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Binary-driven HyperNovae and their nested late X-ray emission

Giovanni Battista Pisani[ab], **Remo Ruffini**[abcd], **Marco Muccino**[ab], **Carlo Luciano Bianco**[ab], **Maxime Enderli**[ac], **Milos Kovacevic**[ac], **Ana Virginia Penacchioni**[de], **Jorge Armando Rueda**[abd], **Yu Wang**[ab], **Elena Zaninoni**[d], **Luca Izzo**[ab]

[a]*Dip. di Fisica, Sapienza Università di Roma, Piazzale Aldo Moro 5, I-00185 Roma, Italy*
[b]*ICRANet, Piazza della Repubblica 10, I-65122 Pescara, Italy*
[c]*Université de Nice Sophia Antipolis, Nice, CEDEX 2, Grand Chateau Parc Valrose*
[d]*ICRANet-Rio, CBPF, Rua Dr. Xavier Sigaud 150, Rio de Janeiro, RJ, 22290-180, Brazil*
[e]*NPE, Av. dos Astronautas, 1758, Sao José dos Campos, SP, Brazil*

E-mail: gb.pisani@icranet.org

Binary-driven hypernova (BdHN) paradigm has been recently proposed to explain the connection between supernovae (SNe) and long GRBs with a total isotropic energy $E_{iso} > 10^{52}$ erg. We found a striking common behaviour in the late time ($t > 2 \times 10^4$ s) X-ray luminosity light curve within GRBs wich fulfill the BdHN paradigm. We currently use such scaling law as a distance indicator for GRBs with no measured redshift which fit the BdHN paradigm. The identification as a BdHN of GRB 090423 at observed $z = 8.2$ strongly suggests that our scaling law could be valid up to very high distances. Furthermore, the common behaviour observed in the X-ray luminosity light curves of BdHNe hides an even deeper feature, namely a "nested" structure, which possibly originates from decays of ultra-heavy nuclei produced by r-processes or from type-I and type-II Fermi mechanisms.

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1. Binary-driven HyperNova

Binary-driven hypernova (BdHN) paradigm has been recently introduced in order to explain the supernovae (SNe) association to long GRBs with a total isotropic energy $E_{iso} > 10^{52}$ erg [1,2,3,4,5,6]. A tight evolved binary system composed of a FeCO-core and a neutron star (NS) is assumed as progenitor. As the FeCO-core undergoes SN explosion, the accretion of a part of its ejecta on the companion NS induces the gravitational collapse of the NS to a black hole (BH) and concurrently the GRB emission occurs. Four distinct emission processes characterize such a system (see Figure 1):

- Episode 1: corresponds to the onset of the FeCO-core SN explosion, creating a newly born NS (νNS). Part of the SN ejecta triggers an hypercritical accretion process onto the NS companion. This leads to an emission, visible in γ–rays, preceding the GRB and presenting a spectrum with a non-relativistically expanding thermal component plus an extra power-law.
- Episode 2: occurs when the companion NS reaches its critical mass and collapses to a BH, emitting a GRB with $\Gamma \sim 100$–1000, following the fireshell model.
- Episode 3: it encompasses both X-ray and GeV prolonged emissions, coming from the interaction between the expanding SN remnant, the νNS, and the BH.
- Episode 4: corresponds to the optical SN emission due to the Nichel decay occurring $\sim$ 10–15 days after the GRB explosion in the cosmological rest-frame. It is only detectable for sources at $z < 1$, in view of the limitations of the current optical telescopes.

2. A common behaviour in the late Episode 3

We selected a Golden Sample (GS) of long GRBs fulfilling the BdHN paradigm: with measured redshift, with $E_{iso} > 10^{52}$ erg, with evidence of SN association, showing a thermal component in the first part of the γ–ray emission (Episode 1), and showing in their X-ray light curve the typical swallow phase followed by the late power-law decay. We found a striking common behaviour in the late time ($t > 2 \times 10^4$ s) X-ray luminosity light curve (Episode 3) of these sources, which is independent from the E_{iso} and the early behaviour of the X-ray light curve (see Figure 2 and, for details, [7]).

3. A new distance indicator

We currently use the scaling law found in [7] (see Figure 2) as a distance indicator for GRBs with no measured redshift which fit the BdHN paradigm. We can infer the value of the redshift of a GRB just some hours after its explosion imposing the overlap of its late time X-ray luminosity light curve with the prototypical one of GRB 090618 [8]. This is what we have done for the two cases of GRB 101023 and GRB 110709B, for which we inferred $z = 0.9$ and $z = 0.75$ respectively (see Figure 3 and [9,10]). The recent identification as a BdHN of GRB 090423 at observed $z = 8.2$ (see Figure 4 and [11]) strongly suggests that our scaling law could be valid up to very high distances. If confirmed, this novel standard candle could be used to test the ΛCDM cosmological parameters back to $\sim$ 600 millions years after the Big-Bang.

4. The nested structure of Episode 3

The common behaviour observed in the X-ray luminosity light curves of BdHNe hides an even deeper feature, namely a "nested" structure [5], sketched in Figure 5. We found that BdHNe with brighter Episode 2 present an Episode 3 which joins earlier the late common power-law decay in X-rays. Viceversa, the low luminous BdHNe show a weaker and longer plateau phase in X-rays. In fact we found a precise anticorrelations, showed in Figure 6, between the average isotropic luminosity of Episode 2, $\langle L_{iso} \rangle$, and the luminosity of the X-ray plateau, L_a, with respect to the time of the end of the X-ray plateau, t^* [5]. The simultaneous occurrence of these features imposes very stringent constraints on any possible theoretical models. In particular, the traditional synchrotron ultra-relativistic scenario of the Collapsar jet model does not appear suitable for explaining these observational facts. We have recently pointed out the possibility of using the nuclear decay of ultra-heavy nuclei originally produced in the close binary phase of Episode 1 by r-process as an energy source of Episode 3. An additional possibility of process-generating a scale-invariant power law in the luminosity evolution and spectrum are the ones expected from type-I and type-II Fermi acceleration mechanisms. For details see [5,6].

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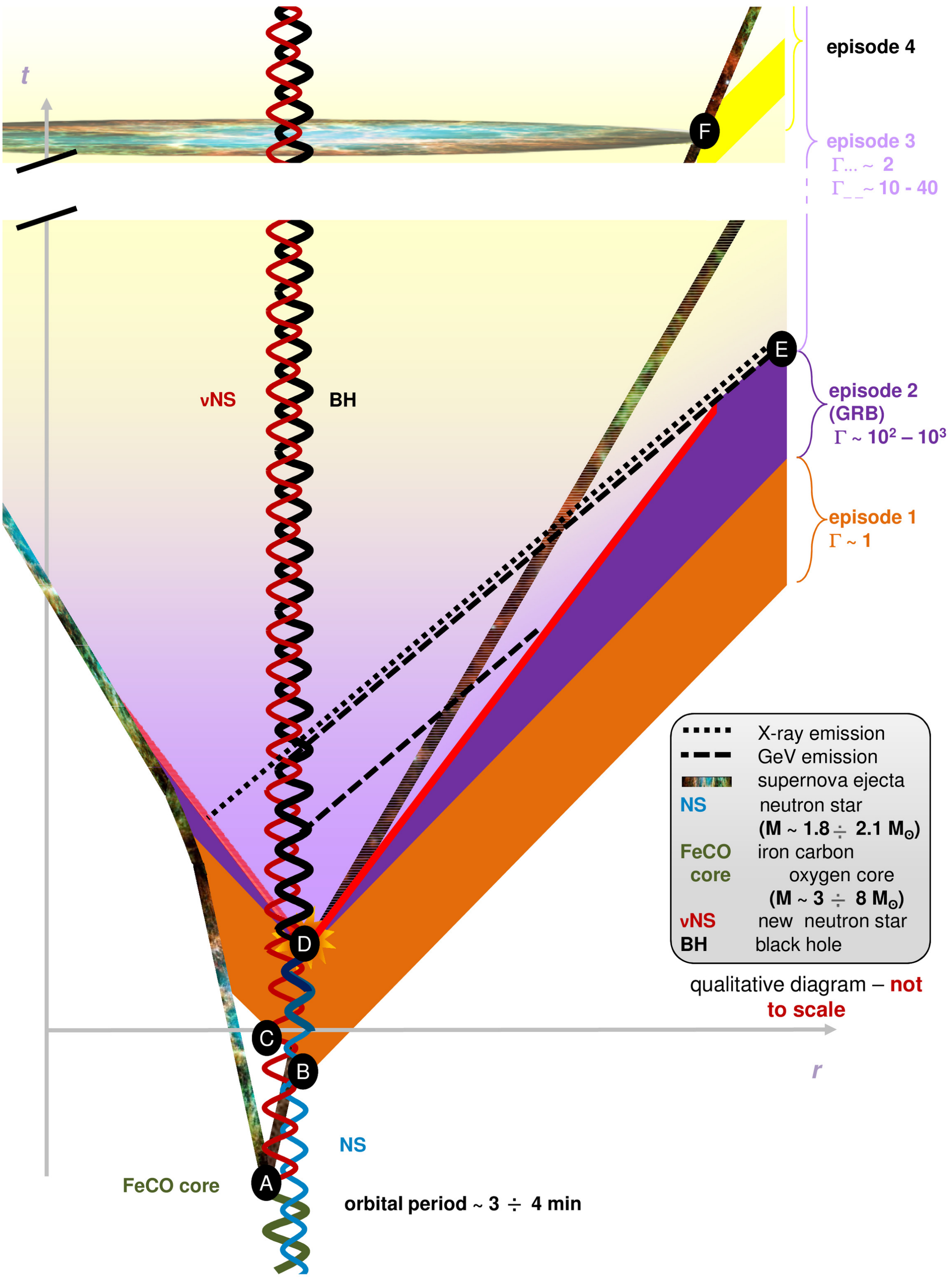

Figure 1: Spacetime diagram (not in scale) illustrating the four Episodes of the BdHN paradigm.

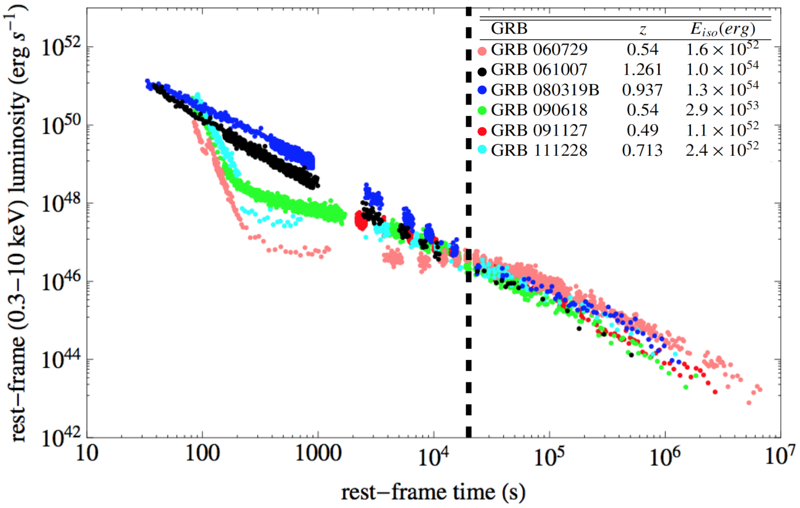

Figure 2: The striking common behaviour at late times ($t > 2 \times 10^4$ s) of the rest-frame 0.3–10 keV luminosity light curves of the GS.

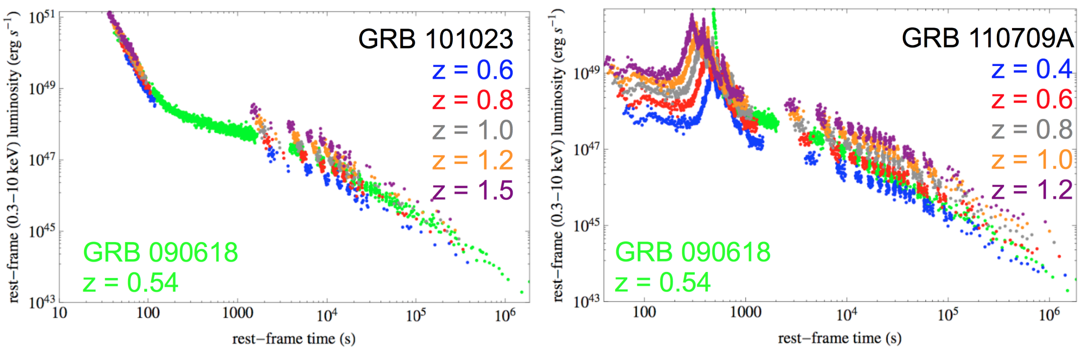

Figure 3: The X-ray luminosity light curve of GRB 101023 (left) and GRB 110709B (right), as if it was observed at different redshifts, compared with the one of GRB 090618 (green dots).

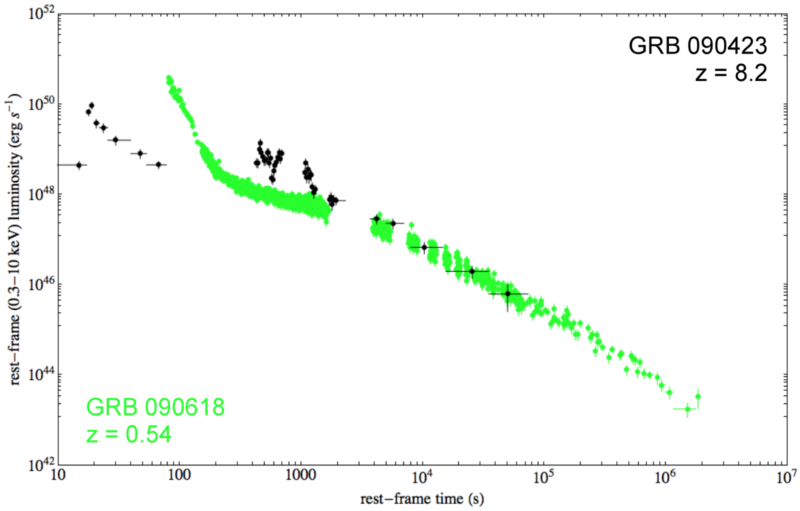

Figure 4: Behavior of the Episode 3 luminosity of GRB 090423 (black dots) compared with the prototype case of GRB 090618 (green dots).

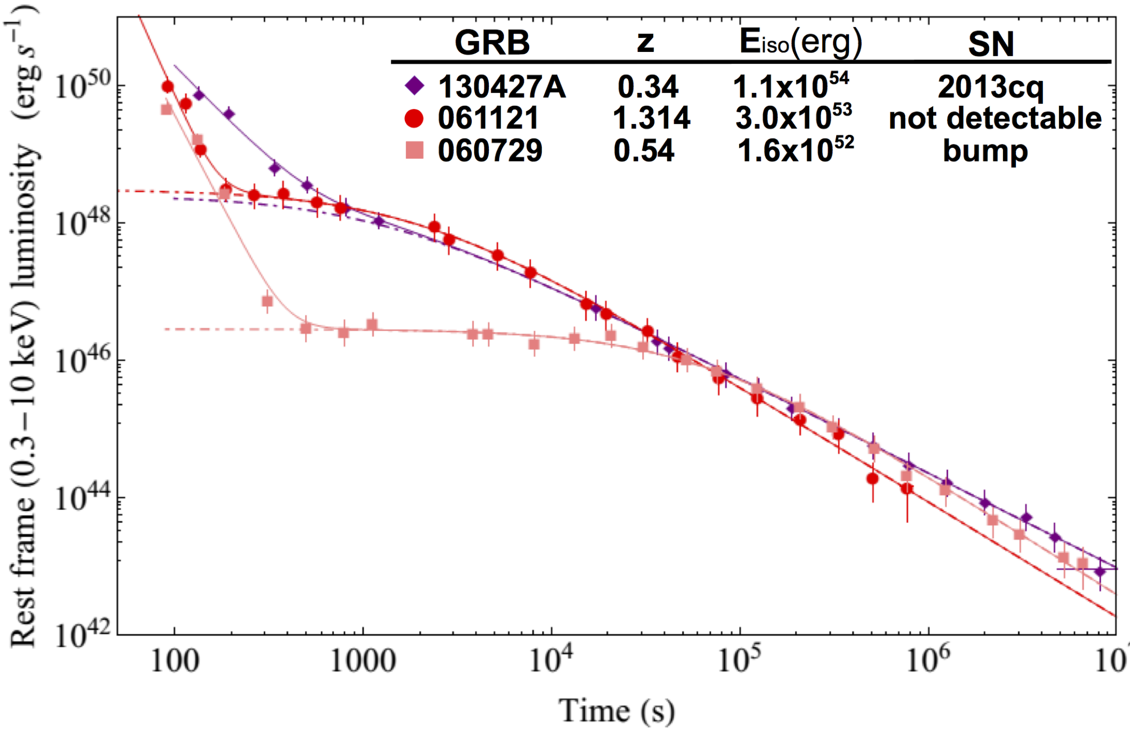

Figure 5: Rest-frame 0.3–10 keV re-binned luminosity light curves of GRB 130427A (purple), GRB 061121, and GRB 060729 (pink).

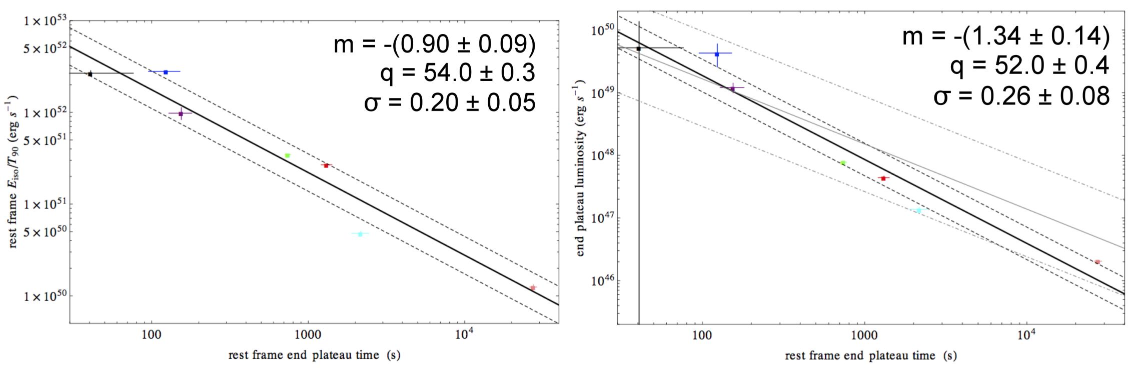

Figure 6: The $\langle L_{iso}\rangle$–t^* (left panel) and the L_a–t^* (right panel) correlations (solid black lines) and the corresponding 1σ confidence levels (dashed black lines). The considered sources are from the GS (same colors as in Figure 2) plus GRB 130427A (purple).