Gamma-ray bursts and magnetars: observational signatures and predictions

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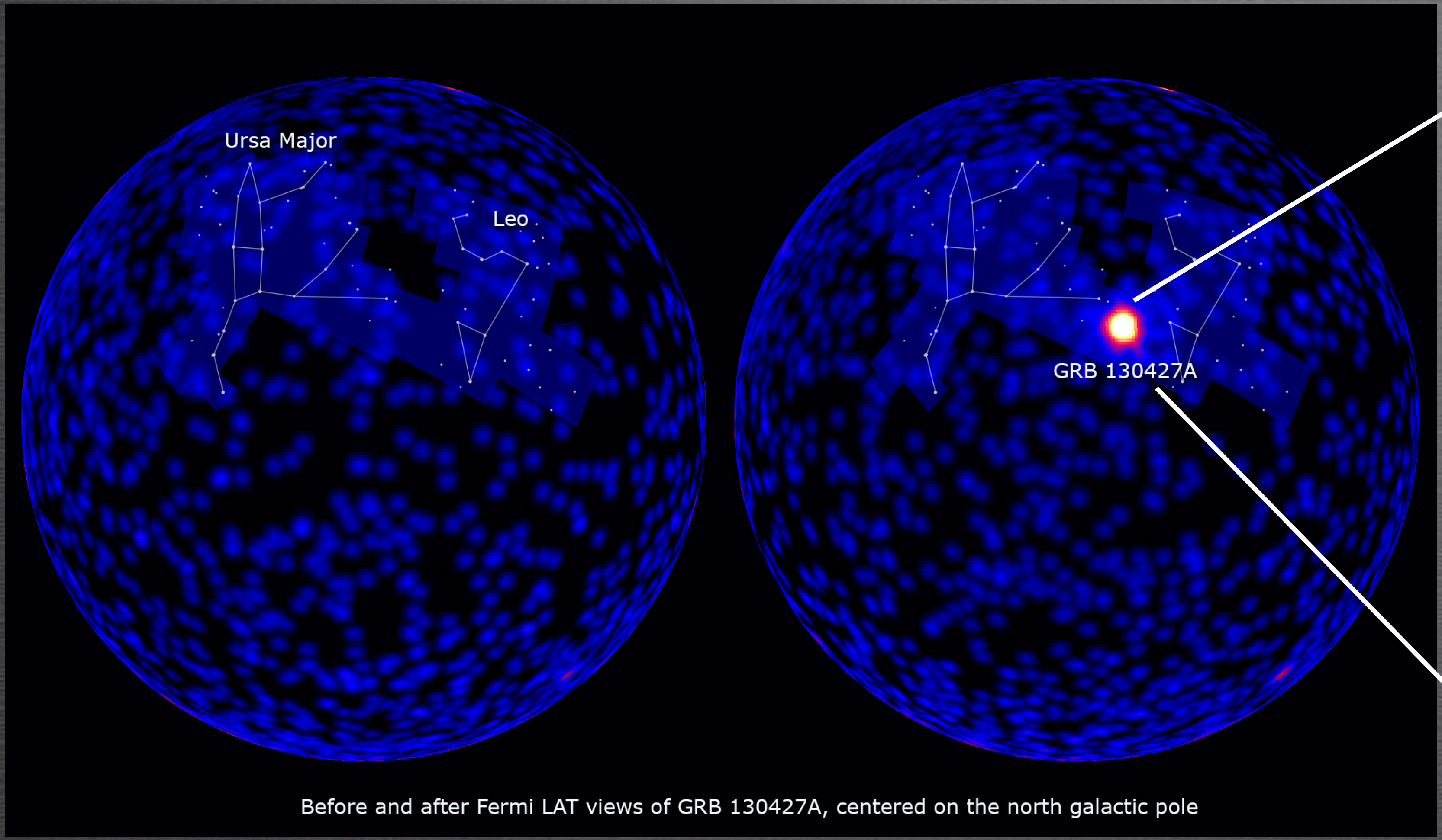
Swift Italian Team

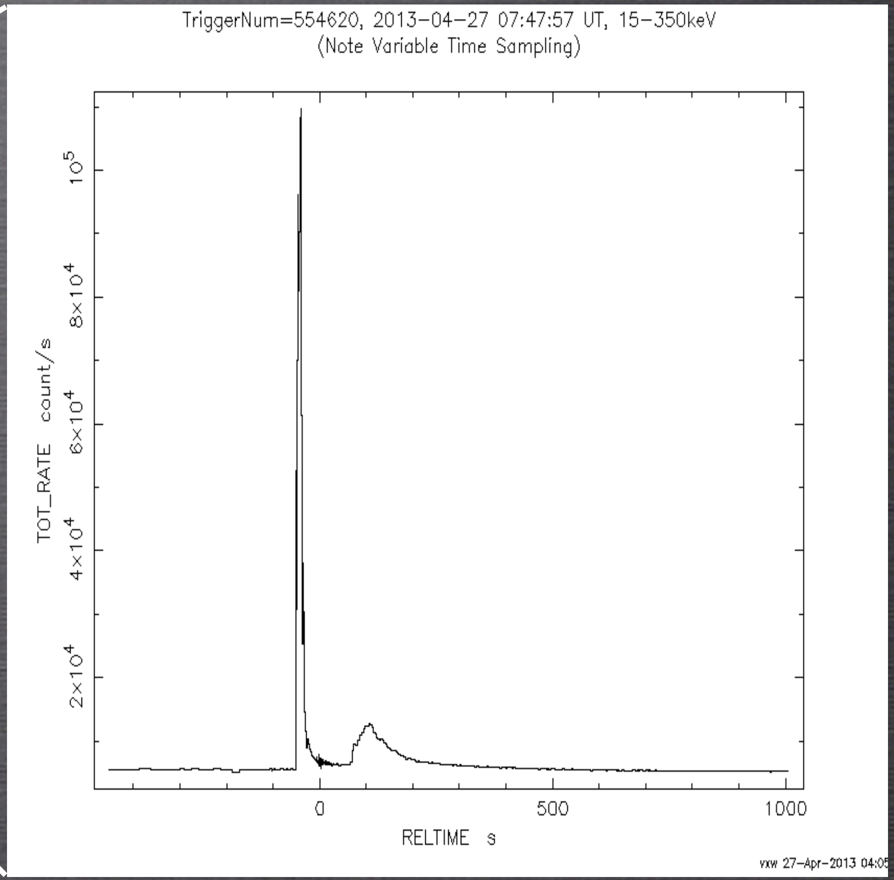
Annual NewCompStar Conference, 15-19 June 2015, Budapest

What is a gamma-ray burst?

Brief, intense flash of gamma-ray radiation



Before and after Fermi LAT views of GRB 130427A, centered on the north galactic pole



Duration: a few ms up to hundreds of s

Fluence: ~10^{-7} - 10^{-3} erg cm^{-2}

Flux: ~10^{-8} - 10^{-4} erg cm^{-2} s^{-1}

Energy range: ~ a few keV up to MeV

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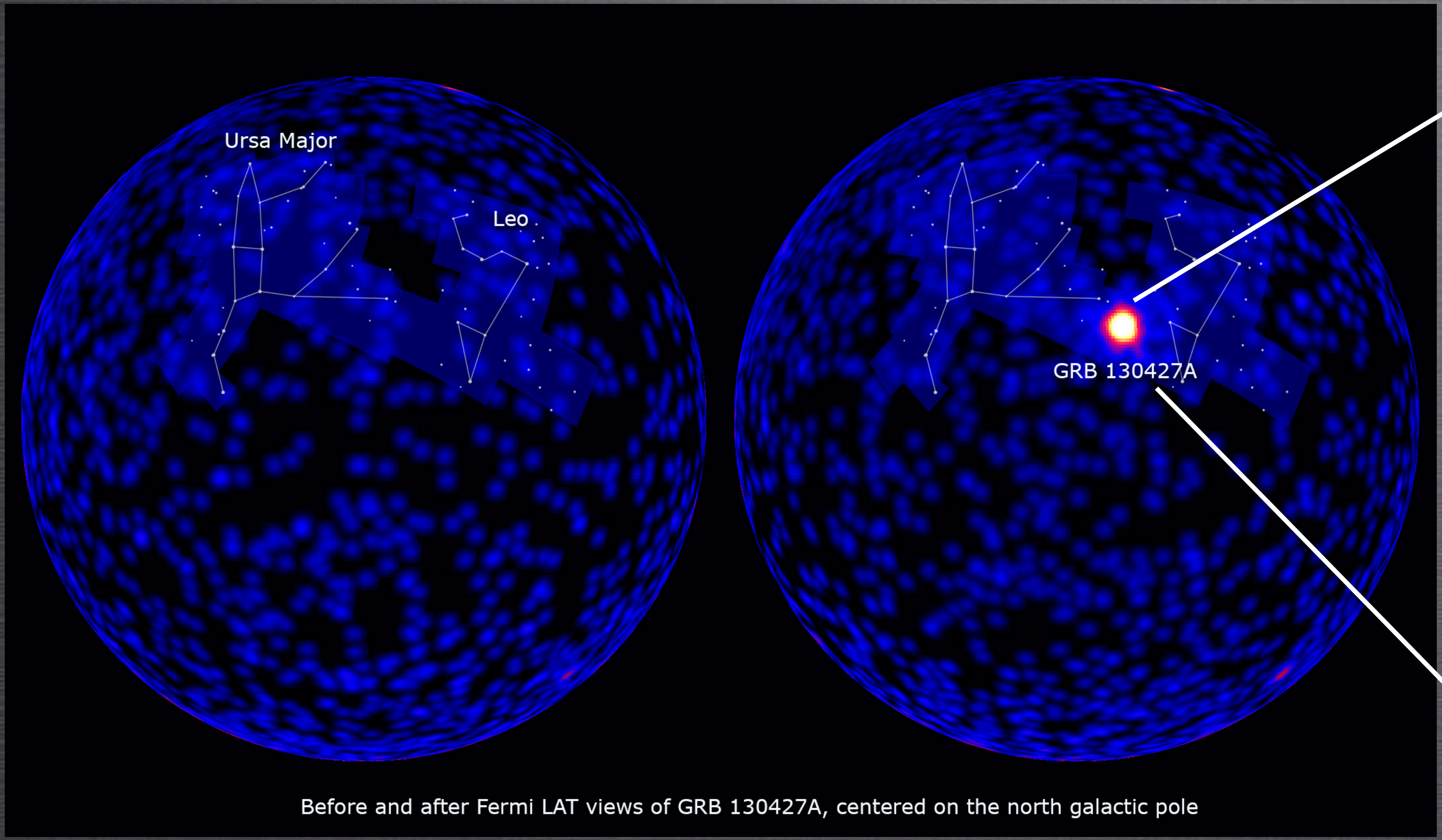

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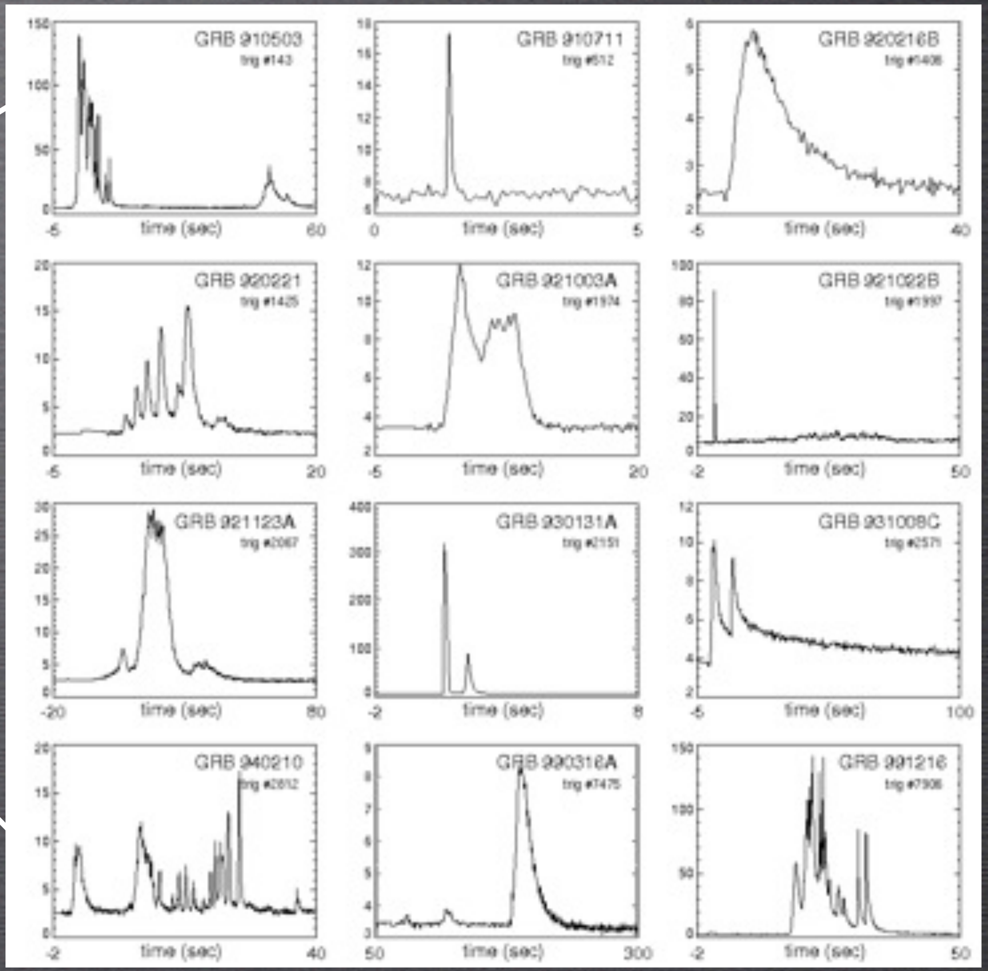
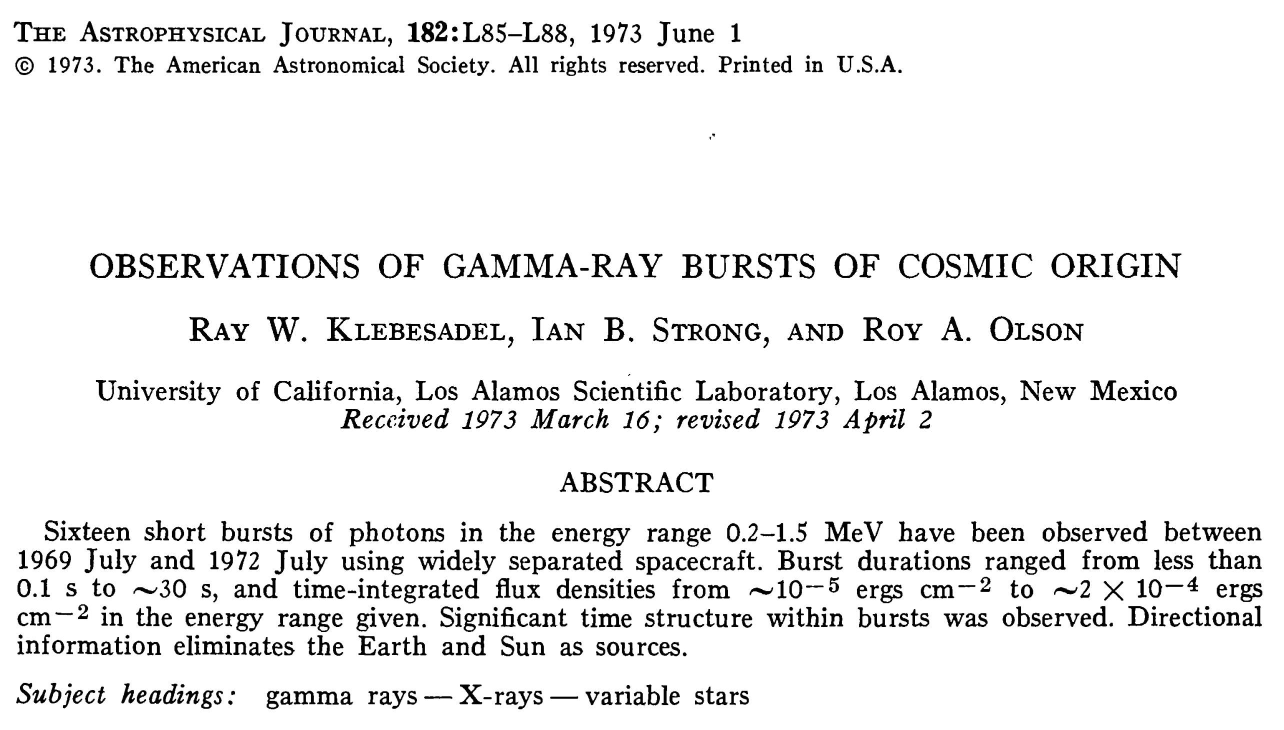


Duration: a few ms up to hundreds of s
Fluence: ~10^{-7} - 10^{-3} erg cm^{-2}
Flux: ~10^{-8} - 10^{-4} erg cm^{-2} s^{-1}
Energy range: ~ a few keV up to MeV

when you observe a GRB you are observing ONE GRB!!!

A bit of history...

- discovered in the ‘60s by the Vela satellites (military program to monitor nuclear tests)
- announced in 1973



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OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

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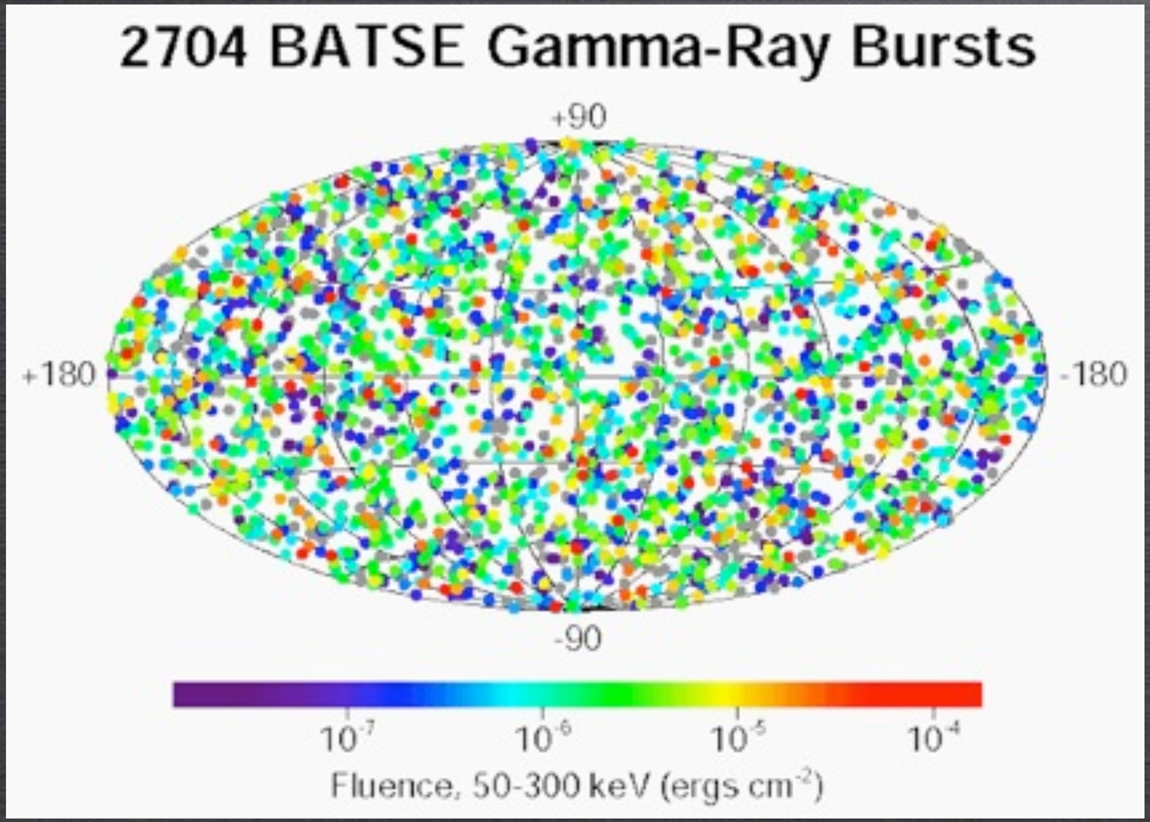
Received 1973 March 16; revised 1973 April 2

ABSTRACT

Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ~30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

Subject headings: gamma rays — X-rays — variable stars

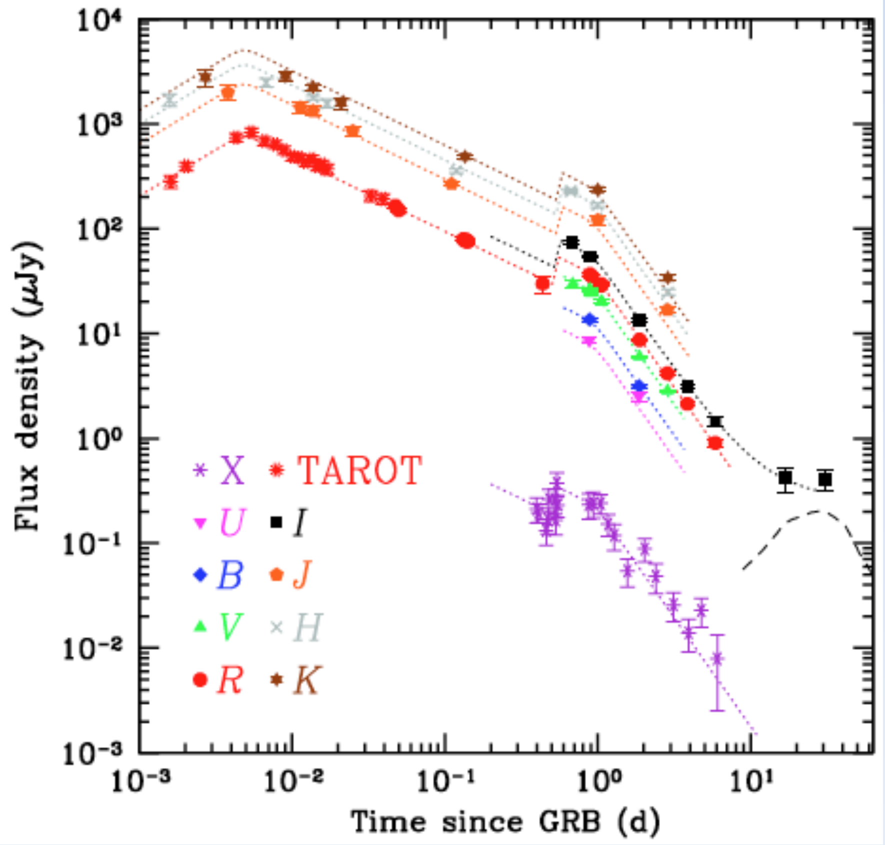


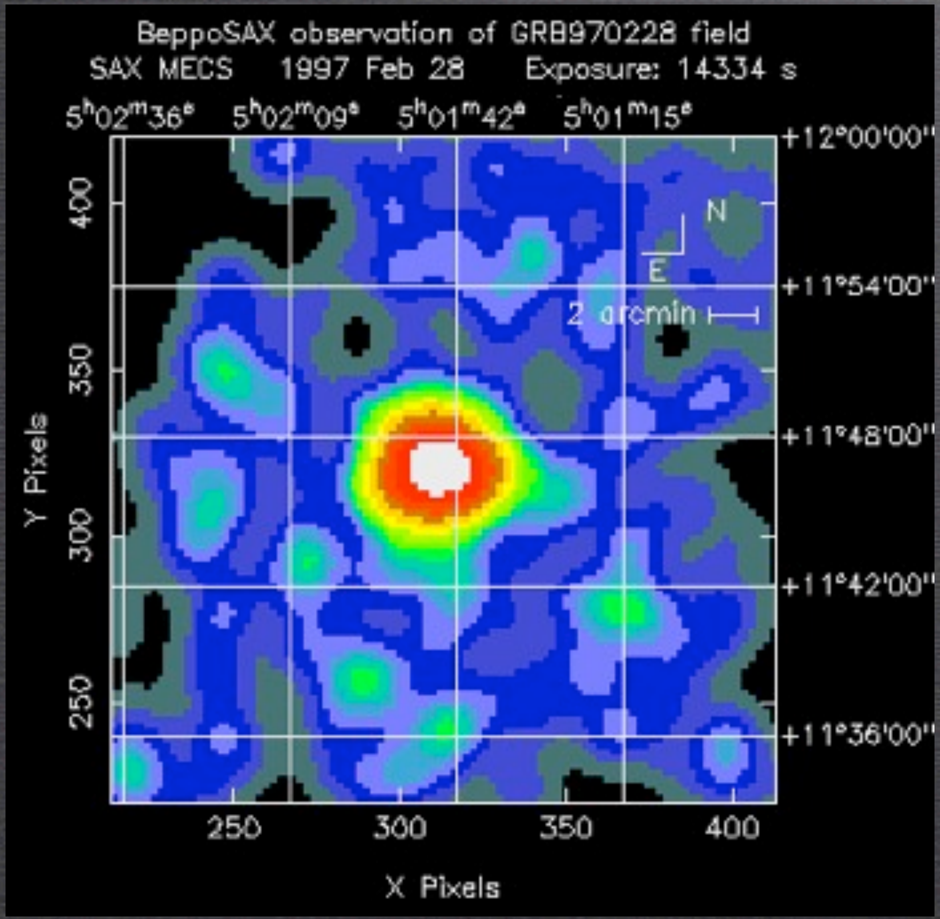
- BATSE instrument (CGRO, 1991): GRBs isotropically distributed over the sky

so they are “likely” extragalactic objects....

- BeppoSAX (1996): discovery of counterpart and localization

They show long-lasting, multiwavelength emission (X, OT, radio): afterglow

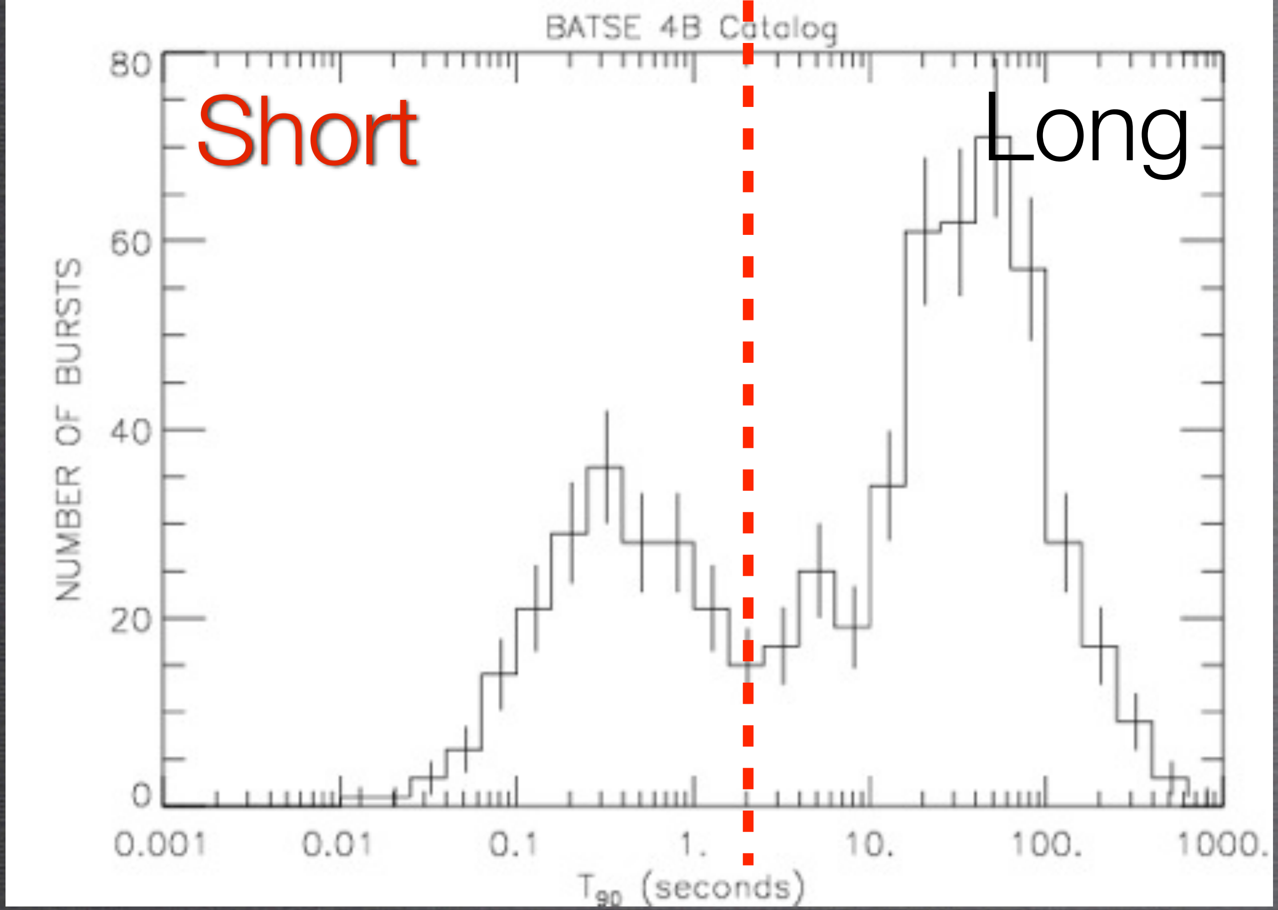




They are distant!!
$\langle z \rangle$ =2.1, z_{max}=8.2

This implies they are the most powerful objects in the Universe ($E_\gamma \sim 10^{52}$ erg)

Two flavors: SGRBs and LGRBs

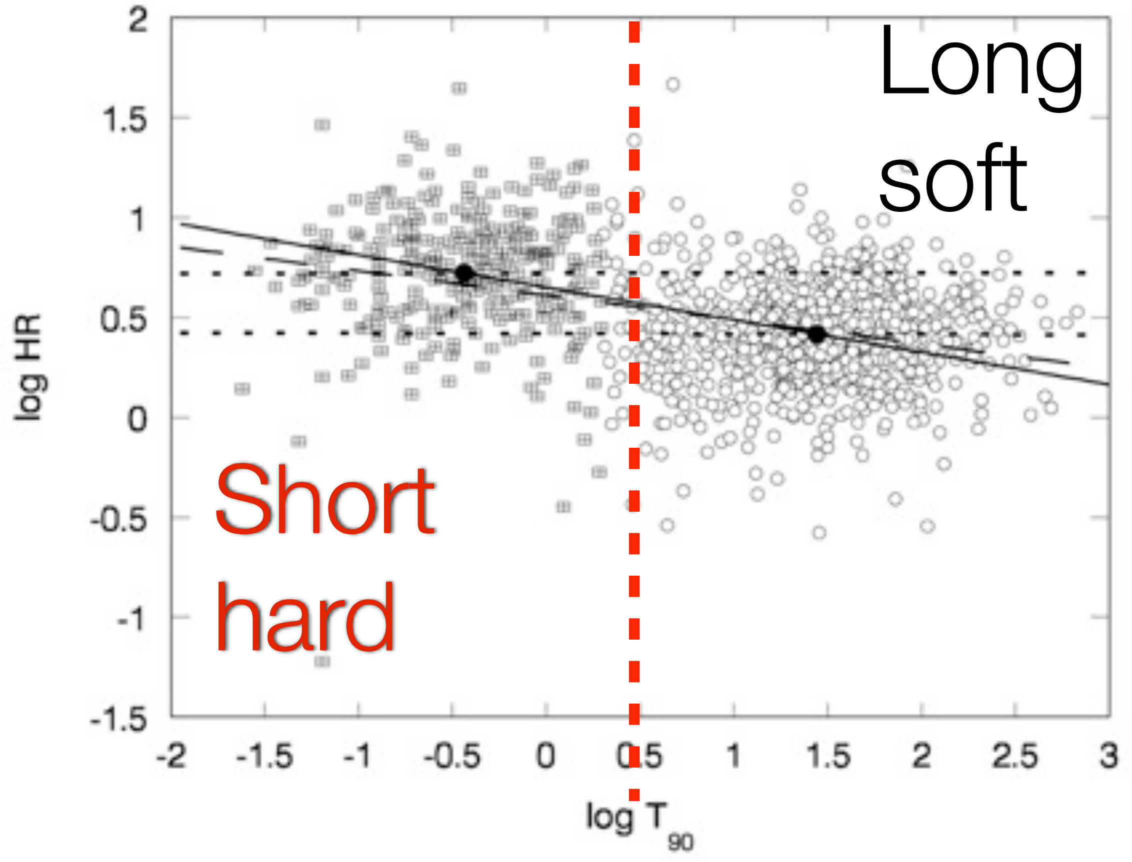


Short GRBs (SGRBs):

- $T_{90}<2$ s
- all type of galaxies (or hostless)
- old stellar population
- NO supernova associated

Long GRBs (LGRBs):

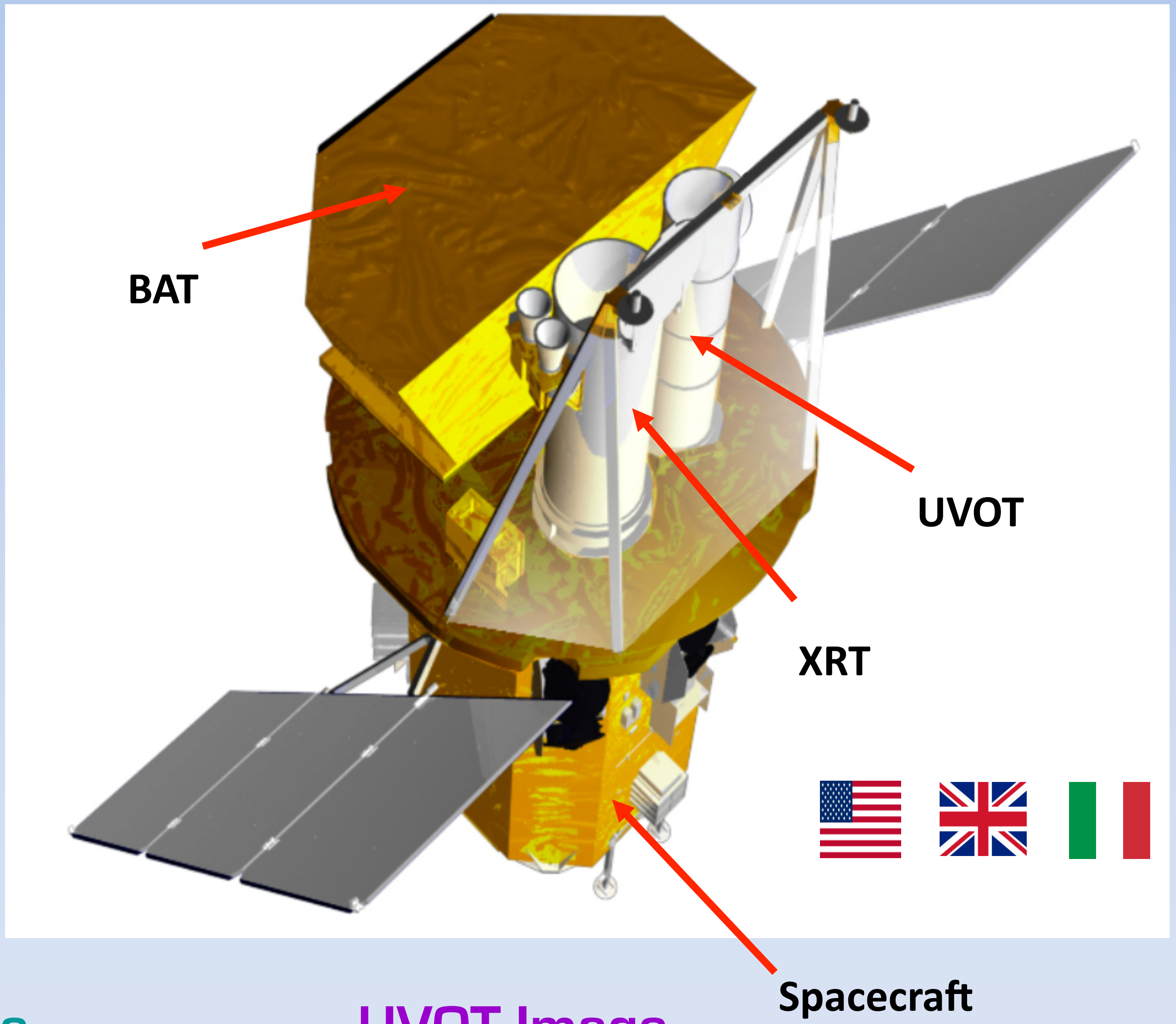
- $T_{90}>2$ s
- star-forming galaxies
- young stellar population
- supernova associated



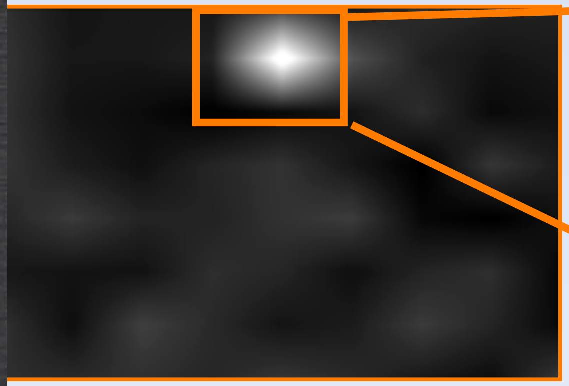
Swift Mission (2004)

Gehrels et al. 2004

- **Burst Alert Telescope (BAT)**
  - 15-150 keV
  - FOV: 2 steradiants
  - Centroid accuracy: 1' - 4'
- **X-Ray Telescope (XRT)**
  - 0.2-10.0 keV
  - FOV: 23.6' x 23.6'
  - Centroid accuracy: 5"
- **UV/Optical Telescope (UVOT)**
  - 30 cm telescope
  - 6 filters (170 nm – 600 nm)
  - FOV: 17' x 17'
  - 24th mag sensitivity (1000 sec)
  - Centroid accuracy: 0.5"

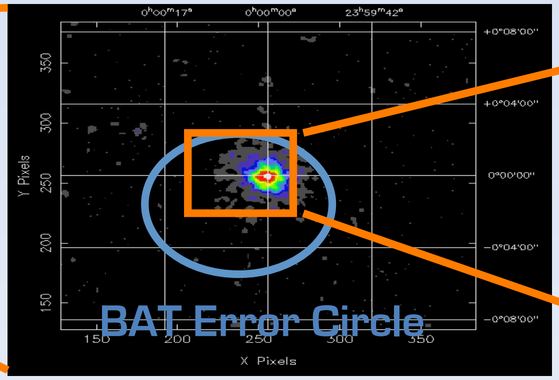


BAT Burst Image



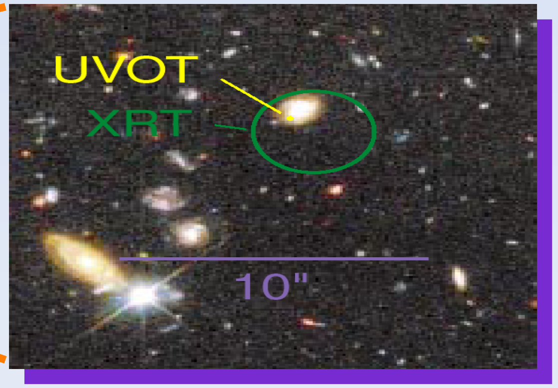
$T<10$ s; $\theta < 4'$

XRT Image



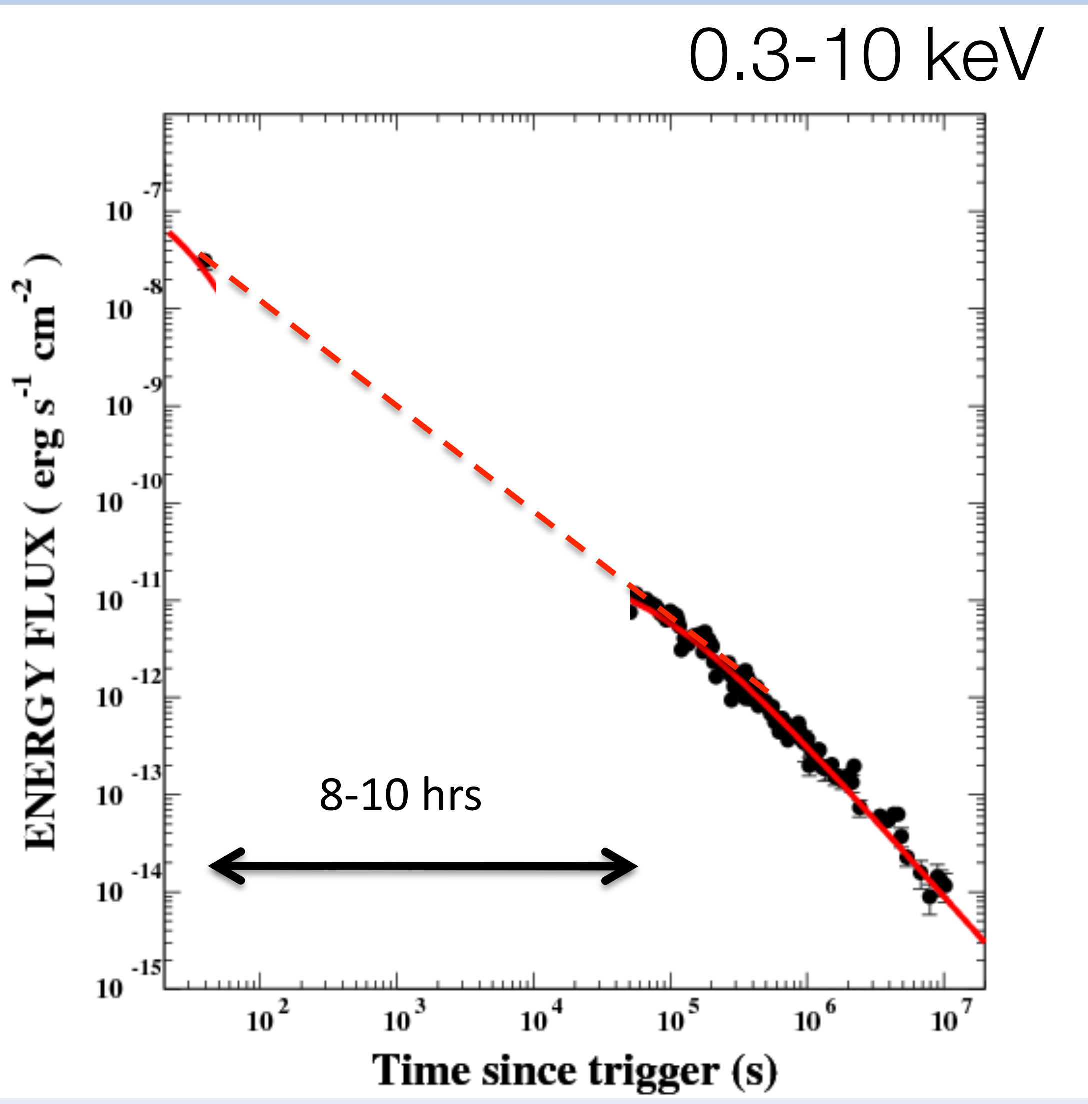
$T<100$ s; $\theta < 5''$

UVOT Image



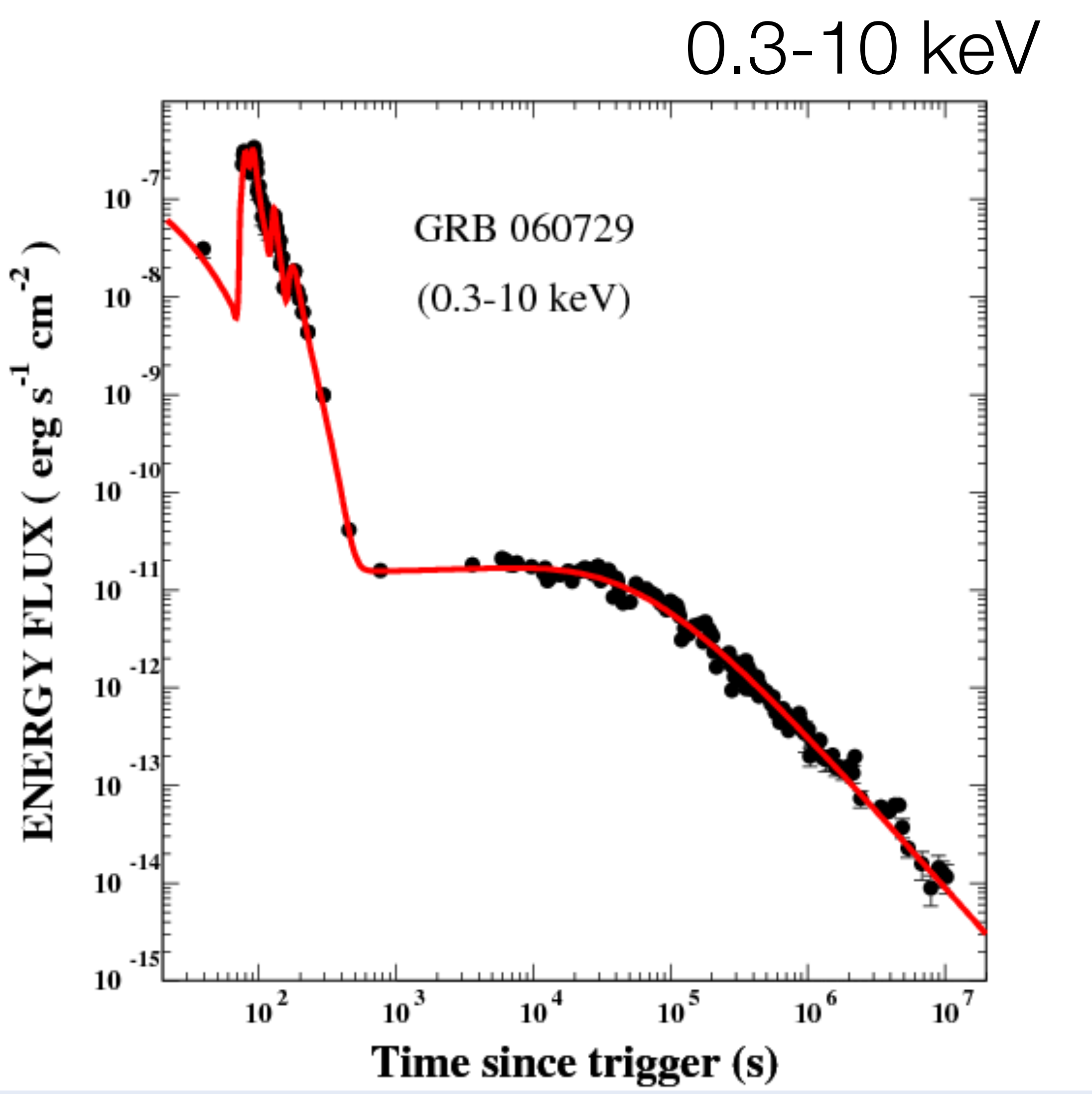
$T<300$ s; $\theta < 0.5''$

The GRB afterglow: pre-Swift



- simple power-law decay at all wavelengths

The GRB afterglow: post-Swift



- complex behavior in 80% cases:
  - ➡ “canonical” light curve (steep-shallow-steep)
  - ➡ “flares” superimposed up to ~ 1000s after the prompt event in ~ 1/3 GRBs

➡ not expected by standard model!!!!

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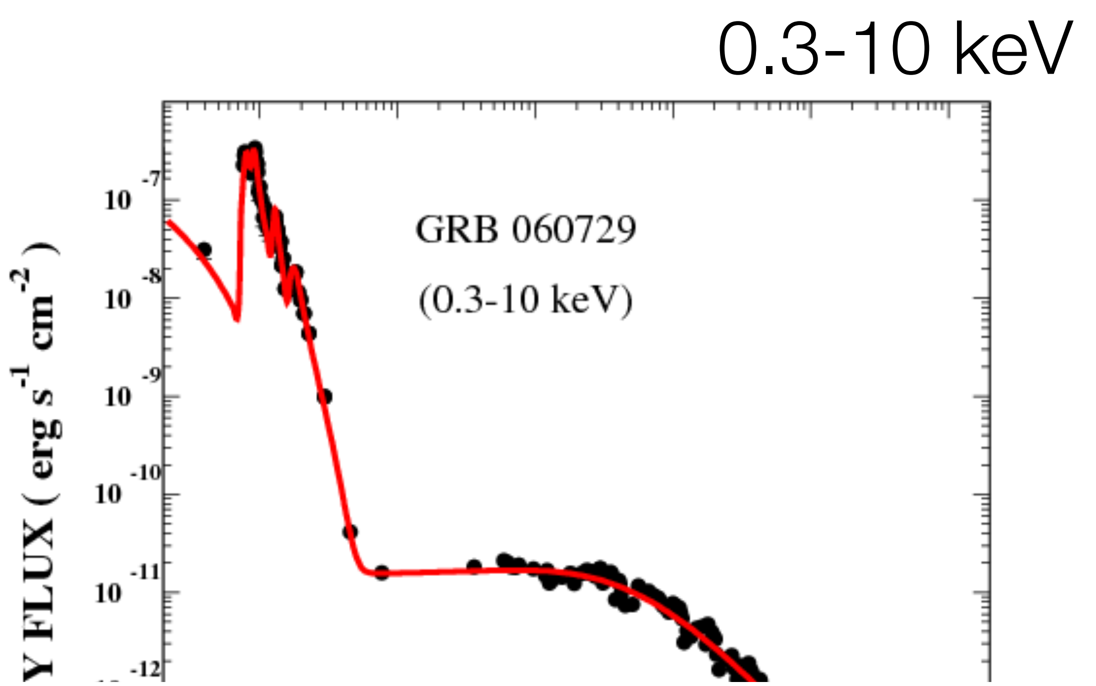

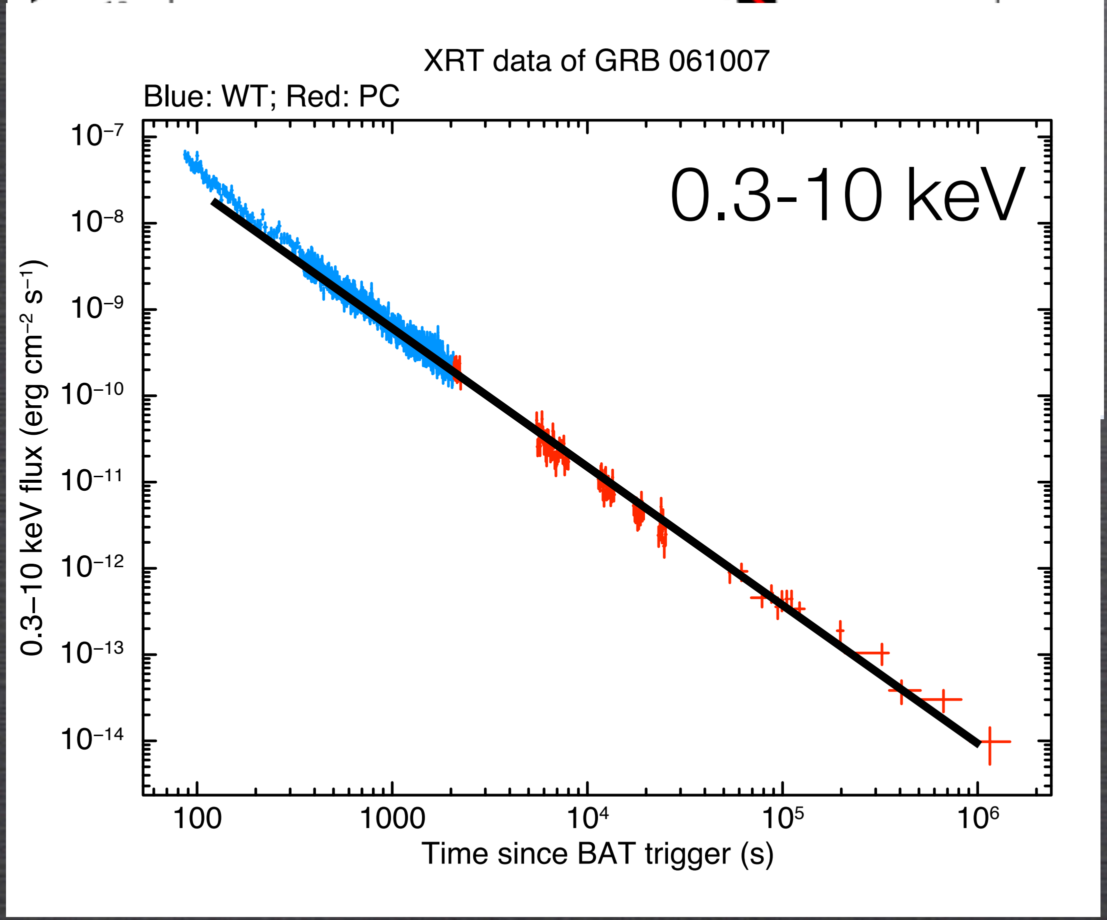

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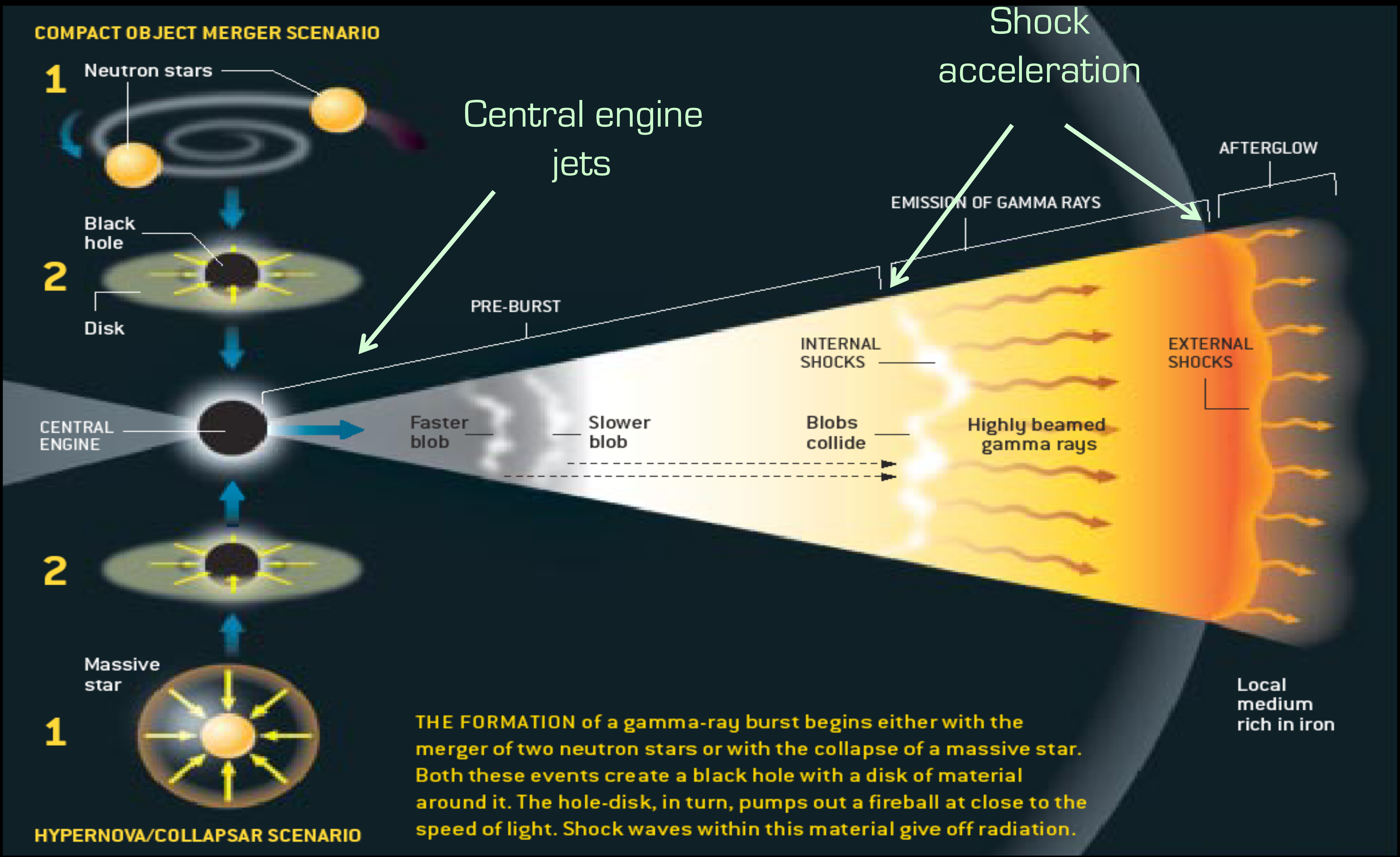
➡ not expected by standard model!!!!

- ✦ but still a fraction of simple power-law decaying afterglows

The GRB standard model (pre-Swift)

The standard model



Central engine jets

Shock acceleration

THE FORMATION of a gamma-ray burst begins either with the merger of two neutron stars or with the collapse of a massive star. Both these events create a black hole with a disk of material around it. The hole-disk, in turn, pumps out a fireball at close to the speed of light. Shock waves within this material give off radiation.

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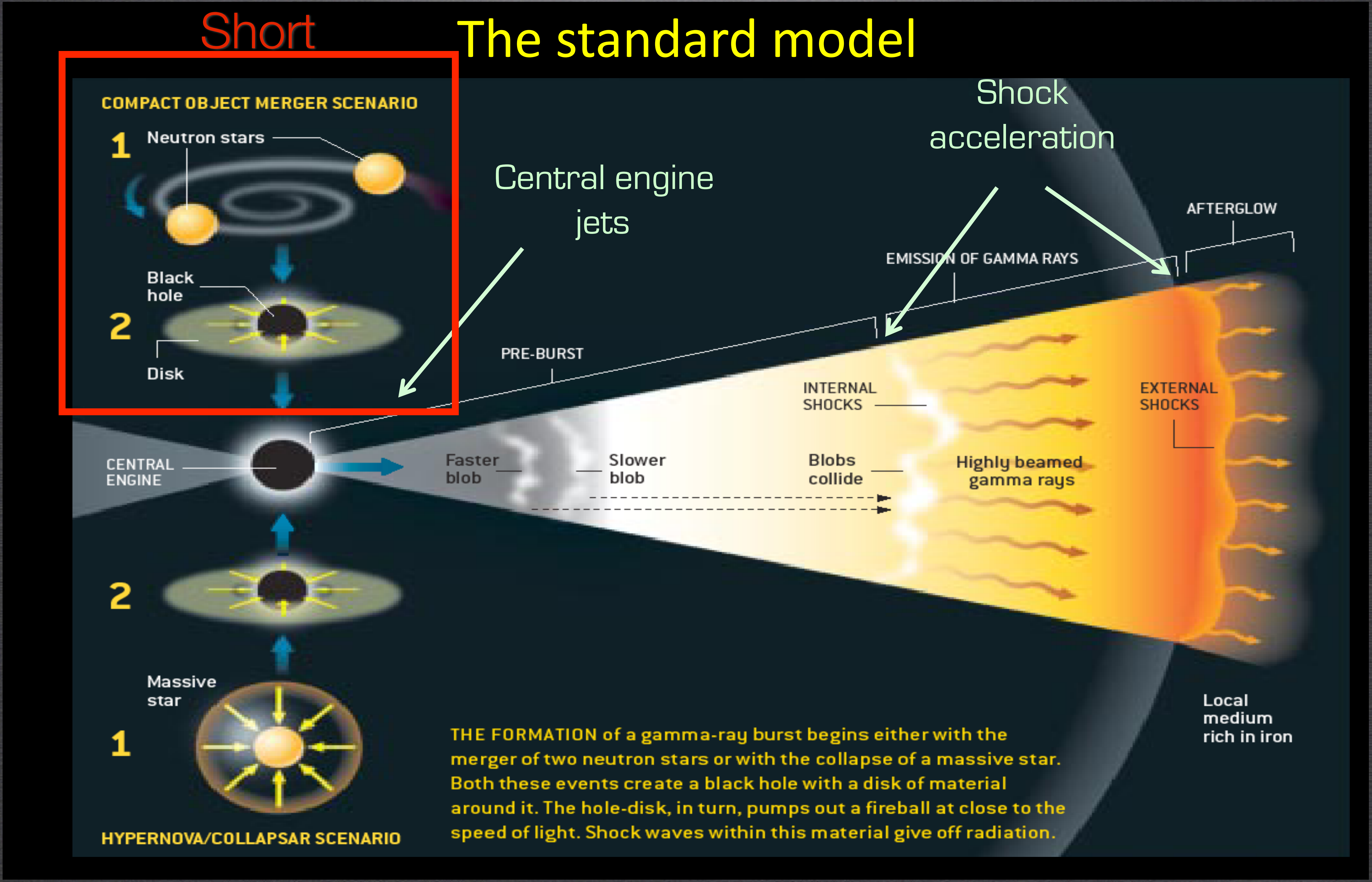

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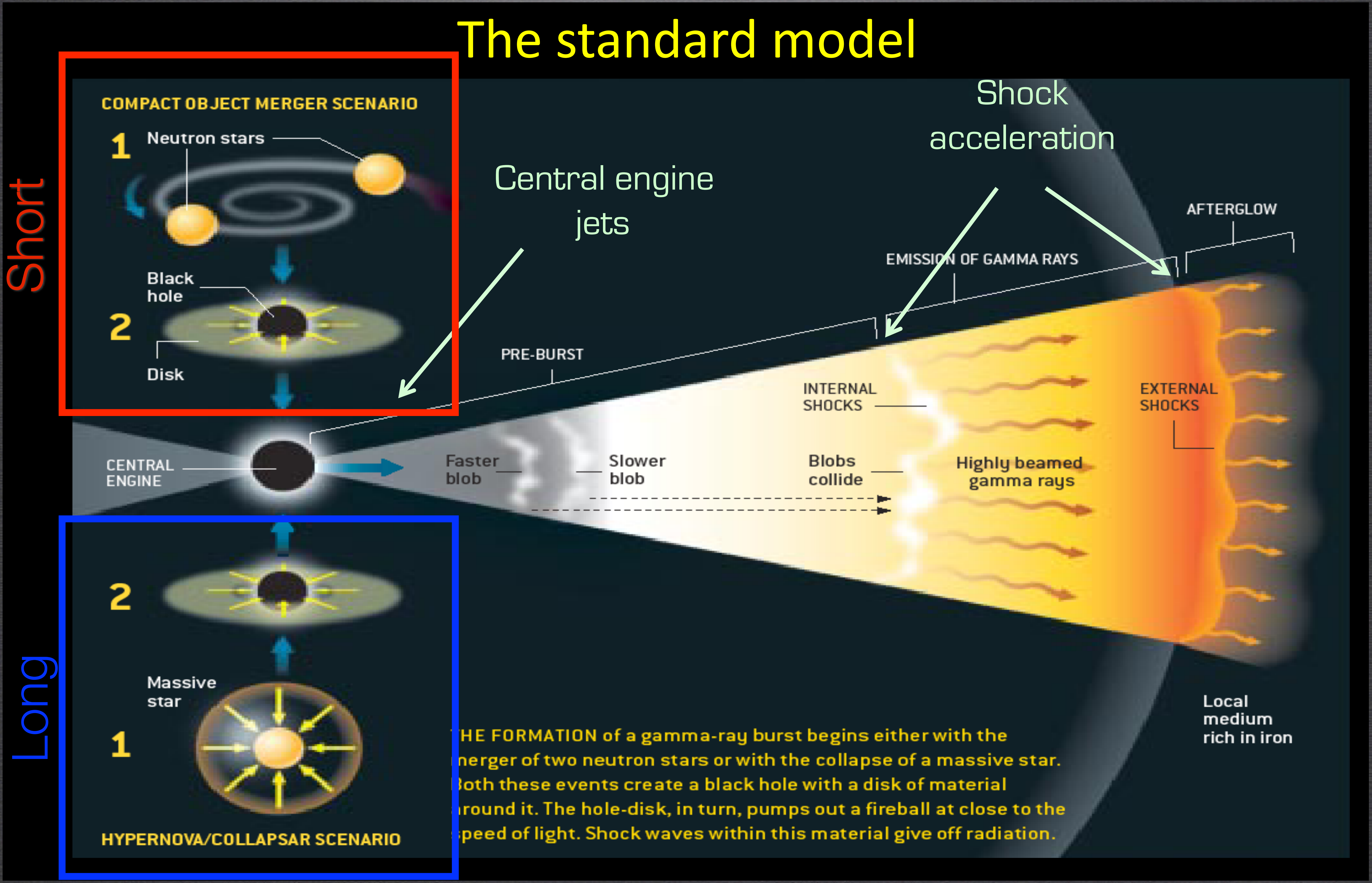

Short

Long

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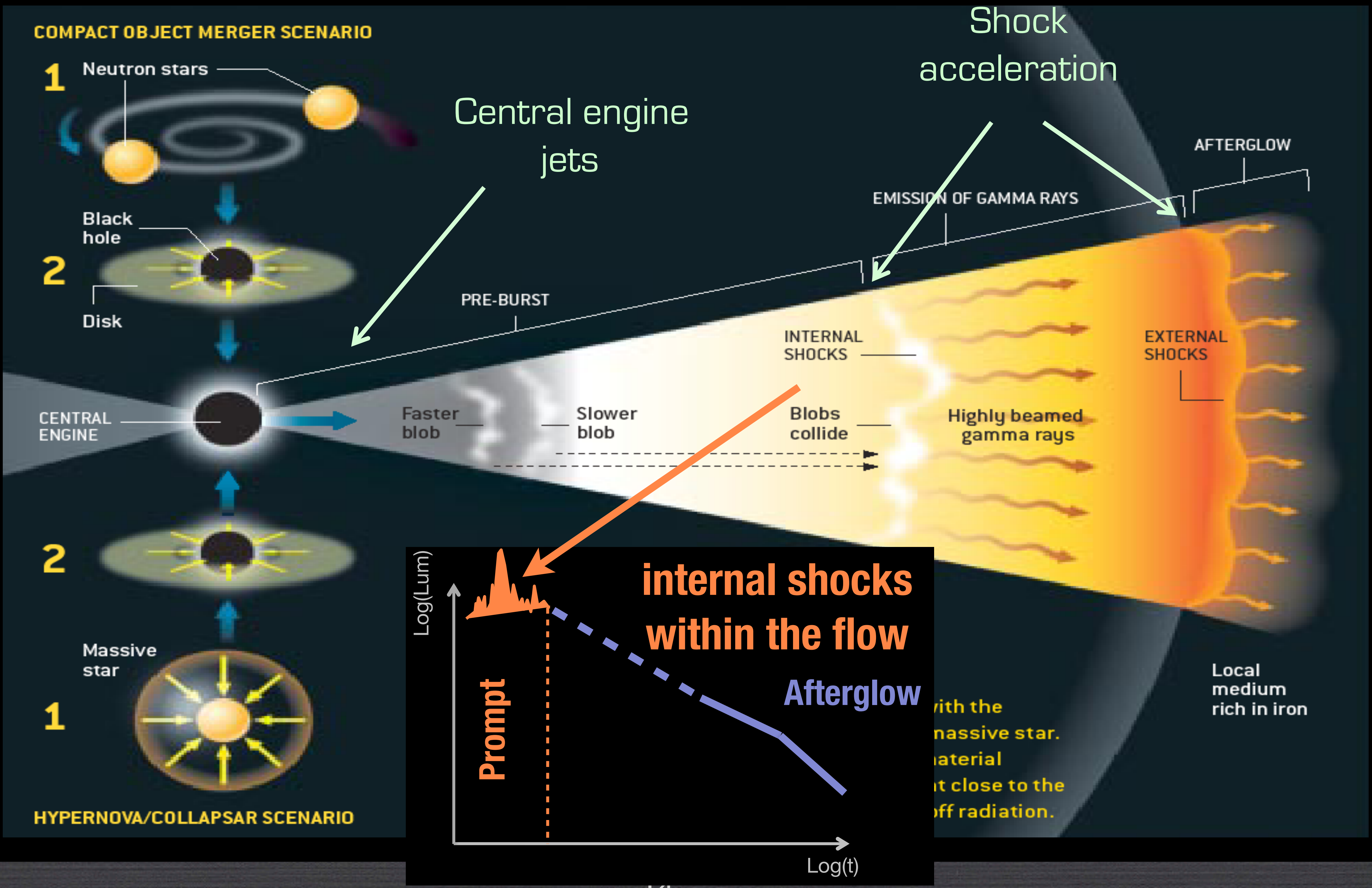


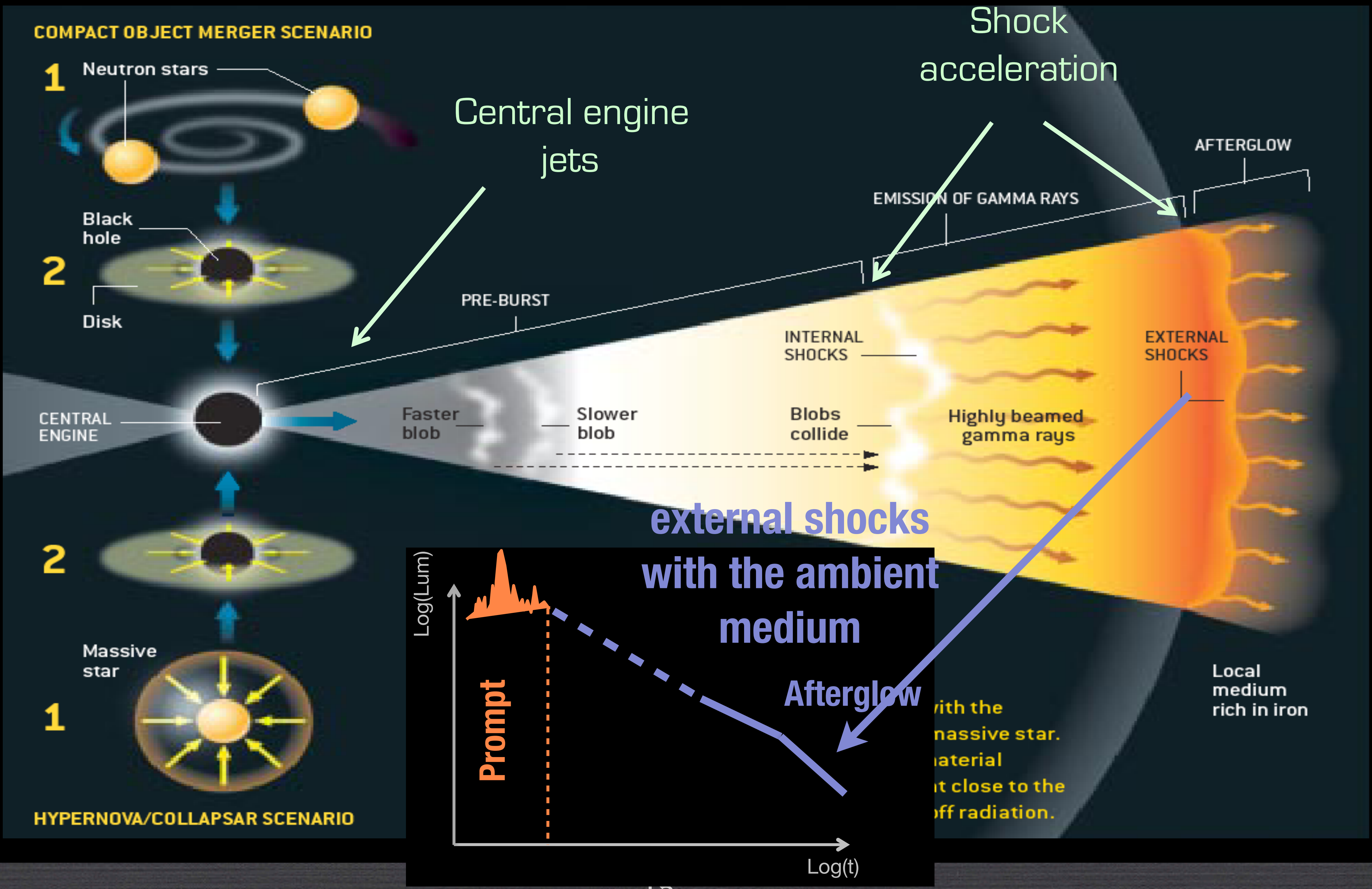
Shock acceleration

Central engine jets

internal shocks within the flow

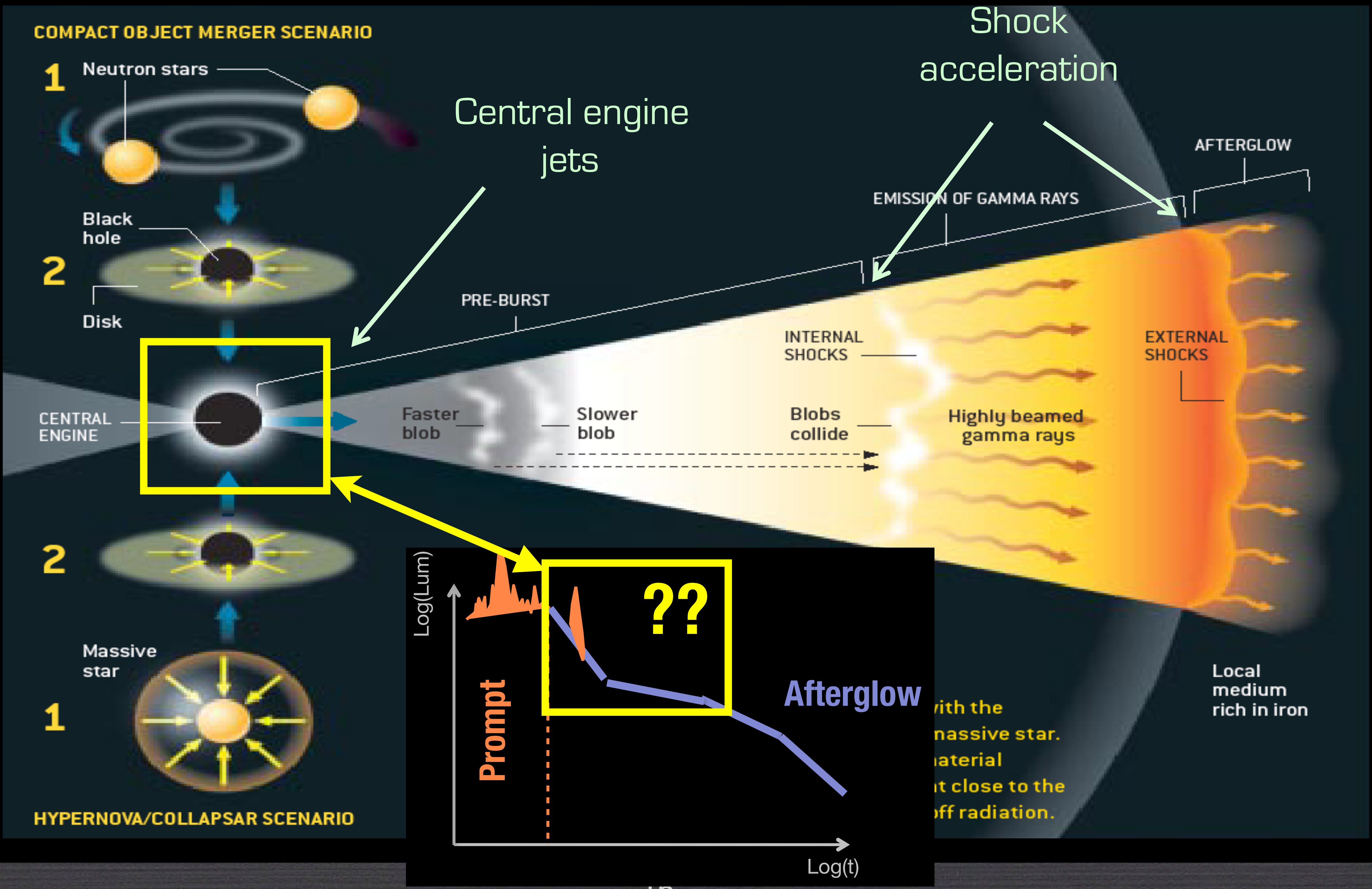
The GRB standard model (pre-Swift)

The standard model

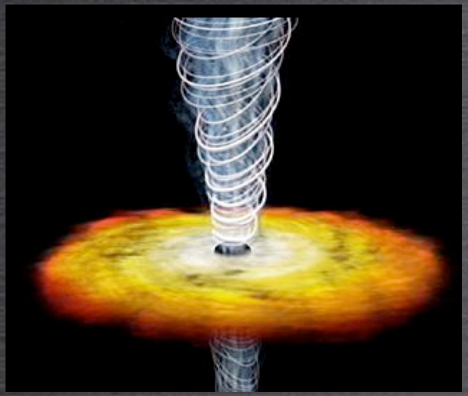


The GRB standard model (post-Swift) ???

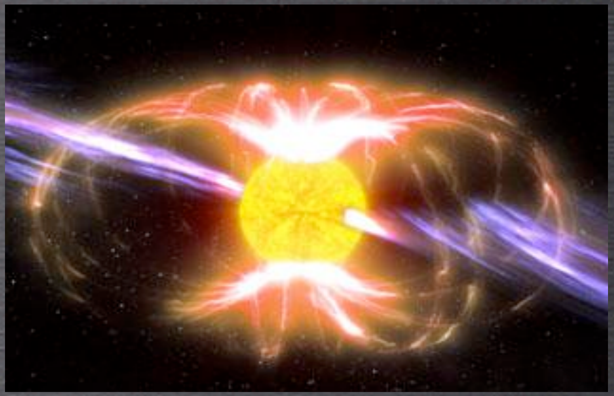
The standard model



What is the central engine of GRBs?



Black holes vs. Magnetars



- GRB powered by accretion

- highly rotating (P~1 ms), huge magnetic field ($B \sim 10^{15}$ G) => energy reservoir
- contribution to GRB power from spindown (~ hours)
- produced in both merging and core-collapse SNe

Woosley & Bloom 2006
Woosley 1993
MacFadyen & Woosley 1999
Kumar et al. 2008

Usov 1992
Duncan & Thompson 1992
Dai & Lu 1998
Zhang & Meszaros 2001
Metzger et al. 2011

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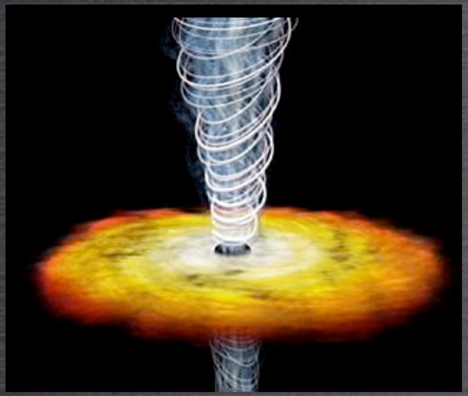

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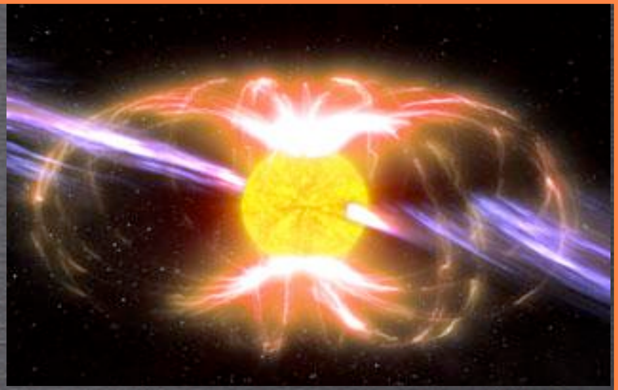

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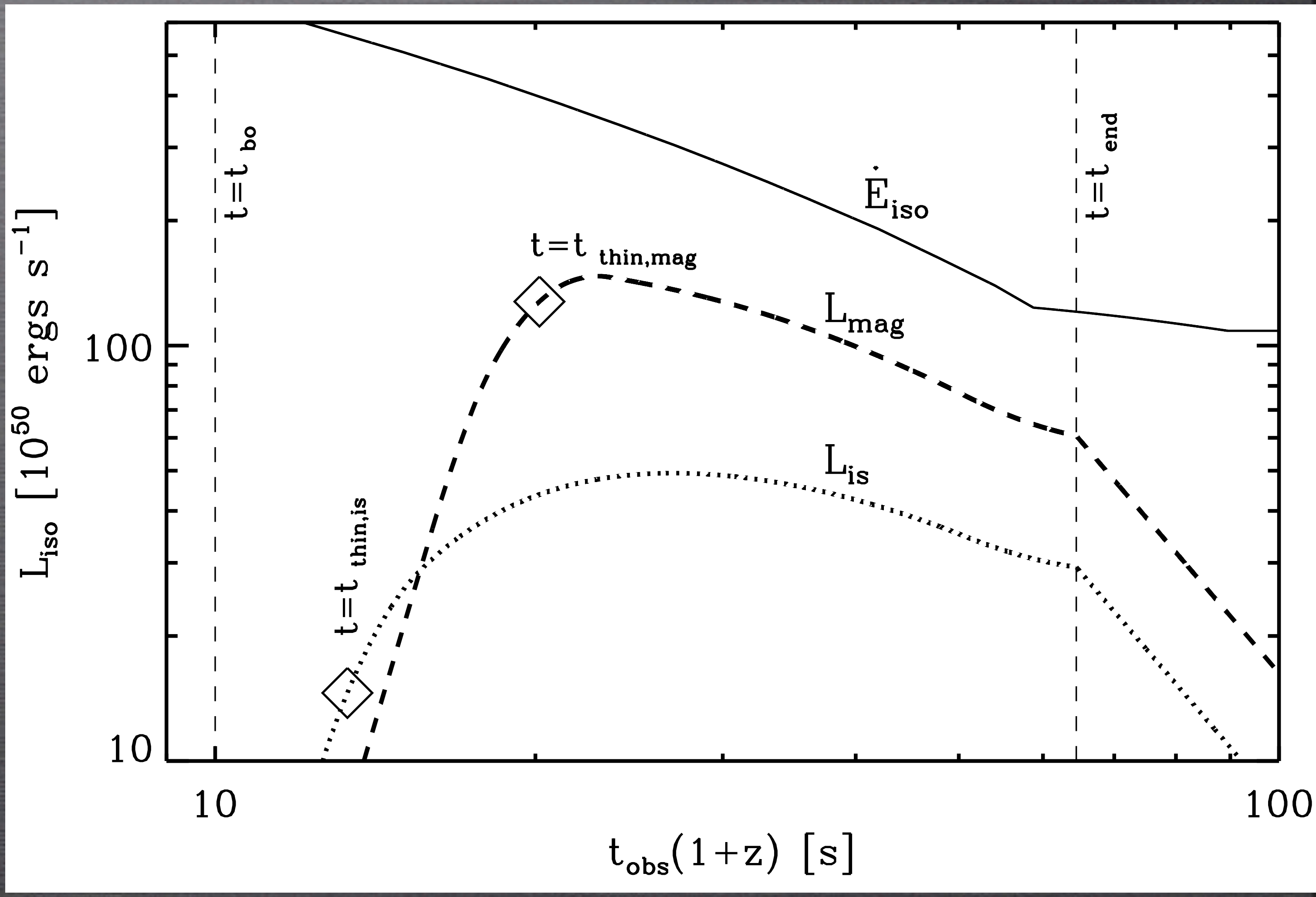
Model for a magnetar central engine

- GRB powered only by the magnetar rotational energy through a wind heated by neutrinos driven by the proto-magnetar
- magnetised ultra-relativistic outflow
- prompt: internal shocks or magnetic reconnection
- dissipation inefficient at late times: interaction with ISM + spindown power



Metzger et al., 2011

Imprints of a magnetar central engine

- 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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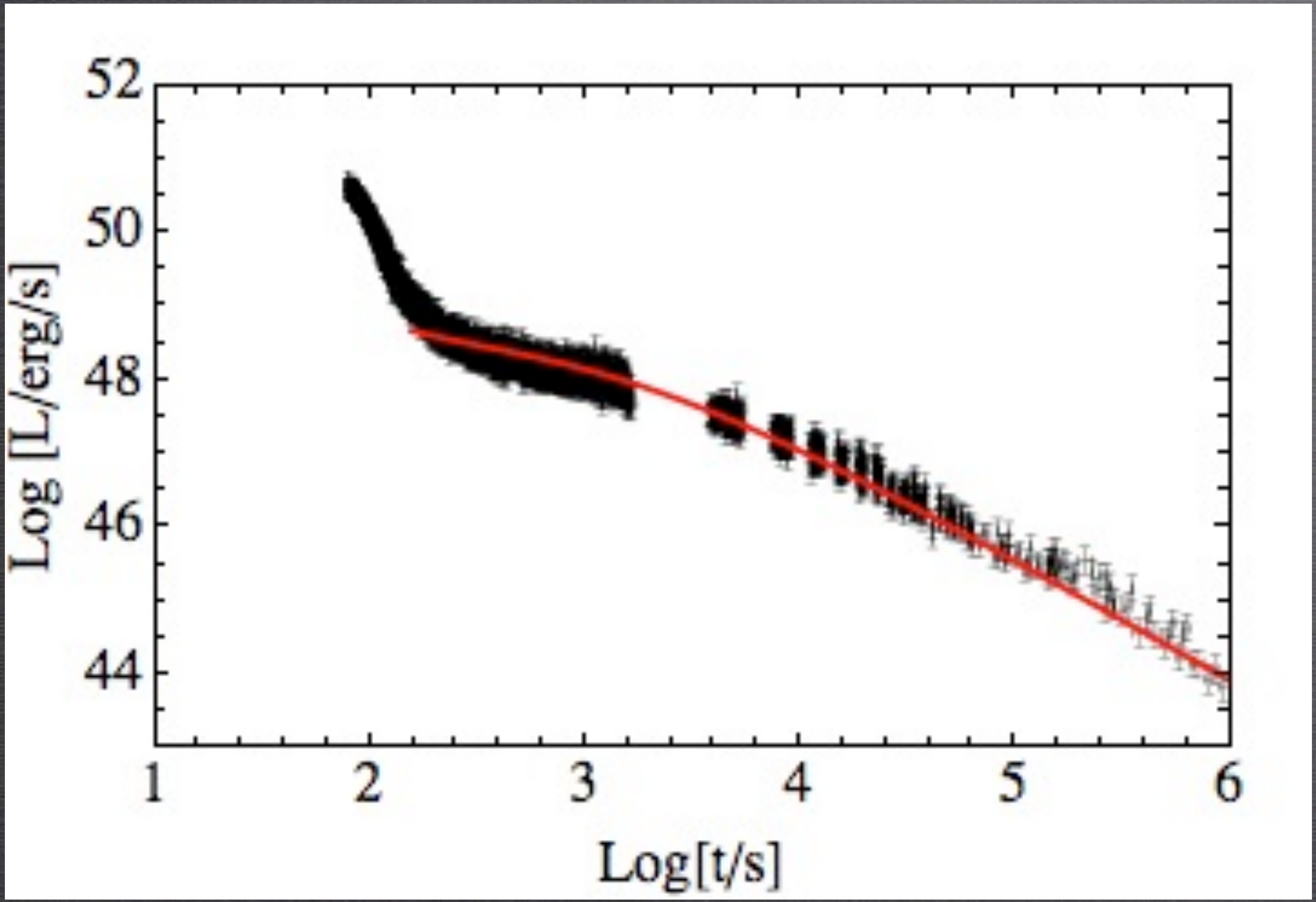
The plateau phase in LGRBs and SGRBs

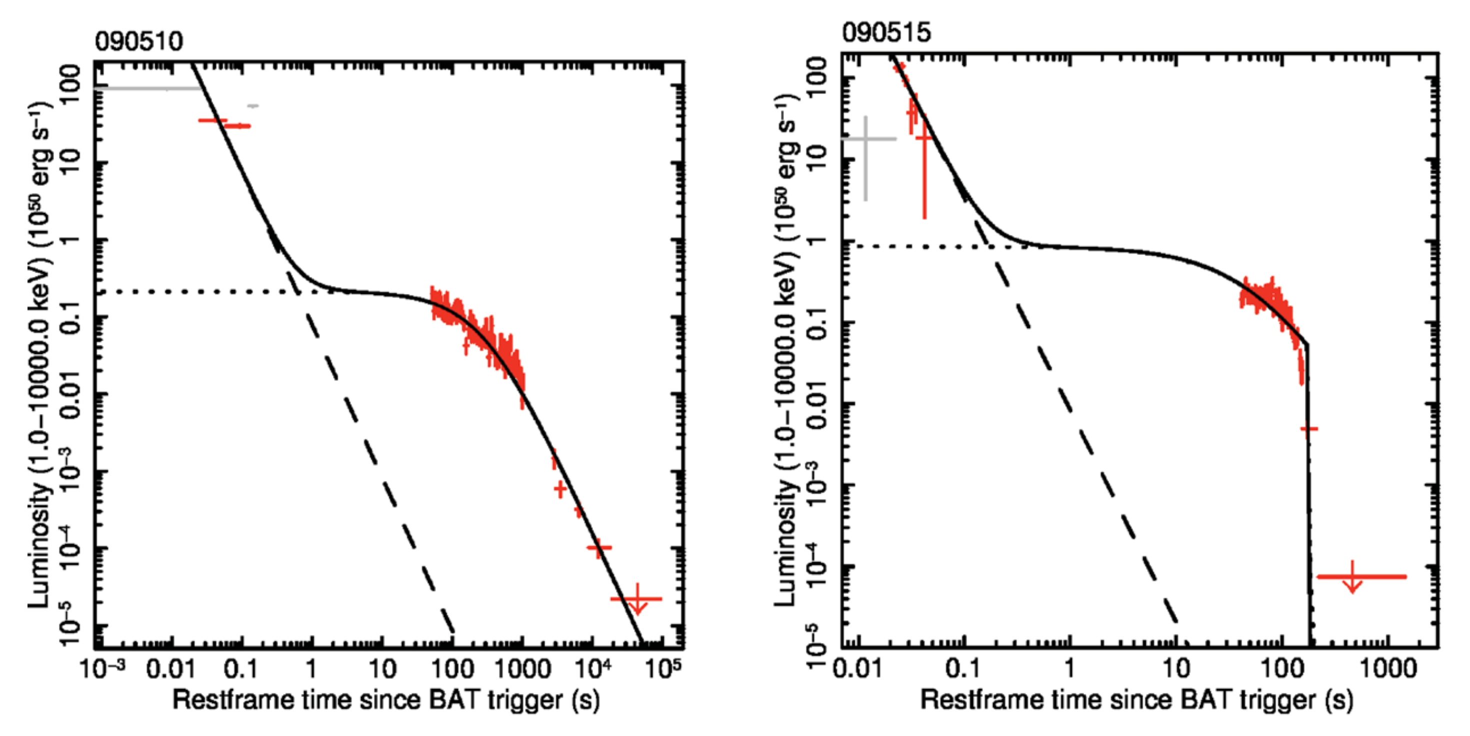


- ~50% LGRBs with "canonical behaviour"
- ~80% deviates from simple power law
- ~50% SGRBs

➡ energy injection into the afterglow lasting ~ hours

Nousek et al., 2005
Tagliaferr et al. 2005
Zhang et al. 2006
Evans et al. 2009
Rowlinson et al. 2013
Margutti et al. 2013
D'Avanzo et al. 2014

The plateau phase in LGRBs and SGRBs



Lyons et al. 2010
Rowlinson et al. 2013

- usually decay ~ $t^{-1.2}$ but occasionally very sharp drop

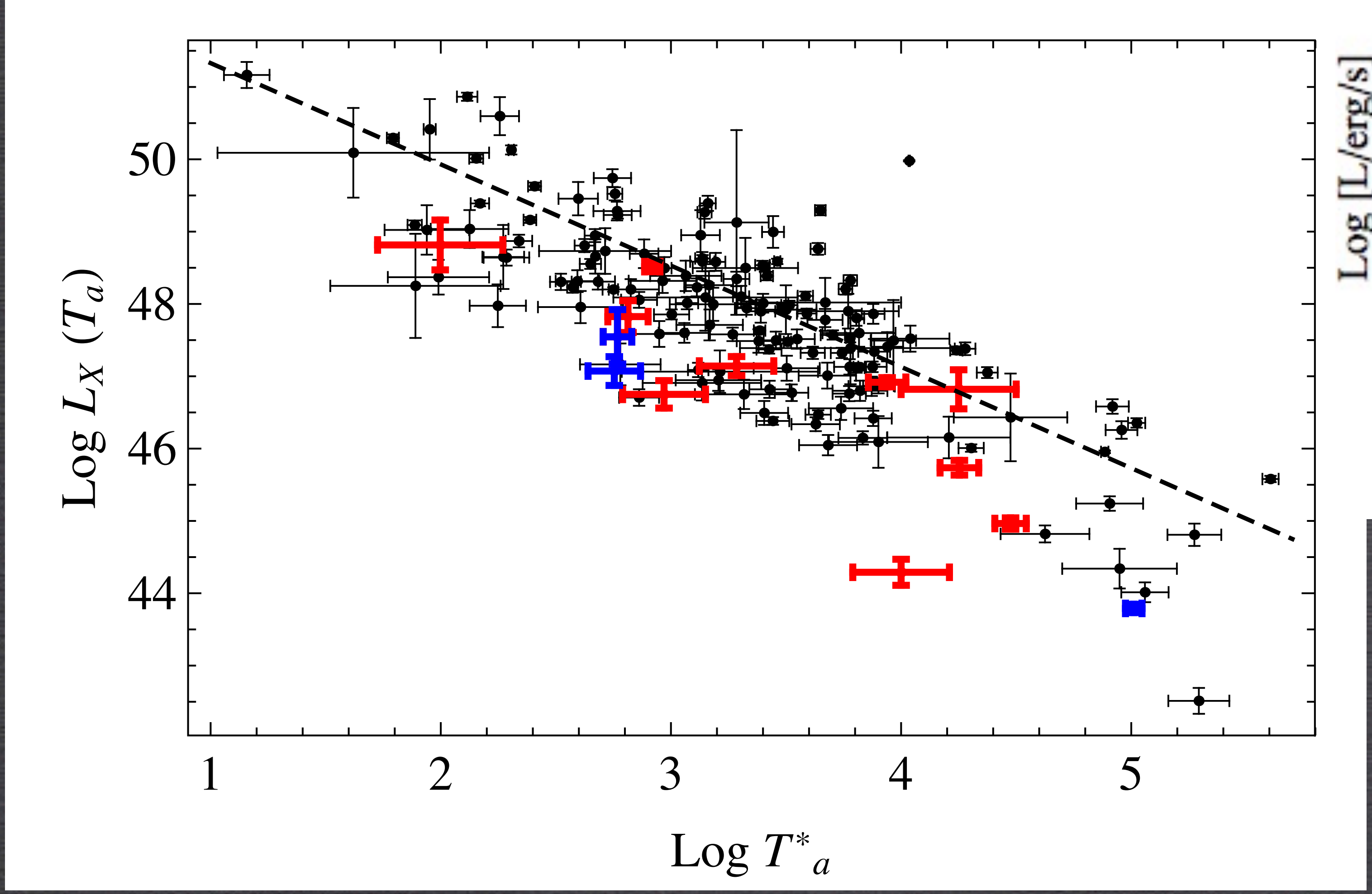
- ~50% LGRBs with “canonical behaviour”
- ~80% deviates from simple power law
- ~50% SGRBs

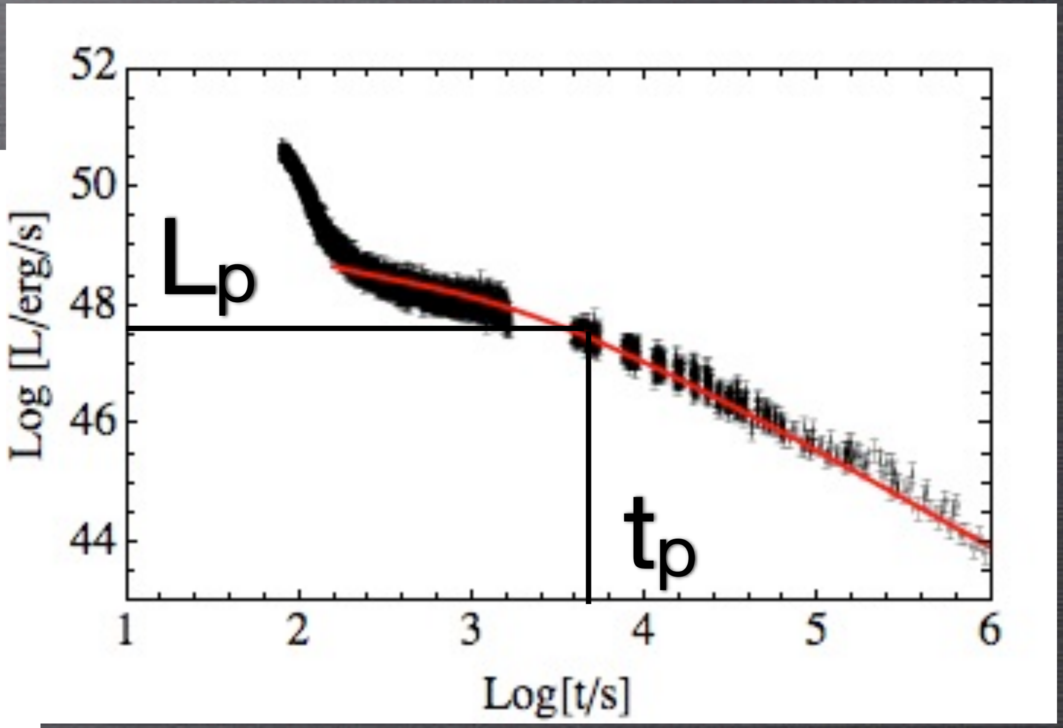
➡ energy injection into the afterglow lasting ~ hours

The plateau phase in LGRBs and SGRBs

Correlations between plateau properties and with the prompt emission:

Luminosity-time correlation





$$L_p = L(t_p):\ L_p \propto t_p^{-\alpha}$$

Dainotti et al. 2008, 2010, 2013
Rowlinson et al. 2014

Imprints of a magnetar central engine

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

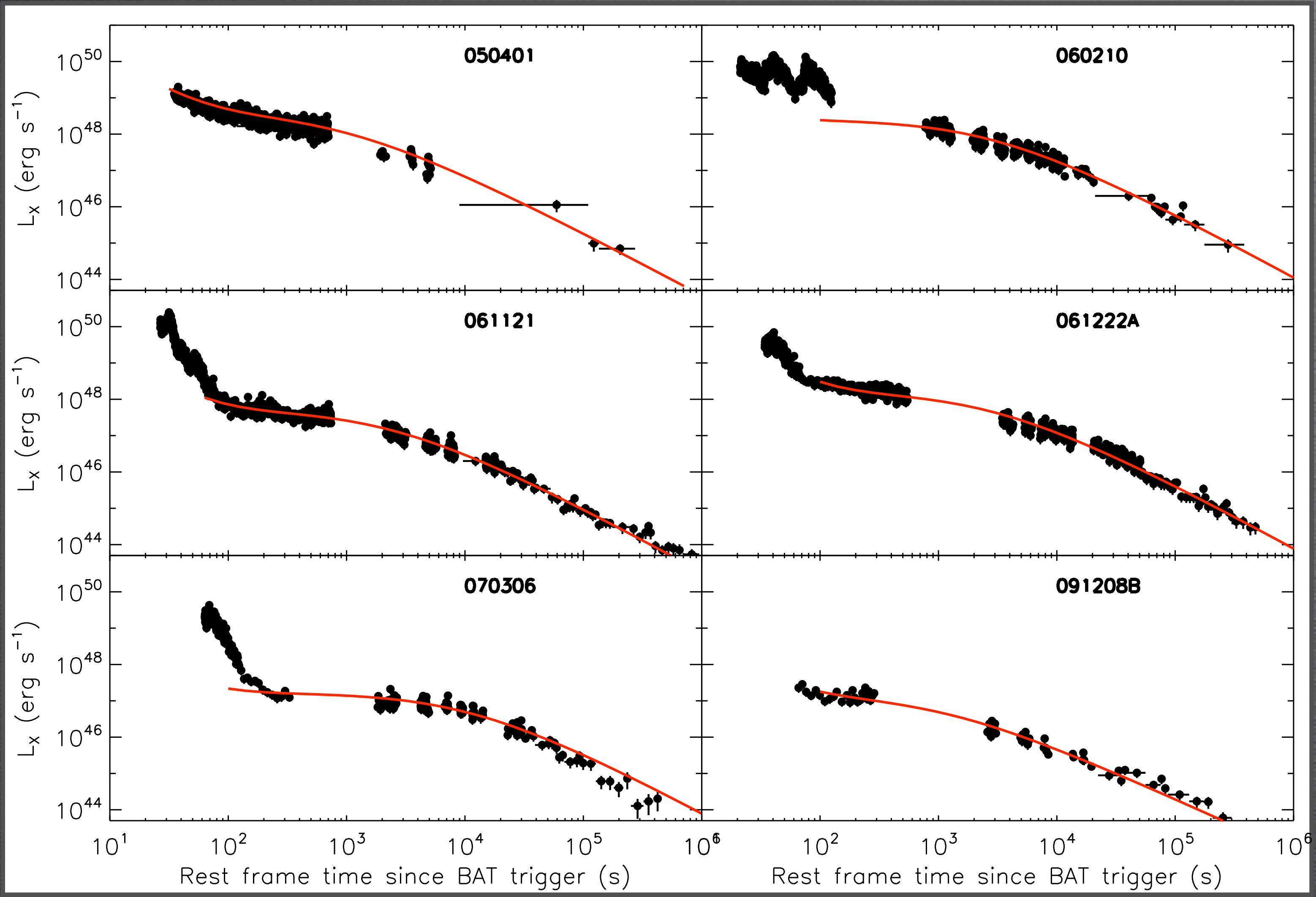
$$t_{\rm sd} = 3 \times 10^{3} B_{15}^{-2} P_{-3}^{2} \, {\rm s} \, ,$$

Spin-down power and timescale sufficient to produce the plateau!

Dai & Lu 1998
Zhang & Meszaros 2001

Imprints of a magnetar central engine

External plateau



Spin-down luminosity + afterglow

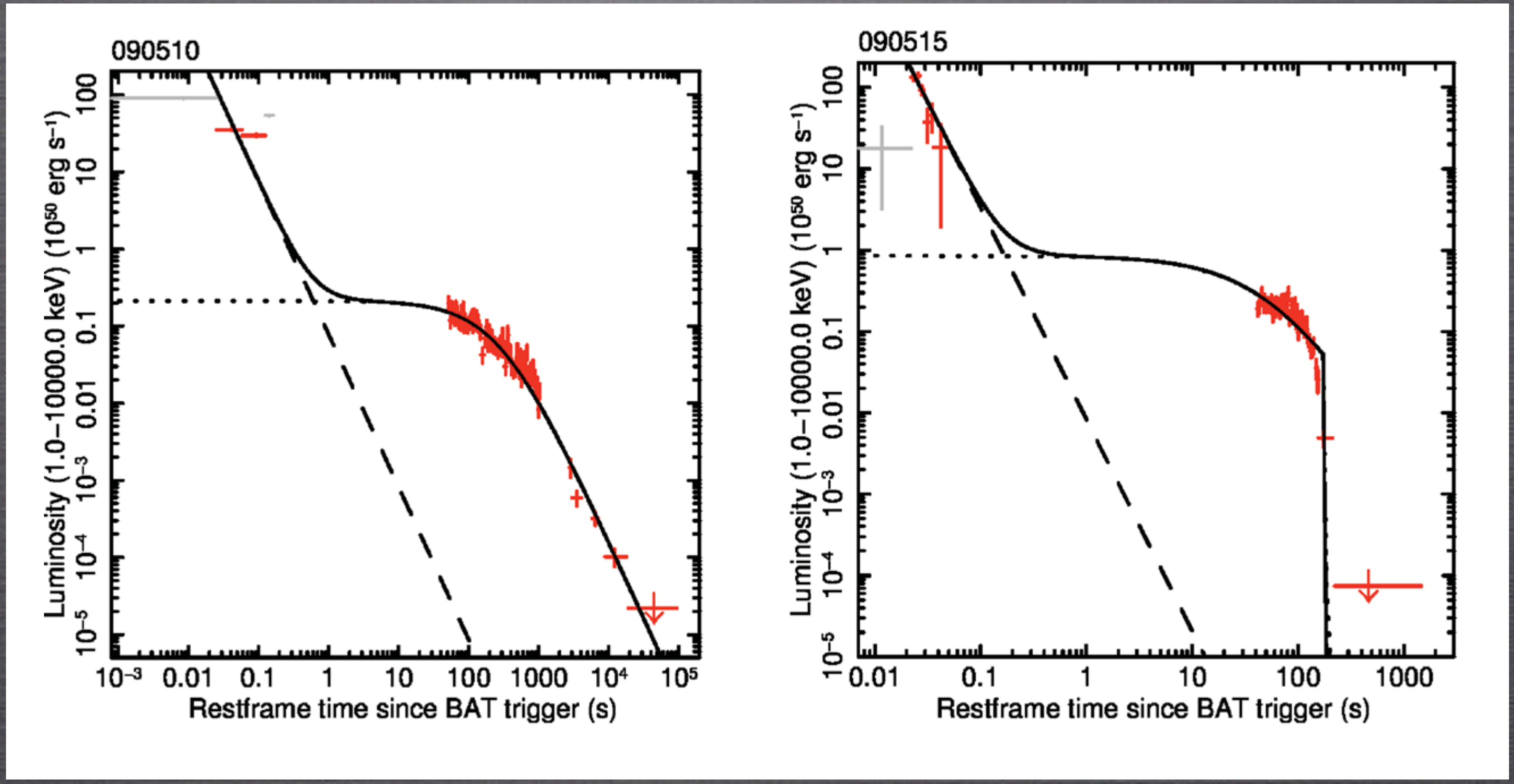
$$E(t) = \frac{L_i}{t^{k'}} \int_{t_\circ}^{t} \frac{t^{k'}}{(1+at)^2} + E_\circ \left(\frac{t_\circ}{t}\right)^{k'}$$

Dall'Osso et al. 2011

Dai & Lu 1998
Zhang & Meszaros 2001
Dall'Osso et al. 2011
Bernardini et al. 2012, 2013

Imprints of a magnetar central engine

Internal plateau



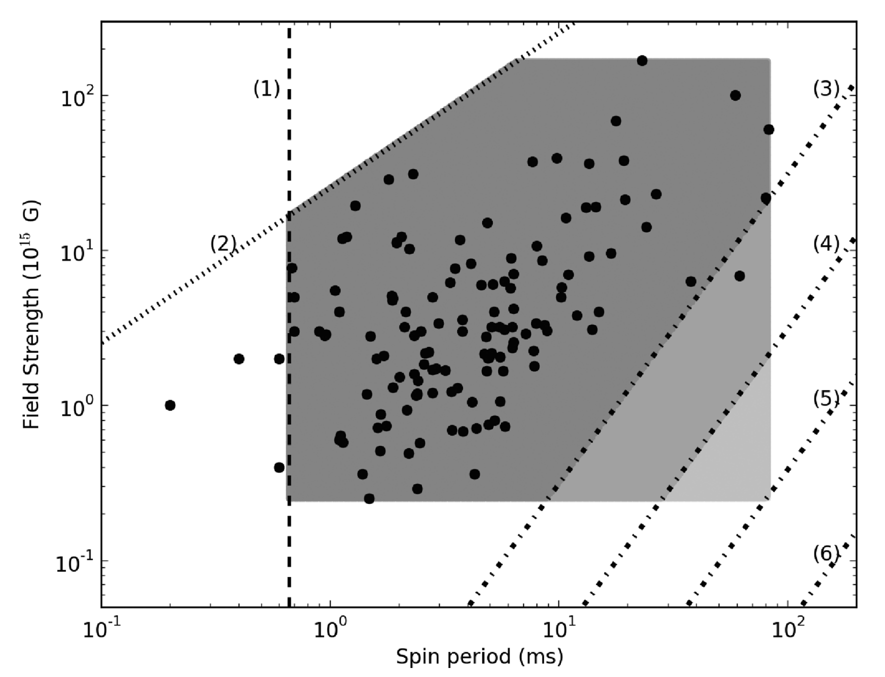
Spin-down luminosity
(negligible aft.)

Spin-down luminosity
+ collapse to BH

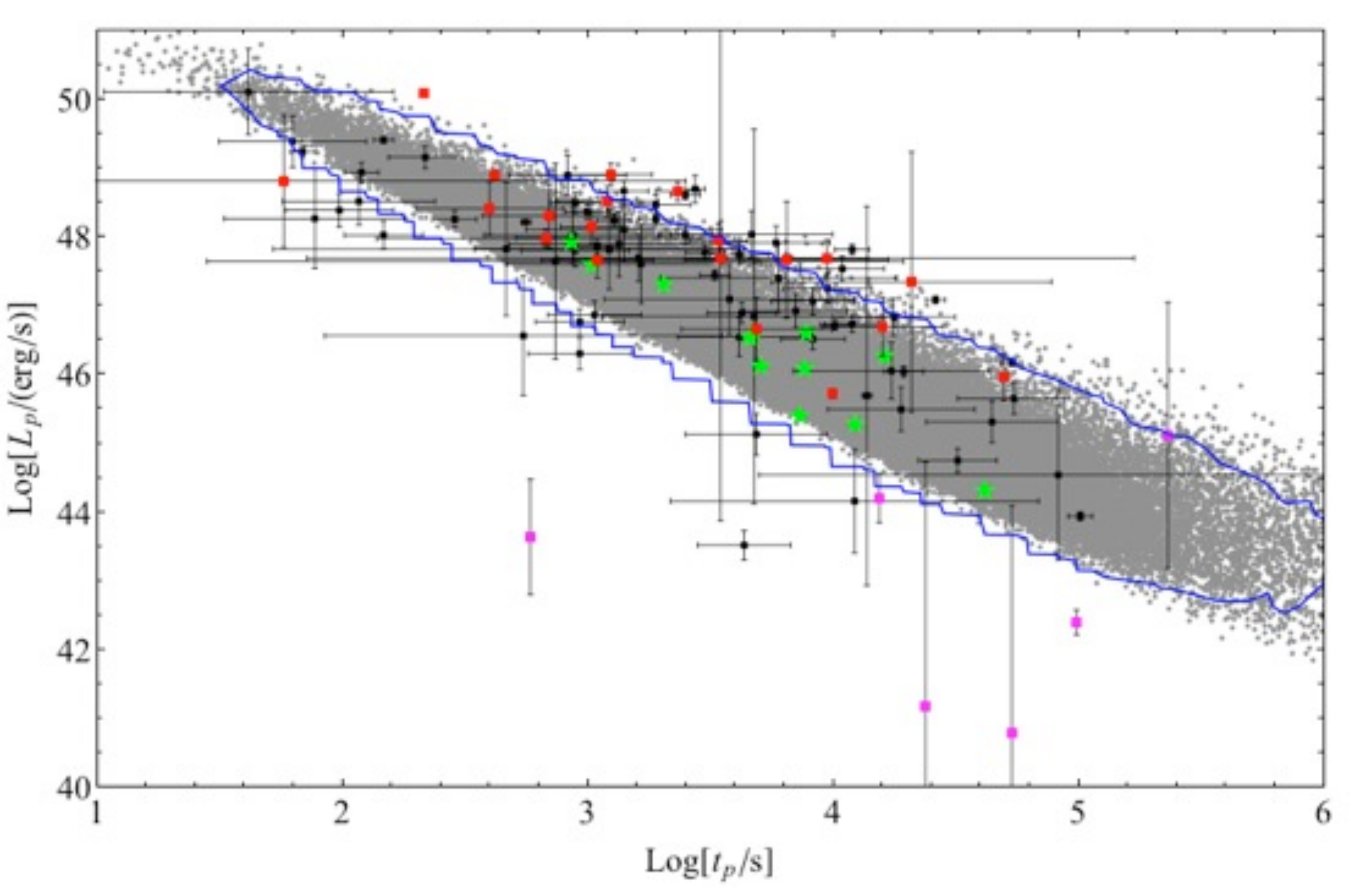
Lyons et al. 2010
Rowlinson et al. 2010, 2013

Imprints of a magnetar central engine

Luminosity-time correlation implied by the model



$$L_p \sim \dot{E}_{\rm sd} \sim B^2 P^{-4} \sim P^{-2} t_{\rm sd}^{-1} \sim P^{-2} t_p^{-1}$$



- normalization and slope from B and P
- scatter from P: 0.66-35 ms

Bernardini et al. 2012
Rowlinson et al. 2014

Imprints of a magnetar central engine

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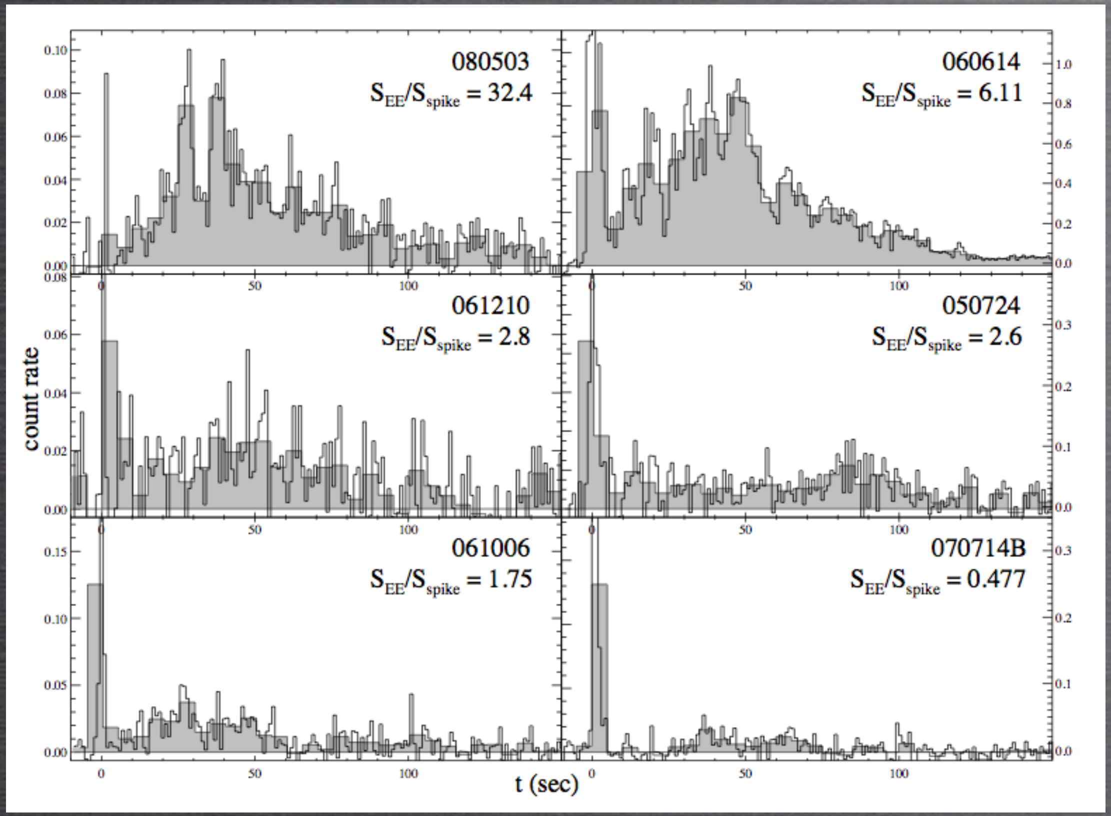
- pre- and post-cursors in LGRBs and SGRBs

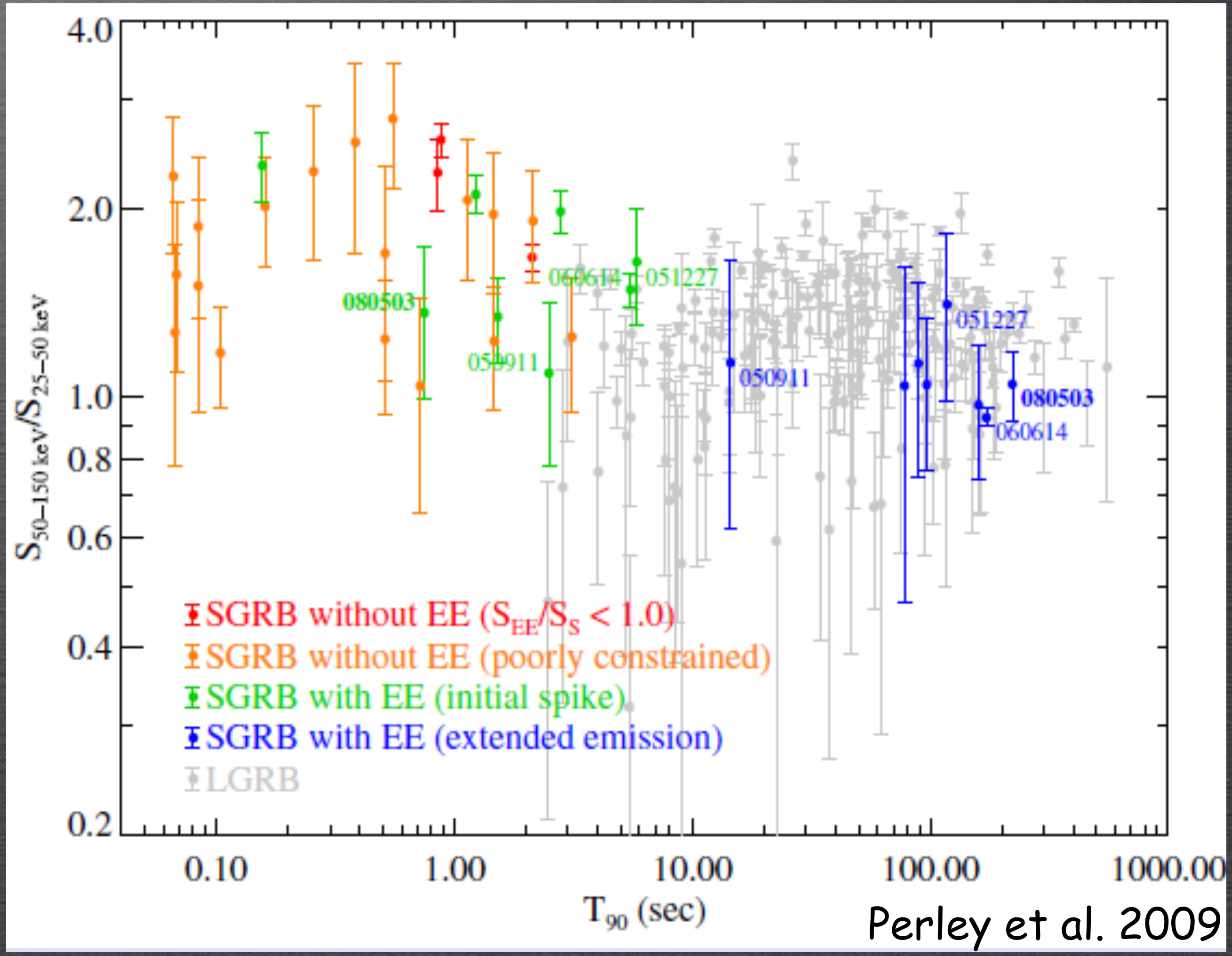
SGRBs with Extended Emission (EE)



- ✦ ~15% rebrightening (EE) in prompt emission ($T_{90} > 2$s)
- ✦ delayed onset of EE

- ✦ hard spike, soft tail
- ✦ lower peak but duration ~ 100 s

➡EE comprises larger fluence



Perley et al. 2009

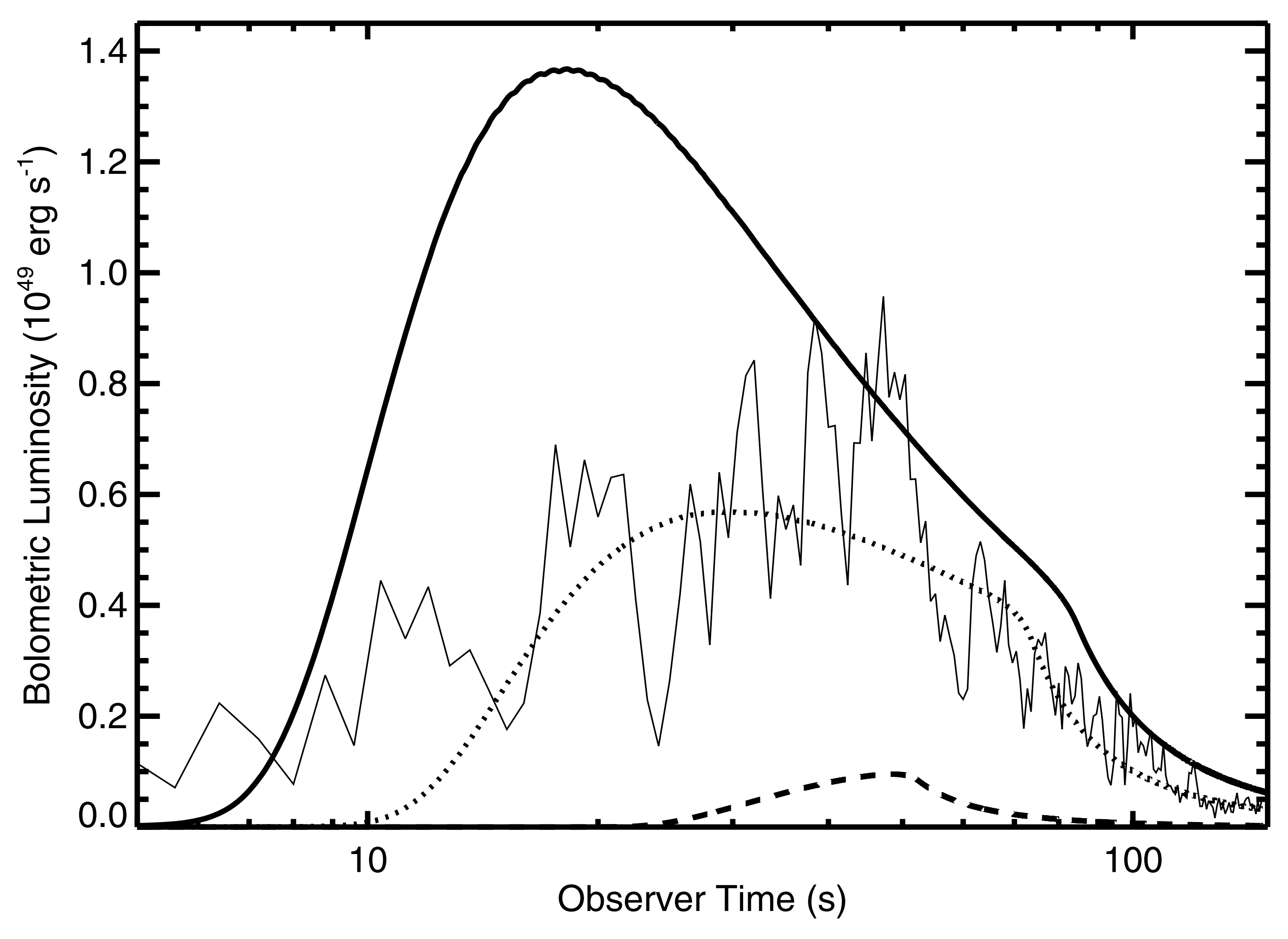
Lazzati et al. 2001
Norris & Bonnell 2006

Imprints of a magnetar central engine

One possibility:

- initial spike <= magnetar powered by accretion
- EE + late time X-rays <= rotational powered wind

Metzger et al. 2008



Imprints of a magnetar central engine

One possibility:

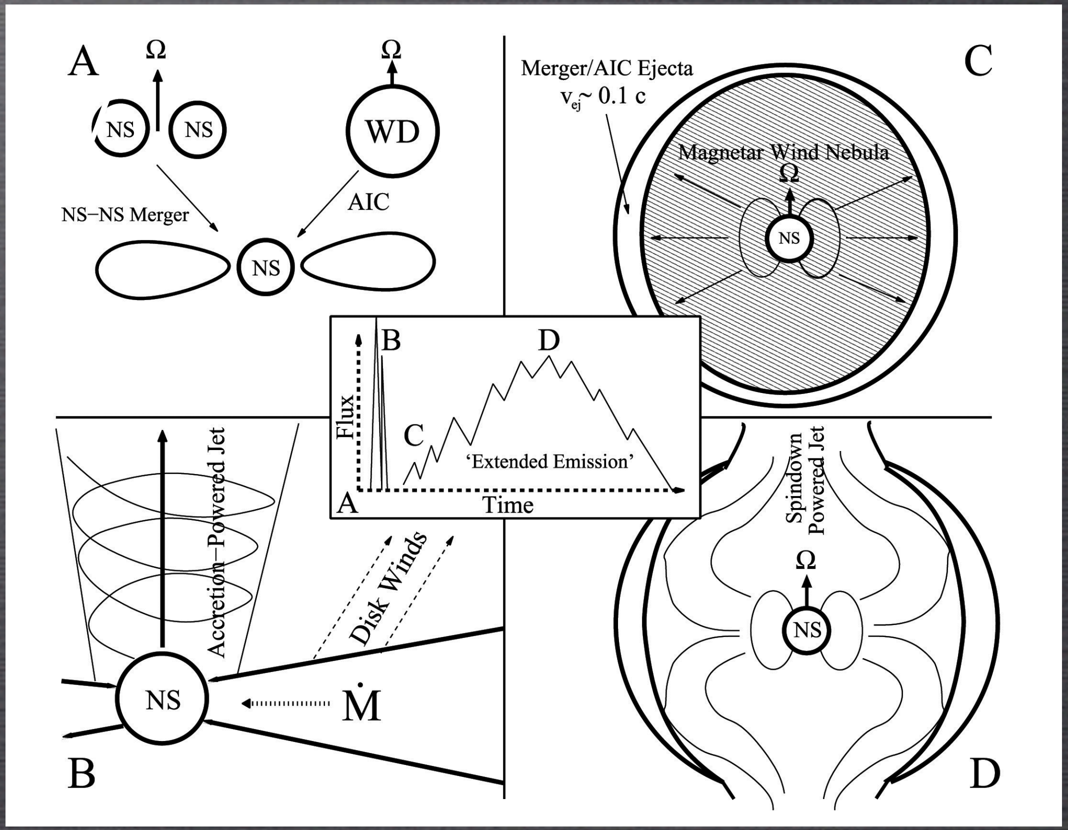
- initial spike <= magnetar powered by accretion
- EE + late time X-rays <= rotational powered wind

Metzger et al. 2008

or:

- initial spike <= magnetar powered accretion
- EE <= propeller
- late X-rays <= rotational powered wind

➡ different mechanisms for different features



Gompertz et al. 2014

Imprints of a magnetar central engine

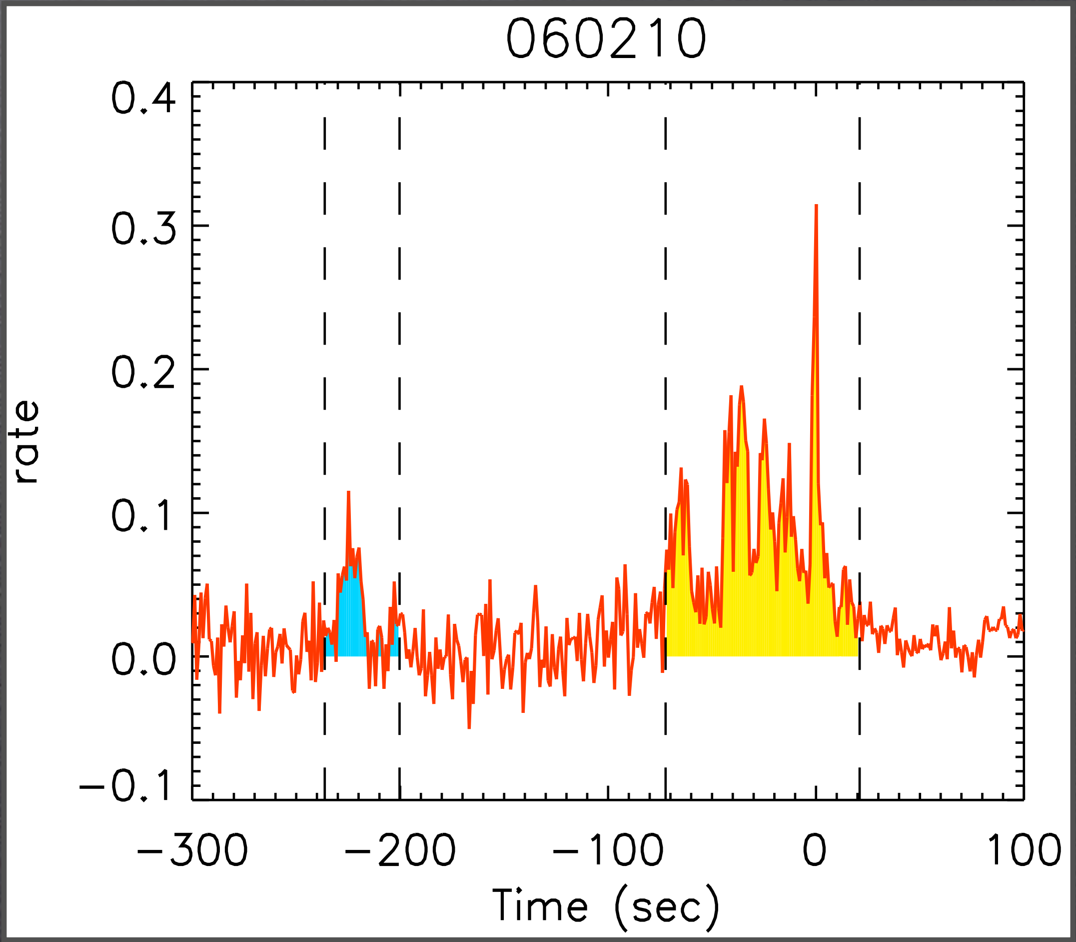
- plateau phase in X-rays of both LGRBs and SGRBs
- extended emission in SGRBs
- **pre- and post-cursors in LGRBs and SGRBs**

PRECURSORS IN GRBs

Emission episodes PRIOR TO the main prompt emission in ~15% of LGRBs:

- quiescent time ~ T_{90}

Koshut et al. 1995
Lazzati 2005
Ramirez-Ruiz & Merloni 01
Burlon et al. 2008, 2009
Troja et al., 2010



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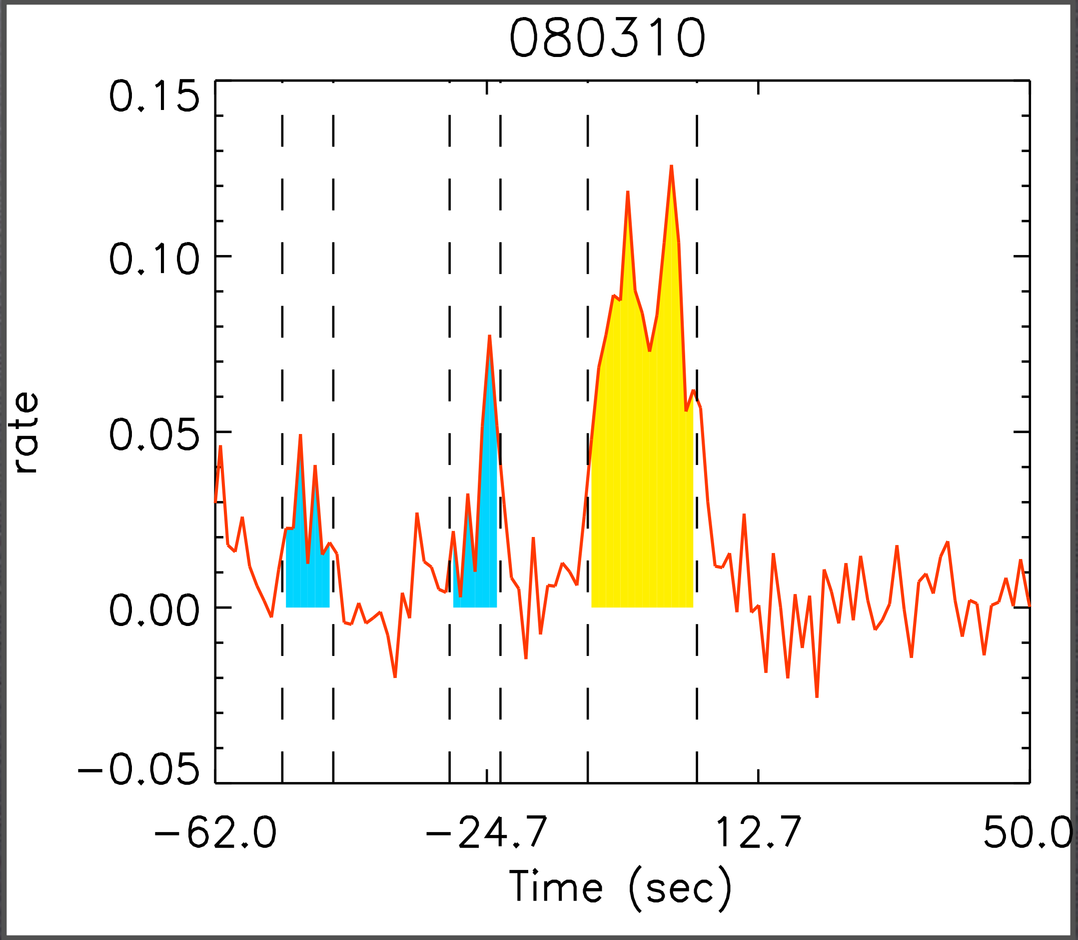

PRECURSORS IN GRBs

Emission episodes PRIOR TO the main prompt emission in ~15% of LGRBs:

- quiescent time ~ T_{90}
- multiple precursors
- negligible or comparable energies

Koshut et al. 1995
Lazzati 2005
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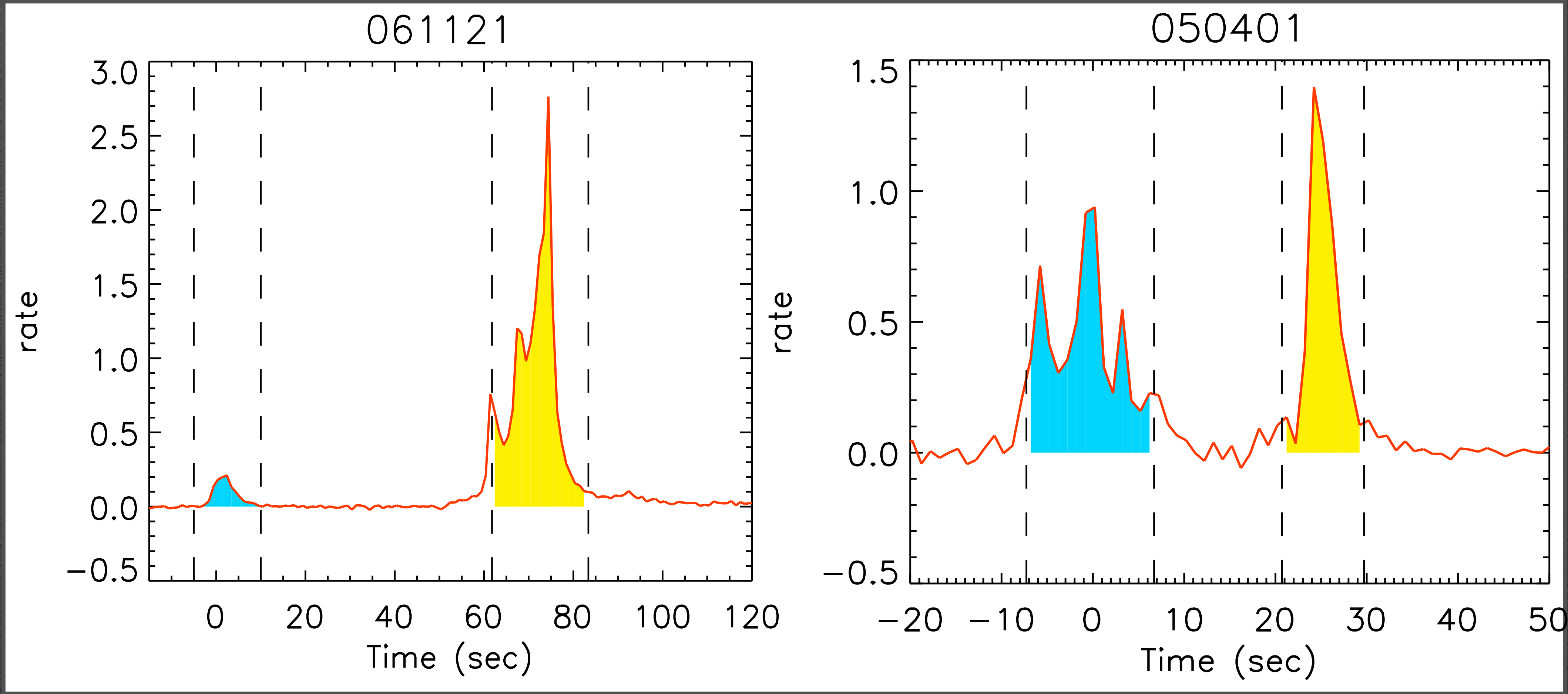
Burlon et al. 2008, 2009
Troja et al., 2010



PRECURSORS IN GRBs

Emission episodes PRIOR TO the main prompt emission in ~15% of LGRBs:

- quiescent time ~ T_{90}
- multiple precursors
- negligible or comparable energies
- also in SGRBs

Koshut et al. 1995
Lazzati 2005
Ramirez-Ruiz & Merloni 01
Burlon et al. 2008, 2009
Troja et al., 2010

X-RAY FLARES

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

- t_{pk} usually ≤ 1000 s, but also at late times

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

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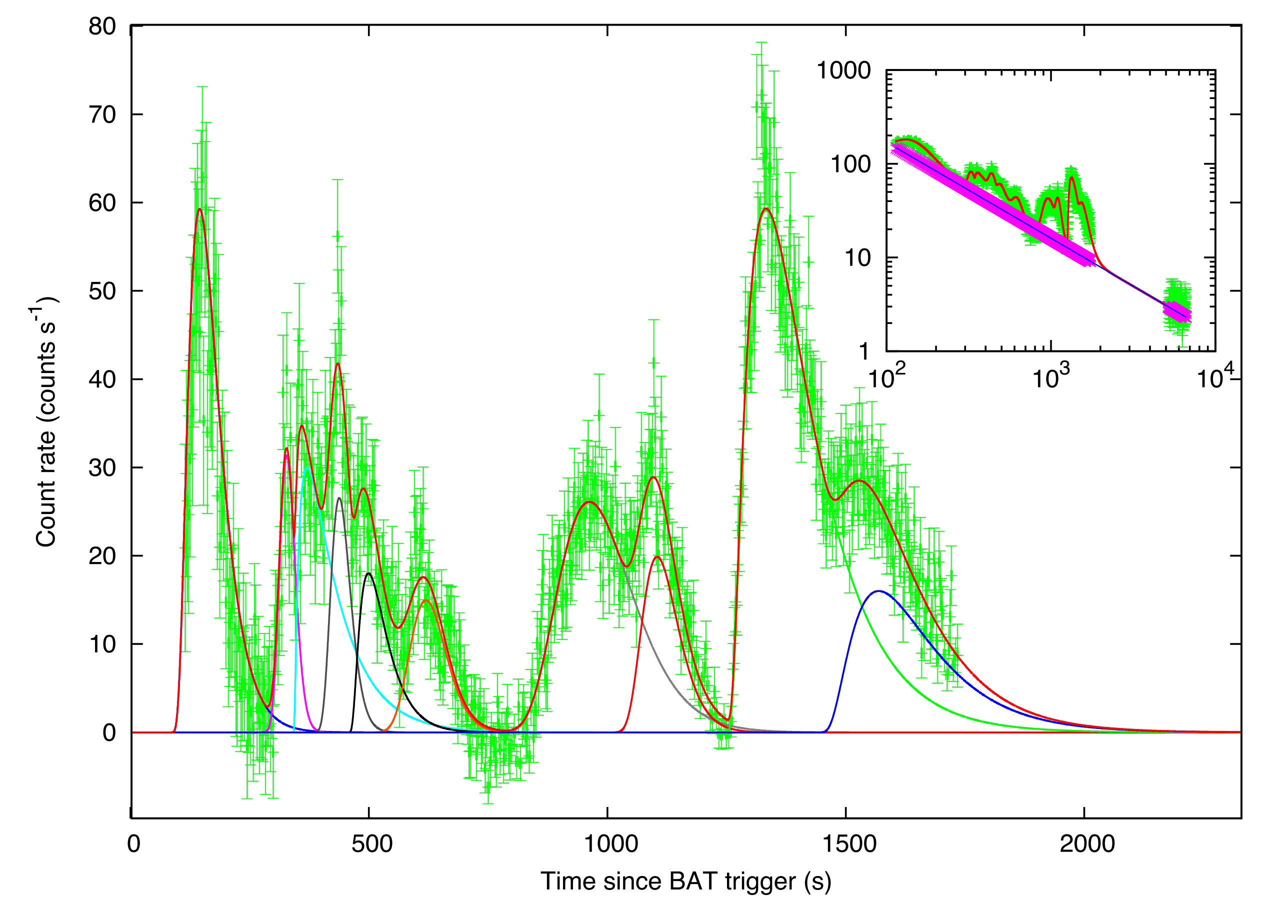

Chincarini et al., 2007, 2010
Margutti et al., 2010, 2011, 2012
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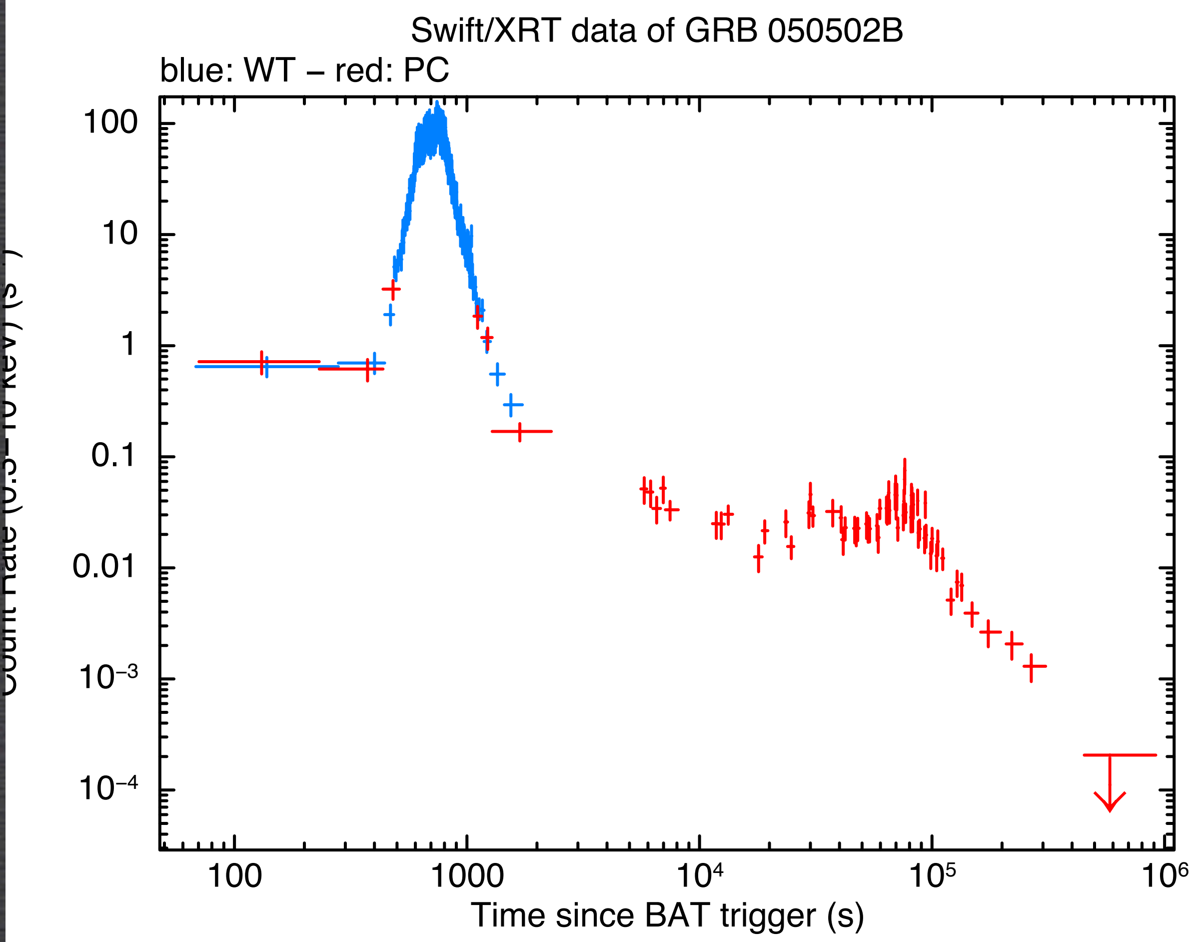

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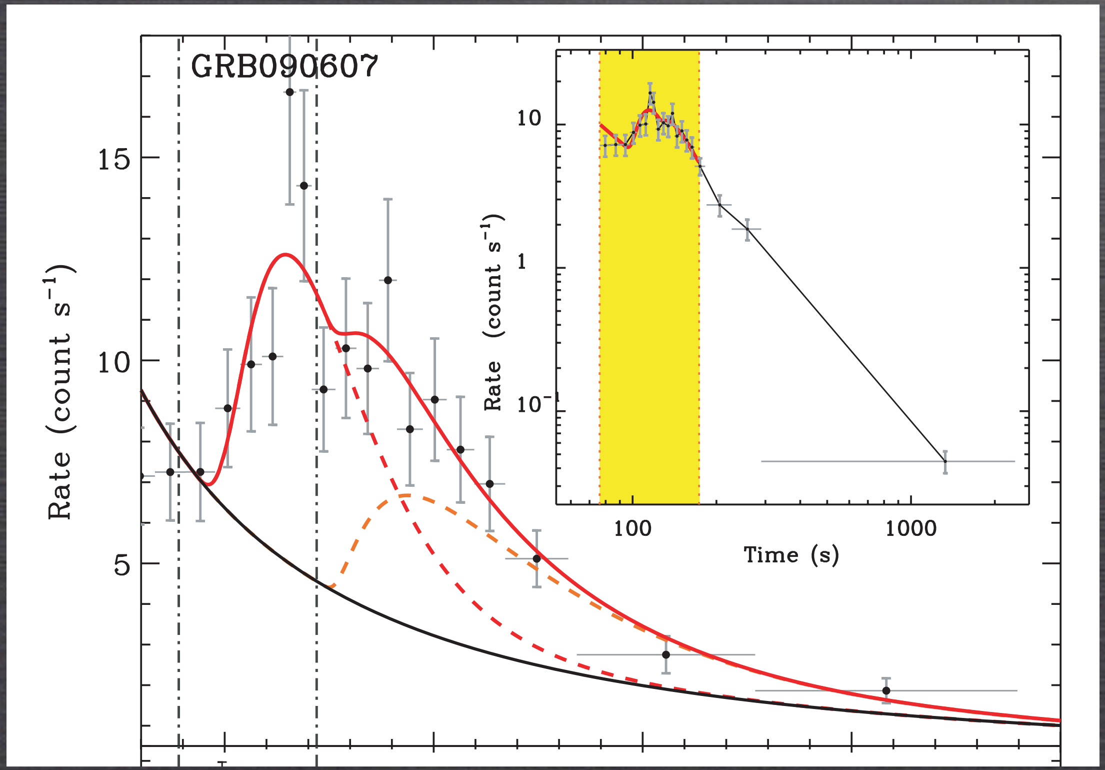
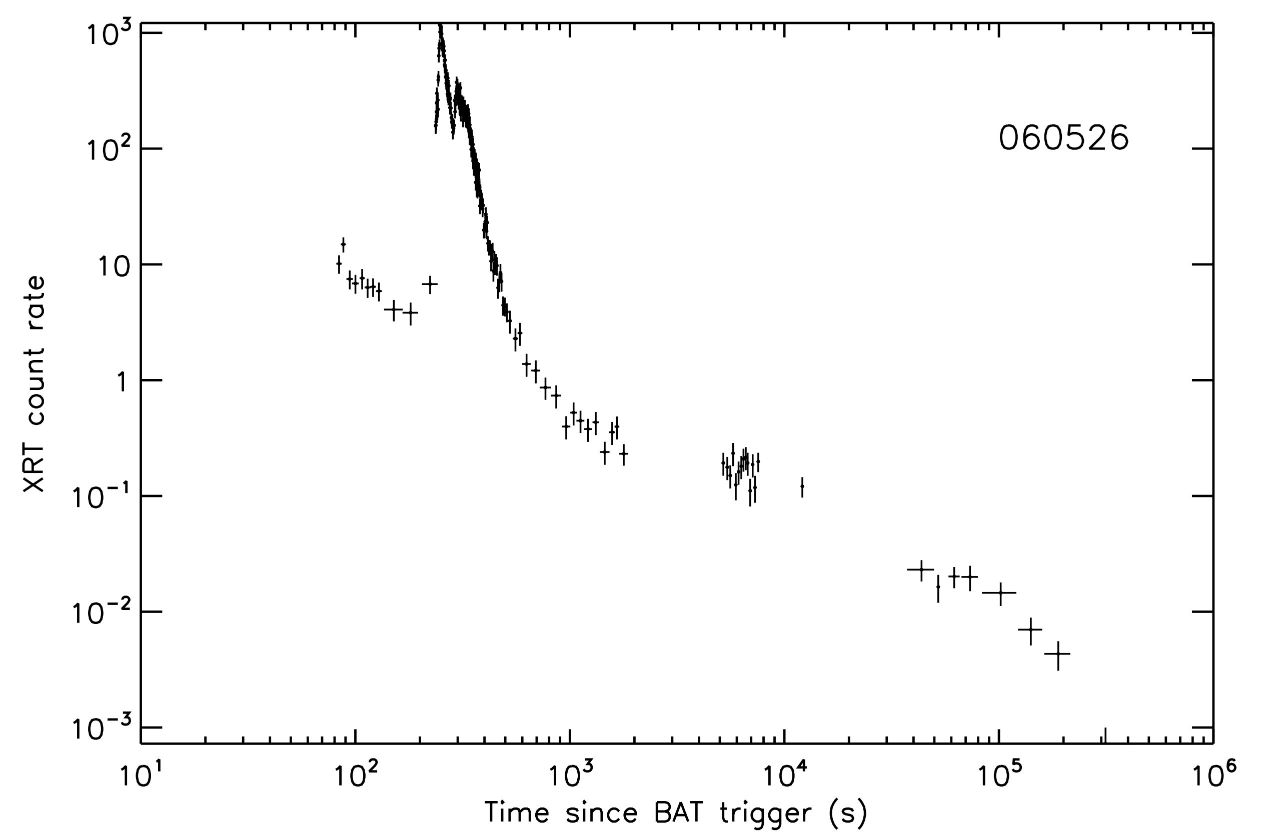


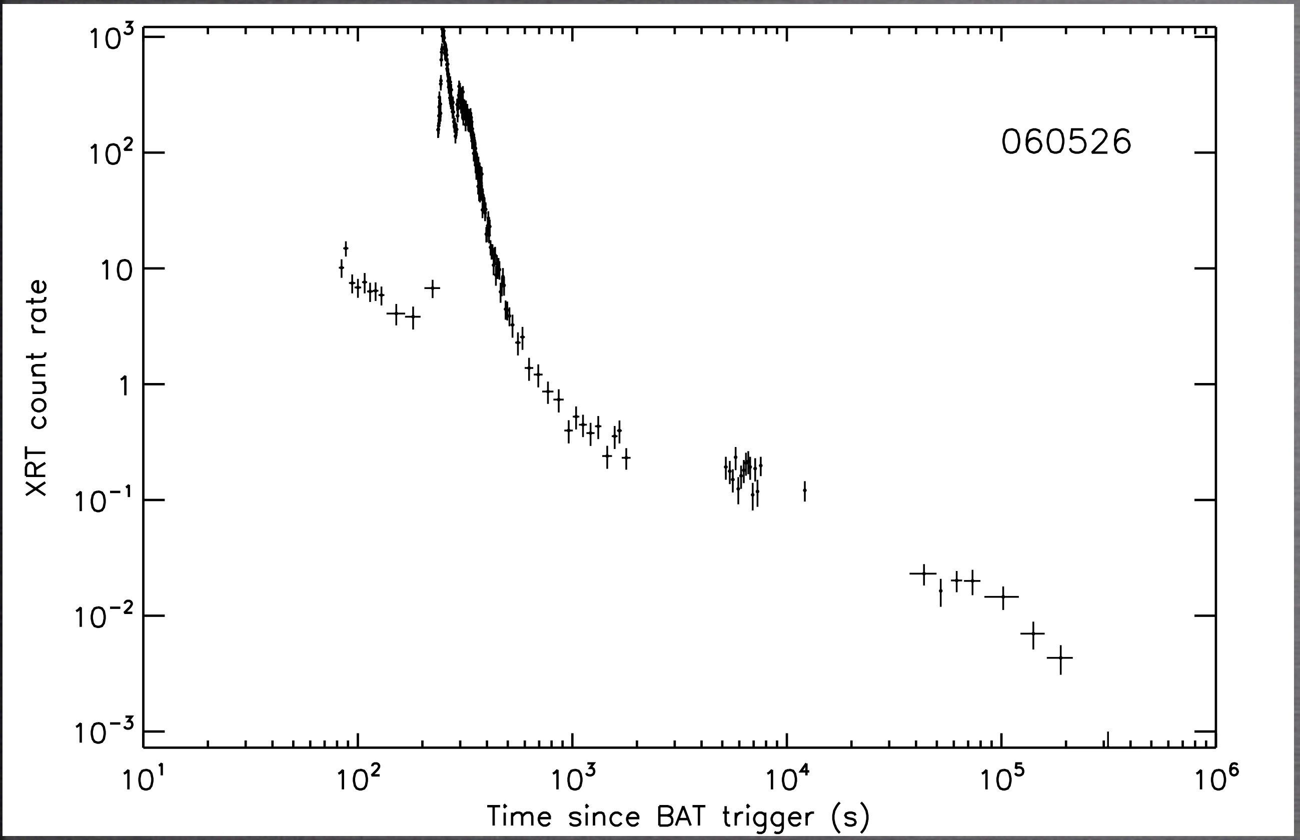
POST-CURSORS: “GIANT” X-RAY FLARES



Among X-ray flares, “Giant” flares:

- $\Delta C/C \approx 50\text{-}1000$
- $E_{\rm flare}$ ~10% $E_{\rm prompt}$ or more
- $E_{\rm pk}$ ~ 5 keV

POST-CURSORS: “GIANT” X-RAY FLARES



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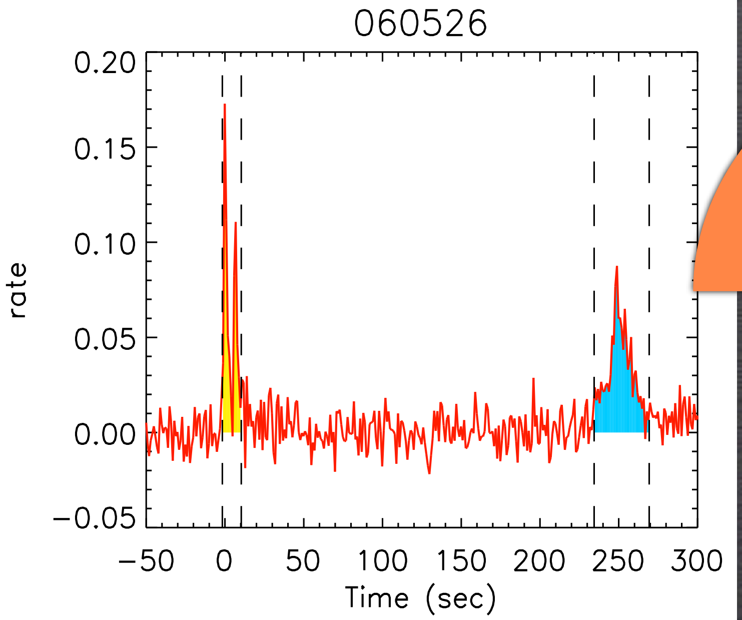
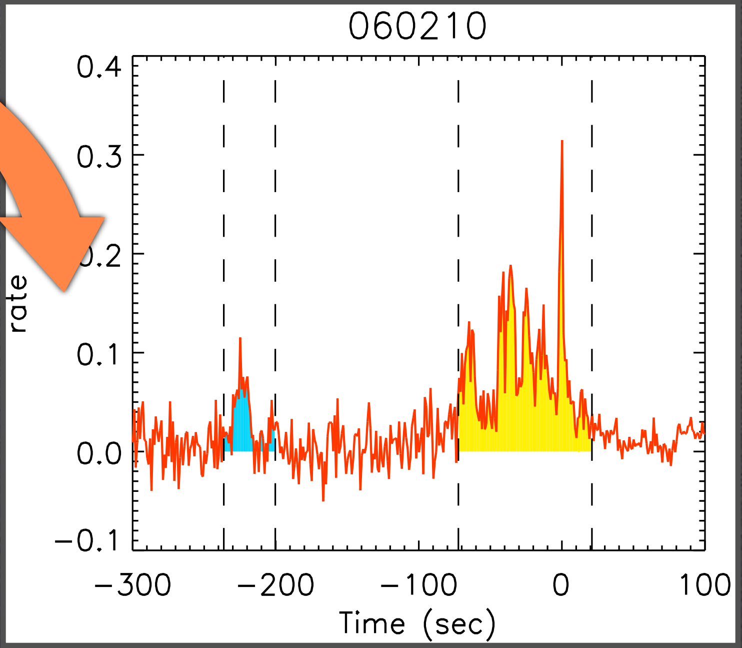
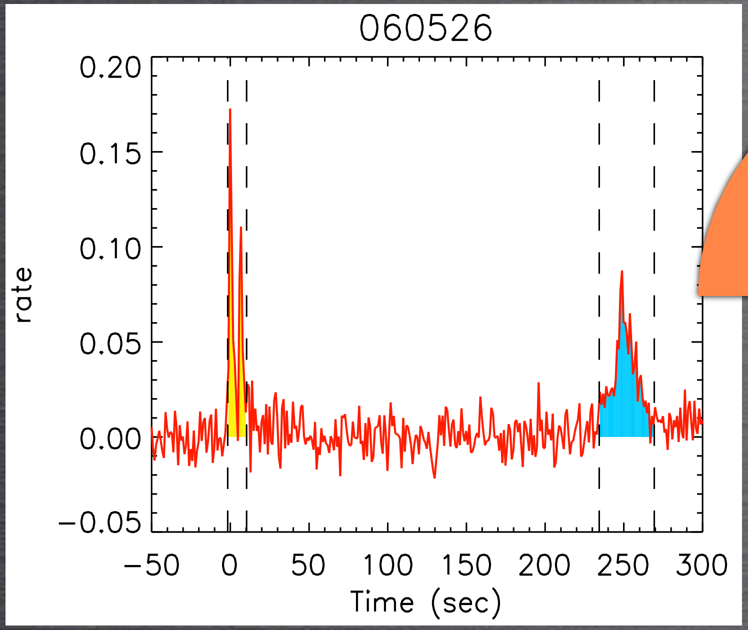
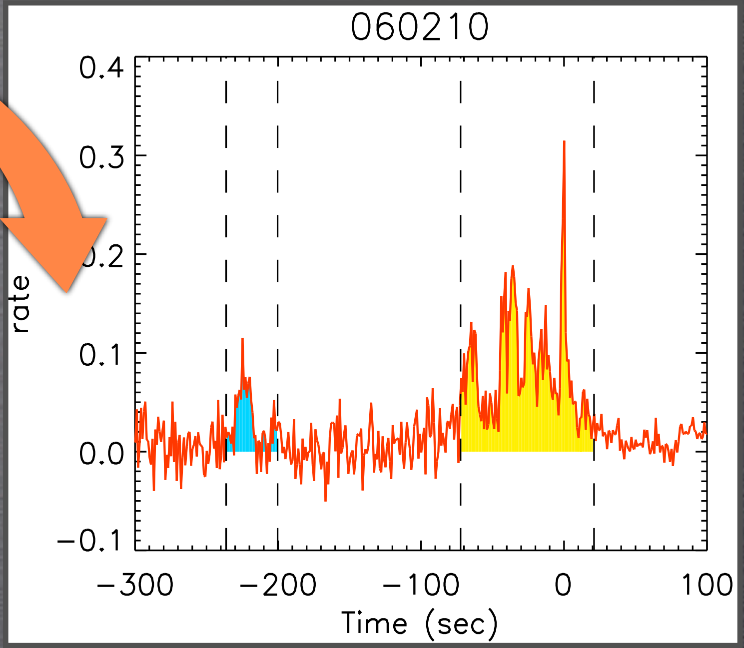
... precursors in the mirror!!!!





PRE- AND POST-CURSORS IN GRBs





How to switch on and off a GRB?

With a **millisecond Magnetar**

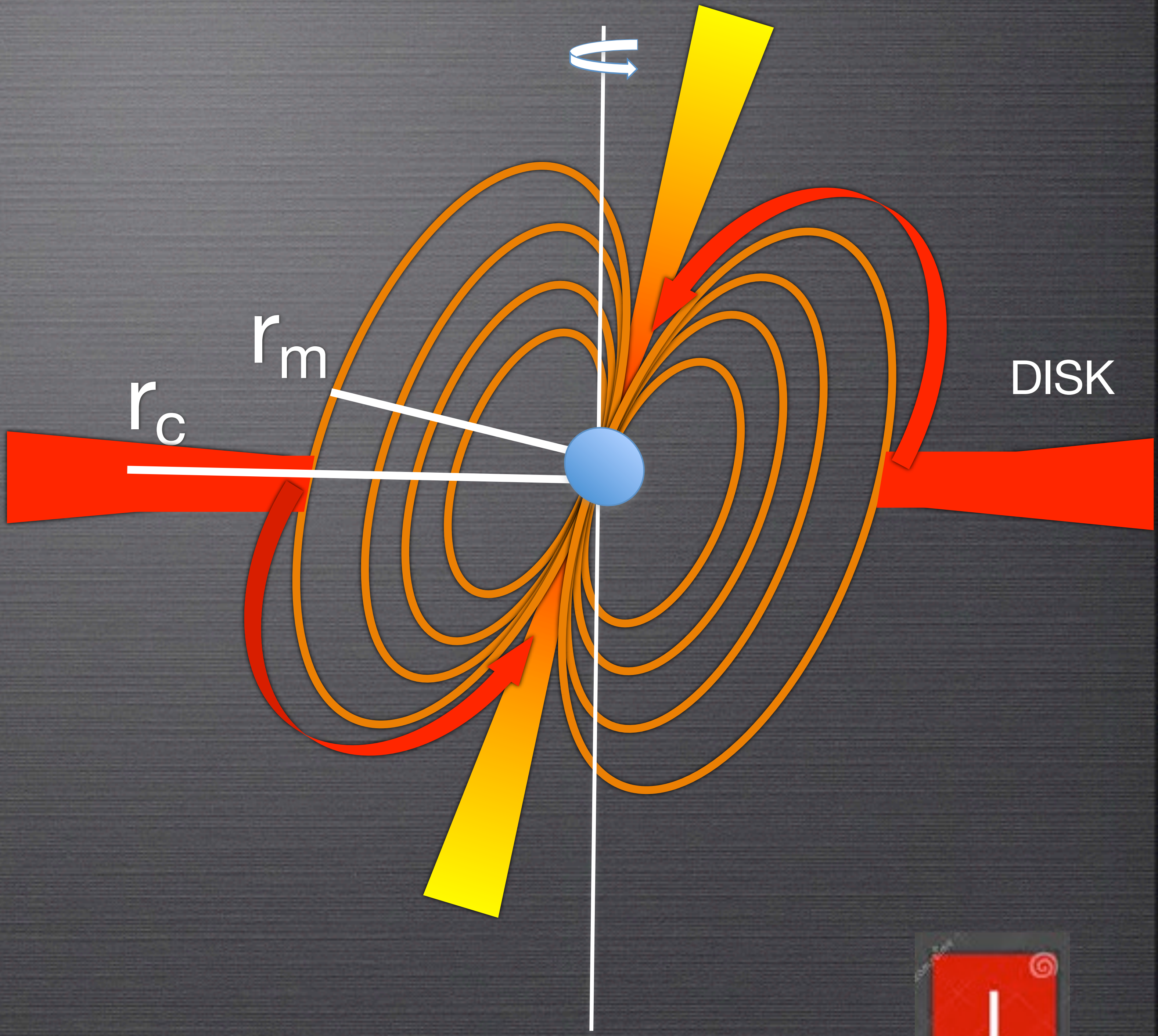
powered by **Accretion**

Usov 1992
Duncan & Thompson 1992
Dai & Lu 1998
Zhang & Meszaros 2001
Metzger et al. 2011

HOW?? ACCRETION-POWERED MAGNETAR

⇒ Accretion phase

$r_m < r_c$

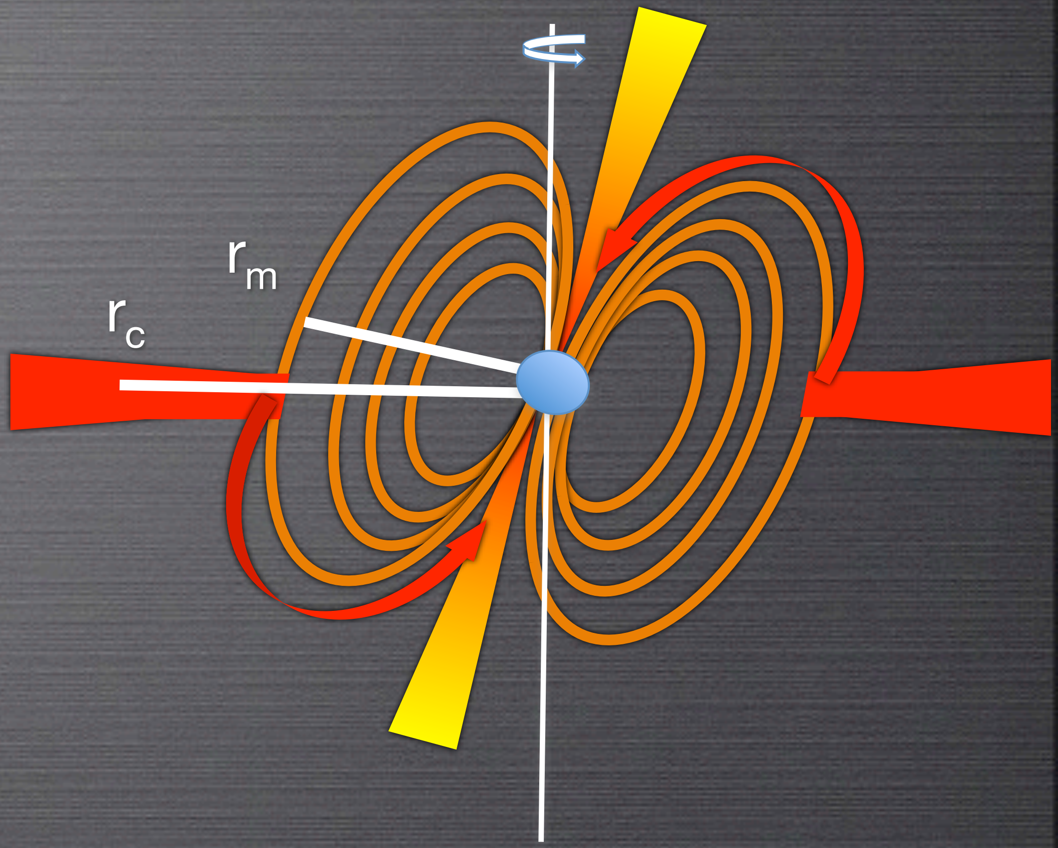


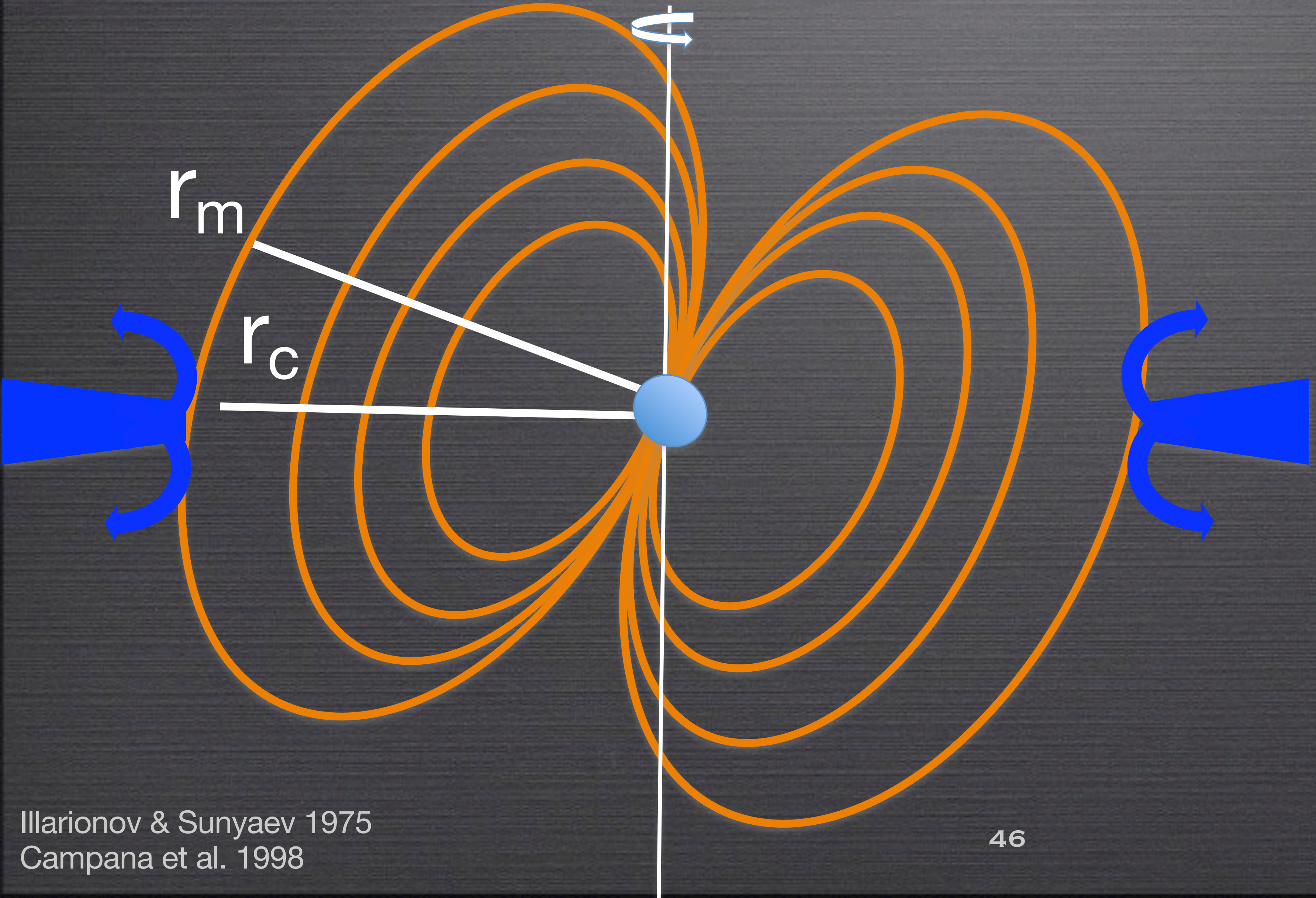
HOW?? ACCRETION-POWERED MAGNETAR

Accretion phase

⇒ Propeller phase

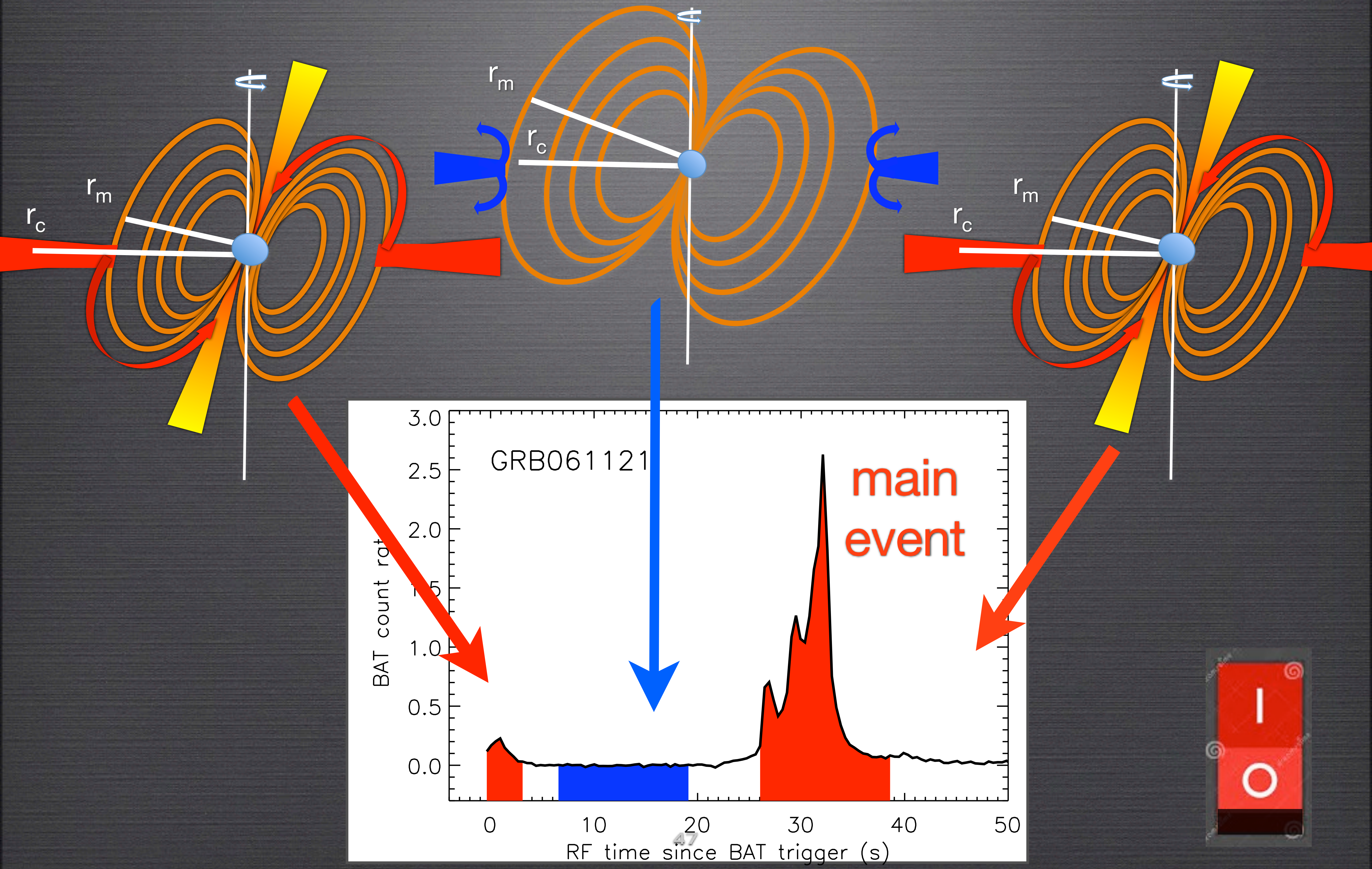
$r_m > r_c$



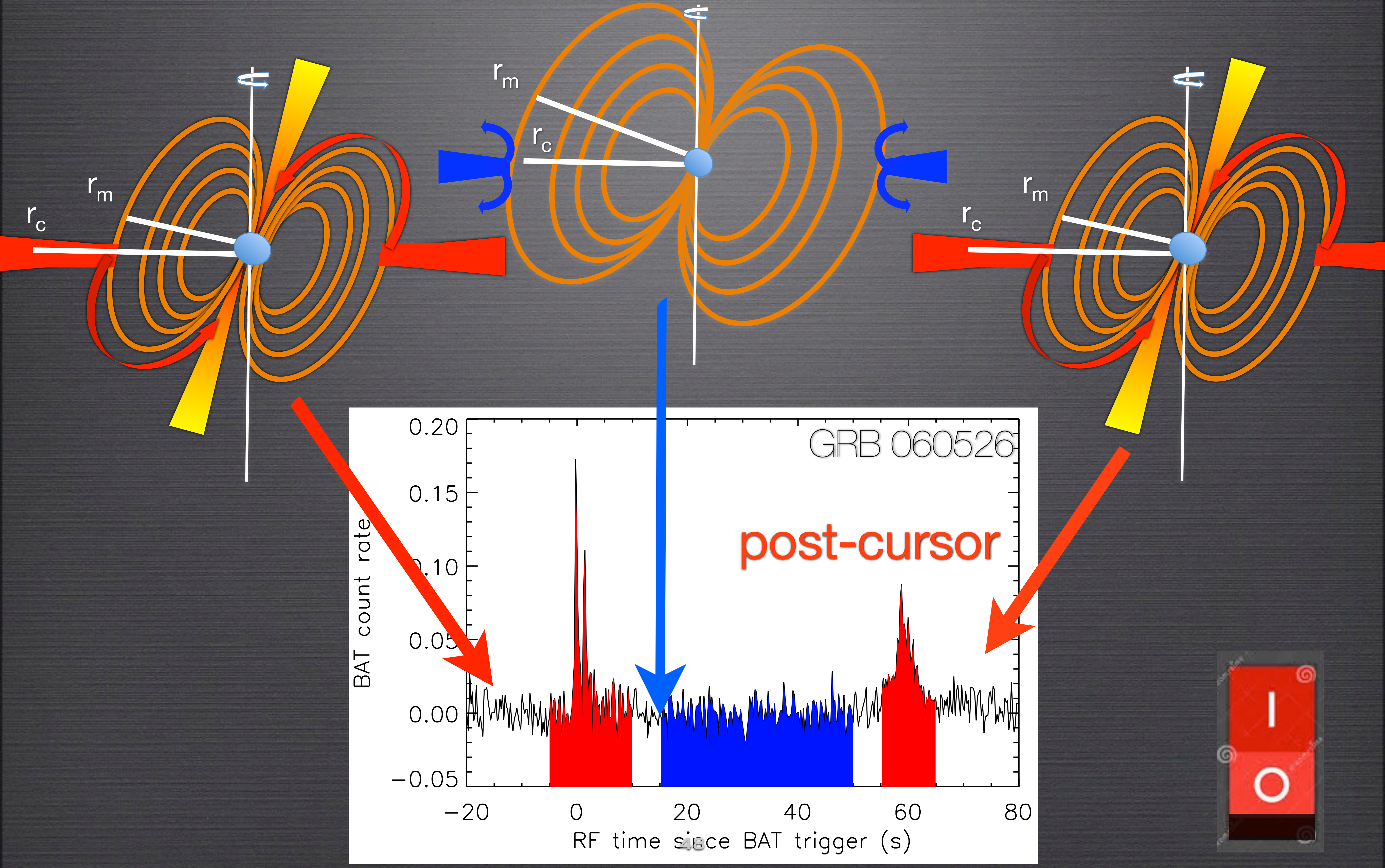


Illarionov & Sunyaev 1975
Campana et al. 1998

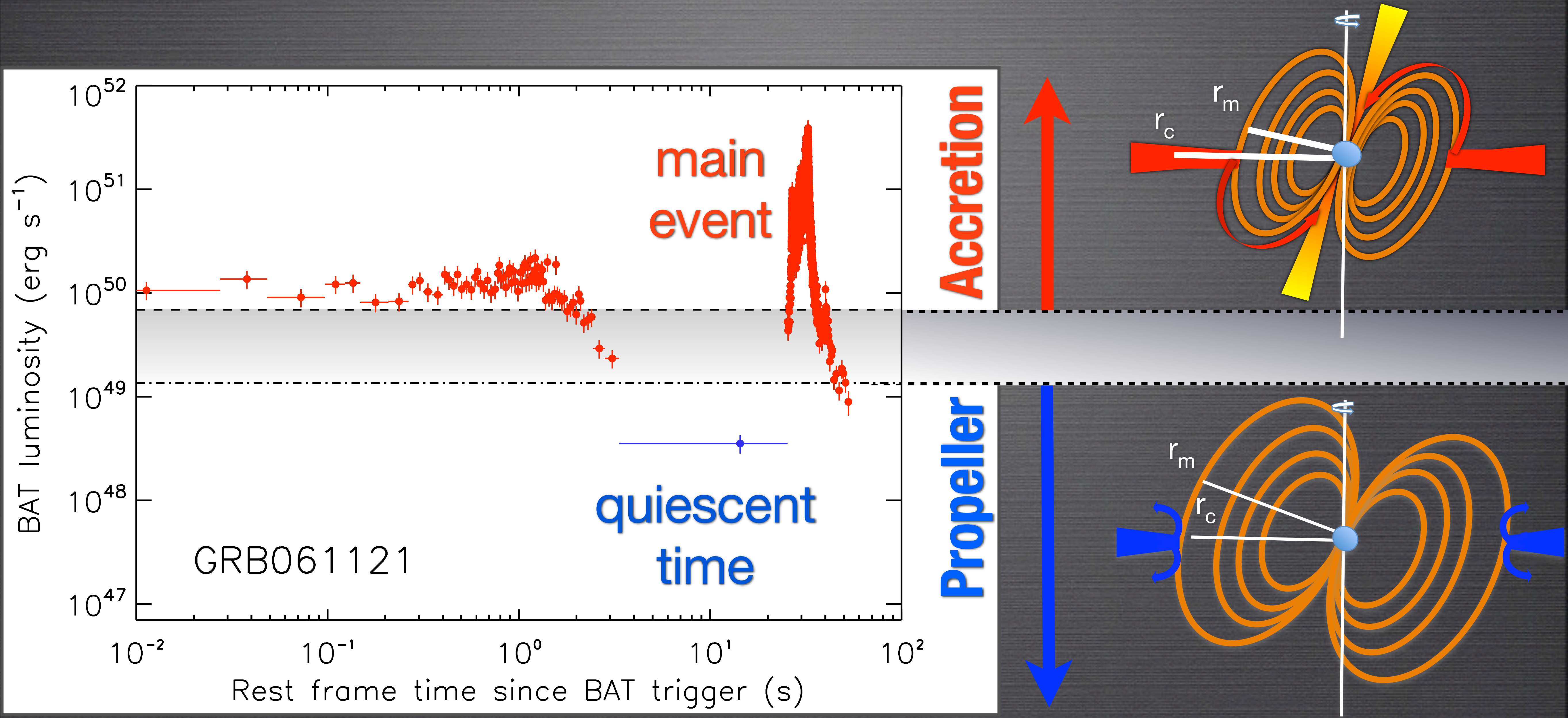
QUIESCENT TIMES?? A PROPELLER PHASE



QUIESCENT TIMES?? A PROPELLER PHASE



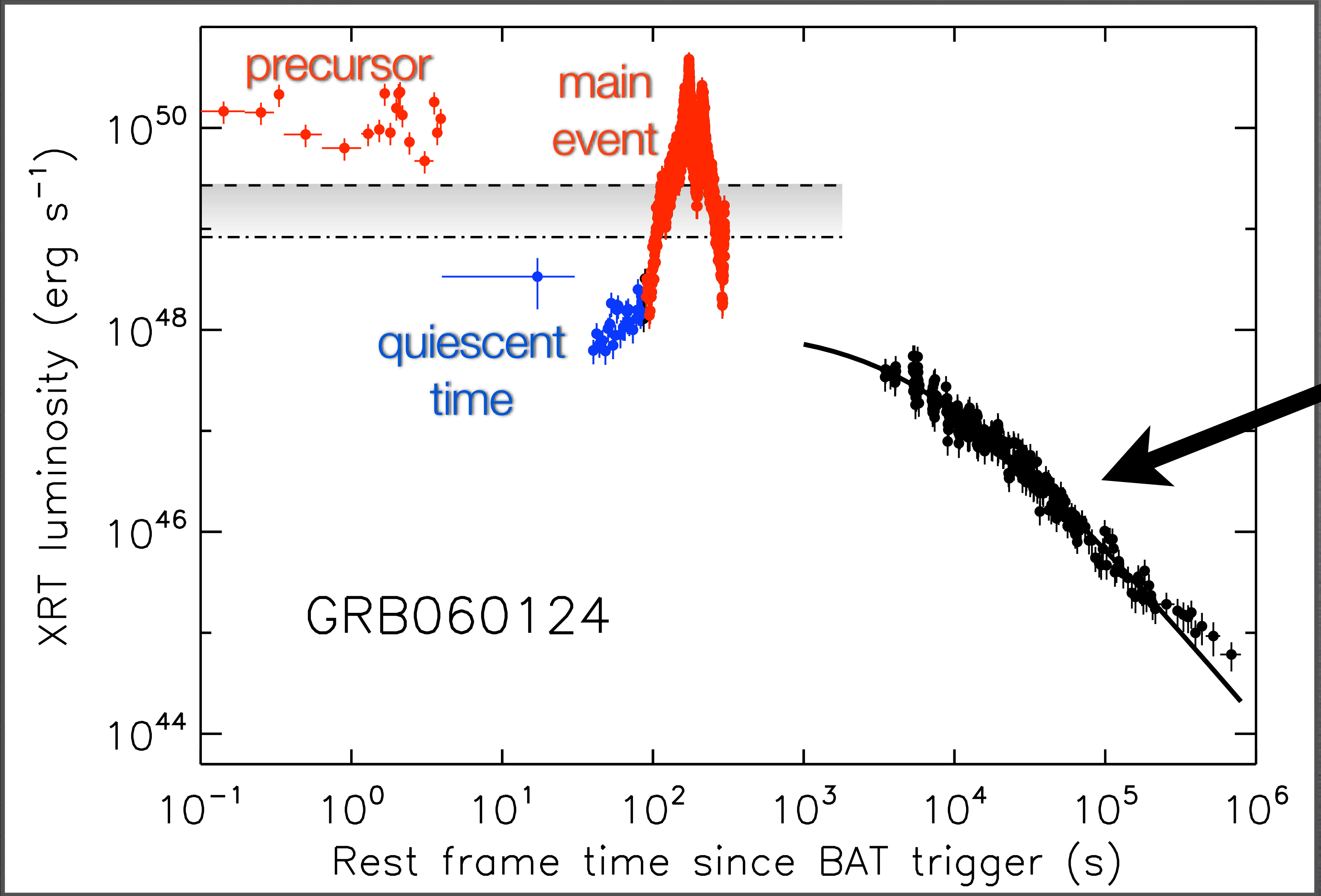
THE PROMPT EMISSION LUMINOSITY



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

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

THE END OF THE PROMPT EMISSION



The magnetar can still influence the GRB emission with its **spin-down power** that is directly related to B and P

Dai & Lu 1998
Zhang & Meszaros 2001
Corsi & Meszaros 2009
Lyons et al. 2010
Dall'Osso et al. 2011
Metzger et al. 2011
Rowlinson et al. 2013, 2014

B AND P FROM THE LATE X-RAY EMISSION

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

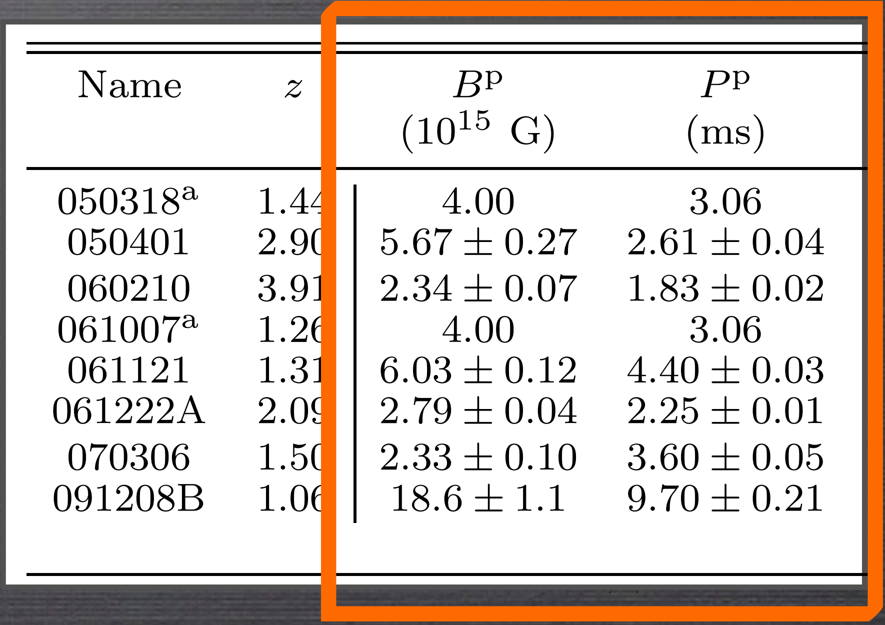
Dall'Osso et al. 2011

⇦

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

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

⇩

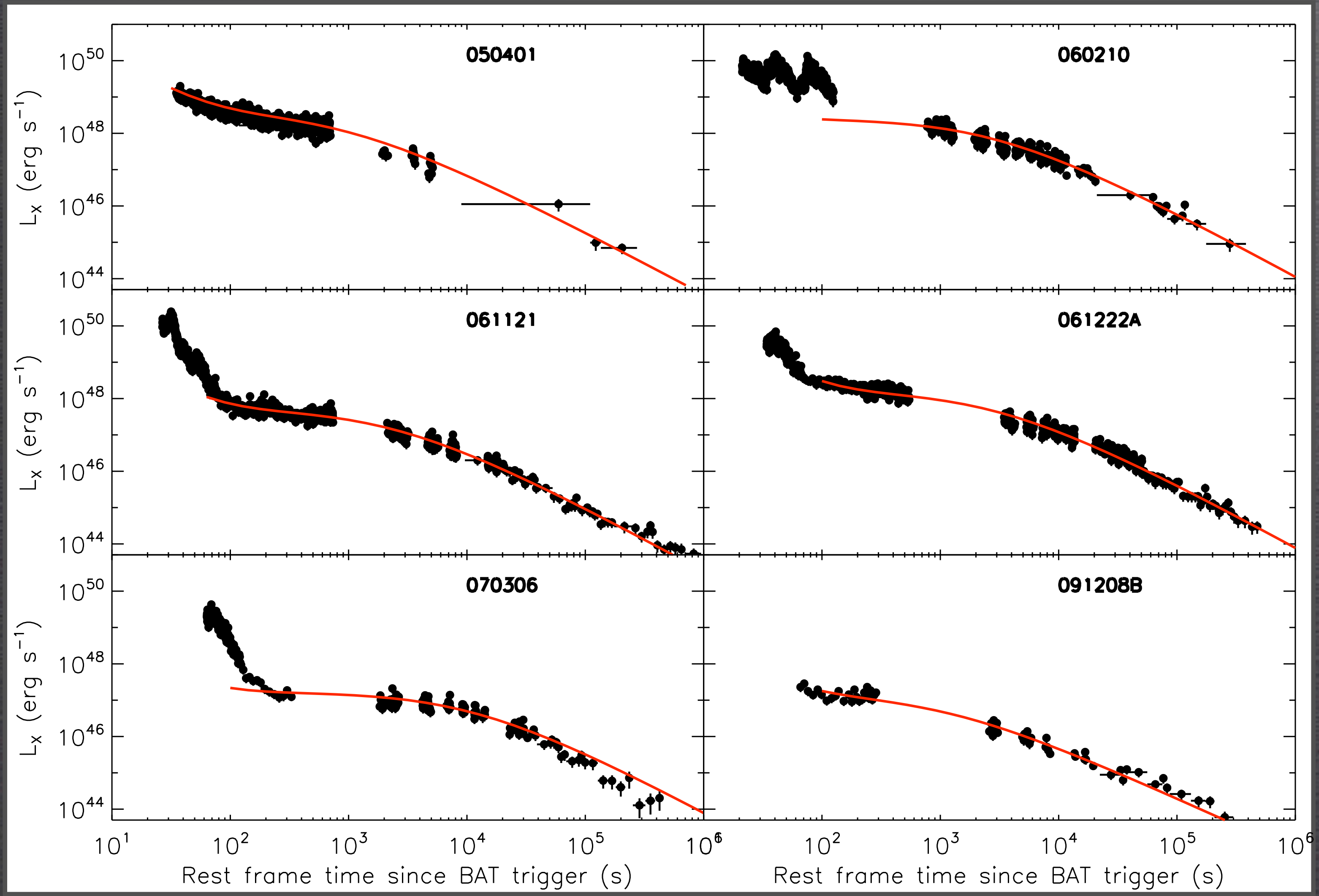


Name	z	B^p (10^{15} G)	P^p (ms)
050318^a	1.44	4.00	3.06
050401	2.90	5.67 ± 0.27	2.61 ± 0.04
060210	3.91	2.34 ± 0.07	1.83 ± 0.02
061007^a	1.26	4.00	3.06
061121	1.31	6.03 ± 0.12	4.40 ± 0.03
061222A	2.09	2.79 ± 0.04	2.25 ± 0.01
070306	1.50	2.33 ± 0.10	3.60 ± 0.05
091208B	1.06	18.6 ± 1.1	9.70 ± 0.21

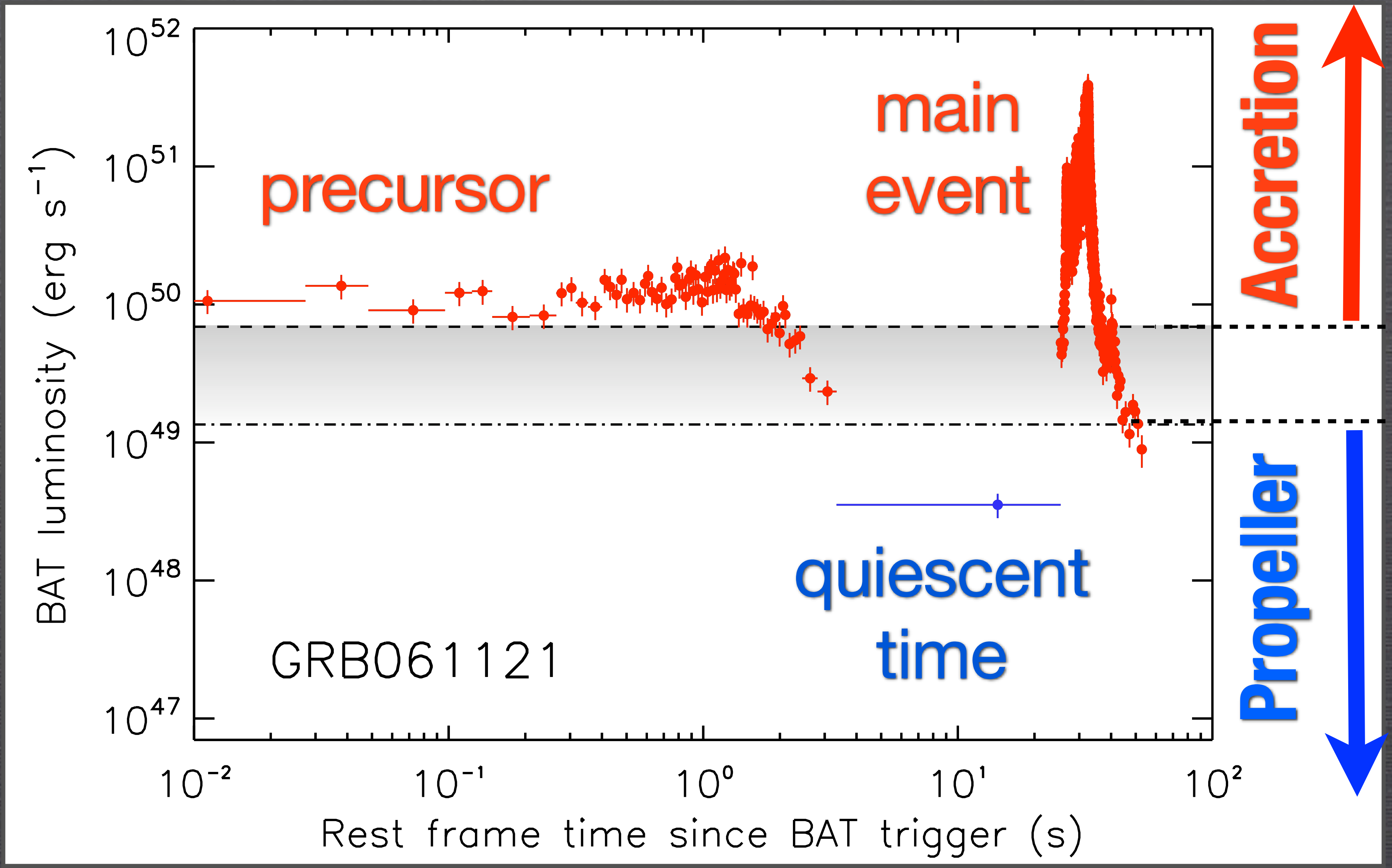
⇩

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

$\langle P \rangle = 3.06$ ms

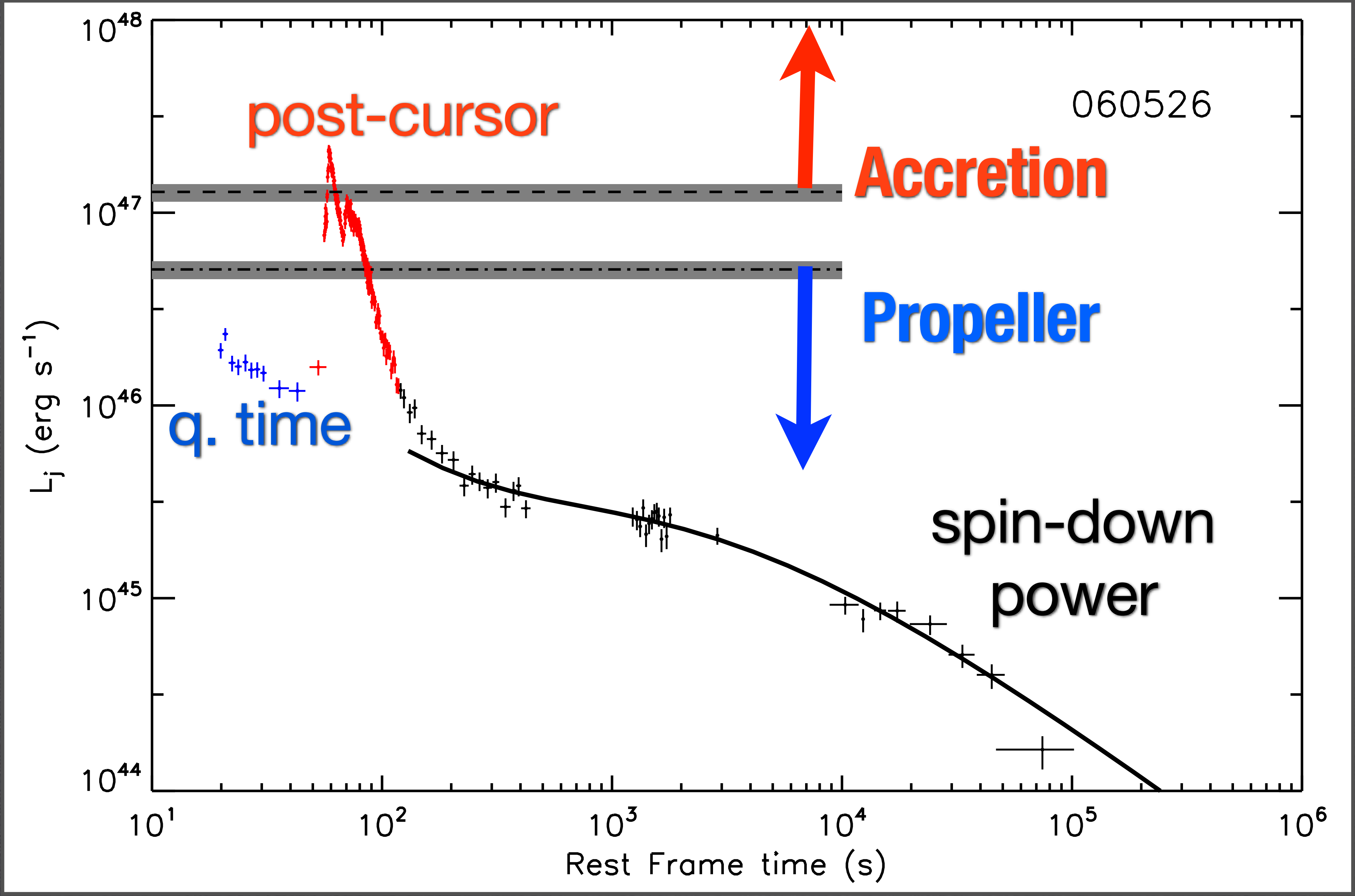


PREDICTIONS ABOUT THE LUMINOSITY FOR THE PROMPT EMISSION...



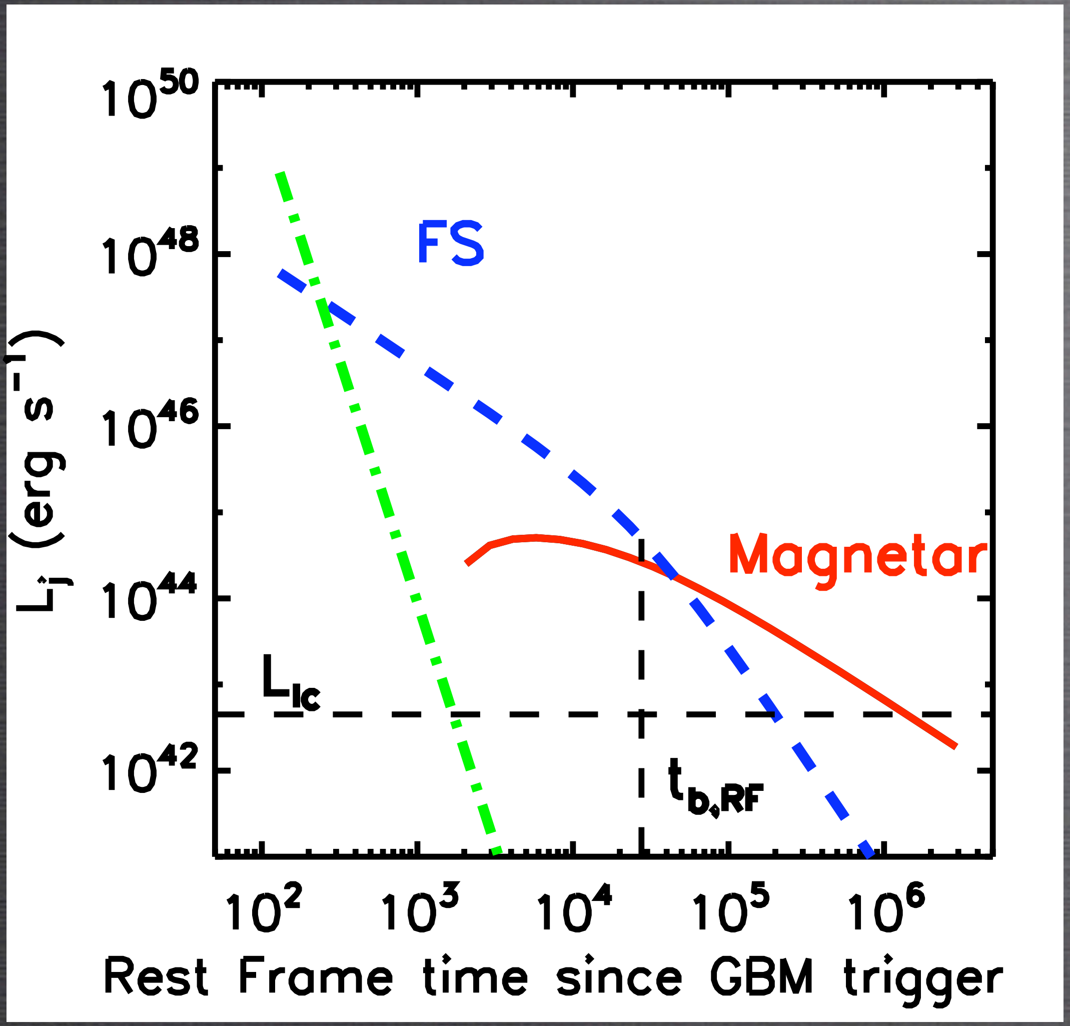
peak luminosities of both precursor and main event are **above L_{min}**

... AND THE POST-CURSORS!!



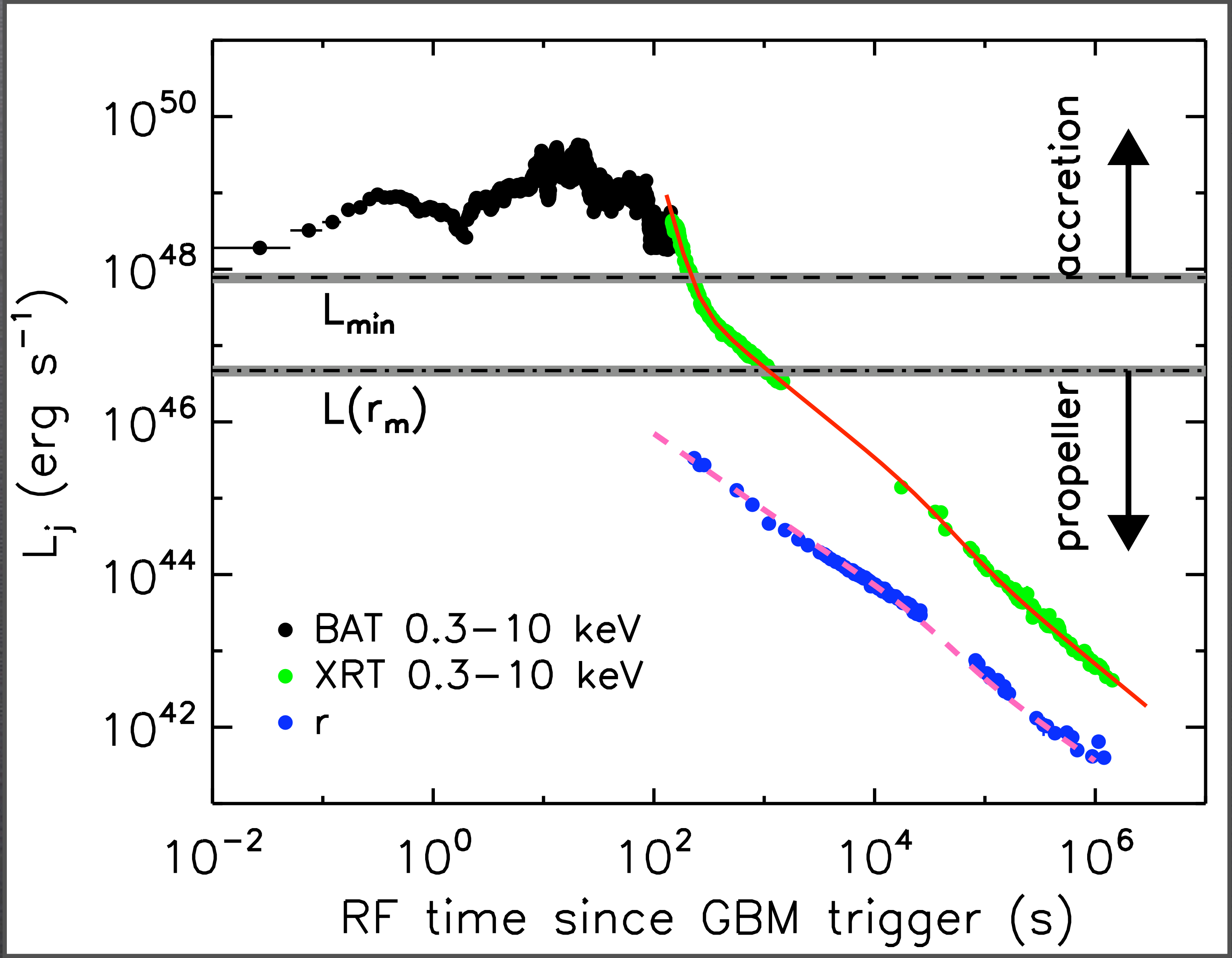
peak luminosity of the post-cursor is **above L_{min}**

GRB 130427A: the "ordinary monster"



Recipe for X-ray emission:

- forward shock emission + jet break
- steep decay (prompt emission)
- **wind of the magnetar**



B= 10^{16} G
P= 24.2 ms

Bernardini et al. 2014

CONCLUSIONS - I

- **Late X-ray emission** (~ 80% LGRBs and ~ 50% SGRBs) powered by the **spin-down of the Magnetar**
- **EE** (~ 15% SGRBs) from **Magnetar, either spin-down or propeller**
- **Precursor** properties (~15% of LGRBs) explained if central engine is an **accretion-powered Magnetar:**
  - ➡ emission <-> accretion power
  - ➡ quiescence <-> propeller phase
- **Post-cursor** emission (aka giant flares) produced by the same mechanism (**but softer spectrum!!**)
- **Potentially larger fraction of GRBs originates from Magnetars**

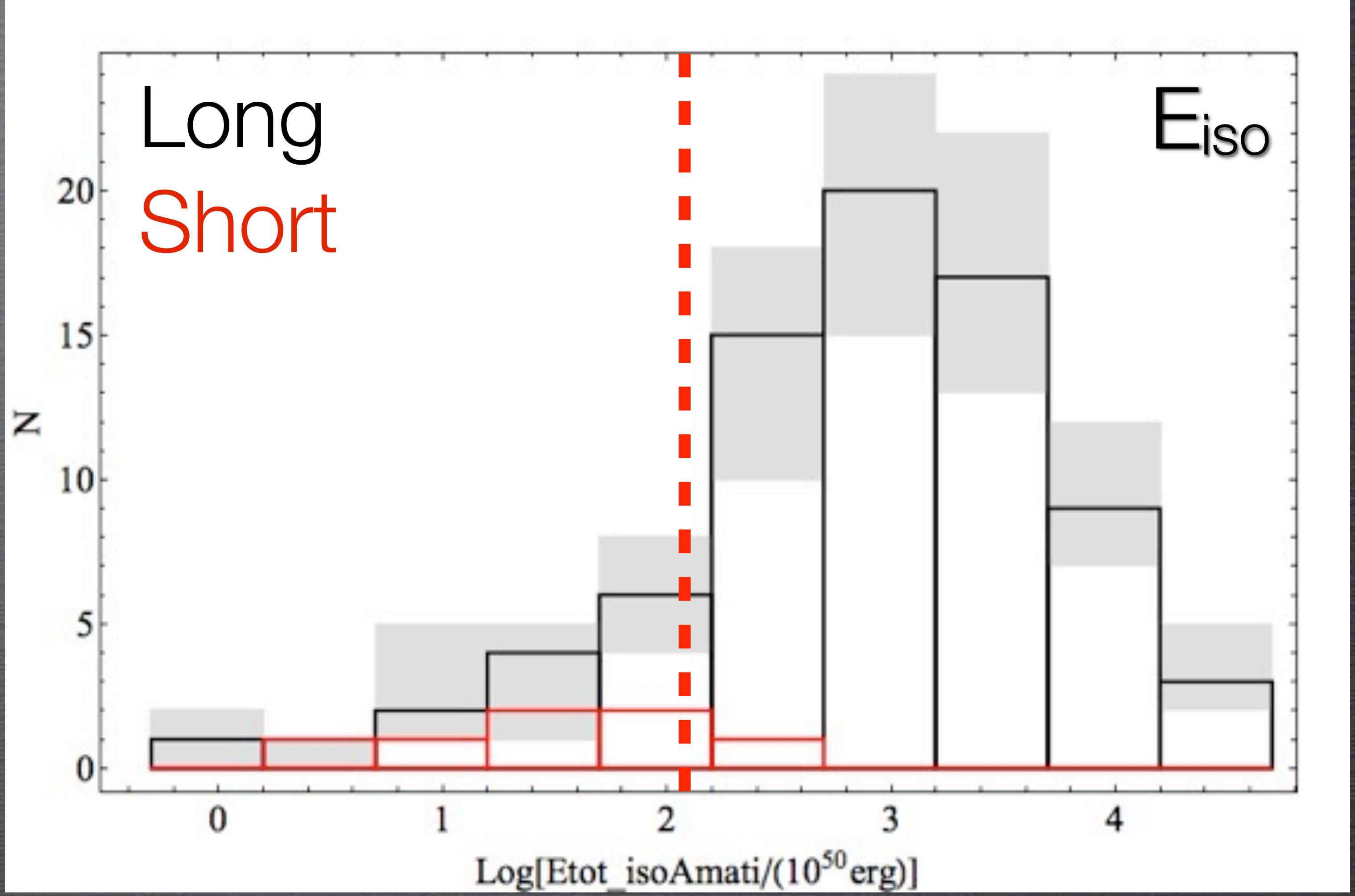
Can magnetars power all GRBs?

- E_{iso} proxy of E_{kin}

➡ SGRBs ok

➡ LGRBs often above limit

Total isotropic bolometric energy



Margutti et al., 2013
Mazzali et al., 2014

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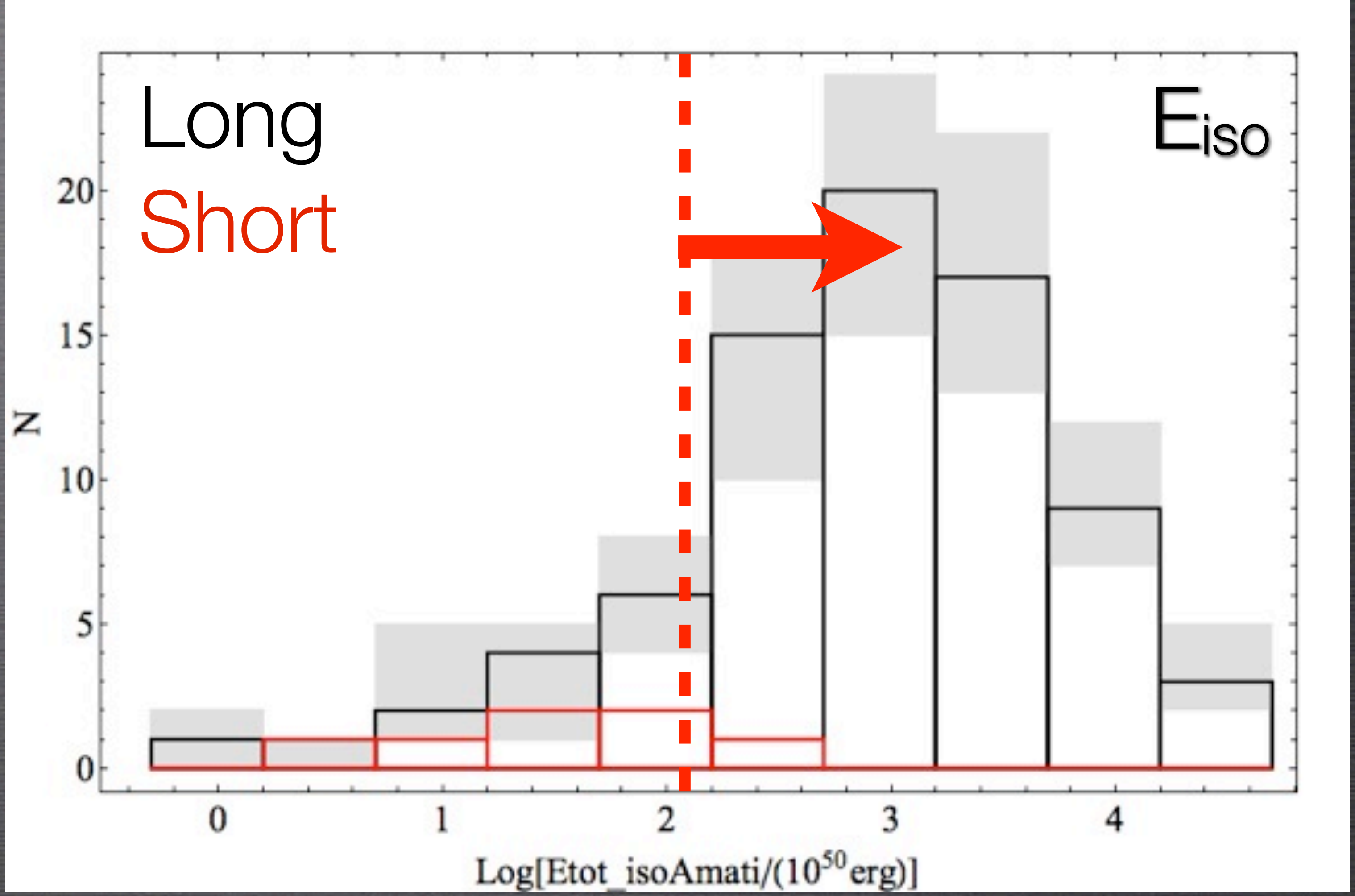

Margutti et al., 2013
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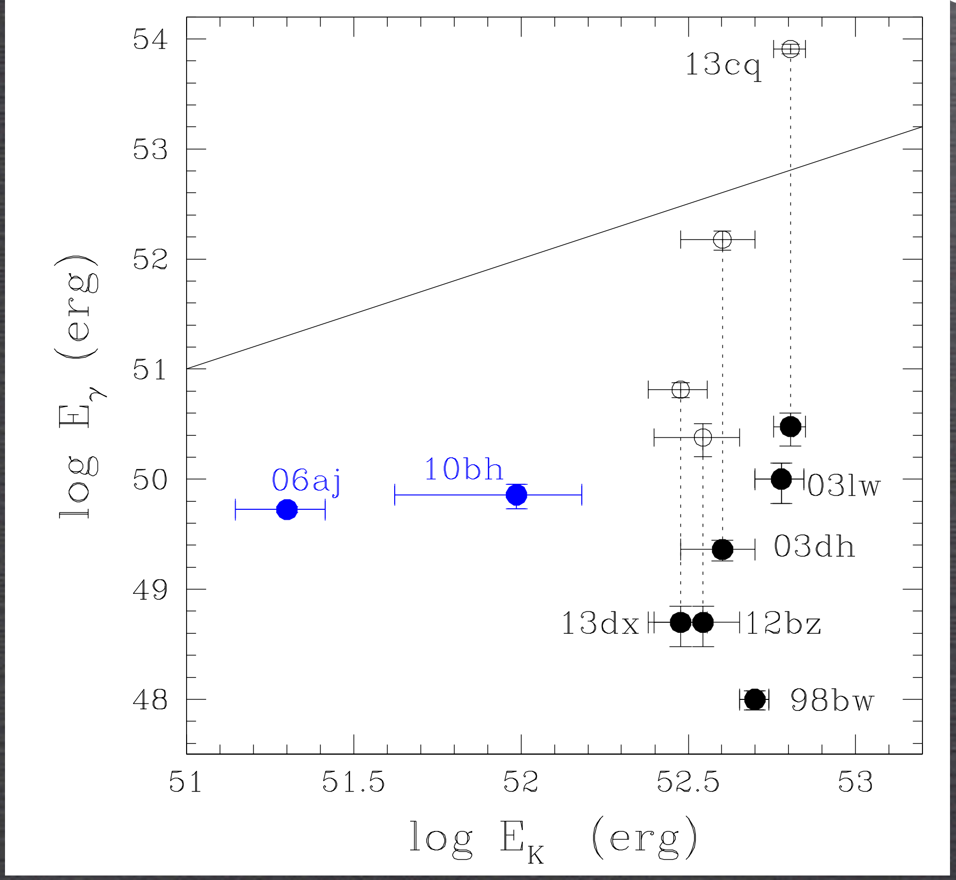

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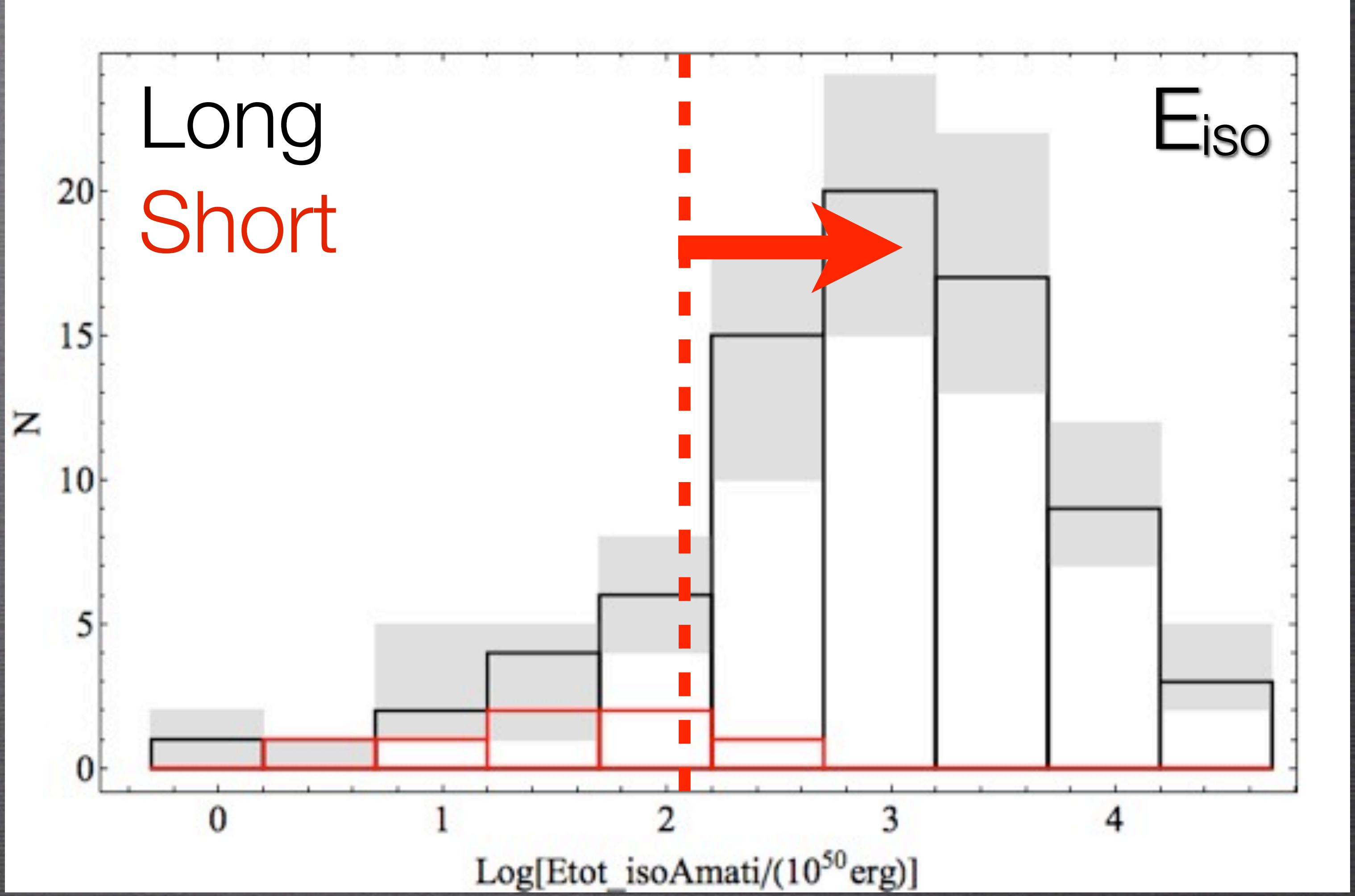

- sufficient to energise the accompanying SN

Margutti et al., 2013
Mazzali et al., 2014

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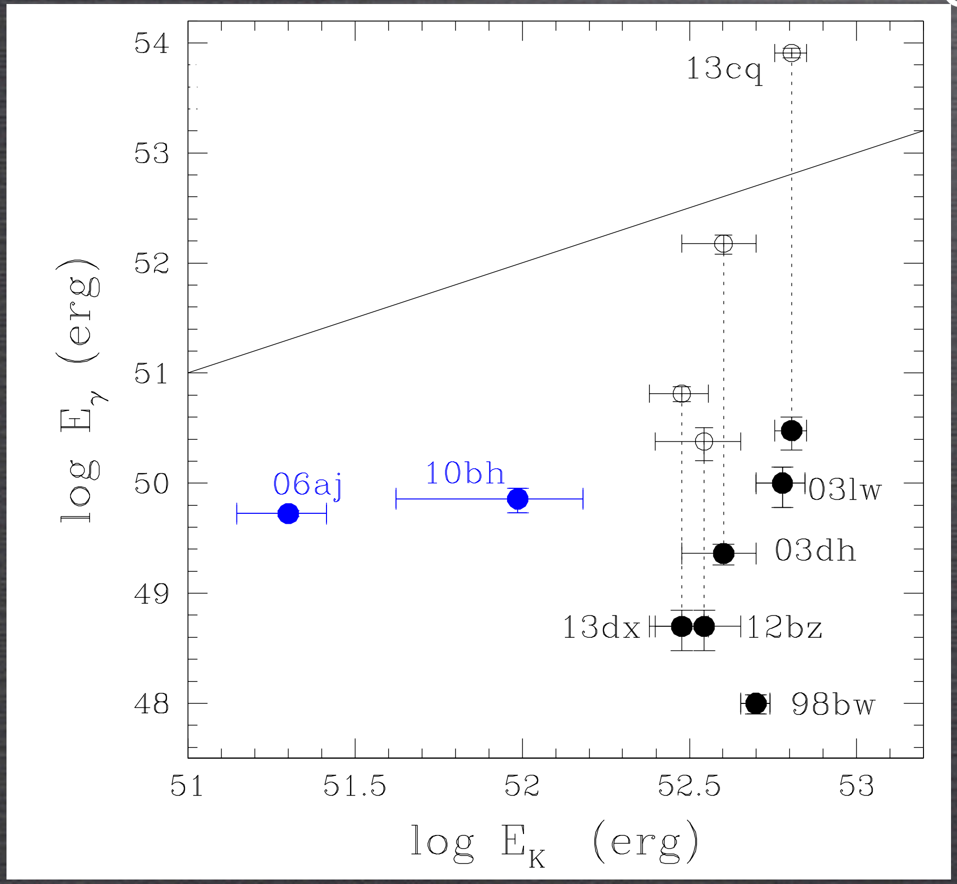

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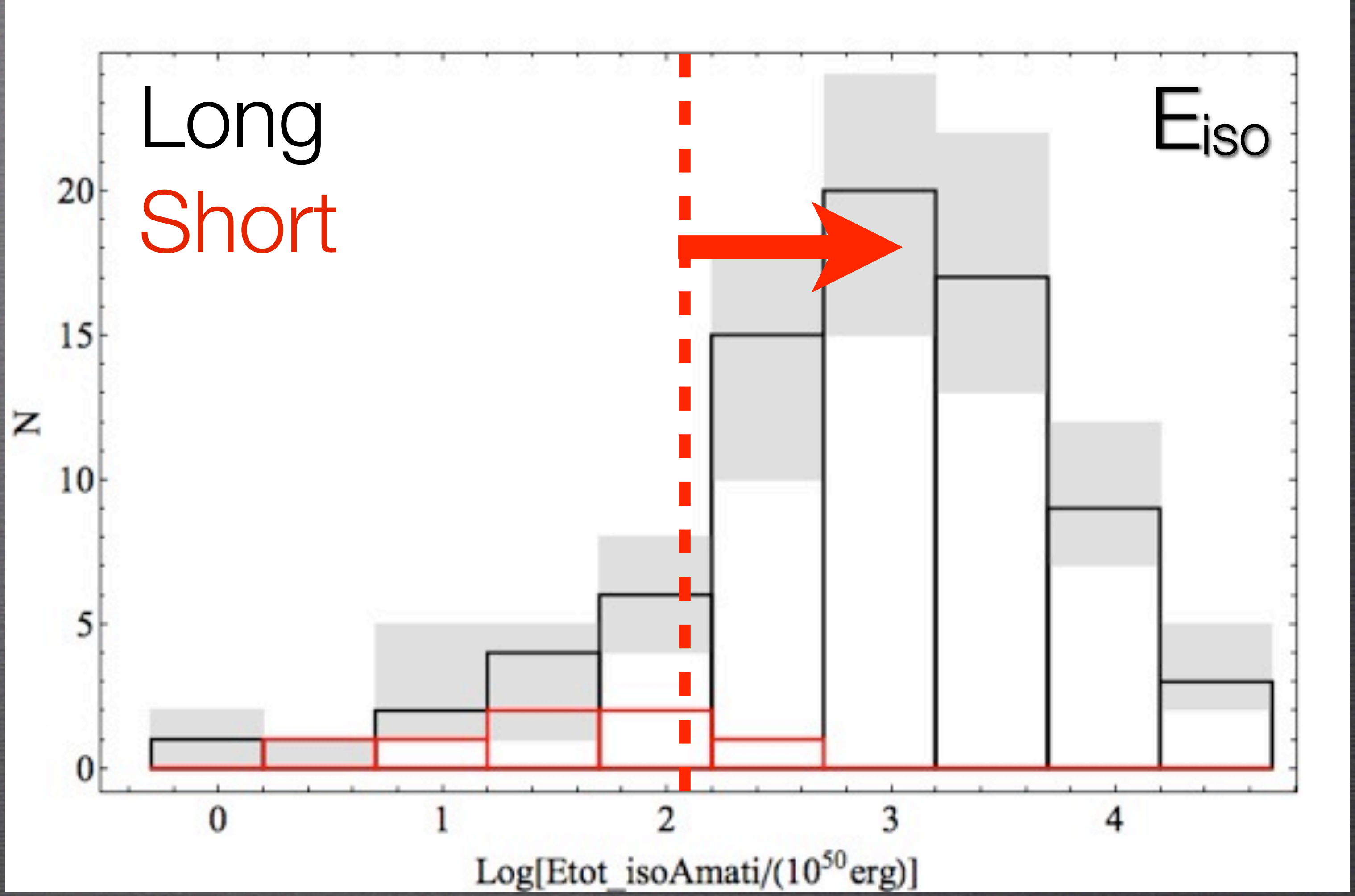
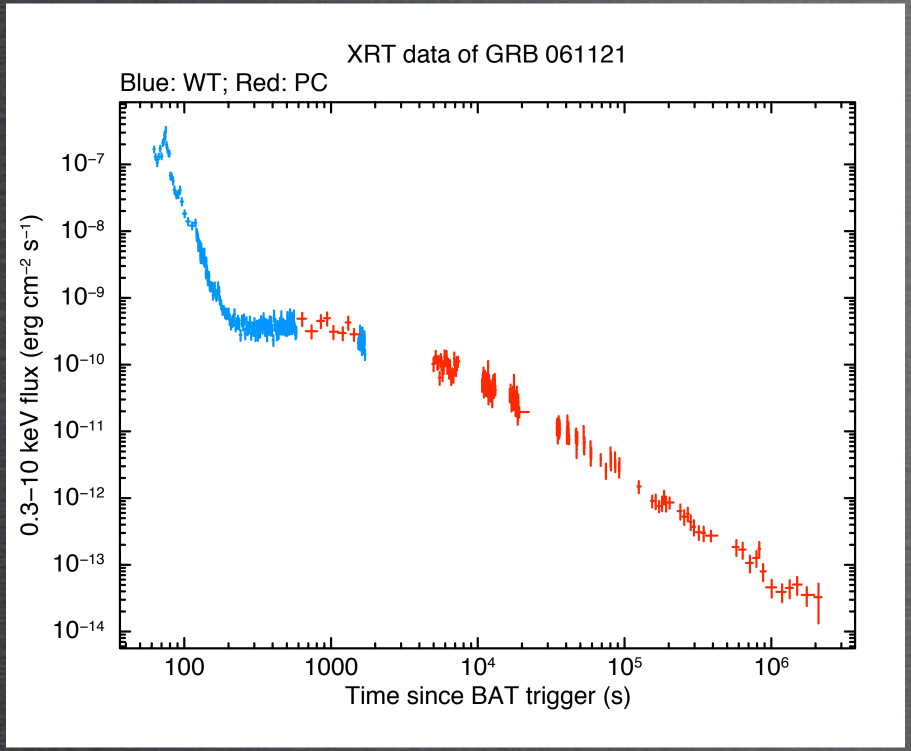


- ✦ sufficient to energise the accompanying SN
- ✦ several LGRBs intrinsically > 10^{54} erg

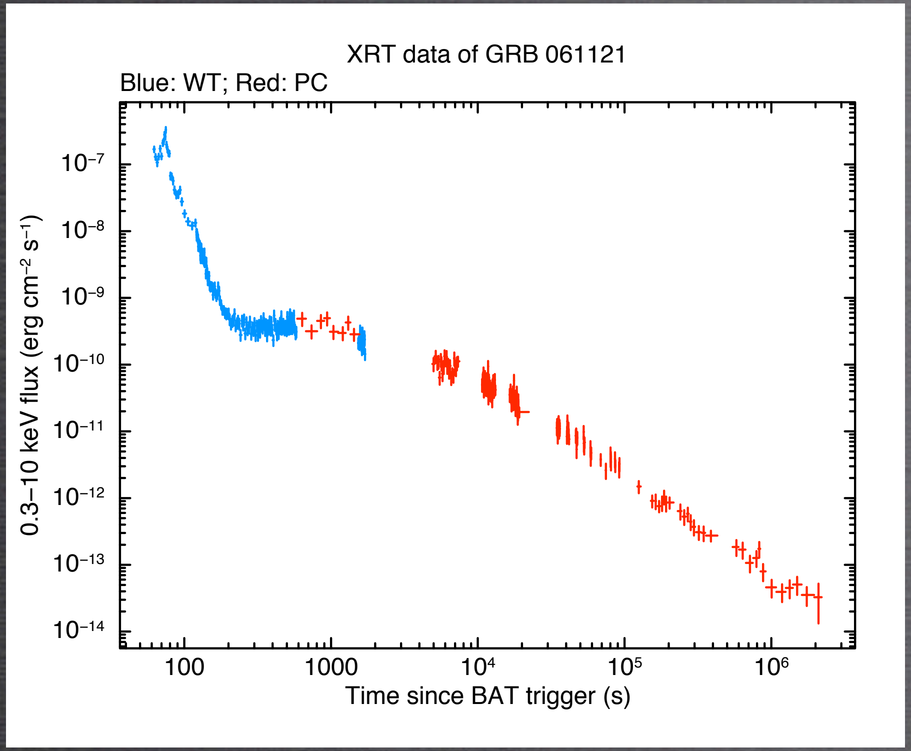
Margutti et al., 2013
Mazzali et al., 2014

Possible solution: magnetars + BHs



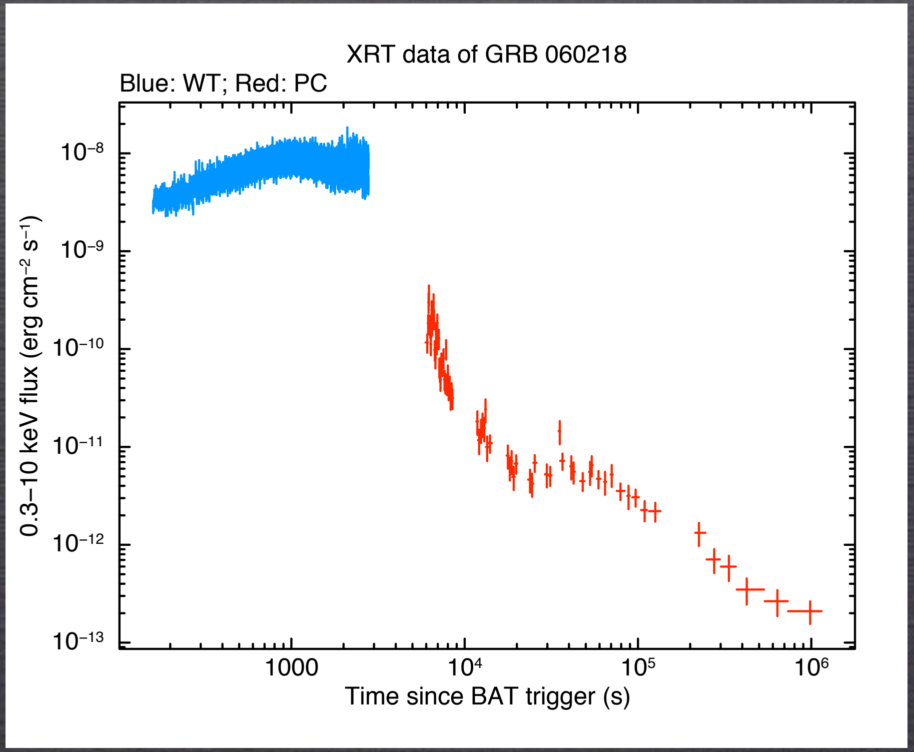
Shallow decaying afterglow: magnetar powering the GRB

Possible solution: magnetars + BHs



Prompt powered by accretion or spindown if fallback not enough to start accretion

Shallow decaying afterglow: magnetar powering the GRB



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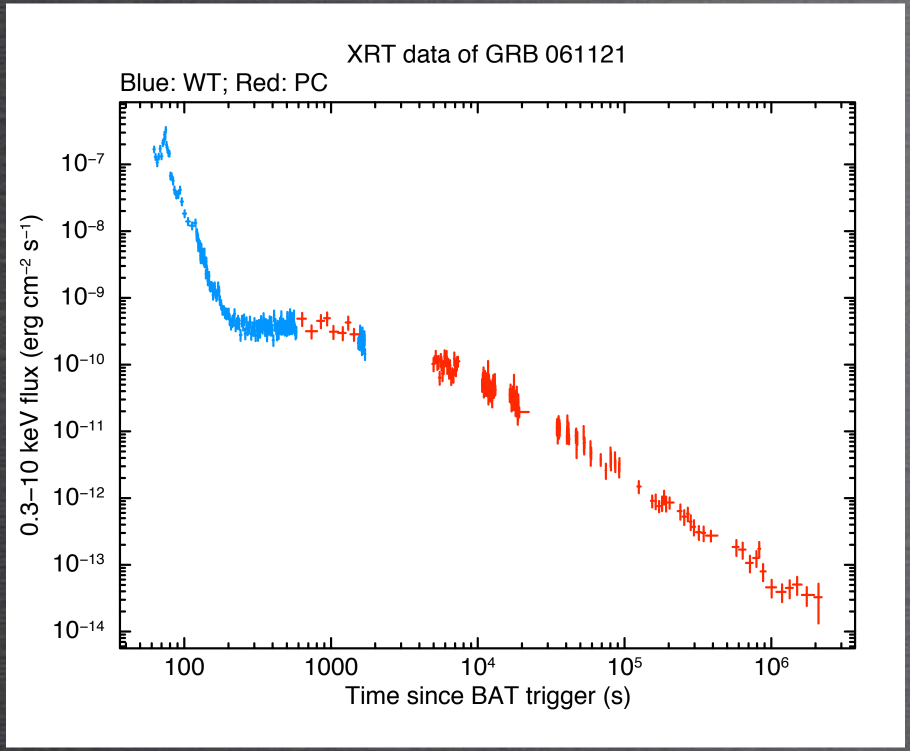

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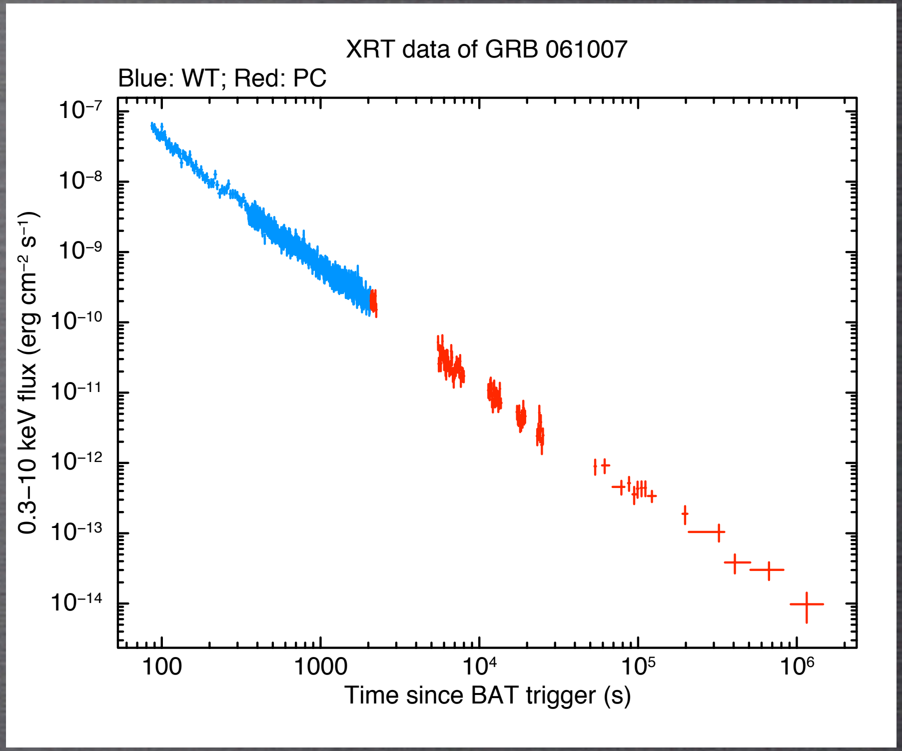

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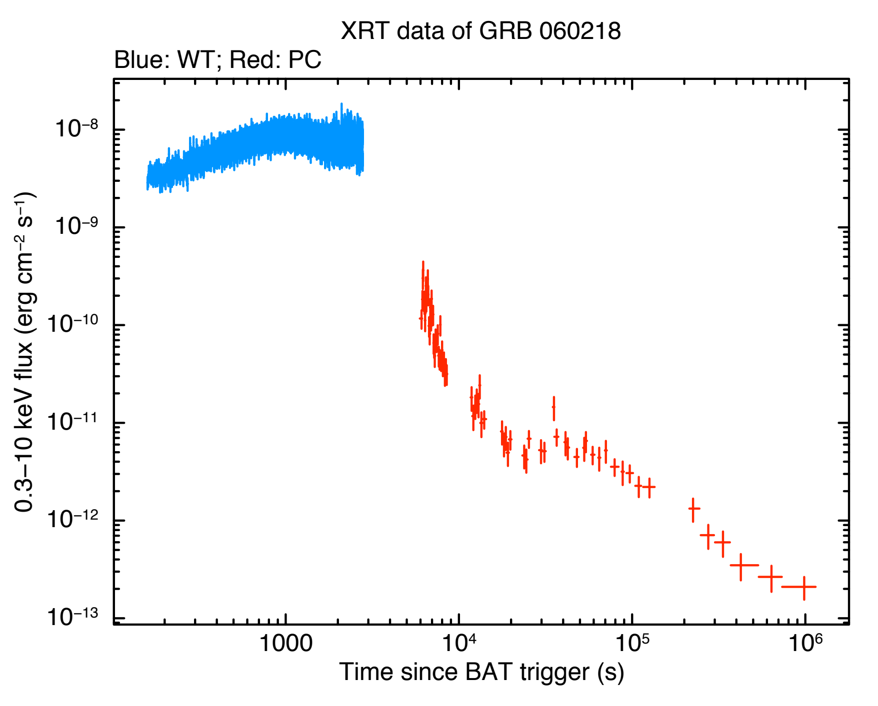


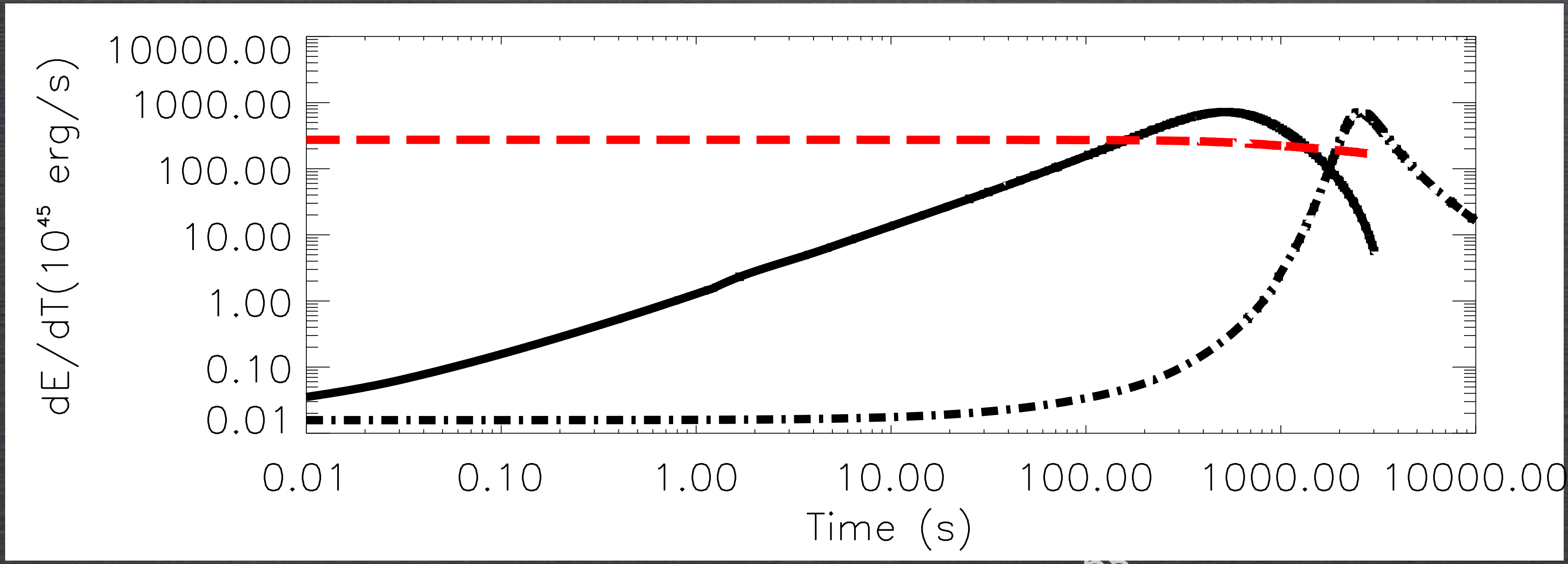
Power-law afterglow: magnetar collapses to black hole during the prompt emission

CONCLUSIONS - II

- Observations point towards magnetars as plausible candidates as GRB central engines
- Are all GRBs powered by magnetars? likely No! but still the majority are consistent with being powered by magnetars
- A lot of effort (observational, theoretical) still need to be done
- Maybe GW will tell... at least for SGRBs!

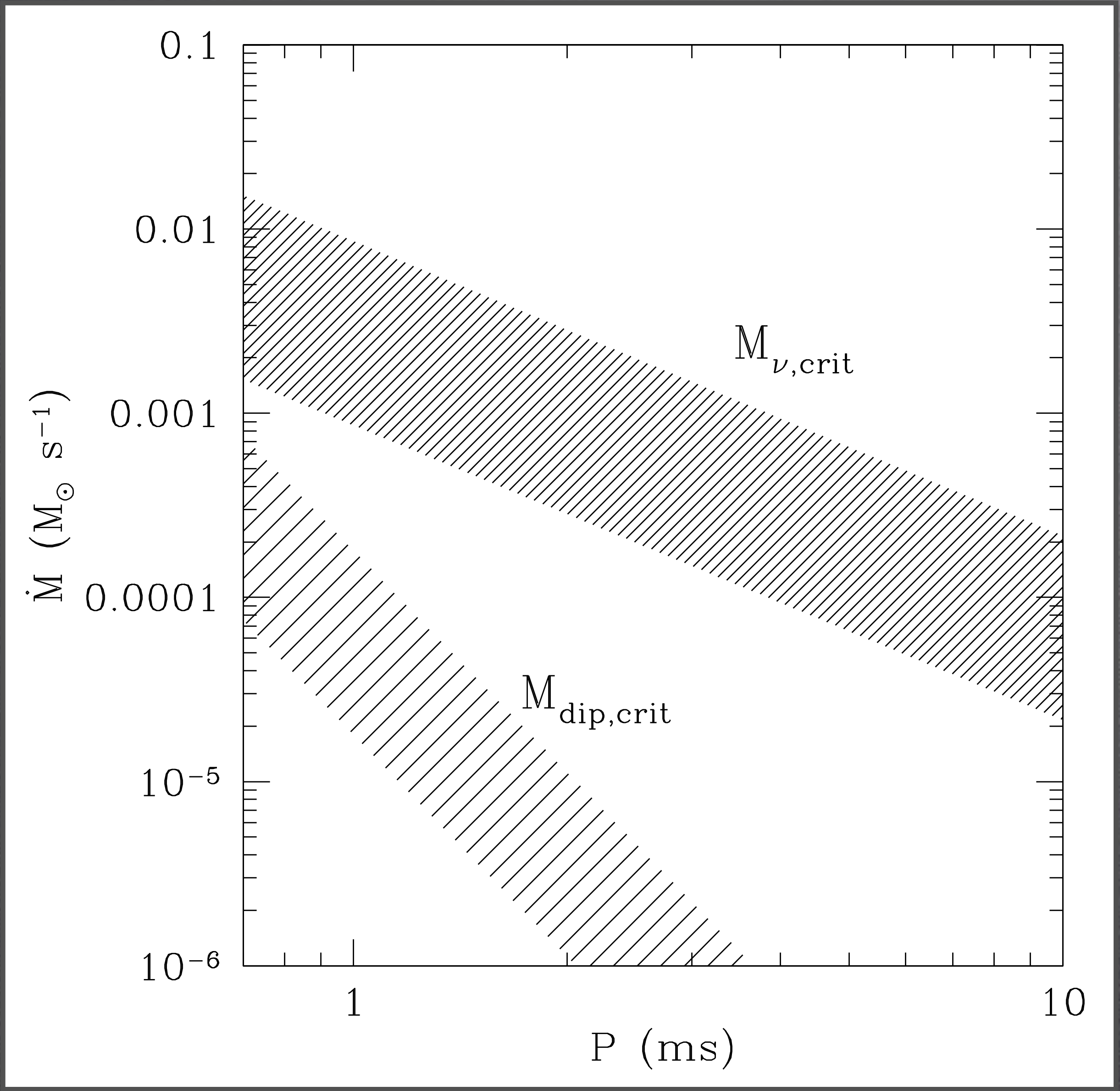
GW emission from proto-magnetars

- Magnetars source of GW if they spin fast enough to excite dynamical ($\beta=0.27$) or secular instabilities ($\beta>0.14$)
- onset of dynamical instabilities at magnetar birth, more likely thanks to spin-up induced by accretion
- signal from secular instabilities detectable over long timescales (~ hours)
- signal from the accompanying SN ($10^{-11}<E_{GW}<10^{-8}\ M_{sun}c^2$)



Corsi & Meszaros, 2009
Piro & Ott, 2011
Ott et al., 2013

Critical accretion rate for fallback



Piro & Ott 2011

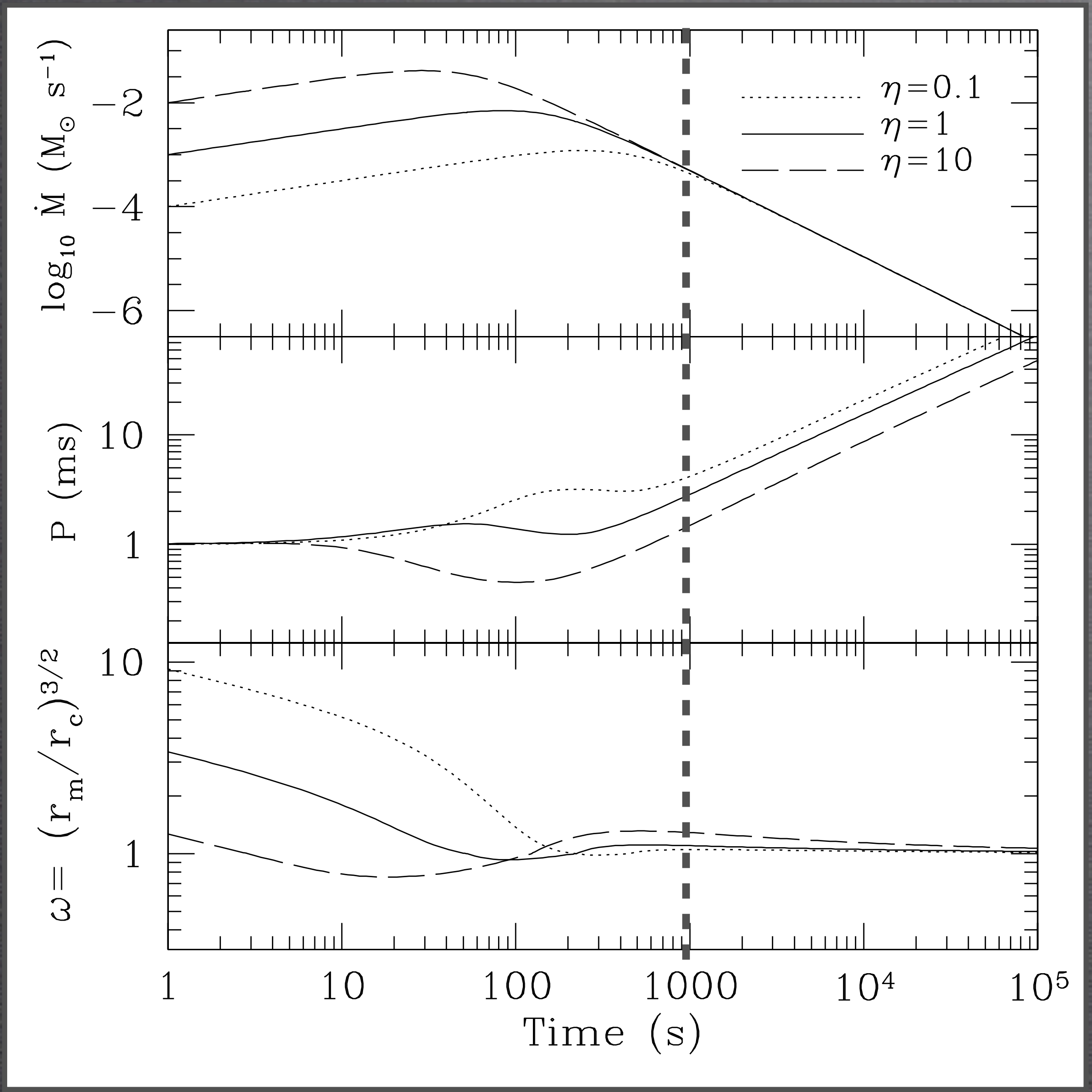
$$p_{\mathrm{ram}} = \frac{\dot{M}}{8\pi}\left(\frac{2GM}{r^5}\right)^{1/2}$$

↕

$$L_{\mathrm{dip}} = \frac{\mu^2\Omega^4}{6c^3}$$

$$L_\nu = \left(\frac{\mu^2\Omega^4}{\dot{M}_\nu}\right)^{2/5} \dot{M}_\nu$$

Spin evolution of the magnetar

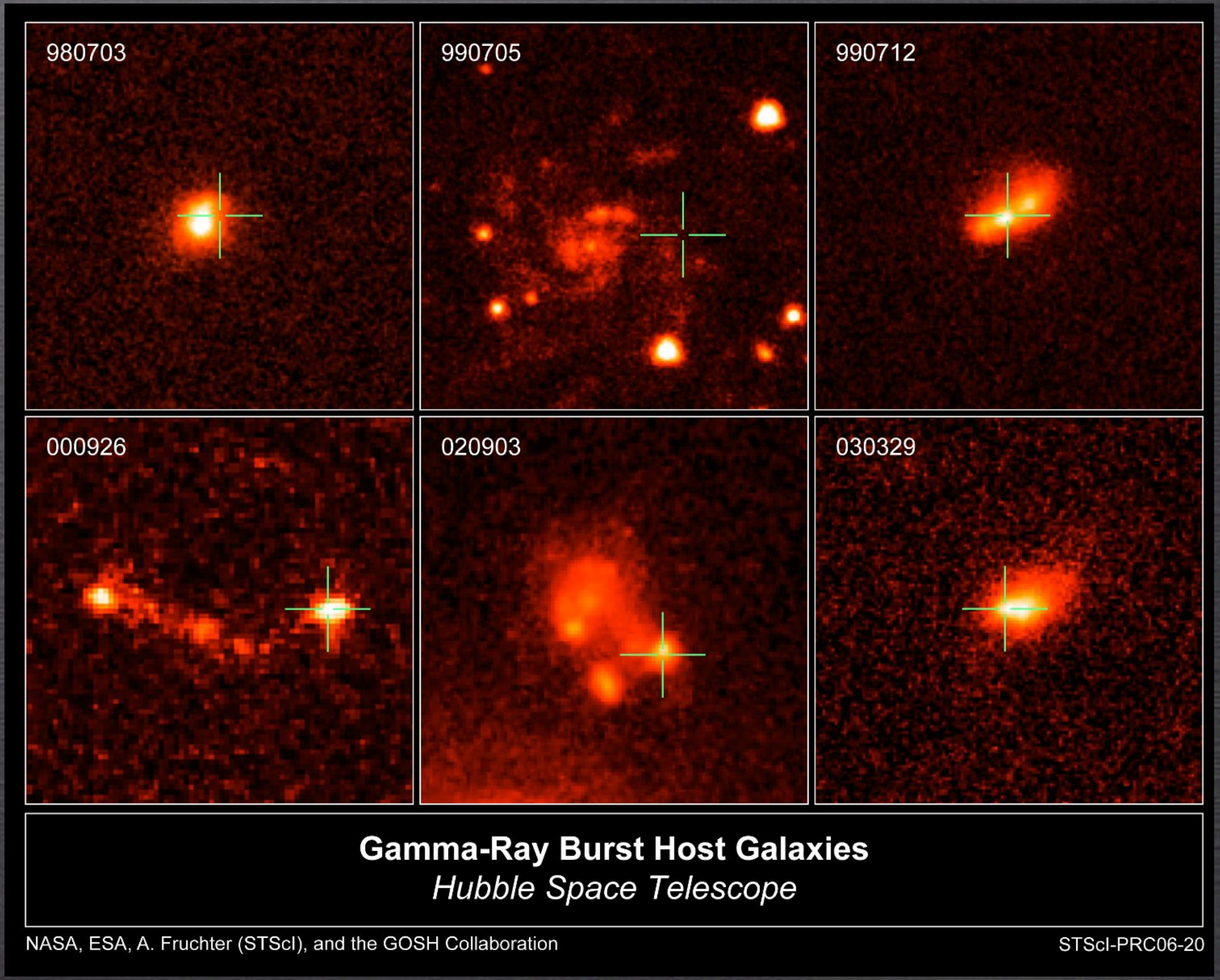


$$I\frac{d\Omega}{dt} = N_{\rm dip} + N_{\rm acc}$$

$$N_{\rm dip} = -\frac{\mu^2\Omega^3}{6c^3}$$

$$N_{\rm acc} = n(\omega)(GMr_m)^{1/2}\dot{M}$$

Piro & Ott 2011



Gamma-Ray Burst Host Galaxies
Hubble Space Telescope

NASA, ESA, A. Fruchter (STScI), and the GOSH Collaboration

STScI-PRC06-20