mathematically-infinitesimal plateaus are invisible to the human eye almost anywhere within the support of the PDF, *except* at the origin $t_\gamma = 0$ under an appropriate transformation. By definition, the PDF has a positive support $t_\gamma \in (0, +\infty)$. Therefore, taking the logarithm of the x-axis (t_γ) pushes the lower limit of the support of the PDF at $t_\gamma = 0$ to negative infinity: $\log(t_\gamma \rightarrow 0) \rightarrow -\infty$. This logarithmic transformation of the x-axis effectively infinitely magnifies the Taylor expansion of $\pi(t_\gamma)$ around $t_\gamma = 0$. This infinite magnification can be intuitively understood by noting that the PDF $\pi(t_\gamma)$ of the distribution must have a *finite value* at the origin $t_\gamma = 0$ with a well-defined *finite* right-hand derivative. When the x-axis is logarithmically transformed, the finite amount of changes in $\pi(t_\gamma)$ span progressively over larger and larger logarithmic ranges on the x-axis, effectively making the PDF look like a plateau as $\log(t_\gamma) \rightarrow -\infty$.

This is precisely the mechanism by which the Collapsar interpretation discussed in §2 attempts to explain the observed plateau in the duration distribution of LGRBs. The invocation of the Collapsar theory of LGRBs, however, appears unnecessary since *all finite-valued statistical distributions with strictly positive support exhibit a plateau toward zero* and there are uncountably infinite number of such statistical distributions. Given that the gamma-ray duration t_γ of both SGRBs and LGRBs is a strictly positive-valued observable random variable, the appearance of a plateau in their t_γ distributions on a $\log(t_\gamma)$-axis is mathematically guaranteed as $t_\gamma \rightarrow 0$. This is true without recourse to any physical theories of GRBs. Figure 1 illustrates this mathematical asymptotic plateau behavior for some of the well-known continuous distributions with positive real support.

3.2 Sample-incompleteness creates plateaus in observational data

Despite the mathematical guarantee of a plateau in strictly-positive finite-valued distributions, the practical visibility of such plateaus in observational data is limited to distributions whose probability mass are heavily concentrated around zero. Note that for a finite sampling, the bulk of observational data originates from regions of high-probability in a distribution. This region of high-probability is concentrated around zero for all finite-valued monotonically-decreasing PDFs, for example, the Exponential or Lomax PDFs as shown in Figure 1a. In such cases, any finite sampling of the distribution inevitably constructs the mathematical plateau of §3.1, making the plateau readily visible.

By contrast, distributions whose probability mass concentrates at non-zero values $t_\gamma \gg 0$ require large sample sizes to observationally construct the mathematically-asymptotic plateau of §3.1. Many prominent statistical distributions with positive support belong to this class, such as F, Chi, Chi-Squared, Gamma, Weibull, Dagum, Lognormal. For an illustration, the near-zero, hard-to-sample, mathematical plateaus of Gamma and Log-normal distribution from this category are depicted in Figure 1b.

Sample-incompleteness, however, can still generate a second kind of plateau in strictly-positive statistical distributions, entirely different from the plateaus of the first kind of mathematical origin discussed in §3.1. Such *observational*

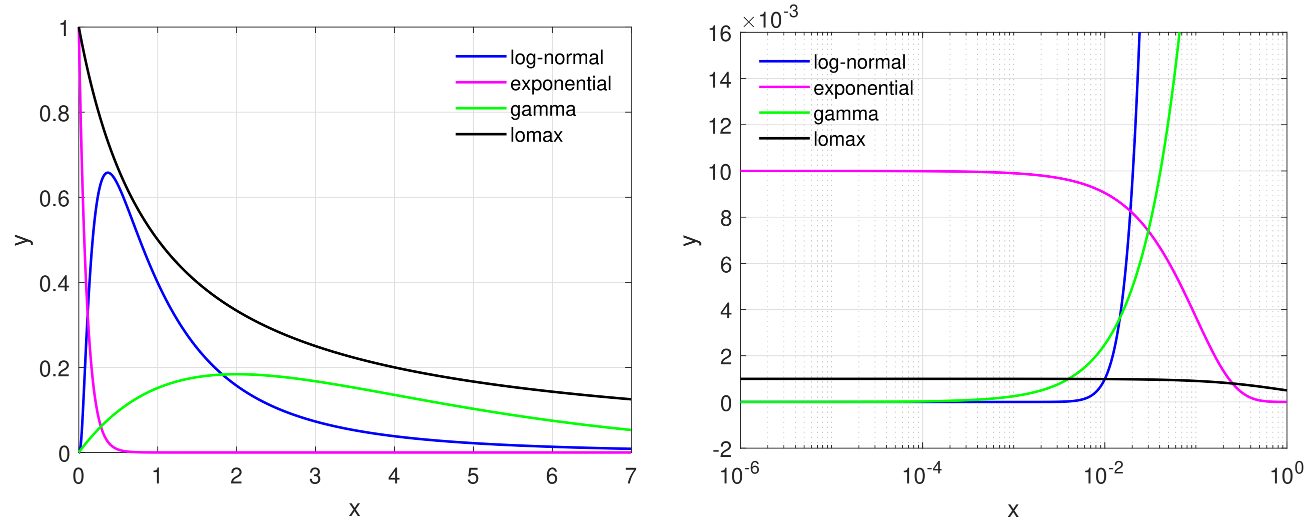


Figure 1. An illustration of the plateau in the distribution of strictly-positive random variables as $x \to 0$. The existence of these plateaus is mathematically guaranteed for all distributions with positive support and finite-valued Probability Density Function (PDF). **(a)** The PDFs of three popular positive-valued statistical distributions. **(b)** A zoom-in on the same PDFs as in plot (a), but at very small values near the origin, on a logarithmic x-axis, illustrating the plateau-like behavior of the distributions near $x = 0$. The appearance of the plateau near the origin ($x = 0$) is guaranteed by the logarithmic transformation of the x-axis. The logarithmic transformation effectively spreads a finite amount of variations in the PDF on the y-axis over a semi-infinite range on the (logarithmic) x-axis.

plateaus result from limited sampling of positive statistical distributions that are highly positively skewed. Recall that plateaus naturally also occur in the neighborhood of the mode of a distribution where the derivative of the PDF is mathematically zero,

$$\left.\frac{\mathrm{d}\pi_\gamma(t_\gamma)}{\mathrm{d}t_\gamma}\right|_{\mathrm{t}_\gamma=\hat{\mathrm{t}}} = 0 \ , \tag{6}$$

This flatness of the PDF around the mode can readily become observationally visible if the distribution sharply rises from some finite value at $t_\gamma = 0$, typically $\pi(t_\gamma = 0) = 0$, to the PDF mode at $t_\gamma = \hat{t}$, and gradually declines to zero as $t_\gamma \to +\infty$. This sharp-rise–gradual-decay is the typical behavior of many positive-valued statistical distributions and the key requirement for generating finite-sample extended plateaus in their PDFs.

Specifically, the value of the Cumulative Distribution Function (CDF) at the mode is a primary factor in the appearance of a finite-sample plateau in the PDF of distributions with strictly-positive support. The integral,

$$\pi_\gamma(t_\gamma < \hat{t}) = \int_0^{\hat{t}} \pi_\gamma(t_\gamma)\mathrm{d}t_\gamma \ , \tag{7}$$

represents the probability that a random value $t_\gamma < \hat{t}$ is sampled from the distribution to the left of the PDF mode $\hat{t}$. Therefore, if the shape of the distribution (in log-log space) is such that the probability of sampling at $t_\gamma < \hat{t}$ is negligible, a plateau appears in the histogram of observational data at $t_\gamma \sim \hat{t}$. The plateau appearance is substantially strengthened and extended if the PDF decays slowly (and concavely) toward $+\infty$ and the observational sample is binned and visualized on a logarithmic x-axis as done in Bromberg et al. (2012).

To illustrate this artificial finite-sample plateau creation in action, consider the Lognormal distribution, widely used in Astronomy for modeling luminosity functions and other observational data (e.g., Balazs et al. 2003; Butler, Bloom & Poznanski 2010; Berkhuijsen & Fletcher 2012; Shahmoradi 2013a,b; Shahmoradi & Nemiroff 2015; Shahmoradi 2017; Medvedev et al. 2017; Zaninetti 2018; Osborne, Shahmoradi & Nemiroff 2020; Yan et al. 2021). The LogNormal distribution is always positively-skewed for any parameter values. This results in an area to the left of the mode of the PDF that is typically negligible as illustrated in Figures 2a and 2e. Hence, the short tail of the LogNormal distribution to the left of its mode is rarely fully observationally constructed, leading to the appearance of a plateau in the PDF on the log-scale near the mode of the distribution. This behavior is not exclusive to LogNormal and is generically seen in many statistical distributions with positive support, some of which are also shown in the rest of the plots of Figure 2.

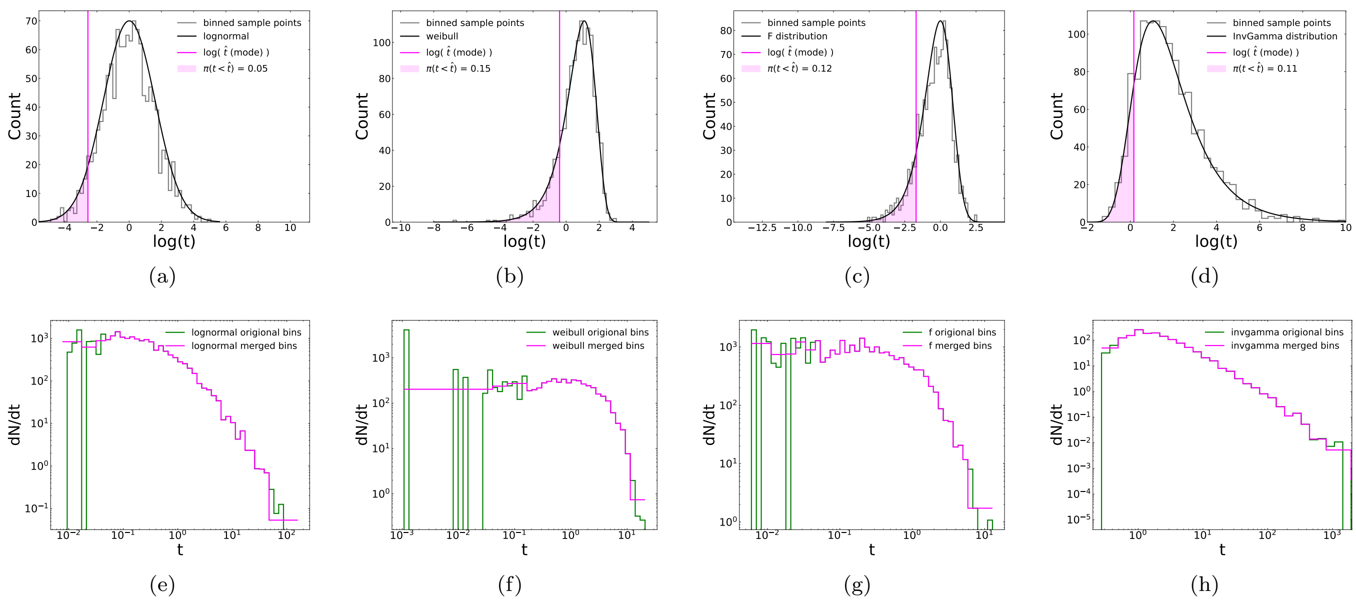


Figure 2. An illustration of the effects of sample incompleteness on plateau formation in statistical distributions. A primary factor in the appearance of finite-sample plateaus near the modes of PDFs is the area to the left of the PDF mode. The smaller this area is, the less opportunities there is to construct the short tail of the PDFs in finite-sampling, thus leading to the appearance of plateaus in the PDFs near their modes. The top plots depict the histograms of the log-transformed random variables drawn from select statistical distributions with positive support. The bottom plots depict the corresponding histograms of the original random variables, but on logarithmic axes.

3.3 Convolution creates plateaus in observational data

In addition to the area to the left of the mode of PDFs with positive support, the smoothness (differentiability) and concavity of the PDF near its mode plays a dominant role in the appearance of finite-sample plateaus. Indeed, a separate class of statistical distributions with strictly-positive support have modes that are neither smooth nor occur at the origin. These distributions, exemplified by the Pareto and Log-Laplace, hardly exhibit plateau behavior under finite sampling. Nevertheless, we show in this section that even the most difficult non-analytic, non-smooth PDFs can exhibit plateaus under convolution.

Recall the convolution of two functions,

$$(f * g)(t) = \int_{-\infty}^{\infty} f(t)g(t-\tau)\, d\tau \ , \qquad (8)$$

acts as a smoothing operation similar to that of weighted averaging. The resulting function from the convolution will be at least as smooth as the individual functions ($f(\cdot)$ or $g(\cdot)$ in (8)). In fact, the convolution operation is identical to a weighted dynamic averaging of $f(\cdot)$ when the weight, $g(\cdot)$, is a probability density function (PDF). In the case of the duration distribution of LGRBs, the convolution performed to obtain the observer-frame duration distribution is the following,

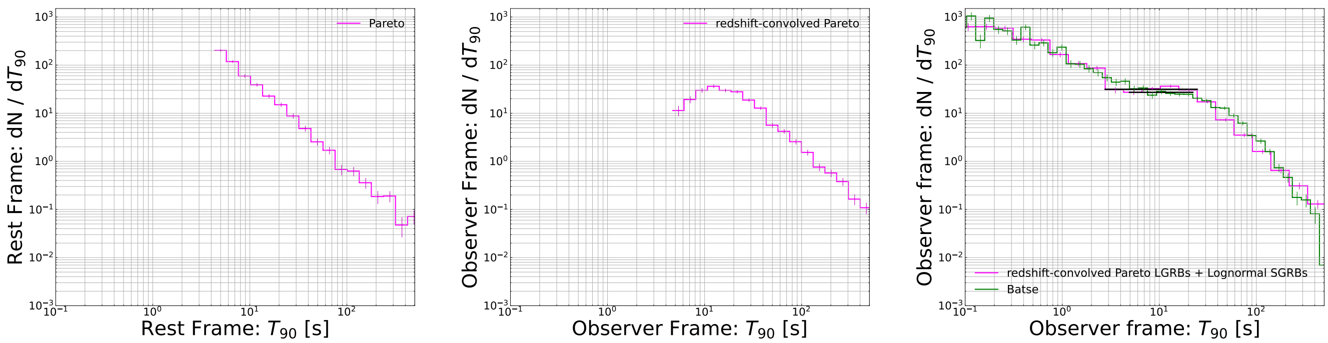
$$\log(t_{\gamma,\mathrm{obs}}) = \log(z+1) + \log(t_{\gamma,\mathrm{int}}) \ , \qquad (9)$$

where "obs" and "int" stand for the observed and intrinsic durations respectively, and z represents GRB redshift.

We demonstrate the effectiveness of convolution in creating plateaus by considering a Pareto PDF for the duration distribution of LGRBs. The Pareto distribution does not exhibit any plateau-like behavior within its support under any circumstances (e.g., see Figure 3a). Yet, when convolved with the redshift distribution of LGRBs, the sharp non-analytical mode of the Pareto PDF transforms into a continuous smooth mode as seen in Figure 3b. Combining the observed convolved duration distribution of LGRBs with the duration distribution of SGRBs further eliminates the appearance of any discontinuity or sharp decline in the short tail of the distribution, leading to a plateau in the mixture distribution that is even longer than the observed plateaus in the duration distributions of BATSE and Fermi catalog GRBs (Figure 3c).

3.4 Sample contamination creates plateaus in observational data

Contamination of the short tail of the duration distribution of LGRBs with SGRBs leads to further extension of the apparent plateaus because the population of SGRBs compensates for any drop in the count of LGRBs toward low durations. Consider again a LogNormal fit to the intrinsic duration distribution of LGRBs. Shahmoradi (2013b,a);



(a) Pareto for intrinsic $t_{\gamma,\mathrm{LGRBs}}$ (b) Observed redshift-convolved $t_{\gamma,\mathrm{LGRBs}}$ (c) Mixture of $t_{\gamma,\mathrm{LGRBs}}$ and $t_{\gamma,\mathrm{SGRBs}}$

Figure 3. An illustration of the smoothing effects of convolution on the Pareto distribution, leading to the appearance of a plateau in $\frac{dN}{dT}$ plot. (a) shows sampled points from a Pareto distribution after performing the bin merging as described in Bromberg et al. (2012). **(b)** shows the same data as in plot **a** but convolved with the redshift distribution of LGRBs (derived from Swift catalog). Plot **(c)** further combines the convolved observed duration distribution of LGRBs with a log-normal fit to the redshift distribution of SGRBs. For comparison, the green line represents the BATSE SGRBs and LGRBs duration distribution. The final observed plateau resulting from the Pareto distribution is 50% longer than the observed plateau in the duration distribution of BATSE LGRBs.

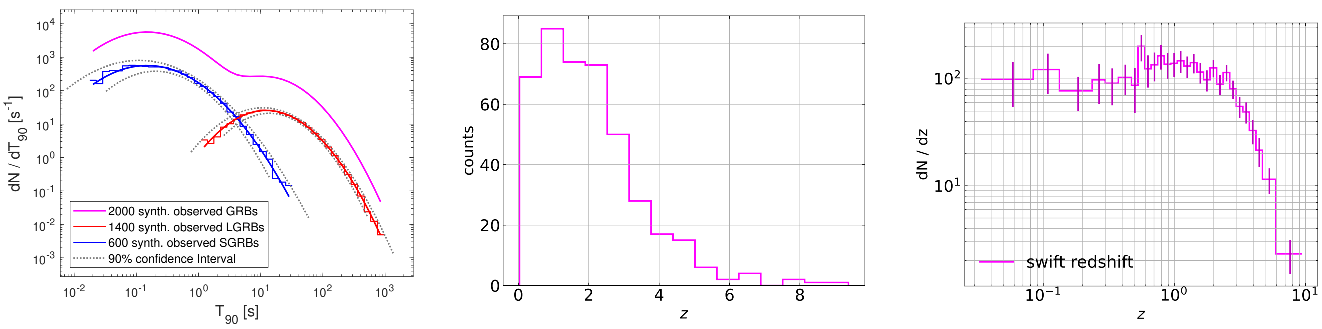
Shahmoradi & Nemiroff (2015); Osborne, Shahmoradi & Nemiroff (2020) argue and provide evidence for goodness of fit of LGRBs and SGRBs prompt duration distributions with LogNormal PDF. The LogNormal distribution does not exhibit an inherent plateau near its short tail. Sample incompleteness, however, creates the appearance of a plateau in the LogNormal fit to the observational LGRB data. This apparent plateau is further extended by the convolution of the intrinsic duration distribution with redshift to obtain the observe-frame duration distribution as illustrated in Figure 4a. Finally, contamination with SGRBs data due to the overlap of the two distributions, completely eradicates any signs of decline in the short tail of LGRBs duration distribution, yielding a perfect plateau appearance in the final mixture distribution as seen in the magenta solid curve in Figure 4a.

4 DISCUSSION

In this manuscript we presented purely mathematical, statistical, and cognitive arguments that strongly favor a non-physical (i.e., non-collapsar) origin for the observed plateau in the duration distribution of LGRBs. The Taylor expansion (3) of the density function of the engine activity time (t_e) near the jet breakout time (t_b) requires the plateau to appear at durations orders of magnitude smaller than the inferred t_b in Bromberg et al. (2012). Bromberg, Nakar & Piran (2011); Bromberg et al. (2012) reconcile this inconsistency by an additional assumption that the engine activity time "is a smooth function and *does not vary* on short timescales in the vicinity of the breakout time". This, however, creates a *circular logic* in the argument for the Collapsar origin of the observed plateau, where Bromberg et al. (2012) impose a flatness condition on the distribution of the engine activity time near the breakout time to obtain a flatness in the prompt duration of LGRBs, which is by definition (2) the same as the engine activity time at $t_\gamma > t_\mathrm{b}$. Alternatively, we can interpret the plateau in the duration distribution of LGRBs as a constraint on the shape of the engine activity time, *under the assumption* that the prompt gamma-emission duration precisely reflects the engine activity time at $t_\gamma > t_\mathrm{b}$, as proposed in Bromberg, Nakar & Piran (2011); Bromberg et al. (2012). In either case, the plateau in the duration distribution of LGRBs does not appear to serve as an observational imprint of the Collapsar model.

We further question any physical origins of the observed plateau by showing that plateaus are ubiquitous in the short tails of statistical distributions with strictly positive support (e.g., Figure 2) and frequently result from a combination of sample incompleteness with the highly positively-skewed nature of such distributions (on natural axes). Even where the intrinsic duration distribution of LGRBs does not exhibit a plateau-behavior in its short tail, we show that its convolution with a redshift distribution can create observed duration distributions that exhibit plateau-like behavior. The presence and extent of the plateaus is further significantly enhanced if SGRBs mix with and *contaminate* the observed duration distribution of LGRBs as is the case with all major GRB catalogs. An example of a perfect plateau resulting from such contamination is depicted in Figure 4a.

To resolve the sample *contamination* problem and minimize the impact of SGRBs duration distribution on the observed plateau in the duration distribution of LGRBs, Bromberg et al. (2012) also restrict their analysis only to soft LGRBs in the BATSE catalog. This is done by remov-



(a) (b) (c)

Figure 4. BATSE-detectable samples of 600 SGRBs and 1400 LGRBs are randomly generated from our respective Monte Carlo universes. In plot **(a)**, SGRBs are represented by the blue bins and LGRBs by the red bins, where each bin is the 50th percentile value of 10,000 synthetic detections. The solid blue and red lines are log-normal fits to the bins in the pre-transformed space. These two fits are summed to produce the solid magenta line, which is multiplied by a factor of 10 to offset it for clarity. The dotted gray lines represent the 90% confidence interval for each binned distribution. Plot **(b)** shows the distribution of observed Swift redshifts in linear space. Lastly, plot **(c)** shows the redshift distribution transformed in the same manner as the duration distribution throughout this manuscript. After performing the transformation as described in Bromberg et al. (2012), the resulting plot displays a plateau in the log-log space although there is no apparent physical origin.

ing any events with a hardness ratio [2] above 2.6. This artificial cutoff preferentially excludes SGRBs from the duration histogram and significantly extends the observed plateau of LGRBs to more than twice the original length. However, in contrast to the arguments of Bromberg et al. (2012), this plateau extension in the population of soft LGRBs has no connection with the Collapsar interpretation of the plateau. It is merely an artifact of further censorships and sample-incompleteness caused by the exclusion of an arbitrarily-chosen subset of data. To illustrate this phenomenon in effect, we follow Shahmoradi (2013b); Shahmoradi & Nemiroff (2015); Osborne, Shahmoradi & Nemiroff (2020) to fit the BATSE catalog data with a comprehensive model for the duration, spectral peak energy, peak luminosity, and isotropic energy of GRBs. Notably, we assume that the duration distributions of both LGRBs and SGRBs follow LogNormal, making no assumption on the existence of plateaus in the duration distributions. Once the fitting is performed, we follow the prescription of Bromberg et al. (2012) to remove the observed events from our Monte Carlo Universe with hardness ratios larger than 2.6. Figure 5 compares the resulting duration histogram for the soft population of LGRBs with the original histogram from the Monte Carlo Universe.

Firstly, plateaus appear in the duration distributions of both LGRBs and SGRBs without even requiring their existence in the model. Secondly, the LGRB plateau extends to about two orders of magnitude when we follow the prescription of Bromberg et al. (2012) to exclude short hard bursts from the histogram. This plateau extension, while purely statistical in its nature, is on par with the reported extension Bromberg et al. (2012) found in the BATSE catalog data.

The specific binning approach used to construct histograms of data also appear to impact moderately to significantly the strength and extent of any plateau in the short

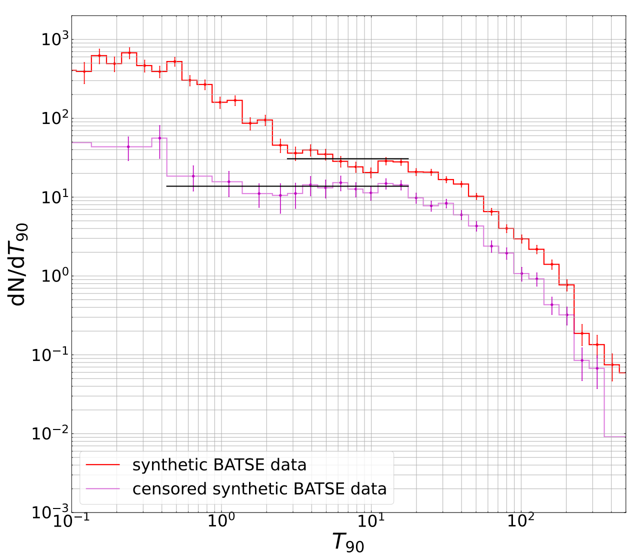


Figure 5. An illustration of the impact of excluding SGRBs from the duration distribution on the observed plateau of LGRBs. The original plateau in the red histogram and the extension of it by removing SGRBs in the magenta histogram are purely statistical (resulting from the LogNormal fits to data as depicted in Figure 4a) and have no connections to the Physics of GRBs or Collapsars whatsoever.

[2] The hardness ratio is defined as the ratio of fluence between BATSE energy channels. In this case, channels 3 (100-300 keV) and 2 (50-100 keV)

tails of distributions. This binning effect is well illustrated in Figures 2e, 2f, and 2g. All of the above arguments point to a non-physical origin for the observed plateau in the duration distribution of LGRBs. In fact, the distributions of other observational properties of GRBs (e.g., the observed redshift distribution as seen in Figure 4c) also exhibit plateaus without any apparent physical origins.

The plateau emerging within the LGRB duration distribution is not unique and can be seen in the population of SGRBs as well. Unlike the population of LGRBs, the decline in the short tail of the duration distribution of SGRBs is readily seen. This decline in the short tail actually offers a hint as to why we don't see such a fall in the short tails of LGRBs duration distribution. Unlike the case for LGRBs, there is no additional distribution which "covers" this decline in the SGRB population. The existence of such a plateau in the SGRB duration distribution is hard to reconcile with the non-Collapsar origin of SGRBs. Moharana & Piran (2017) propose a similar prompt emission mechanism to that of LGRBs (by requiring the SGRB jet has to drill through an envelope) to explain the non-Collapsar plateau seen in the duration distribution of SGRBs. By contrast, the statistical arguments we presented in this manuscript offer a natural explanation for the presence of plateaus in the duration distributions of both GRB populations without recourse to any physical arguments and origins of GRBs. The fact that a wide variety of statistical distributions fit the duration distributions of GRBs equally well as we demonstrated in this manuscript further corroborates the findings of Ghirlanda et al. (2015); Salafia et al. (2020) and serve as reminders to exercise caution in attributing the observed plateaus in the duration distributions of GRBs to their physics.

In sum, we have presented an alternative equally-plausible purely-statistical origin for the observed plateaus in the duration distributions of LGRBs and SGRBs. Our analysis further signifies the relevance and importance of selection effects and data censorship (e.g., Petrosian & Lee 1996; Lloyd & Petrosian 1999; Petrosian, Lloyd-Ronning & Lee 1999; Lloyd, Petrosian & Mallozzi 2000; Hakkila et al. 2003; Band & Preece 2005; Nakar & Piran 2004; Butler et al. 2007; Shahmoradi & Nemiroff 2009; Butler, Kocevski & Bloom 2009; Butler, Bloom & Poznanski 2010; Shahmoradi & Nemiroff 2011a,b; Shahmoradi 2013a; Dainotti et al. 2015; Petrosian, Kitanidis & Kocevski 2015; Coward et al. 2015; Dainotti & Amati 2018; Osborne, Shahmoradi & Nemiroff 2020; Osborne, Bagheri & Shahmoradi 2021; Dainotti et al. 2021; Tarnopolski 2021) in data-driven studies of the Physics of GRBs.

5 DATA AVAILABILITY

All of the data used in this letter as well as the Matlab and Python code used for our analysis can be found here: `https://github.com/cdslaborg/CollapsarSignature`.

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