Exploring the Landscape of Shock Breakout Spectra:

Rapid Thermalization and a New Breakout Regime

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Abstract

The first light that escapes from a supernova explosion is the shock breakout emission, which produces a bright flash of UV or X-rays. Standard theory predicts that the shock breakout spectrum will be a blackbody if the gas and radiation are in thermal equilibrium, and a Comptonized free-free spectrum if not. Using recent results which suggest that thermalization takes place faster than previously thought, we show that another breakout scenario is possible in which the gas and radiation are initially out of equilibrium, but the time to reach equilibrium is shorter than the light-crossing time of the system. In this case, the observed spectrum differs significantly from the standard expectation, as light travel time effects smear the spectrum into a multi-temperature blend of blackbody and free-free components. Including this regime enables a complete categorization of possible shock breakout spectra into five distinct types; we explore the necessary conditions to obtain each type. The scenario with coexisting free-free and blackbody components may be relevant for blue supergiants, or for fast shocks ($v_{\rm sh}\approx0.1c$) in extended envelopes or circumstellar media. We consider an application of this novel breakout scenario to the low-luminosity gamma-ray burst GRB 060218.

Five Shock Breakout Scenarios

- Shock breakout occurs in the outer parts of a star or CSM, at a location called the ‘breakout layer’ where the condition $\tau = c/v_{\rm sh}$ is satisfied.
- There are **three important timescales** which affect the shock breakout spectrum in the planar phase (e.g., Faran & Sari 2019, Katz et al. 2010):
  - $t_{\rm bo}$: the dynamical time of the breakout layer (also its diffusion time)
  - $t_{\rm eq}$: the time for the gas and radiation to reach thermal equilibrium
  - $t_{\rm lc}$: the light-crossing time of the system, i.e. R/c
- The duration of the breakout is set by max($t_{\rm bo}$, $t_{\rm lc}$); after this it enters a phase of planar adiabatic expansion and cooling.
- The observed spectrum is Comptonized free-free emission for $t < t_{\rm eq}$, and blackbody emission for $t > t_{\rm eq}$, smeared by light travel time if $t_{\rm lc} > t_{\rm bo}$.
  - If thermal equilibrium holds from the beginning, $t_{\rm eq} = t_{\rm bo}$.
- Then there are **five possible scenarios**:
  I. $t_{\rm eq} = t_{\rm bo} < t_{\rm lc}$. The duration of the breakout is $t_{\rm lc}$. The spectrum is a blackbody from the beginning.
  II. $t_{\rm bo} < t_{\rm eq} < t_{\rm lc}$. The duration of the breakout is $t_{\rm lc}$. The spectrum is initially a free-free spectrum, but it becomes a blackbody *while the breakout is ongoing*. Due to light travel-time effects, the spectrum is a convolution of blackbody and free-free components for $t_{\rm eq} < t < t_{\rm lc}$.
  III. $t_{\rm bo} < t_{\rm lc} < t_{\rm eq}$. The duration of the breakout is $t_{\rm lc}$. During the breakout, the spectrum is a free-free spectrum; it becomes a blackbody later.
  IV. $t_{\rm lc} < t_{\rm eq} = t_{\rm bo}$. The duration of the breakout is $t_{\rm bo}$. The spectrum is a blackbody from the beginning.
  V. $t_{\rm lc} < t_{\rm bo} < t_{\rm eq}$. The duration of the breakout is $t_{\rm bo}$. During the breakout, the spectrum is a free-free spectrum; it becomes a blackbody later.
- An example of the spectral evolution in each case is shown in Figure 1.

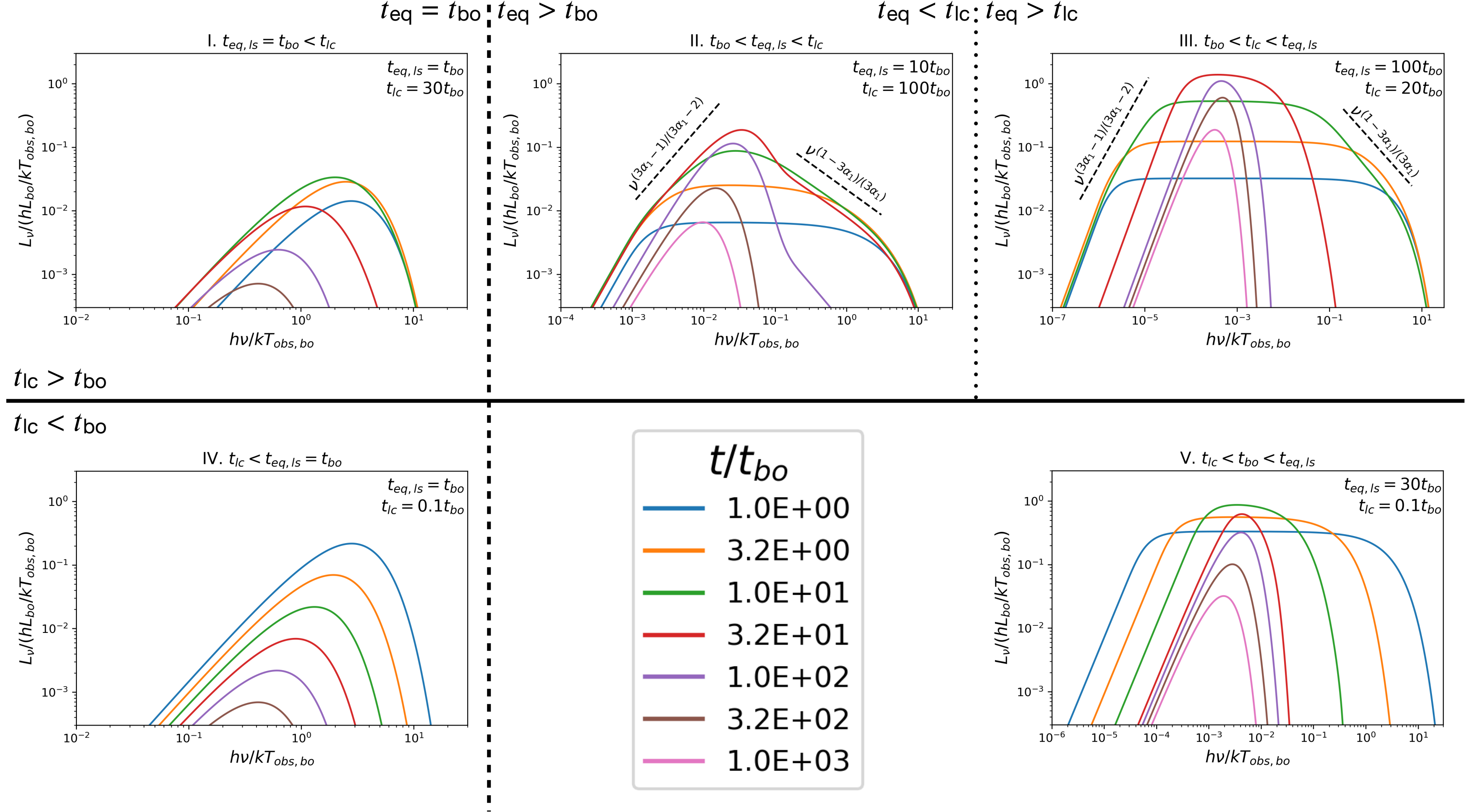

Figure 1. Spectral evolution for the five shock breakout scenarios. To the right of the black dashed line, $t_{\rm eq} > t_{\rm bo}$ and the spectrum is free-free emission at early times. Above the solid black line, $t_{\rm lc} > t_{\rm bo}$ and the early-time spectrum is smeared out by light travel time effects. Note the complicated spectrum that occurs in the top-middle panel, where $t_{\rm bo} < t_{\rm eq} < t_{\rm lc}$ so that blackbody and free-free components are convolved together by light travel time effects. Negligible Comptonization is assumed for simplicity.

Five Possible Types of Spectra

- Near peak light (i.e., at $t \approx$ max($t_{\rm lc}$, $t_{\rm bo}$)), each shock breakout scenario exhibits a different type of spectrum. The **five possible spectral types** are:
  i. A multi-temperature blackbody, smeared by light travel time
  ii. A complicated spectrum where blackbody and free-free components are both present, and both are smeared by light travel time
  iii. A multi-temperature free-free spectrum, smeared by light travel time
  iv. A single-temperature blackbody
  v. A single-temperature free-free spectrum
- In Scenario I, the spectrum is Type i at peak light, and so forth
- The spectrum may change from one type to another over time (see Figure 2)

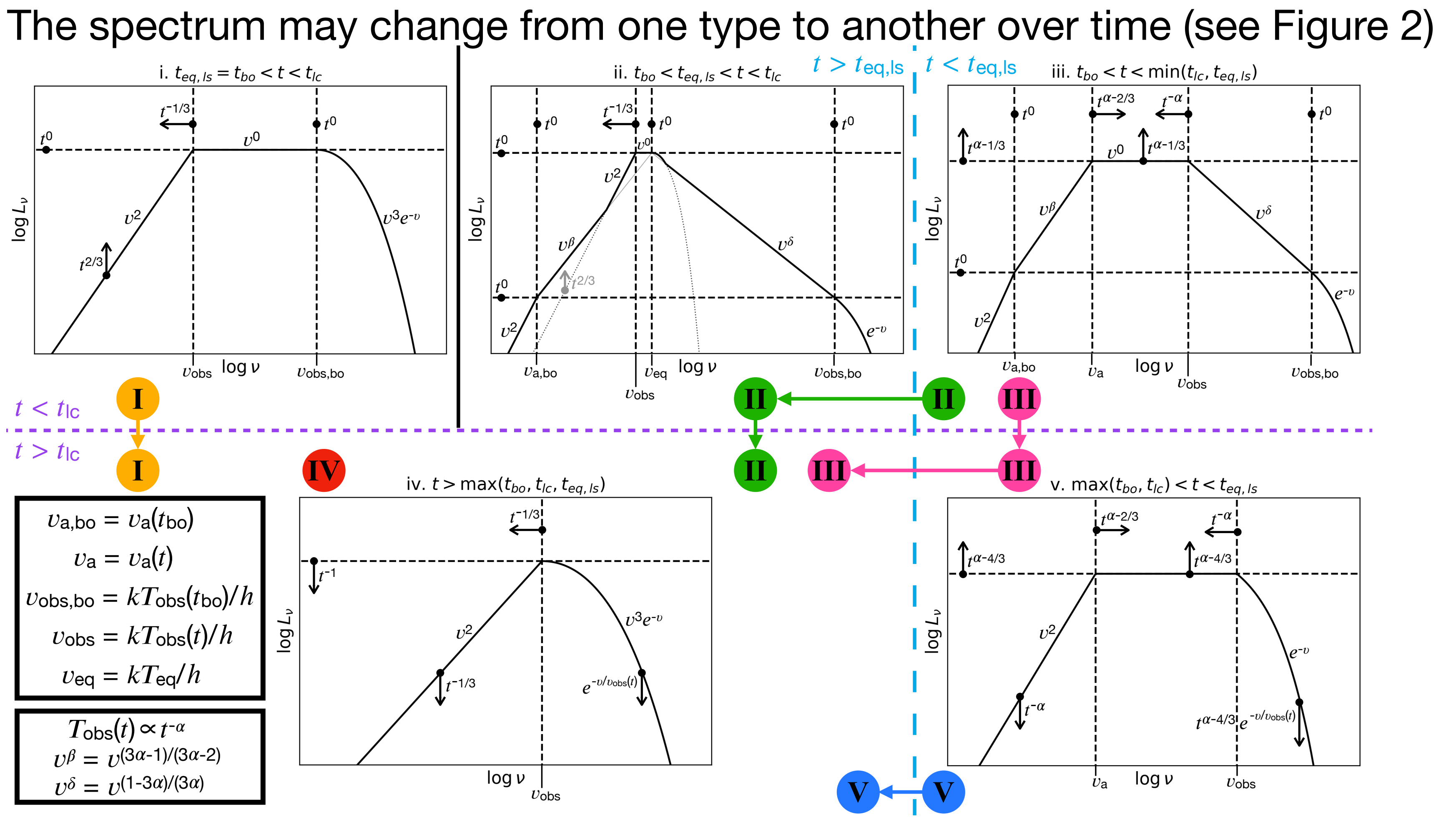

Figure 2. The five possible types of spectra which can occur during the planar phase of shock breakout. The luminosity is assumed to vary as $t^{-4/3}$ for $t < t_{\rm eq}$, and the observed temperature to vary as $t^{-\alpha}$ for $t < t_{\rm eq}$, and as $t^{-1/3}$ for $t < t_{\rm eq}$ (e.g., Nakar & Sari 2010, Faran & Sari 2019). The evolution of the spectrum in scenarios I-V is shown by the colored tokens; crossing the cyan dashed line corresponds to a transition at $t = t_{\rm eq}$, while crossing the purple short-dashed line corresponds to a transition at $t = t_{\rm lc}$.

Which Scenario is Relevant?

- For a given system, the relevant scenario depends on:
  - R: the breakout radius
  - $\rho_{\rm bo}$: the breakout layer’s density
  - $v_{\rm bo}$: the shock velocity at breakout
  - n: the power-law index of the outer density profile, $\rho \propto (1-r/R)^n$
- $\rho_{\rm bo}$ and $v_{\rm bo}$ in turn depend on the explosion energy E and the mass of the breakout medium, M.
- Each breakout scenario corresponds to a distinct region of ($\rho_{\rm bo}$,$v_{\rm bo}$,R,n) parameter space, as shown in Figure 3.

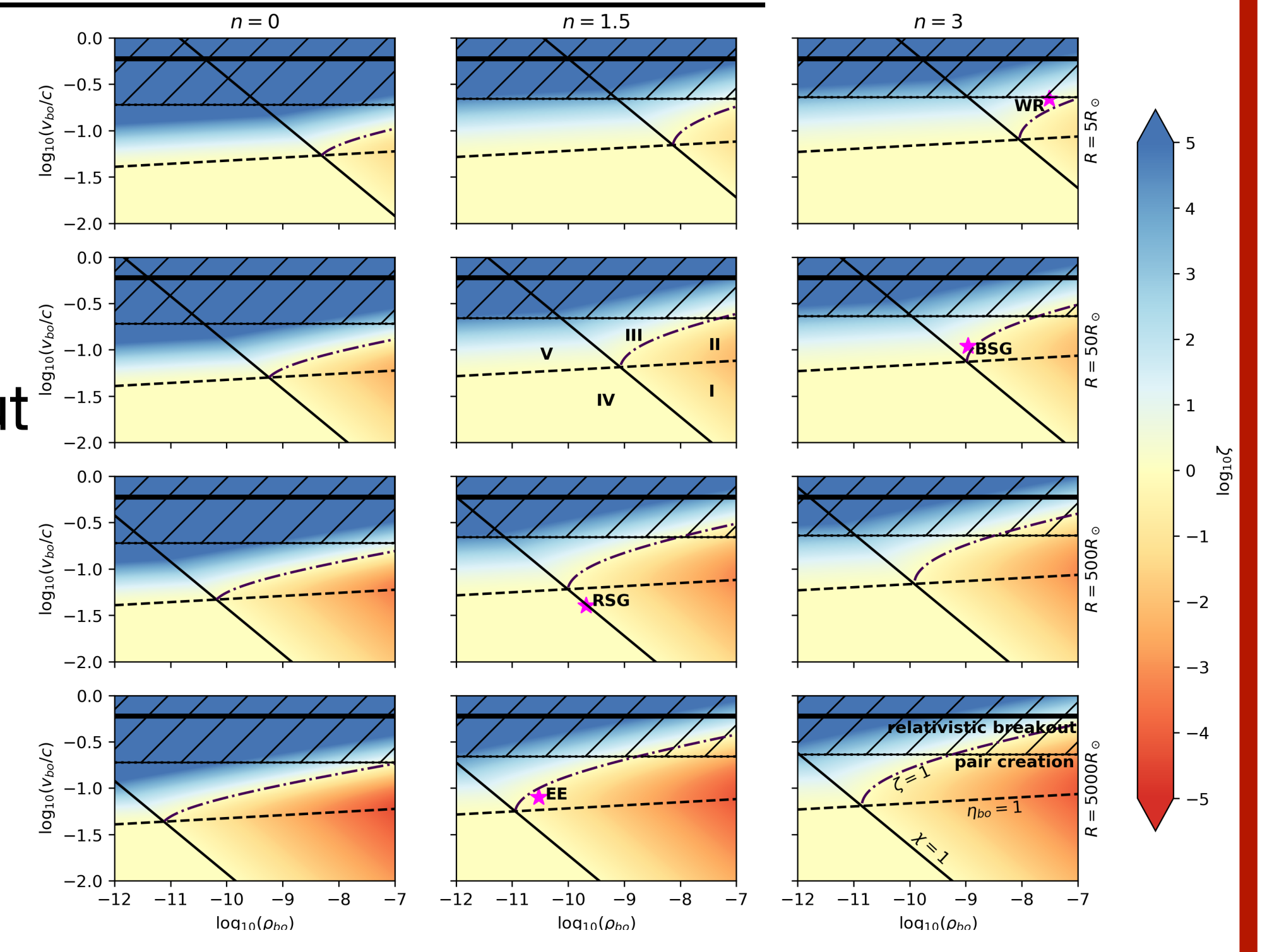

Figure 3. Breakout scenarios I-V as regions in ($\rho_{\rm bo}$,$v_{\rm bo}$,R,n) parameter space. Color indicates the value of $t_{\rm eq}$/max($t_{\rm bo}$,$t_{\rm lc}$). Solid, dashed, and dash-dotted lines indicate the conditions $t_{\rm lc} = t_{\rm bo}$, $t_{\rm lc} = t_{\rm bo}$, and $t_{\rm lc} = t_{\rm bo}$, respectively. In the hatched region the breakout is relativistic and our model is invalid.

Application to GRB 060218

- The peculiar low-luminosity GRB 060218 showed **both thermal and power-law components** in its X-ray spectrum (e.g., Campana et al. 2006, Ghisellini et al. 2007, Kaneko et al. 2007).
- It also has an early optical peak implying an **extended, low-mass envelope** (e.g., Nakar 2015, Irwin & Chevalier 2016). The inferred envelope properties imply **the breakout could be in region II** of Figure 3.
- We model this event as a Scenario II breakout and find a reasonable fit to observations (see Figure 4).

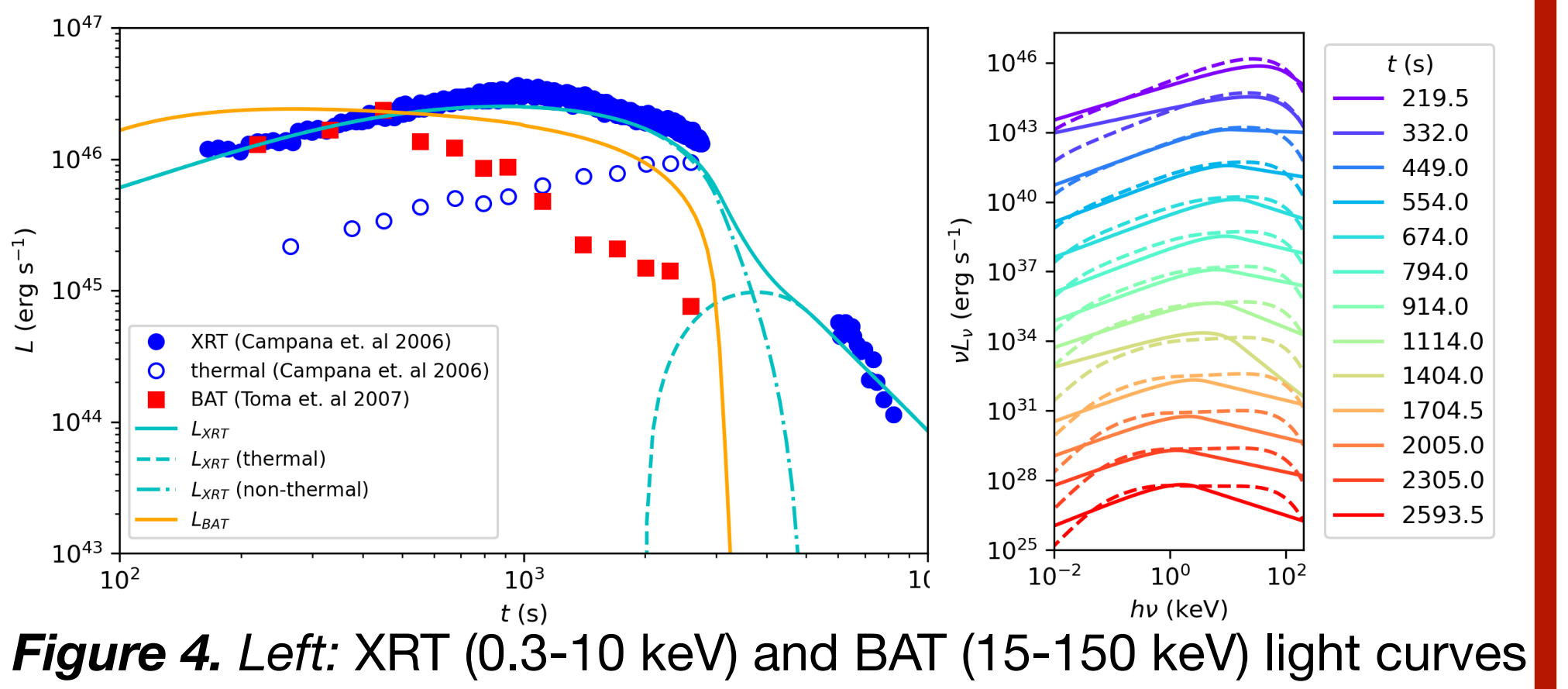

Figure 4. *Left:* XRT (0.3-10 keV) and BAT (15-150 keV) light curves calculated in a Scenario II breakout model with (E,M,R,n)=($10^{50.5}$ erg, 10^{-1} $M_{\rm sun}$, $10^{13.5}$ cm, 0), compared to observations. *Right:* X-ray spectra computed with the same model (dashed), compared to the spectra reported by Toma et al. (solid).

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