GRBs and magnetars: observational signatures

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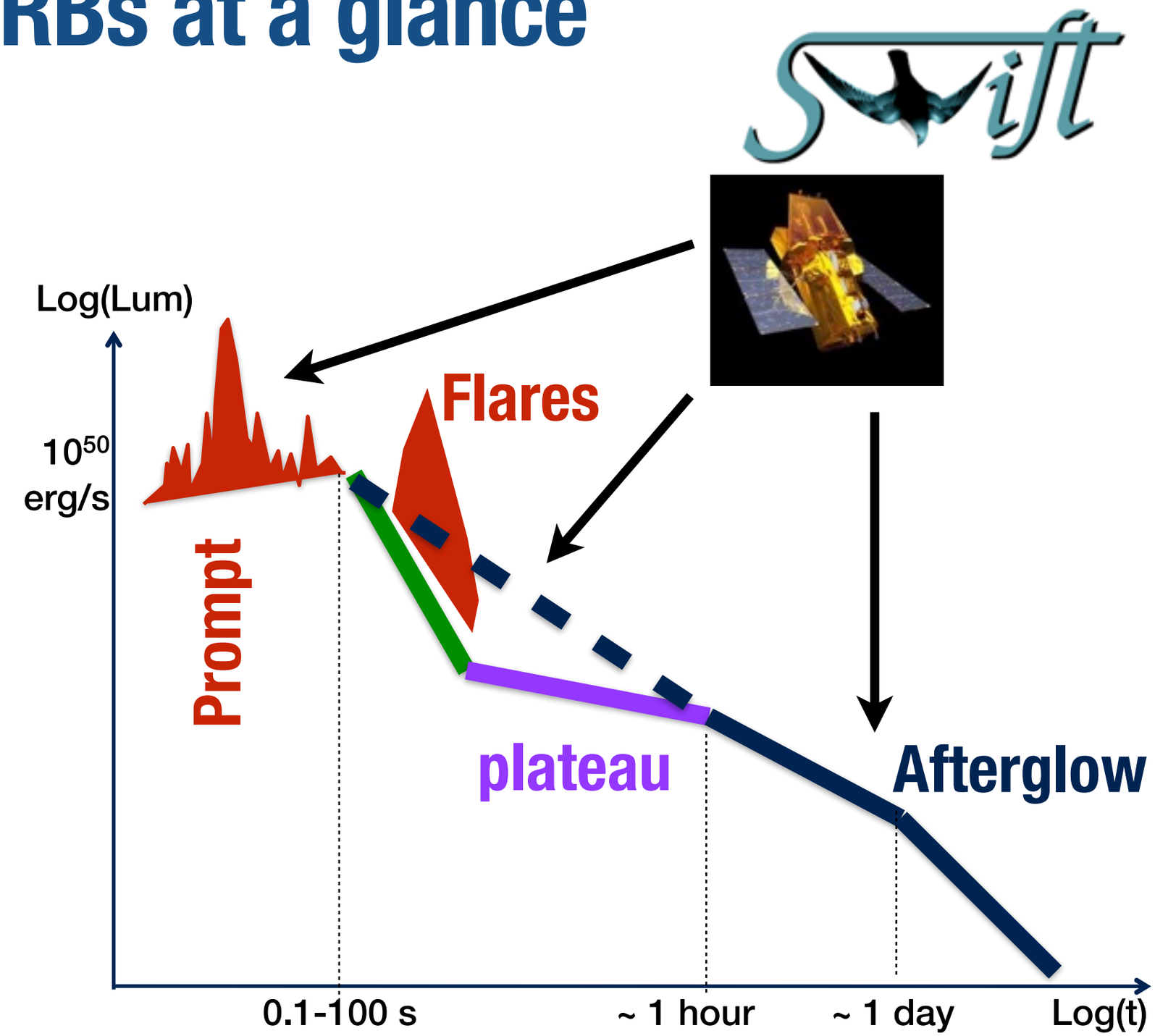
INAF - Osservatorio Astronomico di Brera

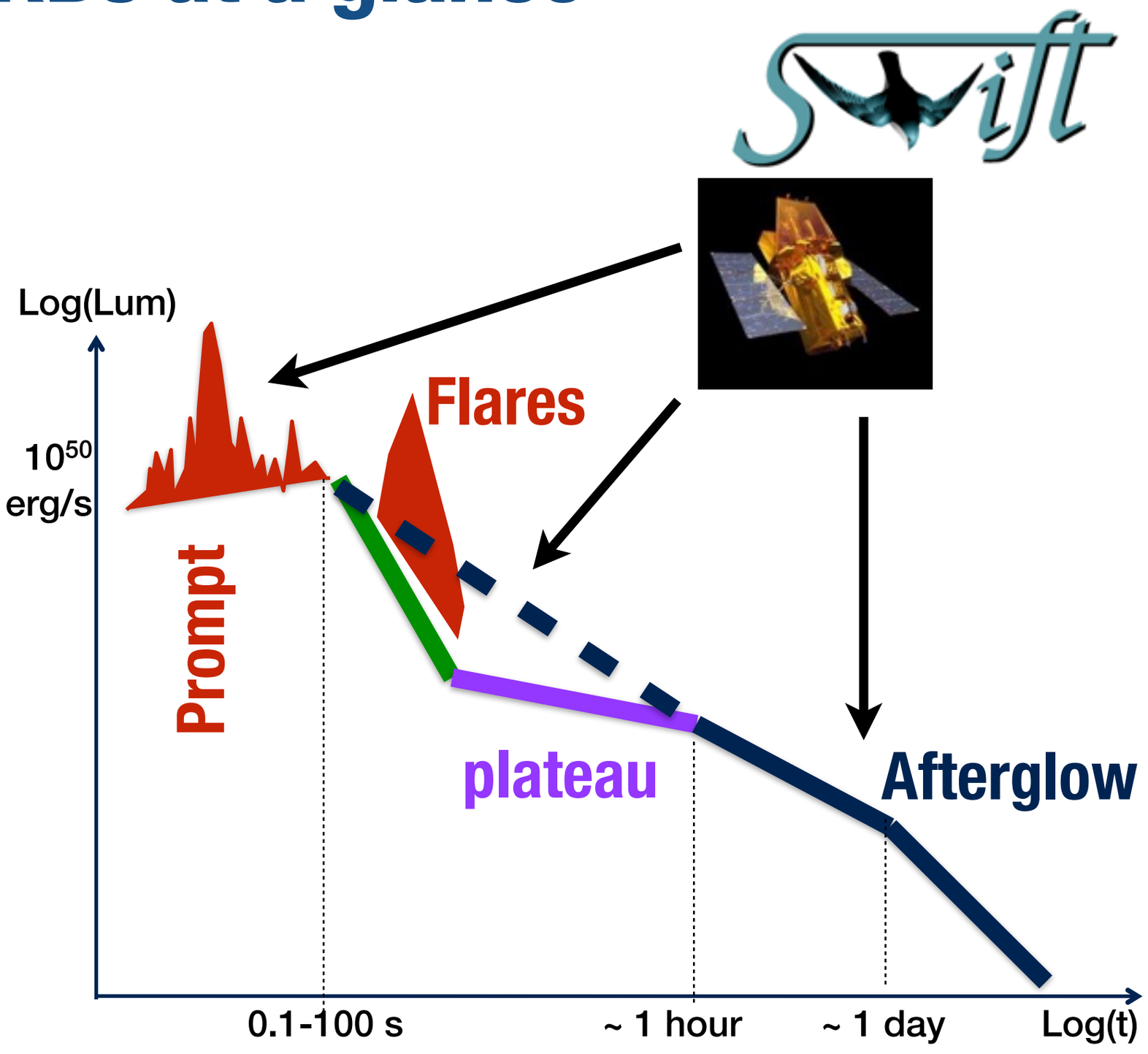
3rd SVOM science workshop, May 13-18 2018, Les Houches (France)

GRBs at a glance



GRBs at a glance

- **“canonical”** X-ray light curve (steep-**plateau**-normal) in ~ 1/2 GRBs
- **X-ray flares** in ~ 1/3 GRBs



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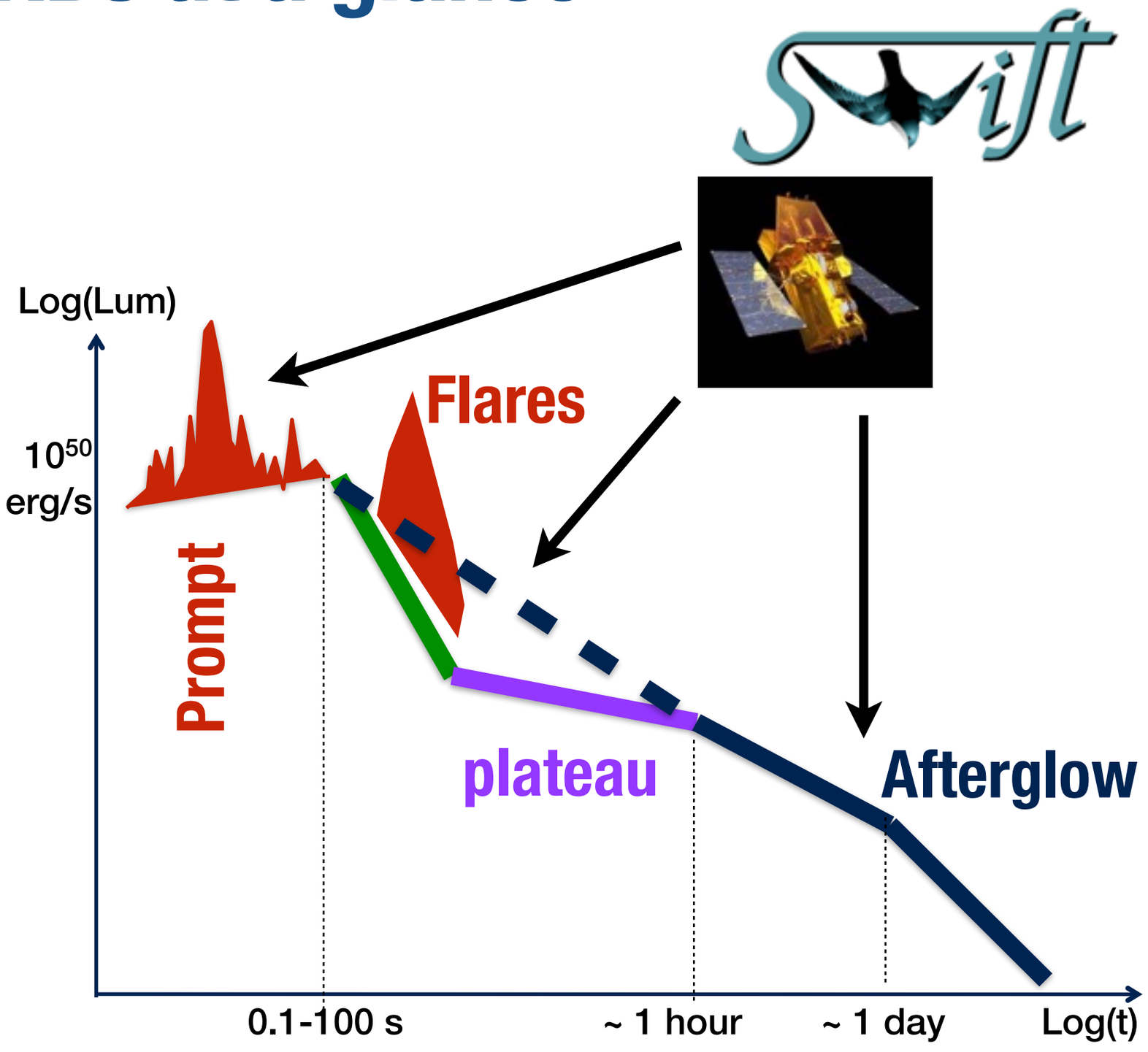
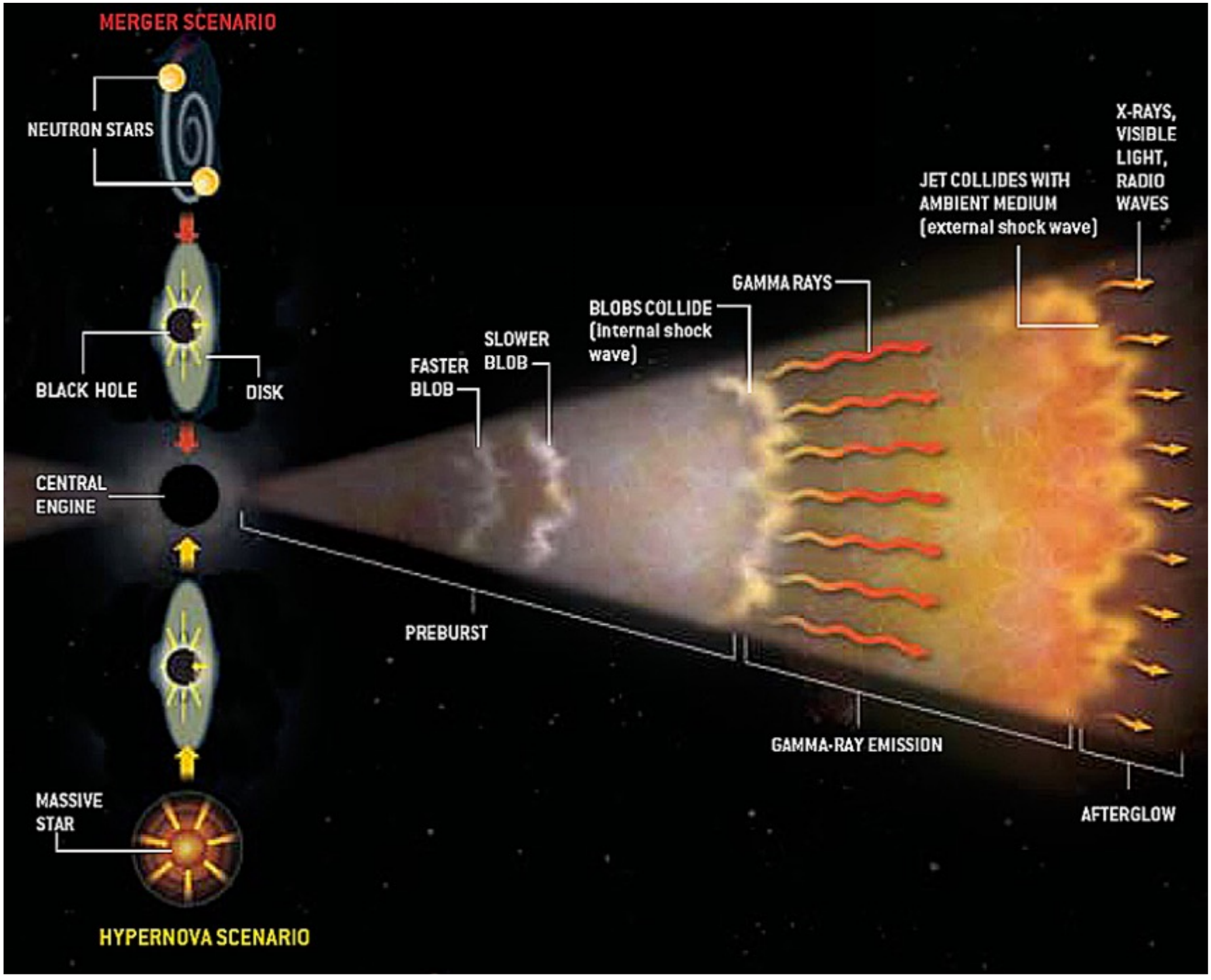


➡ not expected by standard model

GRB standard model

Short GRBs

Long GRBs



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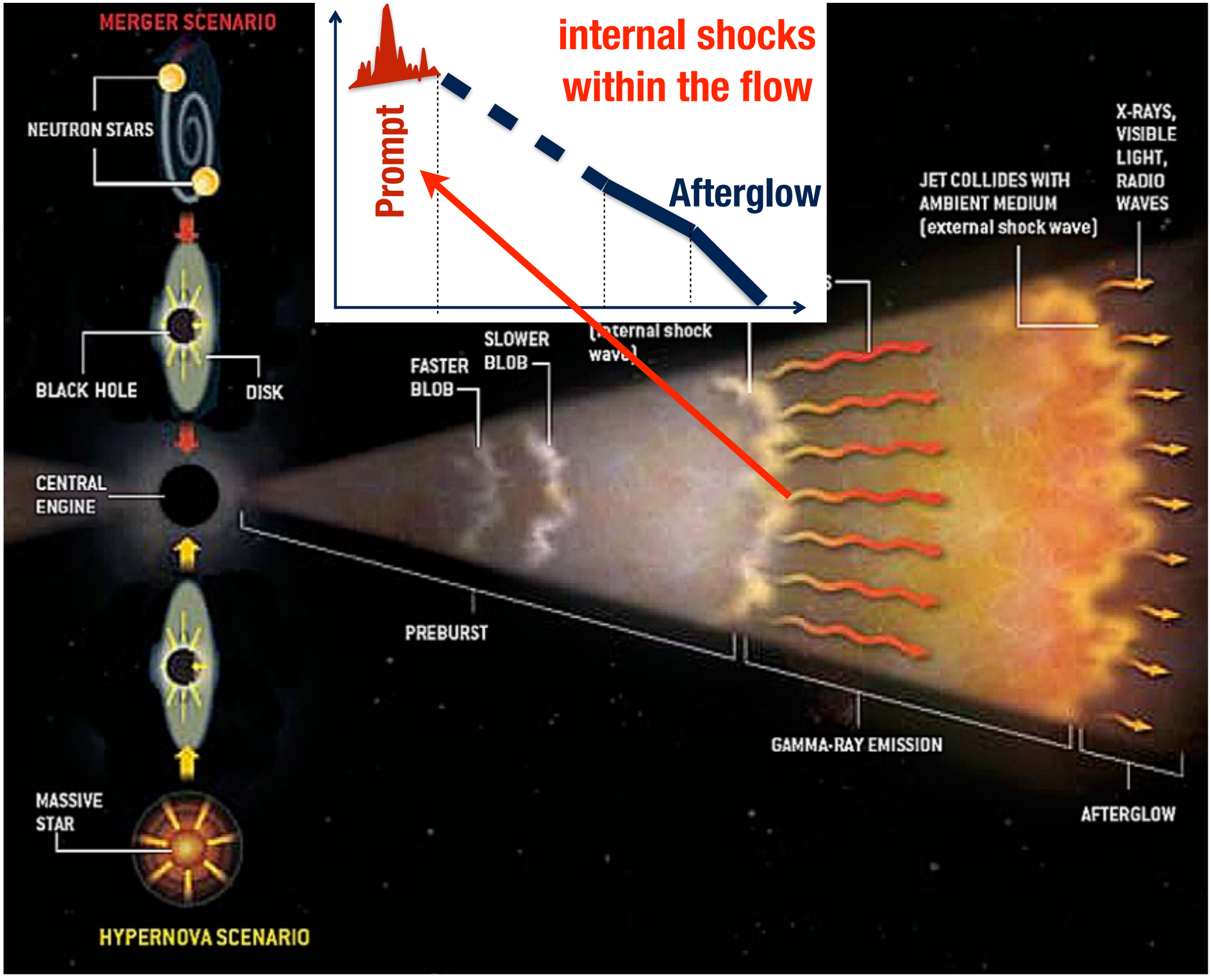

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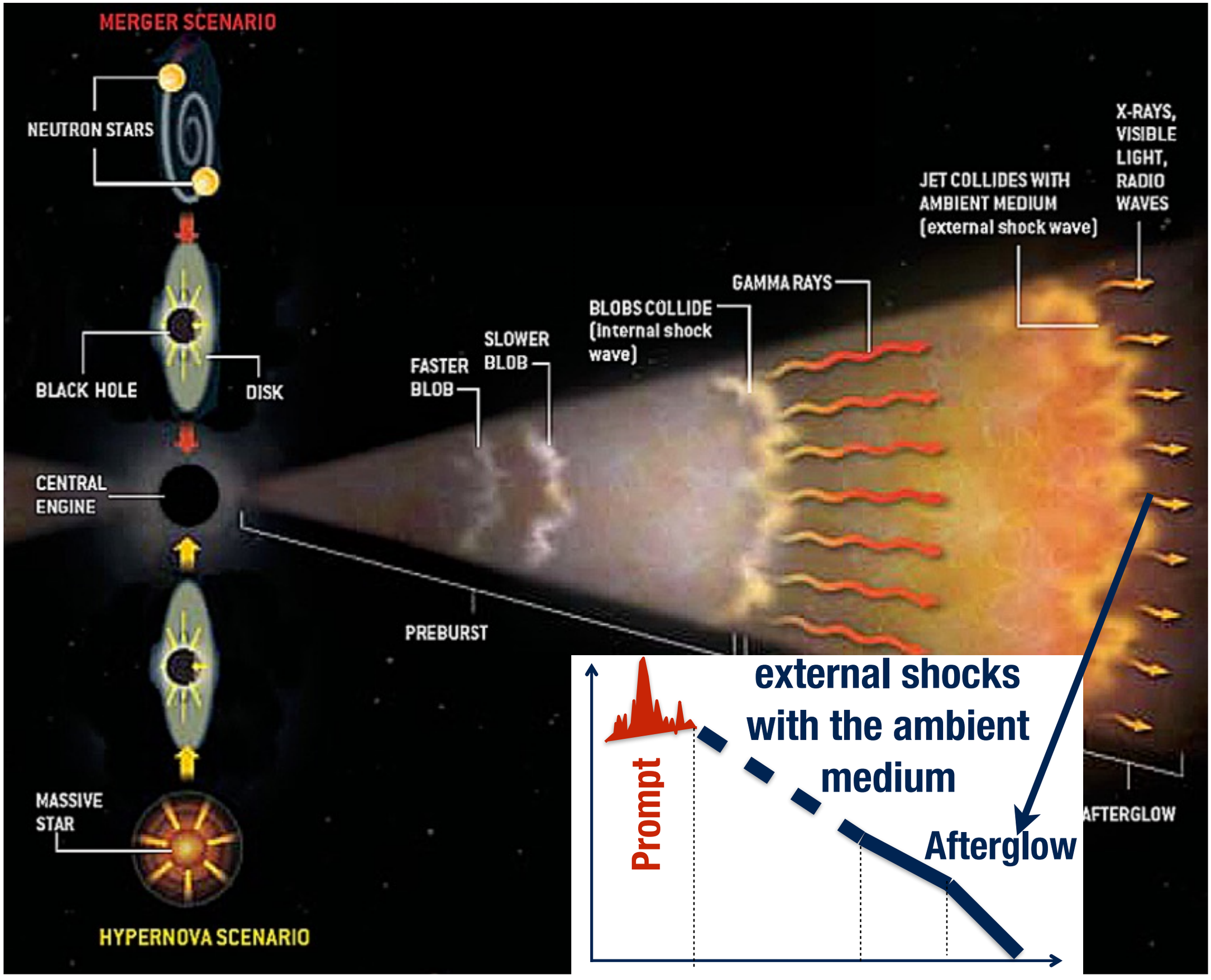
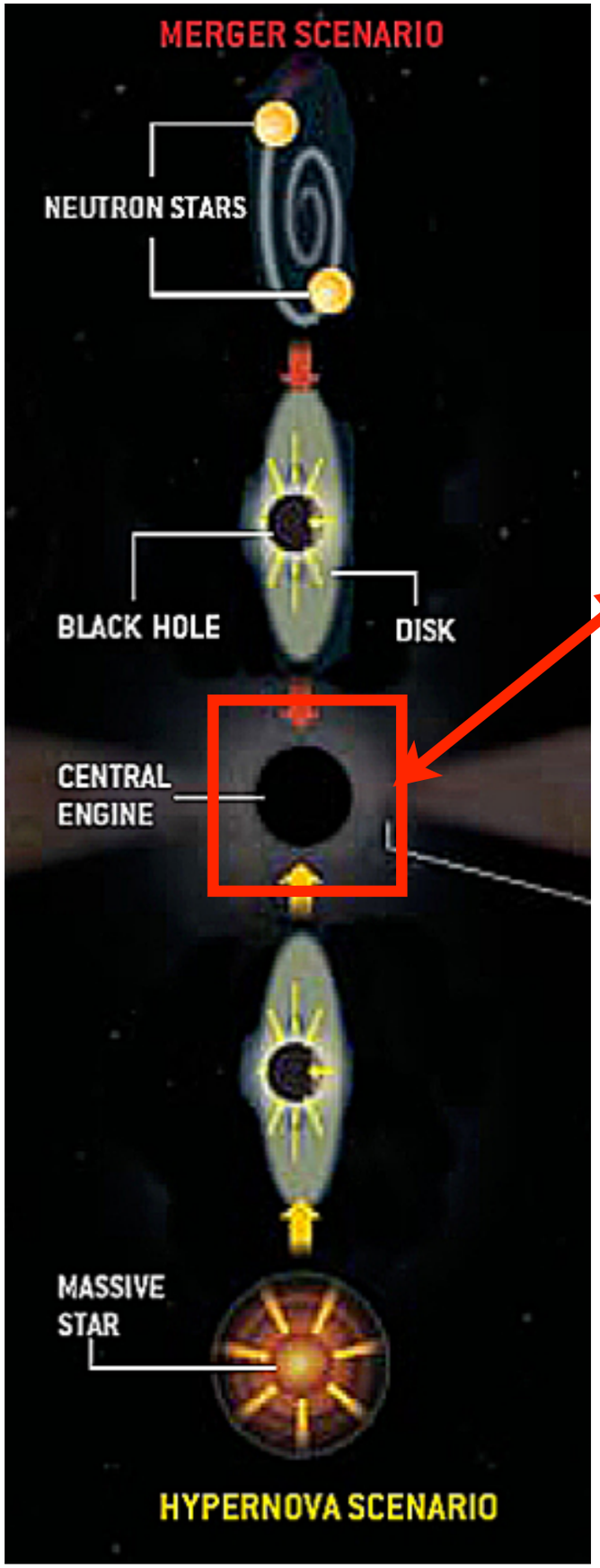
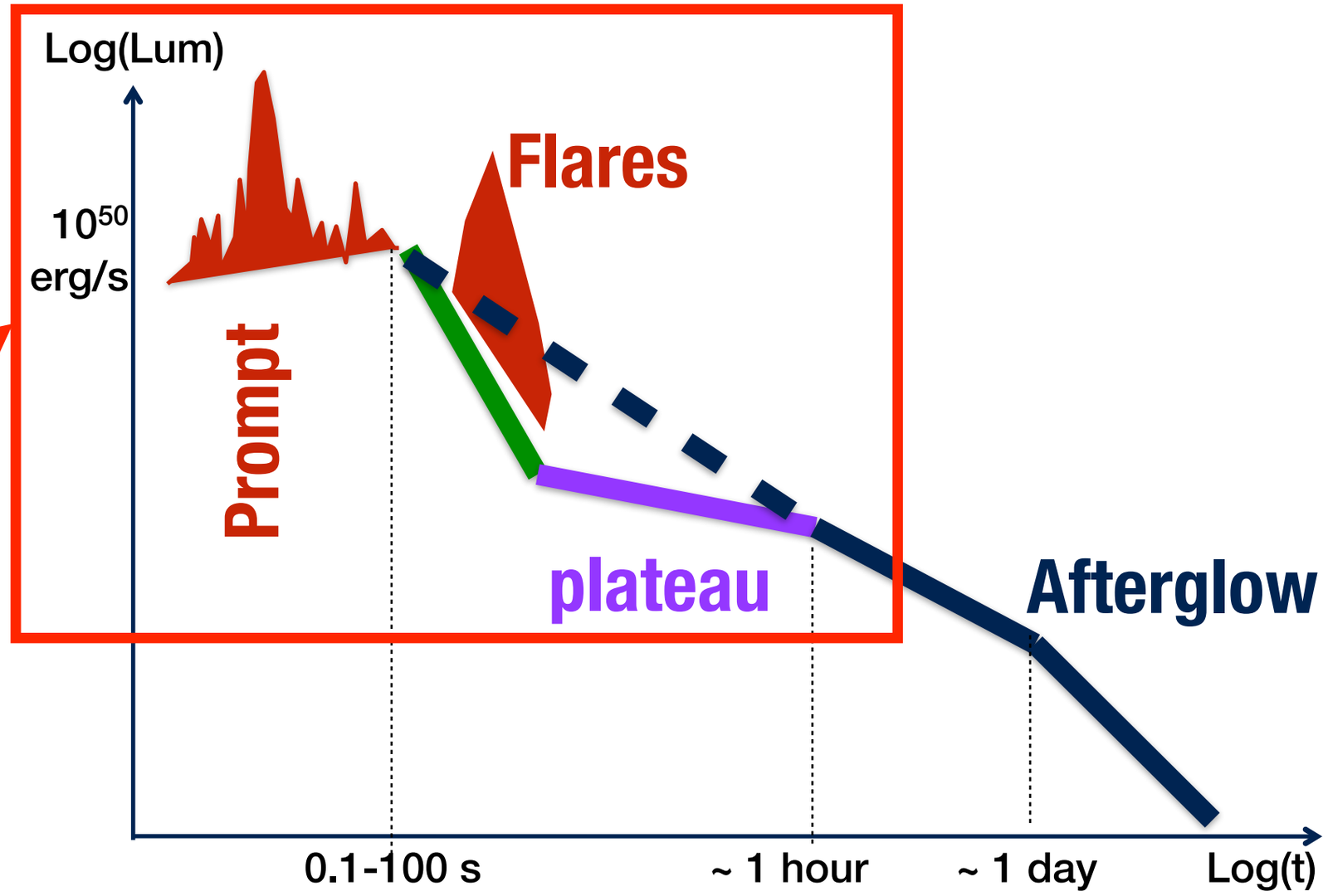


The role of the central engine

Short GRBs

Long GRBs



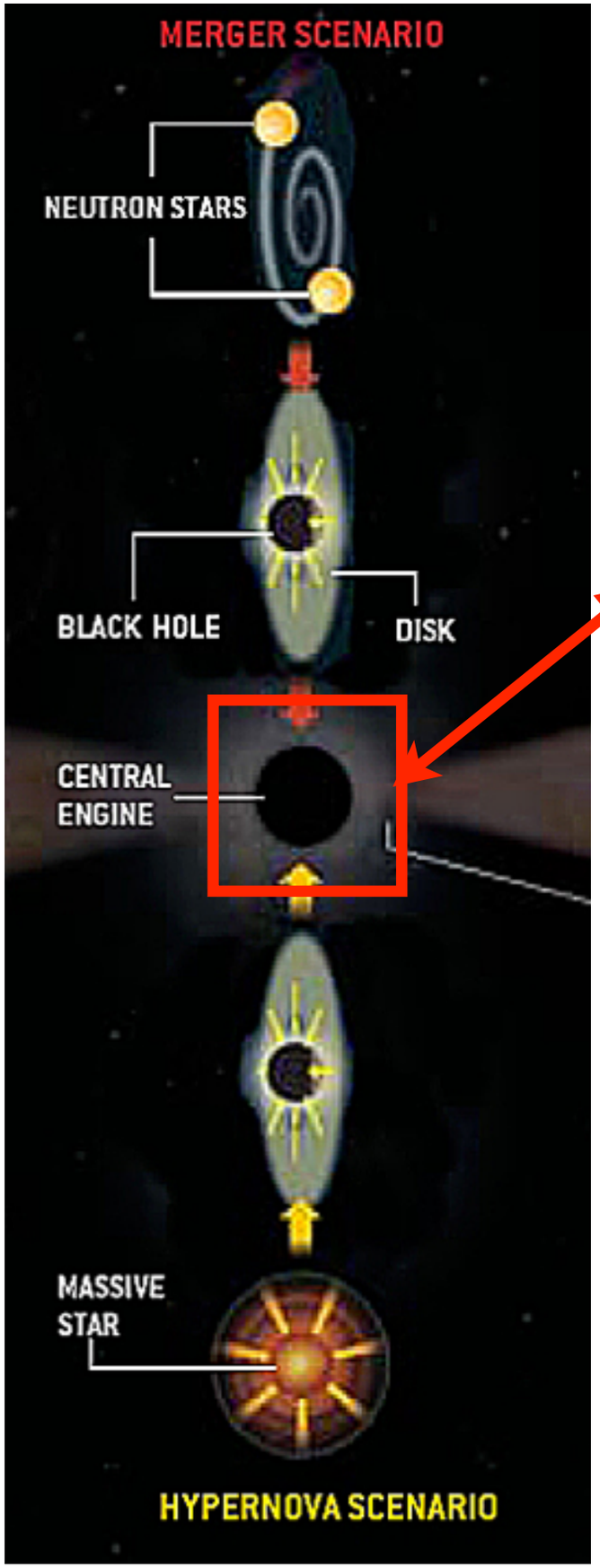


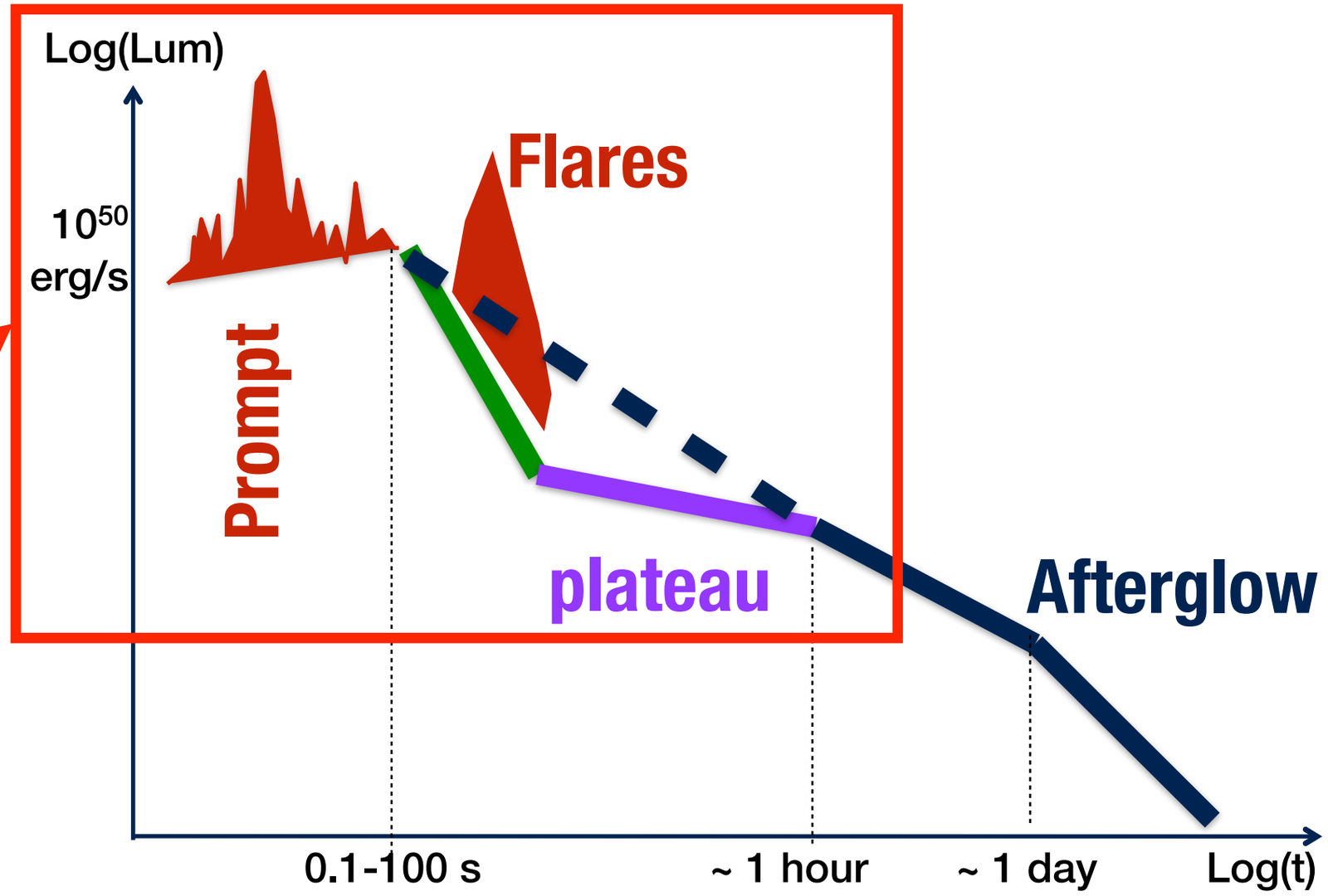
The role of the central engine

Magnetars: highly magnetised (B~ $10^{12\text{-}14}$ G) NSs

Short GRBs

Long GRBs





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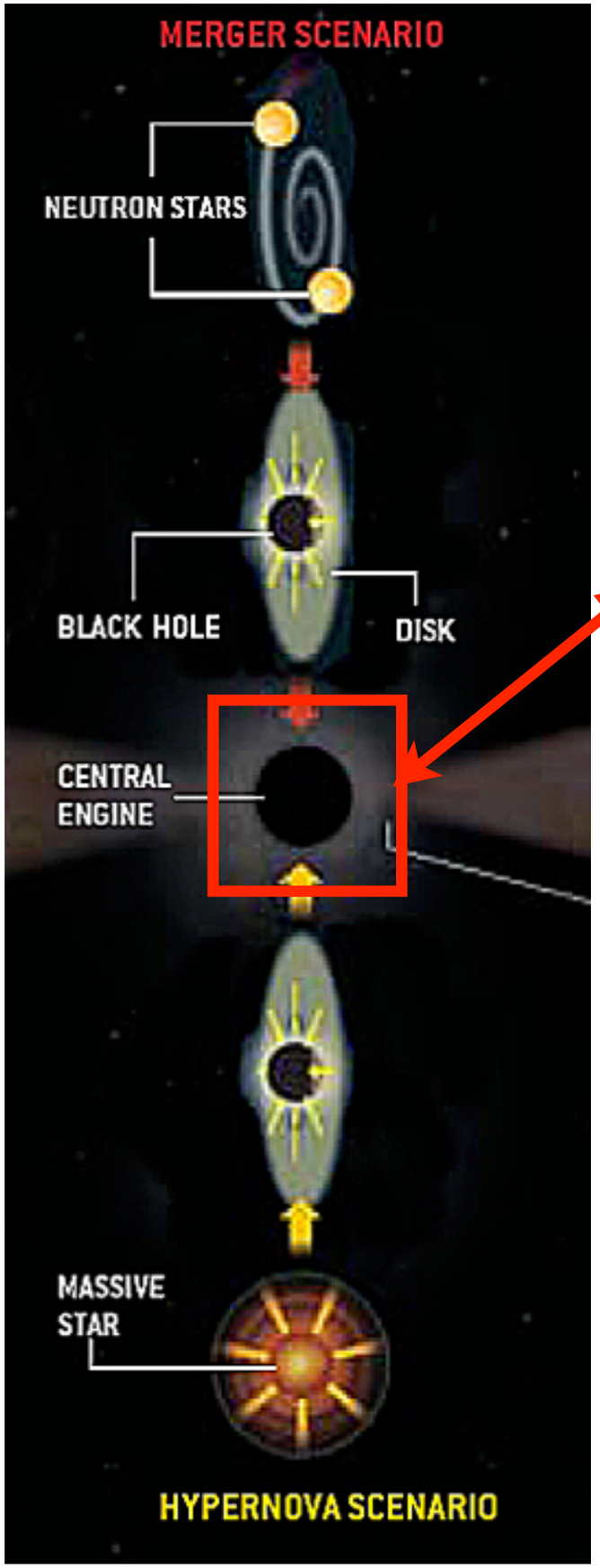

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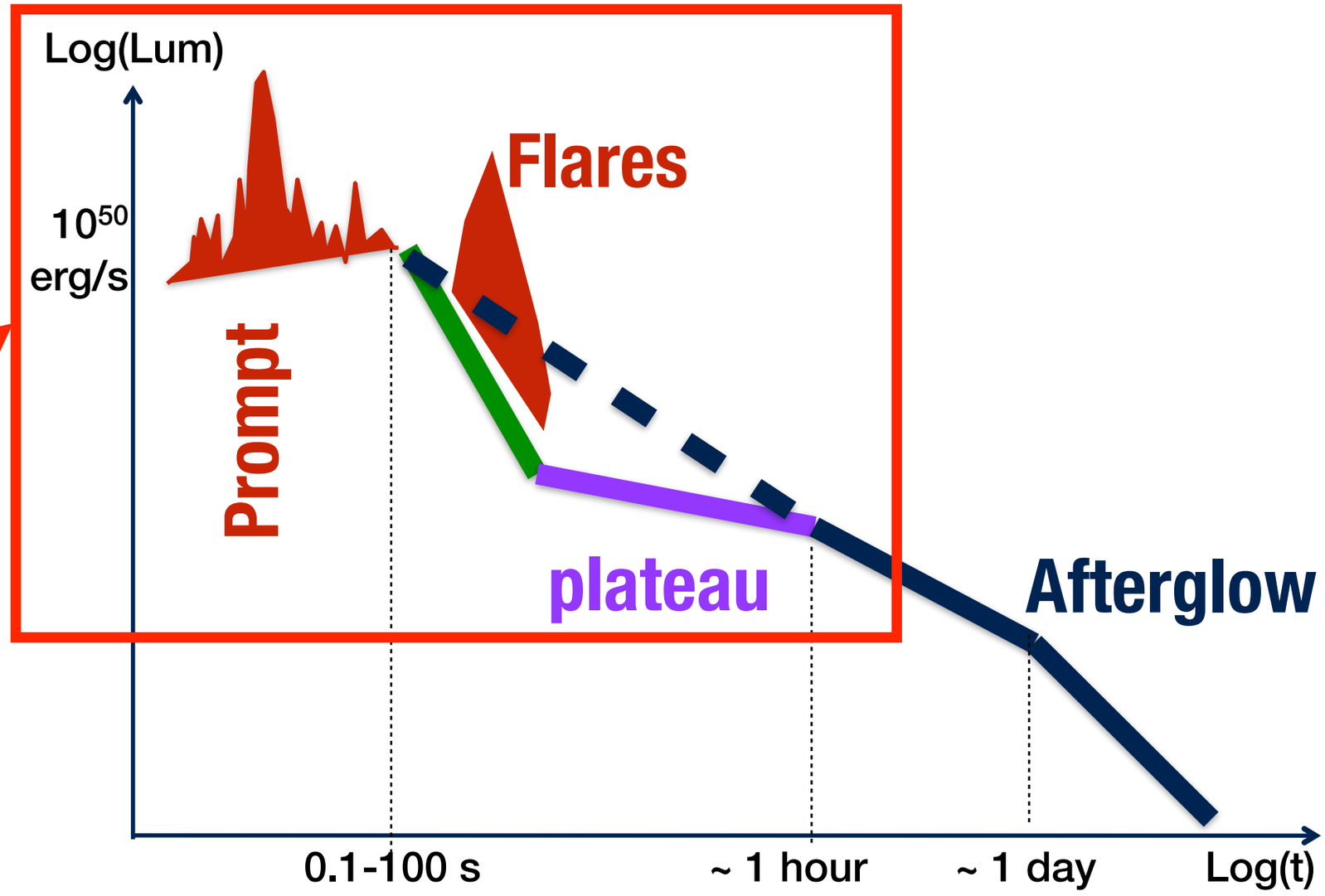

Magnetars competing with BHs as source of GRB power

Observational imprints of the magnetar

- plateau phase in X-rays of both LGRBs and SGRBs
- extended emission in SGRBs
- pre- and post-cursors in LGRBs and SGRBs

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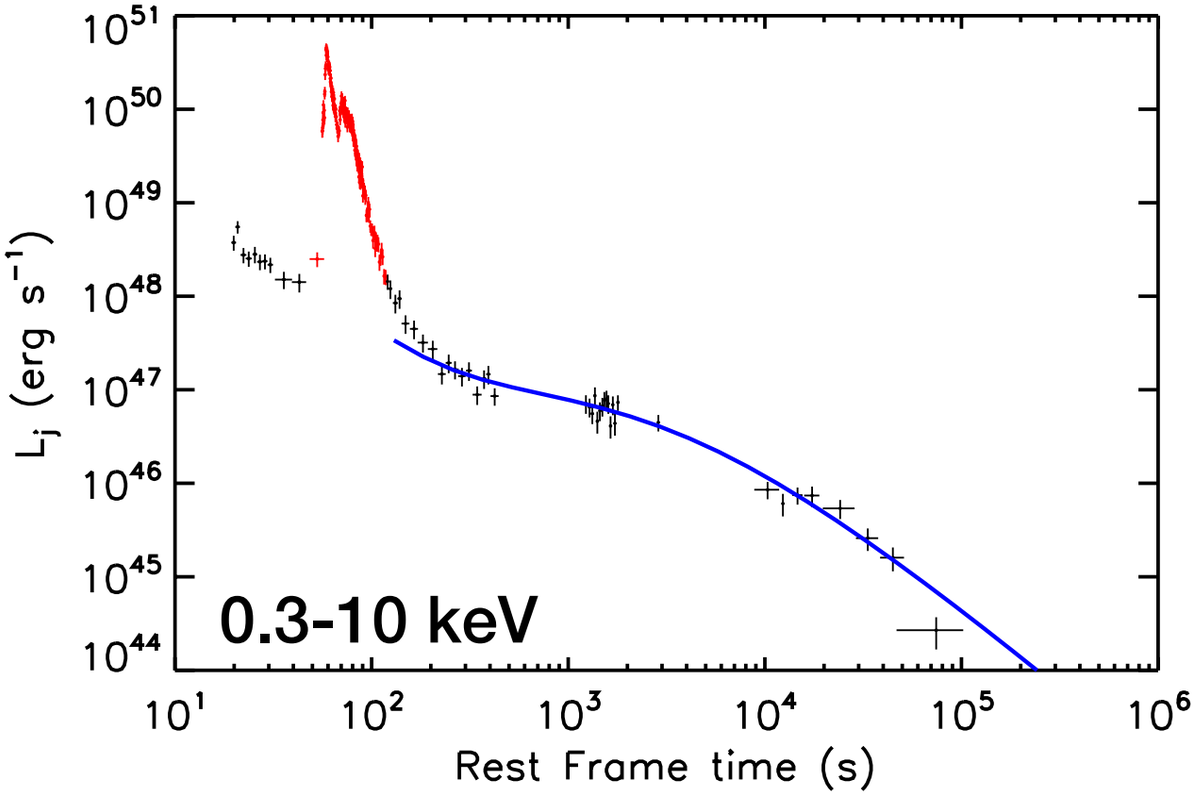
First evidence for magnetars: the GRB plateau



Rowlinson et al. 2013

- **plateau** phase in the X-ray afterglow of LGRBs and SGRBs

➡ **energy injection into the afterglow lasting ~ hours**

Dai & Lu 1998
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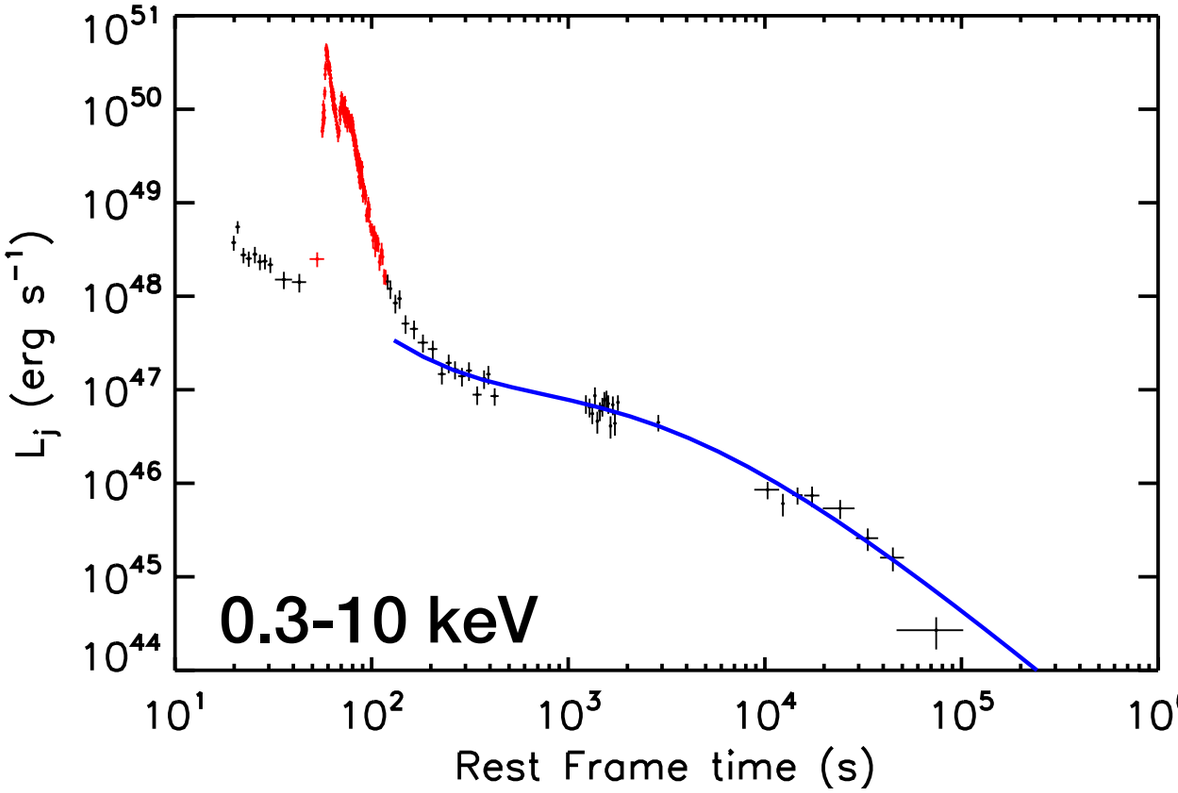

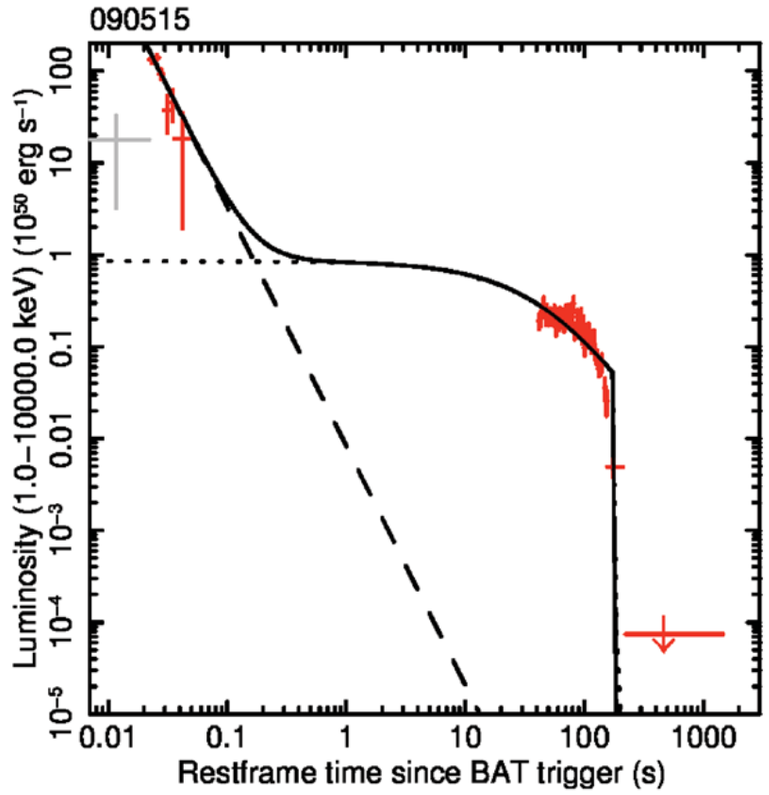

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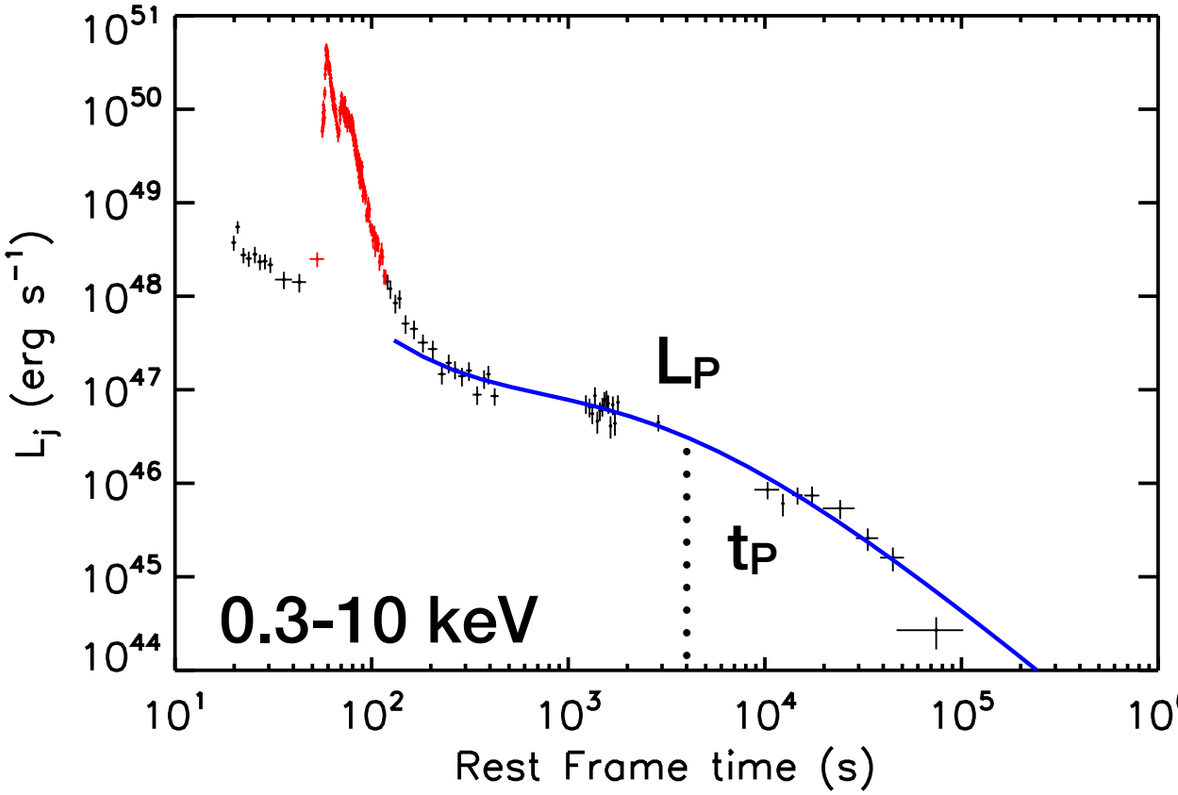

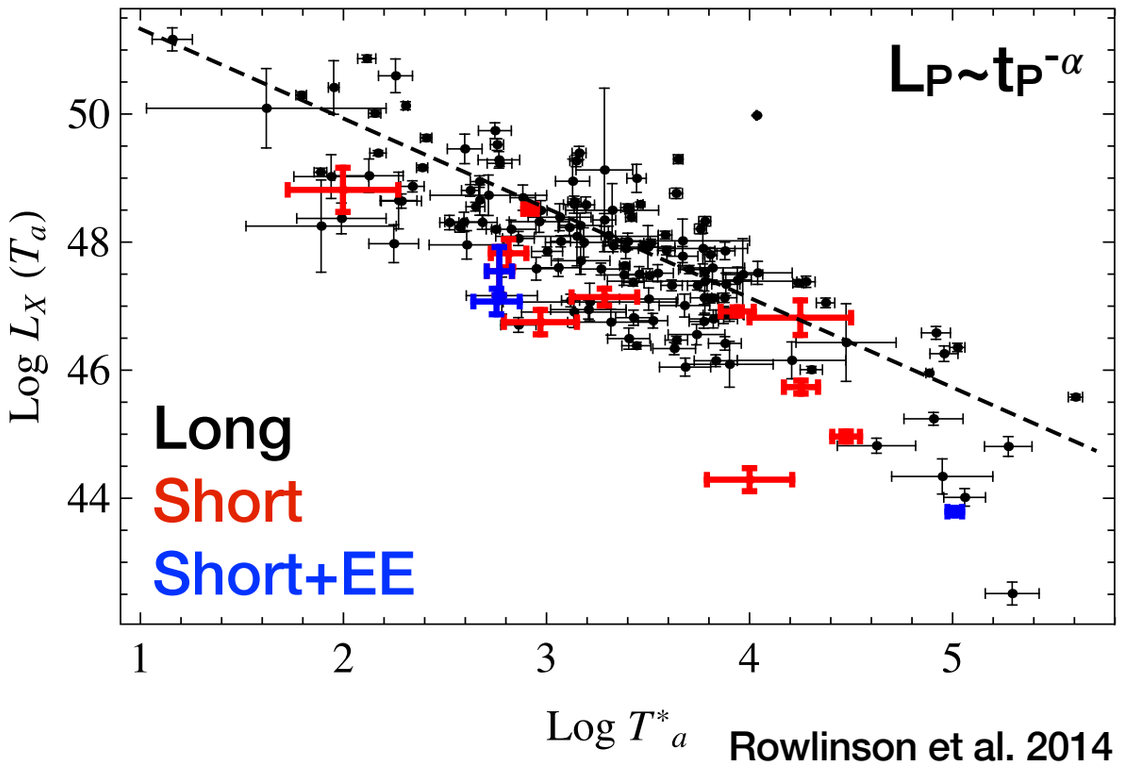

Rowlinson et al. 2014

- **plateau** phase in the X-ray afterglow of LGRBs and SGRBs

➡ **energy injection into the afterglow lasting ~ hours**

- typical decay ~ $t^{-1.2}$ but occasionally very sharp drop
- correlations between the plateau properties and the prompt emission

Dainotti et al. 2008, 2010, 2013, 2015

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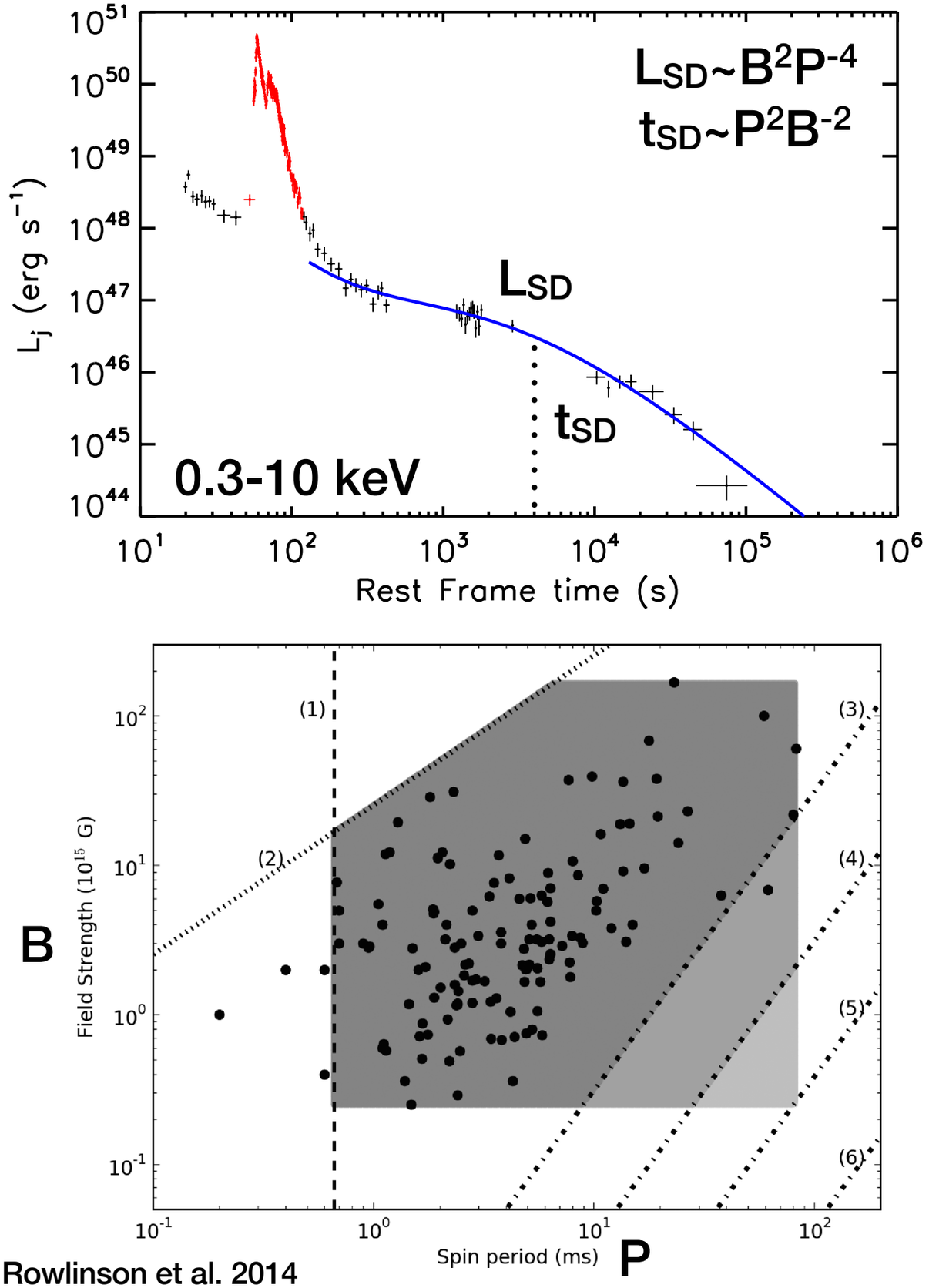

Rowlinson et al. 2014

- magnetar **spin-down power** reproduce the **plateau** features

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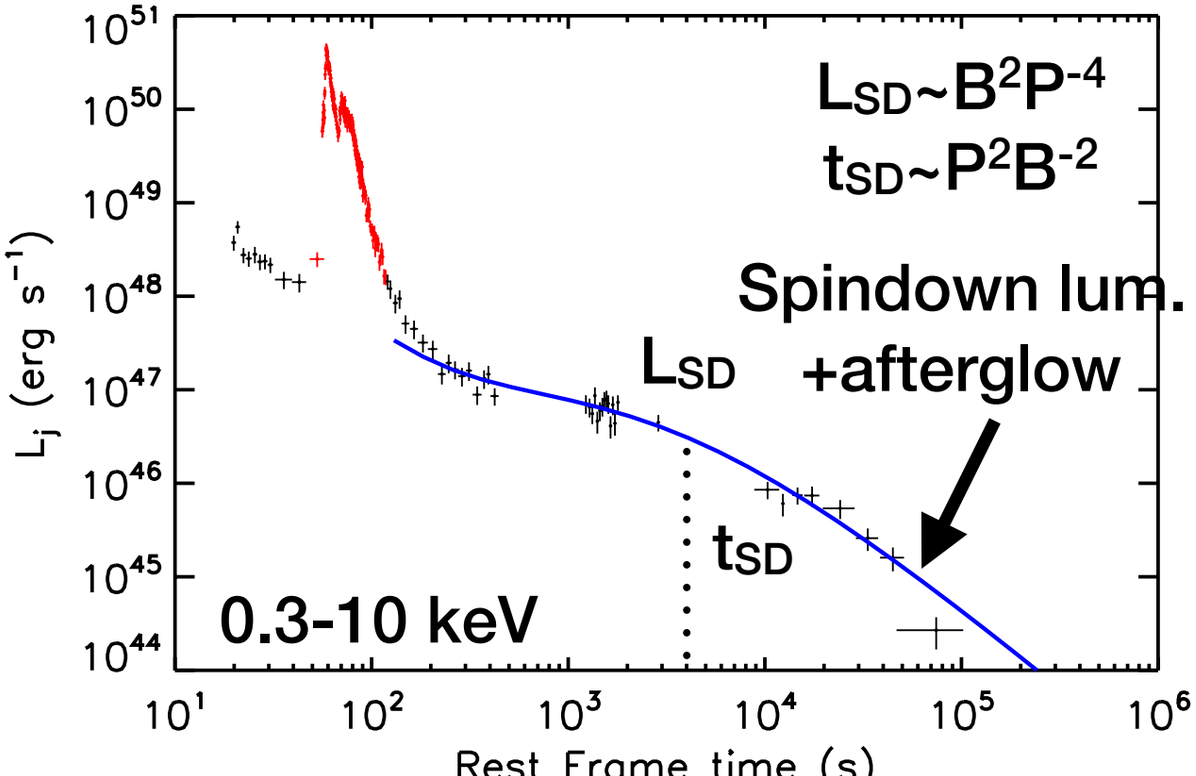

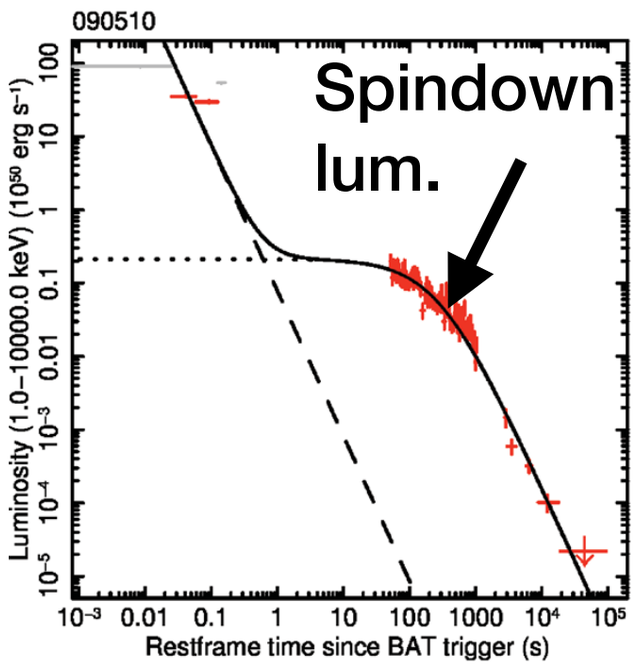

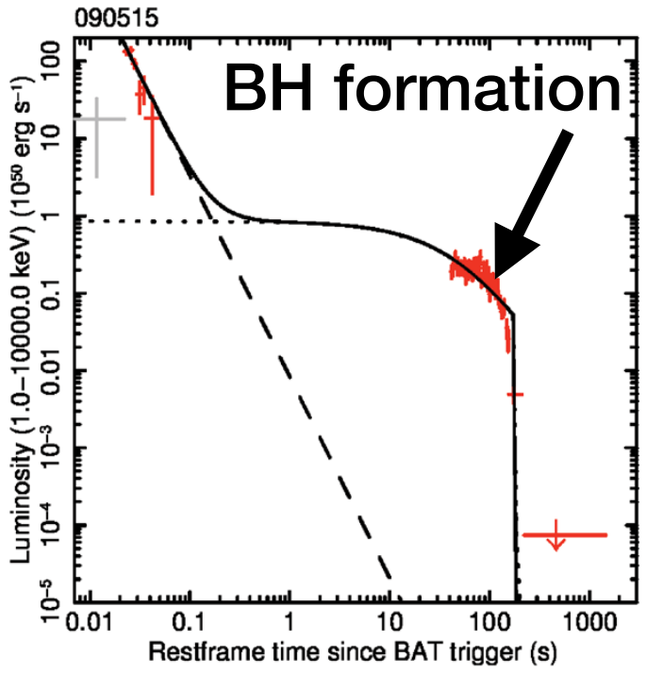

Rowlinson et al. 2013

- magnetar **spin-down power** reproduce the **plateau** features
- **external or internal**
  plateau: long-lived magnetar or collapse to BH

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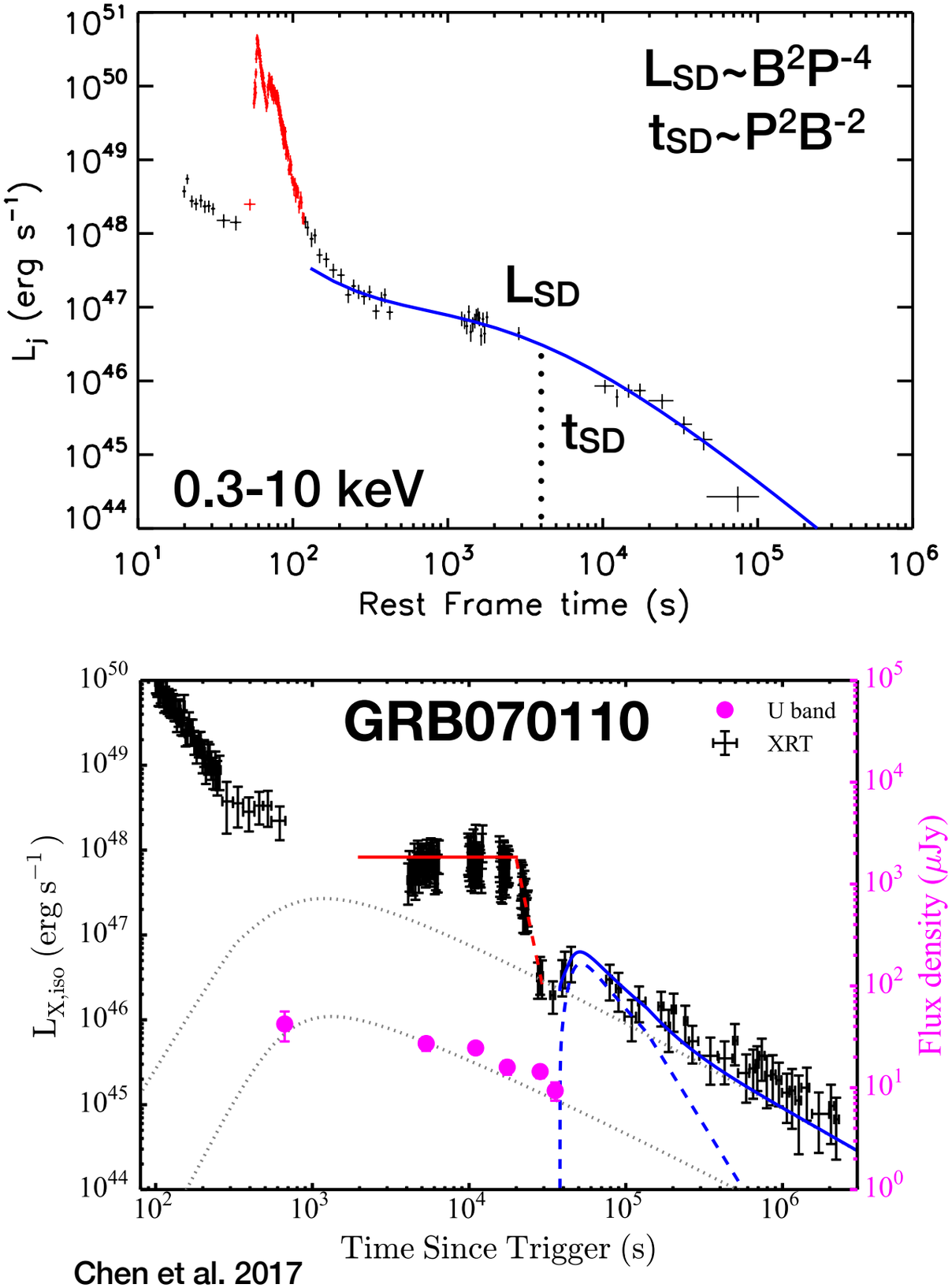

Chen et al. 2017

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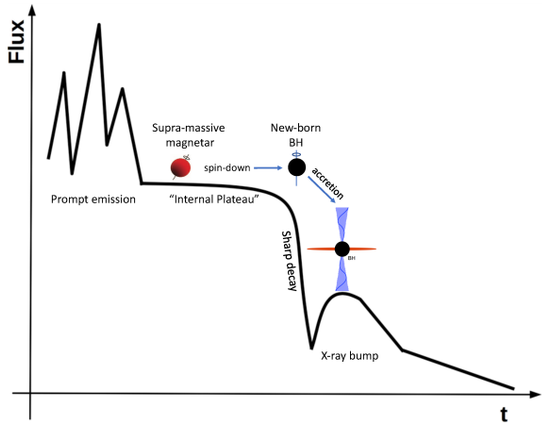

Wu et al. 2013
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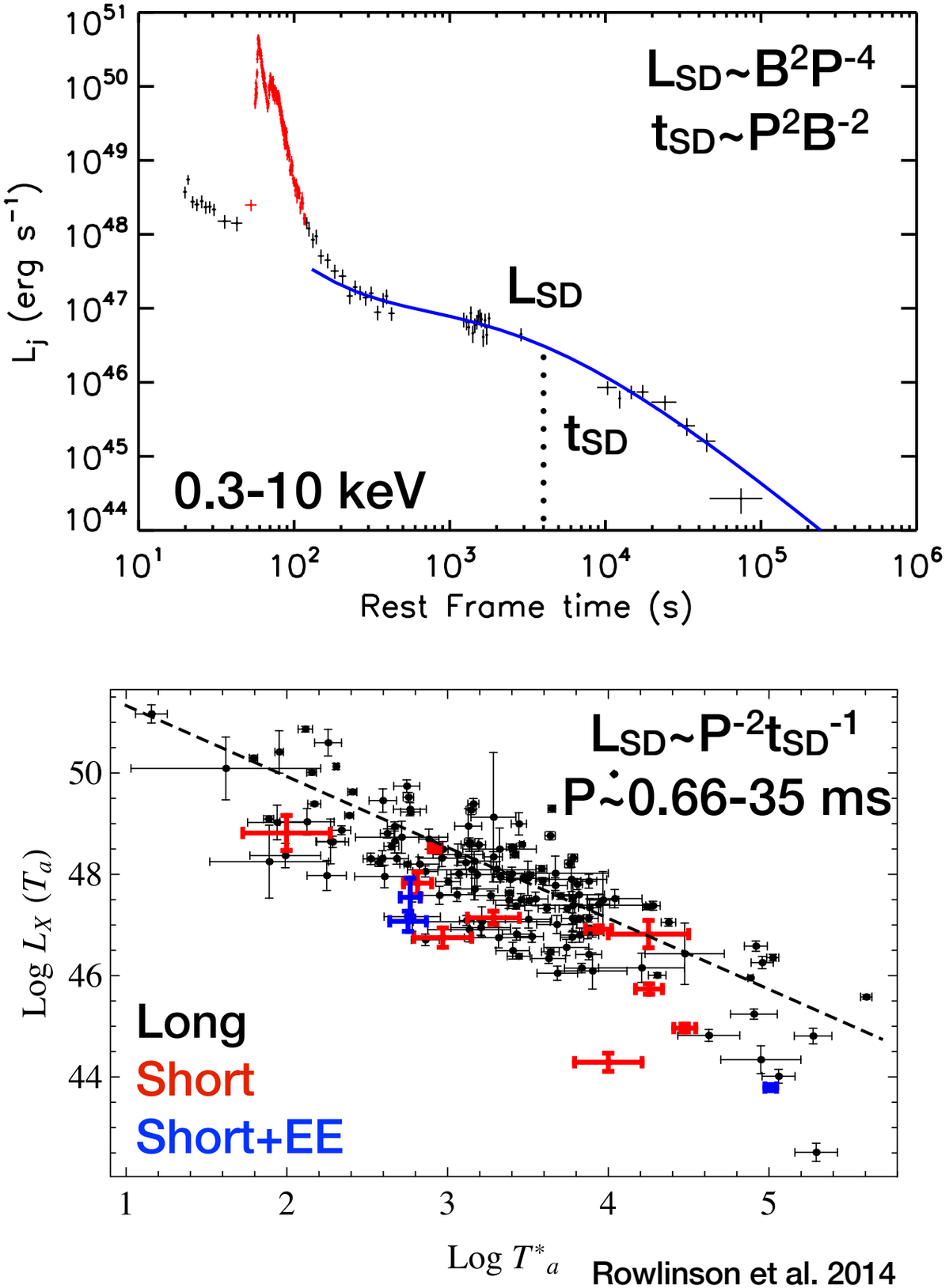

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- **Luminosity-duration correlation implied by the model**

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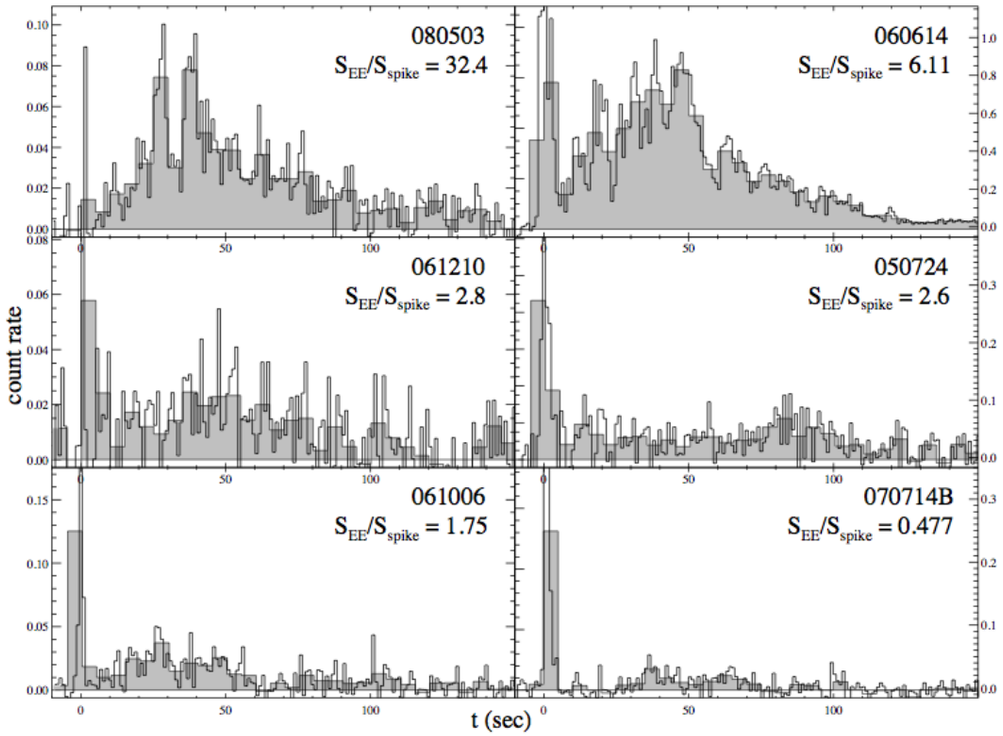
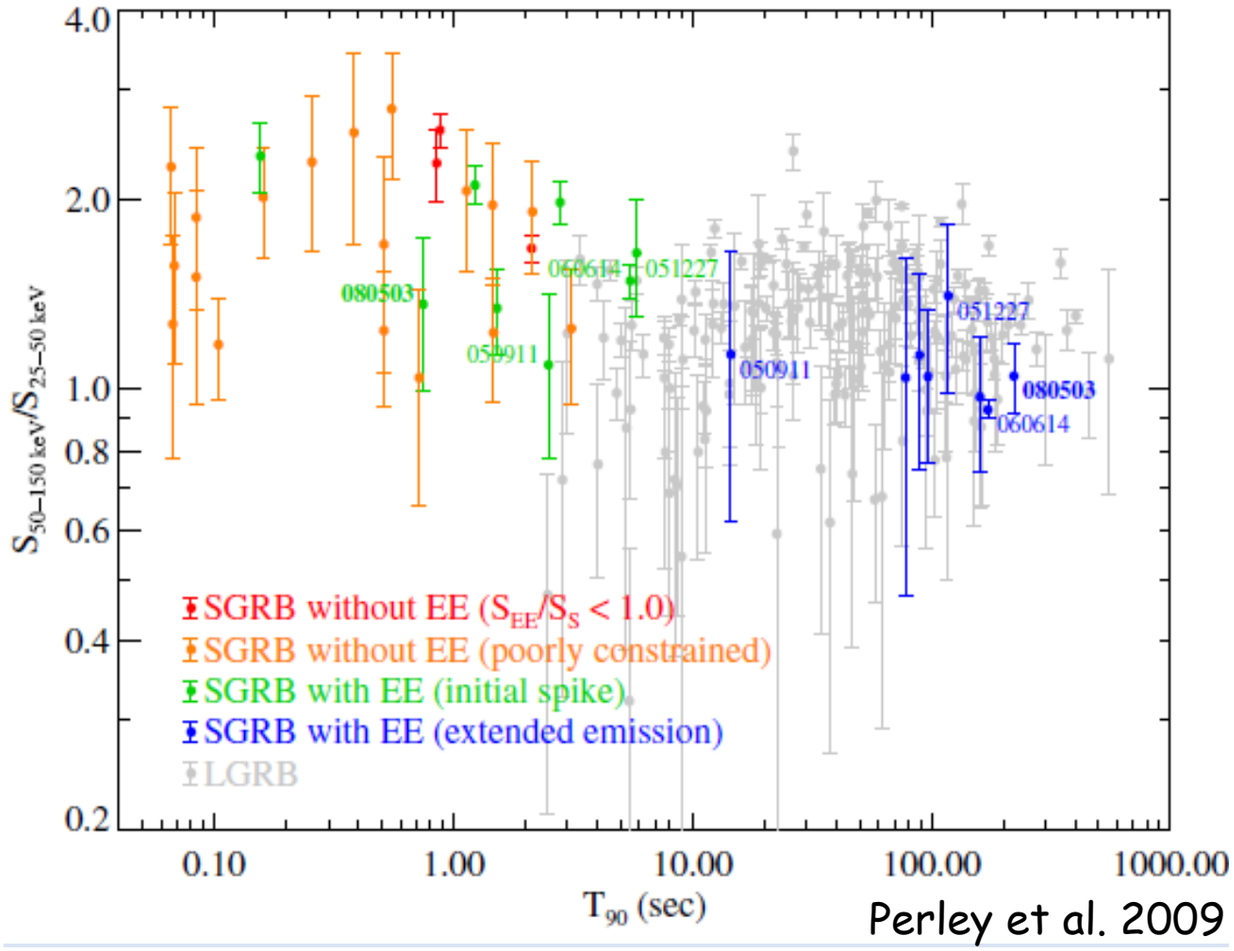
Extended Emission in SGRBs



- delayed onset of **EE** hard spike, soft tail
- lower peak but duration ~ 100 s
- larger fluence than the main event

~15% of SGRBs show an **extended emission (EE)** in the prompt phase

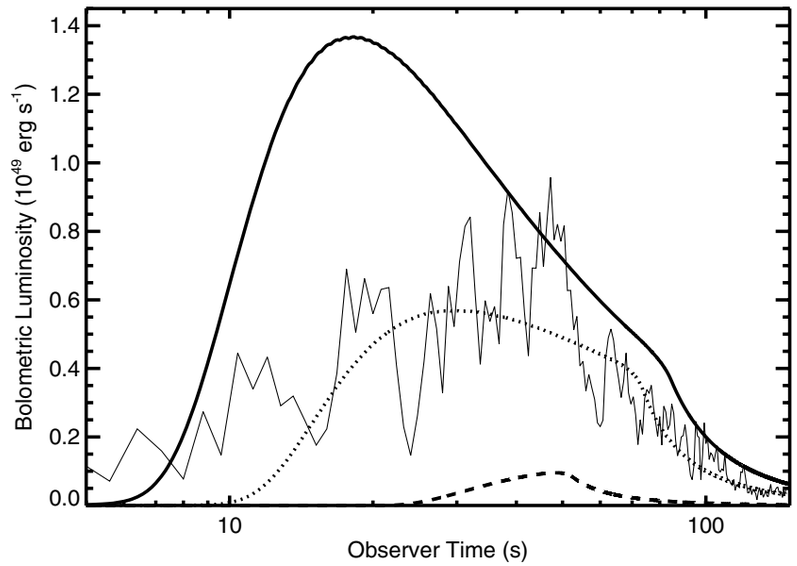


Lazzati et al. 2001
Norris & Bonnell 2006

Extended Emission in SGRBs

- **EE + late time X-rays**: rotational powered wind

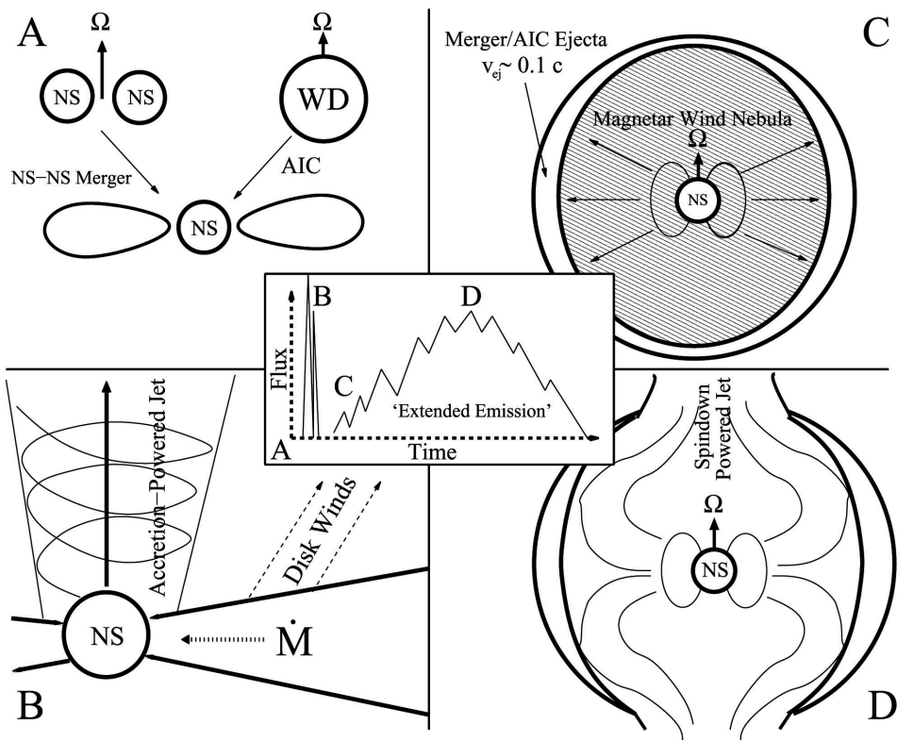
Metzger et al. 2008



- **EE**: propeller (material ejected by centrifugal forces)
- **late X-rays**: rotational powered wind

➡ **different mechanisms for different features**

Gompertz et al. 2014



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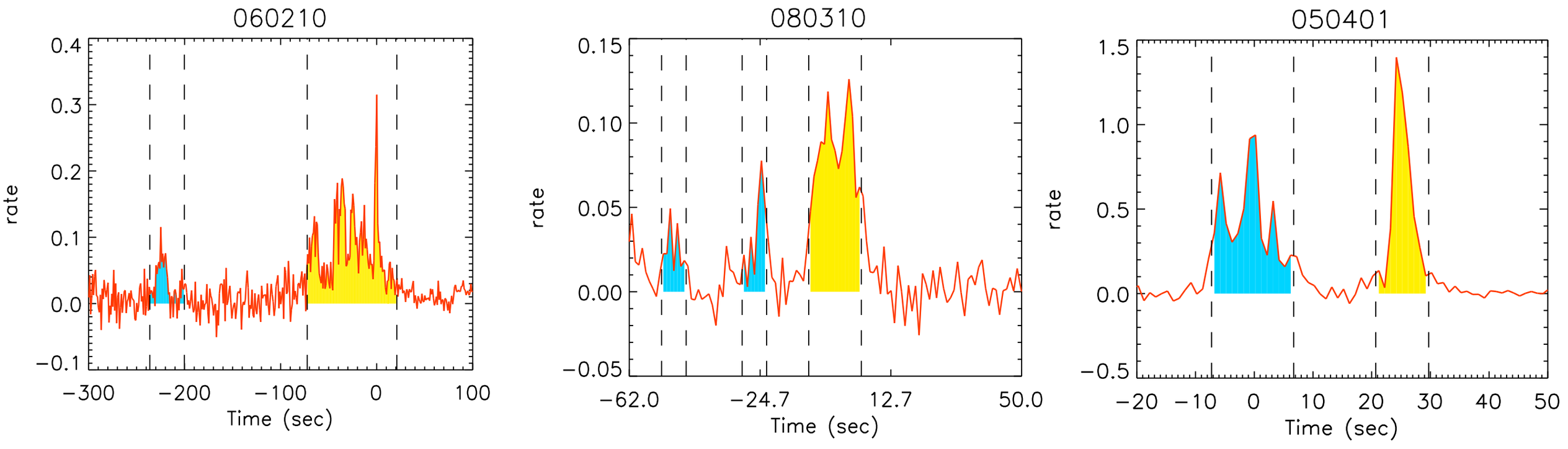
Precursors in GRBs

Emission episodes **PRIOR TO** the main prompt emission of **~10% of LGRBs and SGRBs**:

- quiescent time ~ T_{90}
- multiple precursors
- negligible or comparable energies
- **similar properties w.r.t. the main prompt event**

Koshut et al. 1995
Lazzati 2005
Ramirez-Ruiz & Merloni 2001
Burlon et al. 2008, 2009
Troja et al., 2010
Bernardini et al. 2013



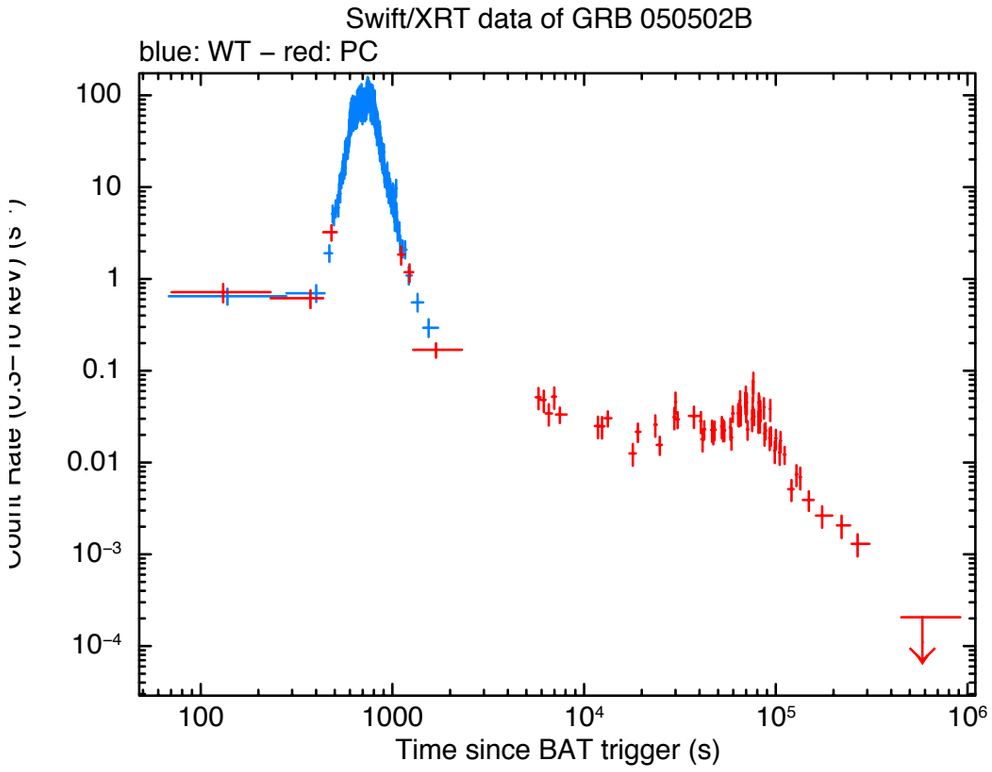
Credit D. Burlon

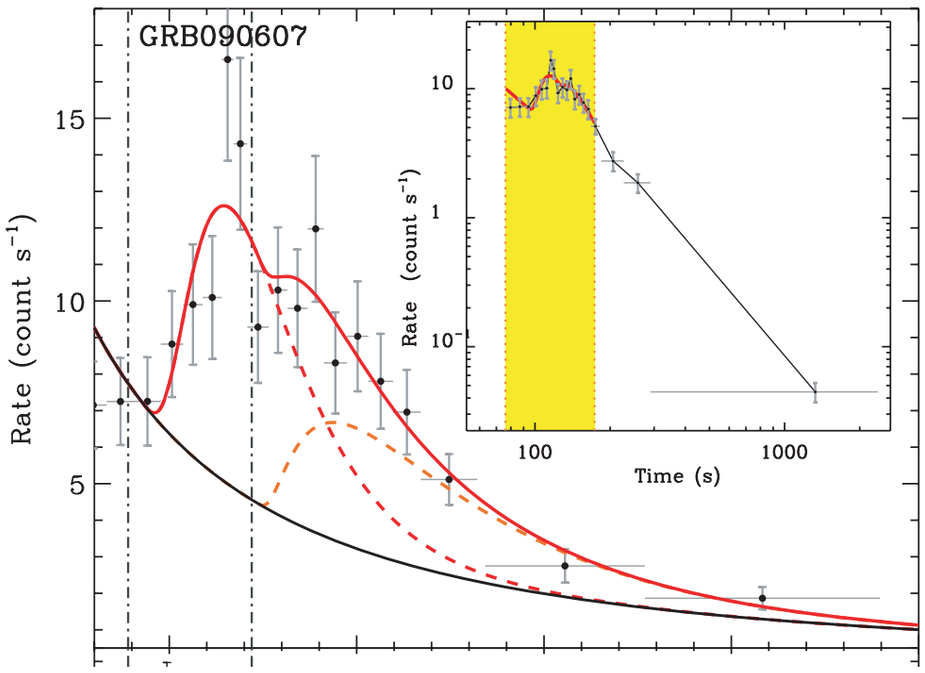
X-ray flares in GRBs

Emission episodes **AFTER** the main prompt emission in **~33% of LGRBs and SGRBs**:

- t_{pk} usually ≤ 1000 s, but also at late times
- multiple flares
- negligible or comparable energies (**"giant" flares**)
- **flares and prompt pulses have likely the same origin**

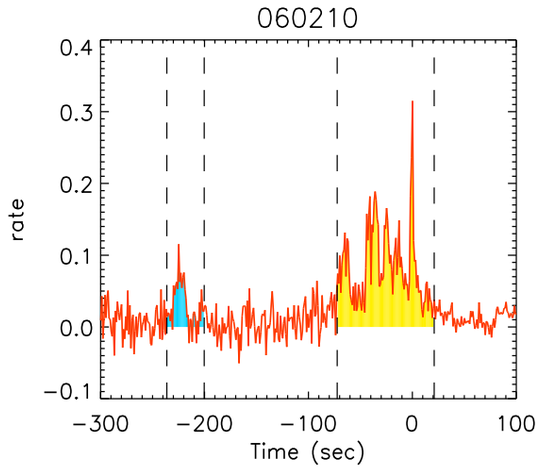
Chincarini et al., 2007, 2010
Margutti et al., 2010, 2011, 2012
Bernardini et al., 2011



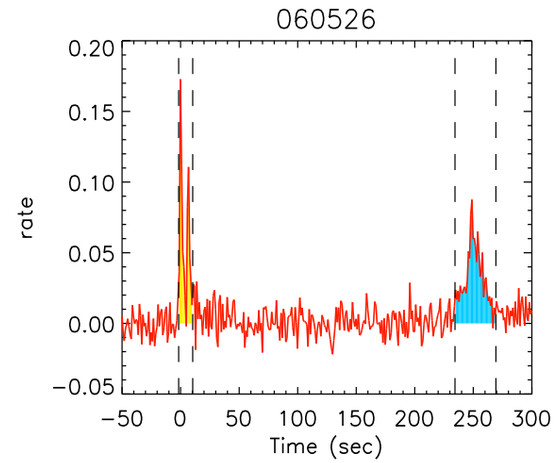


Margutti et al., 2012

The GRB prompt emission activity



precursors



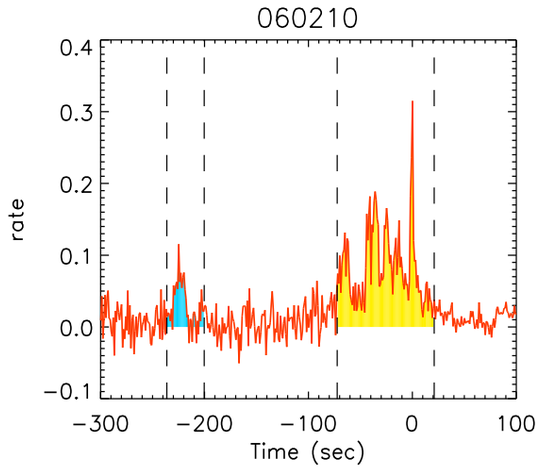
giant flares

- similar properties
- relatively common
- both in L and SGRBs

intermittent prompt emission activity

How to switch on and off a GRB?

The GRB prompt emission activity



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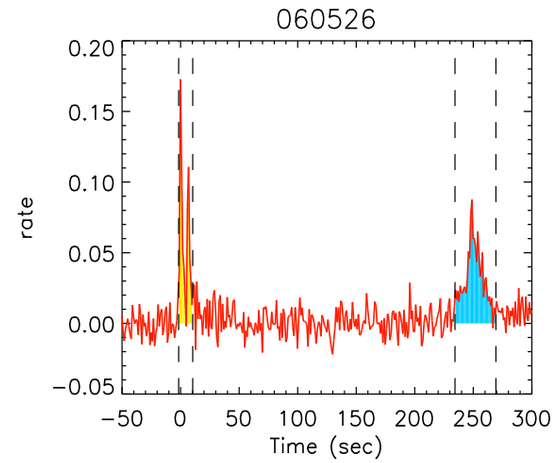

giant flares

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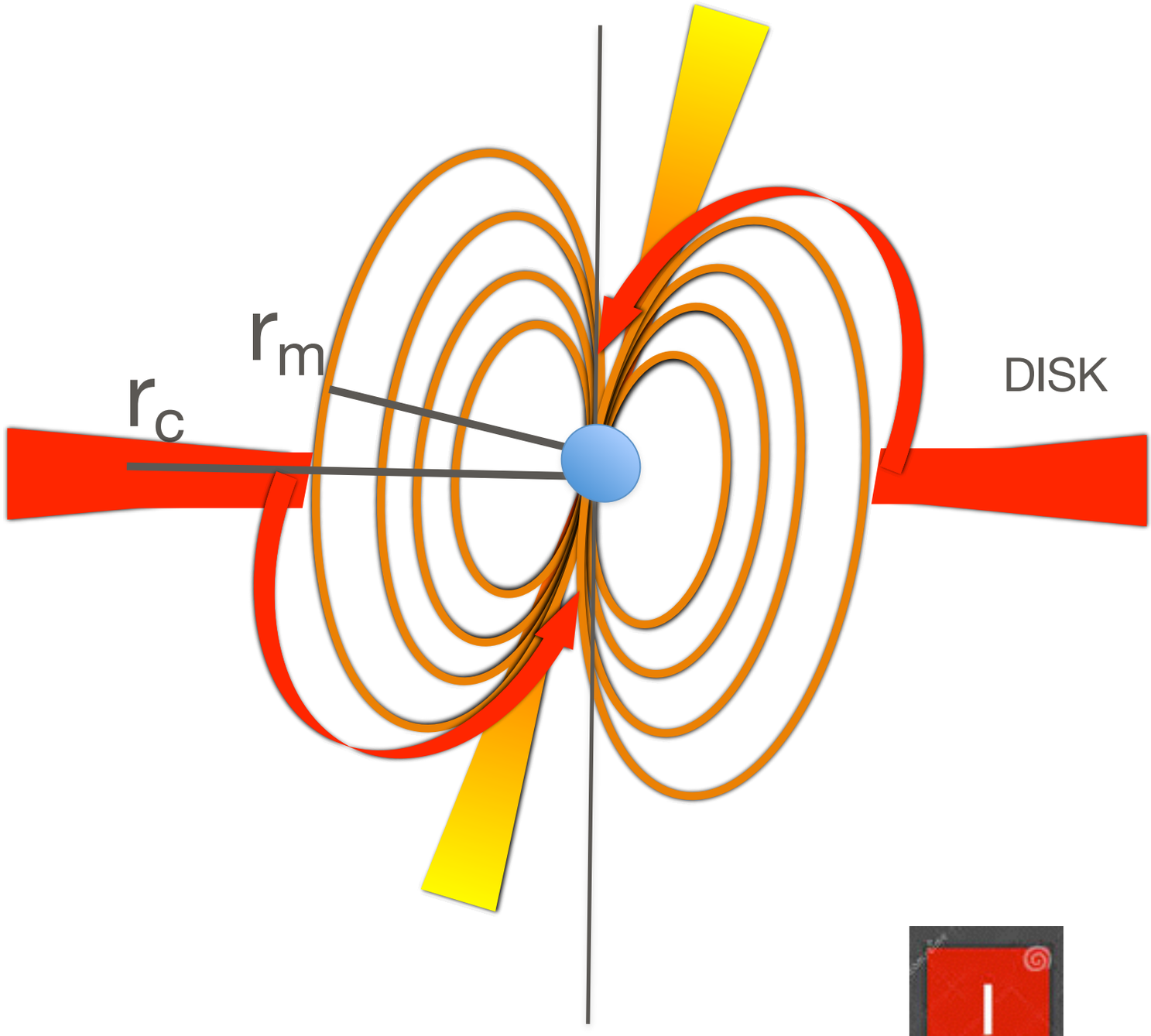
How to switch on and off a GRB?

Prompt emission powered by **accretion** onto the magnetar

Accreting magnetars as source of GRB power

⇒ **Accretion phase**

$r_m < r_c$



Bernardini et al., 2013

Accreting magnetars as source of GRB power

Accretion phase

⇒ **Propeller phase**

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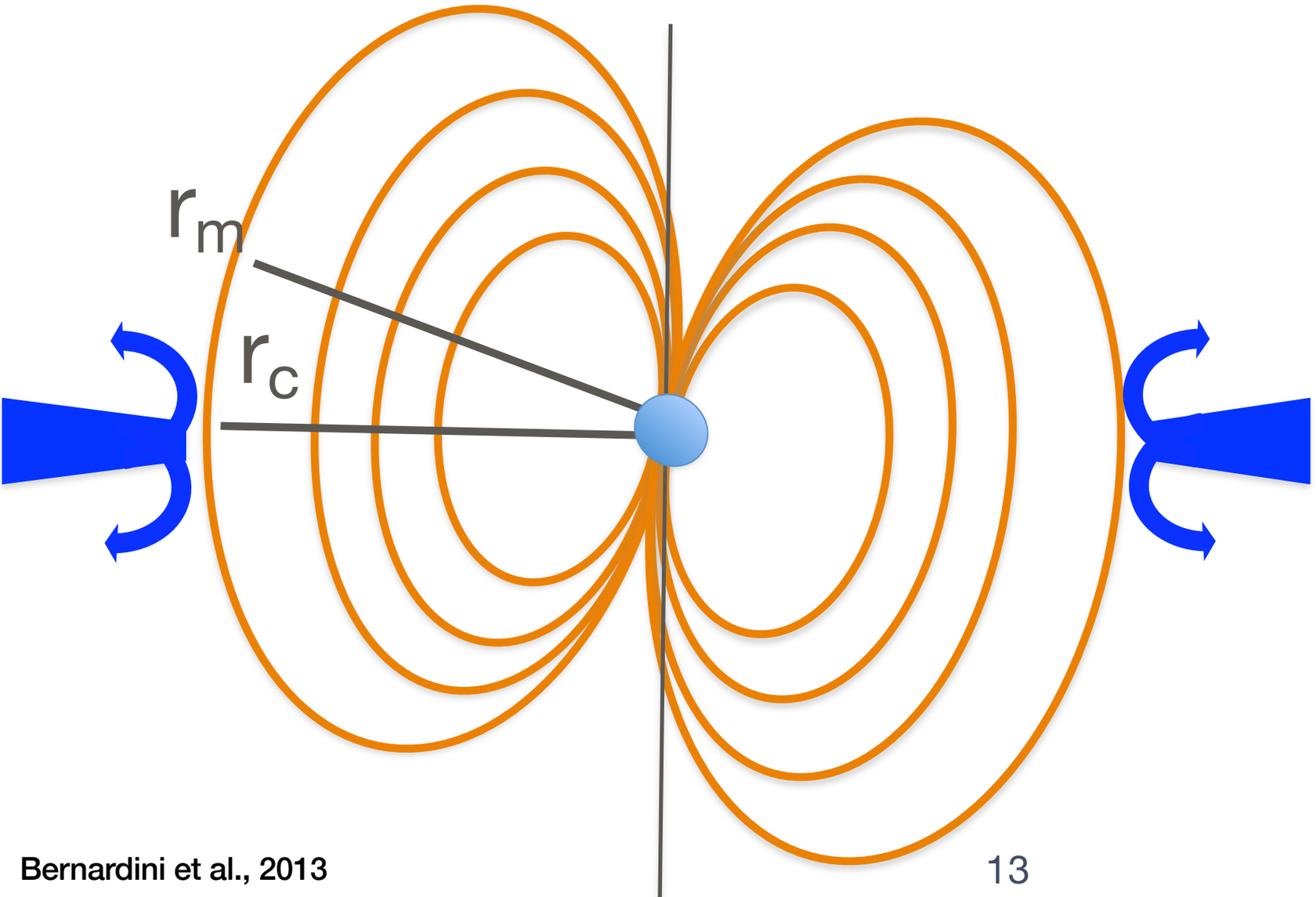
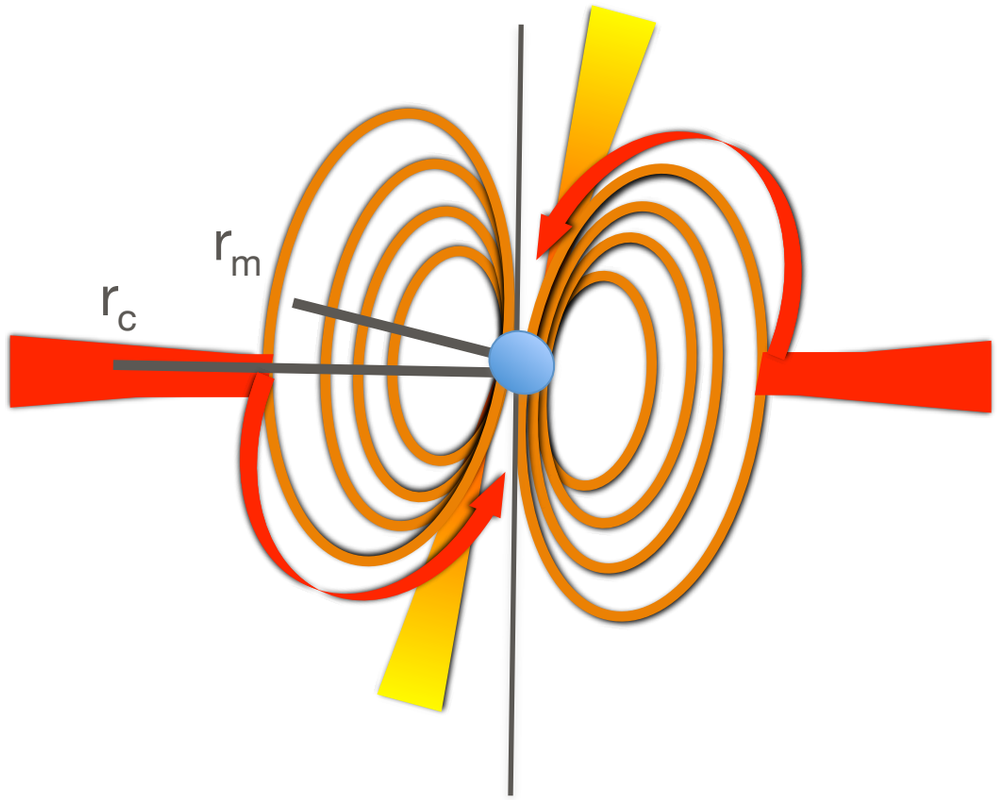
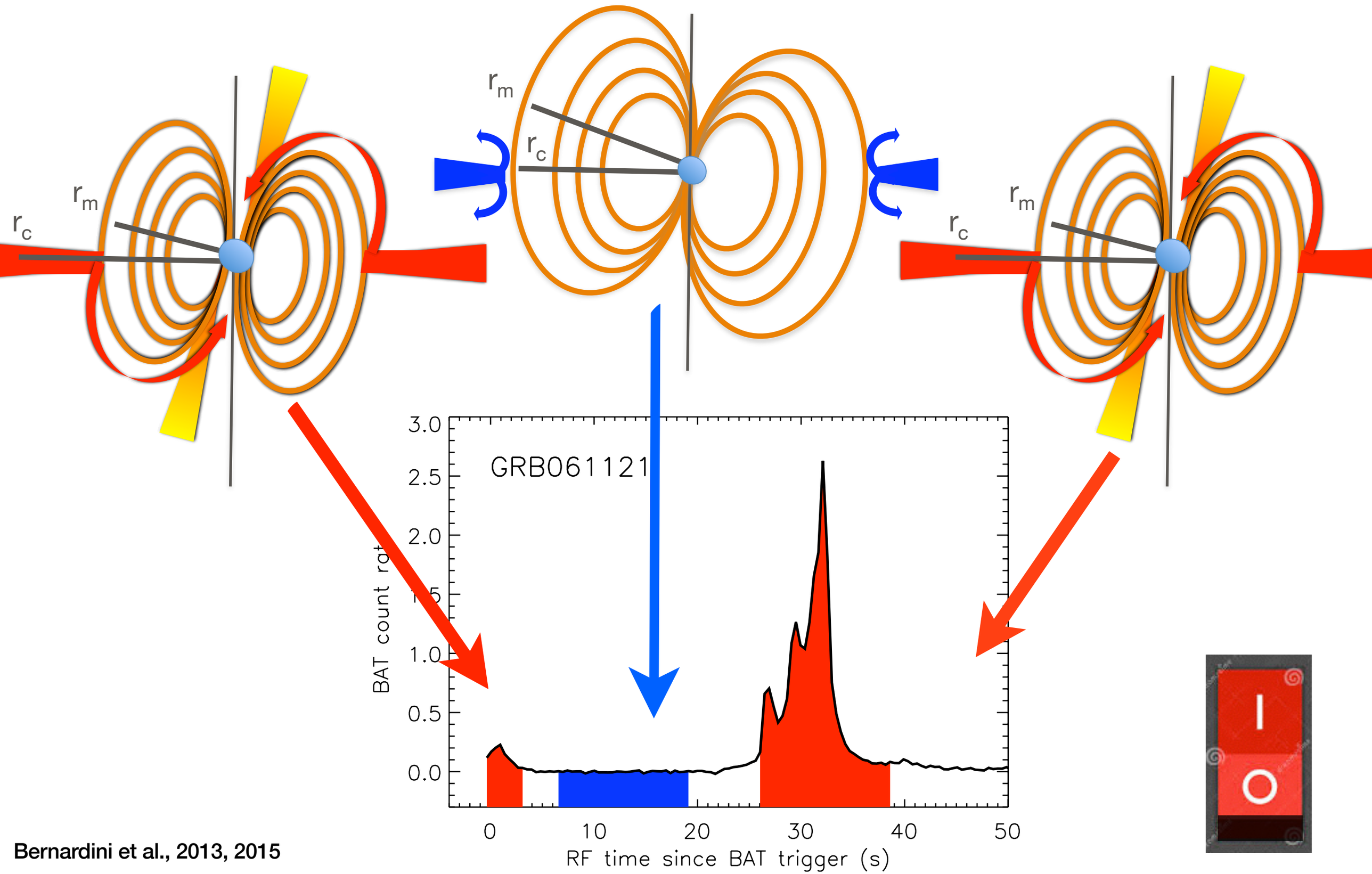




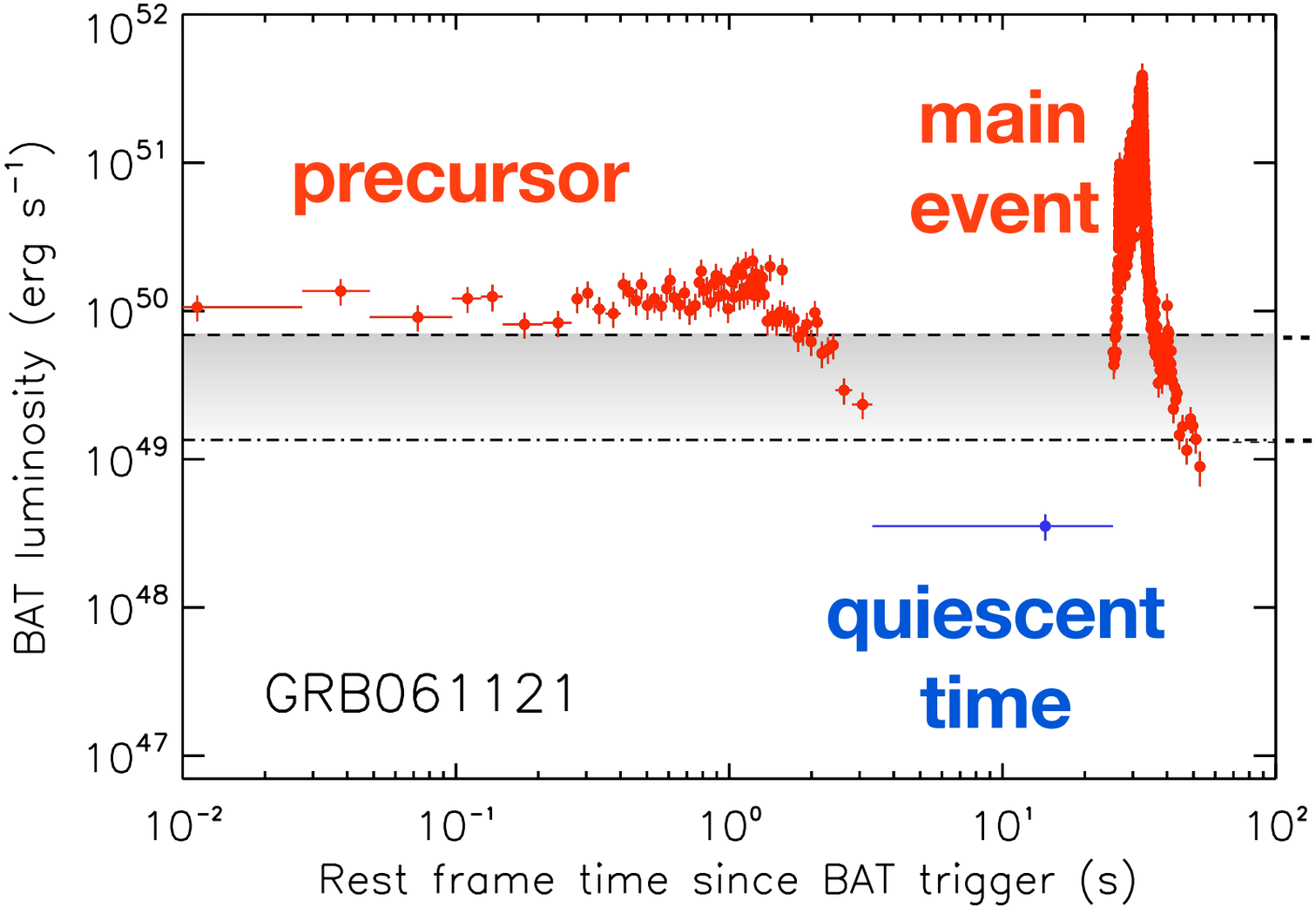
Bernardini et al., 2013

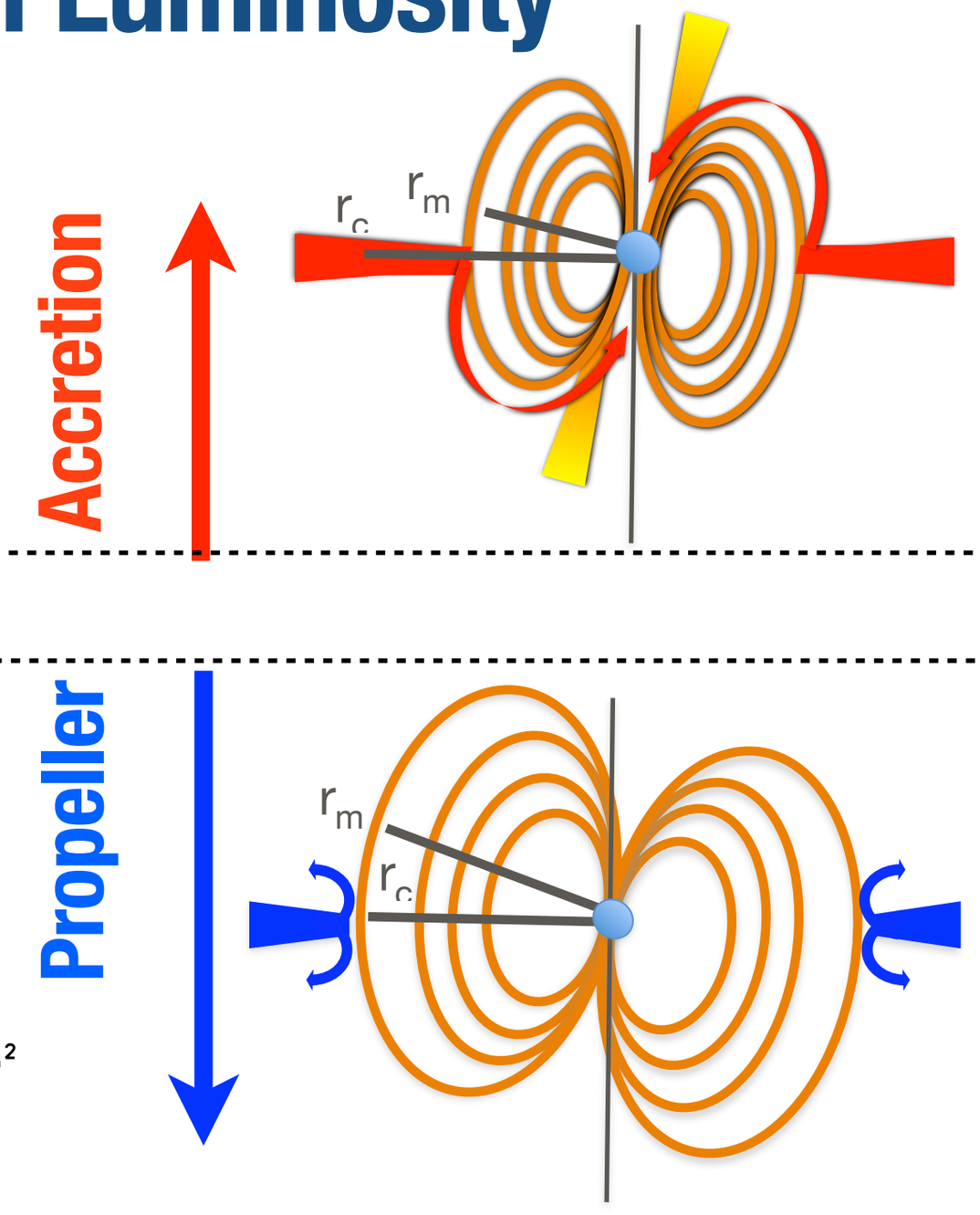
Intermittent prompt emission activity



Bernardini et al., 2013, 2015

The Prompt Emission Luminosity



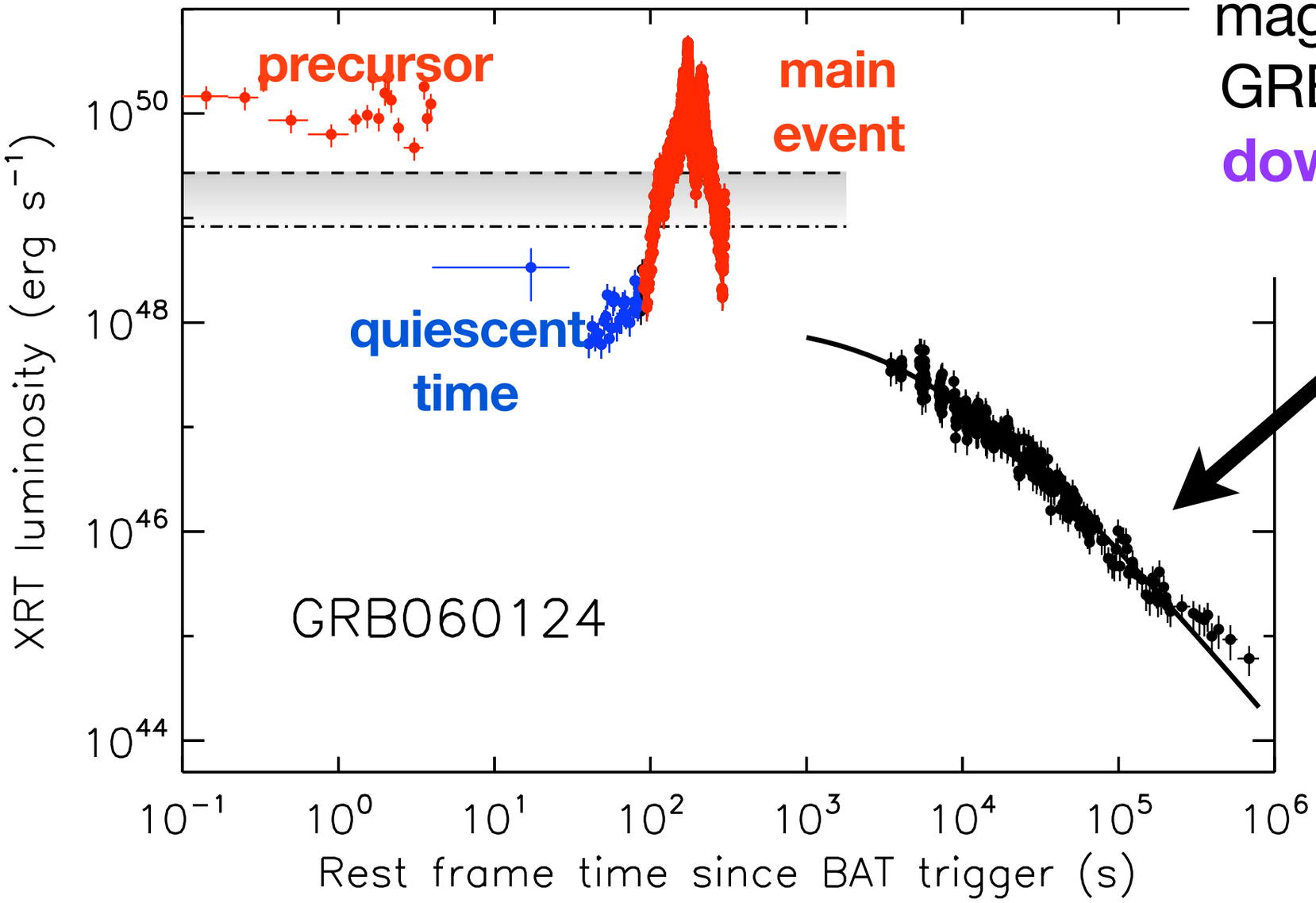


$$L_{\rm min} = 4 \times 10^{50} B_{15}^2 \, P_{-3}^{-7/3} \, {\rm erg \, s^{-1}}$$

$$L(r_{\rm m}) = 2 \times 10^{50} B_{15}^2 \, P_{-3}^{-3} \, {\rm erg \, s^{-1}}$$

⇦ **B~10^{15} G**
P~1 ms

The end of the Prompt Emission



magnetar contribution to the GRB emission with its **spin-down power** that is directly related to **B and P**

$$L_{\rm sd} = 10^{49} B_{15}^2 P_{-3}^{-4} \,{\rm erg\,s^{-1}}$$

$$t_{\rm sd} = 3 \times 10^3 B_{15}^{-2} P_{-3}^{2} \,{\rm s}\,,$$

⇦ **B~10^{15} G**
P~1 ms

Dai & Lu 1998
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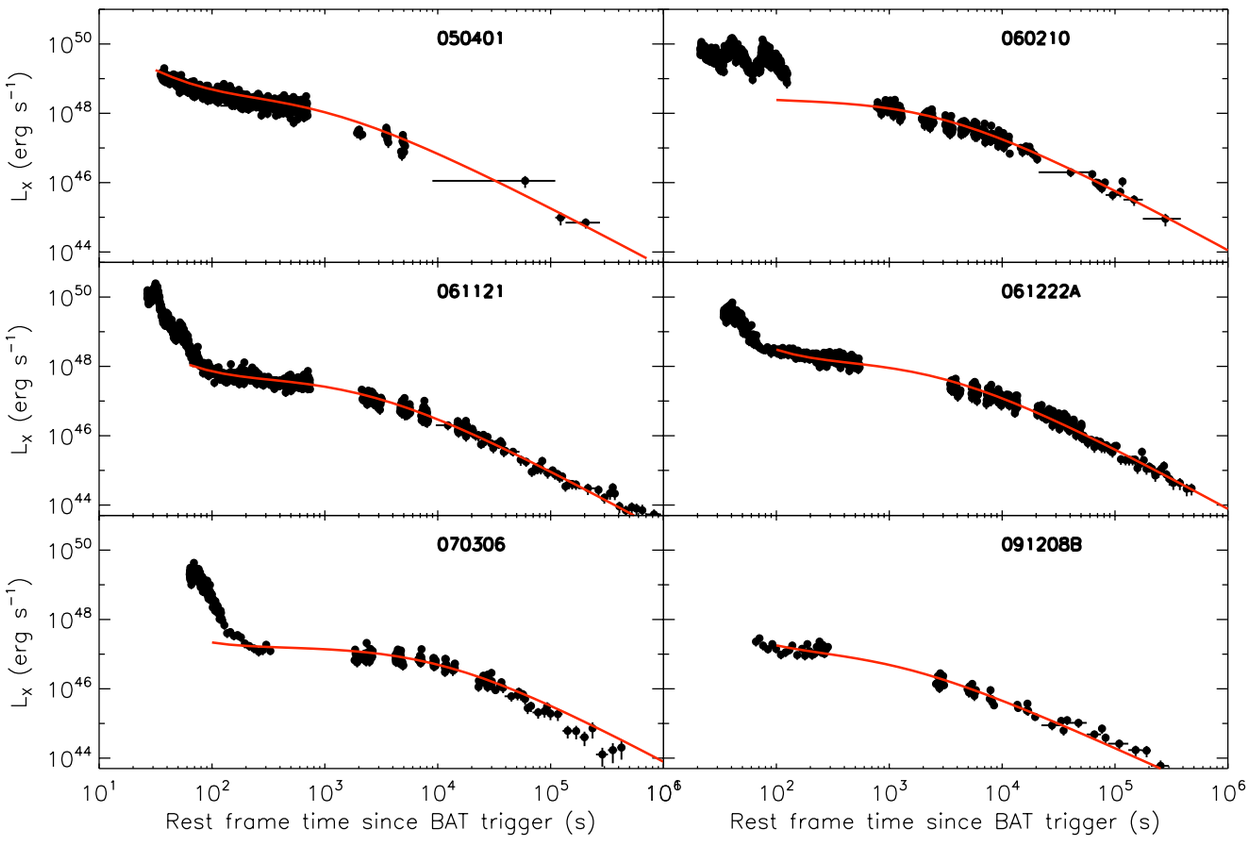
Testing the model with Swift data

1) derive **B and P** from Swift X-ray observations



Bernardini et al.. 2013

$$E(t) = \frac{L_i}{t^{k'}} \int_{t_\circ}^{t} \frac{t^{k'}}{(1+at)^2} + E_\circ \left(\frac{t_\circ}{t}\right)^{k'}$$

Dall'Osso et al. 2011

$a \sim B^2/P^2$

$L_i \sim B^2/P^4$

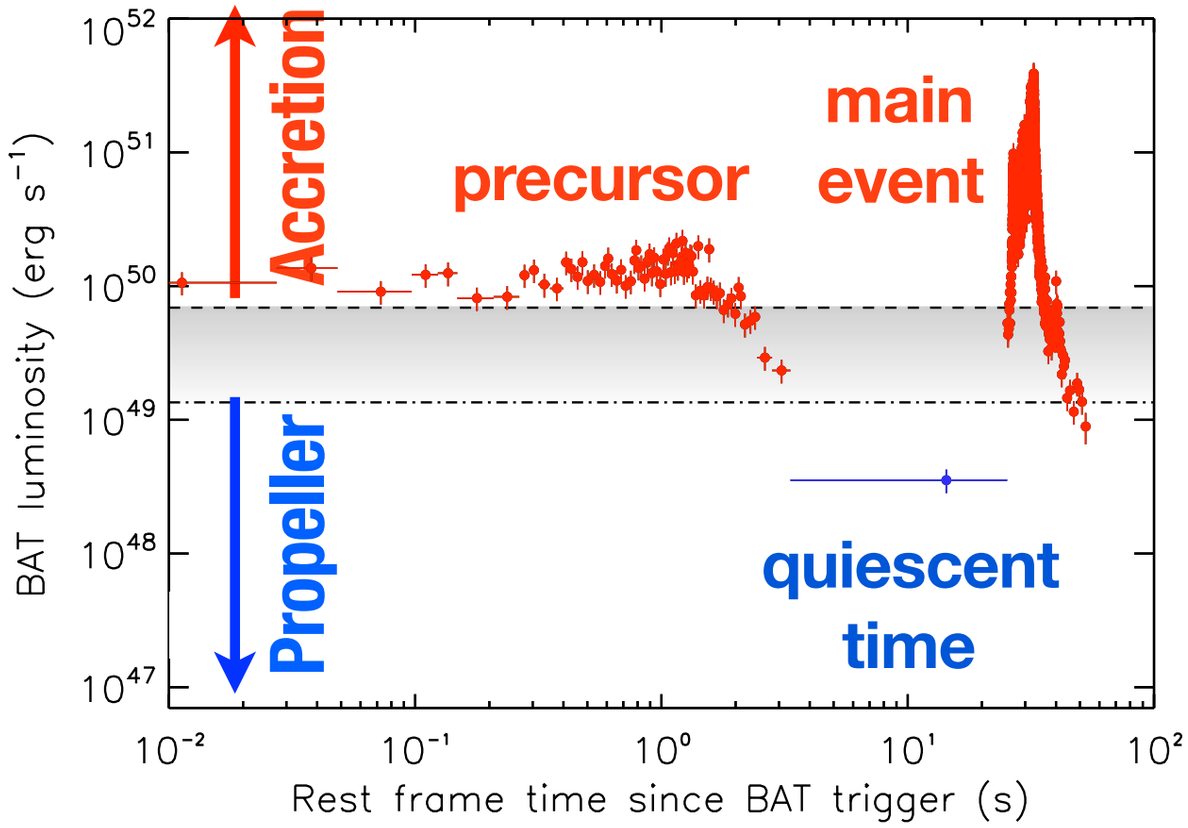
$\langle B \rangle = 4 \times 10^{15}$ G

$\langle P \rangle = 3.06$ ms

Testing the model with Swift data

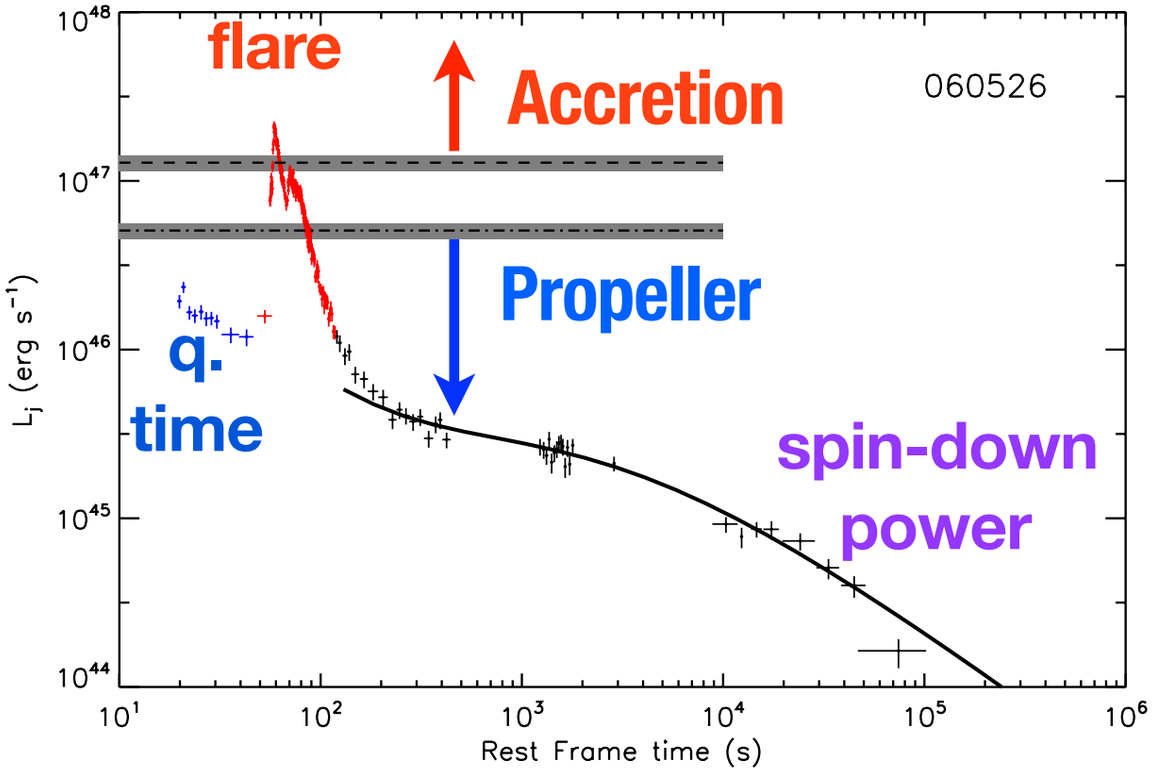
2) use the **B and P** from X-ray observations to test the accretion scenario for **GRBs with precursors and with giant flares**

Swift BAT6 complete sample



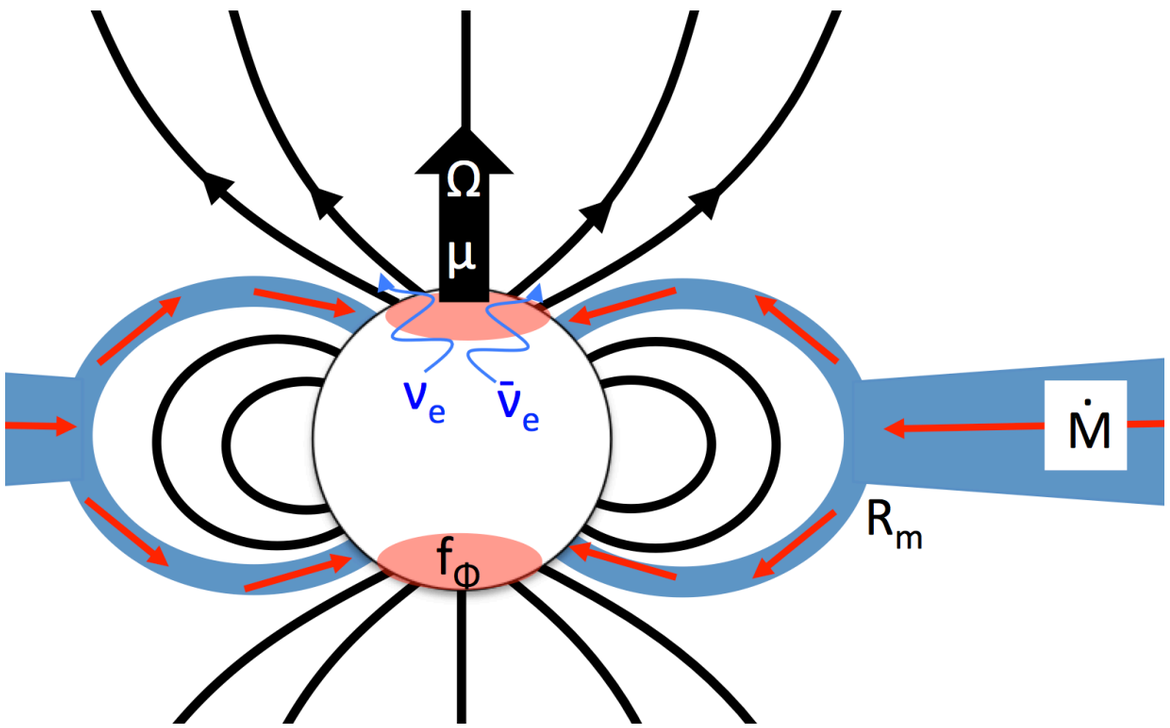
Bernardini et al., 2013

Swift GRBs with "giant" flares ($E_{flare} \geq 10\% E_{tot}$)



Bernardini et al., 2015

Fall-back accretion onto magnetars



Metzger et al., 2018

- GRB powered only by the **magnetar rotational energy** through a wind heated by neutrinos driven by the proto-magnetar

➡ **magnetised ultra-relativistic outflow**

- **accretion** allows for more complex time evolution of the spin-down power, possibly also for **time gaps in the light curve**

Effects of **accretion**:

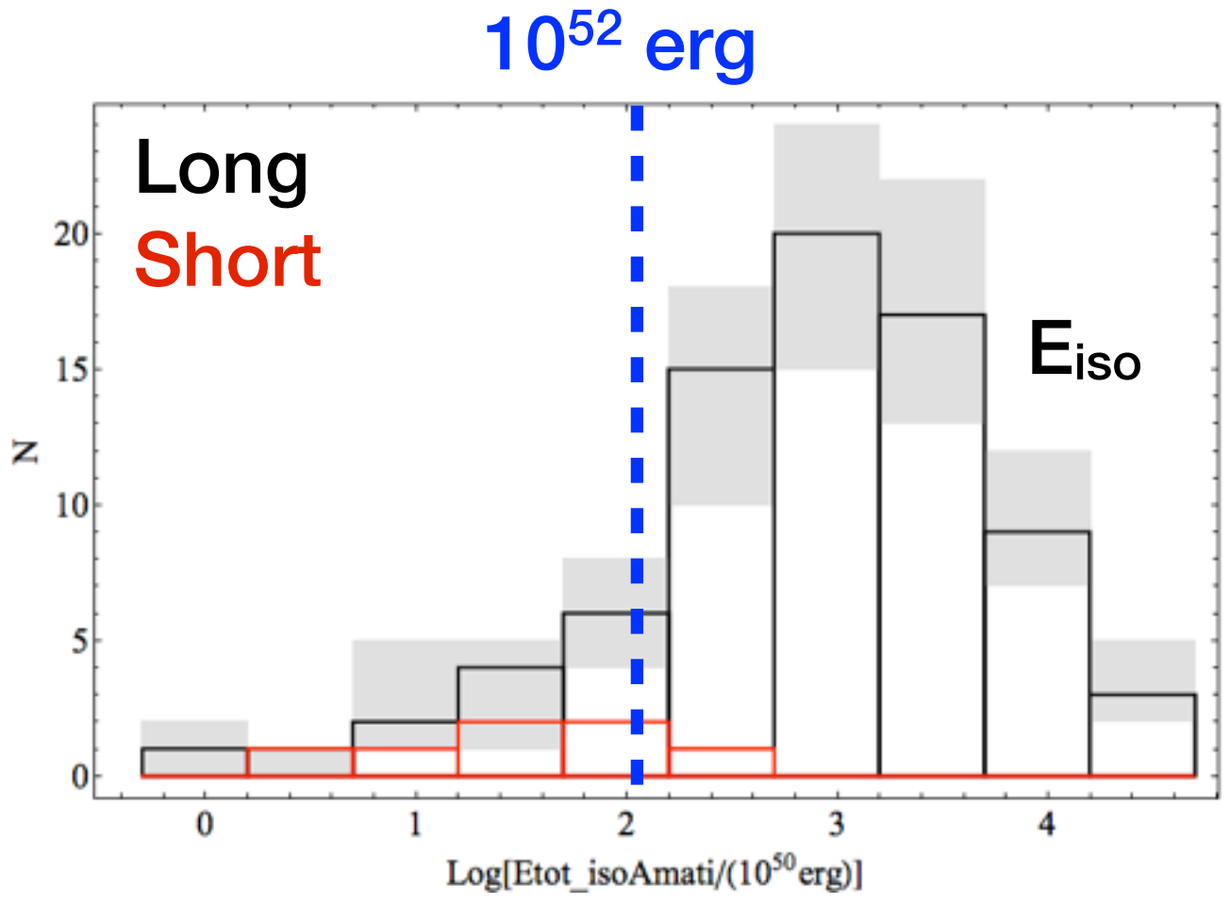
- additional source of energy
- modify the magnetar parameters at birth compared to the estimates from the late X-ray emission

Can magnetars power all GRBs?

Magnetars have a **limited energy budget**

- ➡ SGRBs ok
- ➡ LGRBs often above limit

- ✦ **accretion**: further energy supplier
- ✦ true $E_\gamma < E_{iso}$ due to collimation



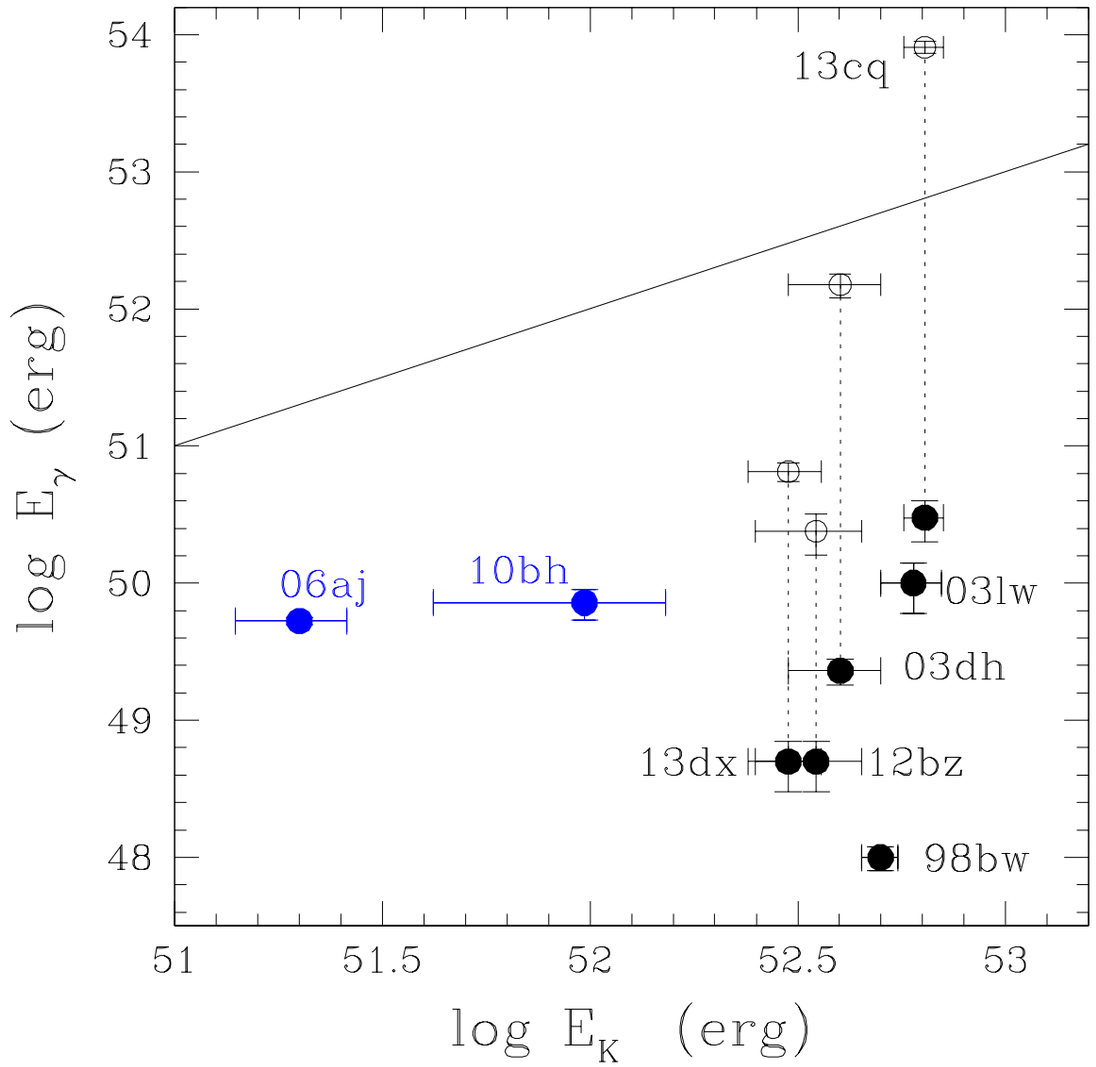
Margutti et al., 2013

Can magnetars power all GRBs?

Magnetars have a **limited energy budget**

- ➡ SGRBs ok
- ➡ LGRBs often above limit

- ✦ accretion: further energy supplier
- ✦ true $E_\gamma < E_{iso}$ due to collimation
- ✦ **sufficient to energise the accompanying SN**



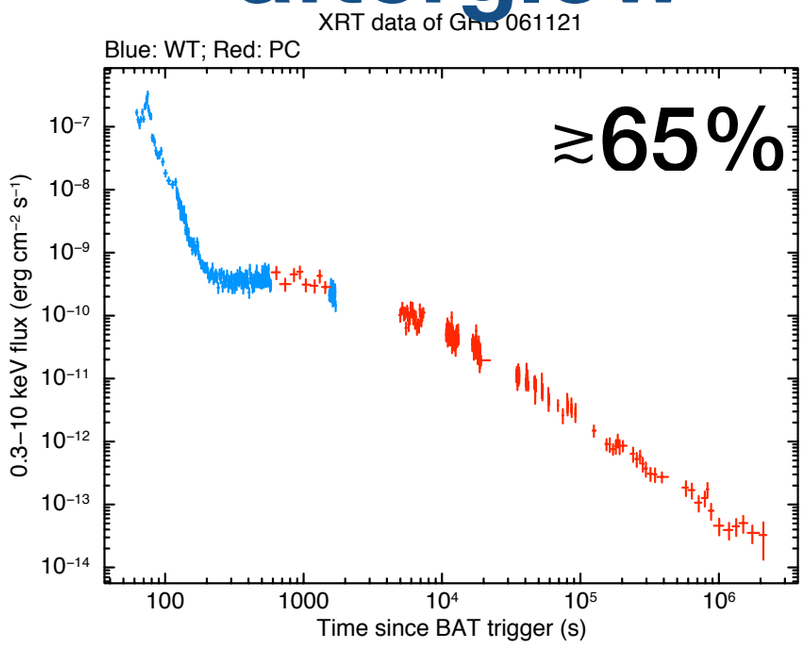
Mazzali et al., 2014

several LGRBs intrinsically > 10^{53} erg

Possible solution: magnetars & BHs

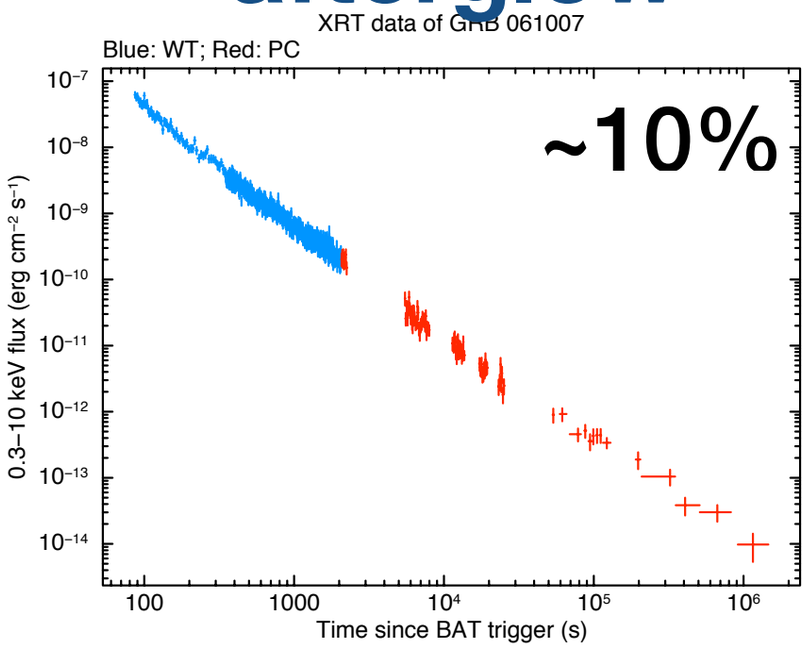
Distinctive features expected in the **X-ray afterglow**:

Shallow decay afterglow



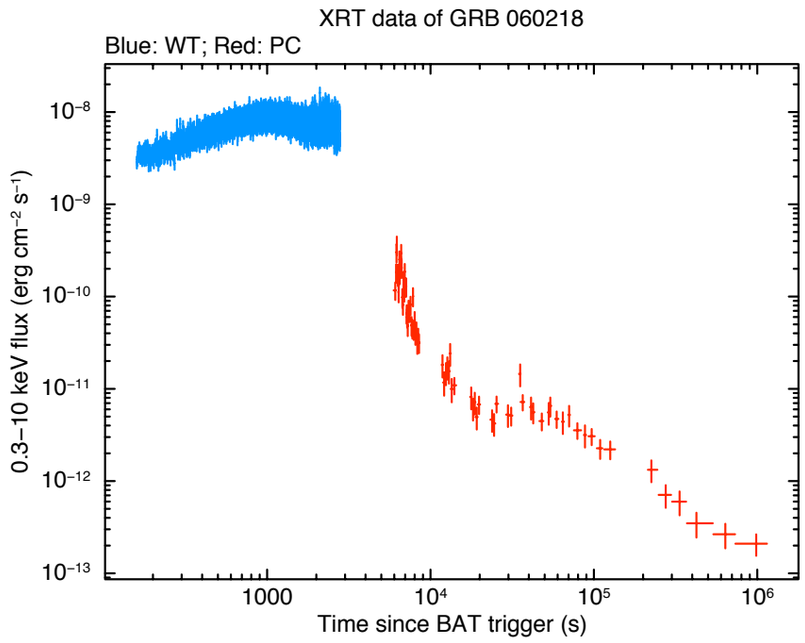
magnetar powered GRB

Power-law afterglow



BH powered GRB

Oddballs



“failed prompt”: fallback not enough to start accretion

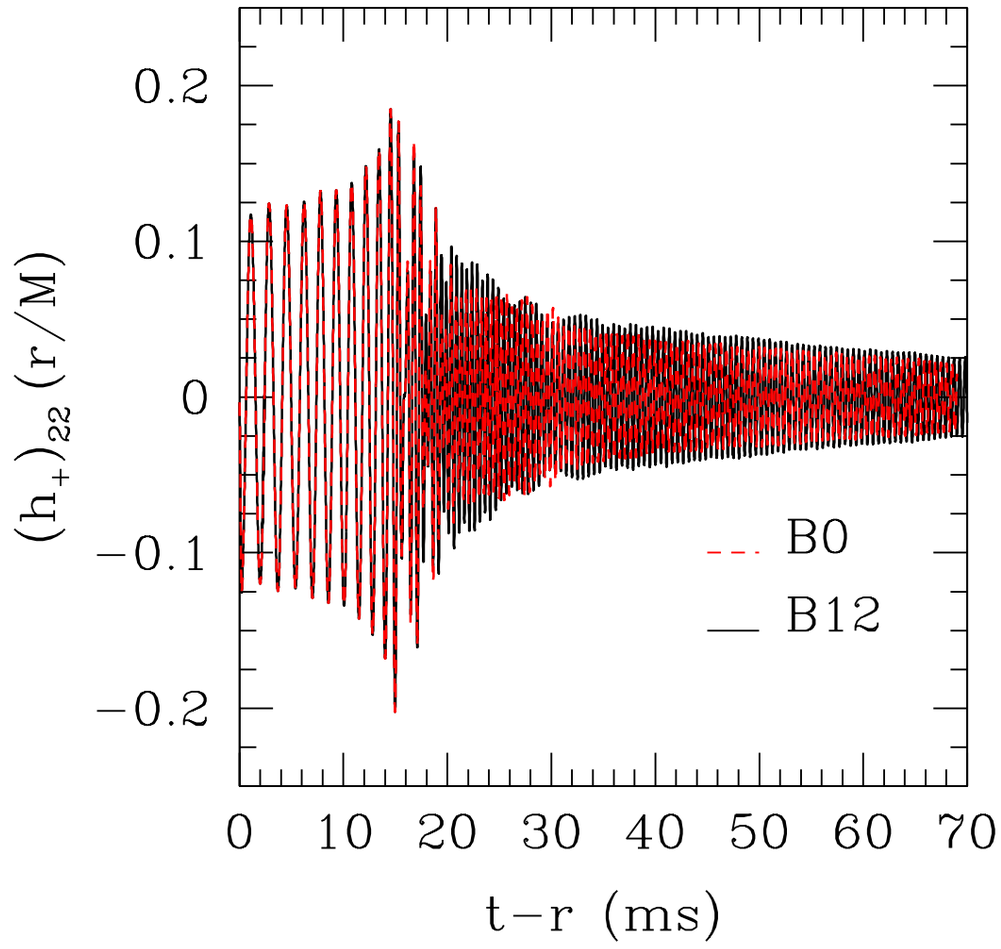
A direct look into the central engine: GWs

- predicted signals from all phases of binary merger

➡ **distinctive GW signals may help in distinguishing between magnetar and BH remnant after merger** (e.g. Giacomazzo & Perna 2012, 2013; Dall'Osso et al., 2015)

- GW 170817/GRB 170817A not conclusive (clues for EM observations)

multi-messenger approach
(GW detection + EM follow-up for source identification) will provide a **smoking gun to unveil the GRB central engine**



Giacomazzo & Perna 2013

Conclusions

- Observations point towards **magnetars as plausible candidates as GRB central engines**:
  - ➡ late X-ray emission powered by the **spin-down of the magnetar**
  - ➡ **initial phase of accretion onto the magnetar** possibly present during the prompt phase
- Are all GRBs powered by magnetars? Not likely but still the **majority are consistent with being powered by magnetars**
- Indirect evidences from GRB observations. Possible **direct proof from GW detection of SGRBs**