Supernova Models Inferred from GRBs

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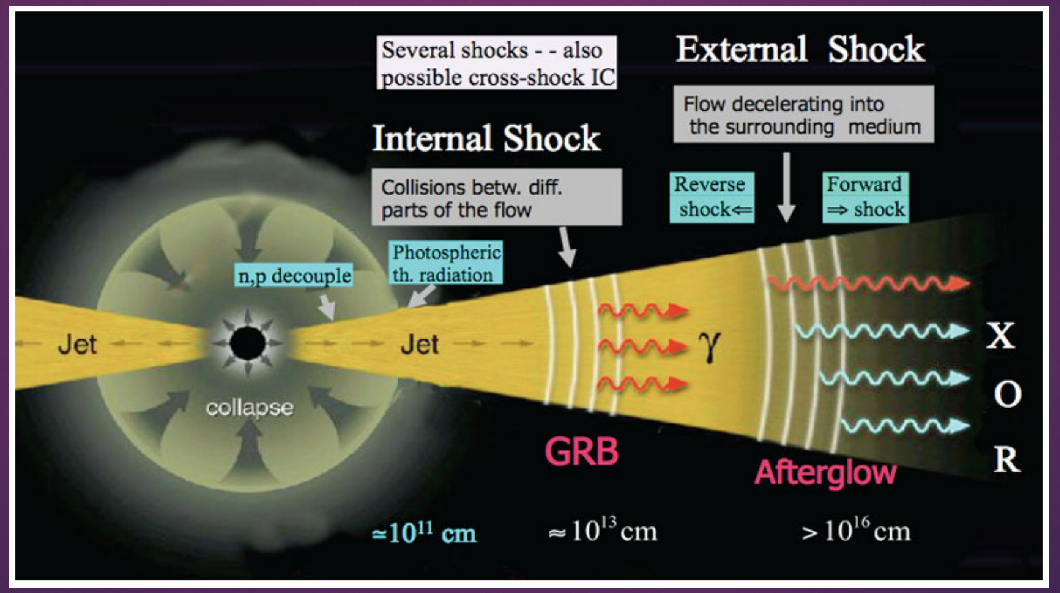
GRB Models:

The Traditional model is based on a relativistic jet, a fireball of an optically thick $e^+ e^-$ -photon-baryon plasma with bulk Lorentz factor of $\Gamma = 10^2 - 10^3$, powered by a massive disk accreting onto a black hole.

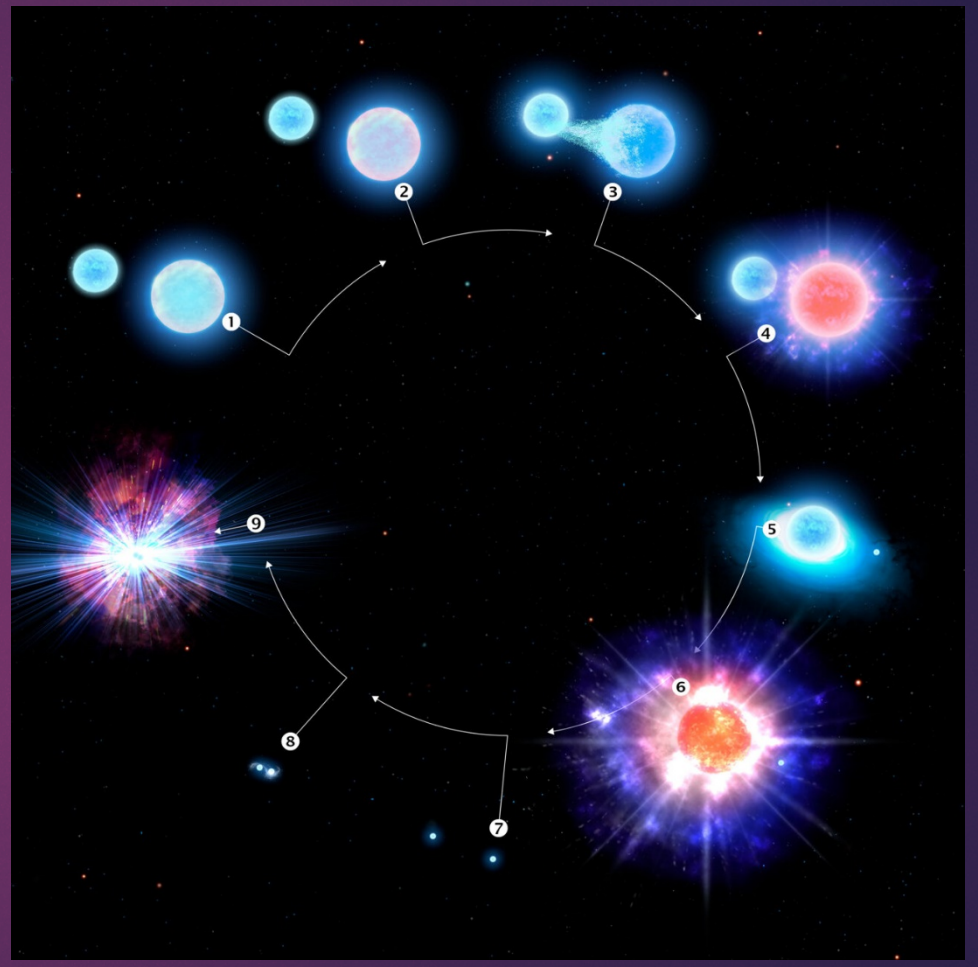


Evidence for Binary Progenitor of GRB

- All super nova associated with long GRB show similar characteristic but associated GRBs releases energetics with seven order of magnitude difference.
- Most massive stars are observed to be components of a binary system
- GRBs are associated with type Ic SNe which show lack of hydrogen and helium. The most effective mechanism to get ride of H and He layers is binary interactions.

Binary Driven Hyper nova (BdHN)

The BdHN model assumes that some long GRB progenitors are binaries composed of a CO star of mass of ~10 $M_{\odot}$ and a companion neutron star (NS) of ~ 2 $M_{\odot}$. The gravitational collapse of the CO star generates an SN explosion and creates a newborn NS (νNS) at its center. The SN ejecta drives an highly super-Eddington accretion process onto the NS companion and a fallback accretion onto the νNS.



Three type of BdHN

BdHN I
The most energetic class of long GRBs, $E_{iso} = 10^{52} - 10^{54}$ orbital period <5 min, The hypercritical accretion onto the companion NS leads it to form a Kerr BH. The NS gains a large angular momentum, $J = 10^{49}\ gcm^{-2}s^{-1}$. Examples are GRB 180720B, GRB 190114C, and GRB 130427A

BdHN II
$E_{iso} = 10^{50} - 10^{52}$, progenitor binary period of ~ 20–40 min, The NS does not form a BH. the fallback accretion leads the νNS to a slower rotation than its BdHN I counterpart. The νNS in BdHN II reaches rotation periods of ~ 10 ms, Examples of BdHN II are GRB 180728A and GRB 190829A

BDHN III
These systems explain low-luminous GRBs with an energy release of $\boldsymbol{E_{iso} = 10^{49} - 10^{50}}$ The orbital period can be as long as hours, The accretion rate onto the NS companion is negligible, and the νNS reaches the period of ~ 50–100 ms,. An example of BdHN III is GRB 171205A.

Physical phenomenon	BdHN type	GRB Episodes							
		0 (SN-rise)	I (νNS-rise)	II (NS-rise)	III (BH-rise overcritical)	IV (BH-rise undercritical)	V (BH echoes)	VI (Afterglows)	VII (SN Ic & HN)
		SN-rise (X-γ)	νNS-rise (X-γ)	NS-rise (X-γ)	UPE (X-γ)	Jetted emission (GeV)	Cavity (X-γ) HXF (X-γ) SXF (X)	X Opt. Rad.	Opt. SN & HN
CO core-collapse [a]	I,II,III	$\otimes$							
νNS accretion[b]	I,II,III		$\otimes$						
NS accretion[b]	I,II			$\otimes$					
BH QED[d]	I				$\otimes$				
BH CED[e]	I					$\otimes$			
BH disk accretion[f]	I						$\otimes$ $\otimes$ $\otimes$		
νNS synchr. + pulsar emission[g]	I,II,III							$\otimes$ $\otimes$ $\otimes$	
Nickel decay + ejecta kinetic energy[h]	I,II,II								$\otimes$
		Section 5.0	Section 5.1	Section 5.1	Section 5.2	Section 5.3	Section 5.4	Section 5.5	Section 5.6

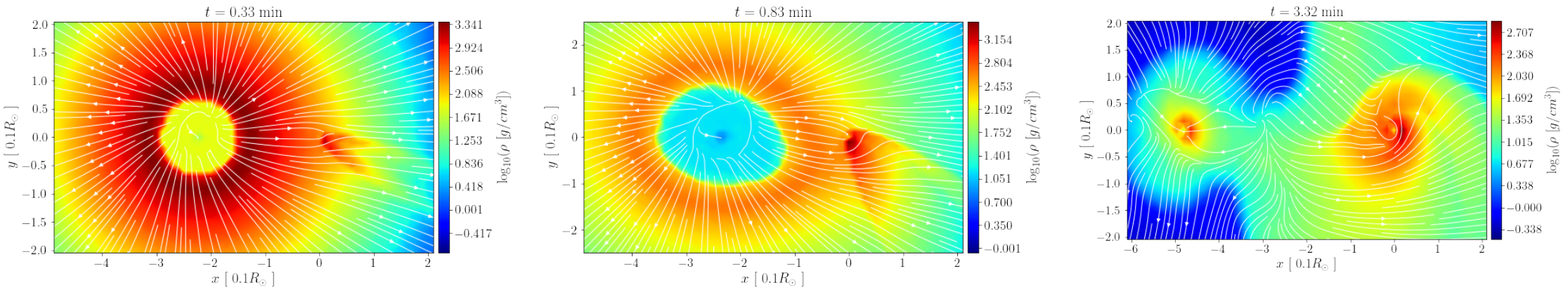
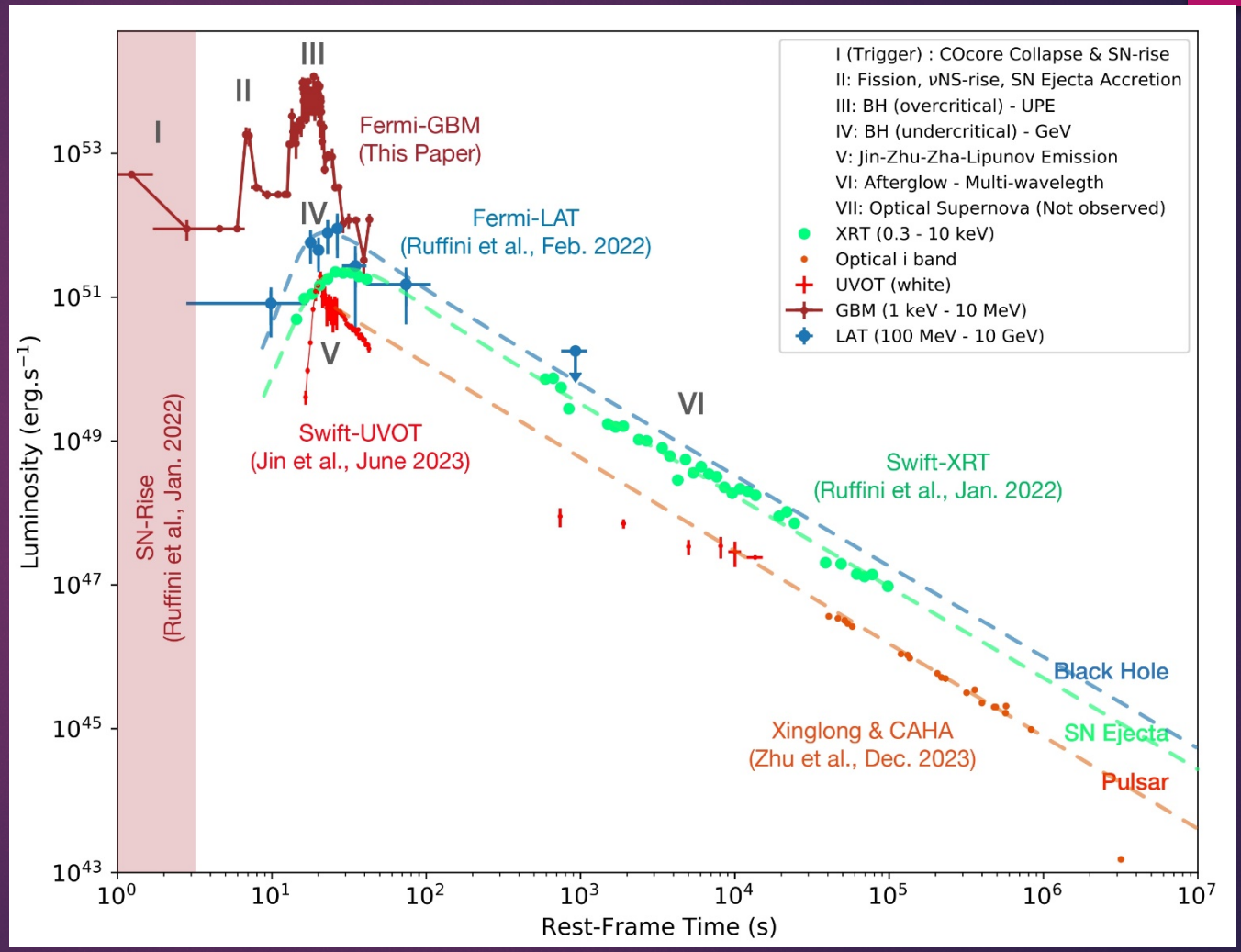
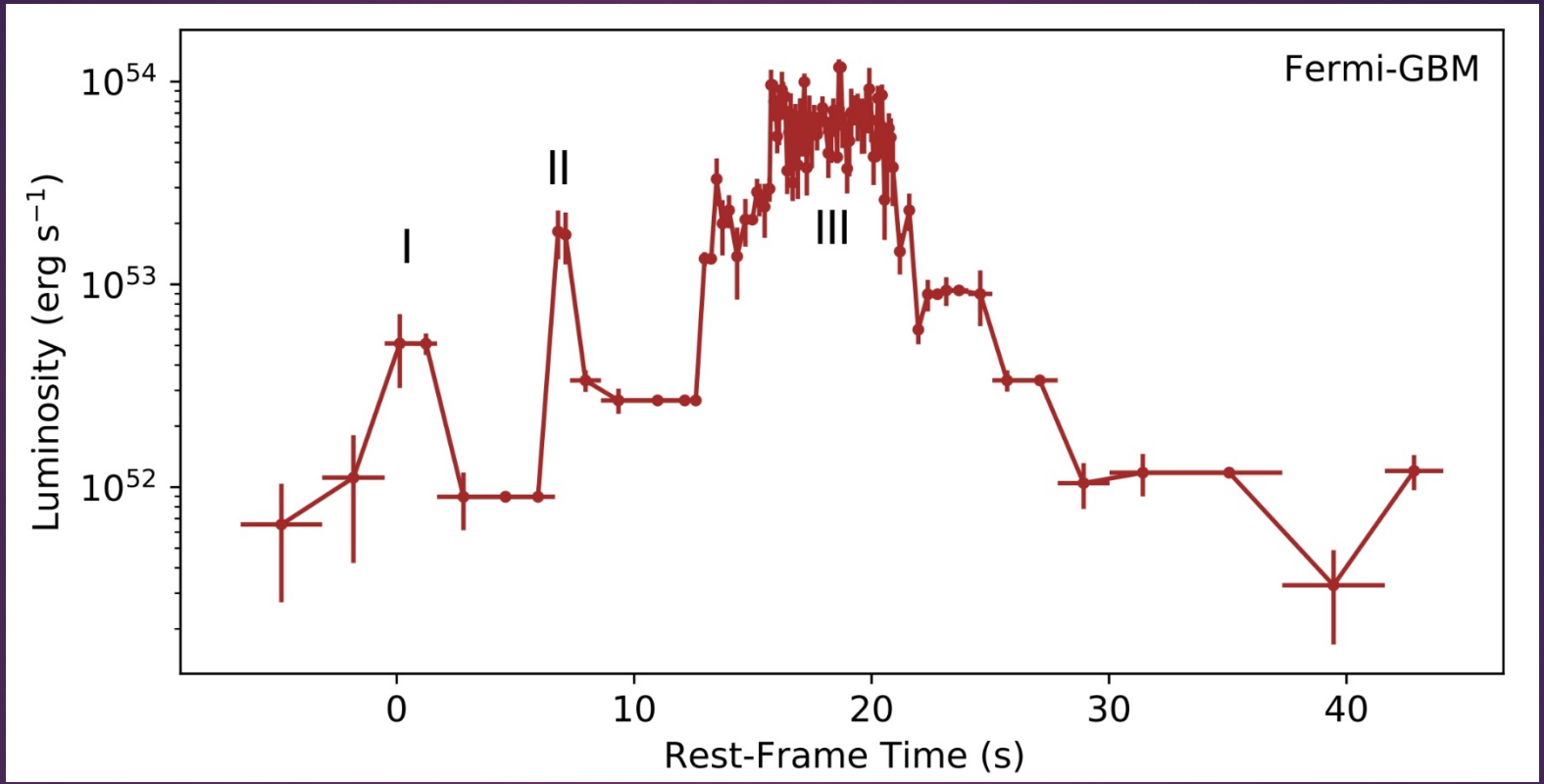


Figure 2. Binary density color map at three selected times from the SN breakout: $t = 0.32$ min (19.2 s, upper panel), $t = 0.83$ min (49.8 s, middle panel), when the NS reaches the critical mass point, and a post-collapse time, $t = 3.17$ min (190.2 s, lower panel). The white curves show the velocity field of the SN ejected material. In this simulation, the pre-SN binary is a CO core of $9M_\odot$ with a $1.4M_\odot$ NS companion. The binary orbital period is 6 minutes. The angular momentum of the NS companion at the beginning of the simulation is $J = 1.2GM_\odot^2/c$.

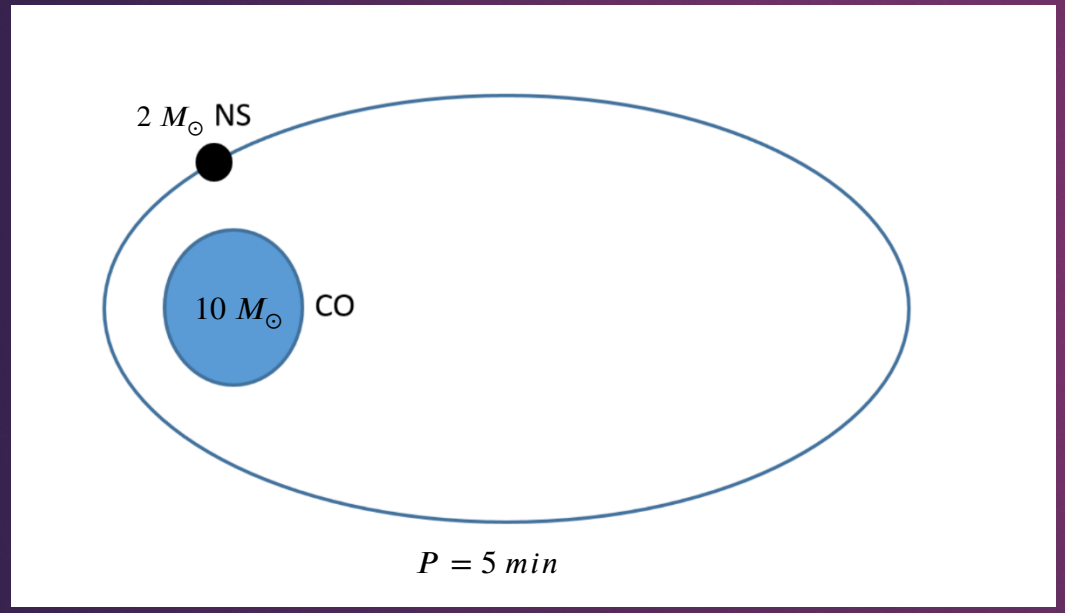
Comprehensive multi-wavelength luminosity light curve of GRB 220101A This plot combines data from Fermi-GBM (1 keV - 10 MeV, red points), Fermi-LAT (100 MeV – 10 GeV, blue points), Swift-XRT (0.3-10 keV, green points), Swift-UVOT (white band, bright red points), and ground-based optical telescopes (Xinglong & CAHA, i-band, orange points). The x-axis is rest-frame time (log scale), and the y-axis is isotropic, k-corrected luminosity (log scale). Roman numerals (I-VI) denote the BdHN episodes. Dashed lines illustrate the distinct rising and the long-term power-law decay behaviors associated with the three main emission components attributed to the Black Hole (GeV), the SN Ejecta (X-ray), and the Pulsar (Optical).

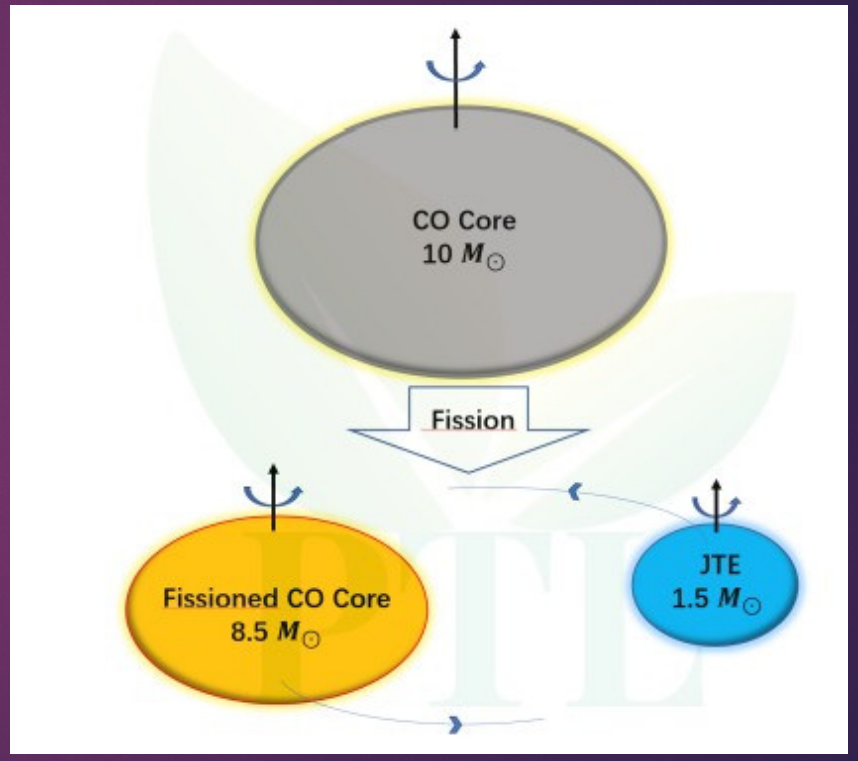




The Isotropic luminosity light-curve from Fermi-GBM of 1 keV to 10 MeV. Including the three episodes of I, II and III.

A model Based on Eccentric binary system with angular momentum transfer





Angular Momentum Transfer

$$v_p > \Omega_c R_c$$

$$\frac{\Omega_c}{\Omega} < \frac{2}{3}\frac{M}{M_c}\frac{\sqrt{(1-e_c^2)}}{g(e_c)}\left(\frac{1+e}{1-e}\right)^{\frac{3}{2}}$$

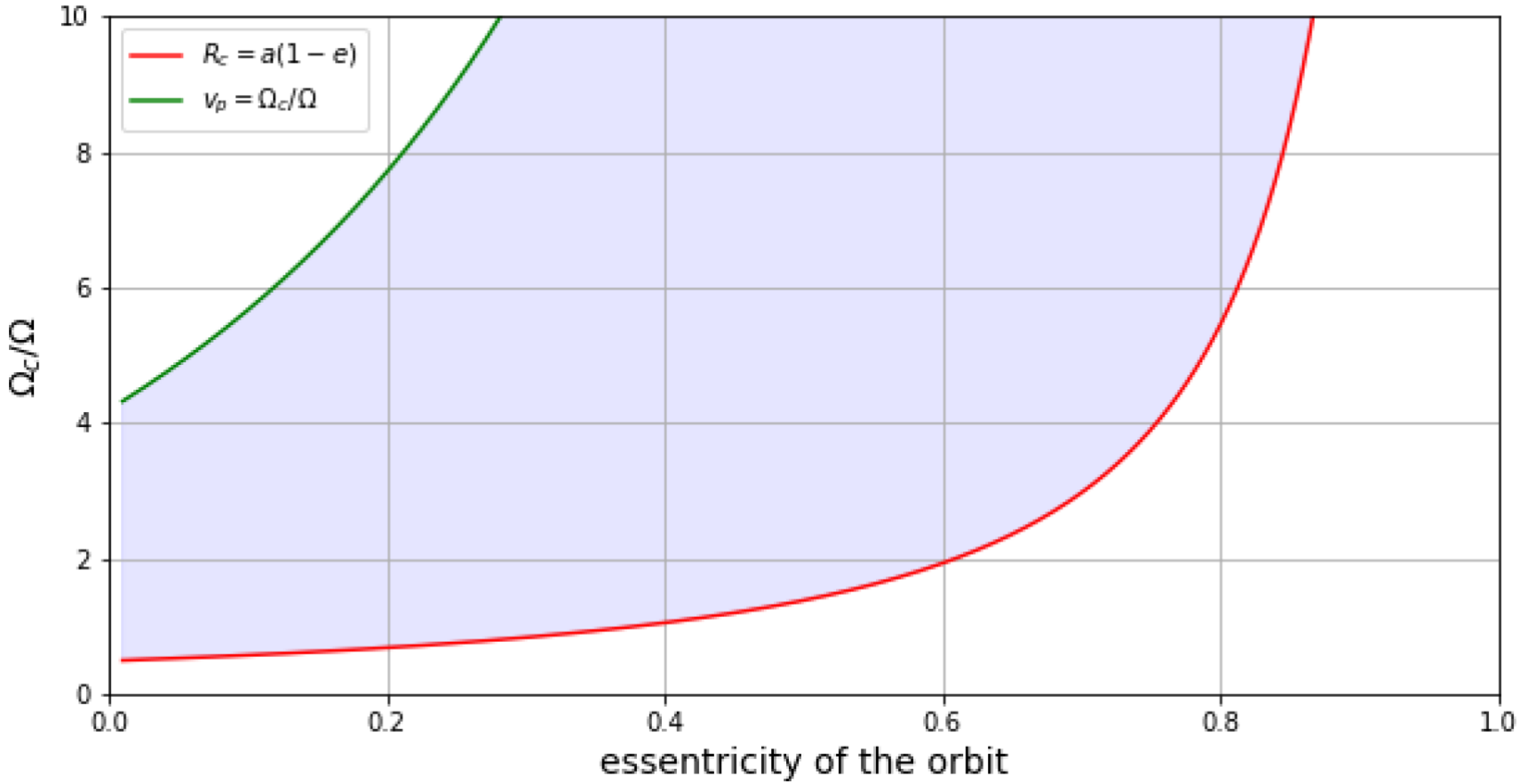
$$\frac{\Omega_c}{\Omega} < 4.44\left(\frac{1+e}{1-e}\right)^{\frac{3}{2}}$$

Preventing from collision

$$a(1-e) > R_c$$

$$\frac{\Omega_c}{\Omega} > \left(\frac{3}{2}\frac{M_c}{M}g(e_c)\right)^{\frac{1}{2}}\frac{1}{(1-e)^{\frac{3}{2}}} > \frac{0.474}{(1-e)^{\frac{3}{2}}}$$

$$g(e_c) = \frac{\sqrt{1-e_c^2}}{e_c^3}(3-2e_c^2)\sin^{-1}e_c - \frac{3(1-e_c^2)}{e_c^2}$$


$R_c = a(1-e)$
$v_p = \Omega_c/\Omega$
Ω_c/Ω
10
8
6
4
2
0
0.0
0.2
0.4
0.6
0.8
1.0
essentricity of the orbit

Conservation of Energy

$$E = E_1 + E_2 + E_{orbit}$$

$$E_i = c_3' \left(\frac{4G^2 M_i^5}{3c_1'} \right)^{\frac{1}{3}} \Omega_f^{\frac{2}{3}}$$

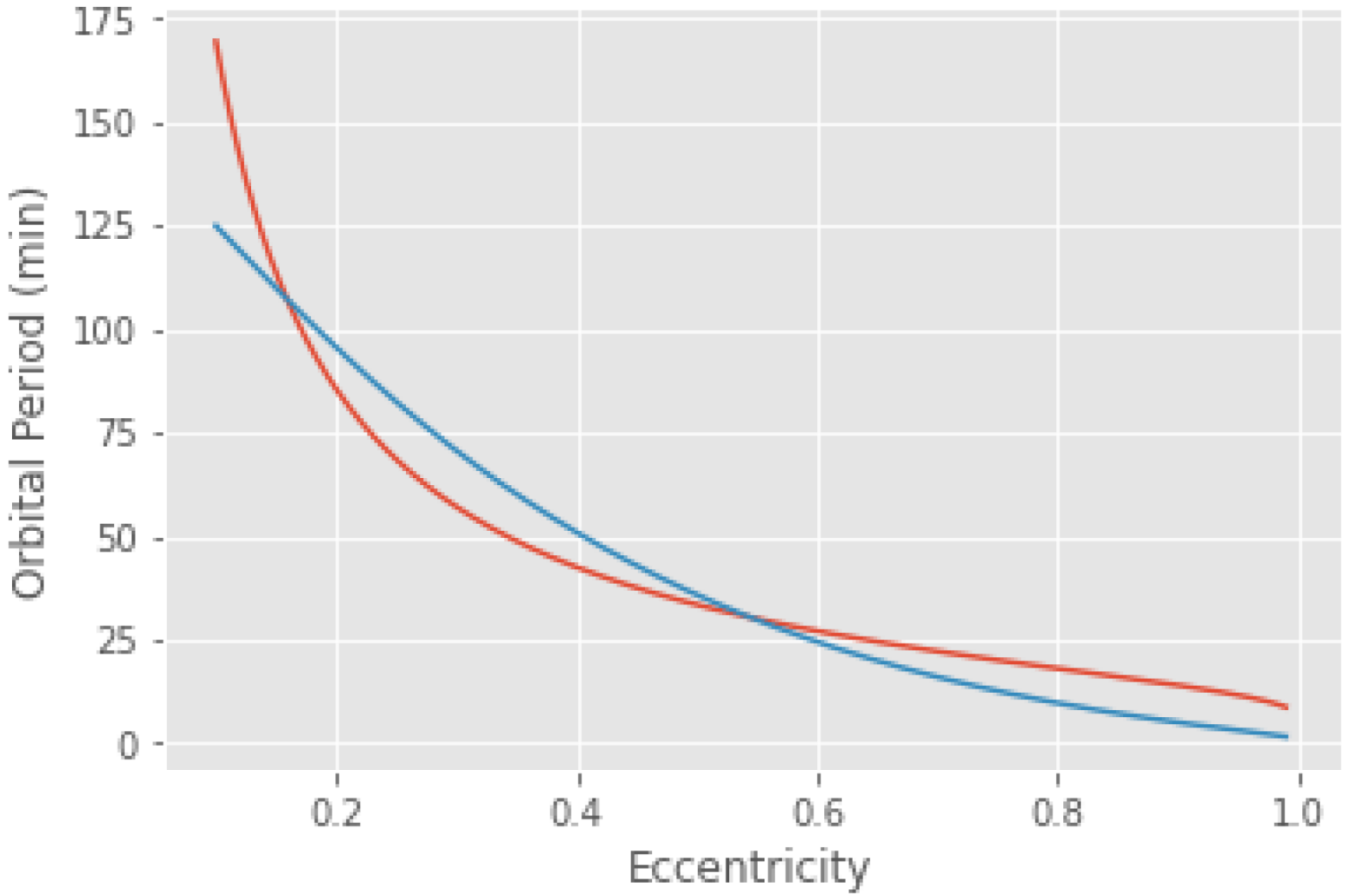
$$E_{orbit} = -\frac{1}{2} M_1 M_2 \left(\frac{G^2}{M} \right)^{\frac{1}{3}} \Omega_f^{\frac{2}{3}}$$

Conservation of Angular momentum

$$J = J_1 + J_2 + J_{orbit}$$

$$J = c_2 \left(\sqrt{\frac{3c_1}{4}} G^2 M^5 \right) \Omega^{-\frac{1}{3}}$$

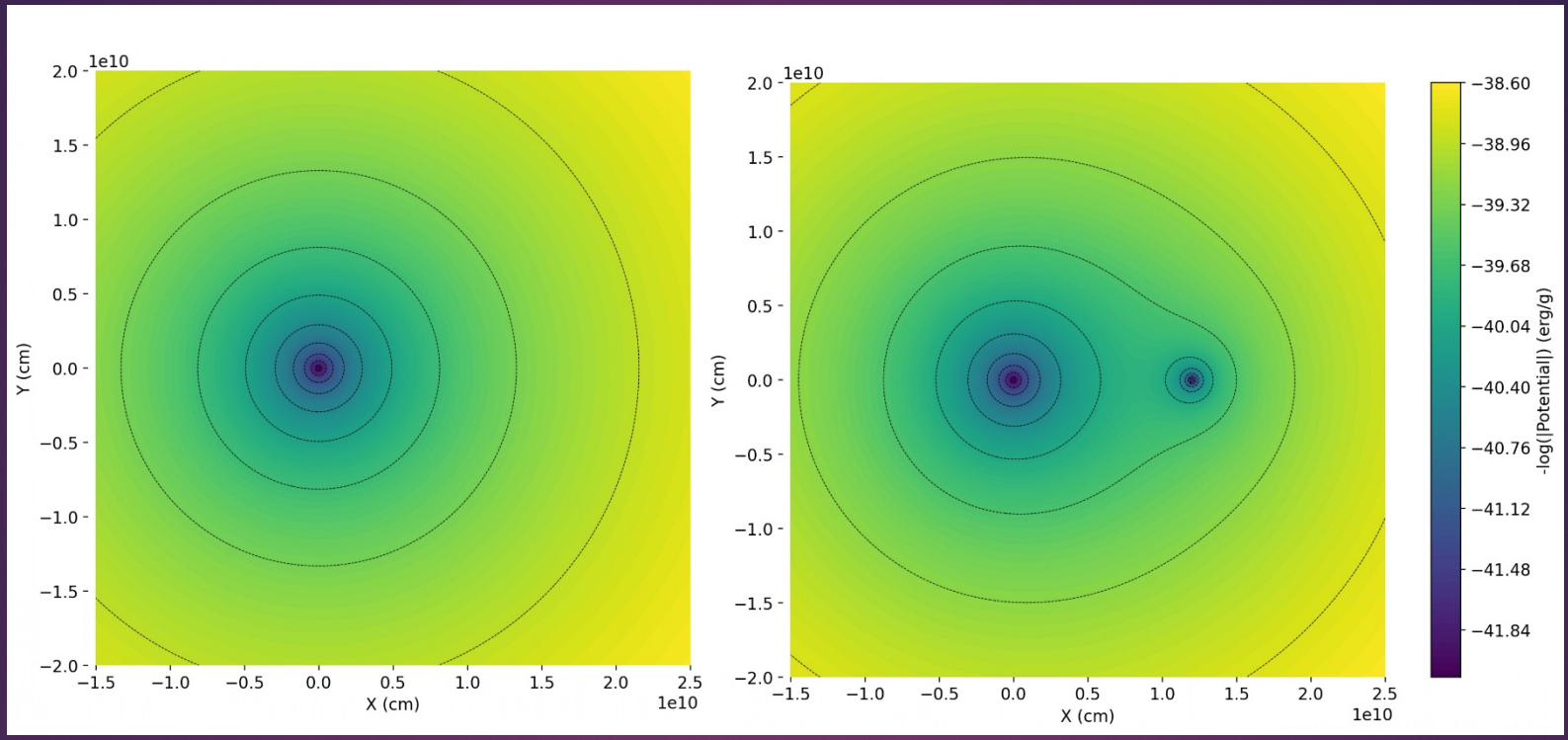
$$\begin{aligned} J_{orbit} &= \Omega_f \left[M_1 \frac{M_2^2}{M^2} \left(\frac{GM}{\Omega_f^2} \right)^{\frac{2}{3}} + M_2 \frac{M_1^2}{M^2} \left(\frac{GM}{\Omega_f^2} \right)^{\frac{2}{3}} \right] \\ &= M_1 M_2 \left(\frac{G^2}{M} \right)^{\frac{1}{3}} \Omega_f^{-\frac{1}{3}} \end{aligned} \tag{11}$$


175
150
125
100
75
50
25
0
Orbital Period (min)
0.2
0.4
0.6
0.8
1.0
Eccentricity

The outcome of the fission, the second column shows period of new binary star after splitting. We assumed that the components are $M_1 = 8.5M_\odot$ and $M_2 = 1.5M_\odot$. The radius and energy of the both newborn cores are given in the next column.

Initial Period(min)	Period after splitting	Orbital Distance	R ($8.5M_\odot$)	R ($1.5M_\odot$)
(1)	(2)	(3)	(4)	(5)
1	1.45	6.34×10^{09}	2.99×10^{09}	1.68×10^{09}
5	7.24	1.85×10^{10}	8.75×10^{09}	4.91×10^{09}
10	14.48	2.94×10^{10}	1.39×10^{10}	7.79×10^{09}
20	28.97	4.67×10^{10}	2.20×10^{10}	1.24×10^{10}
30	43.45	6.12×10^{10}	2.89×10^{10}	1.62×10^{10}

Gravitational Energy ($8.5M_\odot$)	Rotational Energy ($8.5M_\odot$)	Gravitational Energy ($1.5M_\odot$)	Rotational Energy ($1.5M_\odot$)
(6)	(7)	(8)	(9)
-3.86×10^{51}	1.79×10^{50}	-2.14×10^{50}	9.93×10^{48}
-1.32×10^{51}	6.11×10^{49}	-7.32×10^{49}	3.39×10^{48}
-8.31×10^{50}	3.85×10^{49}	-4.61×10^{49}	2.14×10^{48}
-5.23×10^{50}	2.43×10^{49}	-2.91×10^{49}	1.35×10^{48}
-3.99×10^{50}	1.85×10^{49}	-2.22×10^{49}	1.03×10^{48}



Demonstration of gravitational potential contours for two configurations: an isolated CO core (left) and a binary system with the CO core and a neutron star companion (right). The CO core ($M_{CO} = 10\ M_{\odot},\ R_{CO} = 10^{10}\ cm$) and neutron star ($M_{NS} = 2.0\ M_{\odot},\ R_{NS} = 10^{6}\ cm$) potentials are numerically calculated on a spatial grid, with their separation of 2×10^{10} cm.

The Three-body System

The Three-body system is unstable but it can survive for years

The stability time scale T_s, of the three-body system is depend on perturbing force F_p, and perihelion velocity of companion neutron star, v_p

$$\frac{T_s}{P} = \frac{E^2}{v_p F_p \delta t^2}$$

The energy absorbed by new neutron star in each period is given by

$$\delta E = v \,.\, \int_0^P F_p dt$$

The system will survive until the energy of one of components change sign and turn positive.

Two Scenarios

T_c is the time that more massive component of the new binary system need to collapse and explode as a supernova after splitting.

Early scenario : $T_s > T_c$
The more massive component explode to a supernova with no remnant and trigger the GRB event before the three-body system disintegrated. The SN provide both companions NS and νNS with huge ejecta. The companion NS reaches to its critical mass and νNS can develop a relativistic jet.

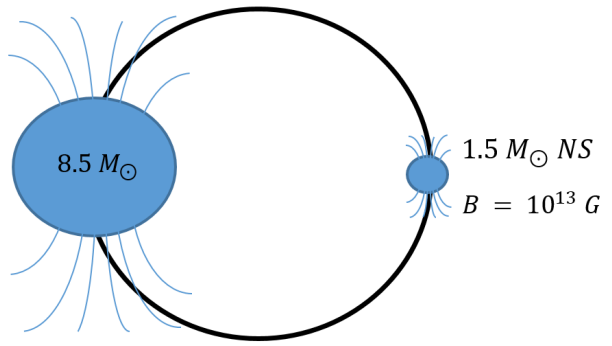
Late Scenario : $T_s < T_c$
One of the components of the three body system acquire enough energy to disintegrate and two remaining evolve as a short or long GRB.

Magnetic Evolution

Magnetic Field of Binary components after splitting

Initial Period(min)	Period After Splitting	Magnetic field Of 8.5 Msun just after splitting	Magnetic field Of 1.5 Msun just after splitting	Magnetic field Of final Neutron star
1	1.43	1.18×10^5	3.8×10^5	1.05×10^{12}
5	7.22	1.17×10^5	3.7×10^5	8.99×10^{12}
10	14.47	1.17×10^5	3.7×10^5	2.27×10^{13}
20	28.95	1.16×10^5	3.6×10^5	5.71×10^{13}
30	43.42	1.16×10^5	3.6×10^5	9.81×10^{13}

Initial magnetic field of CO core $B_{CO} = 10^5\ G$



$B = B_{critical}$