

Research Presentation

Probing magnetar central engines in short GRBs

through fallback accretion and extended X-ray emission

Presented by

Ankur Ghosh

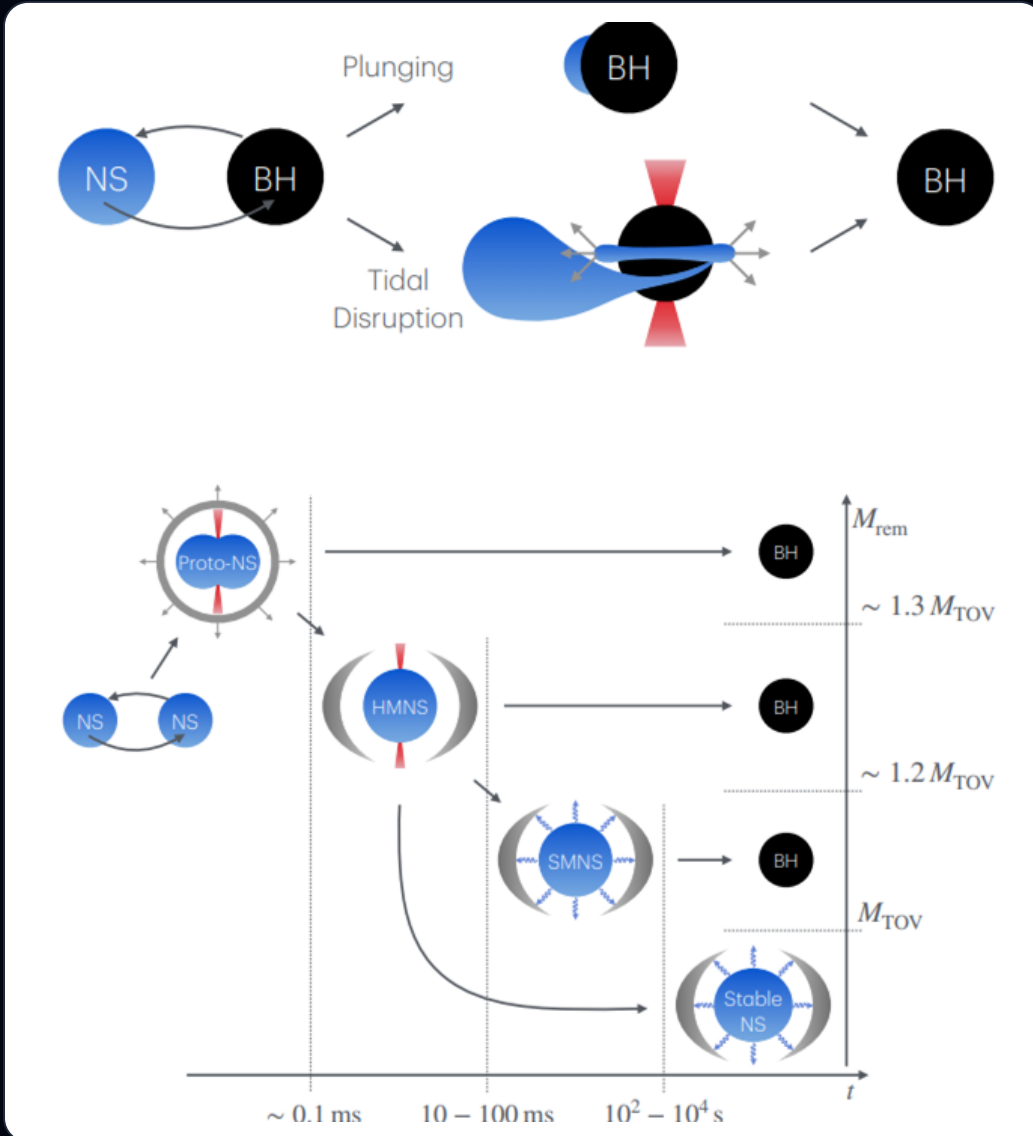
In collaboration with

Vivek Akhileshwar, Soebur Razzaque, Jagdish Joshi,
Lutendo Nyadzani

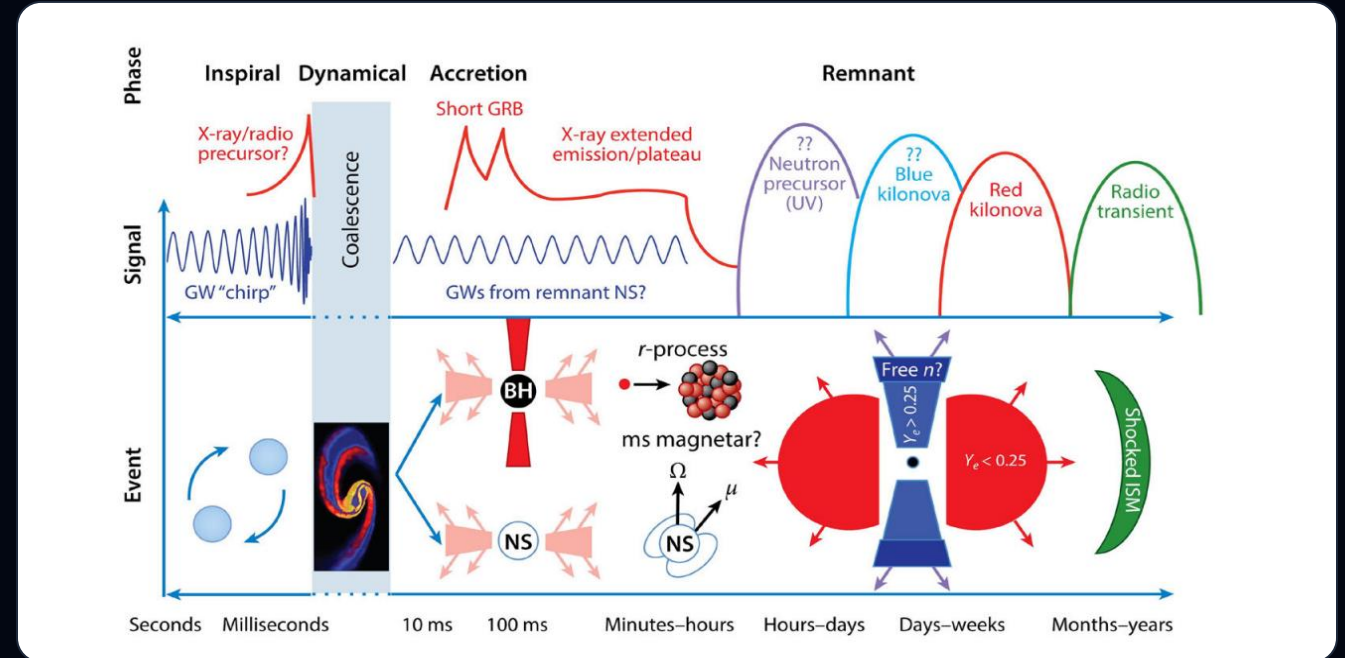
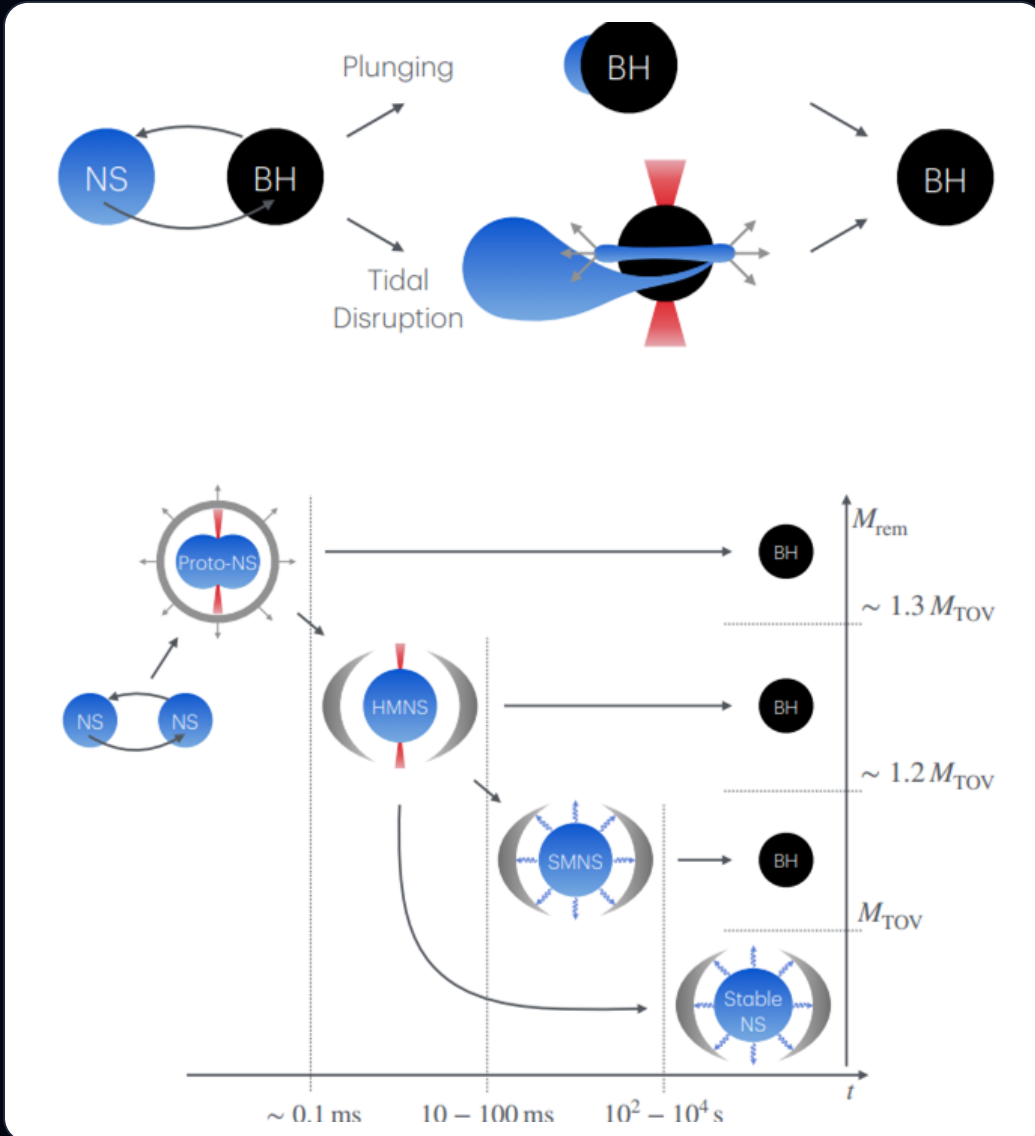
Date: 01.10.2026



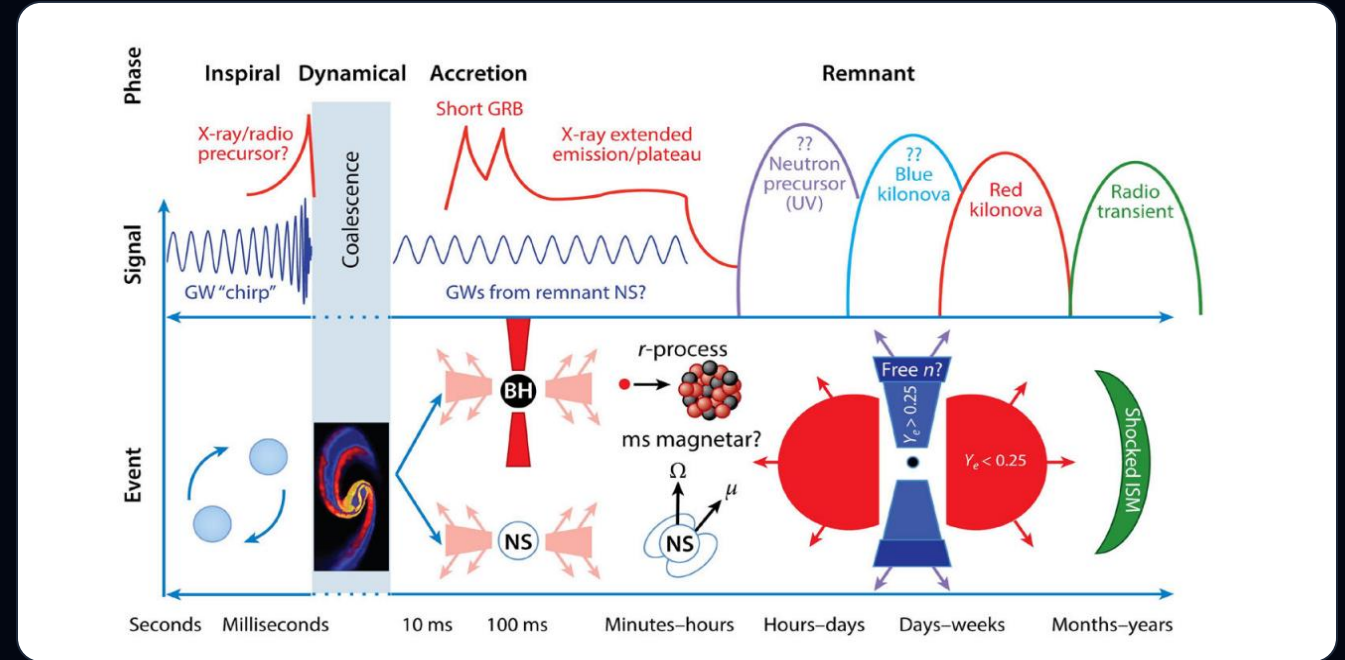
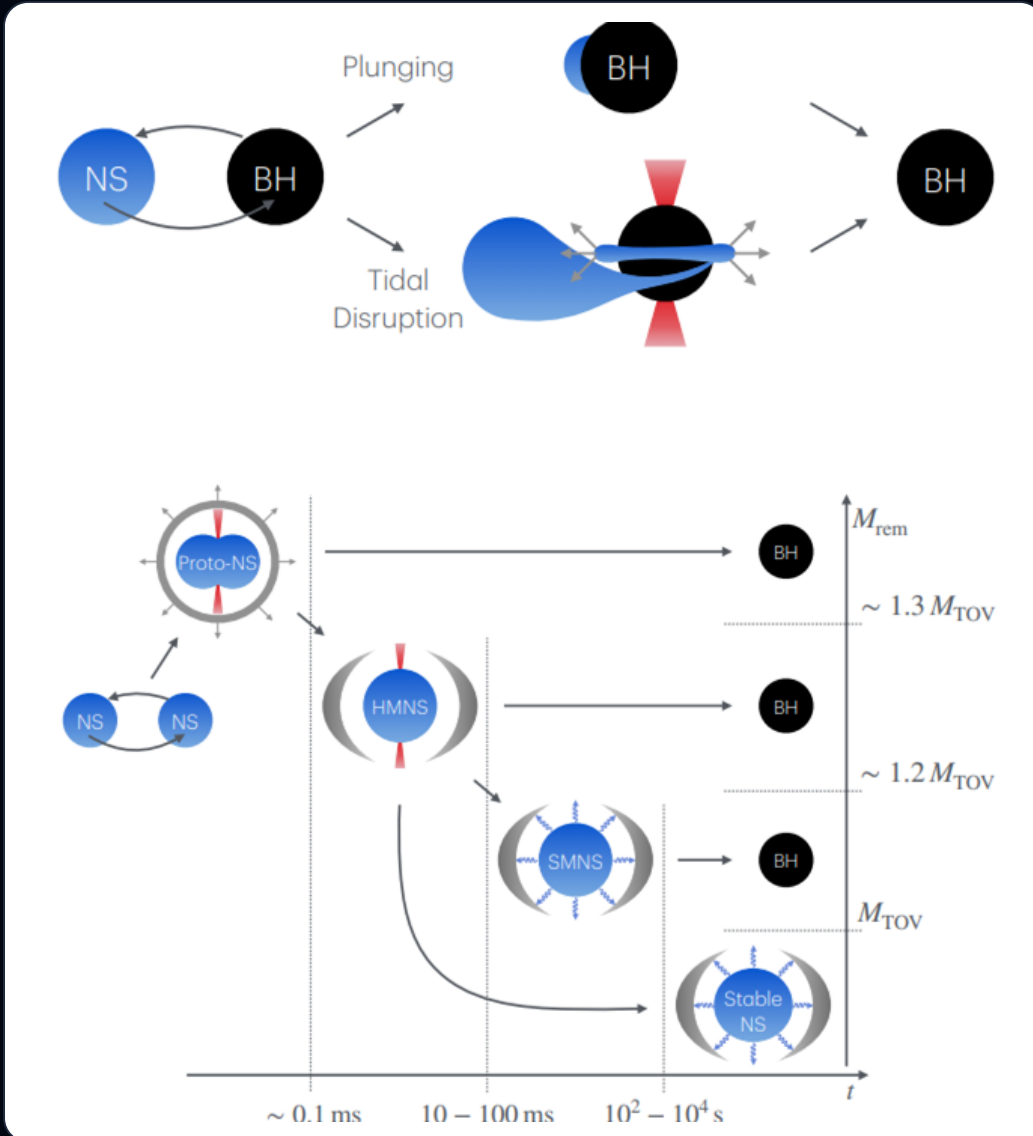
Short GRBs in a blink



Short GRBs in a blink



Short GRBs in a blink

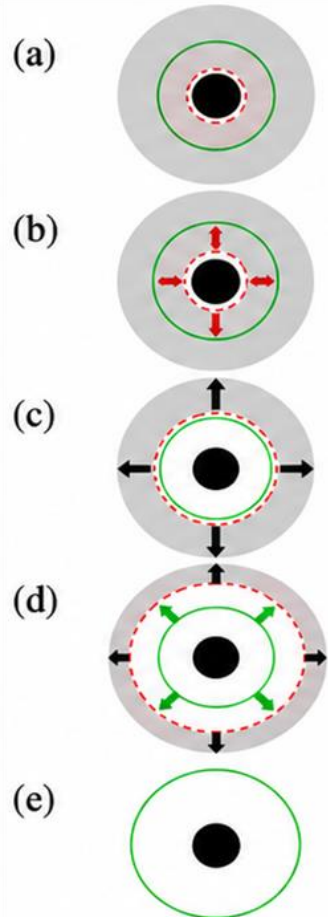


Motivation of Our Study

- 01** Probe the presence of magnetar remnant in short GRBs with extended emission.
- 02** Constrain the magnetar parameters to check the correlation between the parameters and get indirect evidence for binary neutron star masses.

Fallback Accretion and Magnetar Propeller Model

Piro & Ott (2011) and Gompertz et al. (2014)



- Black circle = magnetar; grey region = fallback/accretion disc;
red dashed circle = Alfvén radius r_m ; green circle = corotation radius r_c .
- **Early phase:** $r_m < r_c$, so material accretes onto the magnetar and spins it up.
- As the fallback rate decreases, the magnetosphere expands outward.
- When $r_m > r_c$, the system enters the **propeller regime** and centrifugally ejects inflowing material.
- This extracts **rotational energy** and can power extended emission, flares, variability, and X-ray plateaus.
- At late times, the disc is depleted and **magnetic dipole** spin-down dominates.

$$r_m = \xi \left(\frac{B^4 R^{12}}{32 G M \dot{M}^2} \right)^{1/7}$$

$$r_{co} = \left(\frac{G M P^2}{4 \pi^2} \right)^{1/3}$$

Accretion: $r_m < r_c$ → Propeller: $r_m > r_c$ → Dipole spin-down

Sample Selection Criteria



Sample Selection Criteria



short GRB SAMPLE PROPERTIES

GRB	T_{90} (s)	z	$E_{\gamma, \text{iso}}$ (erg)	$L_{\gamma, \text{iso}}$ (erg s ⁻¹)	Reference
160821B	0.48 ± 0.07	0.162	$(2.1 \pm 0.2) \times 10^{50}$	$(5.1 \pm 0.9) \times 10^{50}$	Lamb et al. (2019)
180805B	1.68	0.661	$(6.7 \pm 0.8) \times 10^{50}$	$(6.6 \pm 0.8) \times 10^{50}$	O'Connor et al. (2022); Hamburg et al. (2018)
181123B	0.26 ± 0.04	1.754	$(2.60 \pm 0.60) \times 10^{50}$	$(2.80 \pm 0.80) \times 10^{51}$	Paterson et al. (2020); Dichiara et al. (2021)
200219A	1.10 ± 0.45	$0.46^{+0.18}_{-0.21} \text{a}$	$(1.50 \pm 1.30) \times 10^{51}$	$(2.00 \pm 1.70) \times 10^{51}$	Jeong & Im (2024); Gupta et al. (2020)
210323A	1.12 ± 0.32	0.733^{b}	$(1.68 \pm 0.14) \times 10^{51}$	$(2.60 \pm 0.80) \times 10^{51}$	Jeong & Im (2024); Shan et al. (2024)
210726A	0.39 ± 0.11	$0.458^{+0.170}_{-0.181} \text{a,c}$	$(2.1 \pm 0.5) \times 10^{49}$	$(7.85^{+3.04}_{-3.06}) \times 10^{49}$	Jeong & Im (2024); Veres & Fermi-GBM Team (2021)
211023B	1.30 ± 0.26	0.862	$(1.05 \pm 0.15) \times 10^{51}$	$(1.50 \pm 0.37) \times 10^{51}$	Laha et al. (2021); Rossi et al. (2021)
230205A	2.30 ± 0.36	0.484 ± 0.090	$(9.6 \pm 4.1) \times 10^{49}$	$(6.2 \pm 3.1) \times 10^{49}$	Sakamoto et al. (2023); Tomasella et al. (2023)
231117A	0.668	0.257	3.8×10^{50}	7.2×10^{50}	Schroeder et al. (2025)

Data collection and conversion

0.3–10 keV flux, with photon index sub plot. BAT binning: 64 ms bins.

[Show full XRT 0.3–10 keV flux plot controls.](#)

Time range: Logarithmic? ☒ Flux range: Logarithmic? ☒ Gamma range: Logarithmic? ☐

Subplot: photon index

Display which bands?

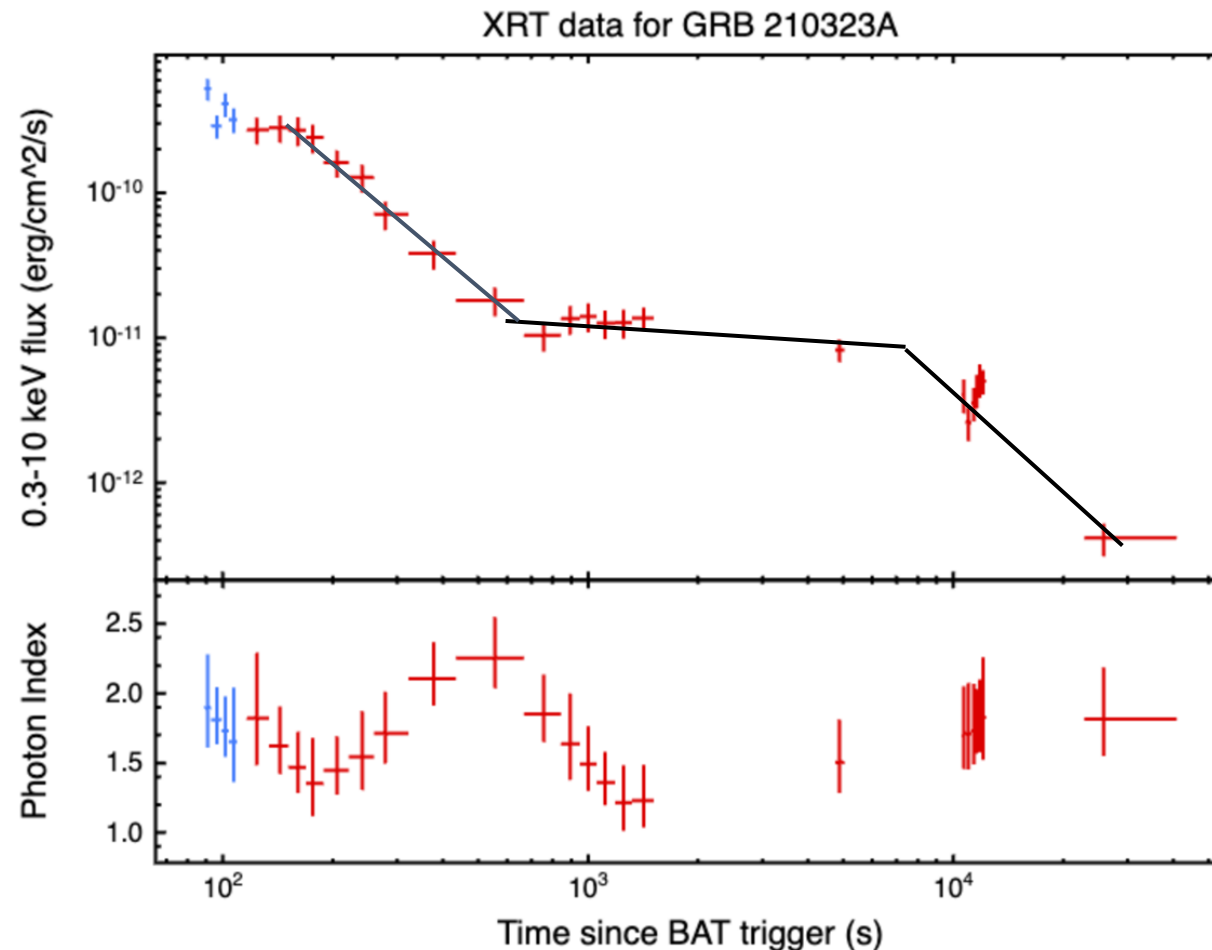
Flux density at 10 keV ☐

0.3–10 keV flux ☒

15–50 keV flux ☐

Show WT systematics? ☒

[What systematics?](#)



Data collection and conversion

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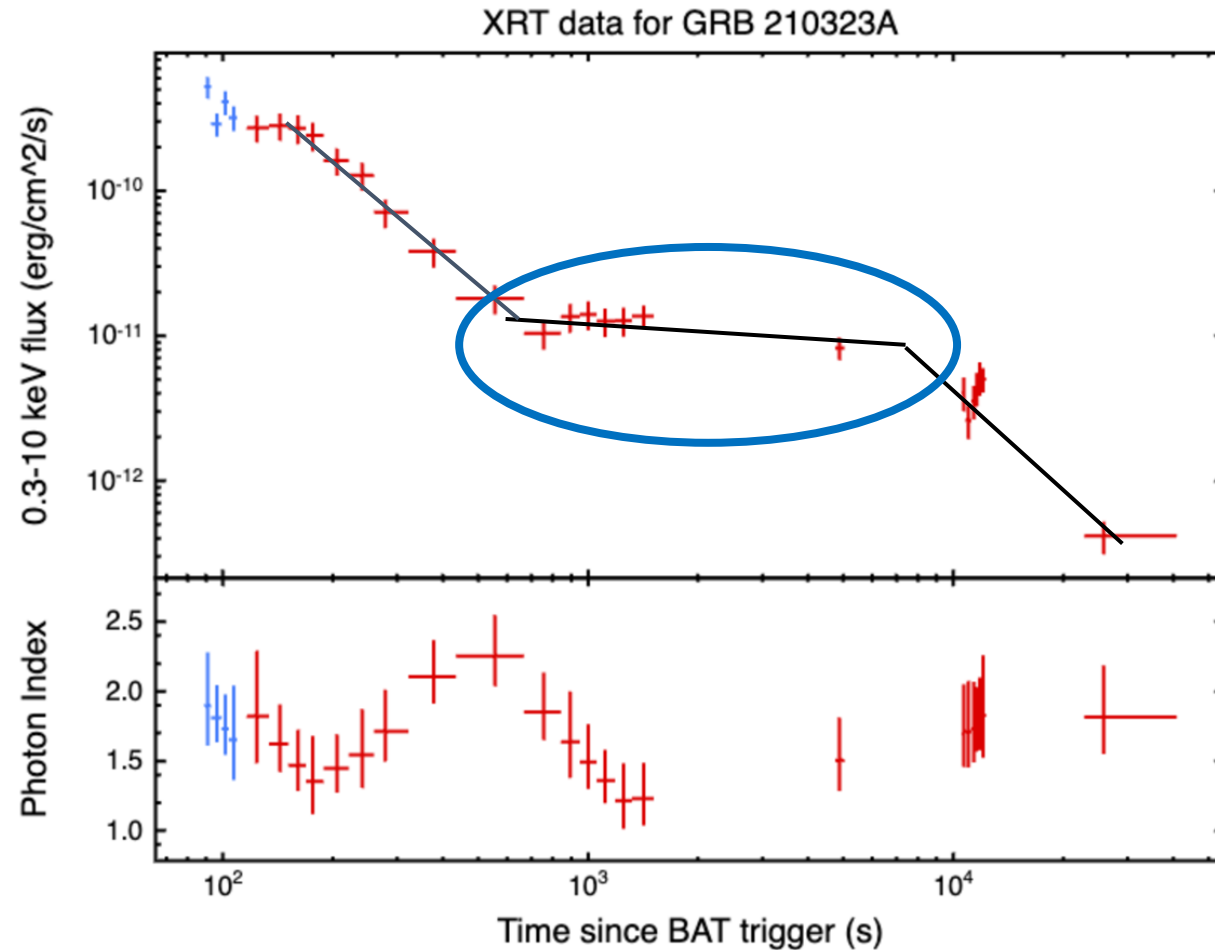
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0.3–10 keV flux ☒

15–50 keV flux ☐

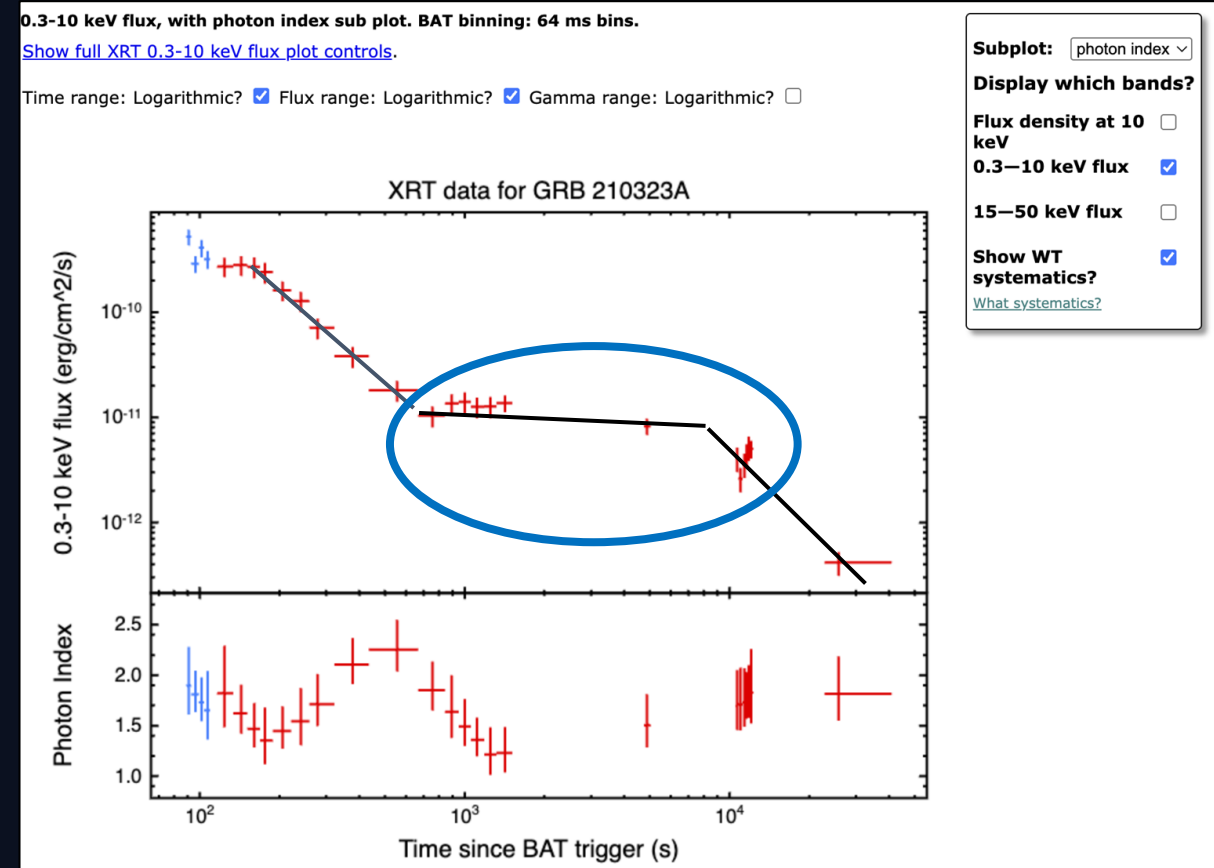
Show WT systematics? ☒

[What systematics?](#)



Data collection and conversion

https://www.swift.ac.uk/burst_analyser/01038247/



$$F_{\text{bol}} = C_{\text{abs}} F_{\text{obs}} (1 + z)^{\Gamma-2} \frac{E_{\text{bol,max}}^{2-\Gamma} - E_{\text{bol,min}}^{2-\Gamma}}{E_{\text{X,max}}^{2-\Gamma} - E_{\text{X,min}}^{2-\Gamma}}.$$

$$L_{\text{bol}}(t_{\text{rest}}) = 4\pi d_L^2 C_{\text{abs}} F_{\text{obs}}(t_{\text{obs}}) k_{\text{bol}}$$

Data collection and conversion

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0.3-10 keV flux, with photon index sub plot. BAT binning: 64 ms bins.

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Subplot:

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Flux density at 10 keV ☐

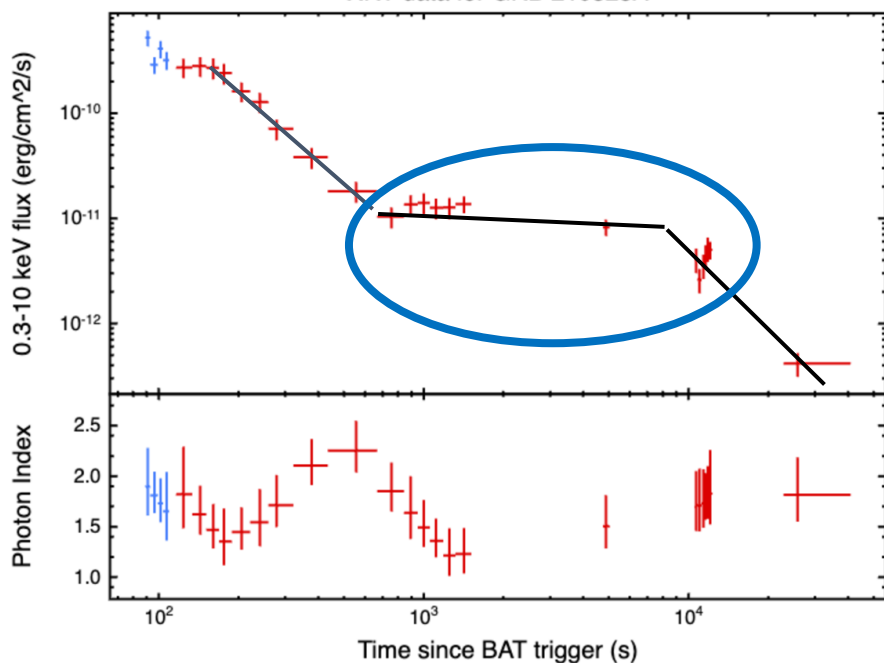
0.3-10 keV flux ☒

15-50 keV flux ☐

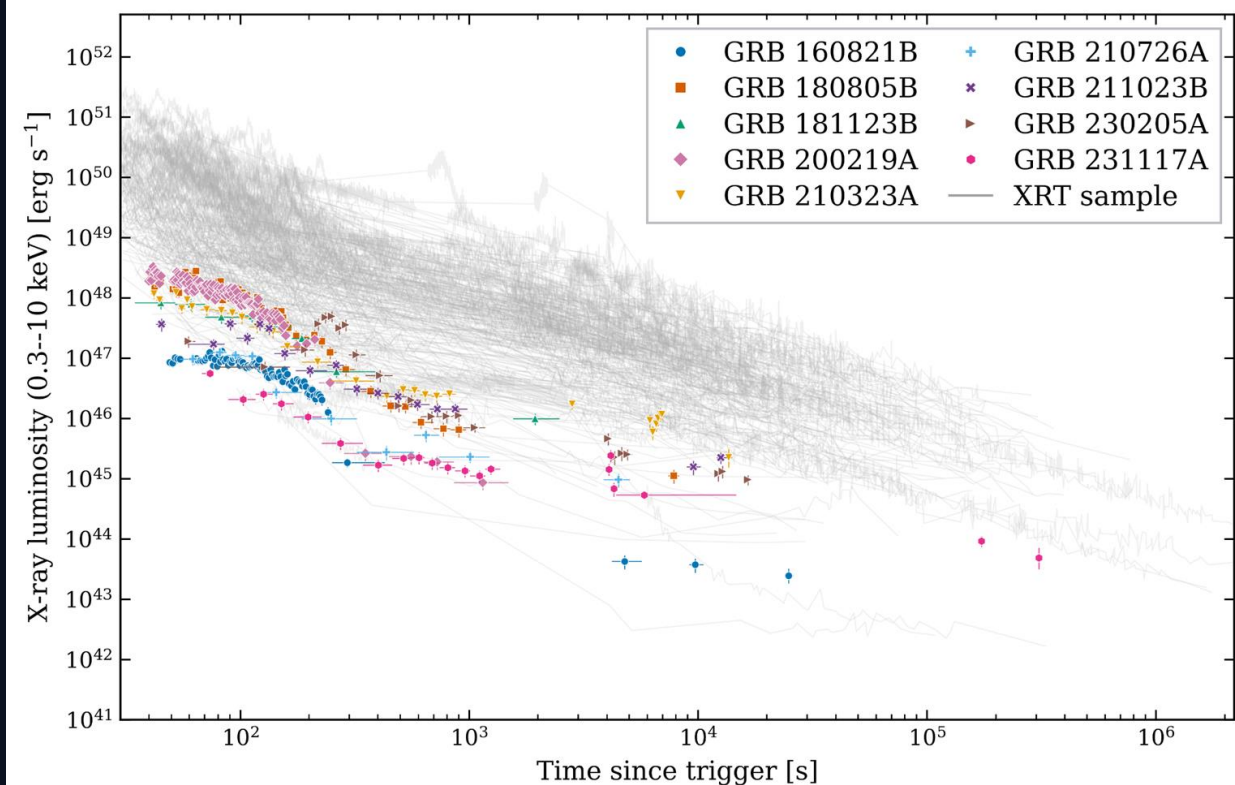
Show WT systematics? ☒

[What systematics?](#)

XRT data for GRB 210323A



Luminosity of sample short GRBs in comparison to other XRT detected GRBs



$$F_{\text{bol}} = C_{\text{abs}} F_{\text{obs}} (1+z)^{\Gamma-2} \frac{E_{\text{bol,max}}^{2-\Gamma} - E_{\text{bol,min}}^{2-\Gamma}}{E_{\text{X,max}}^{2-\Gamma} - E_{\text{X,min}}^{2-\Gamma}}.$$

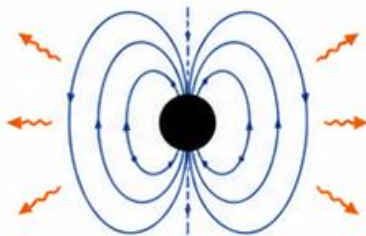
$$L_{\text{bol}}(t_{\text{rest}}) = 4\pi d_L^2 C_{\text{abs}} F_{\text{obs}}(t_{\text{obs}}) k_{\text{bol}}$$

Evolution of Magnetar Models for SGRBs with Extended Emission

Physical picture, mathematical formulation, and schematic light-curve evolution

1 Rowlinson et al. 2013 — dipole plateau

Physical picture



- No explicit accretion disc
- No propeller phase
- Plateau interpreted as dipole spin-down

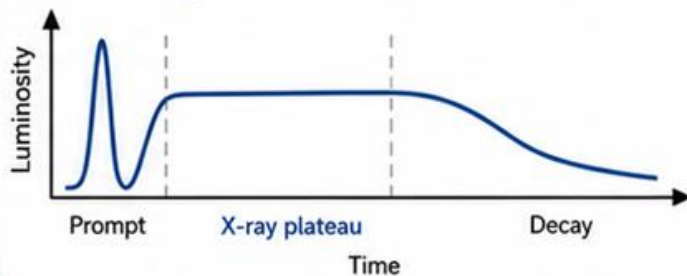
Key equations

$$L(t) = \frac{L_0}{(1 + t/T_{\text{em}})^2}$$

$$T_{\text{em}} \propto I B_p^{-2} P_0^2 R^{-6}$$

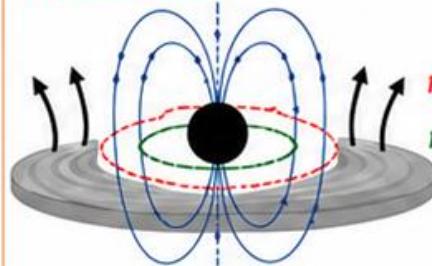
$$L_0 \propto B_p^2 P_0^{-4} R^6$$

Schematic light curve



2 Gompertz et al. 2014 — propeller + static disc

Physical picture



- Static disc drains with time
- Extended emission powered by propeller
- Late plateau from dipole spin-down

Key equations

$$r_m = \mu^{4/7} (GM)^{-1/7} \dot{M}^{-2/7}$$

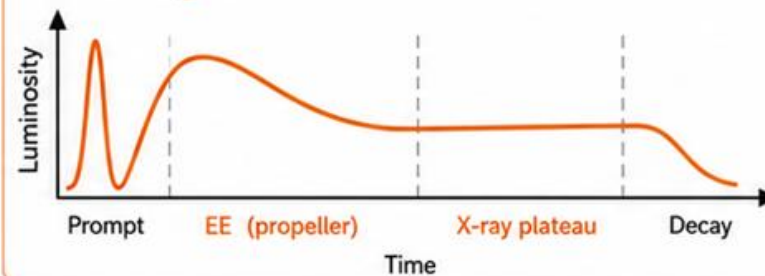
$$r_c = \left(\frac{GM}{\Omega^2} \right)^{1/3}$$

$$\dot{M}_0 = 3 \frac{M_d \nu}{R_d^2}$$

$$\dot{M} = \dot{M}_0 \exp\left(-\frac{3\nu t}{R_d^2}\right)$$

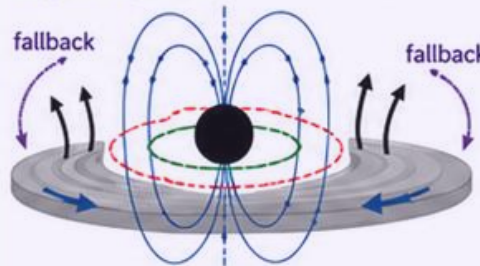
If $r_c > r_m \rightarrow$ accretion;
if $r_c < r_m \rightarrow$ propeller

Schematic light curve



3 Gibson et al. 2017 — fallback-fed propeller

Physical picture



- Fallback replenishes the disc
- Dynamic disc mass and spin evolution
- Can explain variability, flares, and longer dipole plateaus

Key equations

$$\dot{M}_D = \dot{M}_{\text{fb}} - \dot{M}_{\text{prop}} - \dot{M}_{\text{acc}}$$

$$\dot{\omega} = \frac{N_{\text{acc}} + N_{\text{dip}}}{I}$$

$$\dot{M}_{\text{fb}} = \frac{M_{\text{fb}}}{t_{\text{fb}}} \left(\frac{t + t_{\text{fb}}}{t_{\text{fb}}} \right)^{-5/3}$$

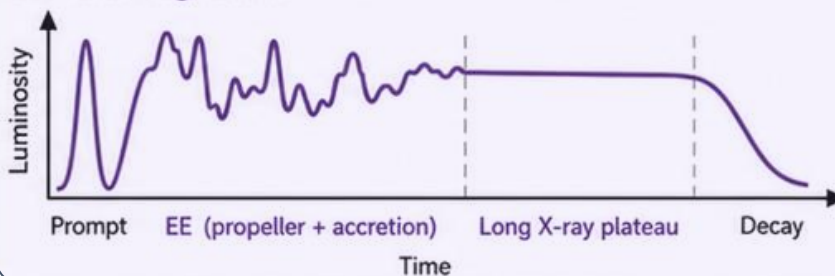
$$\eta_2 = \frac{1}{2} \left[1 + \tanh(n(\omega_{\text{fast}} - 1)) \right]$$

$$\omega_{\text{fast}} = \left(\frac{r_m}{r_c} \right)^{3/2}$$

$$\dot{M}_{\text{prop}} = \eta_2 \frac{M_D}{t_v}$$

$$\dot{M}_{\text{acc}} = (1 - \eta_2) \frac{M_D}{t_v}$$

Schematic light curve



Increasing physical complexity and energy budget

Based on Rowlinson et al. 2013; Gompertz et al. 2014; Gibson et al. 2017.

Magnetar central-engine luminosity model

Propeller + magnetic-dipole channels used to compare the model with bolometric luminosity data

Core equations

REGIME SWITCH

$$\eta_2 = \frac{1}{2} \left[1 + \tanh \left(n \left\{ \left(\frac{r_m}{r_c} \right)^{3/2} - 1 \right\} \right) \right]$$

determines how the disc flow is divided into accretion and propeller ejection

PROPELLER LUMINOSITY

$$L_{\text{prop}} = \eta_{\text{prop}} \left[-N_{\text{acc}} \omega - \eta_2 \frac{GMM_D}{r_m t_v} \right]$$

rotational power extracted from the magnetar minus the energy cost of ejecting matter

DIPOLE LUMINOSITY

$$L_{\text{dip}} = \eta_{\text{dip}} \frac{\mu^2 \omega^4}{6c^3}$$

magnetic spin-down channel; very sensitive to spin period, $L_{\text{dip}} \propto B^2 P^{-4}$

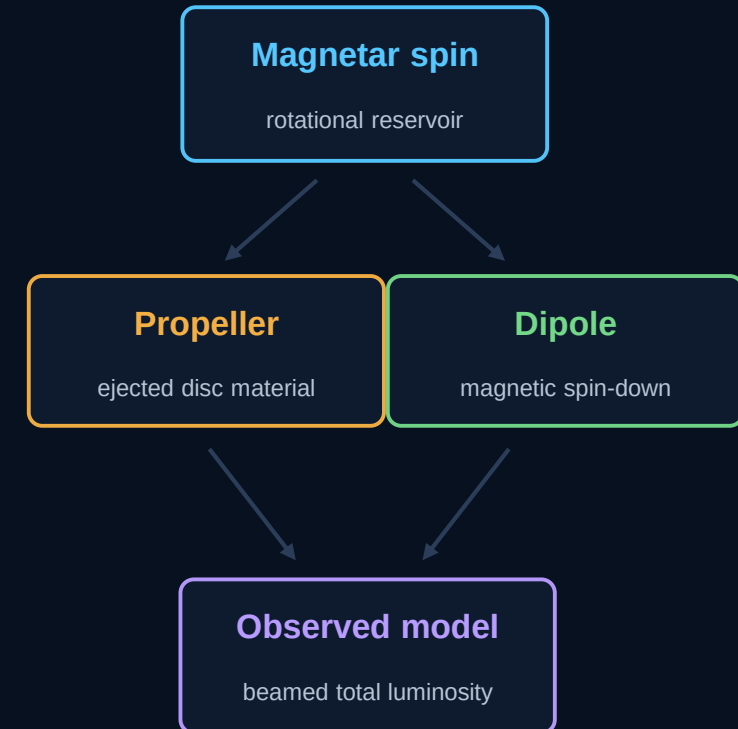
TOTAL MODEL

$$L_{\text{tot}} = \frac{1}{f_B} (L_{\text{prop}} + L_{\text{dip}})$$

beaming-corrected luminosity fitted to the bolometric light curve

Definitions: $\mu = BR^3, \quad \omega = \frac{2\pi}{P}$

Physical readout



Key message

η_2 selects the accretion/propeller regime; η_{prop} and η_{dip} convert engine power into radiation; $1/f_B$ accounts for beaming.

Compare $L_{\text{tot}}(\text{trest})$ with bolometric luminosity.

Magnetar central-engine luminosity model

Propeller + magnetic-dipole channels used to compare the model with bolometric luminosity data

Core equations

REGIME SWITCH

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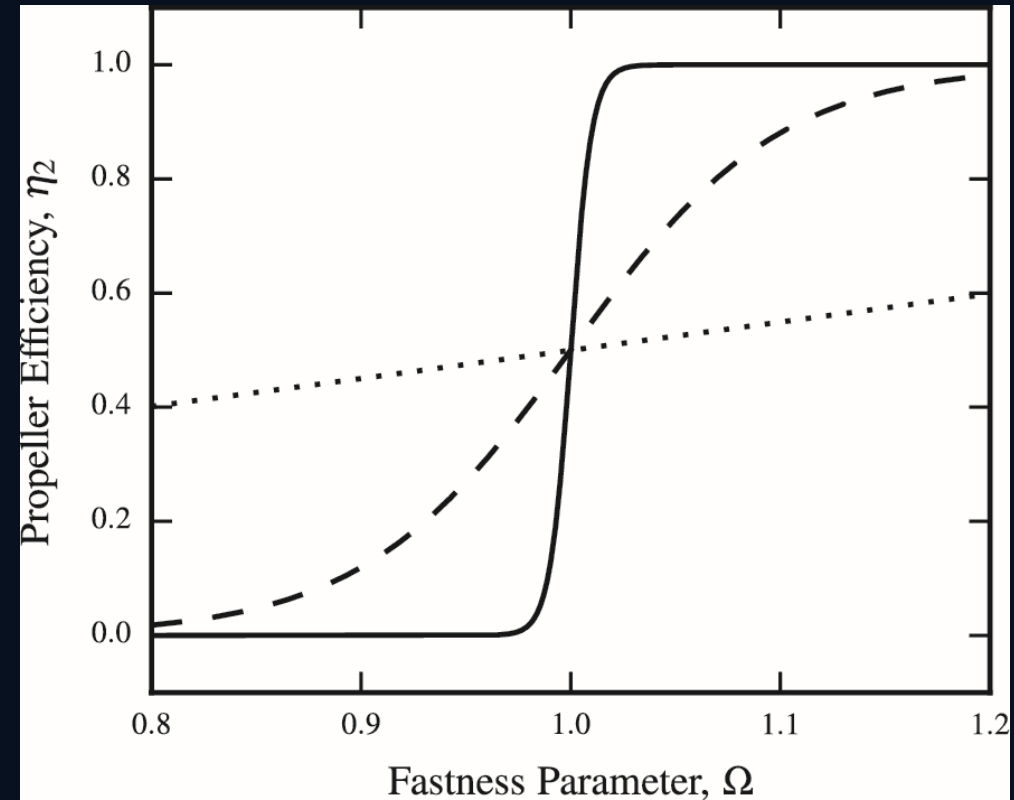
magnetic spin-down channel; very sensitive to spin period, $L_{\text{dip}} \propto B^2 P^{-4}$

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beaming-corrected luminosity fitted to the bolometric light curve

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Fitting Analysis

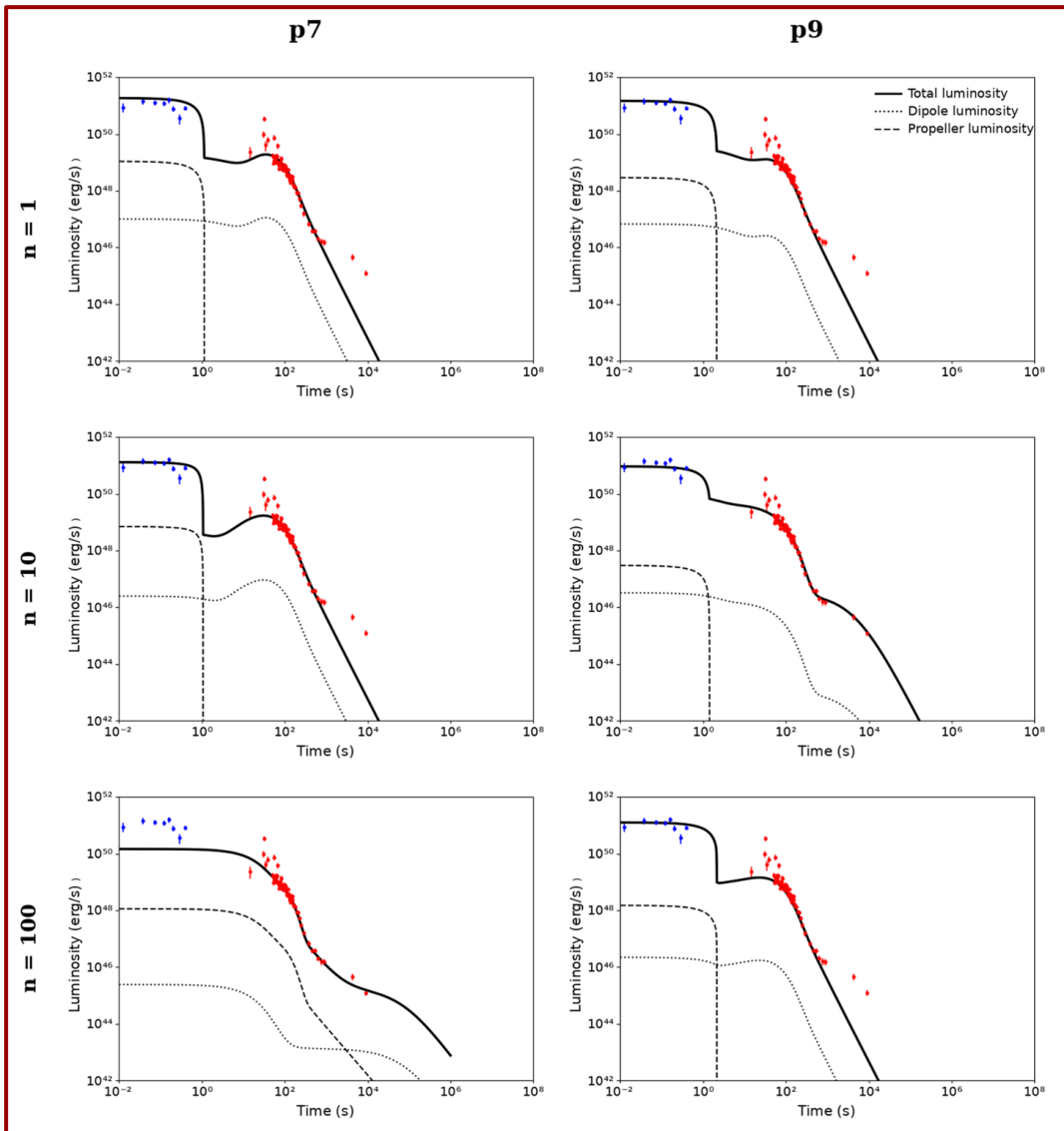
- ☐ Parameter estimation using MCMC sampling within a Bayesian framework.
- ☐ Explored smoothing parameter: $n = 1, 10, 100$.
- ☐ Models tested with 6 to 9 free parameters.
- ☐ Multi-band fitting performed in:
 - ☐ 0.3-10 keV
 - ☐ 15-50 keV
 - ☐ Native Band
- ☐ Model performance evaluated using Reduced χ^2 , AICc, and BIC.

Parameter	Lower Limit	Upper Limit
$B(10^{15}\text{G})$	10^{-3}	10^1
P (ms)	0.69	10
$M_{\text{disc}} (M_{\odot})$	10^{-3}	10^{-1}
R_{disc} (km)	50	2000
ϵ	10^{-1}	10^3
δ	10^{-5}	50
η_{dip}	10^{-2}	1
η_{prop}	10^{-2}	1
$1/f_B$	1	600

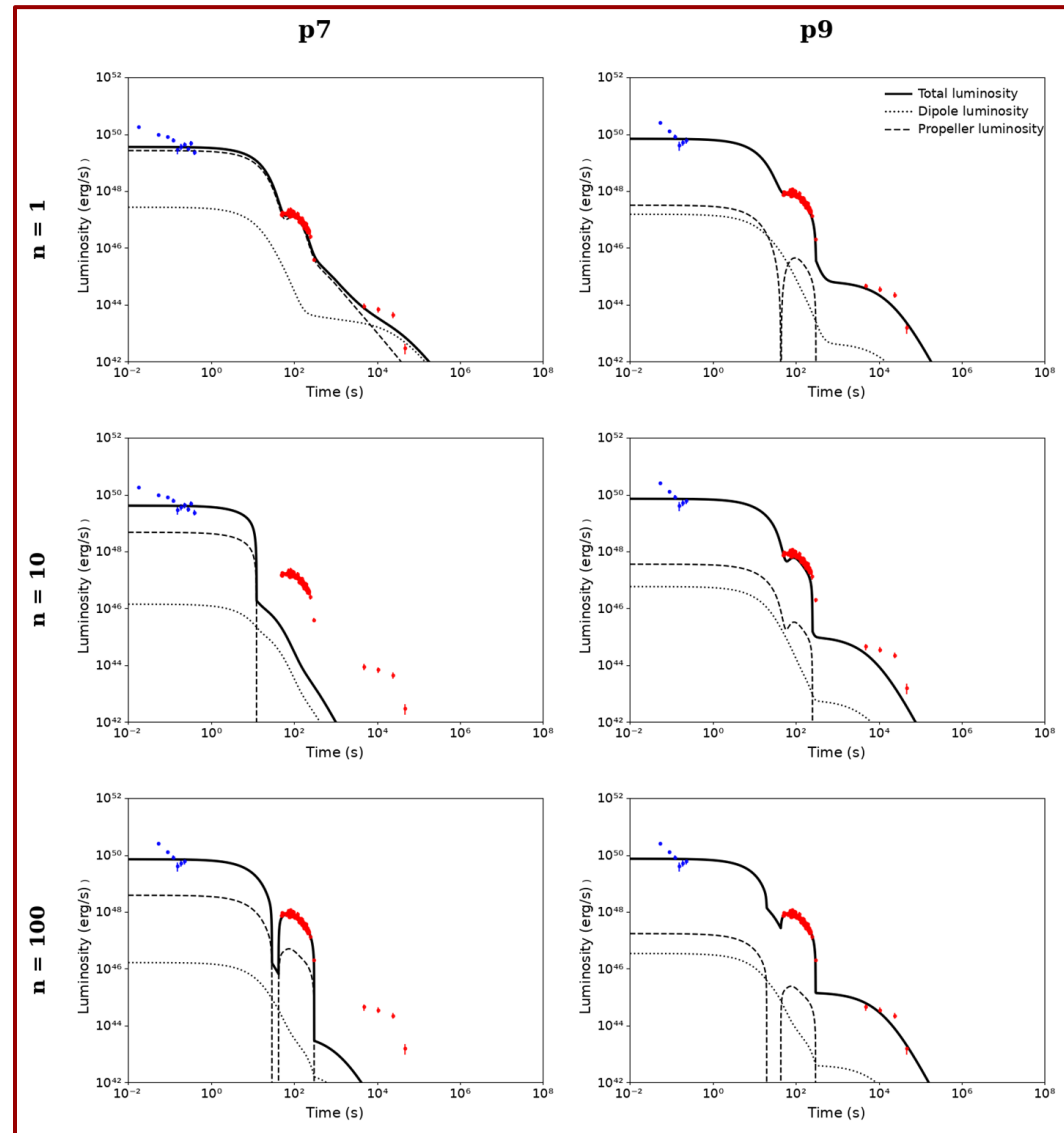
Parameters	Symbol	Physical Meaning	p = 6	p = 7	p = 8	p = 9
Magnetic field	(B)	Magnetar surface field strength	✓	✓	✓	✓
Initial spin period	(P_i)	Initial rotation of magnetar	✓	✓	✓	✓
Initial disc mass	(M_{D,i})	Mass of accretion disc	✓	✓	✓	✓
Disc radius	(R_D)	Size of accretion disc	✓	✓	✓	✓
Fallback timescale ratio	(epsilon)	Controls fallback duration	✓	✓	✓	✓
Fallback mass fraction	(delta)	Available fallback mass	✓	✓	✓	✓
Beaming factor	(1/f_B)	Jet collimation (anisotropy)	X	✓	X	✓
Dipole efficiency	(eta_dip)	Spin-down → radiation efficiency	X	X	✓	✓
Propeller efficiency	(eta_prop)	Propeller → radiation efficiency	X	X	✓	✓

Fitting Results

GRB 160821B

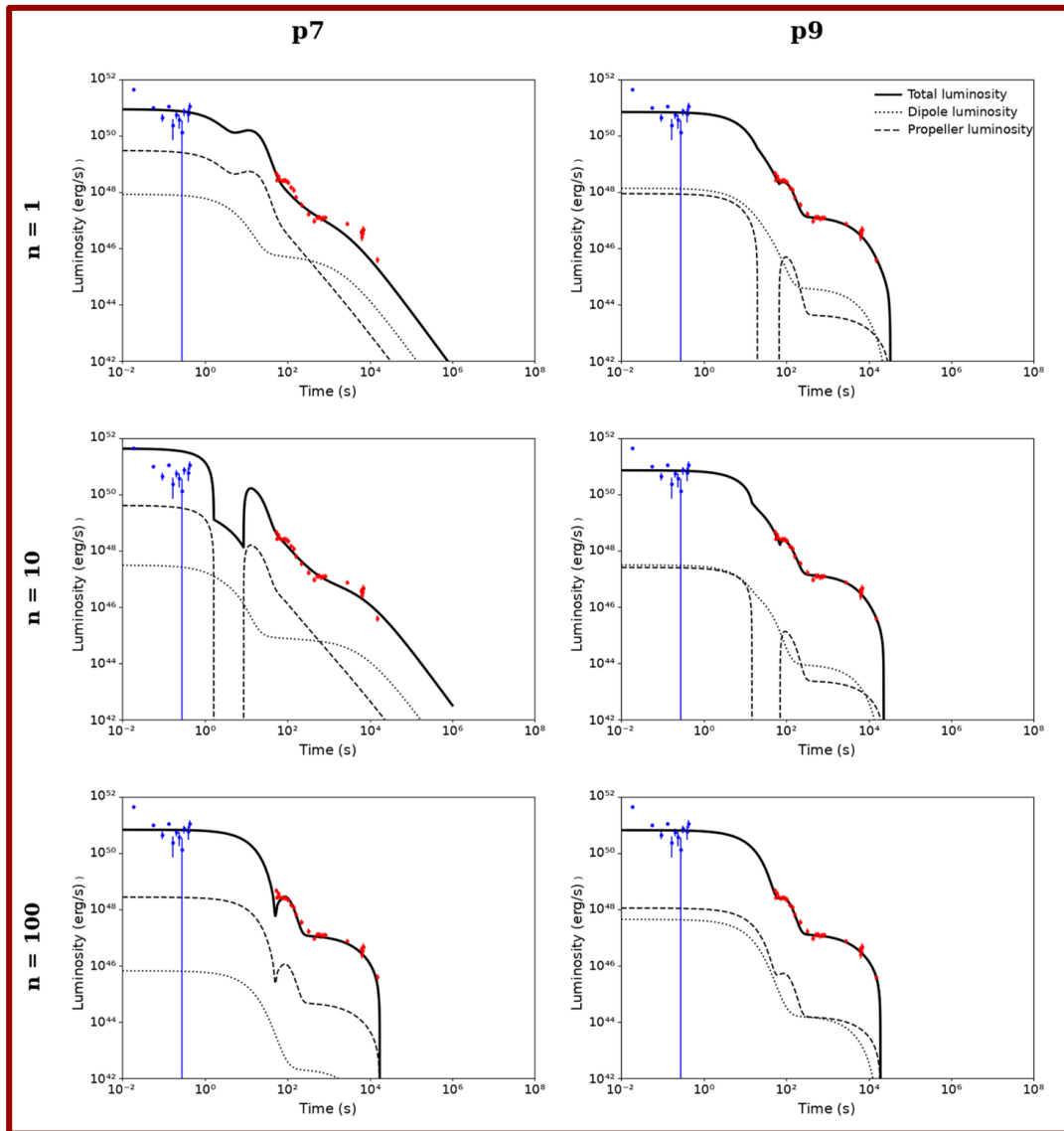


GRB 180805B

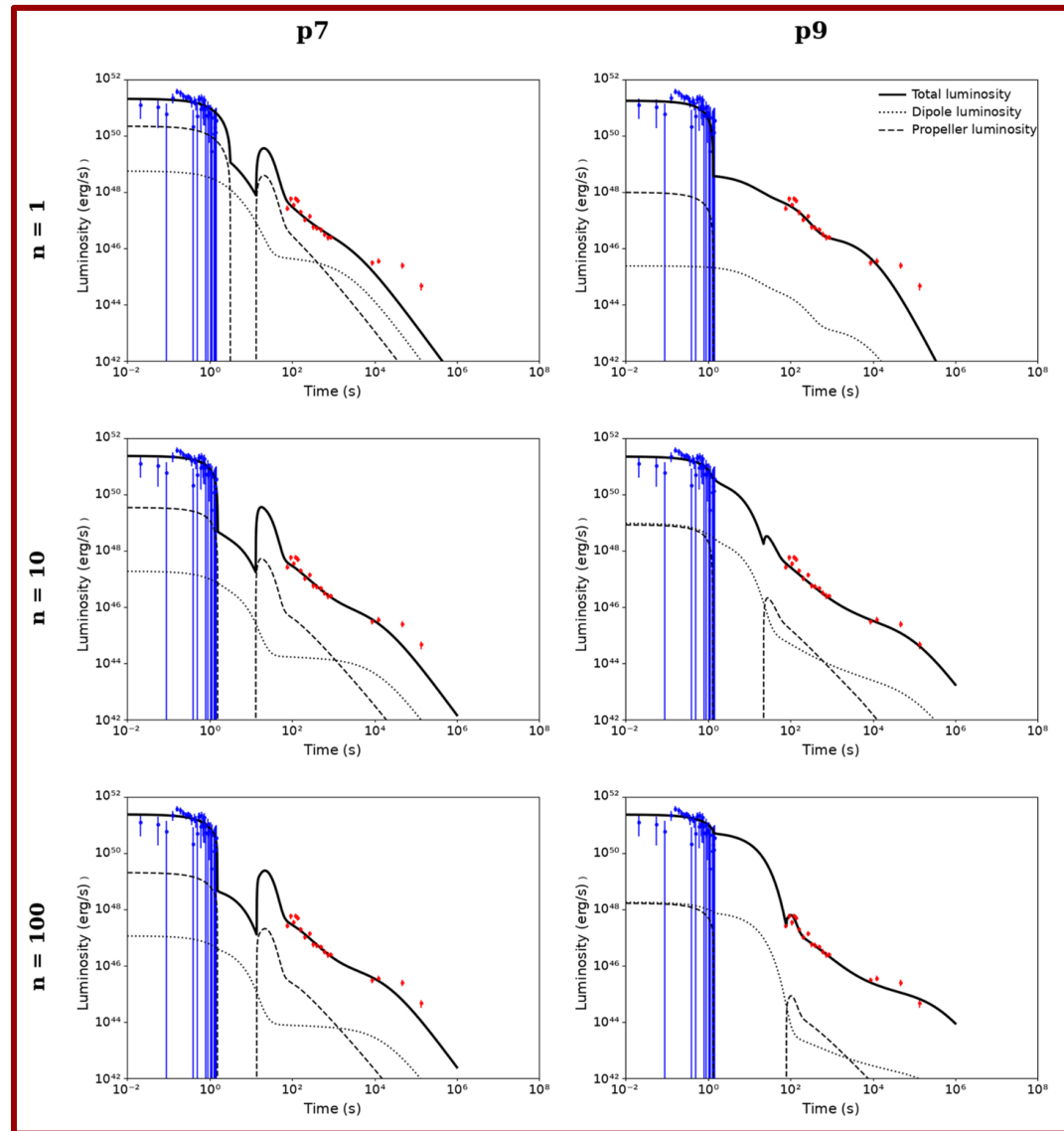


Fitting Results

GRB 210323A



GRB 211023B

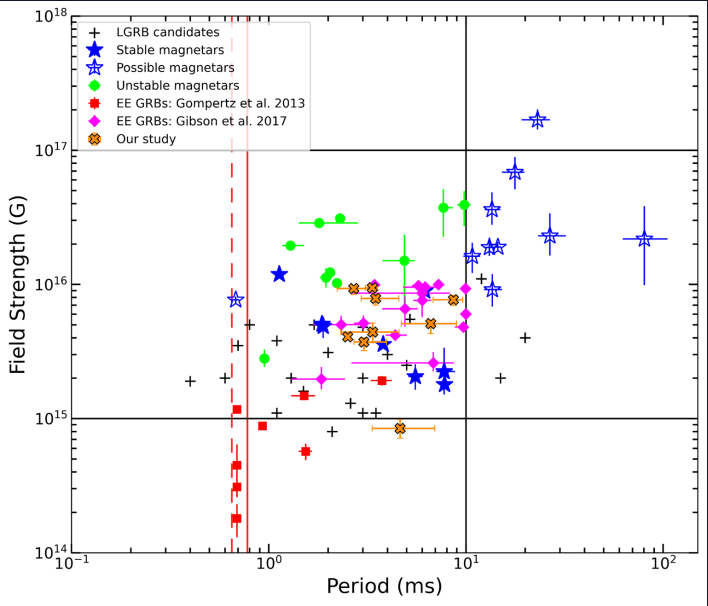


Summary of Derived Fit Parameters

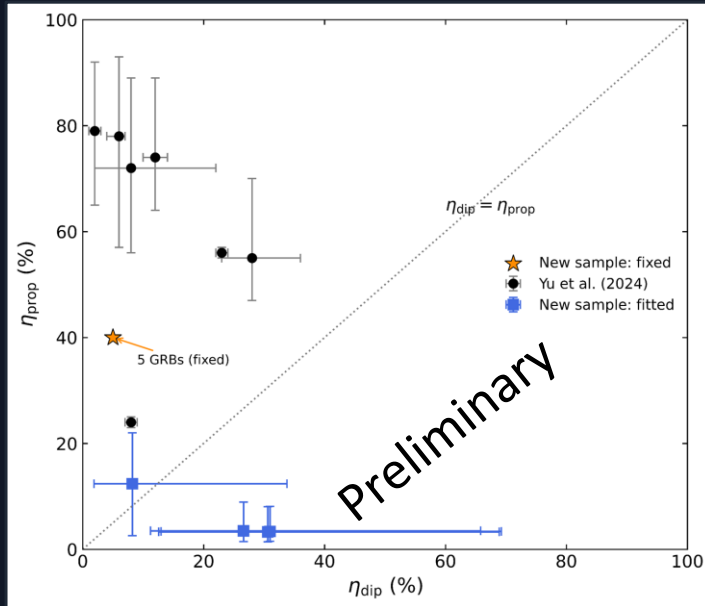
Best-fit magnetar and accretion parameters evaluated across sample GRB events

GRB	Band	Model	$n[F]$	B	P_i	$M_{D,i}$	R_D	ϵ	δ	η_{dip}	η_{prop}	$1/f_B$
				($\times 10^{15}$ G)	(ms)						(%)	(%)
160821B	Native	p9	100	$5.10^{+0.82}_{-0.80}$	$6.63^{+2.32}_{-1.93}$	$0.9^{+0.533}_{-0.295}$	$236.29^{+11.0}_{-10.6}$	$565.96^{+162.1}_{-145.5}$	$4.77^{+1.38}_{-1.24}$	$26.6^{+39.2}_{-15.4}$	$3.48^{+5.45}_{-1.99}$	$360.3^{+636.9}_{-258.4}$
180805B	Native	p9	10	$7.38^{+1.69}_{-1.85}$	$7.48^{+1.64}_{-1.78}$	$5.37^{+2.75}_{-2.28}$	$812.83^{+18.93}_{-18.50}$	$57.54^{+8.53}_{-8.56}$	$0.79^{+0.08}_{-0.09}$	$19.49^{+41.82}_{-14.81}$	$5.24^{+16.63}_{-3.54}$	$2818.38^{+7181.8}_{-2059.8}$
181123B	BAT	p7	1	$9.46^{+0.38}_{-0.61}$	$3.34^{+0.21}_{-0.26}$	$9.55^{+0.22}_{-0.64}$	$516.41^{+76.0}_{-76.3}$	$80.08^{+236.79}_{-56.52}$	$1.23^{+1.524}_{-1.230}$	5[F]	40[F]	$552.75^{+39.3}_{-59.8}$
200219A	XRT	p9	1	$9.34^{+0.49}_{-0.92}$	$2.70^{+0.76}_{-0.47}$	$6.16^{+2.54}_{-2.69}$	$478.63^{+11.08}_{-10.90}$	$0.10^{+0.004}_{-0.001}$	$35.48^{+10.22}_{-14.10}$	$3.46^{+7.00}_{-1.95}$	$23.44^{+16.02}_{-20.35}$	$36.30^{+75.89}_{-21.17}$
210323A	XRT	p9	100	$4.42^{+0.75}_{-0.75}$	$3.36^{+1.21}_{-1.05}$	$2.2^{+1.443}_{-0.742}$	$250.68^{+11.84}_{-11.31}$	$747.94^{+170.70}_{-216.50}$	$0.076^{+0.01327}_{-0.01560}$	$30.6^{+38.28}_{-18.02}$	$3.3^{+4.74}_{-1.87}$	$423.62^{+803.69}_{-291.68}$
210726A	XRT	p7	100	$0.84^{+0.14}_{-0.13}$	$4.63^{+2.32}_{-1.29}$	$3.6^{+1.381}_{-0.939}$	$373.8^{+55.04}_{-55.31}$	$7.98^{+13.436}_{-7.235}$	$0.022^{+0.02495}_{-0.00706}$	5[F]	40[F]	$423.09^{+122.96}_{-157.43}$
211023B	Native	p9	100	$4.23^{+0.75}_{-0.75}$	$2.40^{+1.21}_{-1.05}$	$2.19^{+1.44}_{-0.74}$	$251.19^{+11.84}_{-11.31}$	$741.31^{+170.70}_{-216.50}$	$7.58^{+1.327}_{-1.560} \times 10^{-2}$	$30.98^{+38.28}_{-18.02}$	$3.39^{+4.74}_{-1.87}$	$426.58^{+803.69}_{-291.68}$
230205A	Native	p9	1	$4.75^{+0.84}_{-1.04}$	$6.33^{+2.46}_{-2.40}$	$2.13^{+1.93}_{-0.75}$	$549.54^{+25.89}_{-12.50}$	$33.11^{+16.76}_{-7.99}$	$0.004^{+0.001}_{-0.001}$	$19.94^{+38.92}_{-13.49}$	$5.01^{+10.38}_{-3.32}$	$2238.72^{+5536.67}_{-1717.92}$
231117A	Native	p9	100	$9.98^{+0.01}_{-0.02}$	$3.11^{+0.02}_{-0.03}$	$9.9^{+0.00}_{-0.00}$	$88.27^{+2.08}_{-2.03}$	$0.5^{+1.494}_{-0.339}$	$2.0^{+3.070}_{-1.616} \times 10^{-4}$	$8.2^{+25.57}_{-6.32}$	$12^{+39.60}_{-9.79}$	$406.17^{+1290.86}_{-307.38}$

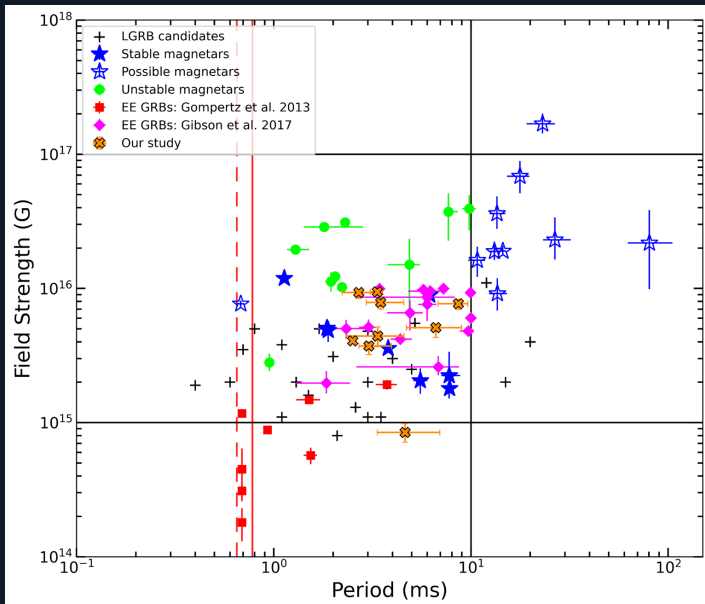
Magnetic Field Strength vs. Spin Period



Efficiency Distribution (η_{dip} vs η_{prop})



Magnetic Field Strength vs. Spin Period



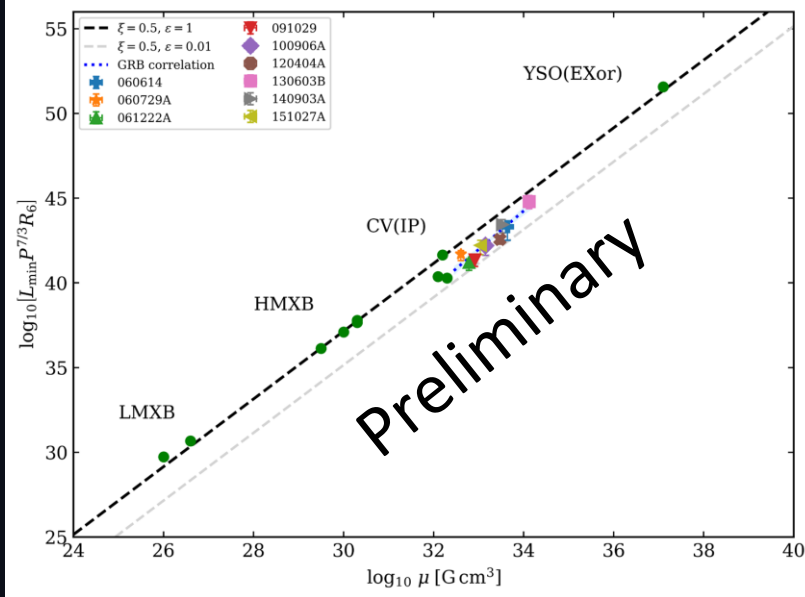
Interpretation of Results | Statistical Parameter Fitting & Sample Correlations

Summary of Derived Fit Parameters

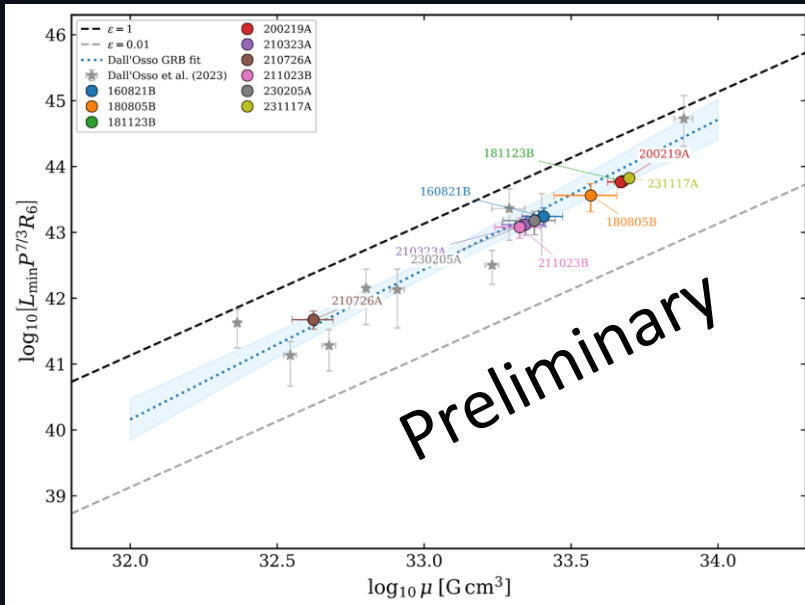
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GRB	Band	Model	$n[F]$	B ($\times 10^{15}$ G)	P_i (ms)	$M_{D,i}$ ($\times 10^{-2} M_{\odot}$)	R_D (km)	ϵ	δ	η_{dip} (%)	η_{prop} (%)	$1/f_B$
160821B	Native	p9	100	$5.10^{+0.82}_{-0.80}$	$6.63^{+2.32}_{-1.93}$	$0.9^{+0.533}_{-0.295}$	$236.29^{+11.0}_{-10.6}$	$565.96^{+162.1}_{-145.5}$	$4.77^{+1.38}_{-1.24}$	$26.6^{+39.2}_{-15.4}$	$3.48^{+5.45}_{-1.99}$	$360.3^{+636.9}_{-258.4}$
180805B	Native	p9	10	$7.38^{+1.69}_{-1.85}$	$7.48^{+1.64}_{-1.78}$	$5.37^{+2.75}_{-2.28}$	$812.83^{+18.93}_{-18.50}$	$57.54^{+8.53}_{-8.56}$	$0.79^{+0.08}_{-0.09}$	$19.49^{+41.82}_{-14.81}$	$5.24^{+16.63}_{-3.54}$	$2818.38^{+7181.8}_{-2059.8}$
181123B	BAT	p7	1	$9.46^{+0.38}_{-0.61}$	$3.34^{+0.21}_{-0.26}$	$9.55^{+0.22}_{-0.64}$	$516.41^{+76.0}_{-76.3}$	$80.08^{+236.79}_{-56.52}$	$1.23^{+1.524}_{-1.230}$	5[F]	40[F]	$552.75^{+39.3}_{-59.8}$
200219A	XRT	p9	1	$9.34^{+0.49}_{-0.92}$	$2.70^{+0.76}_{-0.47}$	$6.16^{+2.54}_{-2.69}$	$478.63^{+11.08}_{-10.90}$	$0.10^{+0.004}_{-0.001}$	$35.48^{+10.22}_{-14.10}$	$3.46^{+7.00}_{-1.95}$	$23.44^{+16.02}_{-20.35}$	$36.30^{+75.89}_{-21.17}$
210323A	XRT	p9	100	$4.42^{+0.75}_{-0.75}$	$3.36^{+1.21}_{-1.05}$	$2.2^{+1.443}_{-0.742}$	$250.68^{+11.84}_{-11.31}$	$747.94^{+170.70}_{-216.50}$	$0.076^{+0.01327}_{-0.01560}$	$30.6^{+38.28}_{-18.02}$	$3.3^{+4.74}_{-1.87}$	$423.62^{+803.69}_{-291.68}$
210726A	XRT	p7	100	$0.84^{+0.14}_{-0.13}$	$4.63^{+2.32}_{-1.29}$	$3.6^{+1.381}_{-0.939}$	$373.8^{+55.04}_{-55.31}$	$7.98^{+13.436}_{-7.235}$	$0.022^{+0.02495}_{-0.00706}$	5[F]	40[F]	$423.09^{+122.96}_{-157.43}$
211023B	Native	p9	100	$4.23^{+0.75}_{-0.75}$	$2.40^{+1.21}_{-1.05}$	$2.19^{+1.44}_{-0.74}$	$251.19^{+11.84}_{-11.31}$	$741.31^{+170.70}_{-216.50}$	$7.58^{+1.327}_{-1.560} \times 10^{-2}$	$30.98^{+38.28}_{-18.02}$	$3.39^{+4.74}_{-1.87}$	$426.58^{+803.69}_{-291.68}$
230205A	Native	p9	1	$4.75^{+0.84}_{-1.04}$	$6.33^{+2.46}_{-2.40}$	$2.13^{+1.93}_{-0.75}$	$549.54^{+25.89}_{-12.50}$	$33.11^{+16.76}_{-7.99}$	$0.004^{+0.001}_{-0.001}$	$19.94^{+38.92}_{-13.49}$	$5.01^{+10.38}_{-3.32}$	$2238.72^{+5536.67}_{-1717.92}$
231117A	Native	p9	100	$9.98^{+0.01}_{-0.02}$	$3.11^{+0.02}_{-0.03}$	$9.9^{+0.00}_{-0.00}$	$88.27^{+2.08}_{-2.03}$	$0.5^{+1.494}_{-0.339}$	$2.0^{+3.070}_{-1.616} \times 10^{-4}$	$8.2^{+25.57}_{-6.32}$	$12^{+39.60}_{-9.79}$	$406.17^{+1290.86}_{-307.38}$

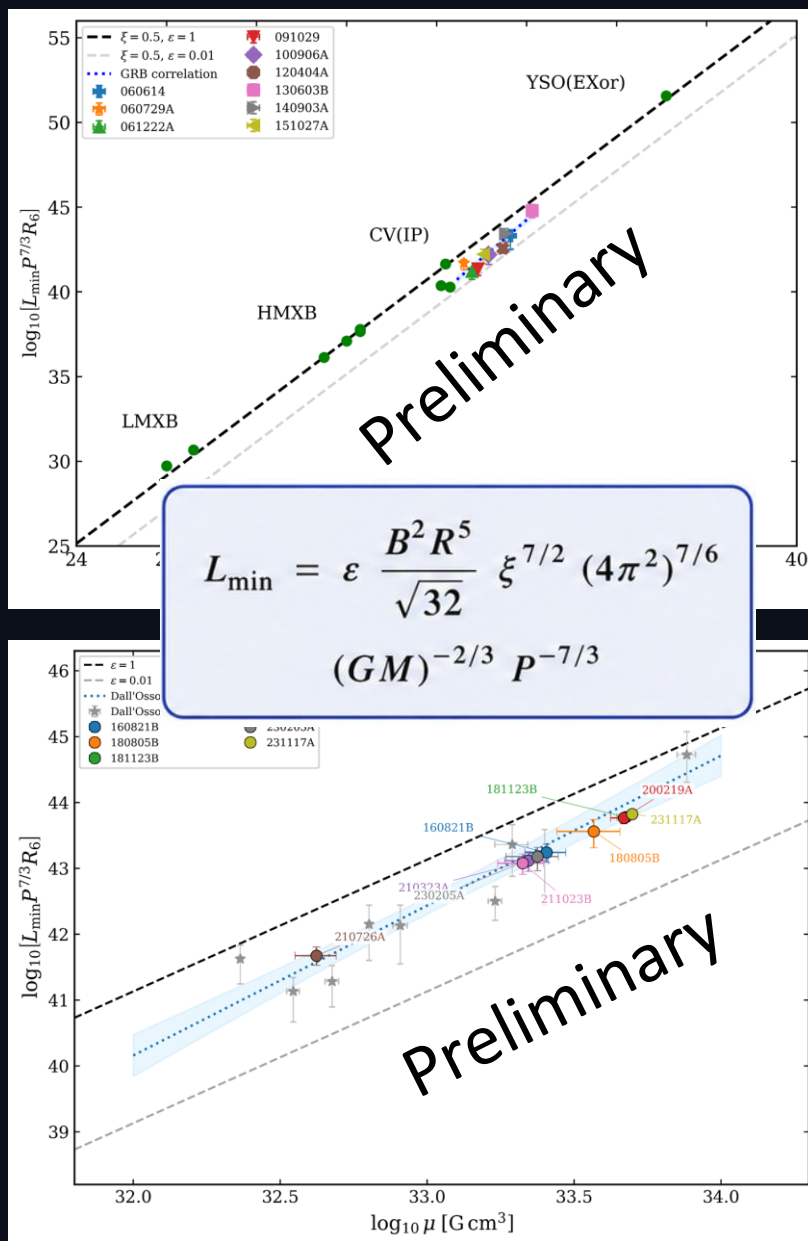
Universal Relation of Accreting Magnetic Stars



$$L_{\min} = \epsilon \frac{B^2 R^5}{\sqrt{32}} \xi^{7/2} (4\pi^2)^{7/6} (GM)^{-2/3} P^{-7/3}$$

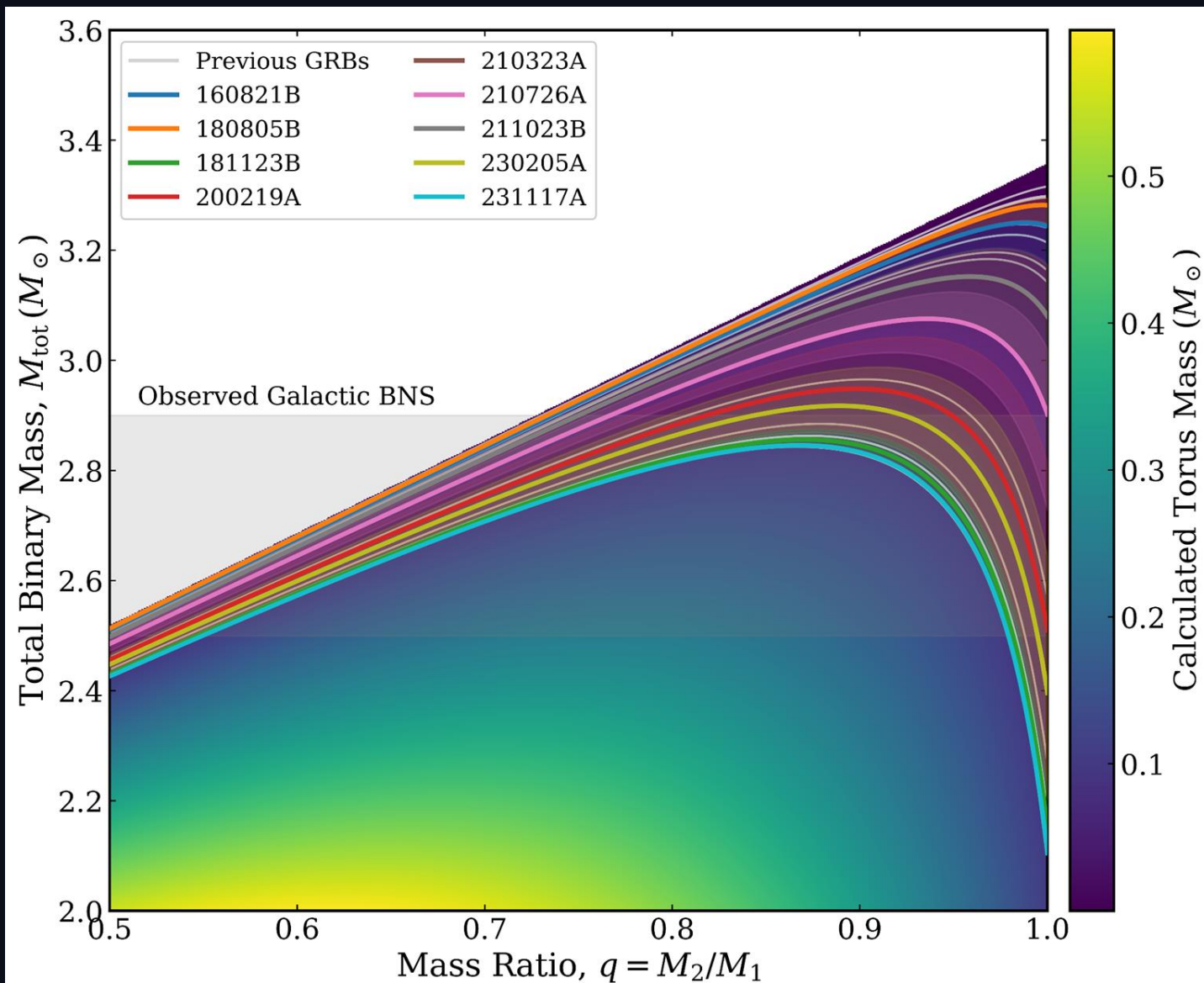


Universal Relation of Accreting Magnetic Stars



Parameter space for the binary neutron star merger

$$M_{\text{torus}} = [c_1(1 - q) + c_2] [c_3(1 + q) - M_{\text{tot}}/M_{\text{max}}]$$



Summary & take-home message

Fallback accretion + magnetar propeller framework for short GRBs with extended X-ray emission

144 → 9

Swift-era short GRBs reduced to the extended-emission target sample

1 Central-engine interpretation

The extended X-ray component is modeled as fallback-fed magnetar activity: early accretion, a propeller phase and late dipole spin-down.

2 Fitting strategy

Bayesian MCMC fitting is performed in 0.3–10 keV, 15–50 keV and native bands; p6–p9 models are compared using χ^2 , AICc and BIC.

3 Physical constraints

Best-fit B, P_i , disc/fallback mass, radius, beaming and efficiencies connect the light curves to remnant and BNS merger parameter space.

Take-home: Extended X-ray emission in short GRBs provides a measurable route to constrain magnetar spin, magnetic field, fallback disc properties and the post-merger remnant.

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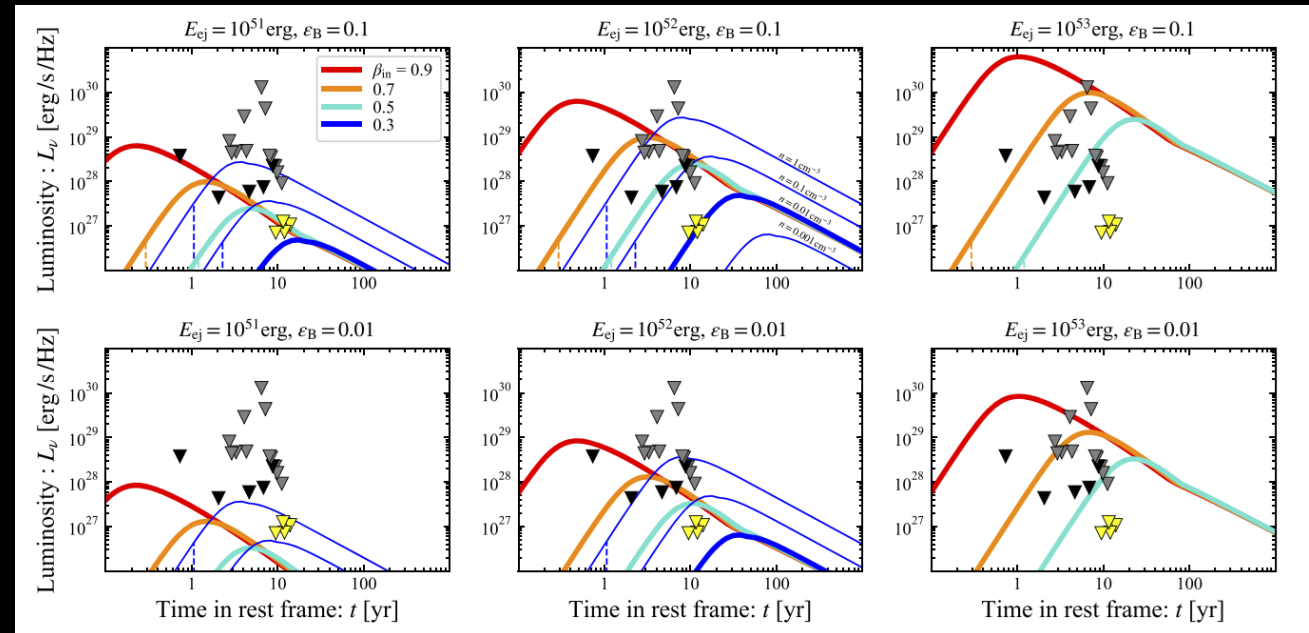
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Take-home: Extended X-ray emission in short GRBs provides a measurable route to constrain magnetar spin, magnetic field, fallback disc property and the post-merger remnant.

Future prospects

Magnetar driven radio emission from kilonova afterglow



Ghosh et al. 2024, Ricci et al. 2021

THANK YOU



Our Future. Reimagined.



Derivation of the Propeller Threshold Luminosity, $L_{\min}$

Propeller onset occurs when the magnetospheric radius equals the corotation radius.

Definitions

$$L_{\min} = \varepsilon \frac{GM\dot{M}_{\min}}{R}$$

$$r_m = \xi \left(\frac{\mu^4}{2GM\dot{M}^2} \right)^{1/7}$$

$$r_{\text{co}} = \left(\frac{GM}{\omega^2} \right)^{1/3}$$

$$\omega = \frac{2\pi}{P}$$

$$\mu = \frac{BR^3}{2}$$

B : Surface magnetic field

R : Stellar radius

M : Stellar mass

P : Spin period

ξ : Dimensionless factor (~ 0.5)

ε : Radiative efficiency (~ 0.1)

G : Gravitational constant

1 At the transition: $r_m = r_{\text{co}}$

2 Substitute $\mu = \frac{BR^3}{2}$ into r_m :

$$r_m = \xi \left(\frac{B^4 R^{12}}{32GM\dot{M}^2} \right)^{1/7}$$

3 Corotation radius: $r_{\text{co}} = \left(\frac{GMP^2}{4\pi^2} \right)^{1/3}$

4 Set $r_m = r_{\text{co}}$ and solve for $\dot{M}_{\min}$:

$$\dot{M}_{\min} = \frac{B^2 R^6}{\sqrt{32}} \xi^{7/2} (4\pi^2)^{-7/6} (GM)^{-5/3} P^{-7/3}$$

5 Substitute into luminosity: $L_{\min} = \varepsilon \frac{GM\dot{M}_{\min}}{R}$

6 Final result:

$$L_{\min} = \varepsilon \frac{B^2 R^5}{\sqrt{32}} \xi^{7/2} (4\pi^2)^{7/6} (GM)^{-2/3} P^{-7/3}$$

7 Scaling takeaway:

$$L_{\min} \propto B^2 P^{-7/3}$$

(for fixed M , R , ξ , and ε)

Dall'Osso et al.2023

8 Compact normalized form:

$$L_{\min} \approx 6.9 \times 10^{46} \varepsilon_{0.2} \xi_{0.5}^{7/2} B_{14}^2 R_6^5 M_{1.4}^{-2/3} P_{(-3)}^{-7/3} \text{ erg s}^{-1}$$

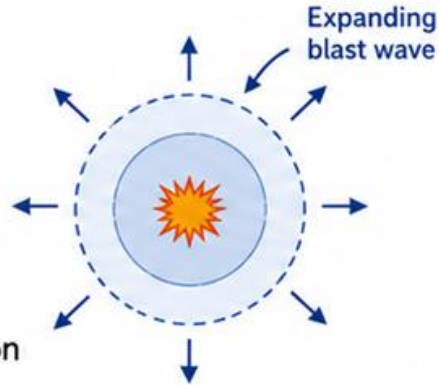
where $\varepsilon_{0.2} = \varepsilon/0.2$, $\xi_{0.5} = \xi/0.5$, $B_{14} = B/10^{14}$ G, $R_6 = R/10^6$ cm,
 $M_{1.4} = M/1.4 M_{\odot}$, $P_{(-3)} = P/10^{-3}$ s

Formulations for continuous energy injection from magnetar

1 Physical picture / assumptions

- Initial impulsive energy input: E_{imp}
- Continuous luminosity source:

$$L(T) = L_0 \left(\frac{T}{T_0} \right)^q$$
- Late-time evolution follows the Blandford–McKee self-similar solution



2 Source-frame differential equation

$$\frac{dE}{dt} = L_0 \left(\frac{t}{t_0} \right)^{q'} - \frac{k'}{t} E$$

- E and t : energy and time in the fixed (source) frame
- q' : dimensionless energy-injection index
- k' : dimensionless radiative-loss index
- assume $q' \neq -1 - k'$

Standard linear ODE form:

$$\frac{dE}{dt} + \frac{k'}{t} E = L_0 \left(\frac{t}{t_0} \right)^{q'}$$

Integrating factor:

$$\mu(t) = \exp \left[\int \frac{k'}{t} dt \right] = t^{k'}$$

3 Analytical solution in the source frame

$$\frac{d}{dt} (t^{k'} E) = L_0 t^{k'} \left(\frac{t}{t_0} \right)^{q'}$$

$$\int \frac{d}{dt} (t^{k'} E) dt = \int L_0 t^{k'} \left(\frac{t}{t_0} \right)^{q'} dt$$

$$E(t) = \frac{L_0 t_0}{k' + q' + 1} \left(\frac{t}{t_0} \right)^{q'+1} + E_{\text{imp}} \left(\frac{t}{t_0} \right)^{-k'}$$

4 Conversion to observer frame

$$\Gamma^2 \propto t^{-m}$$

$$k' = m - 3$$

For an adiabatic blast wave:

$$k' = 0 \Rightarrow m = 3$$

$$dT \approx \frac{dt}{2\Gamma^2}$$

$$T_0 = \frac{t_0}{2(m+1)\Gamma^2(t_0)}$$

$$E(T) = \frac{L_0}{k + q + 1} \left(\frac{T}{T_0} \right)^q T + E_{\text{imp}} \left(\frac{T}{T_0} \right)^{-k}$$

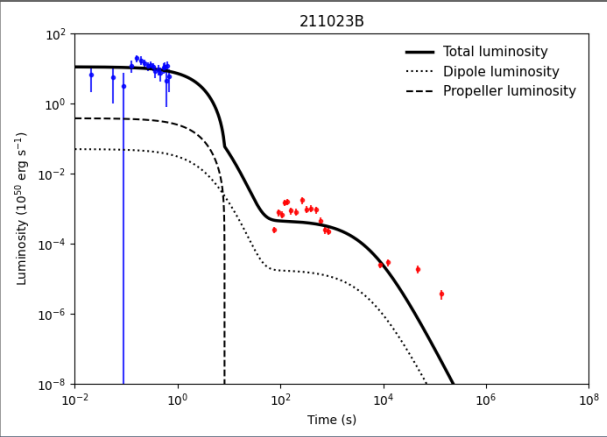
$$L(T) = L_0 \left(\frac{T}{T_0} \right)^q \quad (\text{intrinsic luminosity})$$



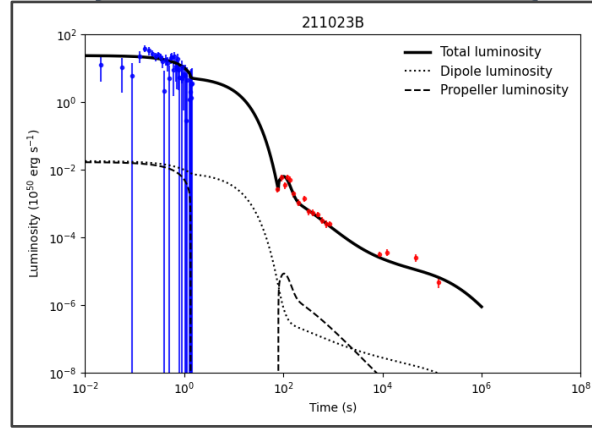
The total energy is the sum of a continuous-injection term and a decaying impulsive term.

GRB 211023B

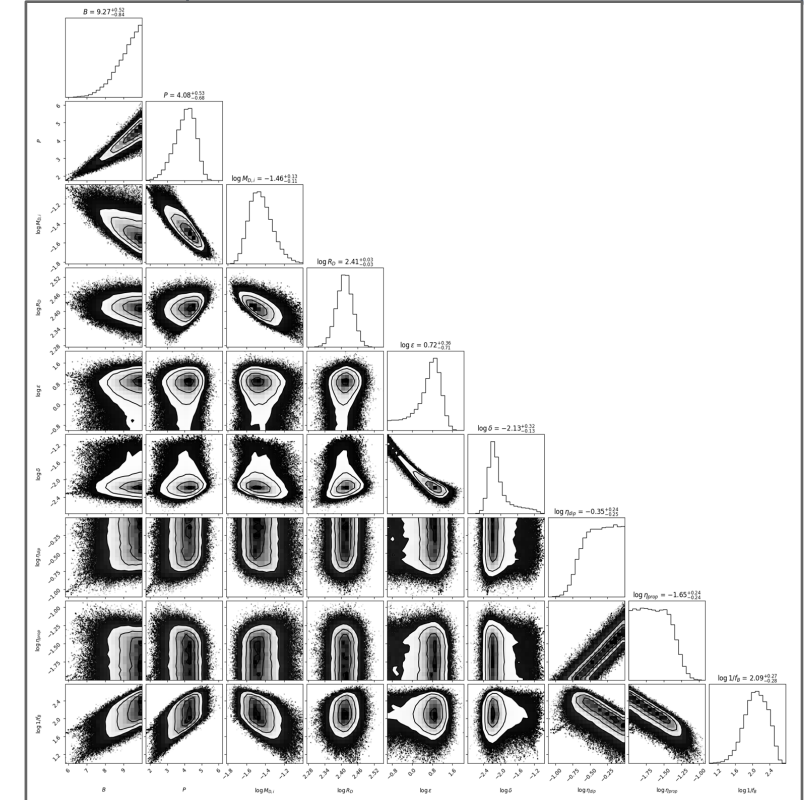
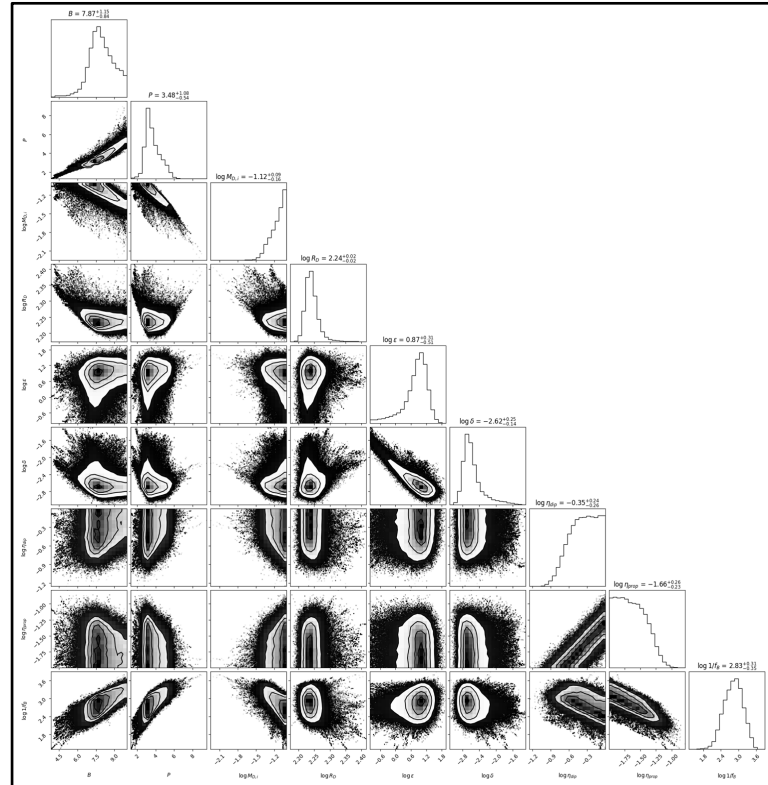
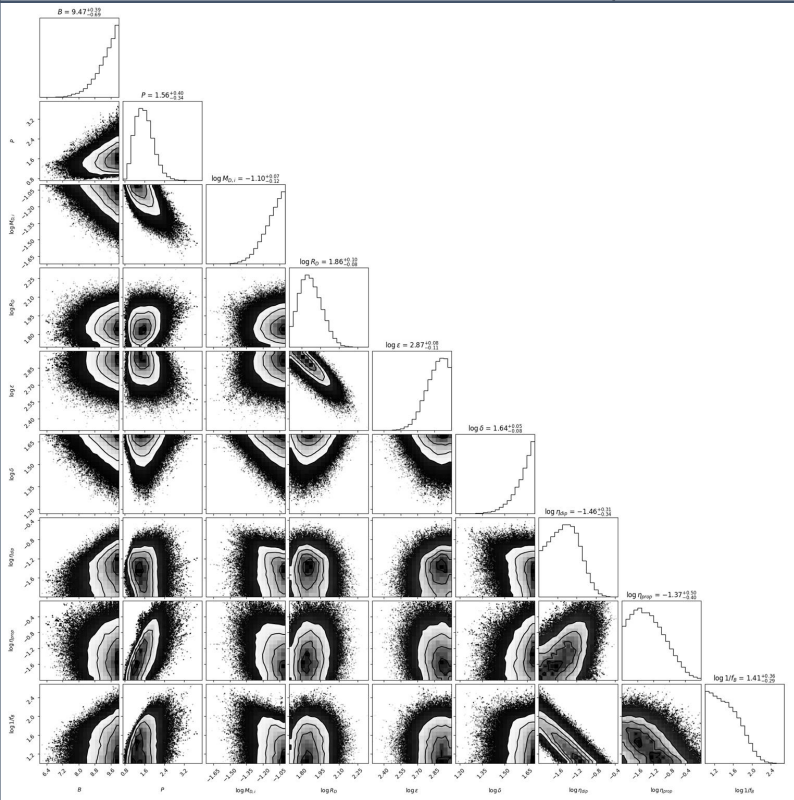
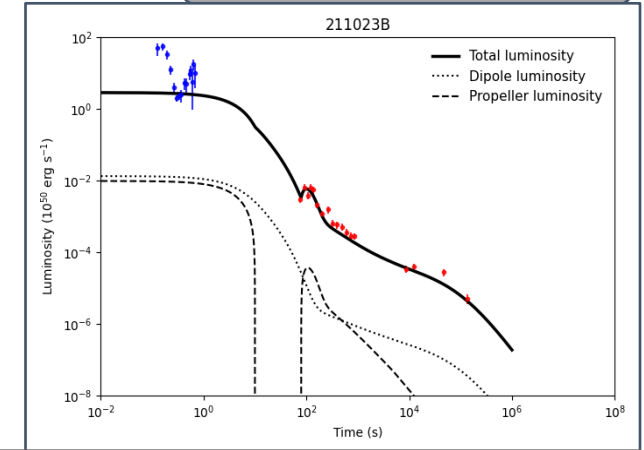
15-50 keV



Native

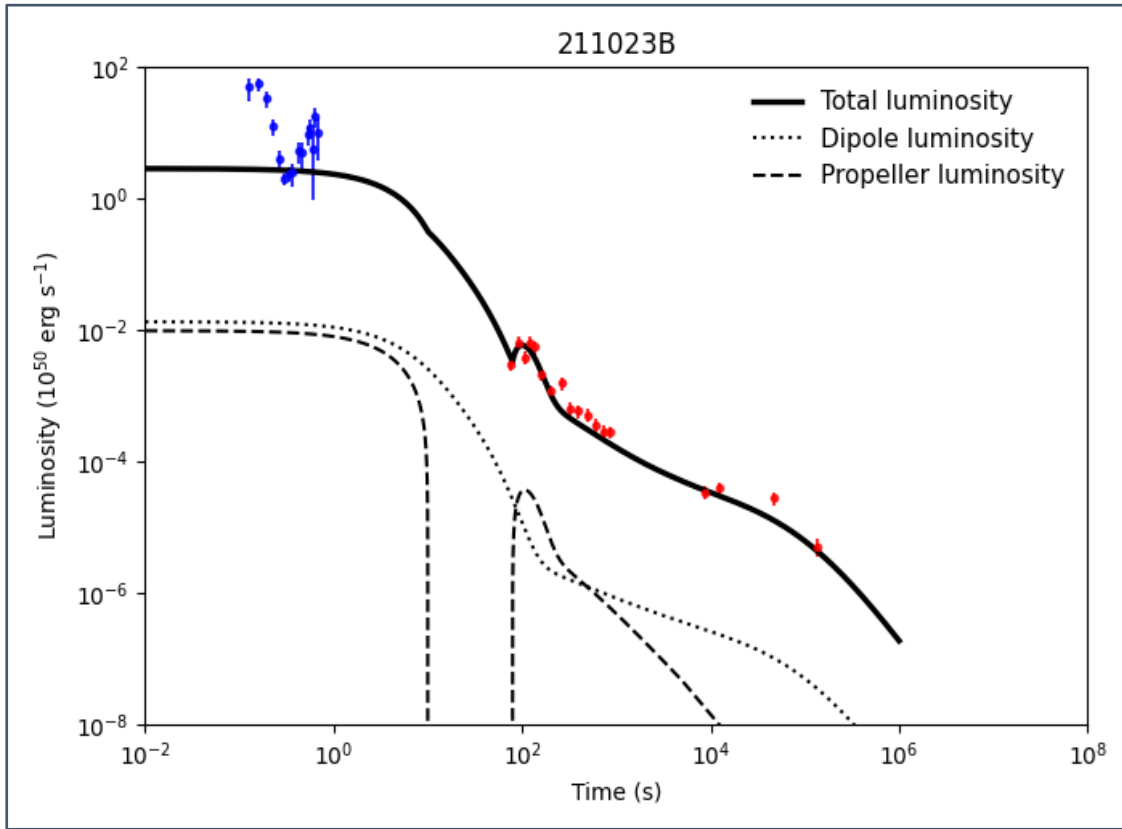


0.3-10 keV

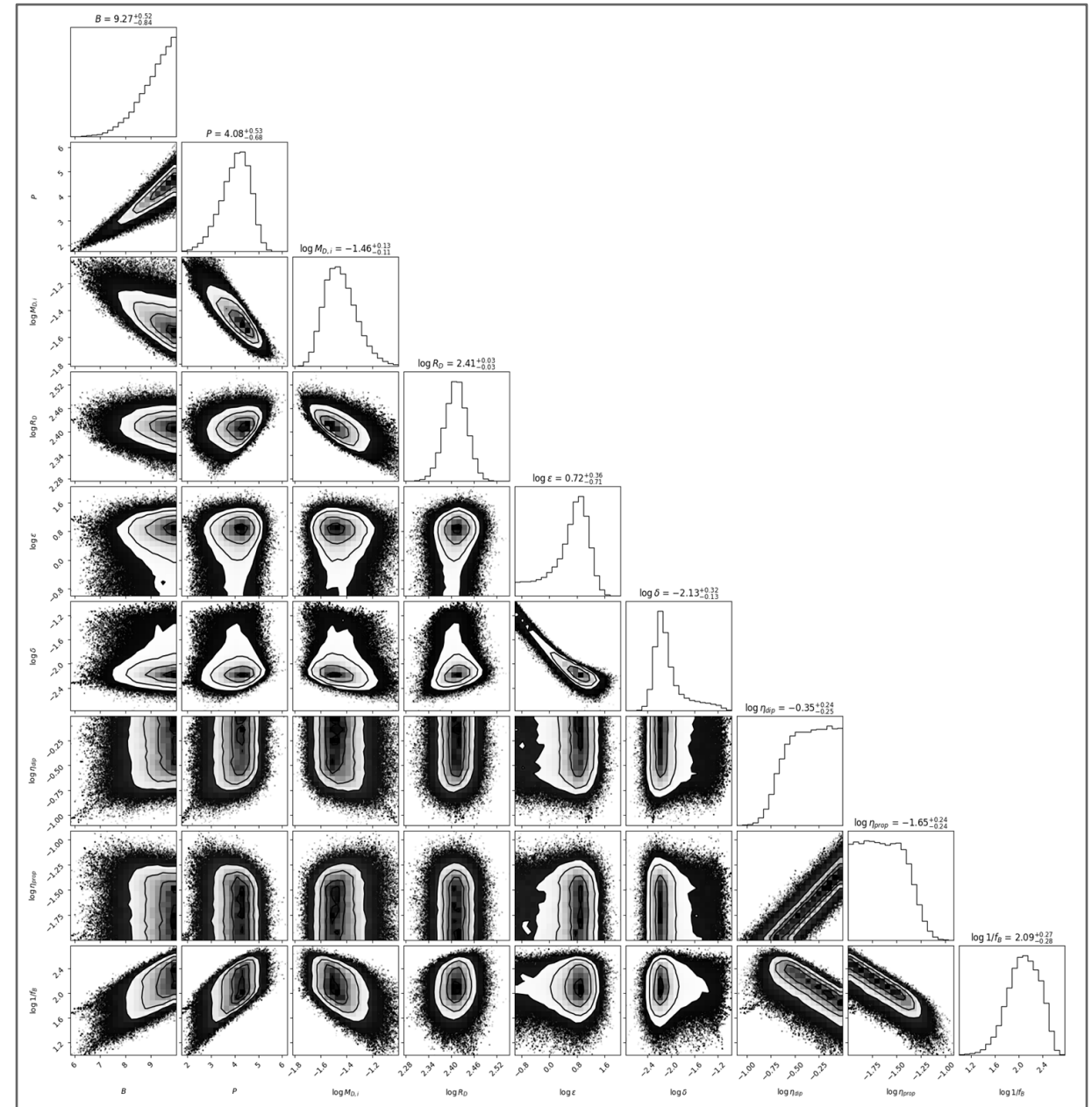


GRB 211023B

0.3-10 keV

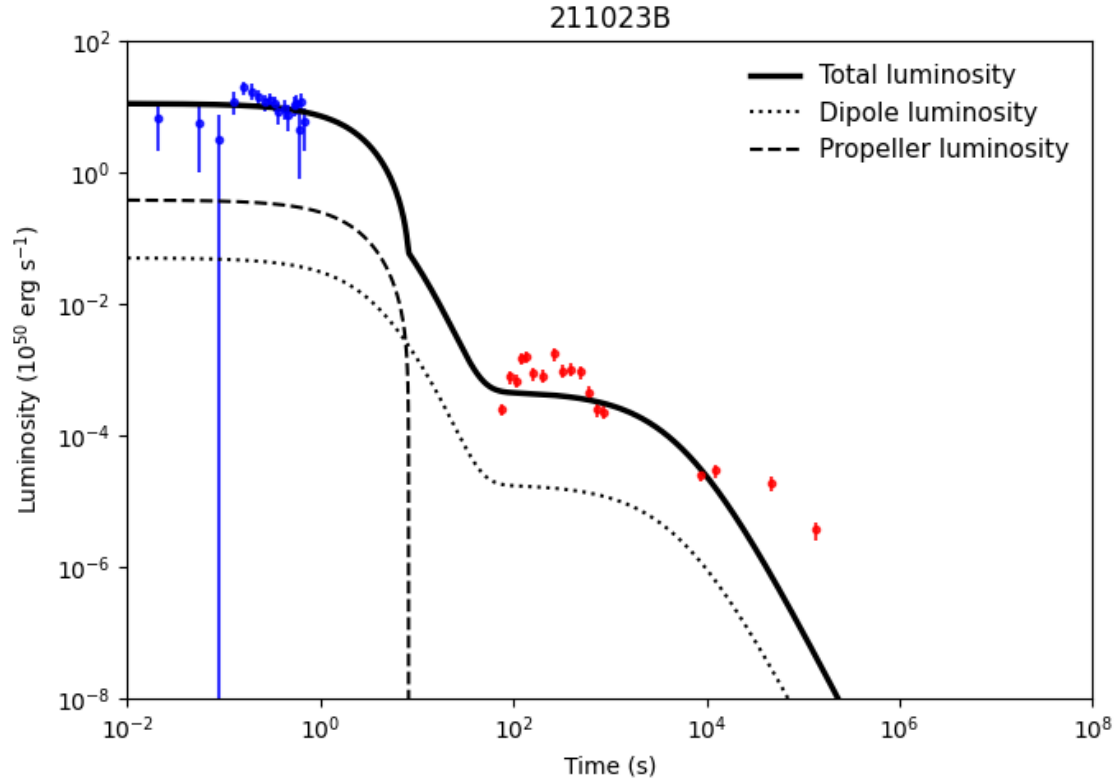


REDUCED_CHI2 = 4.681393000
 AICC = 133.498125961
 BIC = 139.140607057

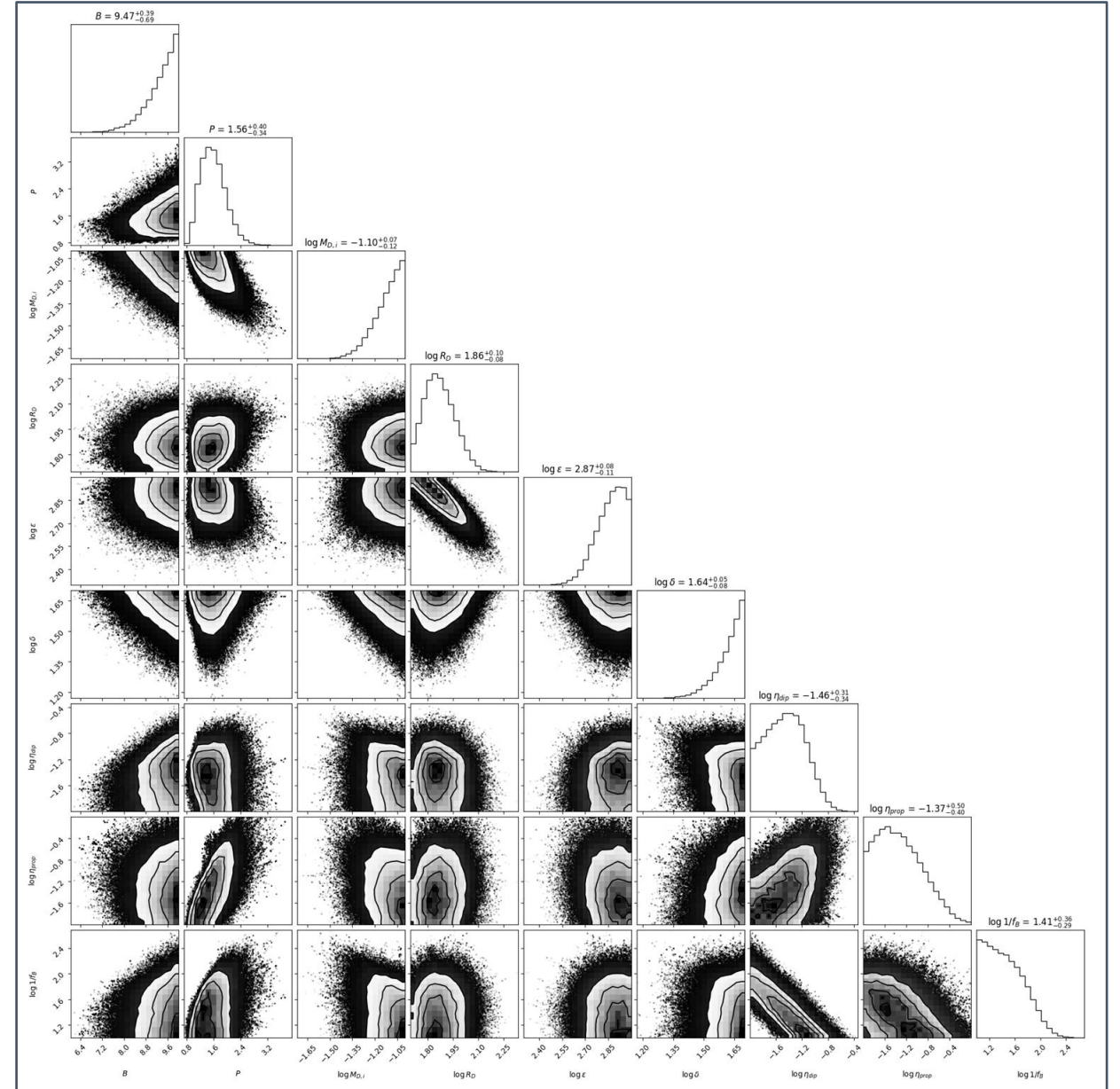


GRB 211023B

15-50 keV

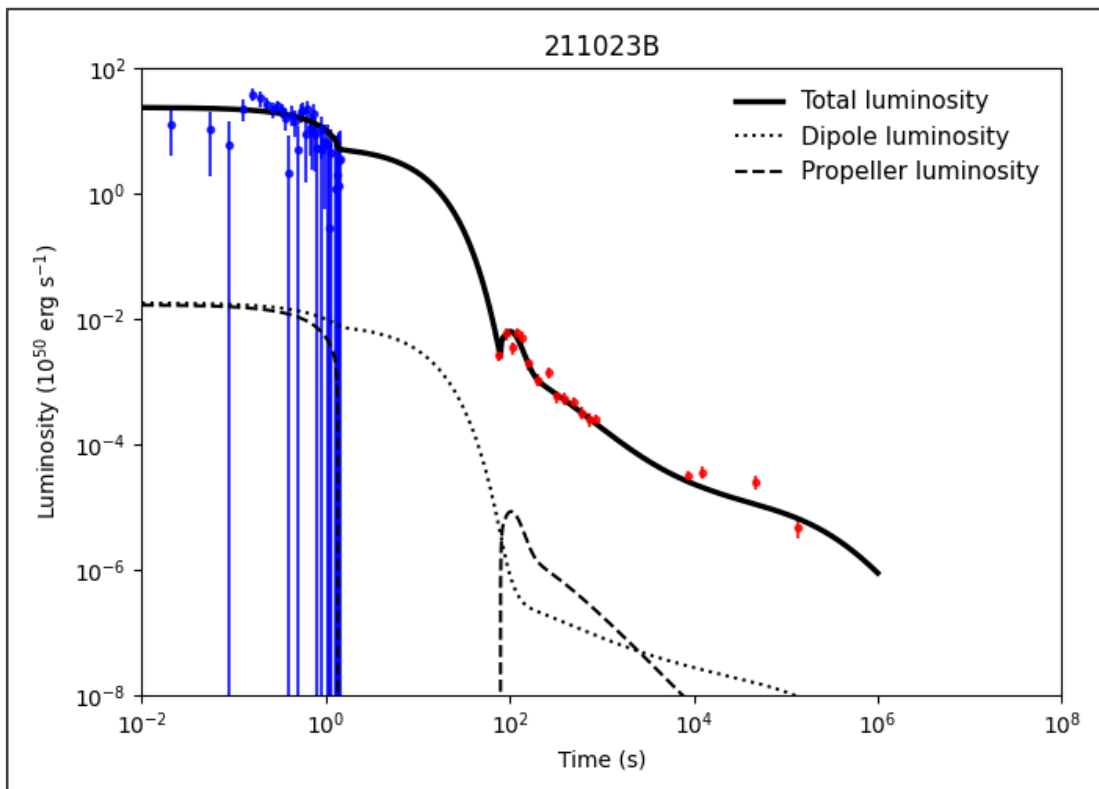


REDUCED_CHI2 = 5.555255543
 AICC = 169.359721043
 BIC = 176.688314566



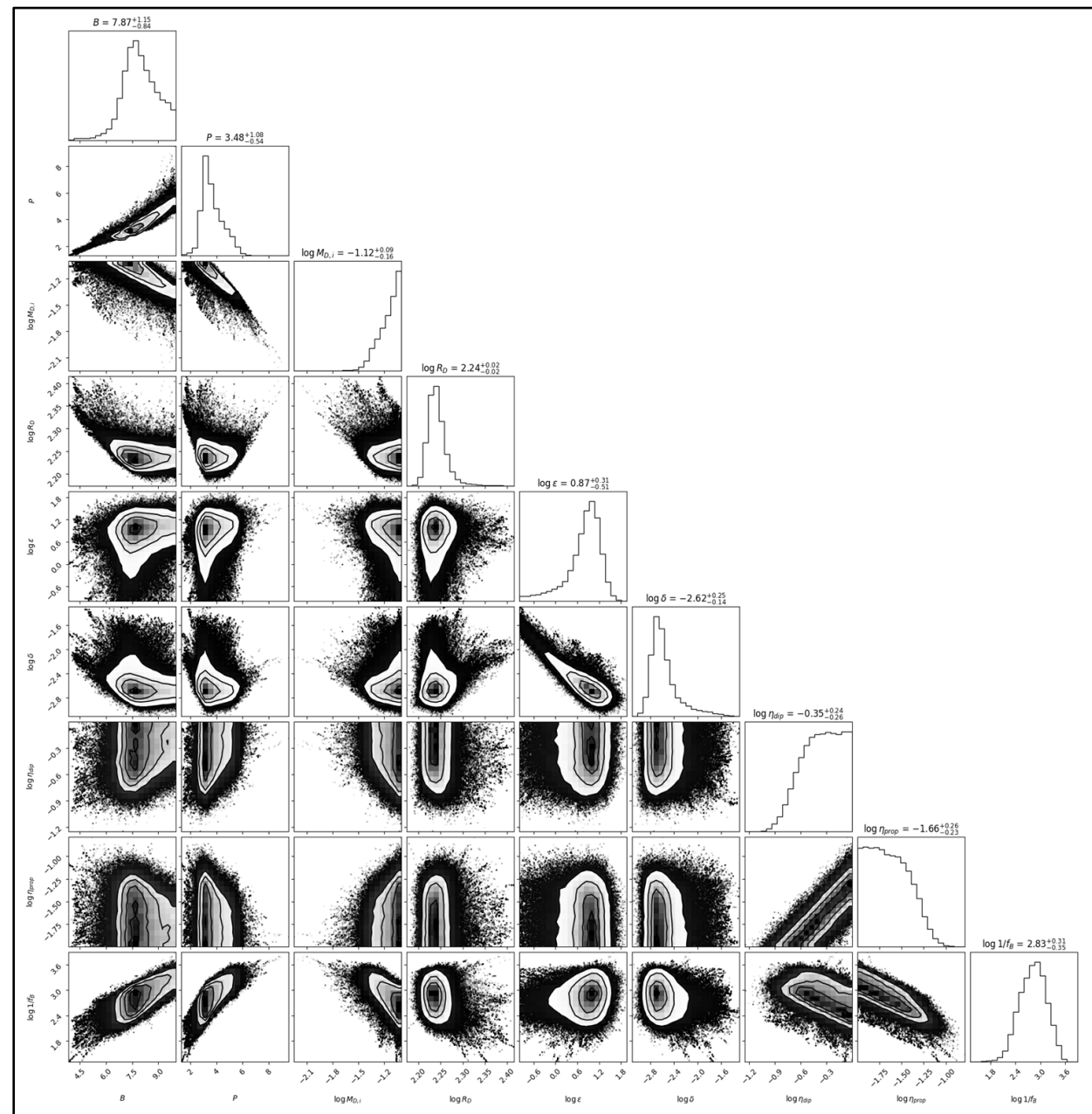
Native

GRB 211023B



$N = 100, p = 9$

REDUCED_CHI2 = 1.602261483
 AICC = 91.0832903
 BIC = 104.629871



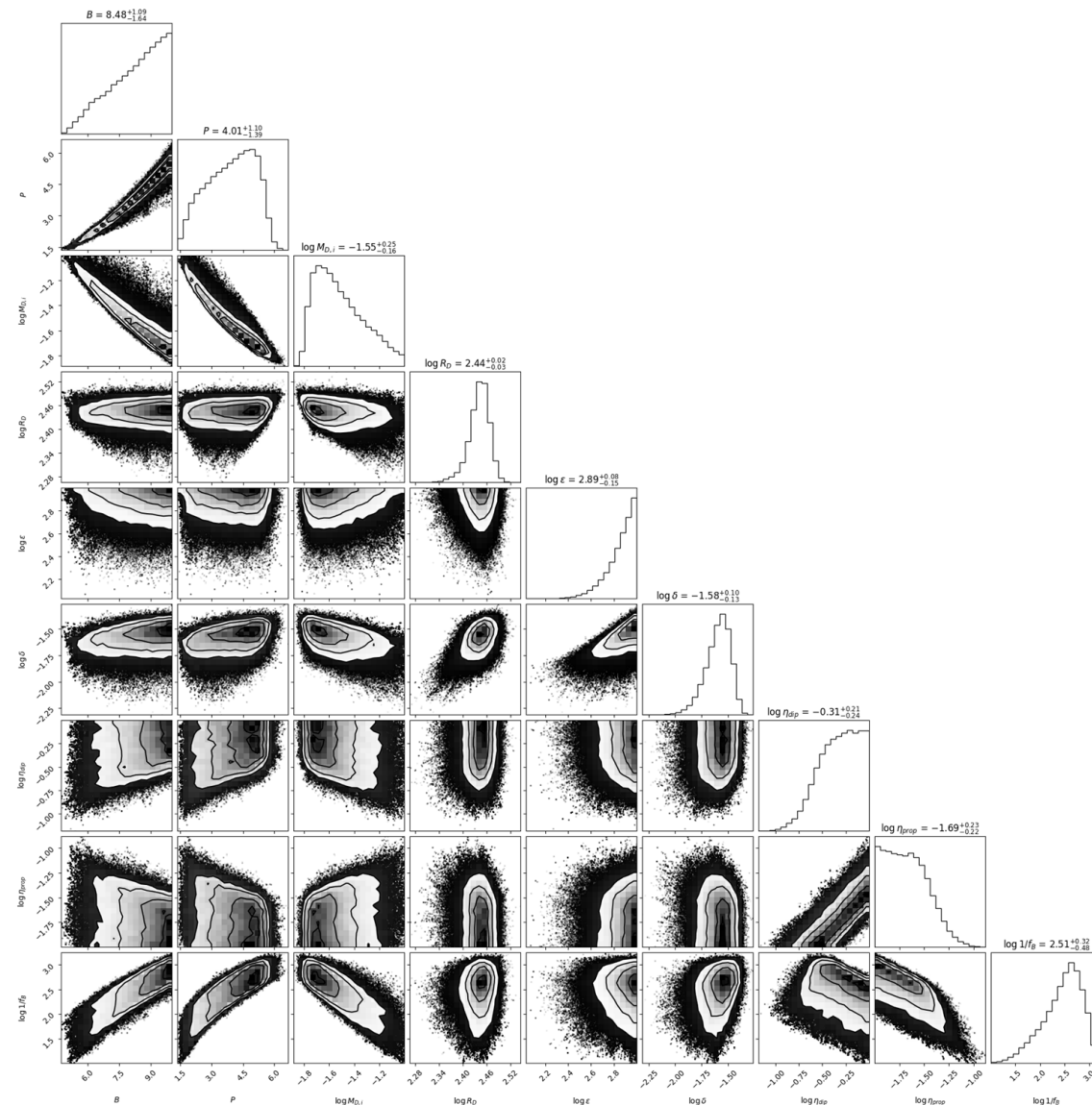
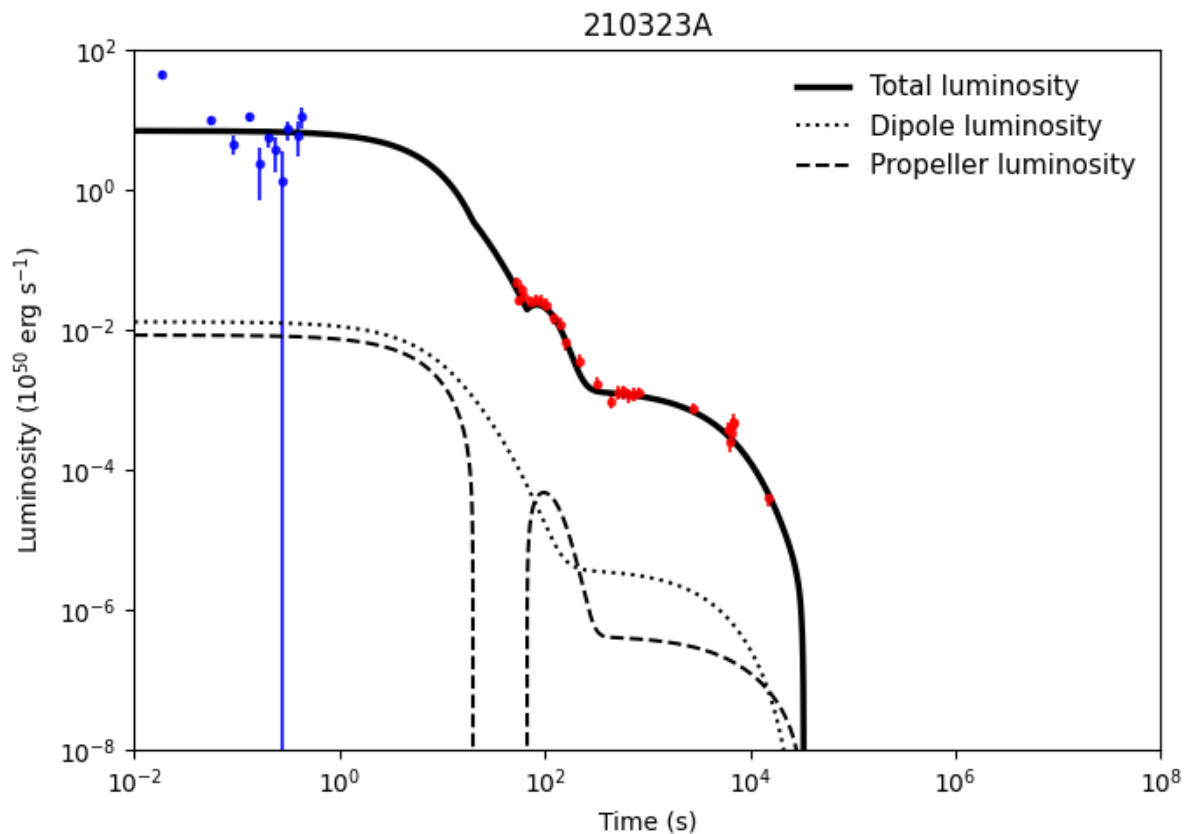
$n=1$

$p=9$

Just to check how the corner and fits are
varying

Testing for different chain of MCMC

GRB 210323A (run = 10000)



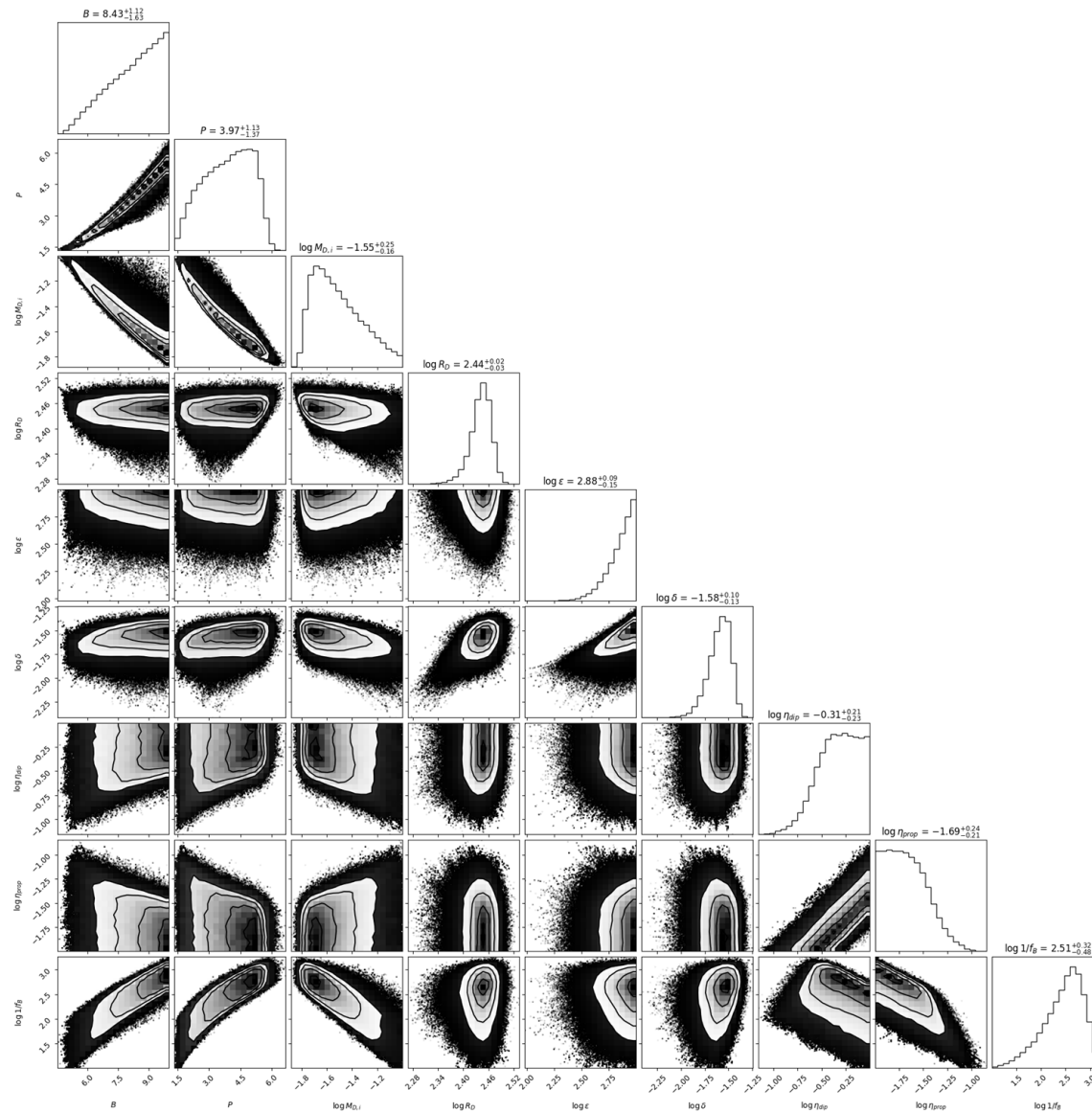
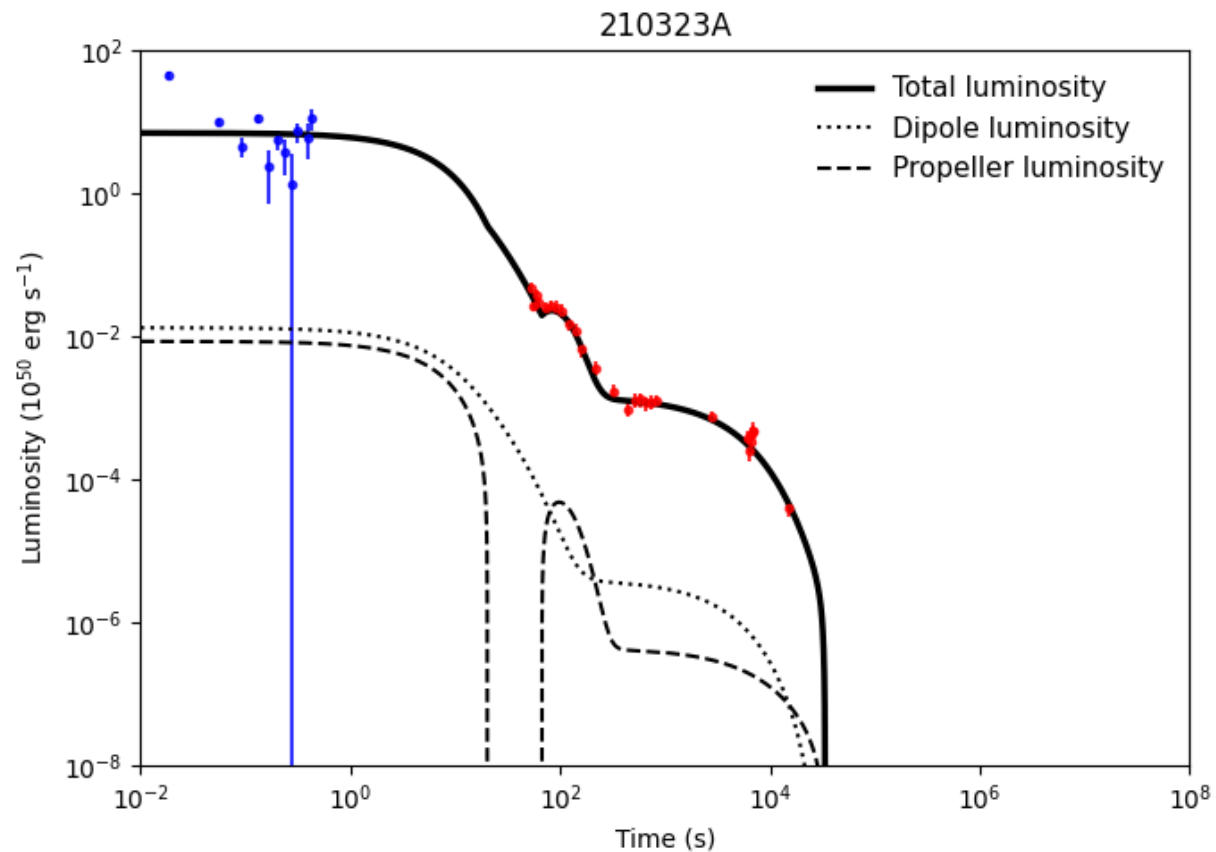
$n=1$

$p=9$

Just to check how the corner and fits are
varying

Testing for different chain of MCMC

GRB 210323A (run = 30000)



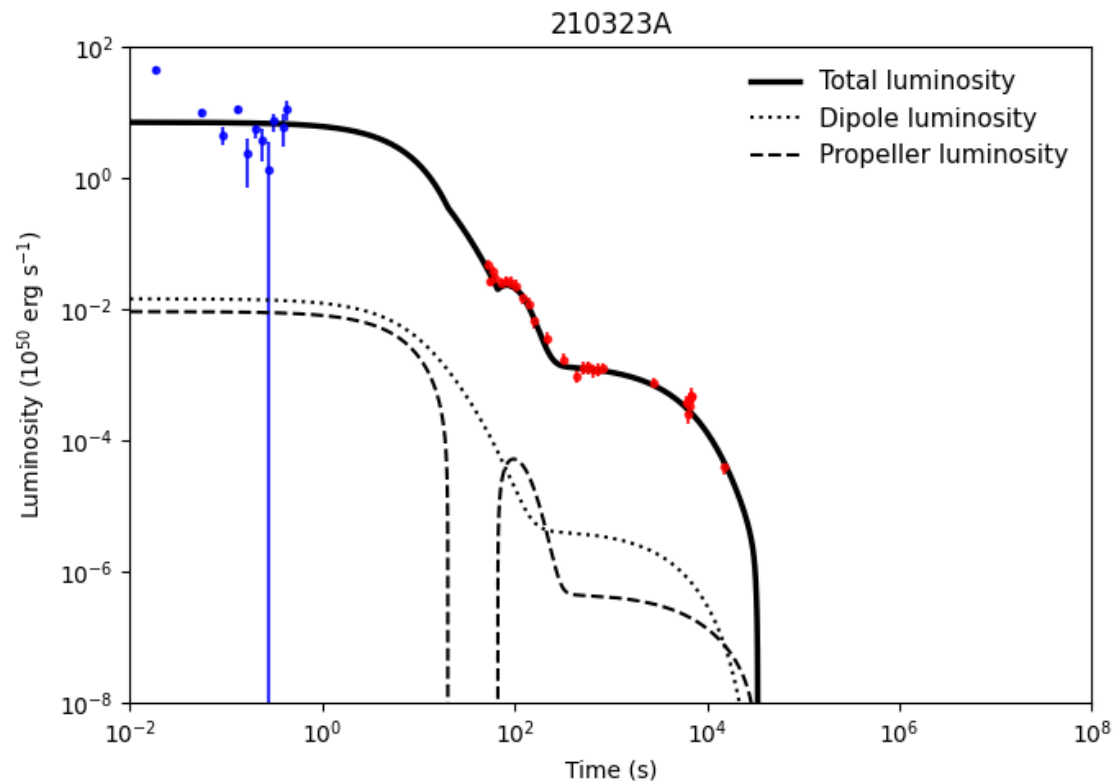
$n=1$

$p=9$

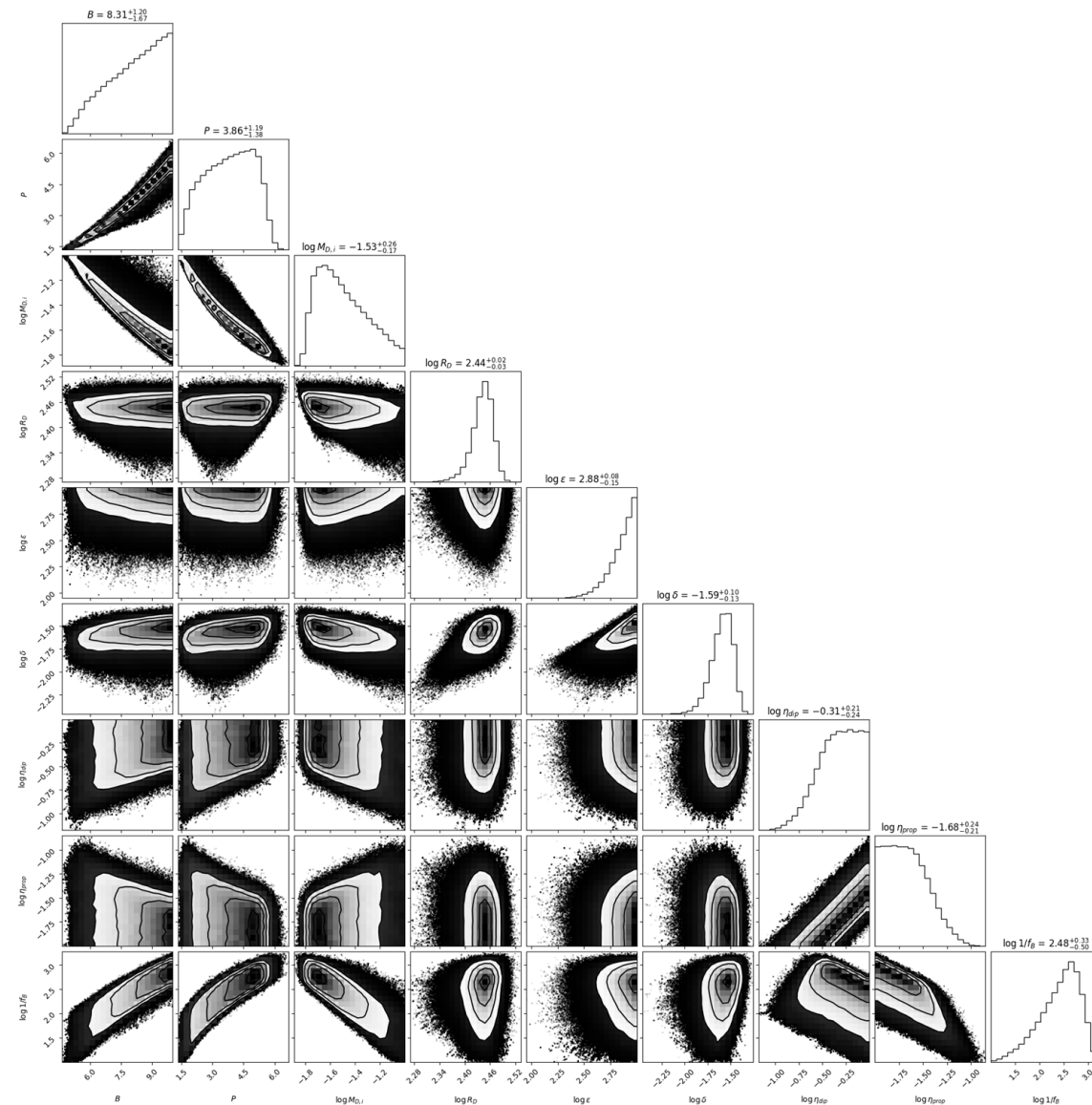
Just to check how the corner and fits are
varying

Testing for different chain of MCMC

GRB 210323A (run = 50000)



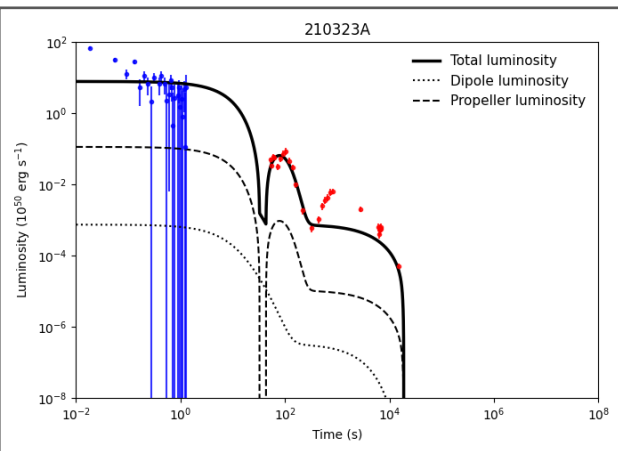
Note that the reduced chi square, AIC and BIC values are almost same which implies the chains are saturated after a certain run



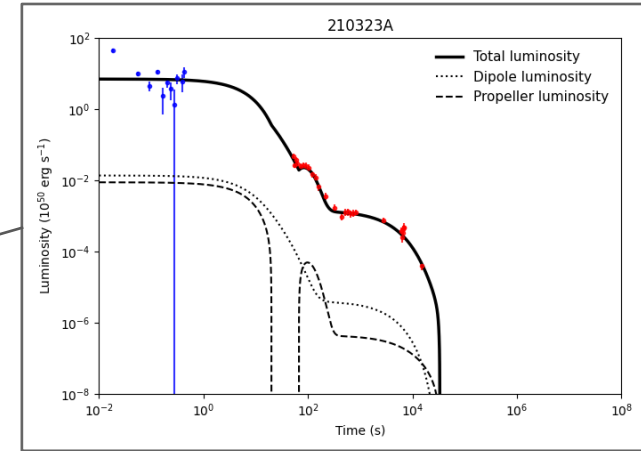
15-50 keV

GRB 210323A

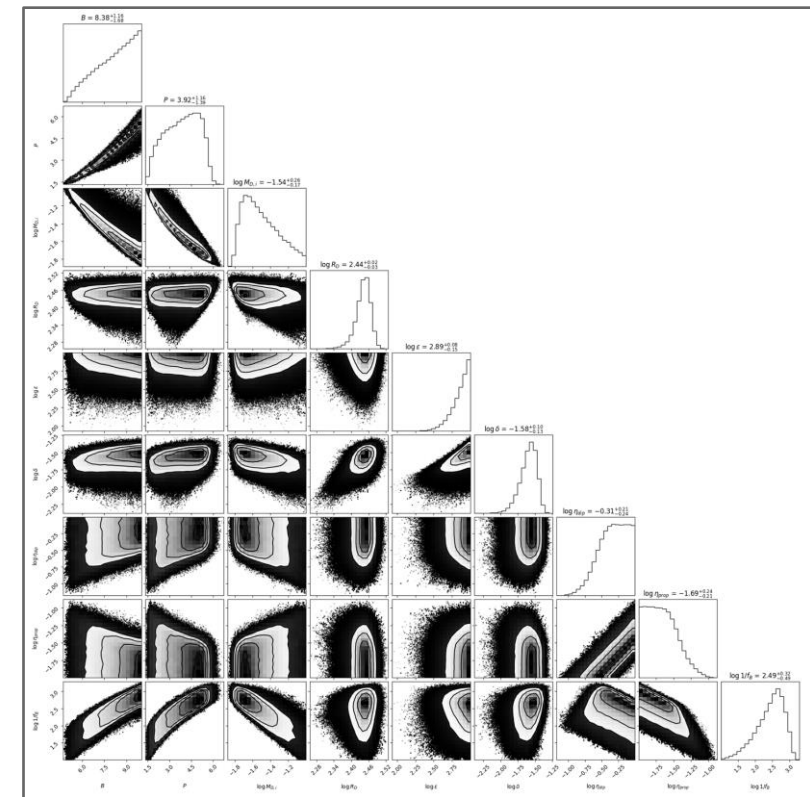
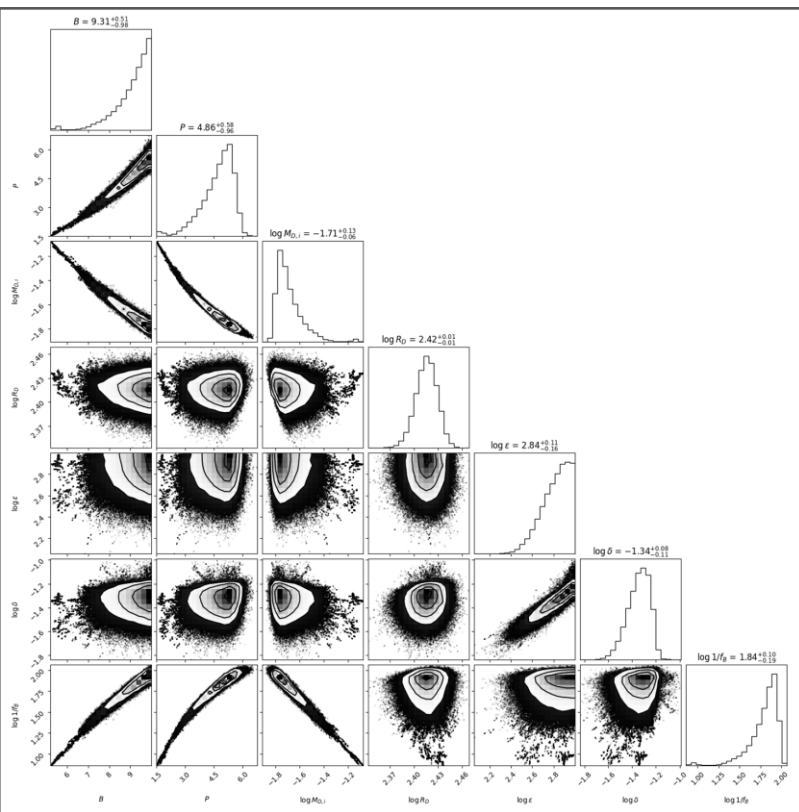
0.3-10 keV



REDUCED_CHI2 = 5.041001405
AICC = 165.576610759
BIC = 173.886314768



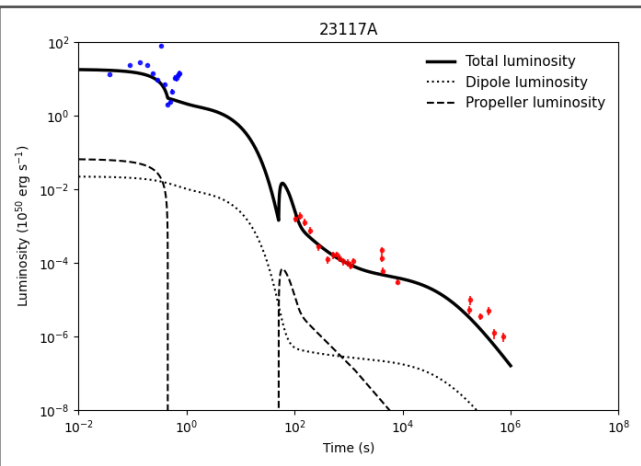
REDUCED_CHI2 = 7.6779295
AICC = 361.9957185
BIC = 373.2988730



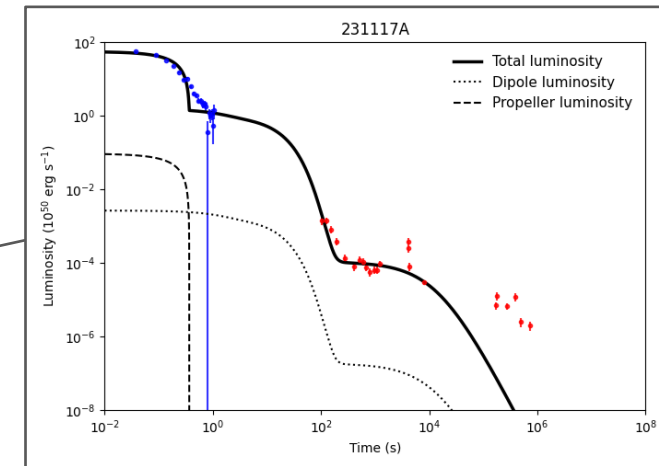
15-50 keV

GRB 231117A

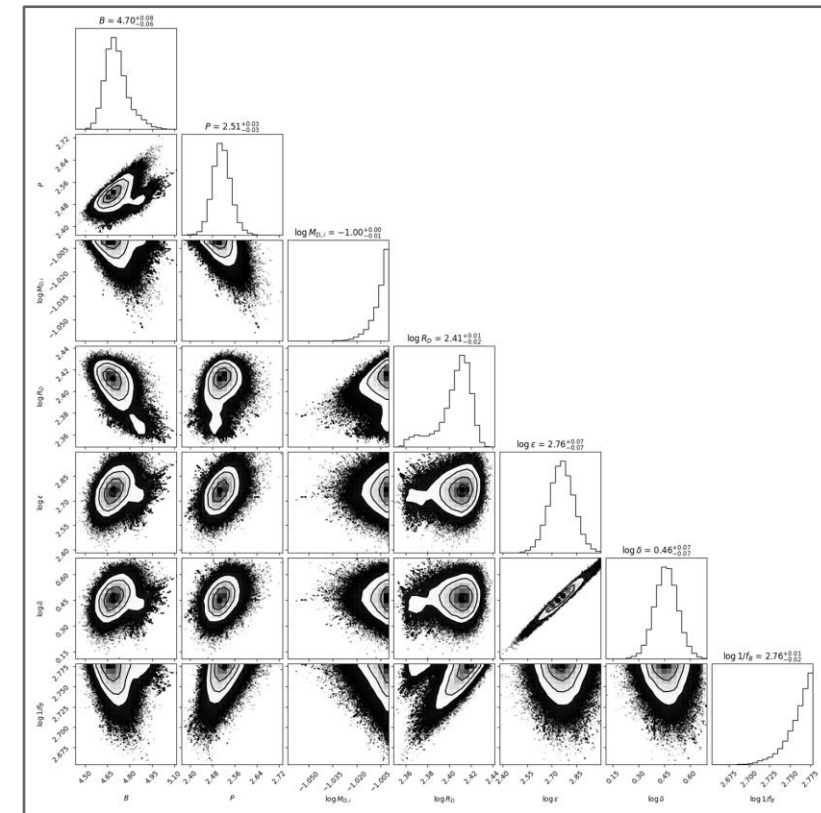
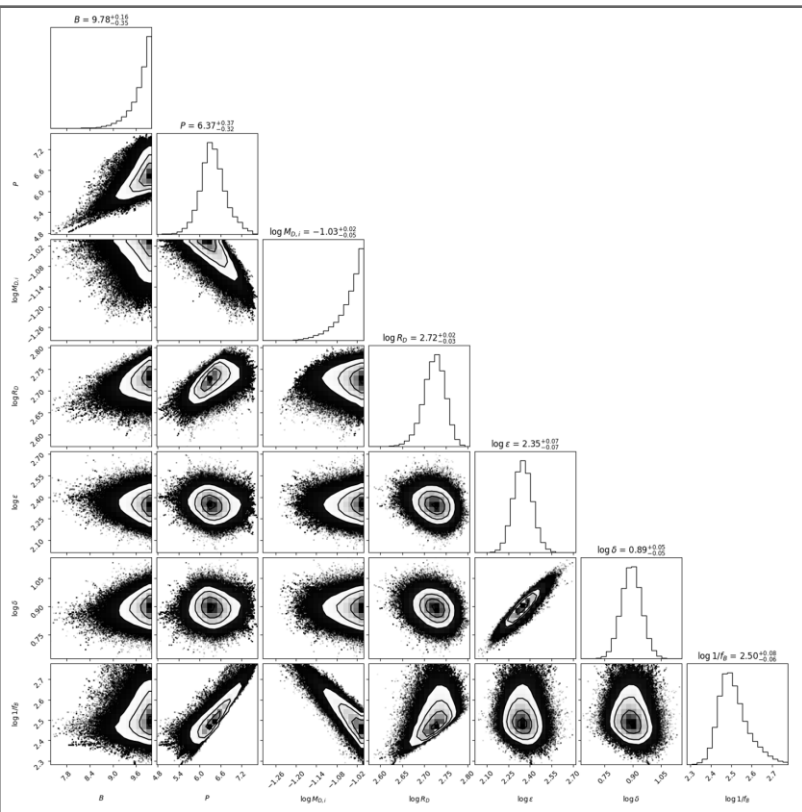
0.3-10 keV

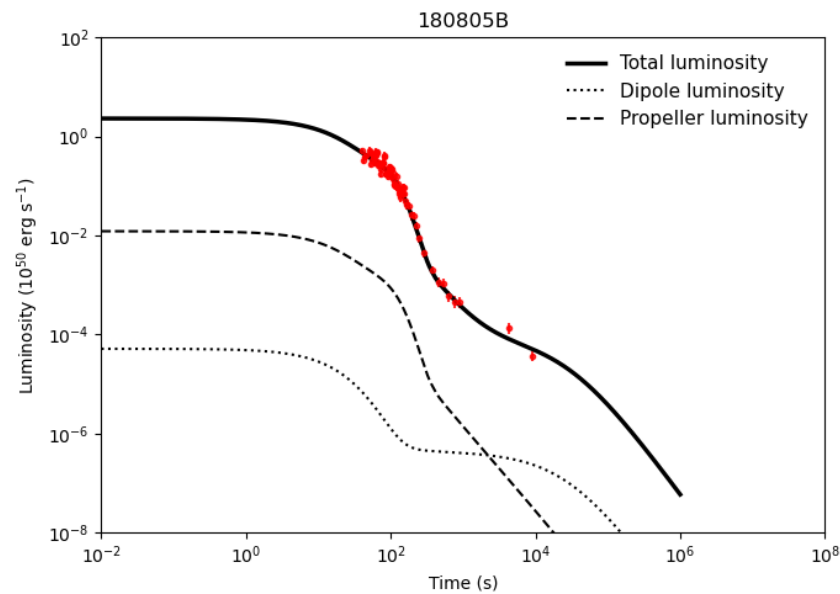


REDUCED_CHI2 =
41.166380135
AICC = 1177.087215222
BIC = 1185.396919231



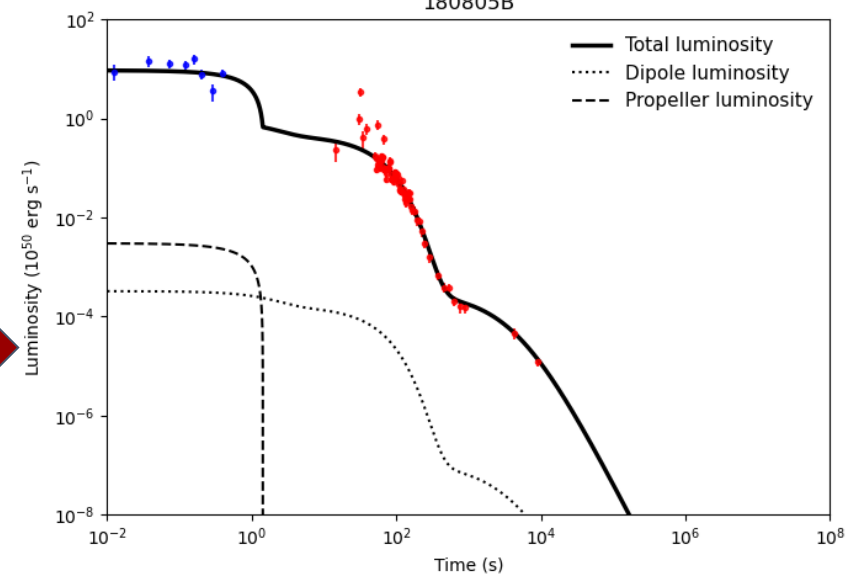
REDUCED_CHI2 = 16.2551098
AICC = 602.2950642
BIC = 611.6732806





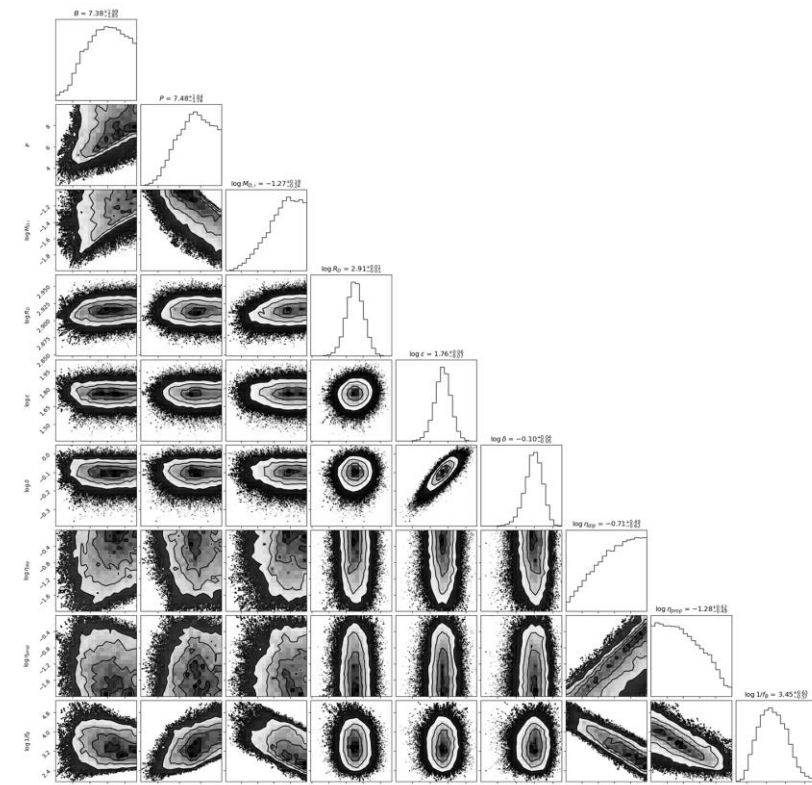
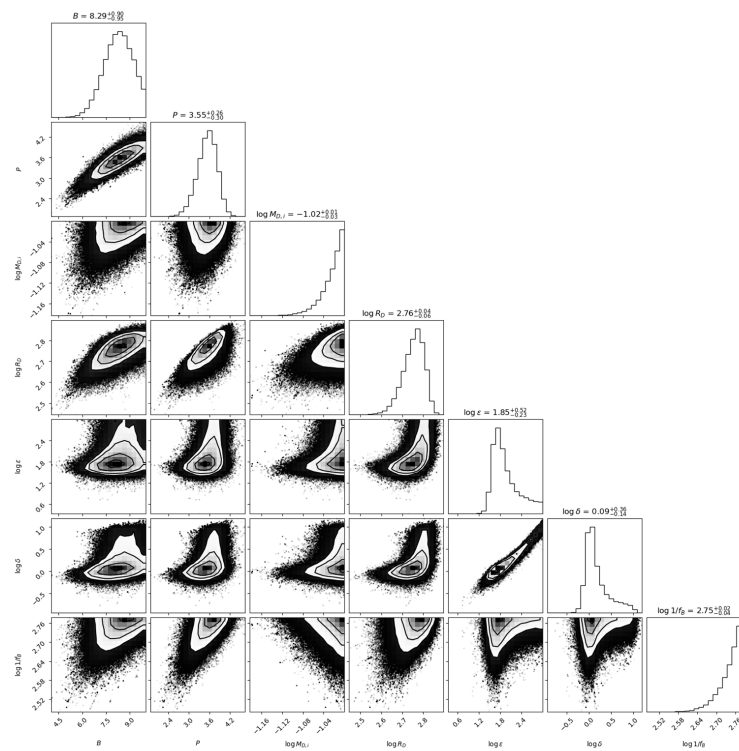
GRB 180805B

Native
p=9

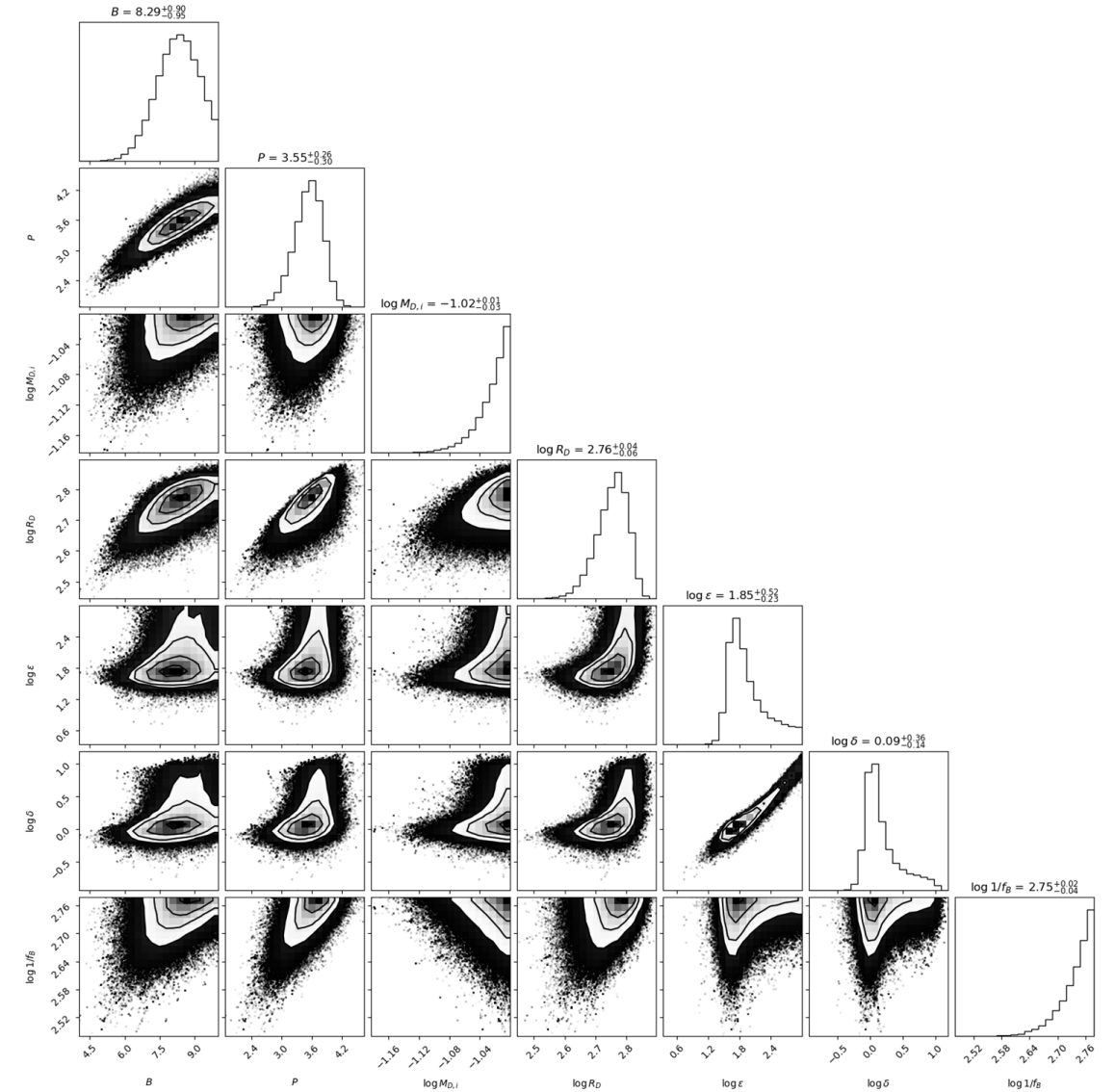
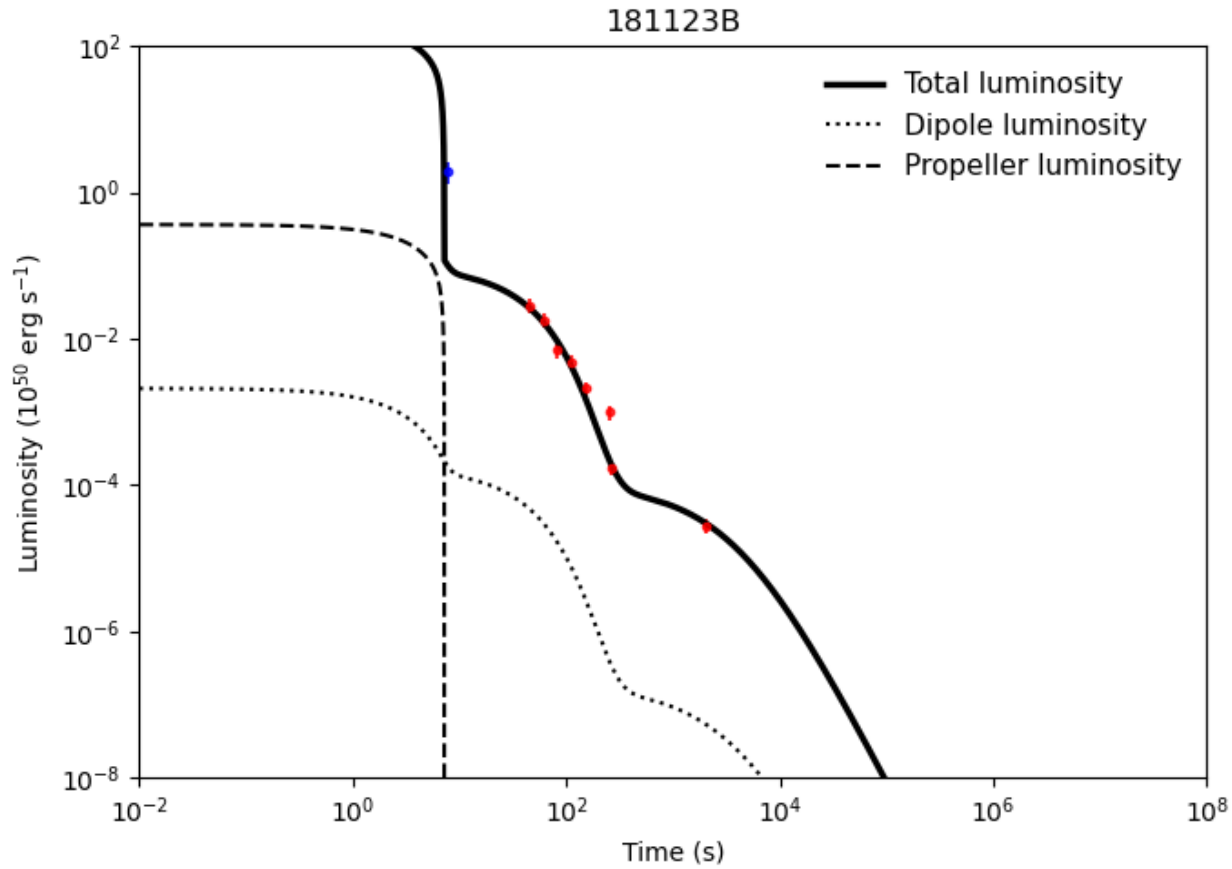


Selection on the
basis of BIC
value

XRT
p=7

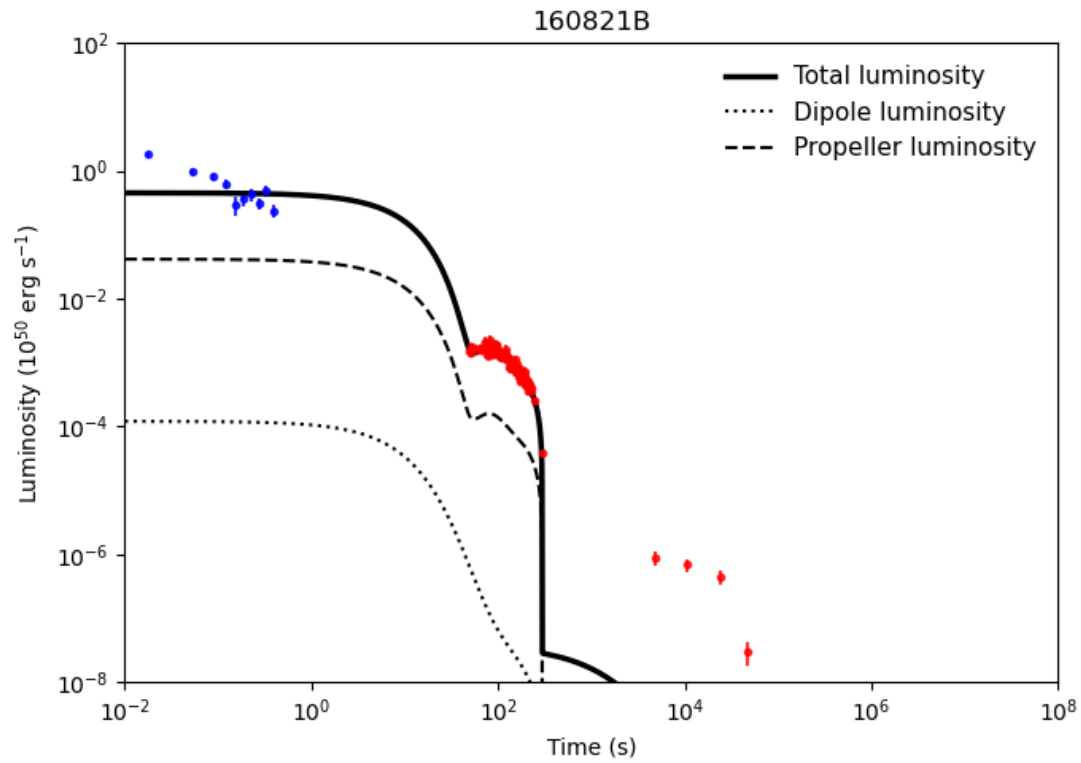


GRB 181123B

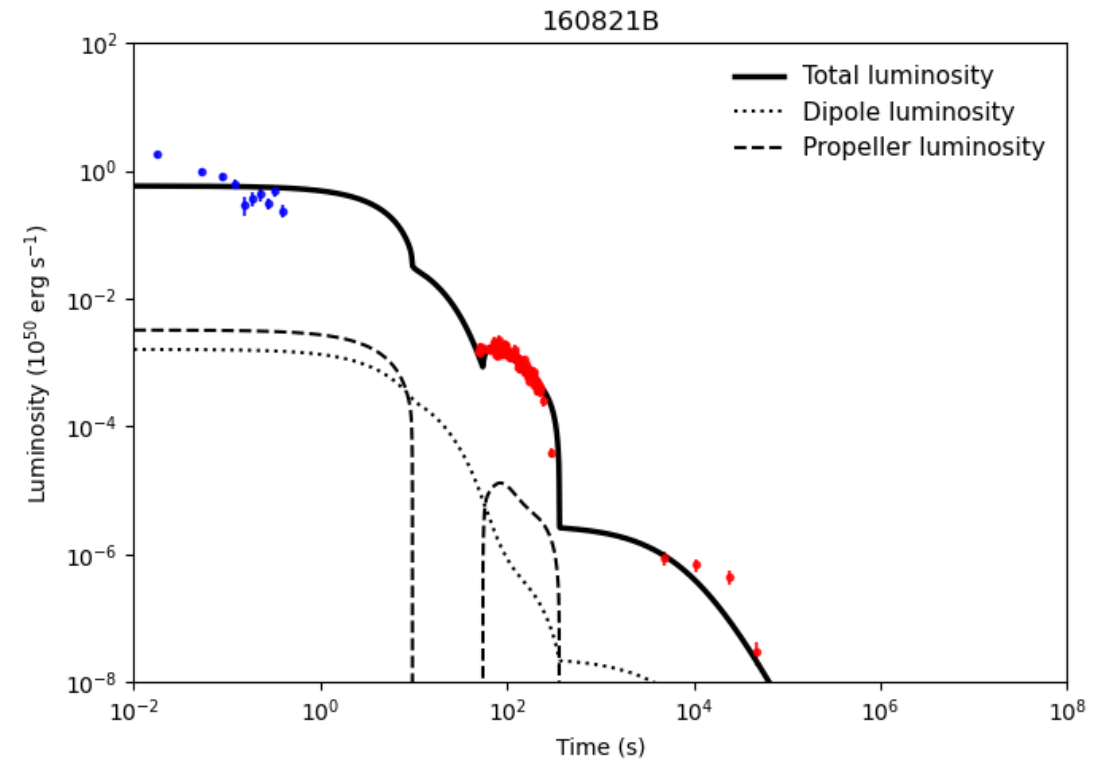


GRB160821B

P=7

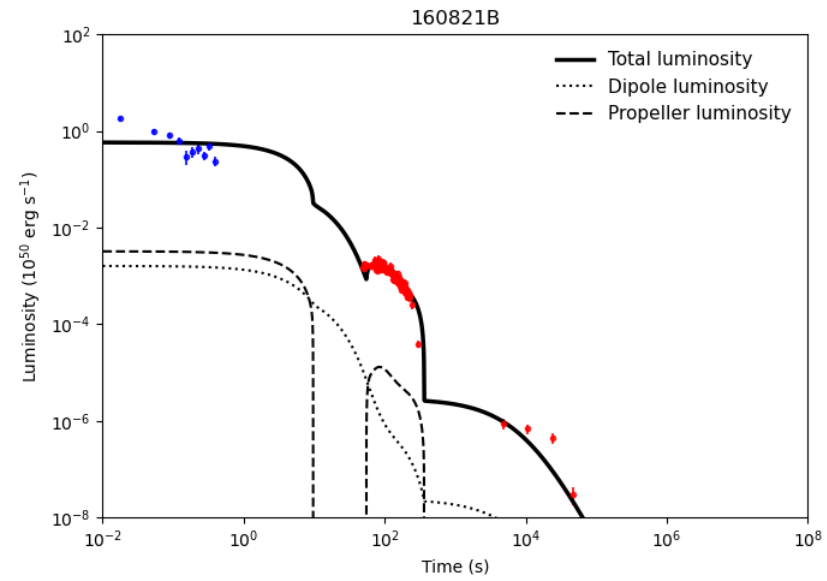


P=9

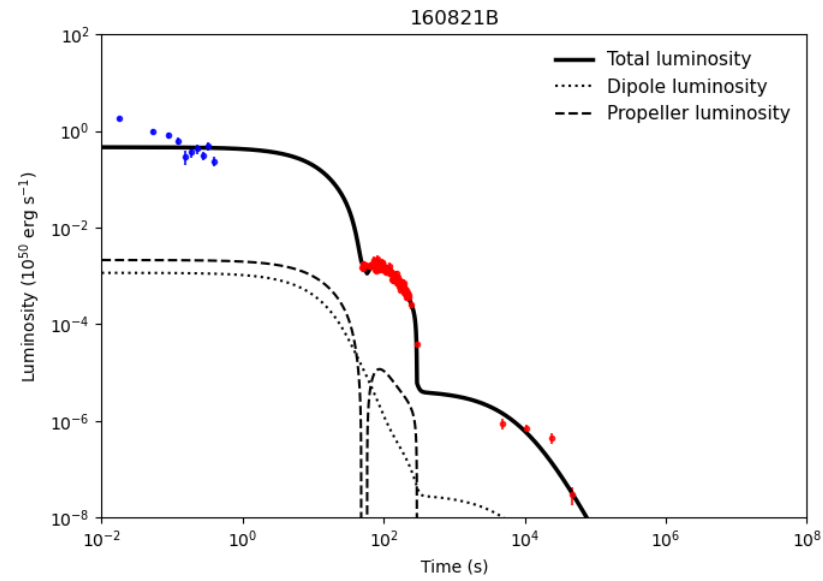


GRB160821B

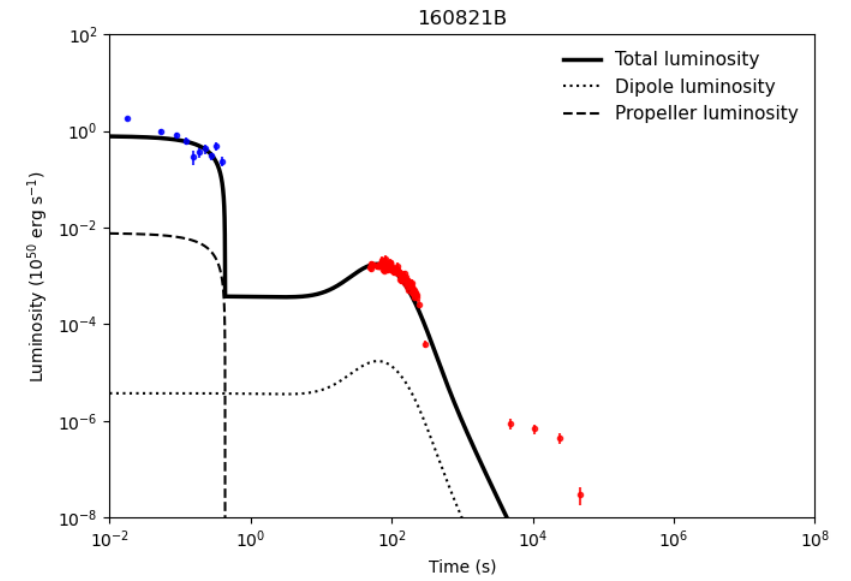
n=100



n=10

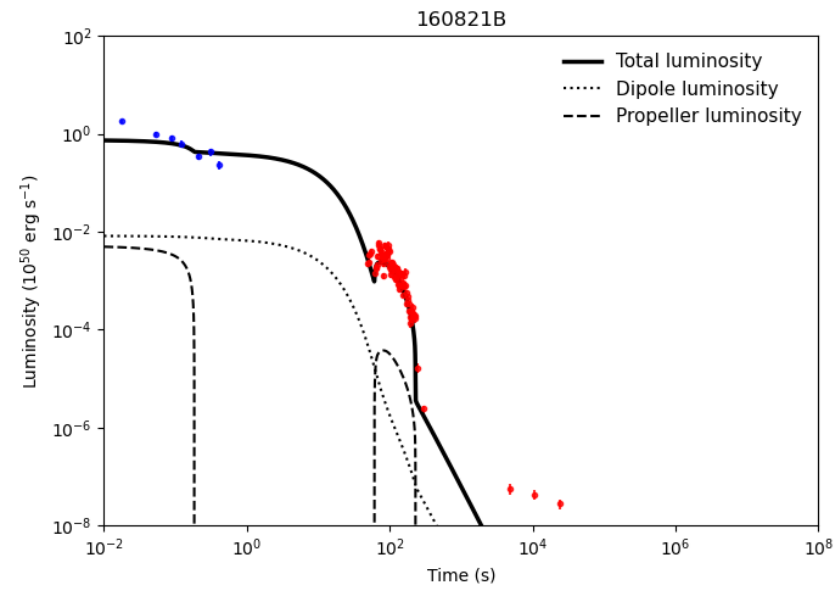


n=1

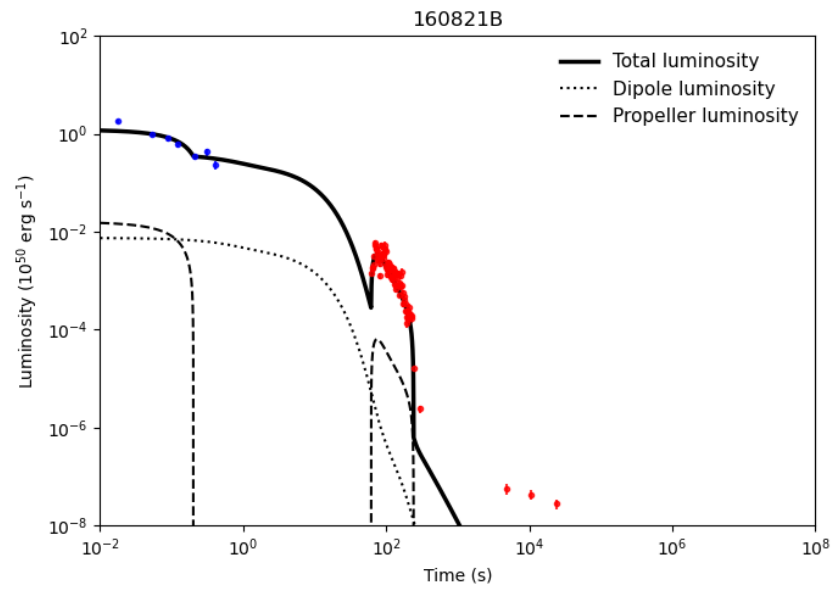


GRB160821B

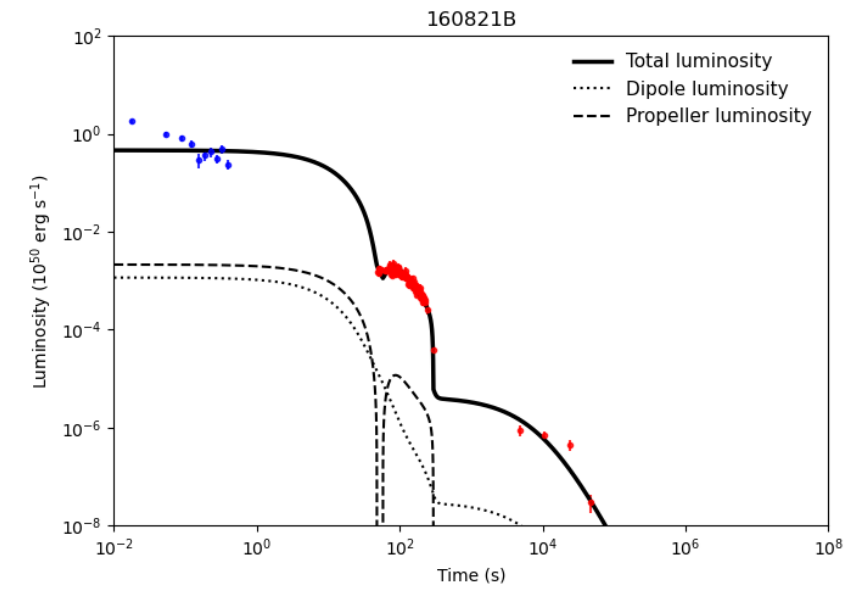
0.3-10 keV



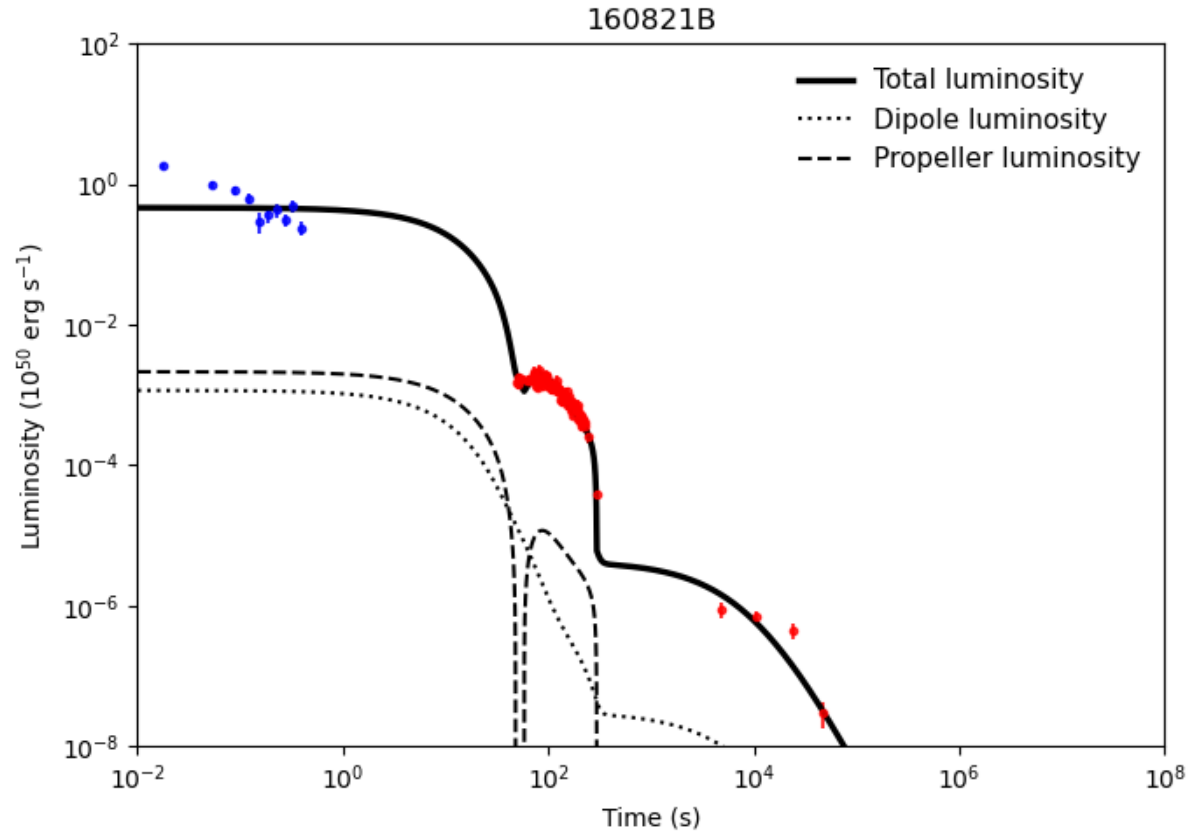
15-50 keV



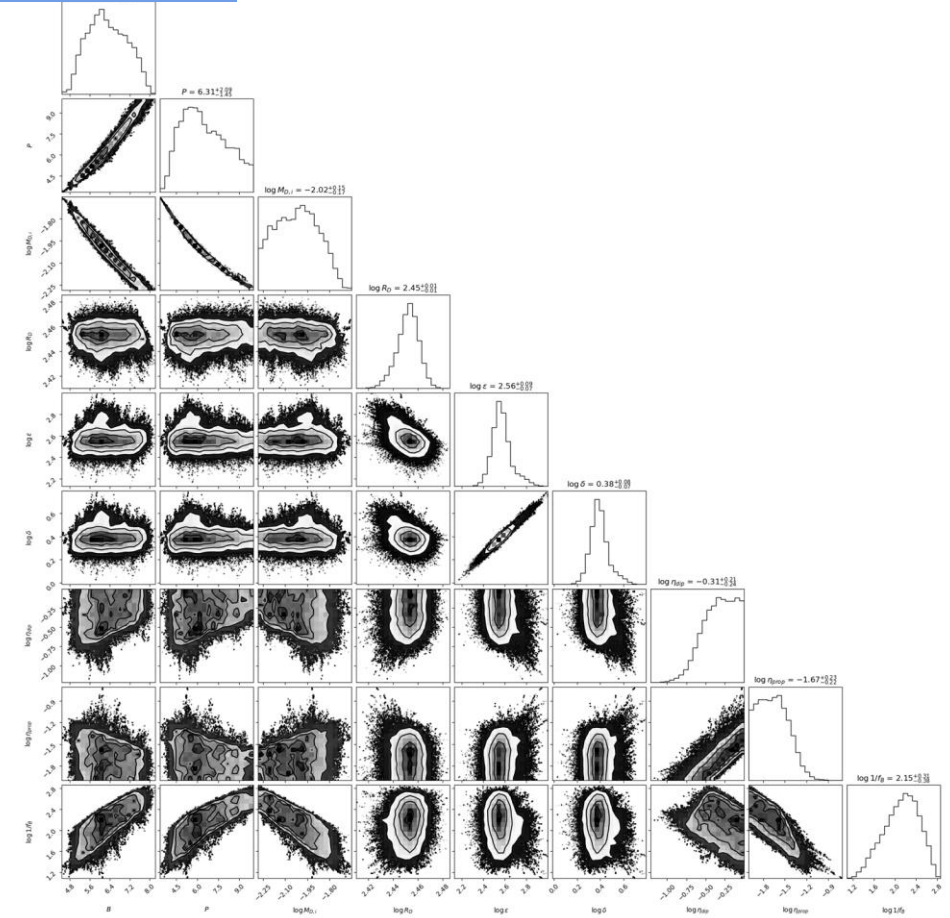
Native



GRB160821B



Reduced chi square: **2.74**
 AICc: **264**
 BIC: **285**

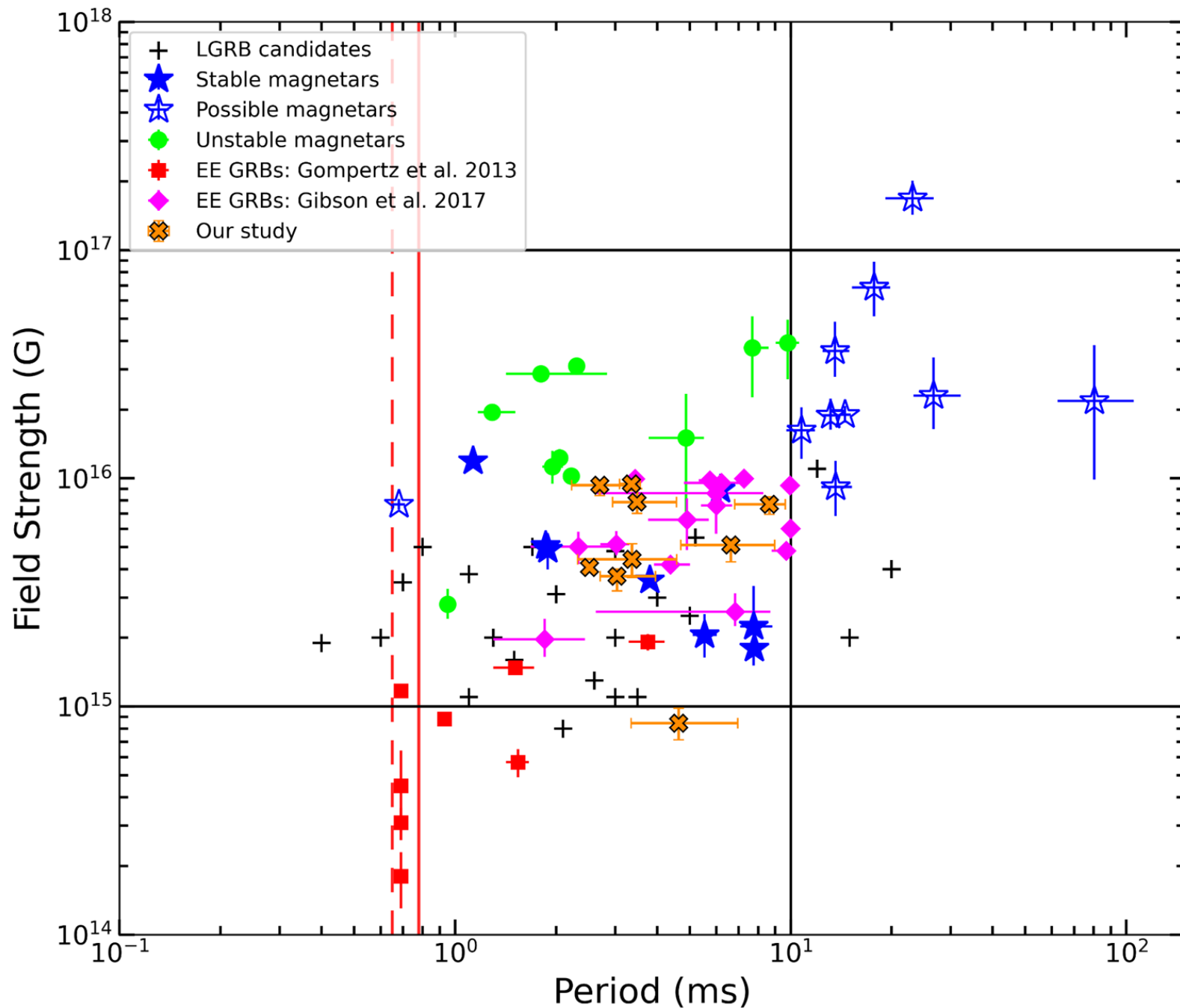


Final results from our sample

GRB's	B(10^{15} G)	+error	-error	P(ms)	+error	-error
160821B	5,1051259	0,32	0,8	6,6359463	2,32	1,93
180805B	7,698902	0,6	0,73	8,624124	1	1,82
181123B	9,463543	0,38	0,61	3,34862	0,21	0,26
200219A	9,3443683	0,49	0,92	2,6952299	0,76	0,47
210323A	4,4256328	0,75	0,75	3,3667295	1,21	1,05
210726A	0,8448808	0,14	0,13	4,634168	2,32	1,29
211023B	7,868869	1,15	0,84	3,4842762	1,08	0,54
230205A	3,723654	0,28	0,51	3,035577	0,92	0,33
231117A	4,071362	0,08	0,06	2,513169	0,03	0,03

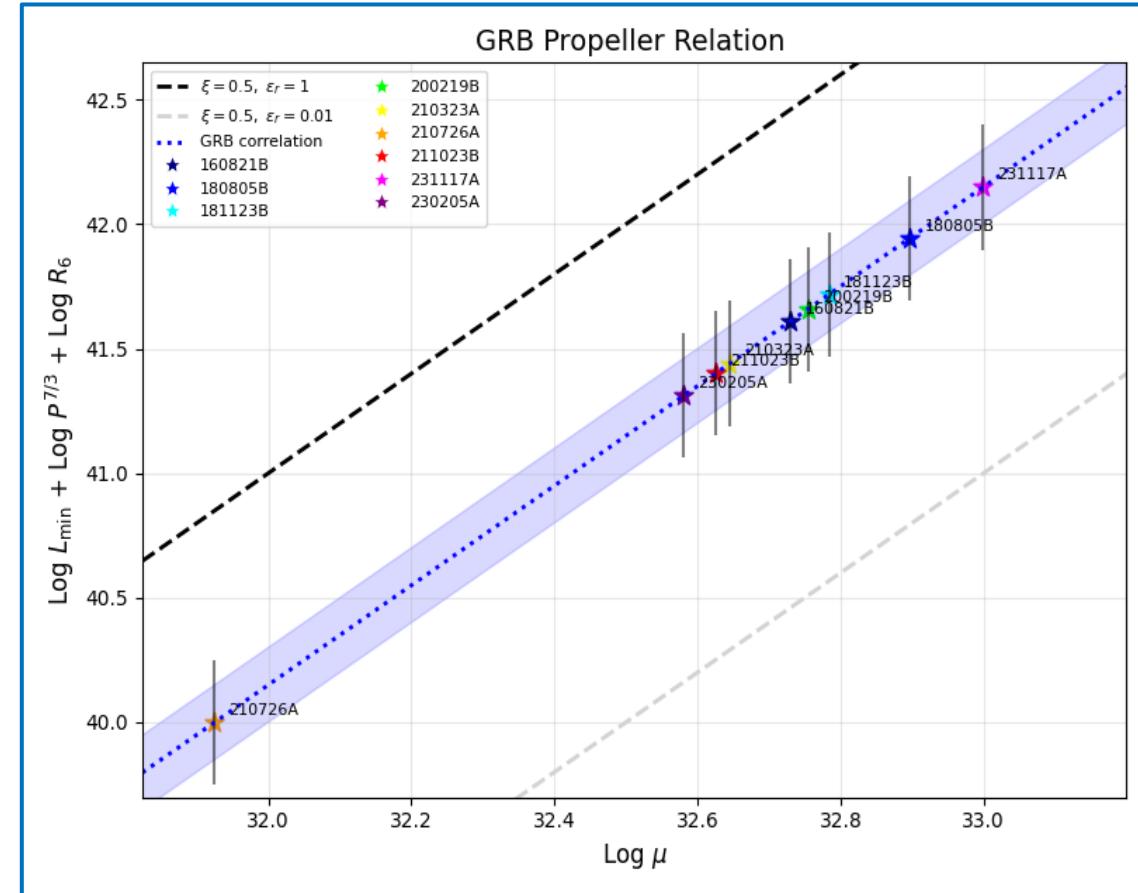
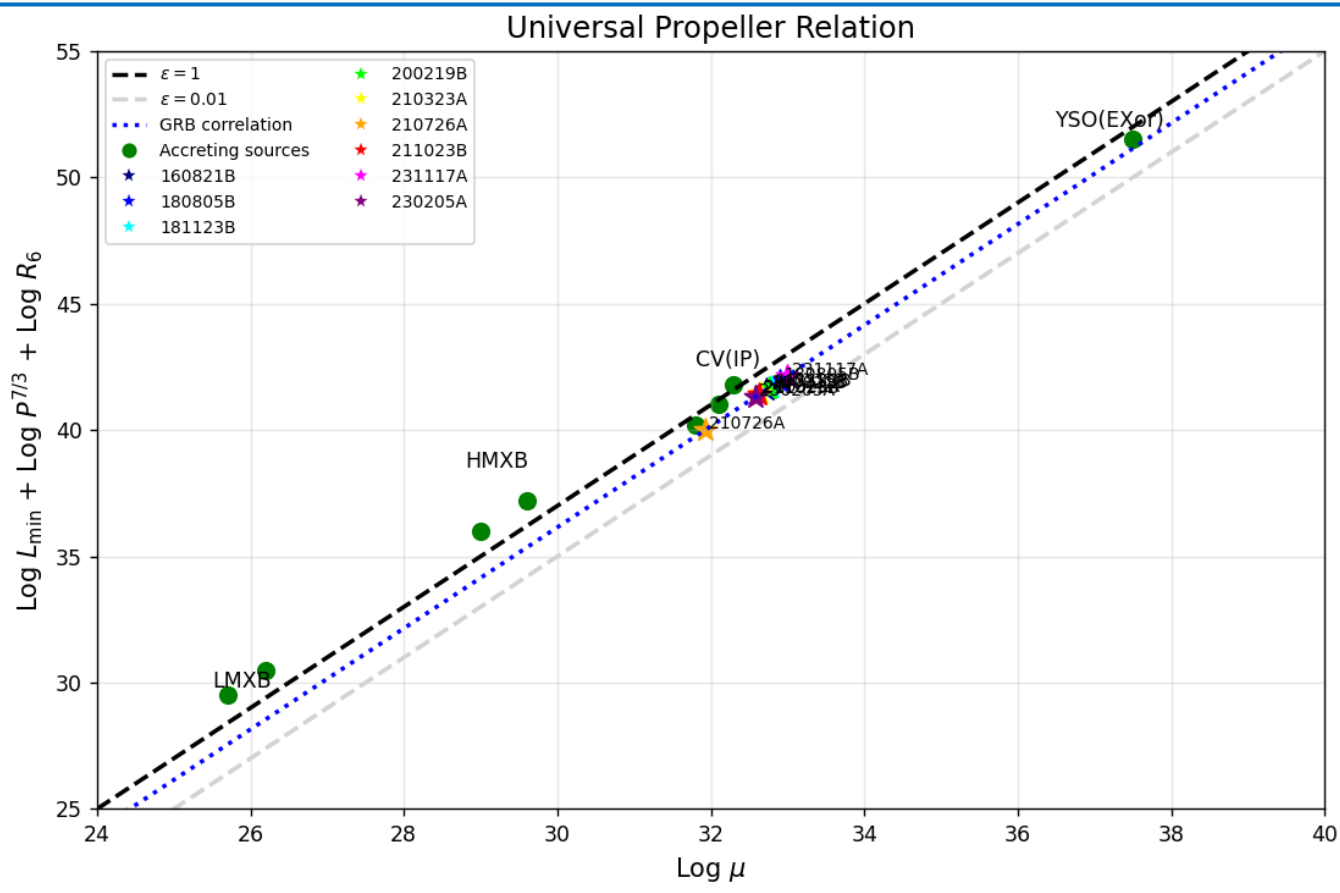
Final results from our sample

GRB	Model	Reduced chi-square	AICc	BIC
160821B	p9	2.75	264.46	285.80
180805B	p7	2.08	145.04	158.98
181123B	p7	5.31	70.52	61.93
200219A	p7	3.56	410.47	428.92
210323A	p9	5.04	165.58	173.89
210726A	p7	6.38	70.92	56.72
211023B	p9	1.60	91.08	104.63
230205A	p7	3.86	114.96	120.95
231117A	p7	16.26	602.30	611.67



Magnetic field
vs spin period
parameter
space

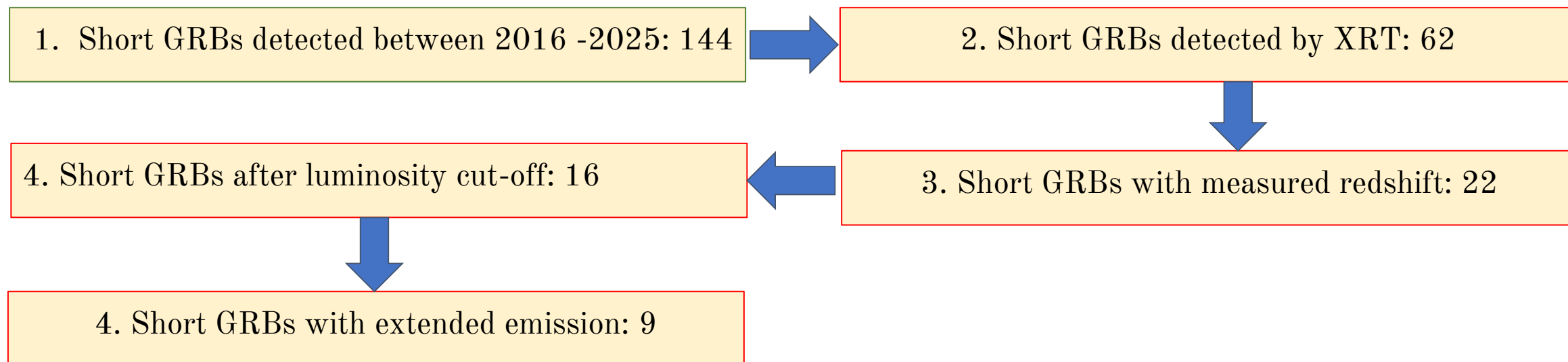
Universal Relation of Accreting Magnetic Stars



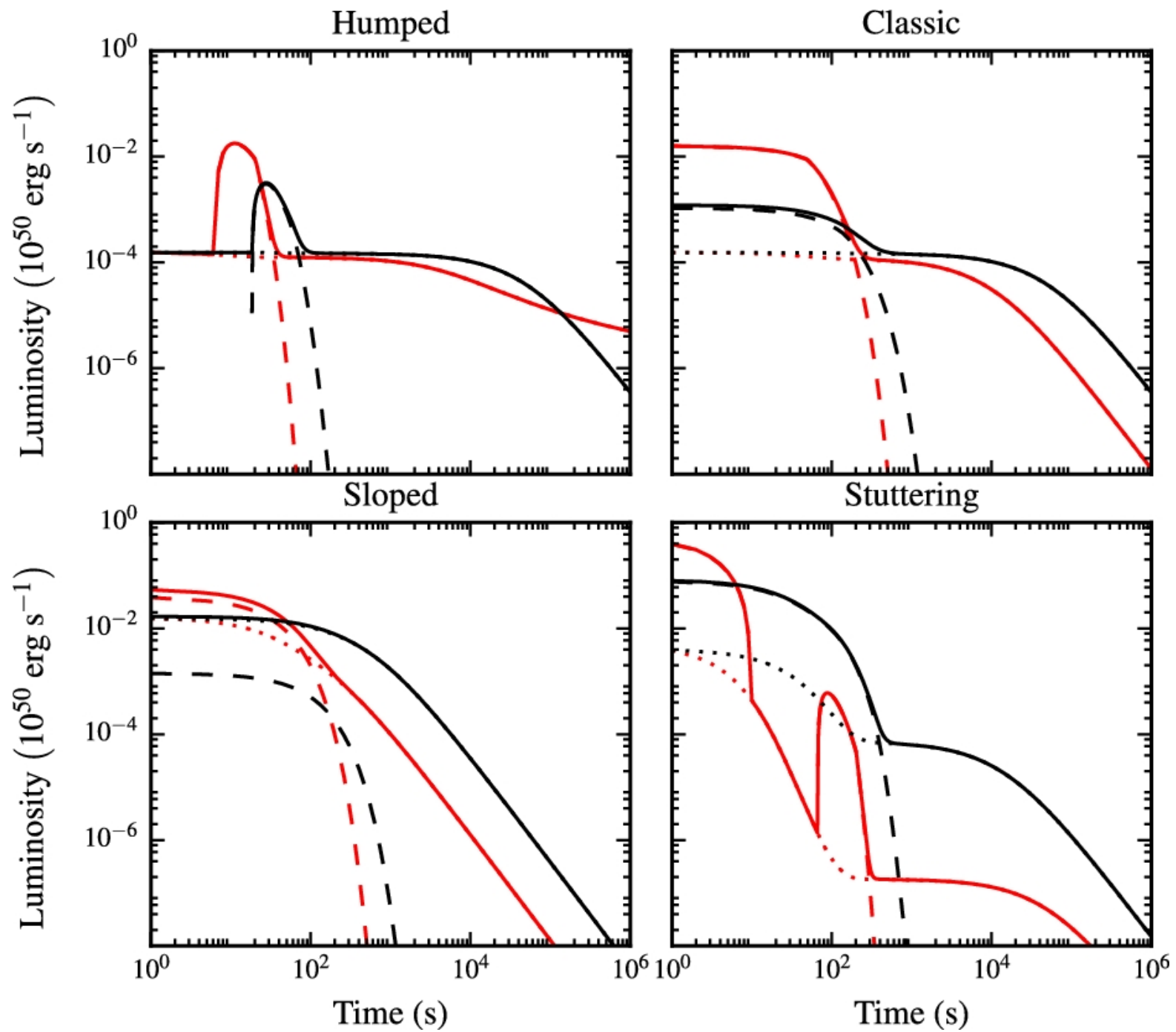
Final results from our sample

GRB	Band	n	Model	B	P	η_{dip} (%)	η_{prop} (%)	$1/f_B$
160821B	Native	10	p9	6.25	6.31	49.0	2.13	140.39
180805B	XRT	100	p7	7.89	3.12	5[F]	40[F]	4.69
181123B	BAT	1	p7	8.84	4.47	5[F]	40[F]	539.53
200219A	Native	10	p7	6.70	4.37	5[F]	40[F]	78.60
210323A	XRT	1	p9	8.38	3.92	48.45	2.05	312.03
210726A	BAT	100	p7	0.84	4.63	5[F]	40[F]	423.09
211023B	Native	100	p9	7.87	3.48	44.84	2.19	682.00
230205A	Native	100	p7	3.81	6.51	5[F]	40[F]	327.31
231117A	BAT	10	p7	4.70	2.51	5[F]	40[F]	580.38

Sample Selection Criteria

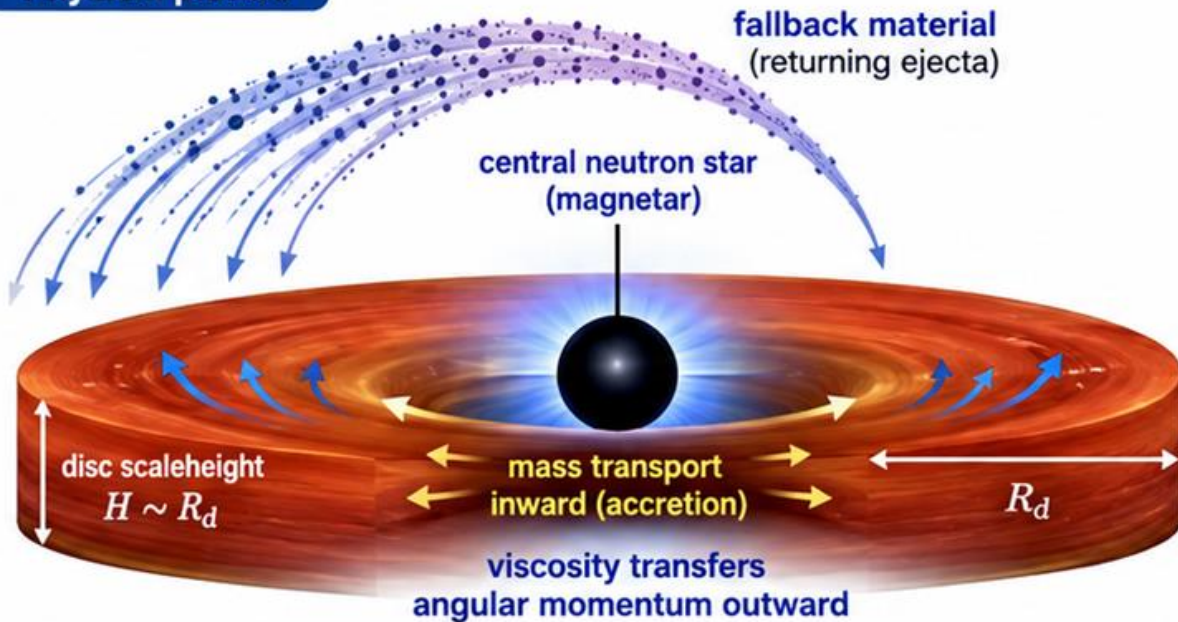


GRB	T_{90} (s)	z	$E_{\gamma, \text{iso}}$ (erg)	$L_{\gamma, \text{iso}}$ (erg s ⁻¹)	Reference
160821B	0.48 ± 0.07	0.162	$(2.1 \pm 0.2) \times 10^{50}$	$(5.1 \pm 0.9) \times 10^{50}$	Lamb et al. (2019)
180805B	1.68	0.661	$(6.7 \pm 0.8) \times 10^{50}$	$(6.6 \pm 0.8) \times 10^{50}$	O'Connor et al. (2022); Hamburg et al. (2018)
181123B	0.26 ± 0.04	1.754	$(2.60 \pm 0.60) \times 10^{50}$	$(2.80 \pm 0.80) \times 10^{51}$	Paterson et al. (2020); Dichiaro et al. (2021)
200219A	1.10 ± 0.45	$0.46^{+0.18}_{-0.21} \text{a}$	$(1.50 \pm 1.30) \times 10^{51}$	$(2.00 \pm 1.70) \times 10^{51}$	Jeong & Im (2024); Gupta et al. (2020)
210323A	1.12 ± 0.32	0.733^{b}	$(1.68 \pm 0.14) \times 10^{51}$	$(2.60 \pm 0.80) \times 10^{51}$	Jeong & Im (2024); Shan et al. (2024)
210726A	0.39 ± 0.11	$0.458^{+0.170}_{-0.181} \text{a,c}$	$\sim 1.0 \times 10^{49}$	$\sim 1.2 \times 10^{49}$	Jeong & Im (2024); ?
211023B	0.70	0.862^{d}	$\sim 1.0 \times 10^{51}$	$\sim 2.7 \times 10^{51}$	?
230205A	2.20	0.429^{e}	$\sim 1.0 \times 10^{51}$	$\sim 6.5 \times 10^{50}$	?
231117A	0.668	0.257	3.8×10^{50}	7.2×10^{50}	Schroeder et al. (2025)



Fallback Accretion Disc: Physical Picture and Mathematics

Physical picture



Material cannot accrete directly onto the neutron star. It must first lose angular momentum via viscous torques.

Mathematical description

- 1 Thick disc assumption: $H = R_d$
- 2 Ballistic fallback rate: $\dot{M}_{fb} \propto t^{-5/3}$
- 3 Viscous-disc accretion rate: $\dot{M} \propto t^{-4/3}$
- 4 Initial accretion rate: $\dot{M}_0 = \frac{3M_d \nu}{R_d^2}$
- 5 Viscous timescale: $t_{visc} = \frac{R_d^2}{3\nu}$
- 6 Exponential decay case: $\dot{M}(t) = \dot{M}_0 \exp\left(-\frac{3\nu t}{R_d^2}\right) = \dot{M}_0 \exp\left(-\frac{t}{t_{visc}}\right)$

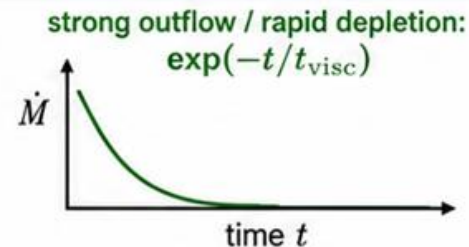
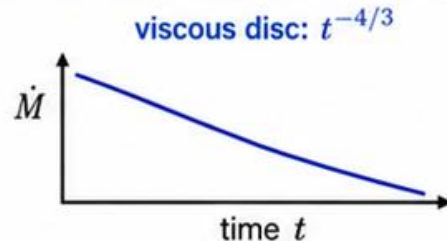
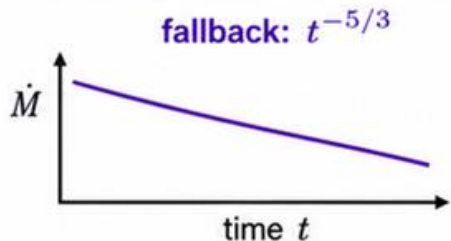
Interpretation

- Large M_d or large $\nu \rightarrow$ higher initial accretion rate
- Larger $R_d \rightarrow$ slower evolution



Possible accretion histories

(qualitative comparison)



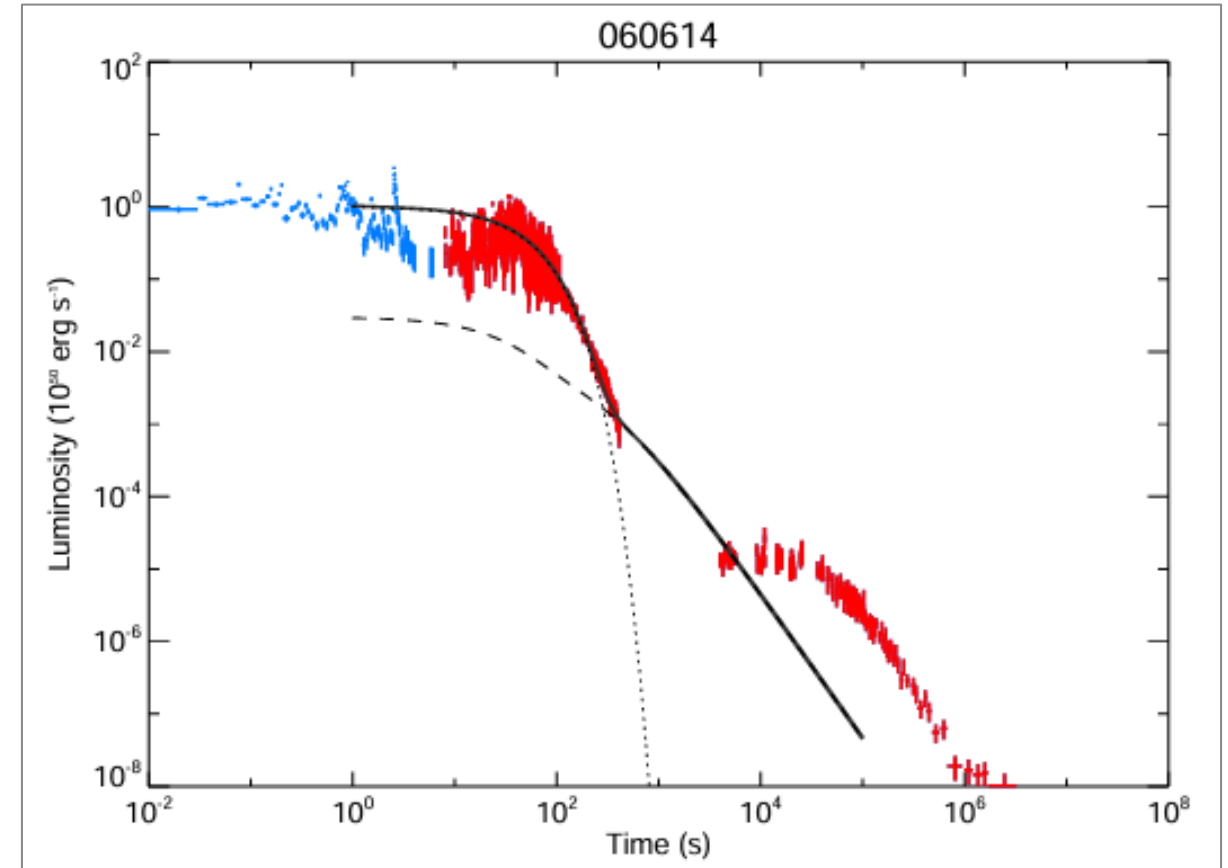
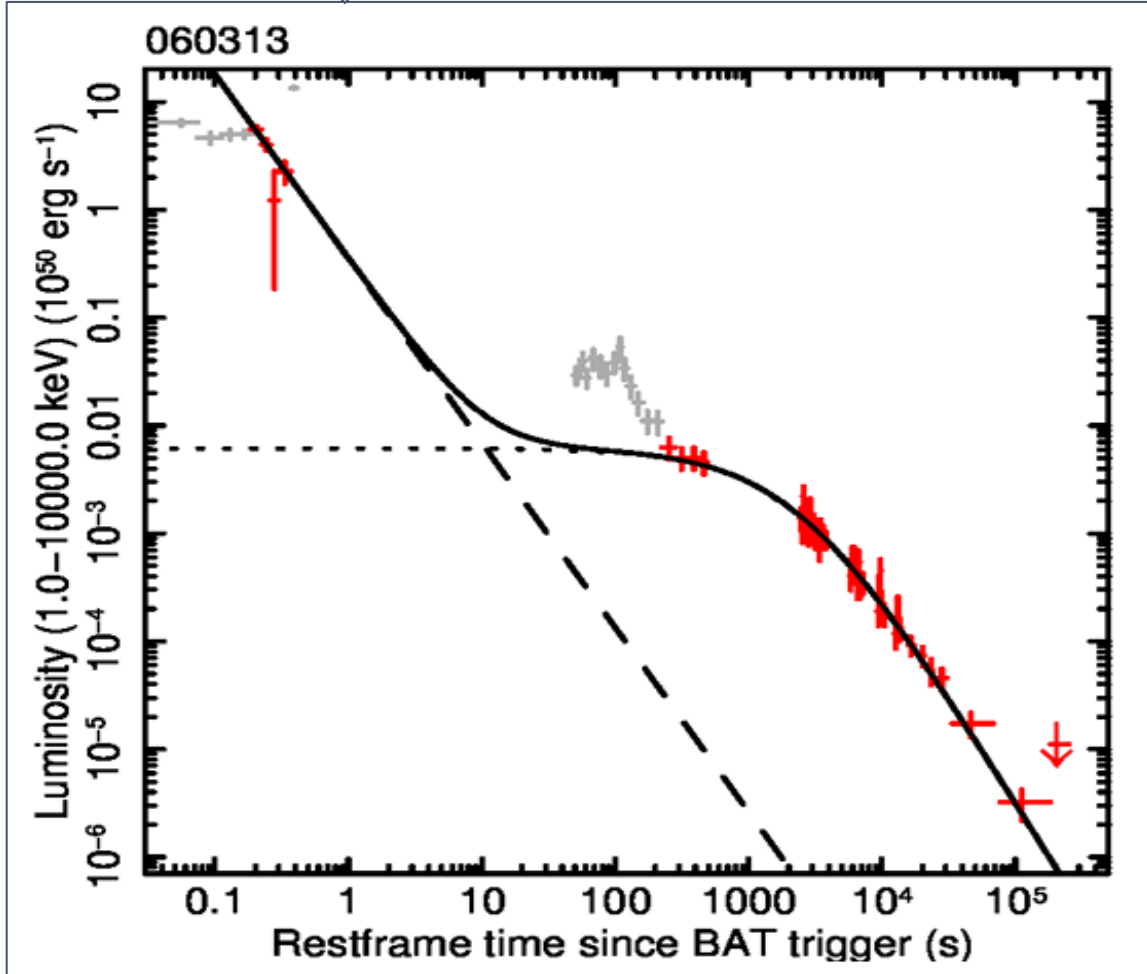
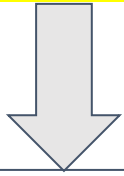
Notes

All plots are qualitative and shown on log-log axes.

$\dot{M}$: mass accretion rate



Fallback returns to the disc, viscosity removes angular momentum, and the accretion history controls the observed light curve.



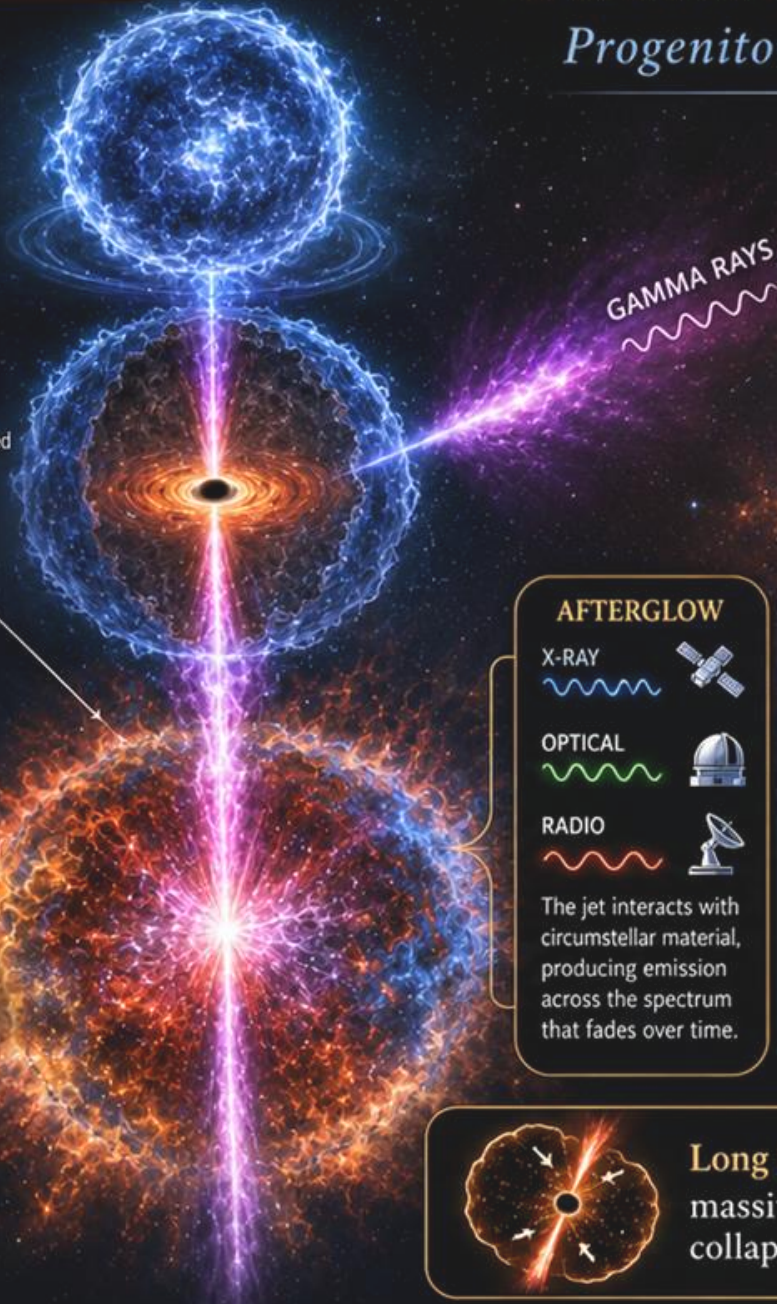
LONG GRBs

Gamma-Ray Bursts

Progenitors of Long and Short GRBs

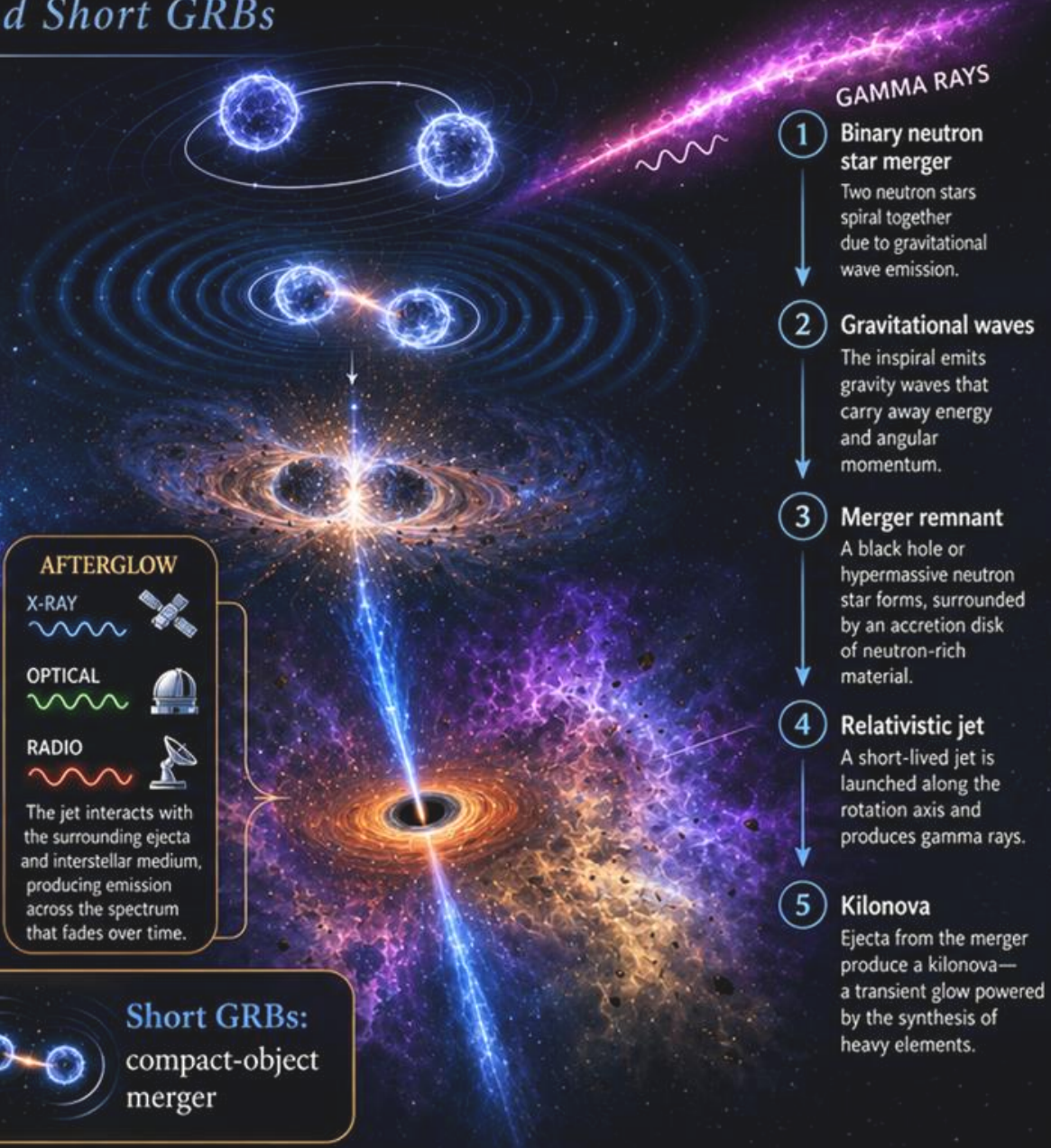
SHORT GRBs

- 1 Massive star collapse**
A rapidly rotating, stripped-envelope star exhausts its fuel and collapses.
- 2 Black hole + accretion disk**
Core collapse forms a black hole surrounded by an accretion disk.
- 3 Relativistic jet**
Twin jets launched from the poles accelerate to near the speed of light and punch through the star.
- 4 Supernova**
The jet breaks out, producing a powerful supernova explosion that lights up the surroundings.



AFTERGLOW

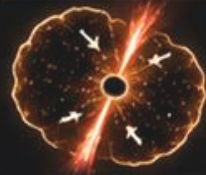
X-RAY 
OPTICAL 
RADIO 
The jet interacts with circumstellar material, producing emission across the spectrum that fades over time.



- 1 Binary neutron star merger**
Two neutron stars spiral together due to gravitational wave emission.
- 2 Gravitational waves**
The inspiral emits gravity waves that carry away energy and angular momentum.
- 3 Merger remnant**
A black hole or hypermassive neutron star forms, surrounded by an accretion disk of neutron-rich material.
- 4 Relativistic jet**
A short-lived jet is launched along the rotation axis and produces gamma rays.
- 5 Kilonova**
Ejecta from the merger produce a kilonova—a transient glow powered by the synthesis of heavy elements.

AFTERGLOW

X-RAY 
OPTICAL 
RADIO 
The jet interacts with the surrounding ejecta and interstellar medium, producing emission across the spectrum that fades over time.

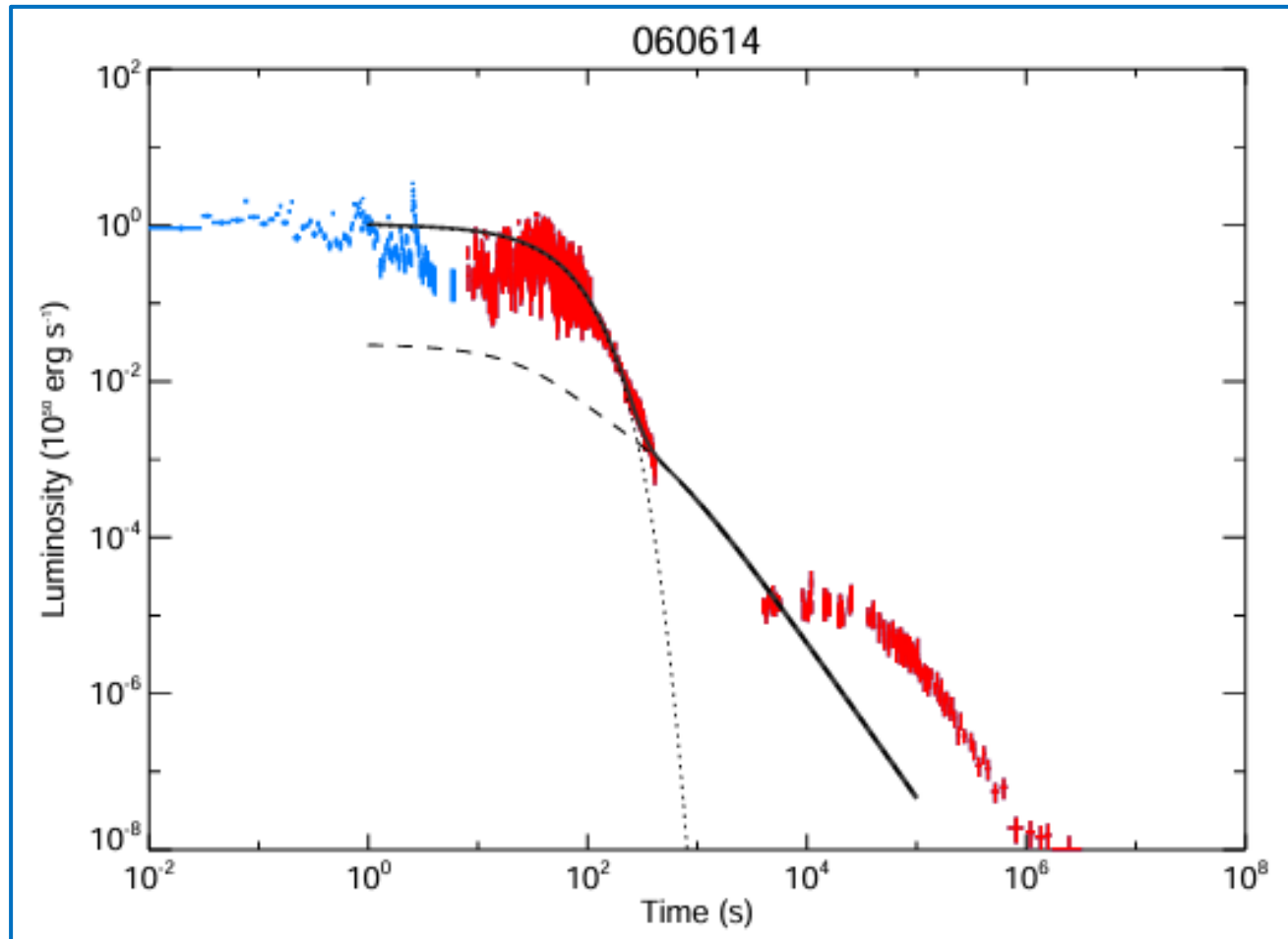


Long GRBs:
massive-star
collapse

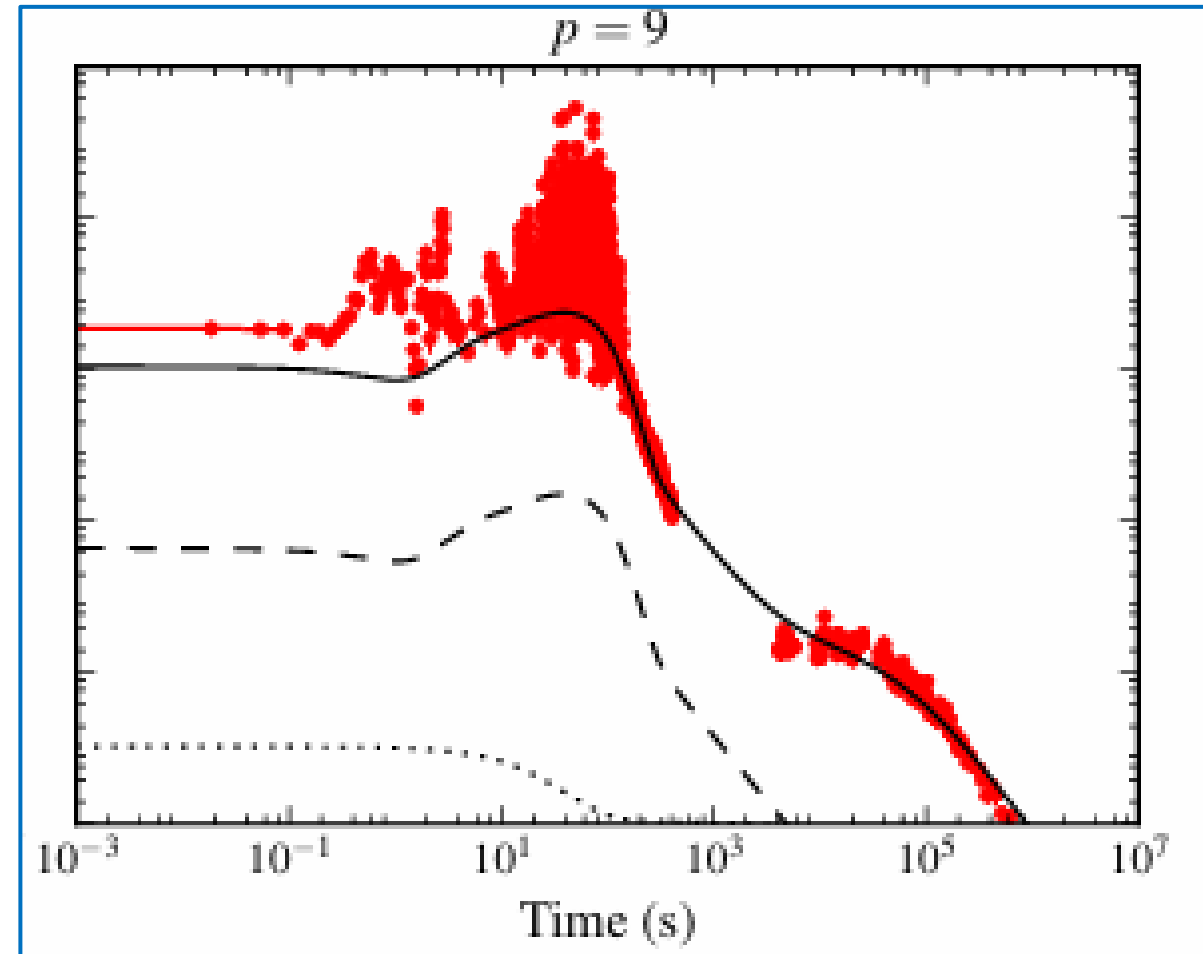


Short GRBs:
compact-object
merger

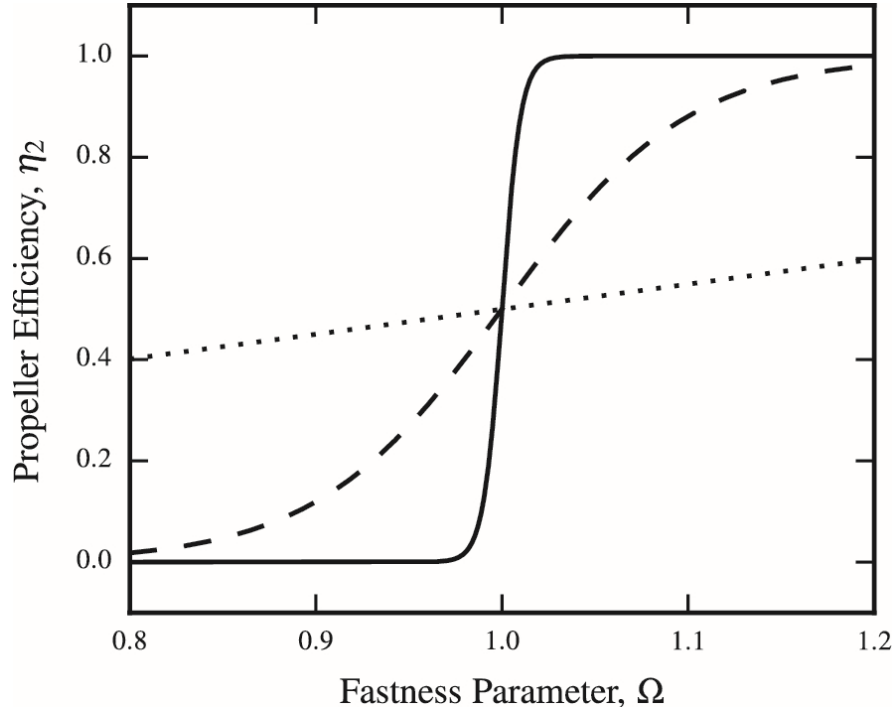
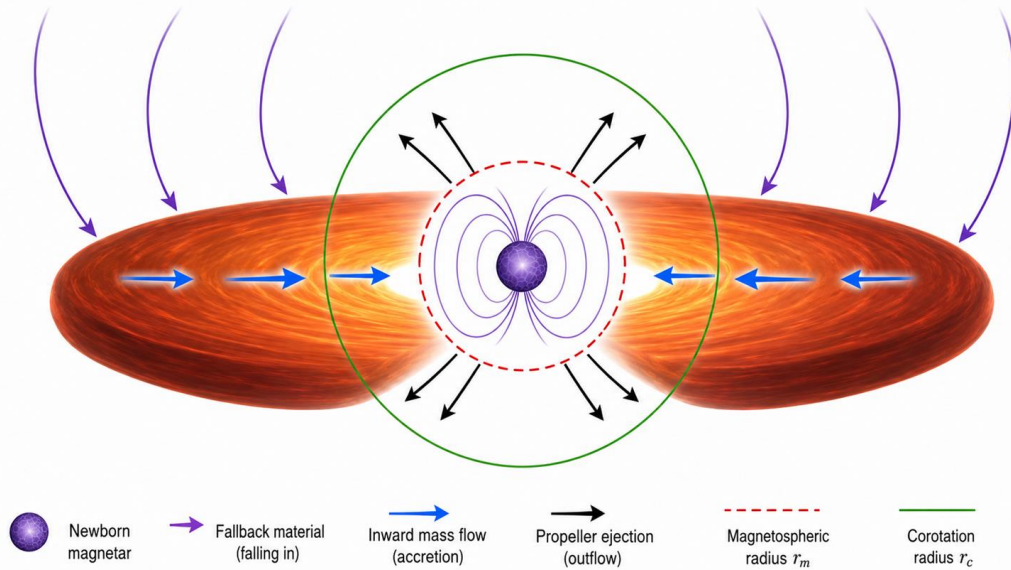
Gompertz Model



Gibson's Model



Gibson's Magnetar Model



1. Radii and regime switch

Alfvén radius

$$r_m = \mu^{4/7} (GM)^{-1/7} \left(\frac{3M_D(t)}{t_\nu} \right)^{-2/7}$$

Corotation radius

$$r_c = \left(\frac{GM}{\omega^2} \right)^{1/3}$$

Switch:
 $r_c > r_m$ accretion
 $r_c < r_m$ propeller

$$r_m \leq 0.9 r_{lc}, \quad r_{lc} = \frac{c}{\omega}$$

2. Coupled ODEs

Disc mass balance

$$\dot{M}_D = \dot{M}_{fb} - \dot{M}_{prop} - \dot{M}_{acc}$$

Magnetar spin evolution

$$\dot{\omega} = \frac{N_{acc} + N_{dip}}{I} \quad I = 0.35MR^2$$

Disc mass and spin are solved together, so the light-curve morphology follows the evolving engine.

3. Fallback feeding

Fallback rate added to the disc:

$$\dot{M}_{fb} = \frac{M_{fb}}{t_{fb}} \left(\frac{t + t_{fb}}{t_{fb}} \right)^{-5/3}$$

Parameterization used by Gibson et al.:

$$M_{fb} = \delta M_{D,i}, \quad t_{fb} = \epsilon t_\nu$$

4. Propeller efficiency

Smooth switch-on:

$$\eta_2 = \frac{1}{2} [1 + \tanh\{n(\Omega - 1)\}]$$

$$\Omega = \left(\frac{r_m}{r_c} \right)^{3/2}$$

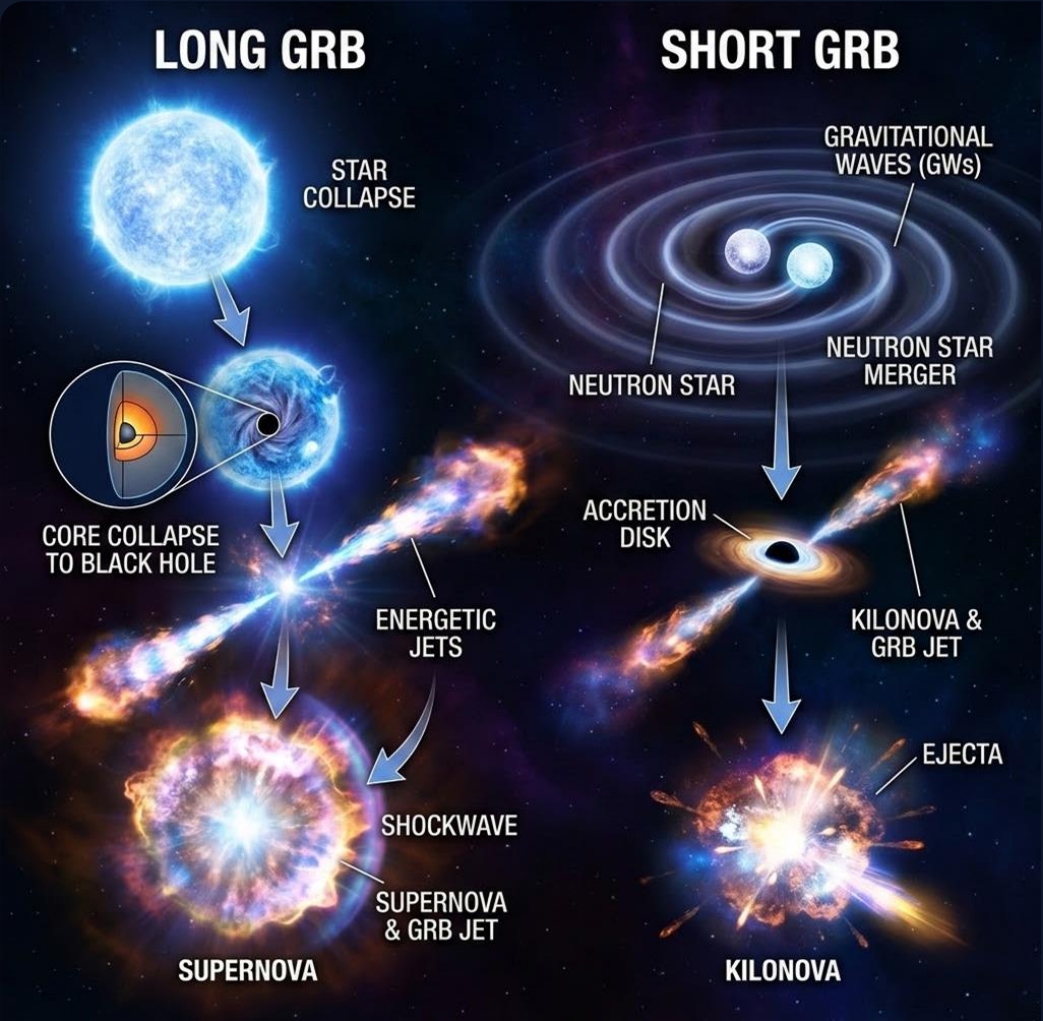
Mass partition:

$$\dot{M}_{prop} = \eta_2 \frac{M_D}{t_\nu} \quad \dot{M}_{acc} = (1 - \eta_2) \frac{M_D}{t_\nu}$$

Fallback-fed evolution: disc replenished → r_m/r_c changes → propeller ejects → spin-down

GRB Classification: Long vs. Short GRBs

Progenitor Models & Physical Channels



Property	Long GRBs	Short GRBs
Duration (T90)	> 2 Seconds	< 2 Seconds
Hardness Ratio	Soft (Lower HR)	Hard (Higher HR)
Progenitor	Core Collapse of Massive Stars (Collapsars)	Compact Object Merger (BNS / NS-BH)
Counterparts	Associated Supernovae (SNe)	Associated Kilonovae (KNe) & GWs
Spectral Lag	Significant positive spectral lag	Negligible or zero spectral lag
Host Environment	Star-forming starburst galaxies	Both elliptical & star-forming galaxies
Central Engine	Accreting Black Hole	Magnetar / Black Hole

Theoretical Model & Observational Signatures

Extended Emission in Short GRBs

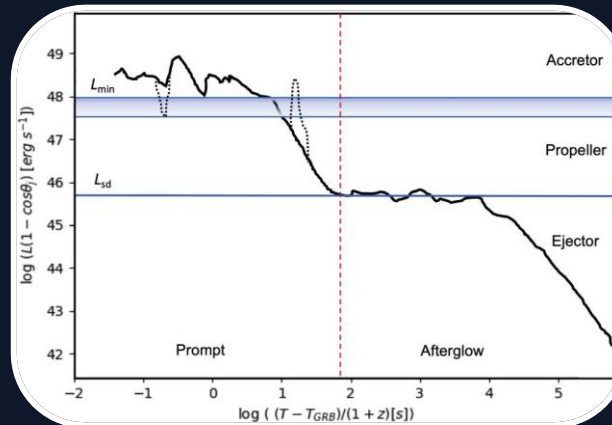
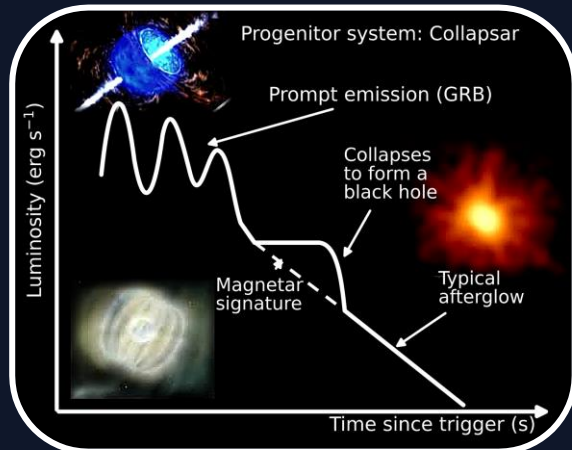
Theoretical Framework & Fallback Accretion

1. Fallback Radiation & Kilonova Interaction



R. Duqué et al.: Extended emission in short gamma-ray bursts from fallback accretion

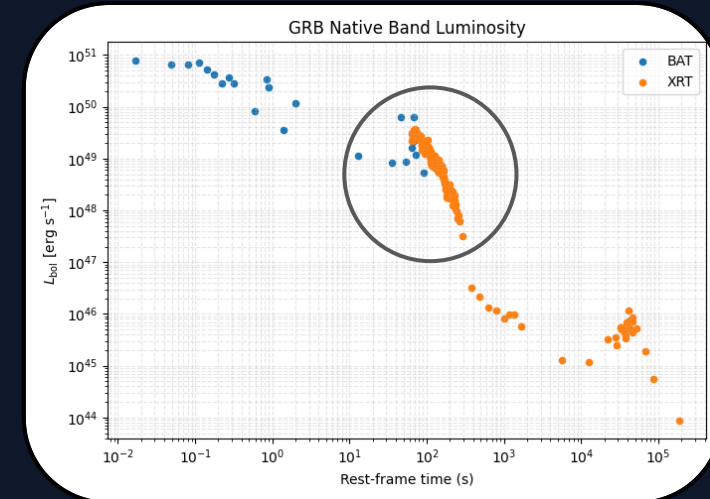
2. Central Engine Luminosity Phases (Accretor / Propeller / Ejector)



<https://spacenews.com/evidence-suggests-grbs-are-powered-by-strongest-magnetic-fields/>

Swift Observational Light Curves

GRB 050724 — Re-brightening / Flare Component



https://www.swift.ac.uk/burst_analyser/

GRB 160821B — Extended X-ray Emission Feature

