FRB-Italy
2025

Incidence of afterglow plateaus in GRBs associated with binary NS mergers

L. Guglielmi (Unibo), **G. Stratta (INAF/OAS)**, S. Dall'Osso (INAF/IRA), P. Singh (GU Frankfurt), M. Brusa (Unibo) and R. Perna (Stoney Brook University NY)

Bologna 7-9 Maggio 2025

Credits: NRAO

FRB-Italy 2025

How to identify and accurately localise newly born magnetars

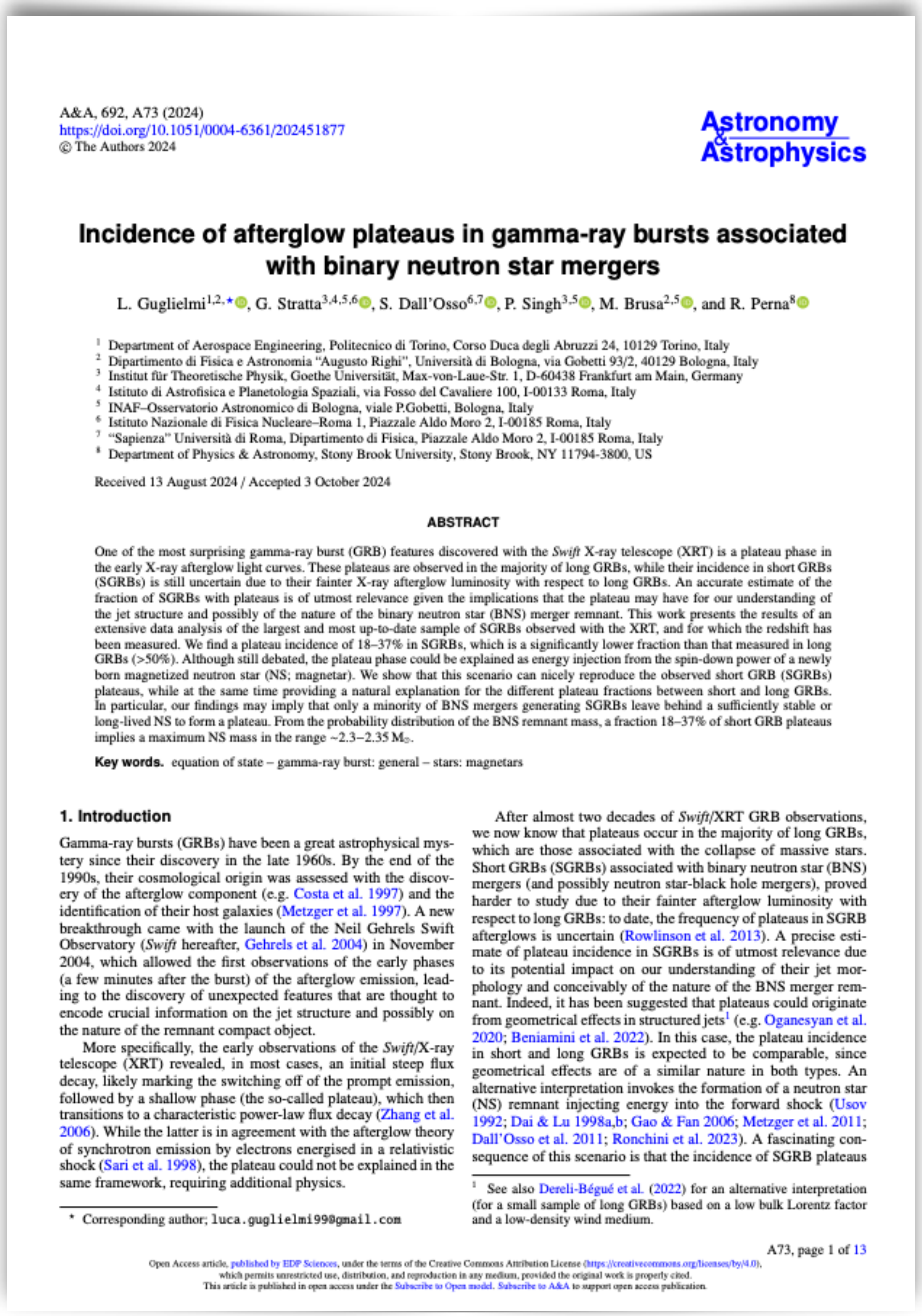
L. Guglielmi (Unibo), **G. Stratta (INAF/OAS)**, S. Dall’Osso (INAF/IRA), P. Singh (GU Frankfurt), M. Brusa (Unibo) and R. Perna (Stoney Brook University NY)

Bologna 7-9 Maggio 2025

Credits: NRAO

Outline

- X-ray plateaus: main properties and possible interpretations
- Our work: computing the incidence of X-ray plateaus in binary driven GRBs
- Results and Conclusions



A&A, 692, A73 (2024)
https://doi.org/10.1051/0004-6361/202451877

Astronomy & Astrophysics

Incidence of afterglow plateaus in gamma-ray bursts associated with binary neutron star mergers

L. Guglielmi[1,2,⋆], G. Stratta[3,4,5,6], S. Dall'Osso[6,7], P. Singh[3,5], M. Brusa[2,5], and R. Perna[8]

[1] Department of Aerospace Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
[2] Dipartimento di Fisica e Astronomia "Augusto Righi", Università di Bologna, via Gobetti 93/2, 40129 Bologna, Italy
[3] Institut für Theoretische Physik, Goethe Universität, Max-von-Laue-Str. 1, D-60438 Frankfurt am Main, Germany
[4] Istituto di Astrofisica e Planetologia Spaziali, via Fosso del Cavaliere 100, I-00133 Roma, Italy
[5] INAF–Osservatorio Astronomico di Bologna, viale P.Gobetti, Bologna, Italy
[6] Istituto Nazionale di Fisica Nucleare–Roma 1, Piazzale Aldo Moro 2, I-00185 Roma, Italy
[7] "Sapienza" Università di Roma, Dipartimento di Fisica, Piazzale Aldo Moro 2, I-00185 Roma, Italy
[8] Department of Physics & Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, US

Received 13 August 2024 / Accepted 3 October 2024

ABSTRACT

One of the most surprising gamma-ray burst (GRB) features discovered with the *Swift* X-ray telescope (XRT) is a plateau phase in the early X-ray afterglow light curves. These plateaus are observed in the majority of long GRBs, while their incidence in short GRBs (SGRBs) is still uncertain due to their fainter X-ray afterglow luminosity with respect to long GRBs. An accurate estimate of the fraction of SGRBs with plateaus is of utmost relevance given the implications that the plateau may have for our understanding of the jet structure and possibly of the nature of the binary neutron star (BNS) merger remnant. This work presents the results of an extensive data analysis of the largest and most up-to-date sample of SGRBs observed with the XRT, and for which the redshift has been measured. We find a plateau incidence of 18–37% in SGRBs, which is a significantly lower fraction than that measured in long GRBs (>50%). Although still debated, the plateau phase could be explained as energy injection from the spin-down power of a newly born magnetized neutron star (NS; magnetar). We show that this scenario can nicely reproduce the observed short GRB (SGRBs) plateaus, while at the same time providing a natural explanation for the different plateau fractions between short and long GRBs. In particular, our findings may imply that only a minority of BNS mergers generating SGRBs leave behind a sufficiently stable or long-lived NS to form a plateau. From the probability distribution of the BNS remnant mass, a fraction 18–37% of short GRB plateaus implies a maximum NS mass in the range ~2.3–2.35 $M_\odot$.

Key words. equation of state – gamma-ray burst: general – stars: magnetars

1. Introduction

Gamma-ray bursts (GRBs) have been a great astrophysical mystery since their discovery in the late 1960s. By the end of the 1990s, their cosmological origin was assessed with the discovery of the afterglow component (e.g. Costa et al. 1997) and the identification of their host galaxies (Metzger et al. 1997). A new breakthrough came with the launch of the Neil Gehrels Swift Observatory (*Swift* hereafter, Gehrels et al. 2004) in November 2004, which allowed the first observations of the early phases (a few minutes after the burst) of the afterglow emission, leading to the discovery of unexpected features that are thought to encode crucial information on the jet structure and possibly on the nature of the remnant compact object.

More specifically, the early observations of the *Swift*/X-ray telescope (XRT) revealed, in most cases, an initial steep flux decay, likely marking the switching off of the prompt emission, followed by a shallow phase (the so-called plateau), which then transitions to a characteristic power-law flux decay (Zhang et al. 2006). While the latter is in agreement with the afterglow theory of synchrotron emission by electrons energised in a relativistic shock (Sari et al. 1998), the plateau could not be explained in the same framework, requiring additional physics.

After almost two decades of *Swift*/XRT GRB observations, we now know that plateaus occur in the majority of long GRBs, which are those associated with the collapse of massive stars. Short GRBs (SGRBs) associated with binary neutron star (BNS) mergers (and possibly neutron star-black hole mergers), proved harder to study due to their fainter afterglow luminosity with respect to long GRBs: to date, the frequency of plateaus in SGRB afterglows is uncertain (Rowlinson et al. 2013). A precise estimate of plateau incidence in SGRBs is of utmost relevance due to its potential impact on our understanding of their jet morphology and conceivably of the nature of the BNS merger remnant. Indeed, it has been suggested that plateaus could originate from geometrical effects in structured jets[1] (e.g. Oganesyan et al. 2020; Beniamini et al. 2022). In this case, the plateau incidence in short and long GRBs is expected to be comparable, since geometrical effects are of a similar nature in both types. An alternative interpretation invokes the formation of a neutron star (NS) remnant injecting energy into the forward shock (Usov 1992; Dai & Lu 1998a,b; Gao & Fan 2006; Metzger et al. 2011; Dall'Osso et al. 2011; Ronchini et al. 2023). A fascinating consequence of this scenario is that the incidence of SGRB plateaus

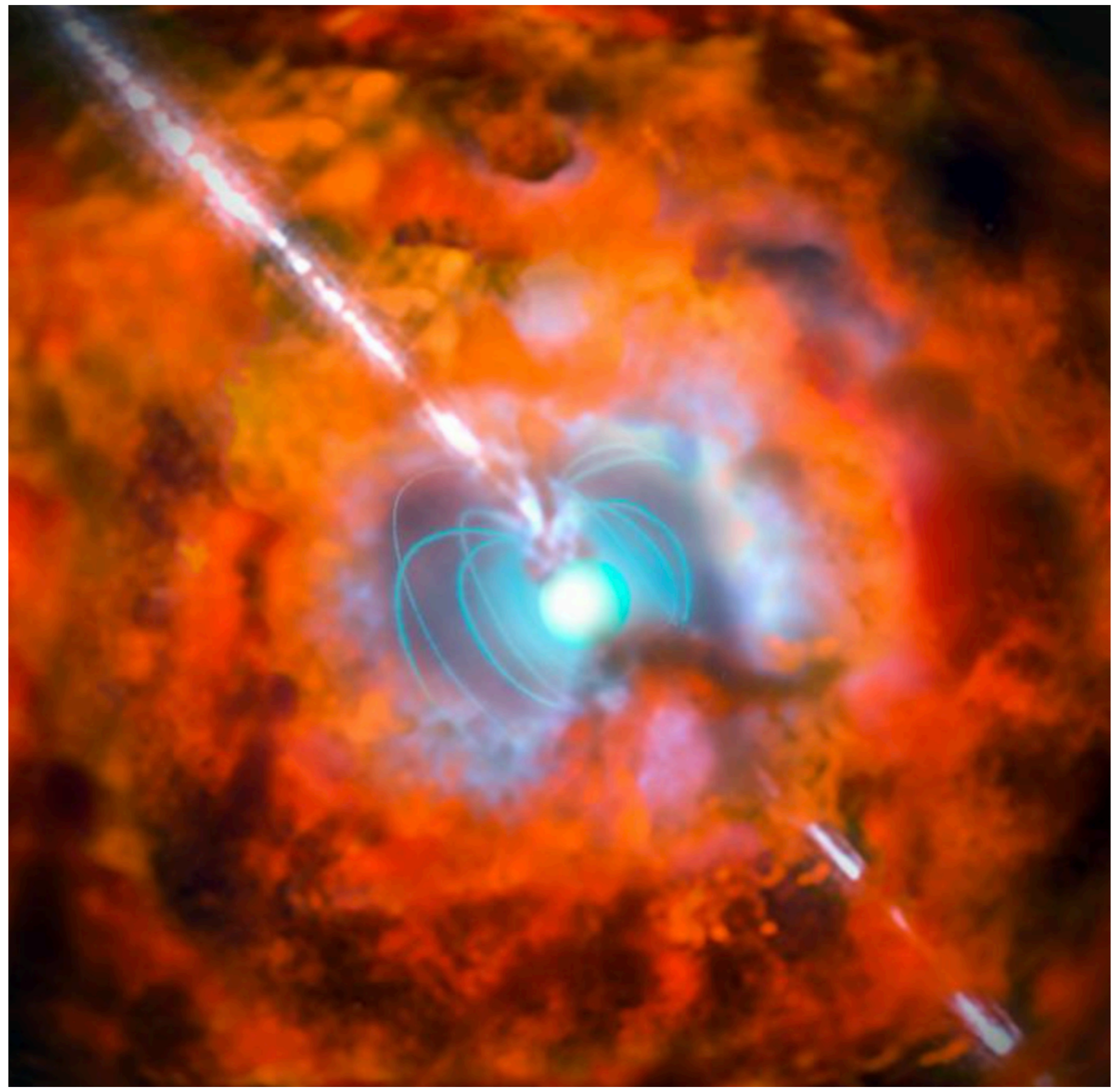
⋆ Corresponding author; luca.guglielmi99@gmail.com

[1] See also Dereli-Bégué et al. (2022) for an alternative interpretation (for a small sample of long GRBs) based on a low bulk Lorentz factor and a low-density wind medium.

Guglielmi, Stratta, Dall'Osso et al. 2024 A&A 692, 73

GRB remnant: BH or NS?

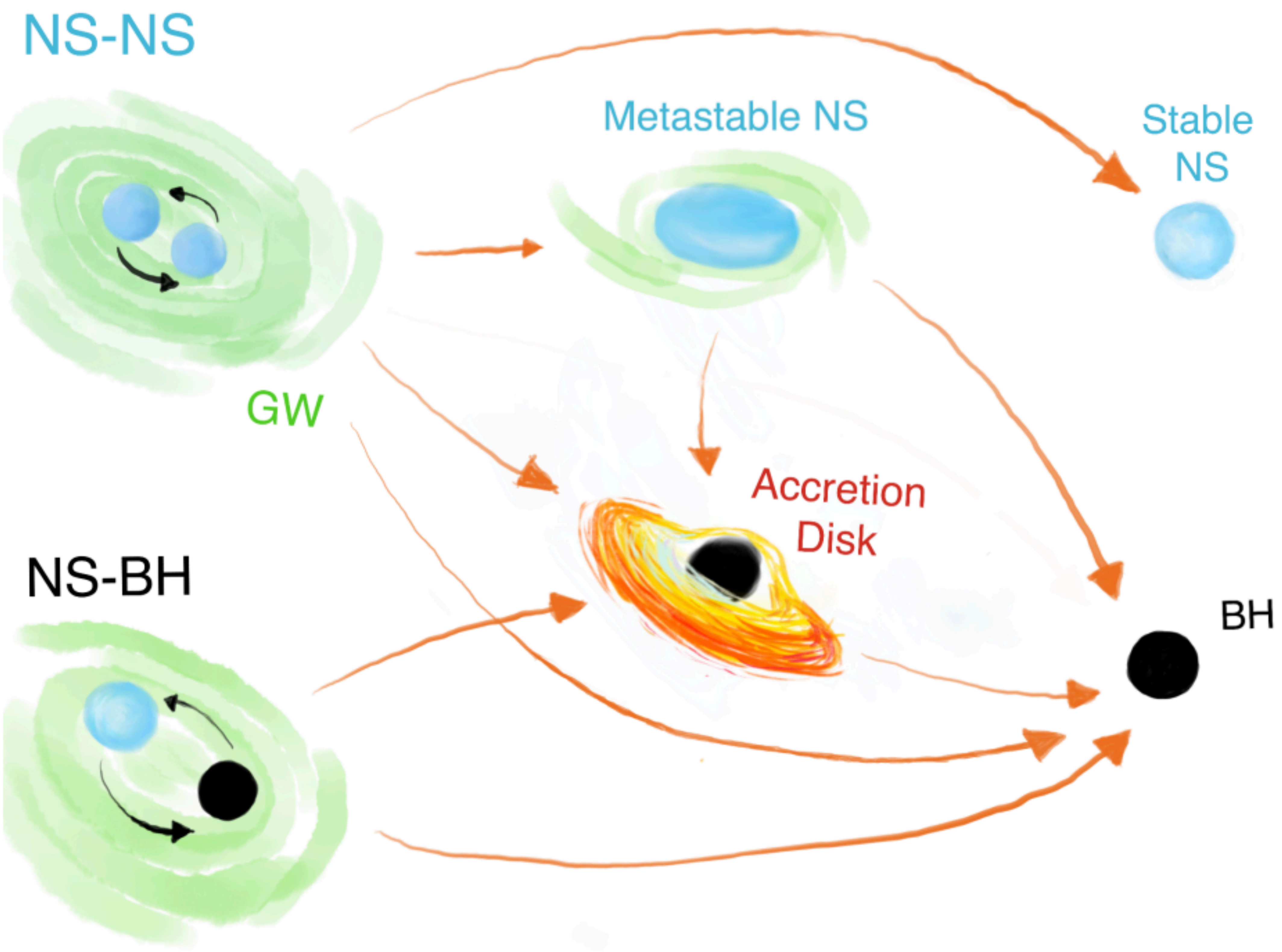
Long GRBs or **Type I GRBs** from collapsars



Credit: ESO

GRB afterglow properties can shed light on the remnant nature and production efficiency

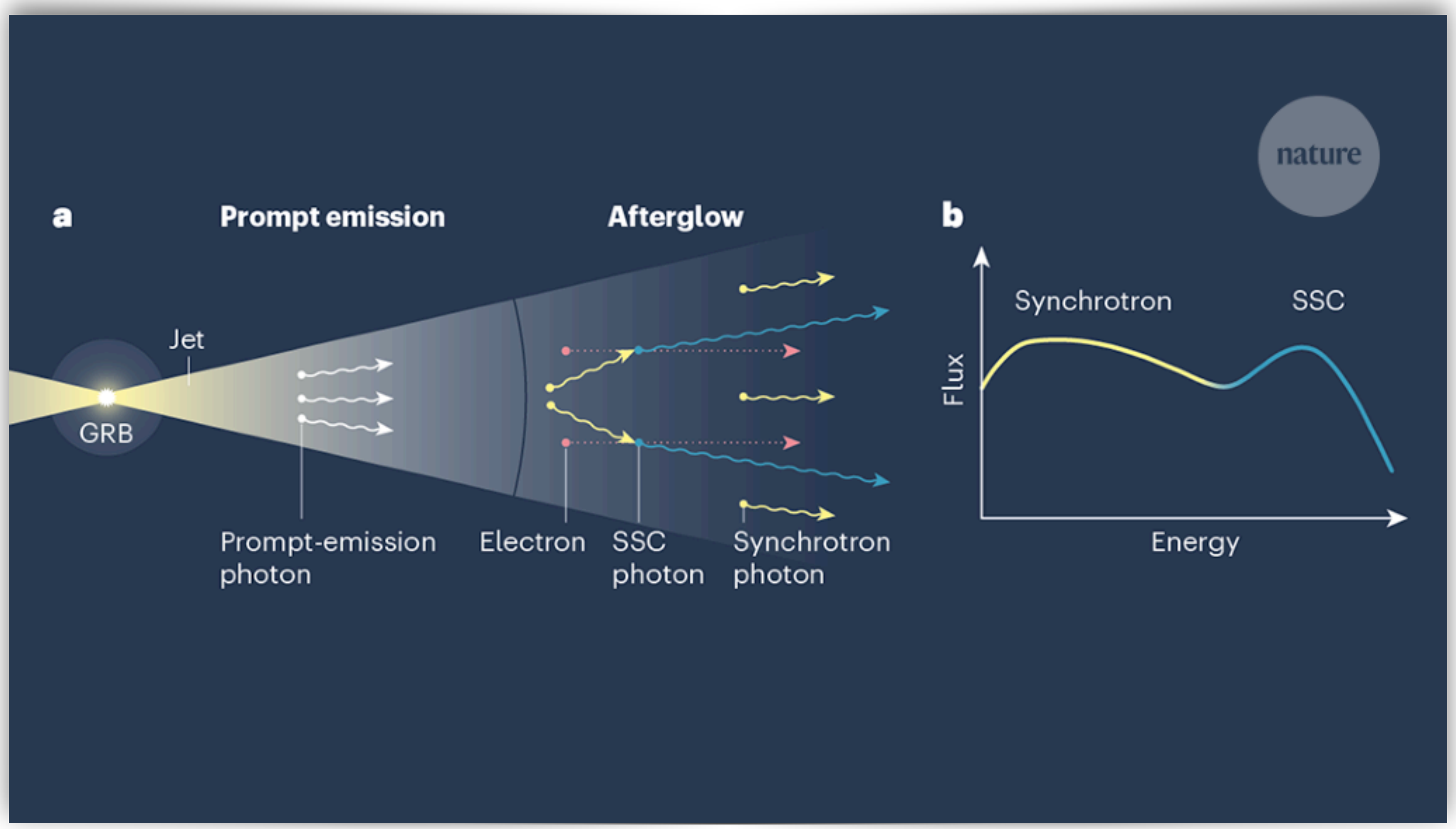
Short GRBs or **Type II GRBs** from compact binary mergers



Ascenzi+2011

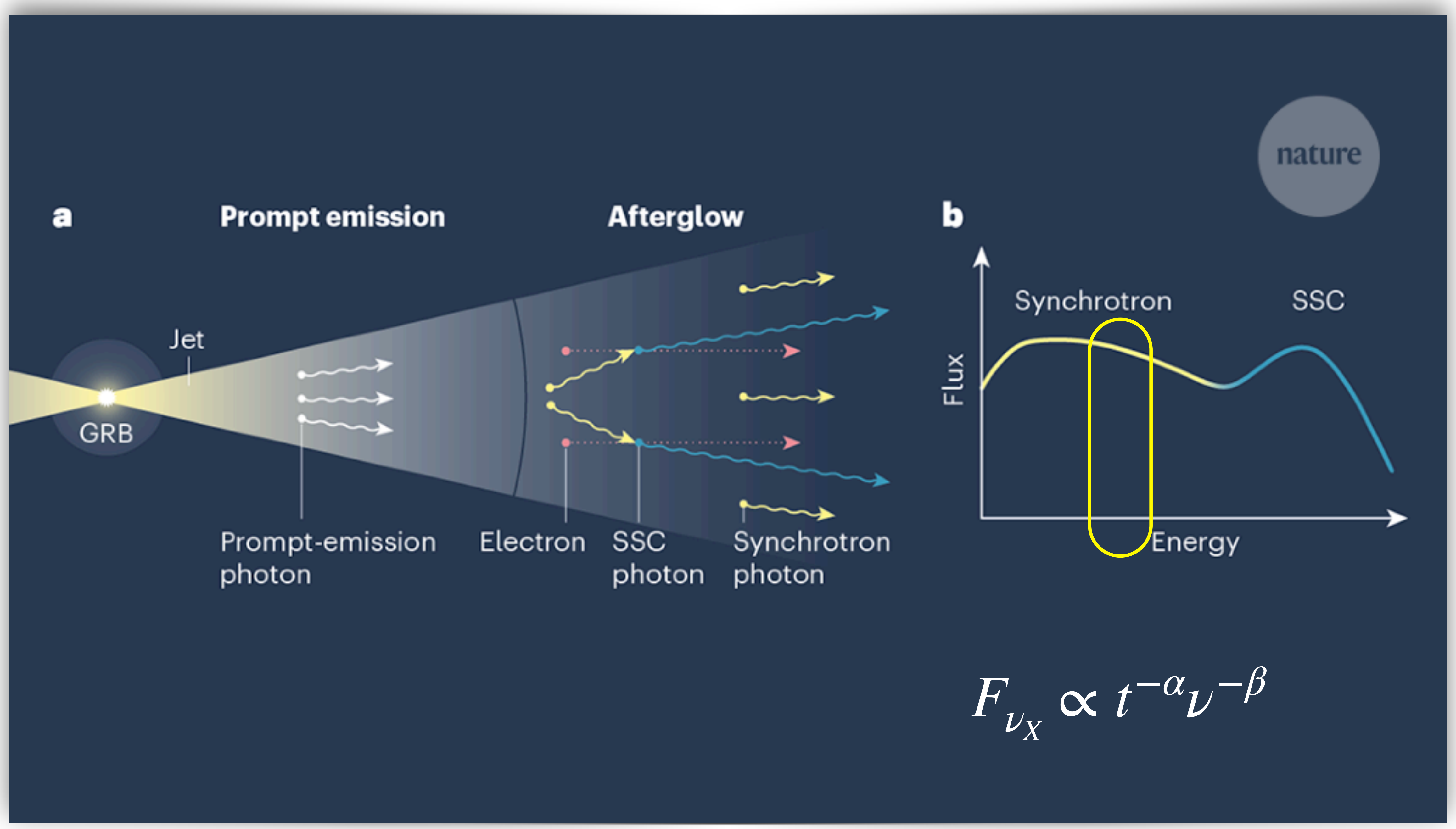
GRB afterglow

B. Zhang 2019



GRB afterglow

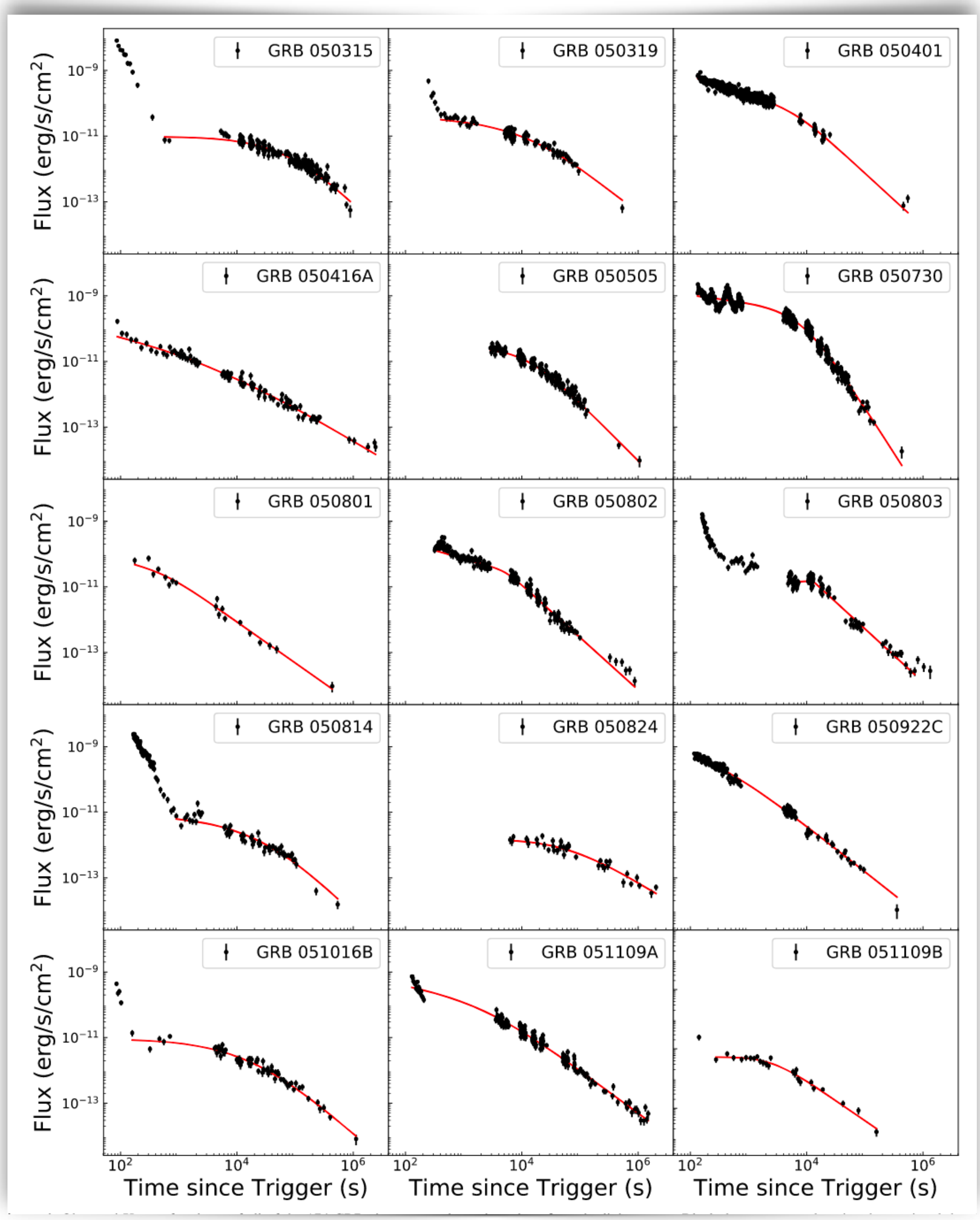
B. Zhang 2019



- After min-hrs from the burst -> slow cooling regime of the bulk of the electrons -> X-ray flux decays following a power-law
- Assuming the jet is plunging into a constant density ISM, at early epochs $\alpha \geq$ 0.7-0.8
- At late epochs (~day), $\alpha \geq$ 1.2-1.5 and $\Delta\beta > 0$

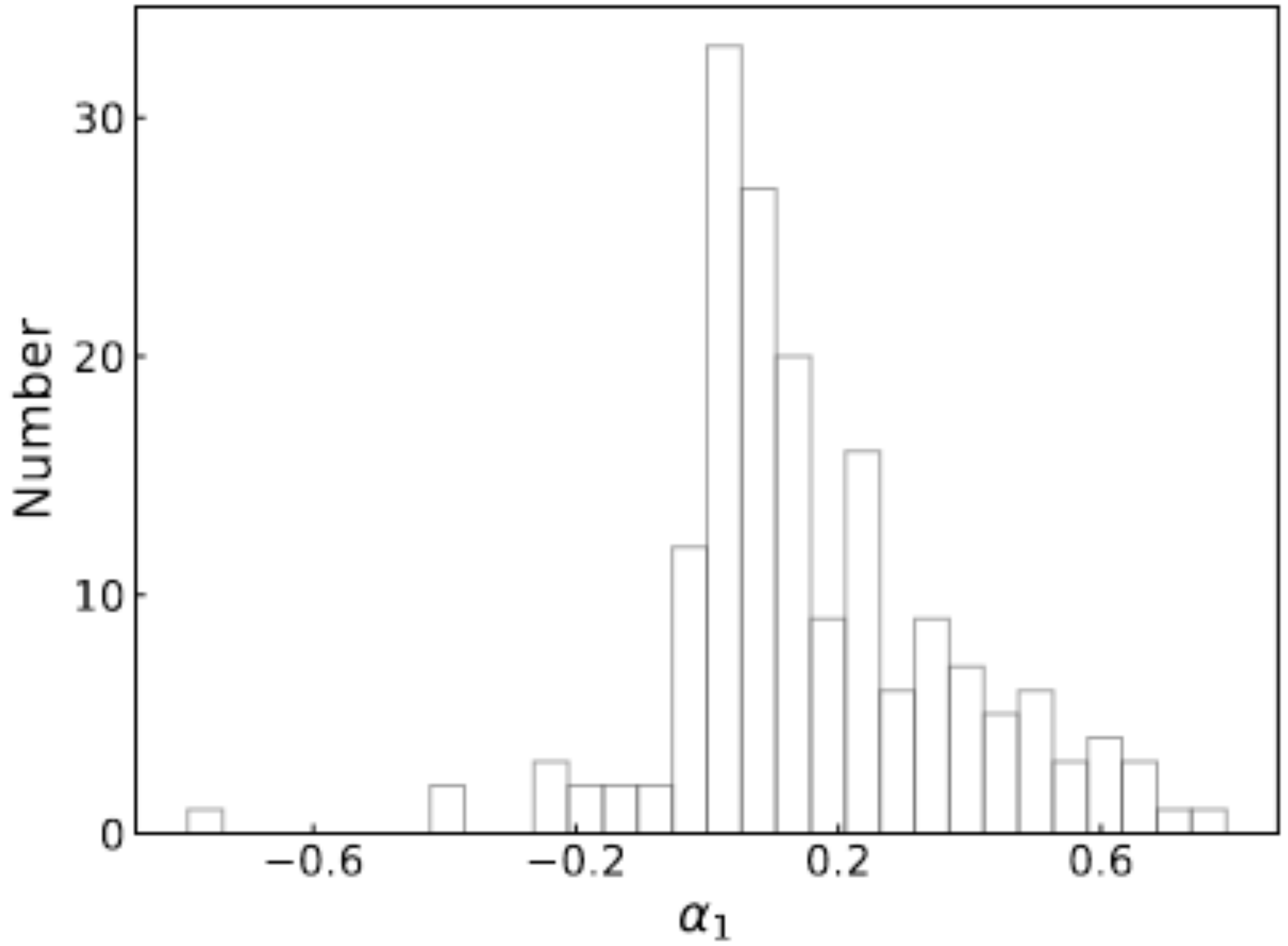
(e.g. Granot & Sari 2002, Zhang et al. 2006)

X-ray afterglow plateaus

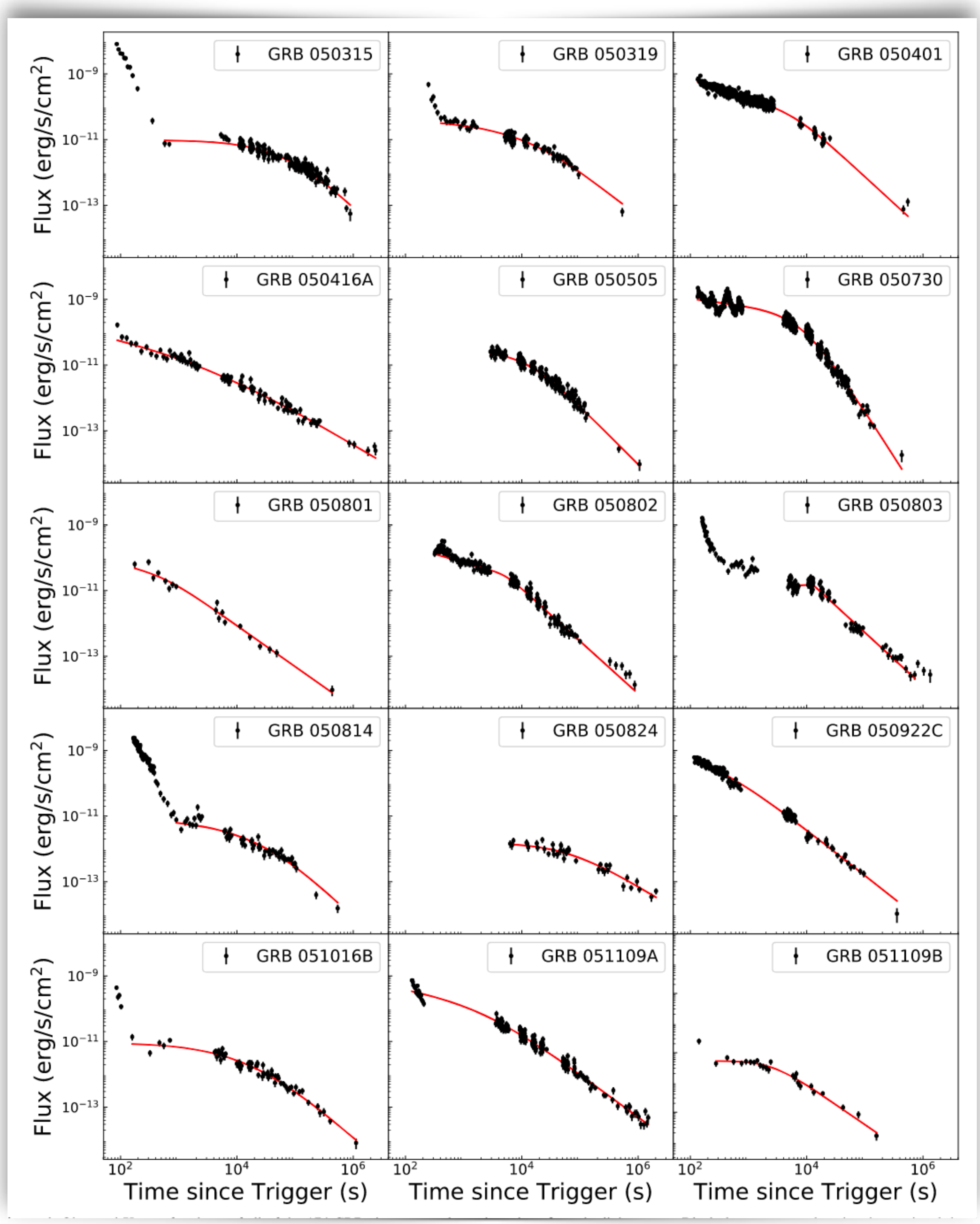


Tang et al. 2019

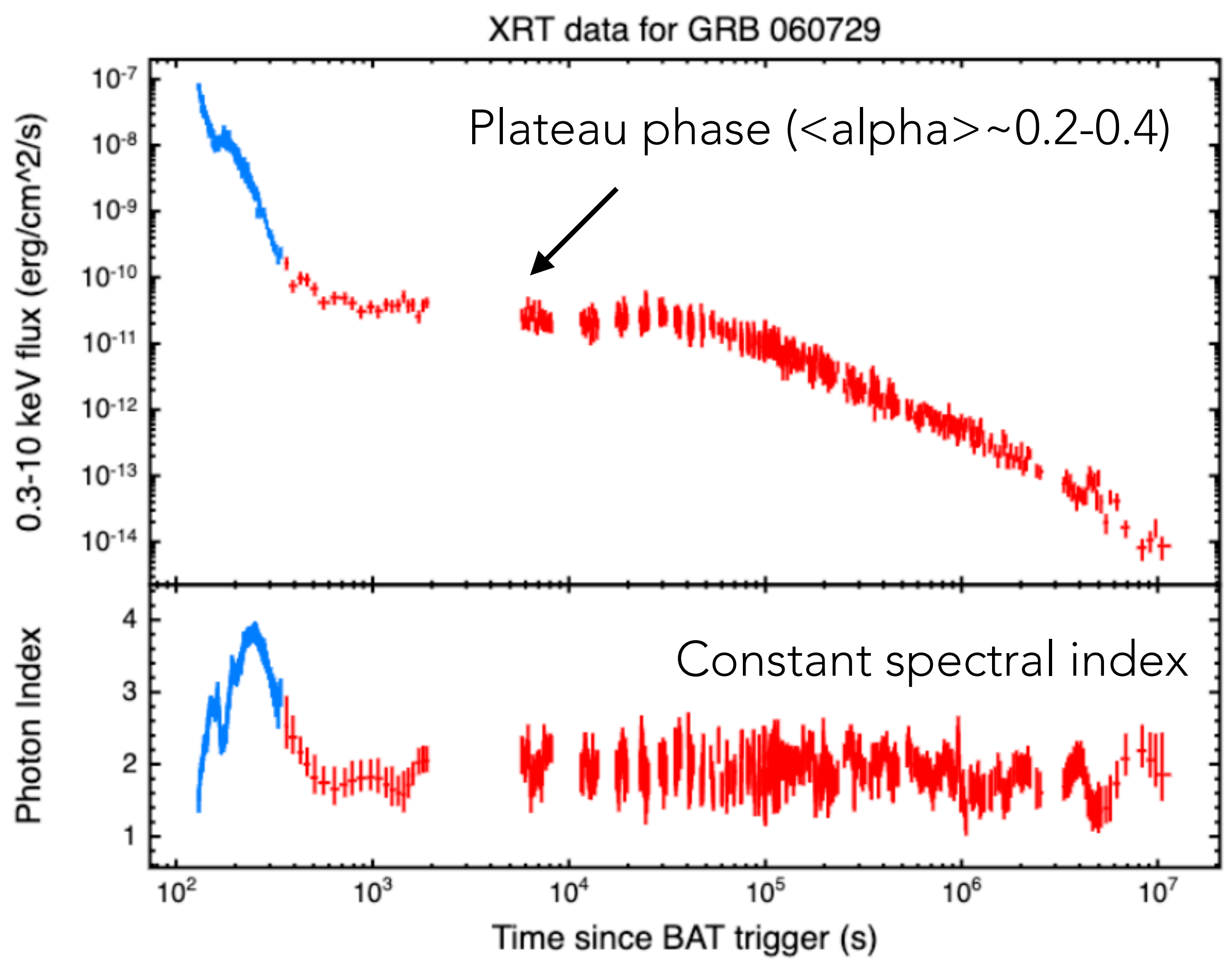
Early X-ray flux evolution (a few x100s-10ks) in the majority of GRBs is too shallow



X-ray afterglow plateaus



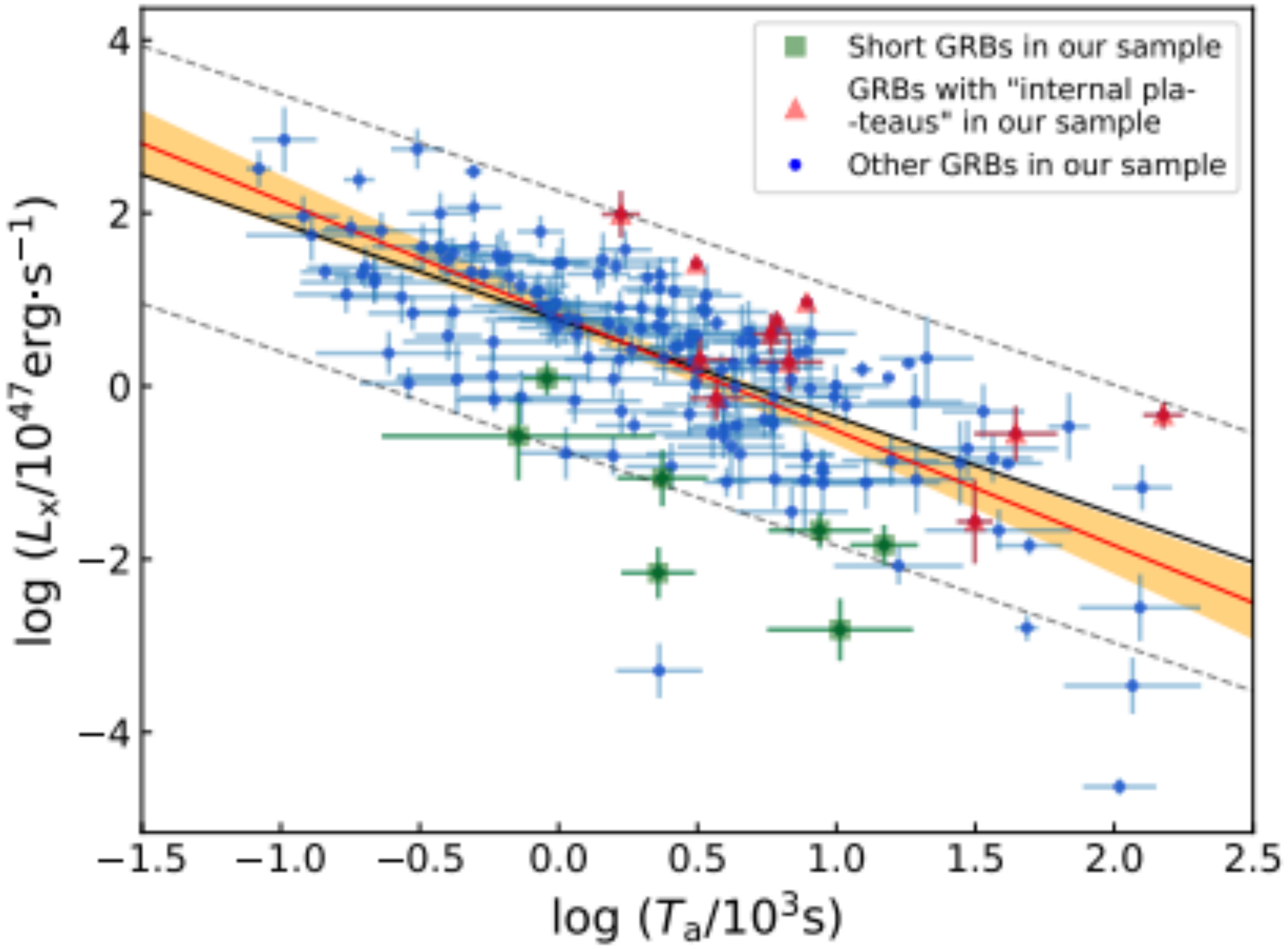
Liang et al. 2007, Litao Zhao et al. 2019 (~200 GRBs)

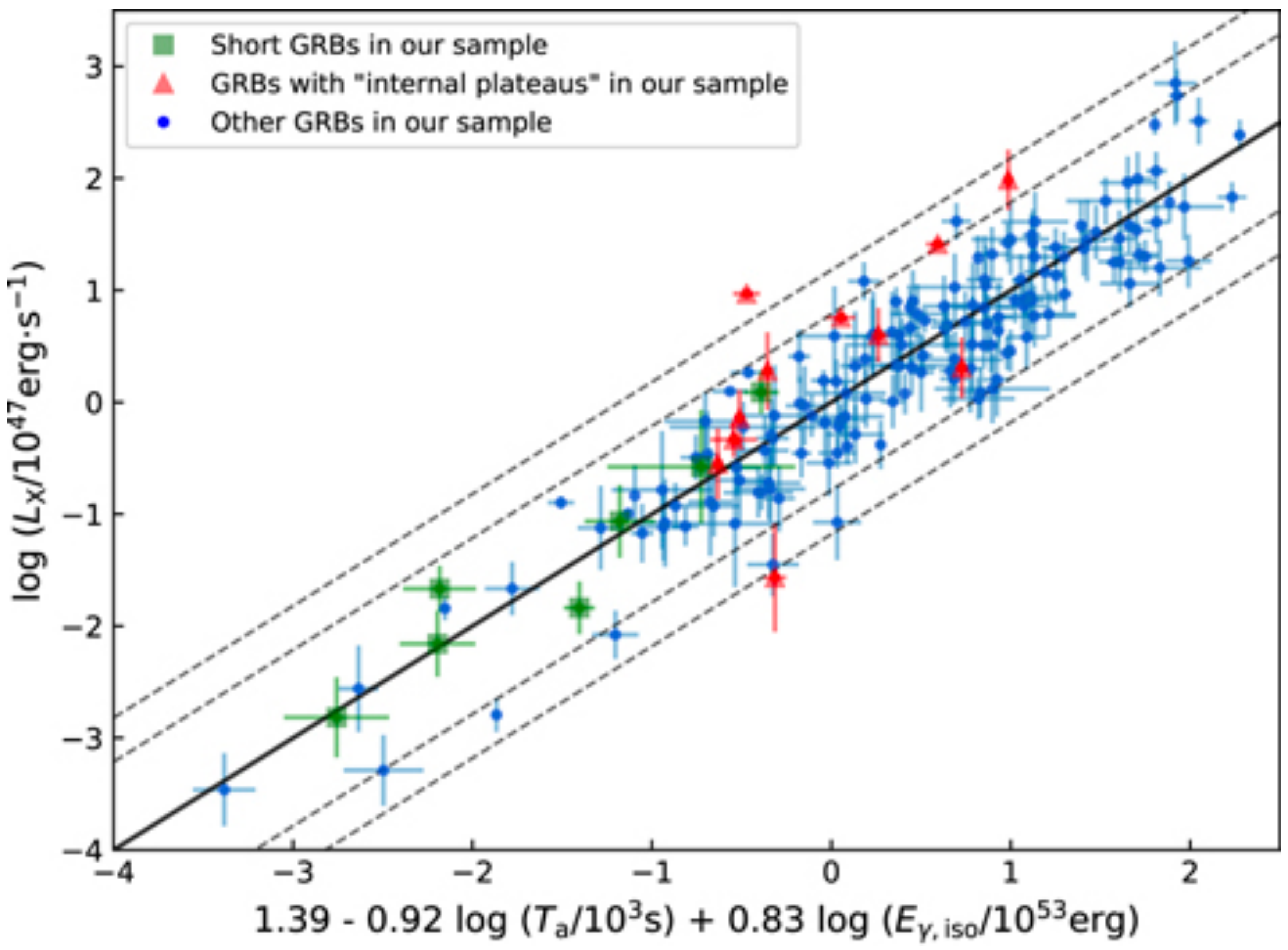


Plateau phase strongly challenges the standard sync. radiation scenario

X-ray afterglow plateaus

Tang et al. 2019



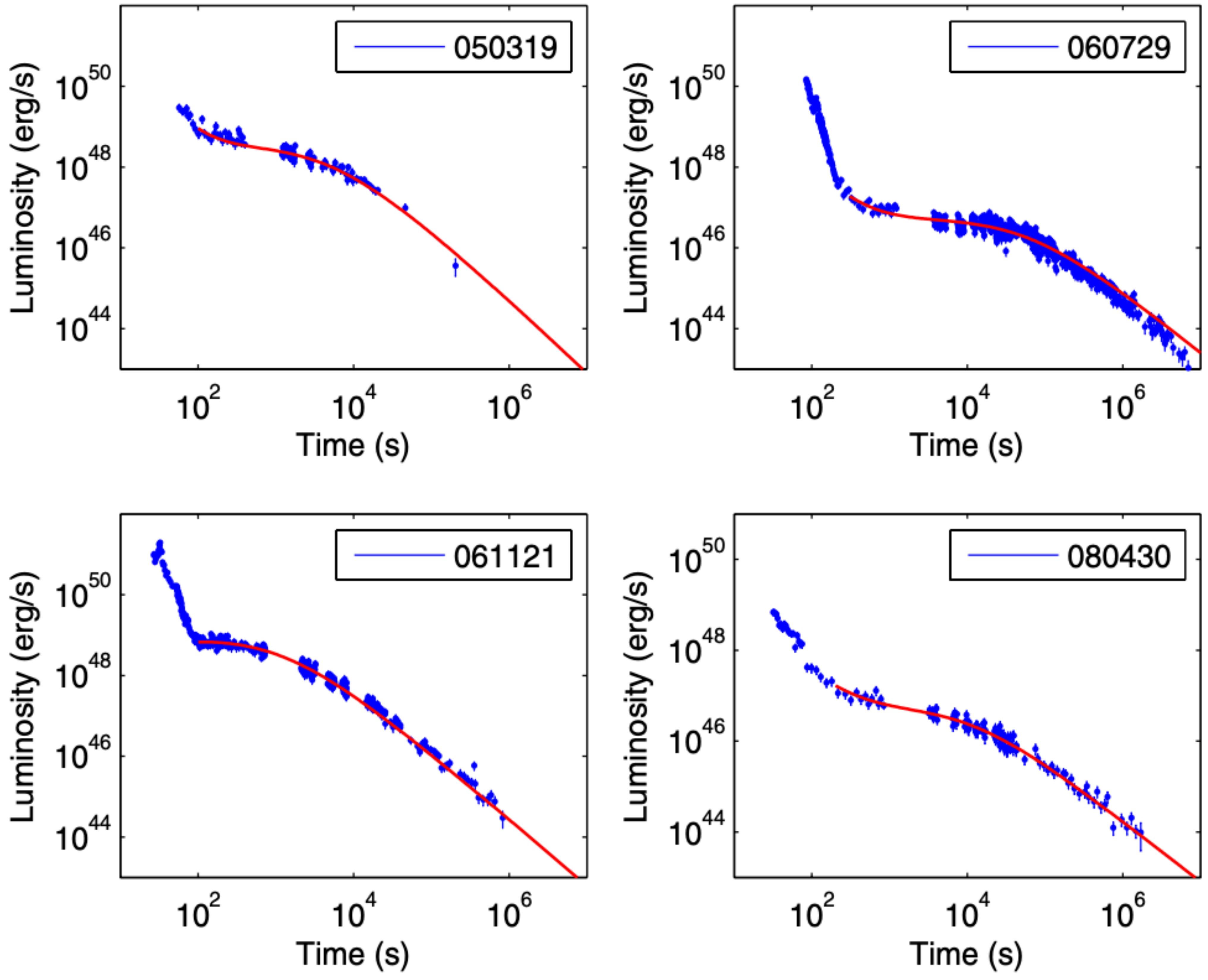


$L_{p,x} \propto T_{p,x}^{-1}$ …common energy reservoir?

$L_{p,x} \propto T_{p,x}^{-1} E_{iso}^{0.8}$ …Energy reservoir from with central engine?

X-ray plateau origin from spin-down NS

- $E_{NS} = 0.5I\omega^2 \sim 3 \times 10^{52}$ erg for P~1ms
- $L_{SD}(t) = \dfrac{E_{NS}}{\tau(1 + t/\tau)^2}$ (e.g. Zhang & Meszaros 2001) accurately reproduce X-ray plateaus (e.g. Dall'Osso+2011, Rowlinson+2013, Bernardini+2013, Stratta+2018)
- $L_{SD}(\tau) \propto \tau^{-1}$naturally reproduces the $L_{x,p}$ and $T_{x,p}$ anticorrelation



Dall'Osso+2011

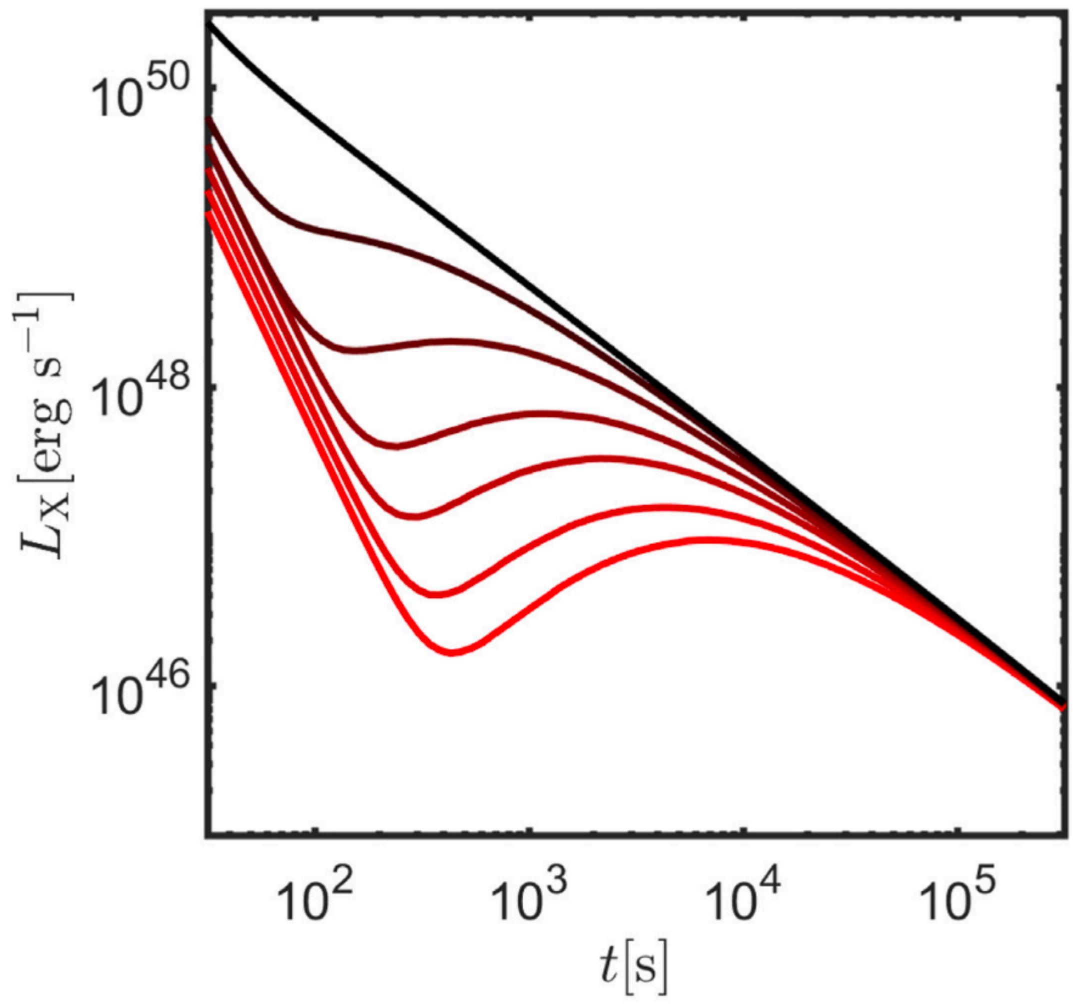
e.g Lyons+2010; Bernardini+2012; Rowlinson+2013; Bernardini+2013; Stratta+2018 Stratta+2022; Dall'Osso+2023

X-ray plateau origin from structured jet effects

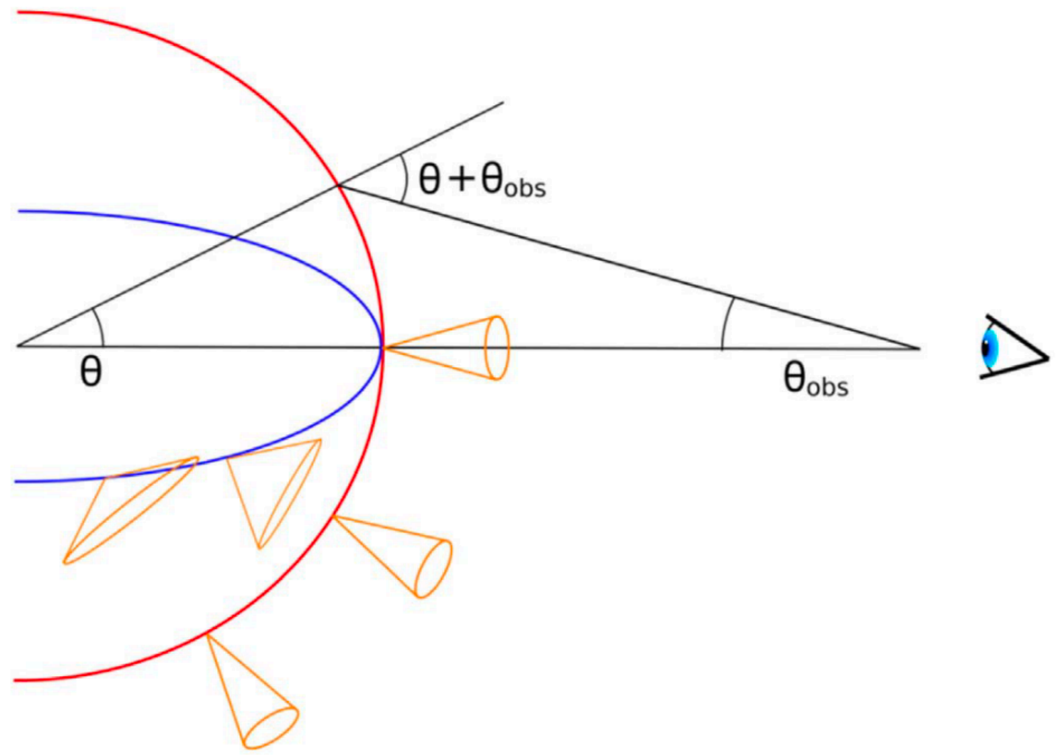
- X-ray plateaus are <u>afterglow emission viewed slightly off-axis</u> with $\theta_{obs} \geq \theta_j$ (e.g. Eichler & Granot 2006, Beniamini+2020)

- X-ray plateaus are <u>prompt high-latitude emission</u> dominating the afterglow emission (Oganesyan+2020)

- So far, no extensive test of these models on the large available data set has been published yet

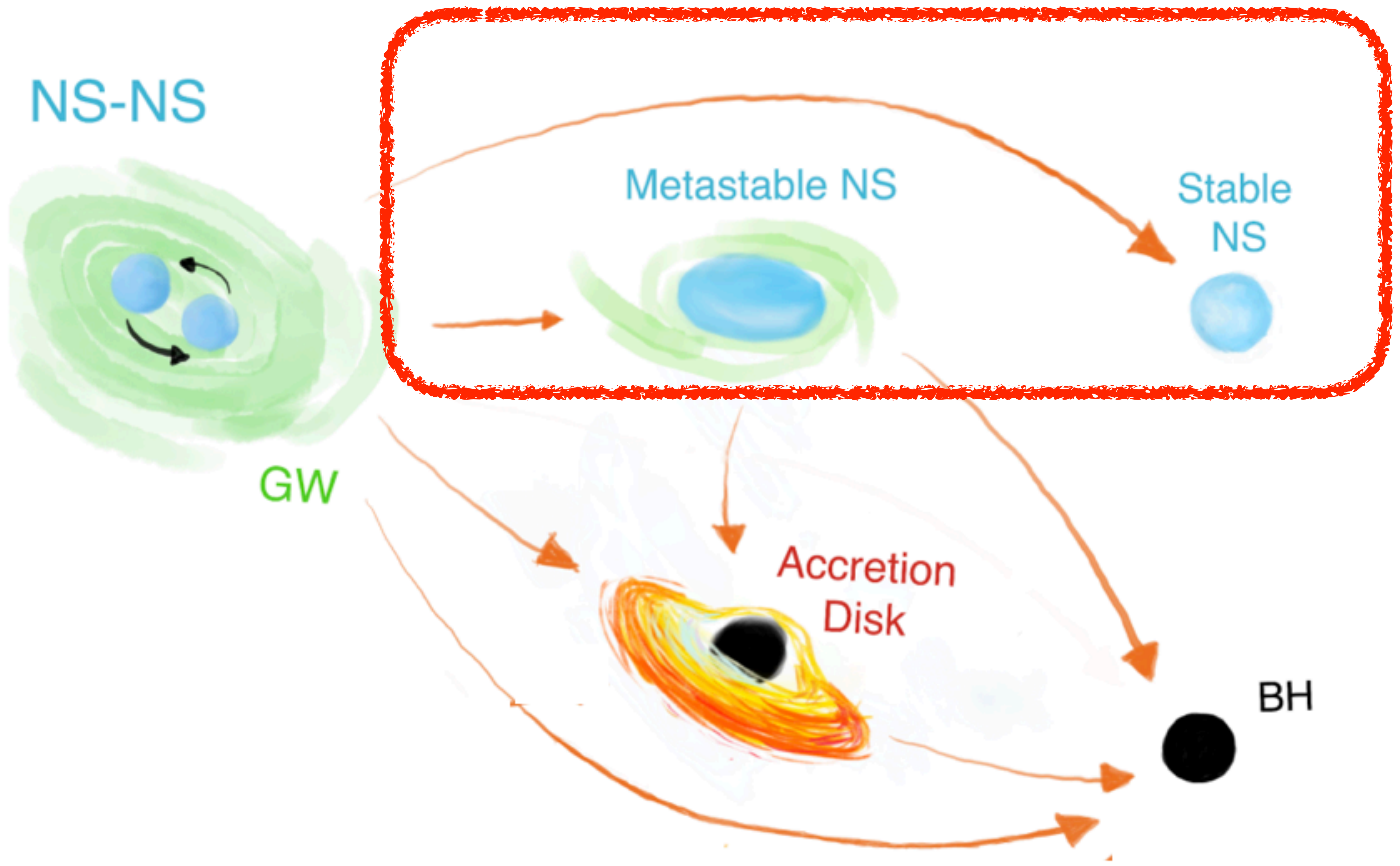


Beniamini+2020



Oganesyan et al. 2020

X-ray plateaus in GRBs from NS-NS mergers



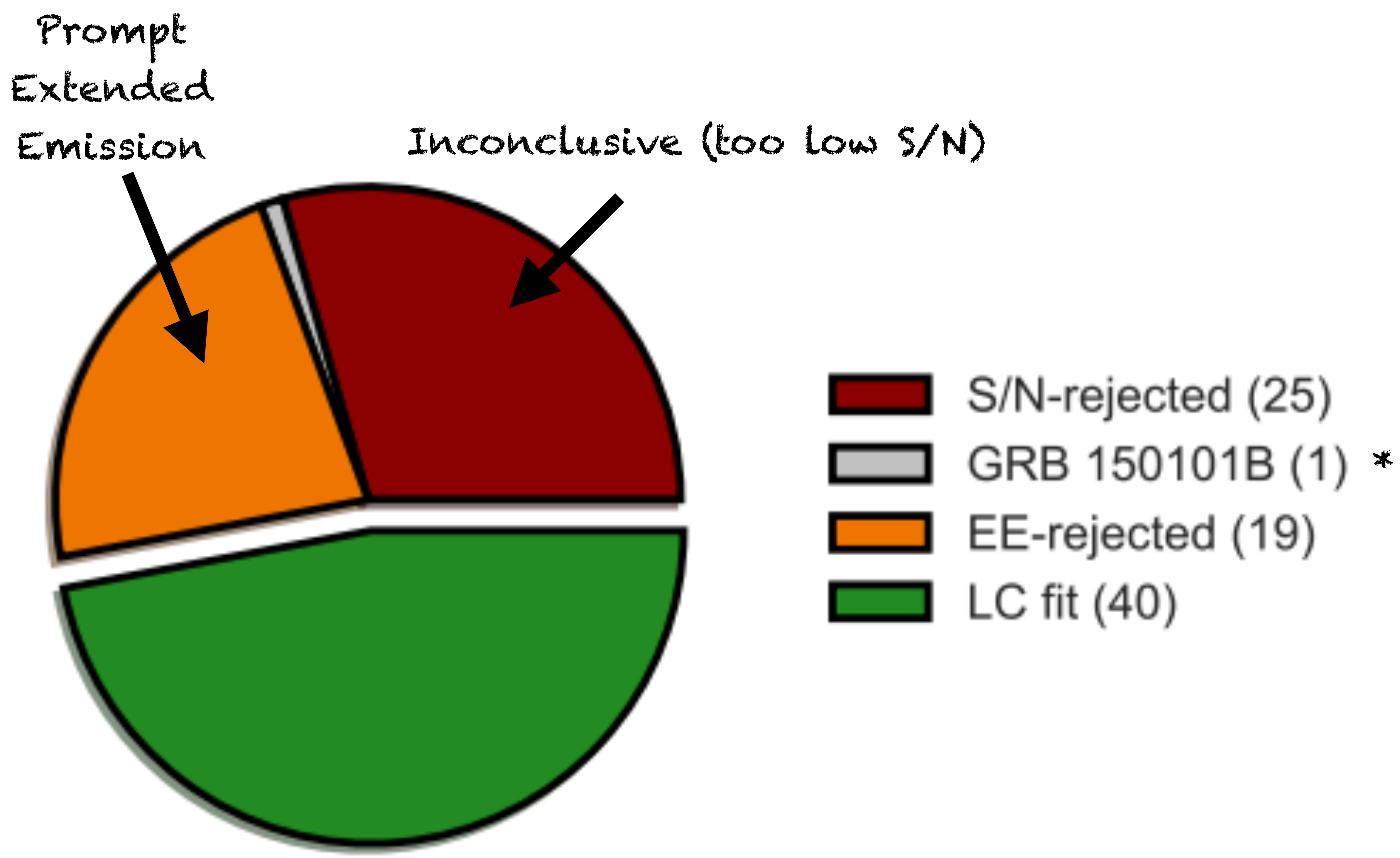
Adapted from Ascenzi+2011

- X-ray plateaus in the afterglow of GRBs from NS-NS mergers mark the formation of a NS remnant

- Incidence of X-rays plateaus in these GRBs —> proxy of the fraction of NS-NS mergers that generate a NS remnant

X-ray plateaus in GRBs from NS-NS mergers

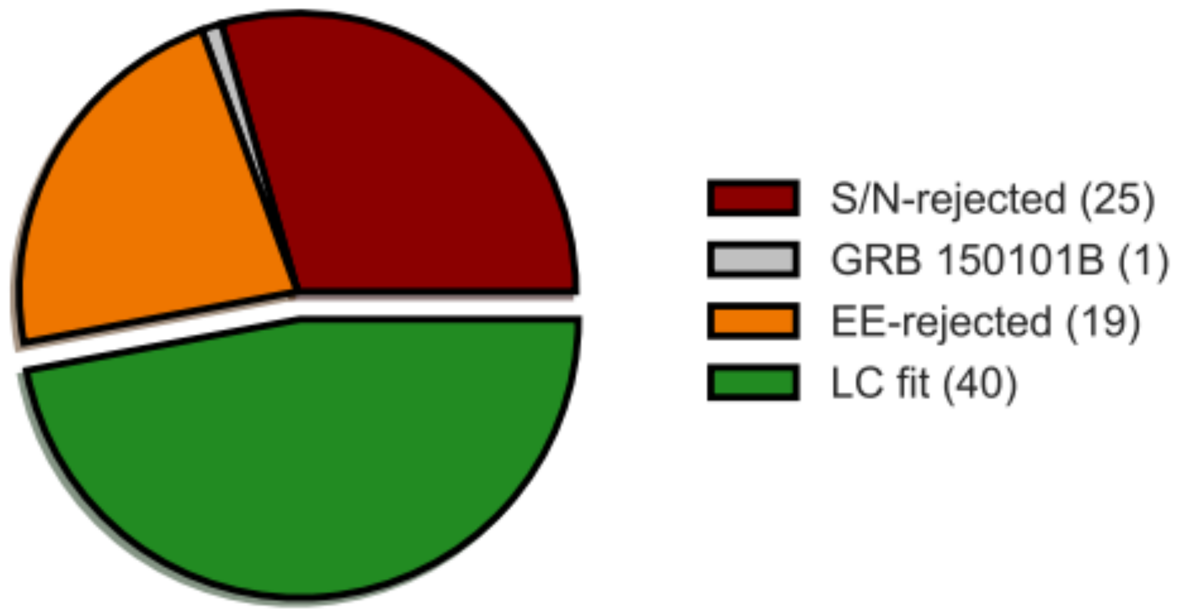
- Initial sample: all TypeII GRBs with Swift/XRT observed from May 2005 to Dec 2021, with known redshift (based on Fong+2022, O'Connor+2022) -> **85 GRBs**
- X-ray light curves from publicly available UK SDC Swift XRT Repository
- To robustly identify a plateau in the X-ray afterglow, we requested XRT tot cts >100 (S/N > 10)



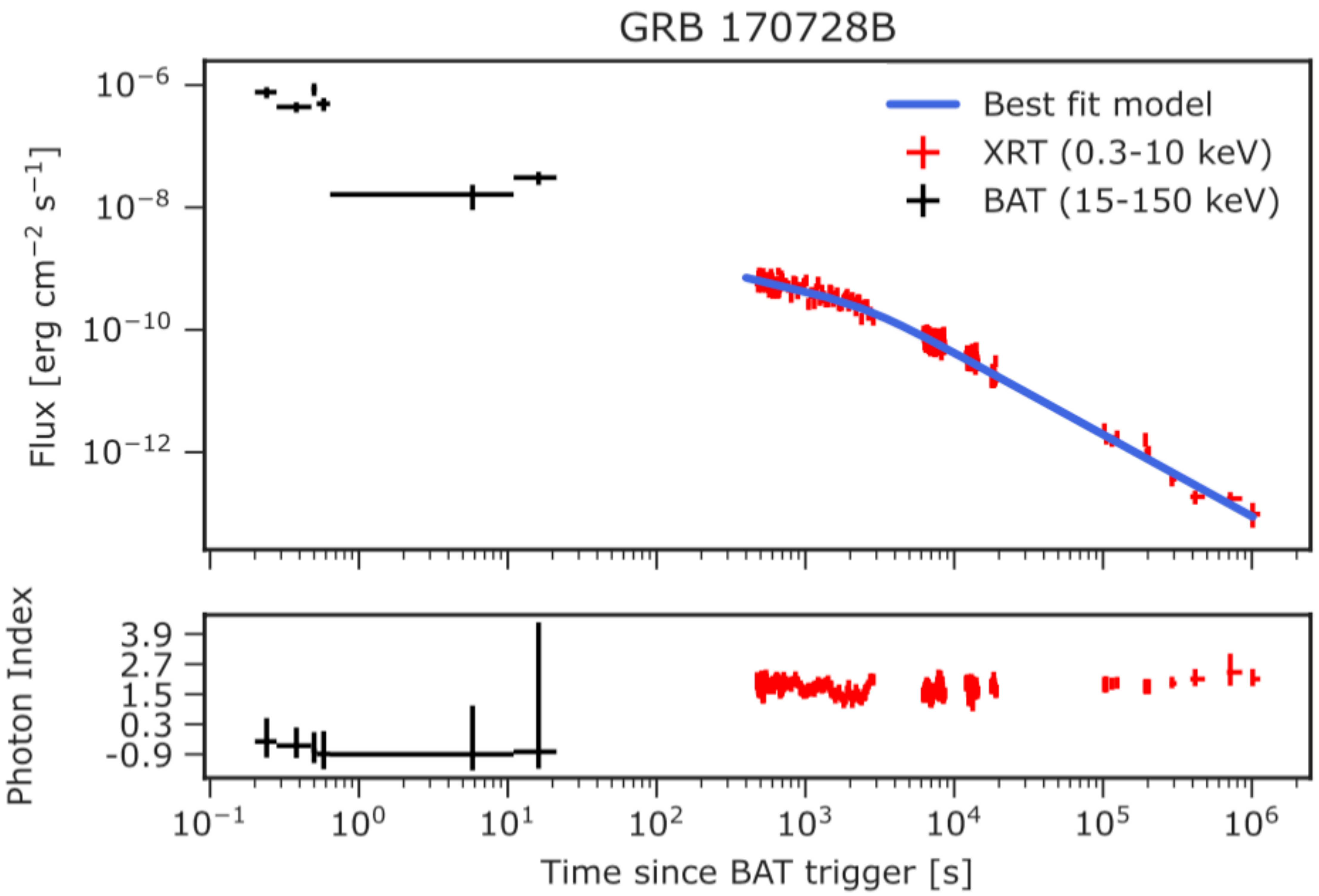
Guglielmi+2024

* GRB 150101B: very late XRT observations (>1 day)

“LC fit”: Incidence of plateaus

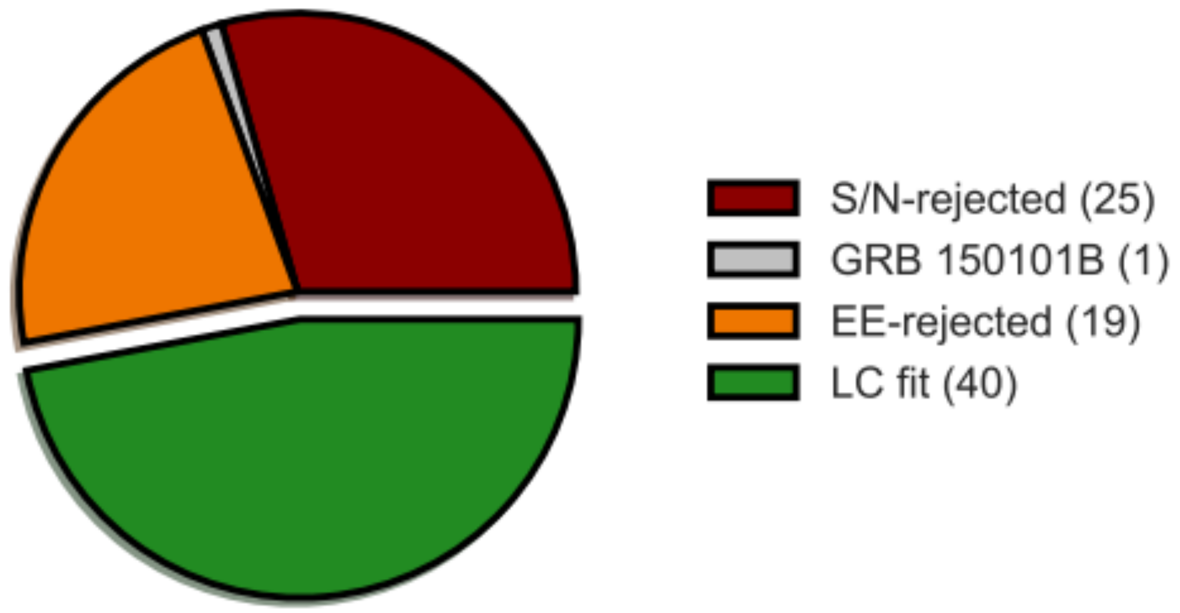


- We find **15/40 (37.5%)** X-ray aflterglow light curves are compatible with a broken power law, with:
  - initial decay index $\alpha < 0.75$
  - no evidence of significant spectral evolution before and after the temporal break



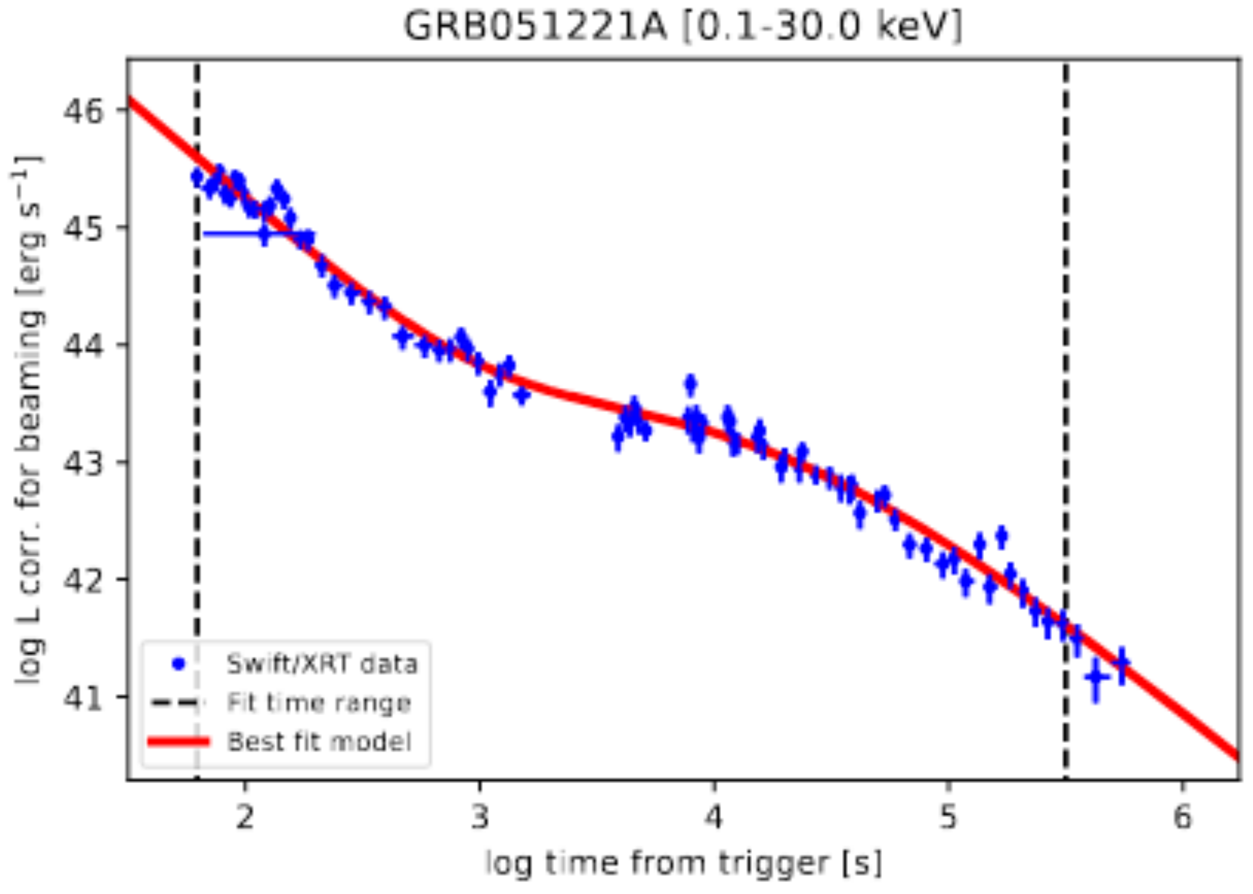
Guglielmi+2024

“LC fit”: Testing the magnetar scenario



Following Dall’Osso et al. 2011, **13/15** events could be modelled assuming energy injection into the forward shock from a newly-born spinning-down magnetar

GRB name	Input		Output				
	z	θ_j (deg)	B (10^{14} G)	P (ms)	$\tau_{sd} \approx 680\left(\frac{P_{ms}}{B_{15}}\right)^2$ (ks)	χ^2	ν
051221A	0.5464	6.0	(29 ± 2)	(12.8 ± 0.3)	13.3 ± 2.1	125	77
060614	0.125	12.6	(37 ± 3)	(24 ± 1)	34 ± 9	1749	465
070714B	0.923	8.6	(132 ± 40)	(11 ± 2)	0.5 ± 0.3	284	79
090510	0.903	2.3	(82 ± 7)	(4.5 ± 0.2)	0.20 ± 0.04	80	63
110402A	0.854	15.0	(96 ± 37)	(14 ± 1)	1.4 ± 1.1	42.0	16
130603B	0.3568	6.3	(110 ± 2)	(13.2 ± 0.2)	0.98 ± 0.04	137	70
140903A	0.3529	4.0	(32 ± 4)	(8 ± 0.3)	4.5 ± 1.2	56	36
150424A	0.3	4.3	(36 ± 4)	(16 ± 1)	13 ± 3	243	115
151229A	0.63	5.0	(67 ± 9)	(4.3 ± 0.9)	0.3 ± 0.1	142	56
161001A	0.67	5.0	(47 ± 6)	(4.2 ± 0.2)	0.5 ± 0.1	88	54
170728B	1.272	3.5	(20 ± 1)	(1.50 ± 0.03)	0.39 ± 0.04	232	193
210323A	0.733	2.9	(51 ± 11)	(8.7 ± 0.6)	2.0 ± 0.9	62	18
211211A	0.0763	6.9	(286 ± 26)	(27 ± 1)	0.6 ± 0.1	779	265

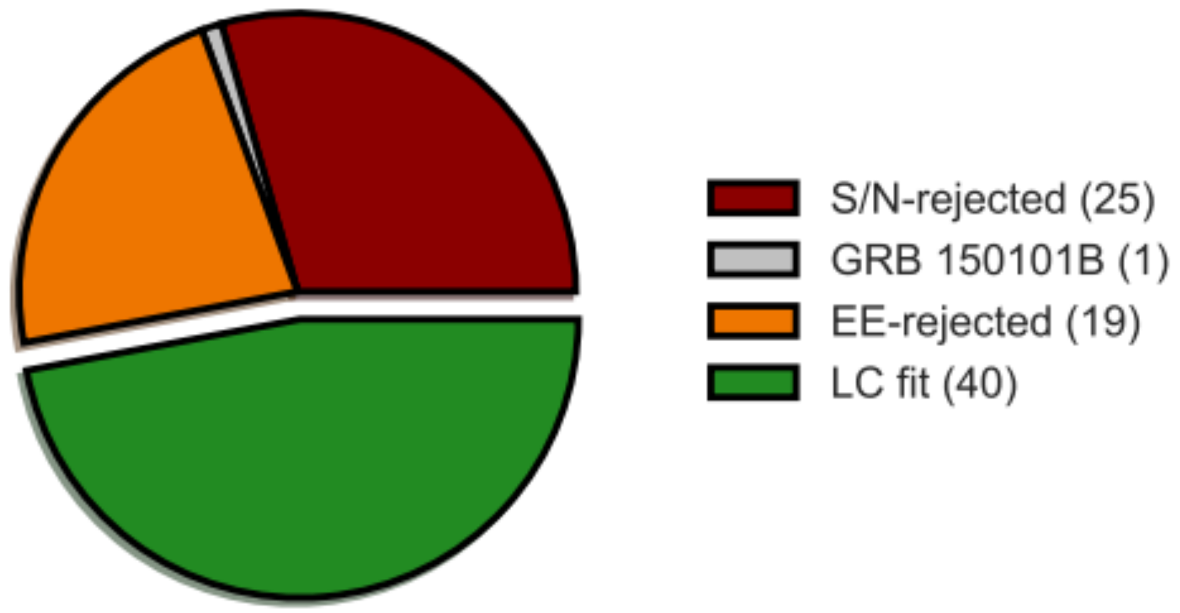


Two discarded events:

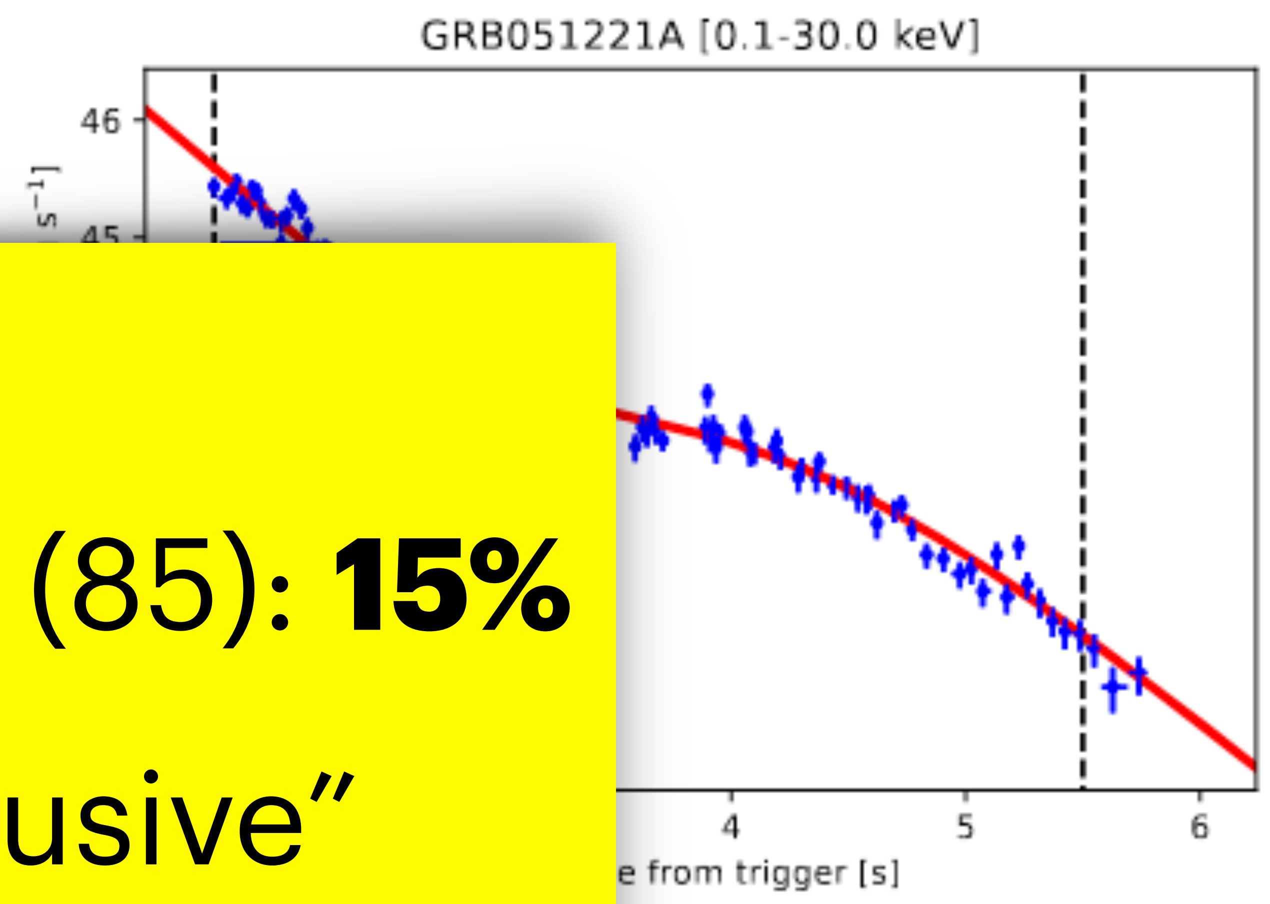
- GRB180618A has too short plateau duration to allow model parameter estimates
- GRB061201 provided not plausible B and P values (B>5.6x10^{16}G, P>38ms)

Guglielmi+2024

“LC fit”: Testing the magnetar scenario



Following Dall’Osso et al. 2011, **13/15** events could be modelled assuming energy injection into the forward shock from a newly-born spinning-down magne



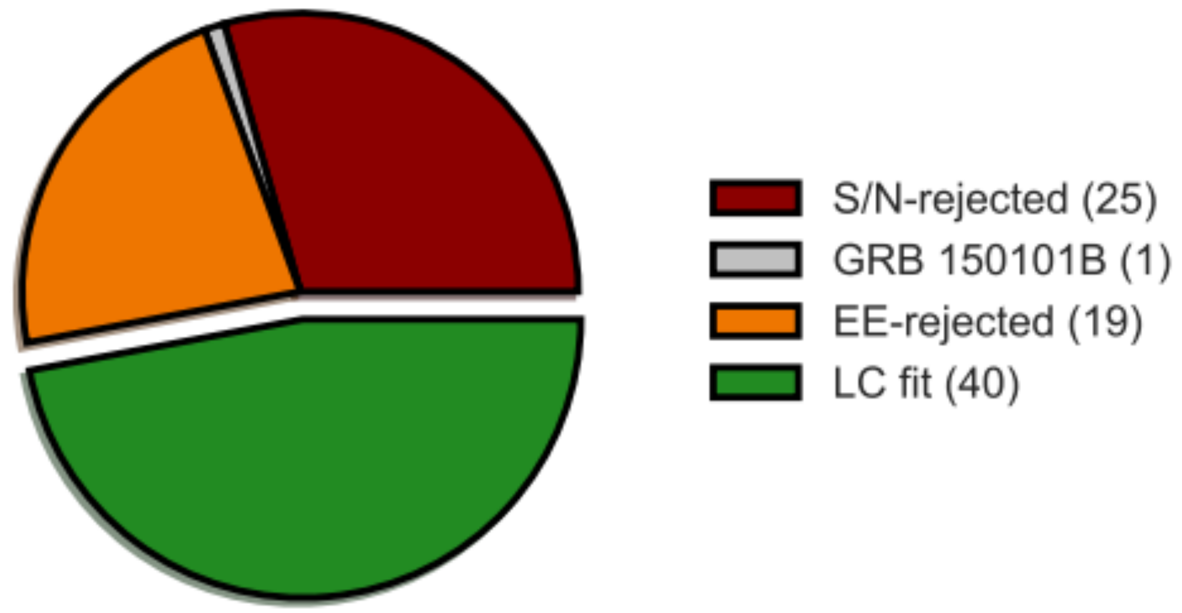
- With respect to the whole analysed sample (85): **15%**
- By excluding from the sample the “inconclusive” ones (25 low S/N + 150101B) and the EE (40): **32.5%**

GRB name							
051221A							
060614							
070714B							
090510							
110402A							
130603B							
140903A	0.3529	4.0	(32 ± 4)	(8 ± 0.3)	4.5 ± 1.2	56	36
150424A	0.3	4.3	(36 ± 4)	(16 ± 1)	13 ± 3	243	115
151229A	0.63	5.0	(67 ± 9)	(4.3 ± 0.9)	0.3 ± 0.1	142	56
161001A	0.67	5.0	(47 ± 6)	(4.2 ± 0.2)	0.5 ± 0.1	88	54
170728B	1.272	3.5	(20 ± 1)	(1.50 ± 0.03)	0.39 ± 0.04	232	193
210323A	0.733	2.9	(51 ± 11)	(8.7 ± 0.6)	2.0 ± 0.9	62	18
211211A	0.0763	6.9	(286 ± 26)	(27 ± 1)	0.6 ± 0.1	779	265

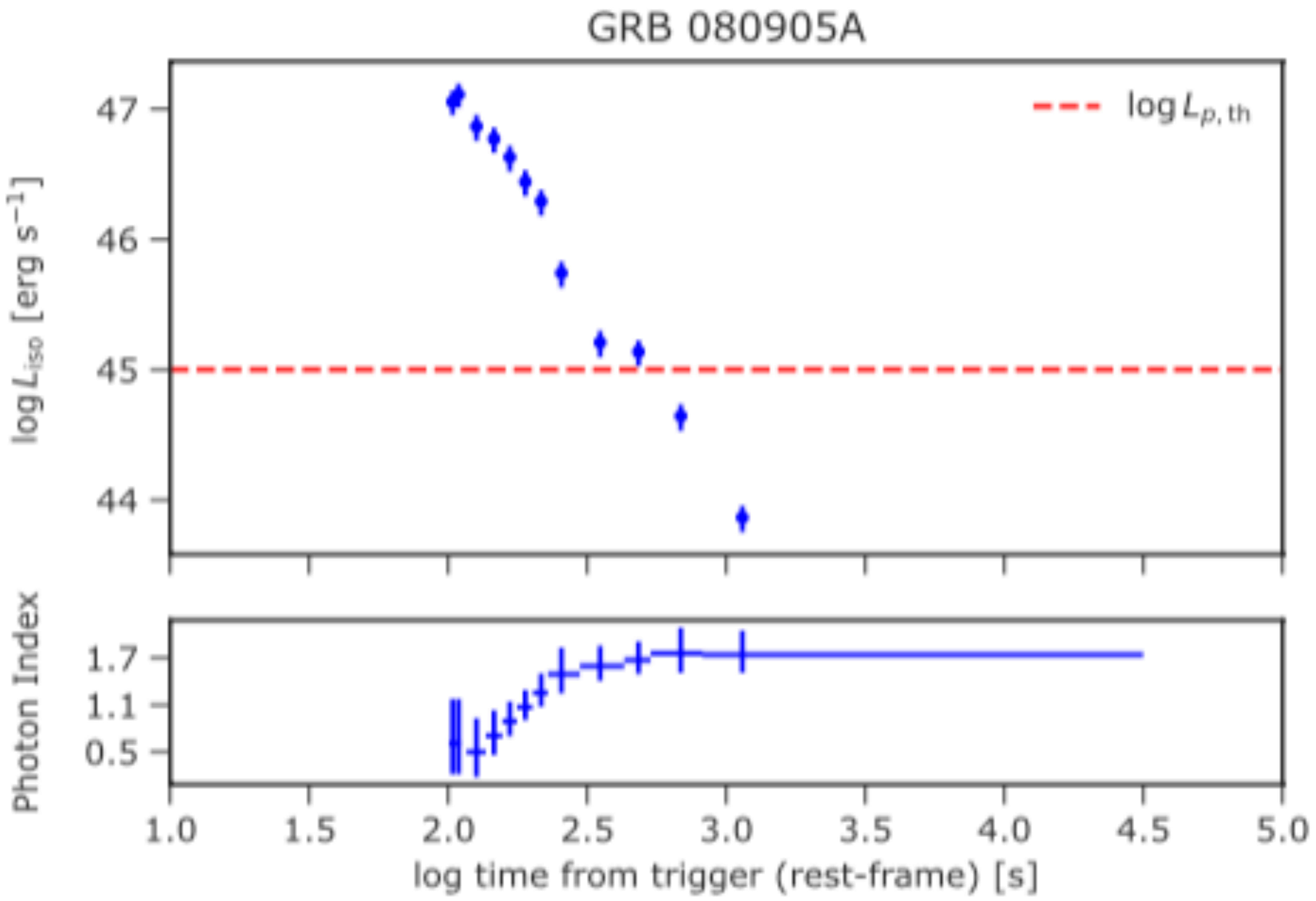
Two discarded events:
- GRB180618A has too short plateau duration to allow model parameter estimates
- GRB061201 provided not plausible B and P values (B>5.6x10^{16}G, P>38ms)

Guglielmi+2024

“EE-rejected”: excluding the presence of a magnetar



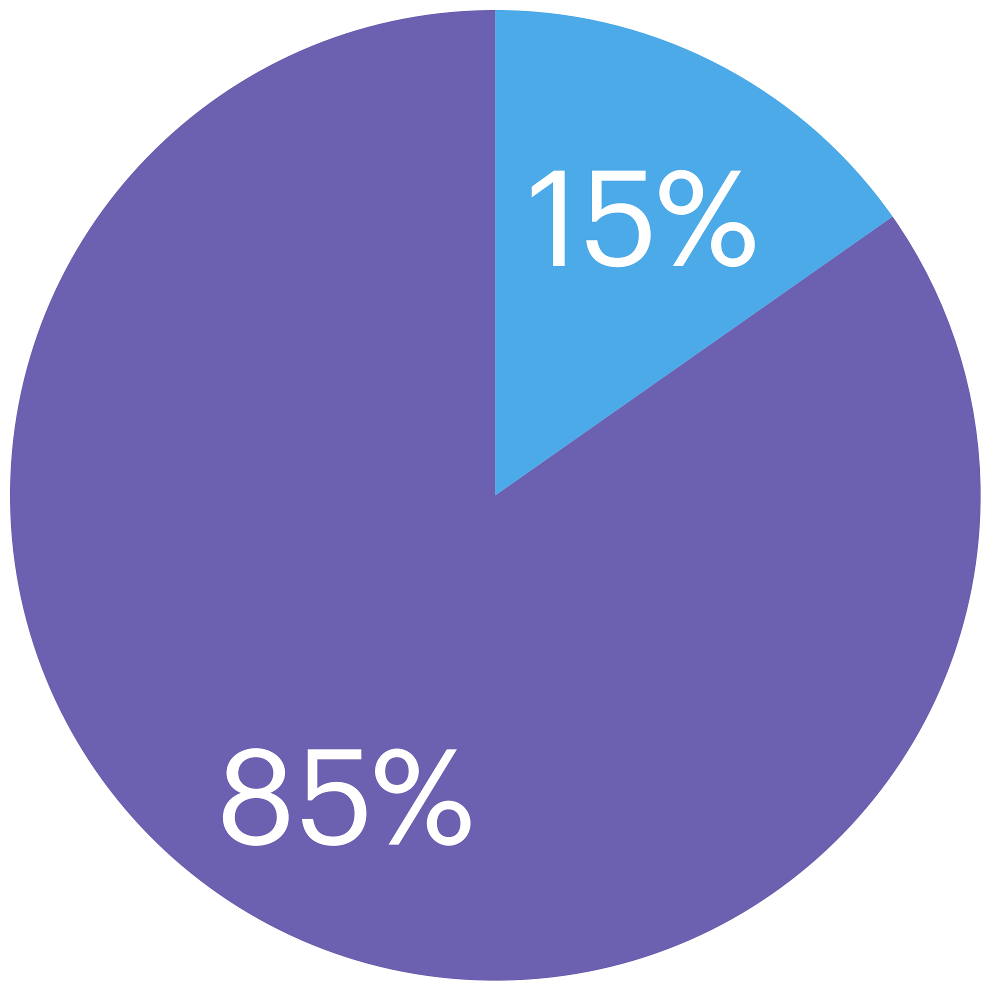
- If a magnetar remnant is formed, we can define a plausible **minimum spin-down luminosity Lmin ~ 3x10^{45} erg/s** by assuming:
  - Maximum spin-down timescales of ~10^{5} s
  - Maximum spin period of P ~ 30 ms, corresponding to a rotational energy of ~3x10^{49} erg
- Following Dall’Osso et al. 2023, we also compare the minimum luminosity detected with XRT with the prompt emission luminosity, excluding ratios larger >30
- We found that 9/19 “EE” light curves, clearly show fainter fluxes, incompatible with the presence of a magnetar
- The remainder **10 EE events were declared “inconclusive”**



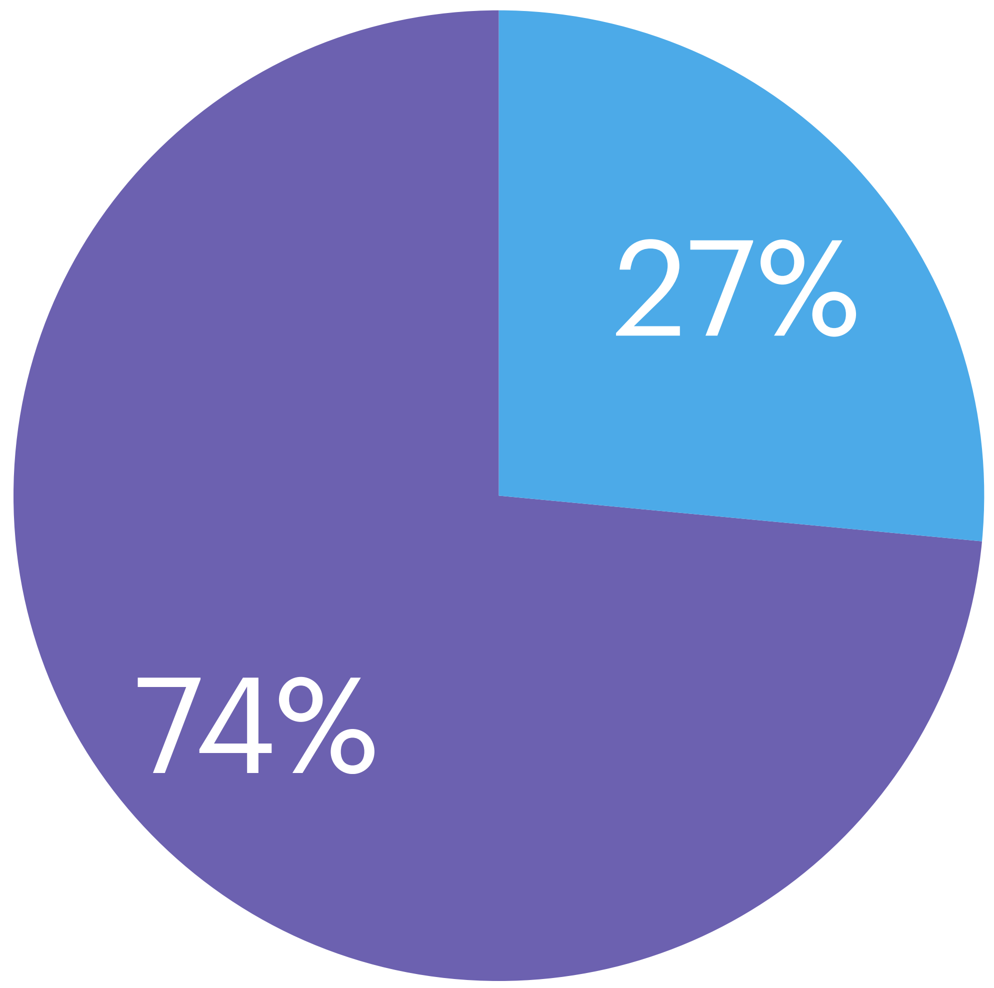
Guglielmi+2024

Summary

- 15 GRBs show an X-ray plateau
- For 13 events, plateau is compatible with the magnetar scenario
  - With respect to the whole analysed sample (85): **15%**
  - By excluding from the sample the "inconclusive" ones (25 low S/N + 150101B + 10 "EE") (49): **26.5%**

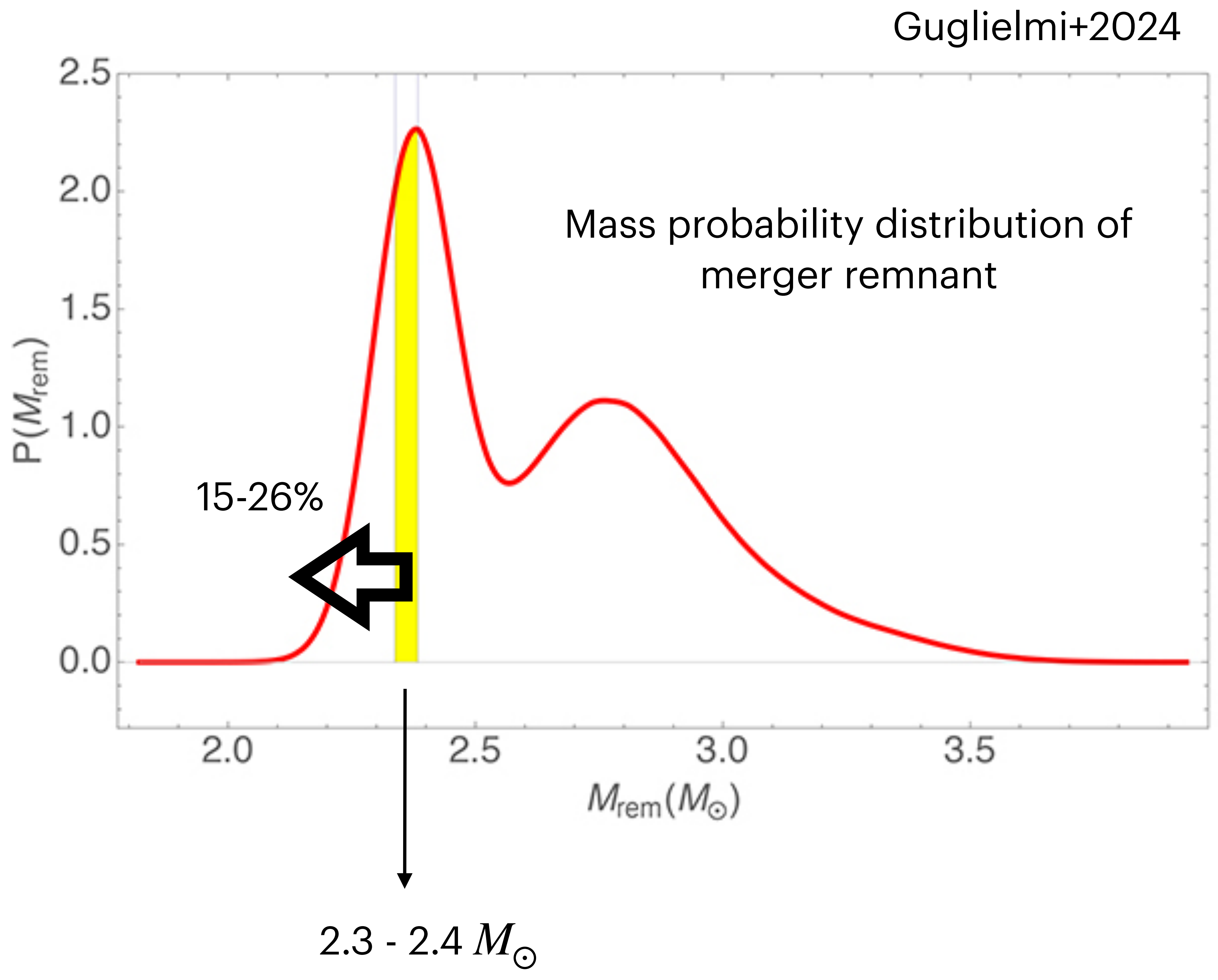


~ 1/6



~ 1/4

Compatibility with predicted NS maximum mass



- We computed the **probability distribution of remnant mass** by adopting a double-peaked Gaussian for the mass distribution of NSs in binaries
- The percentage of GRB compatible with a magnetar remnant (15-26%) is reached for a remnant mass of Mrem=(2.31–2.41) $M_\odot$
- Depending on the NS stability Mrem>~M_{TOV} -> compatible with most M_{TOV} estimates so far (e.g. Margalit et al. 2022)

Conclusions

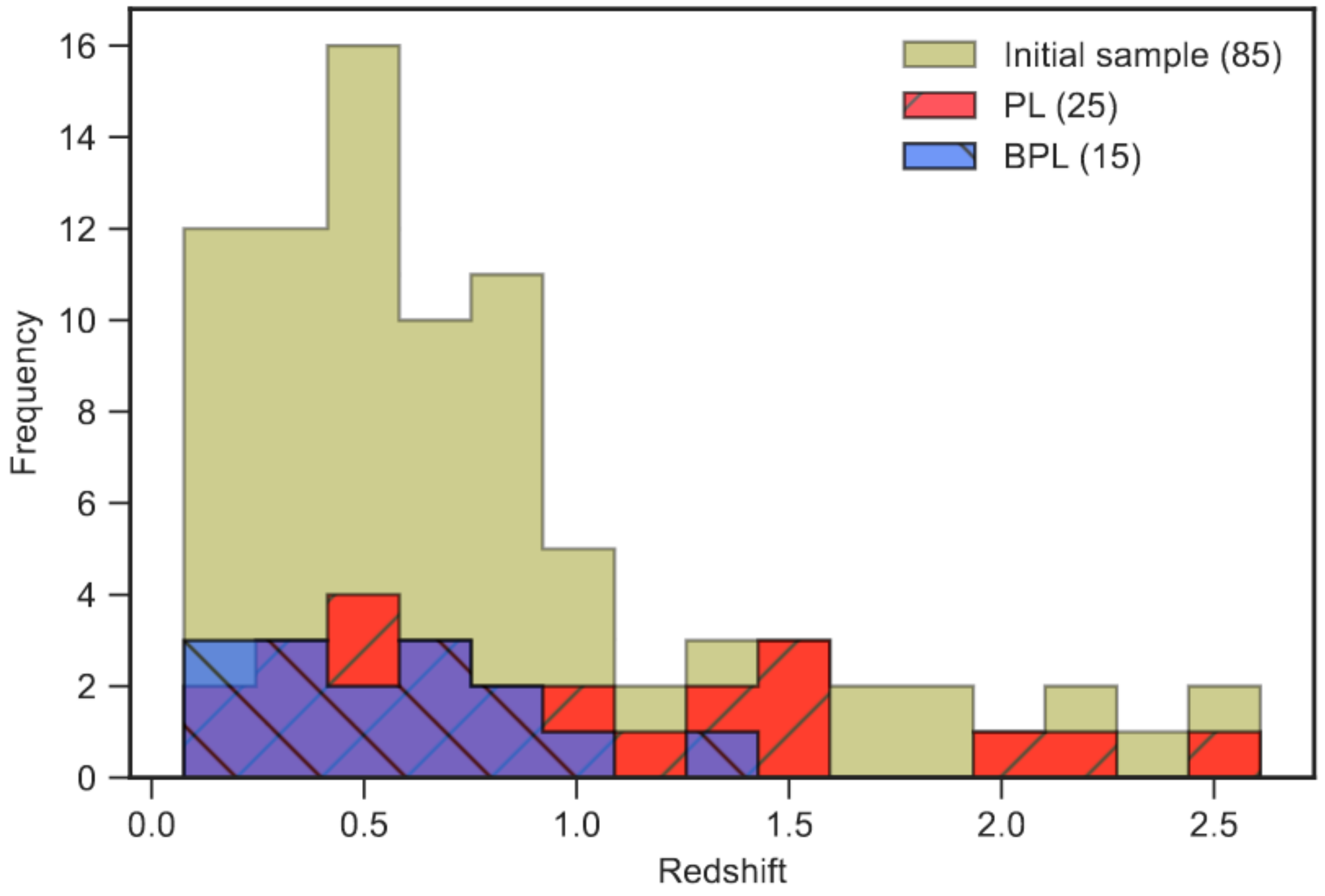
- GRB **X-ray afterglow plateaus likely indicate the presence of a magnetar remnant -> potential FRB sources** where to look at given the accurate sky localisation from afterglow MW campaigns

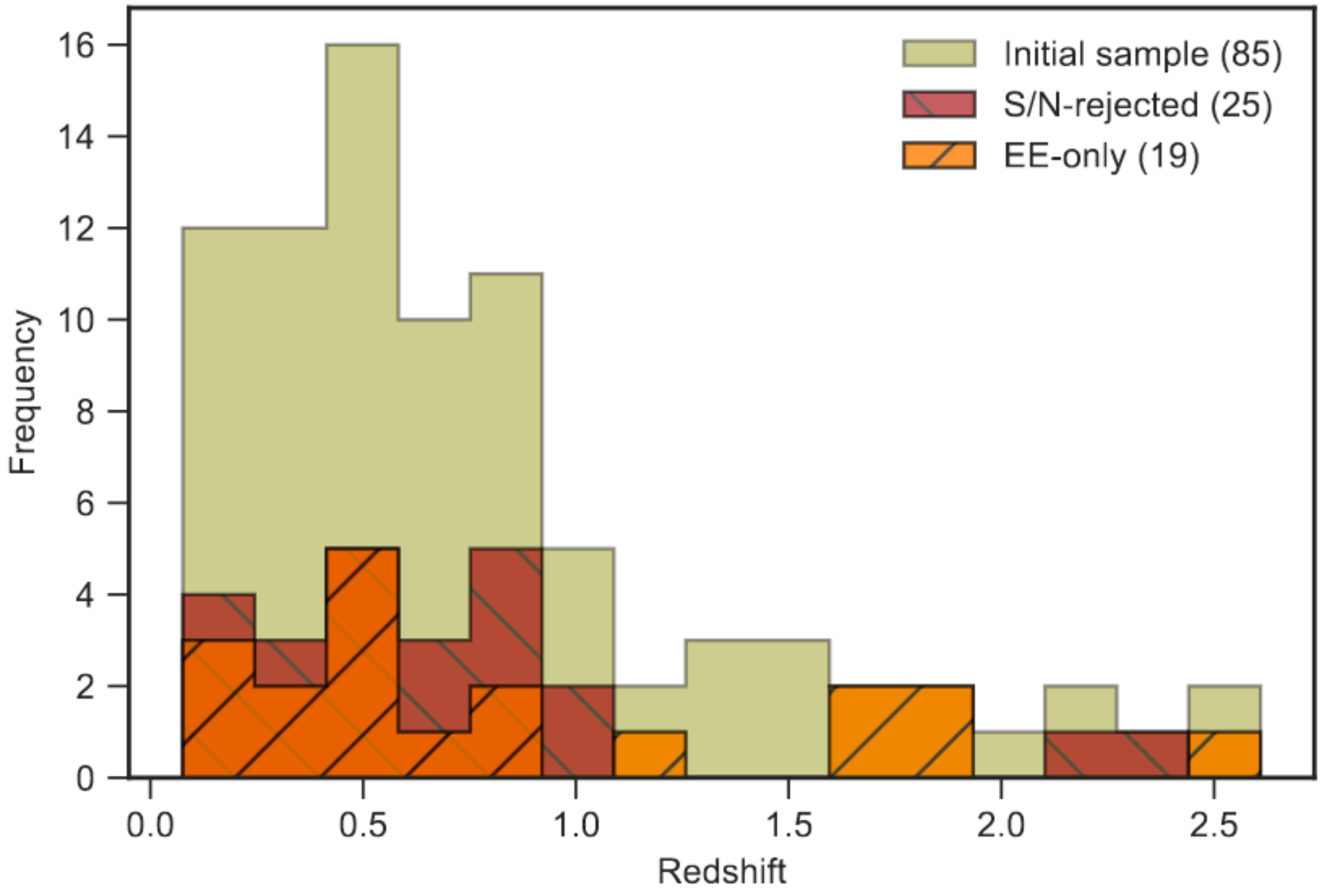
- By analyzing all Swift Type II GRBs detected from 2005 to 2021 with known redshift, we found that **a fraction of ~ 1/6 - 1/4 is compatible with originating a magnetar remnant**

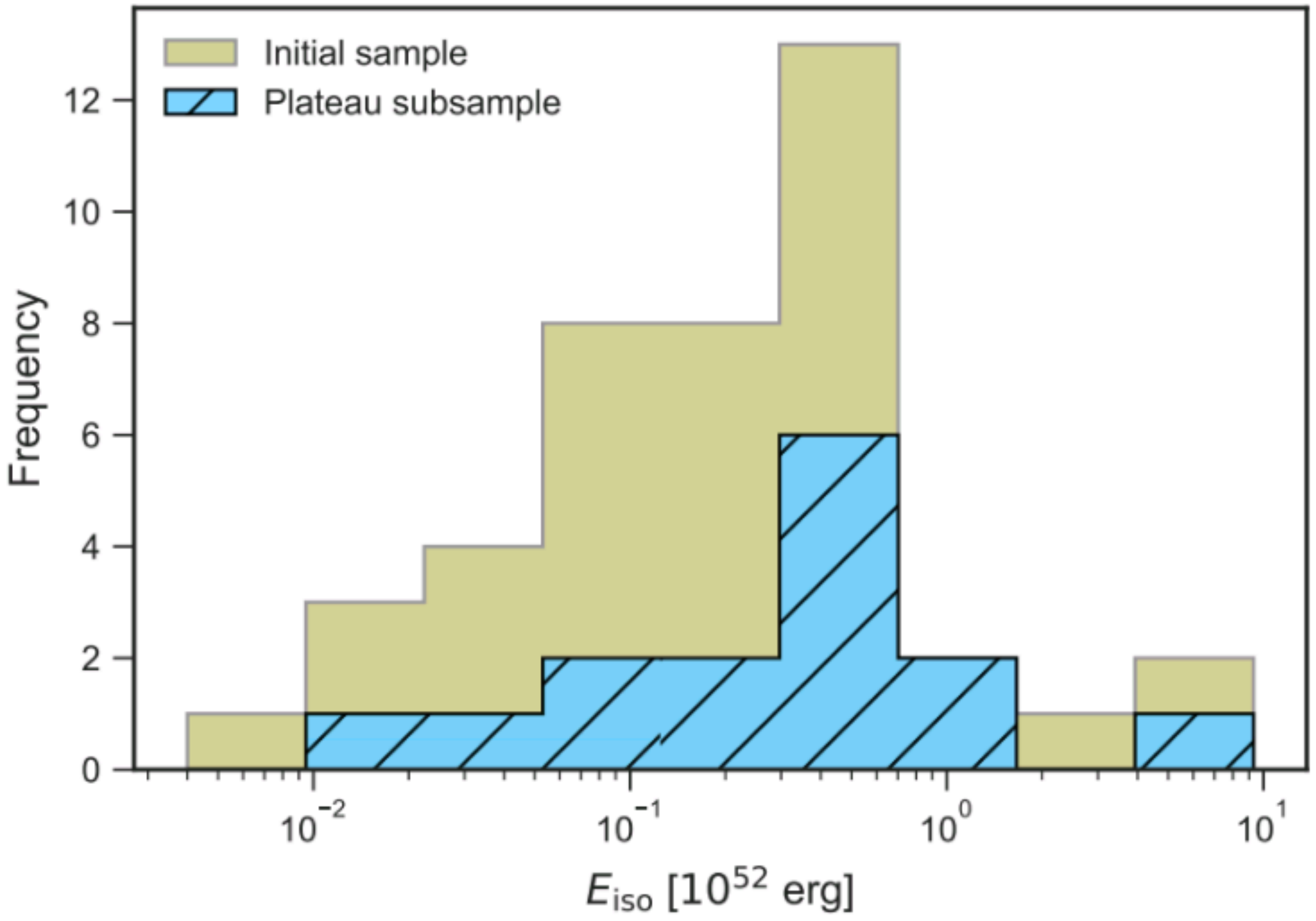
- **Larger samples of identified magnetars can be achieved with future BNS merger and post-merger detections with next generation GW interferometers (as ET)**, for which accurate sky localisation will be provided through not collimated **Kilonova** counterparts (e.g. Loffredo et al. 2025)

Thank you :)

Extra slides

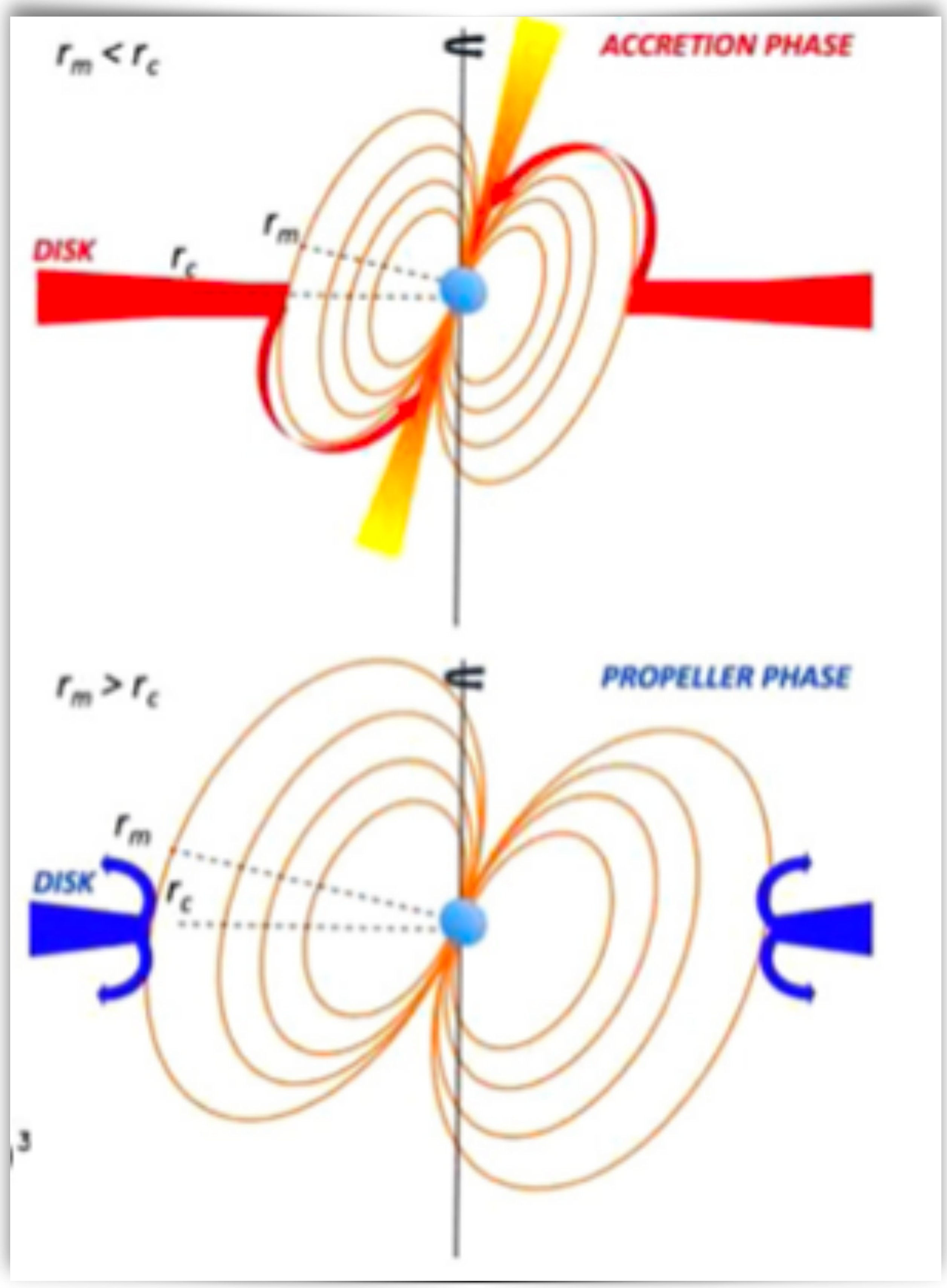


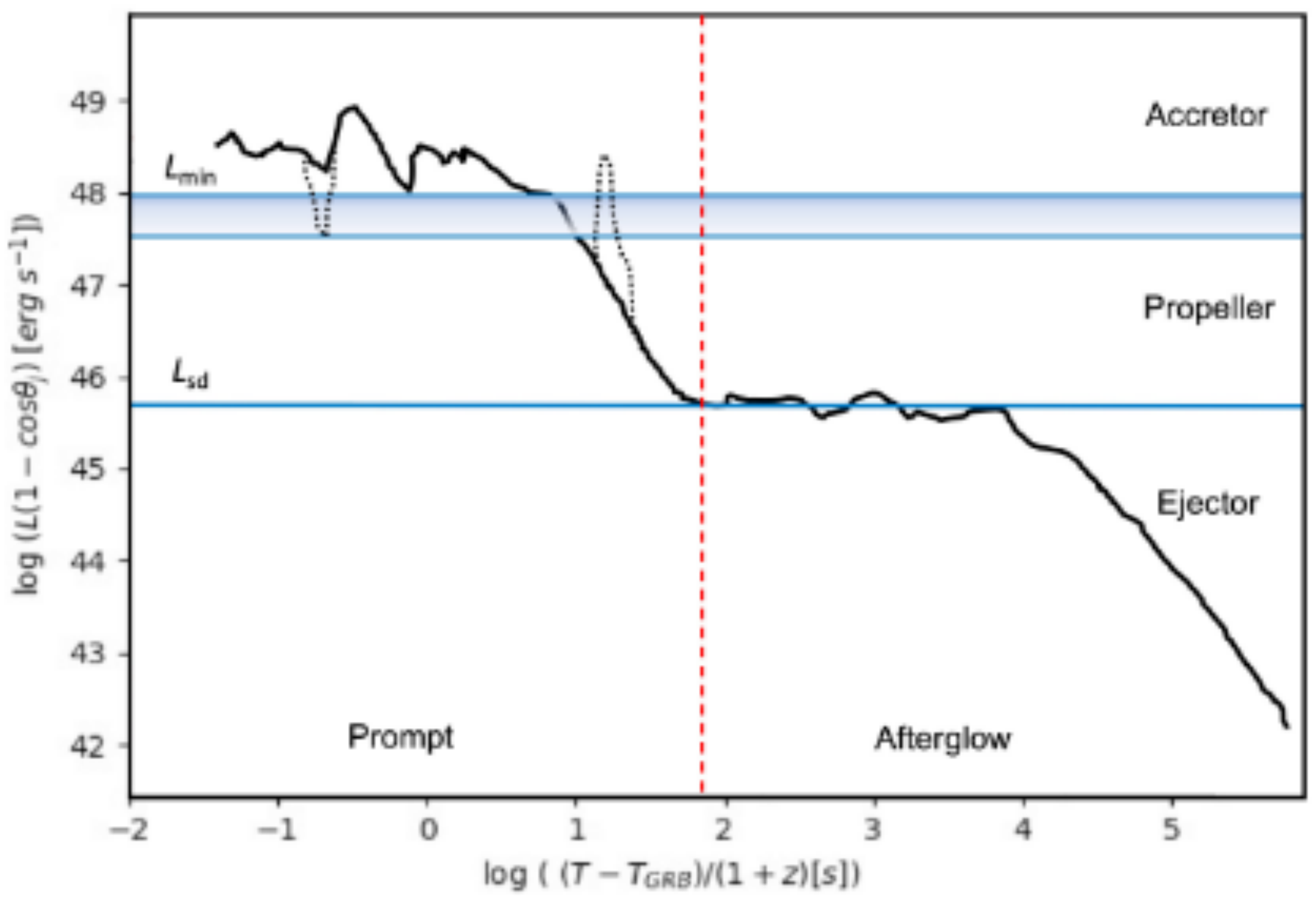


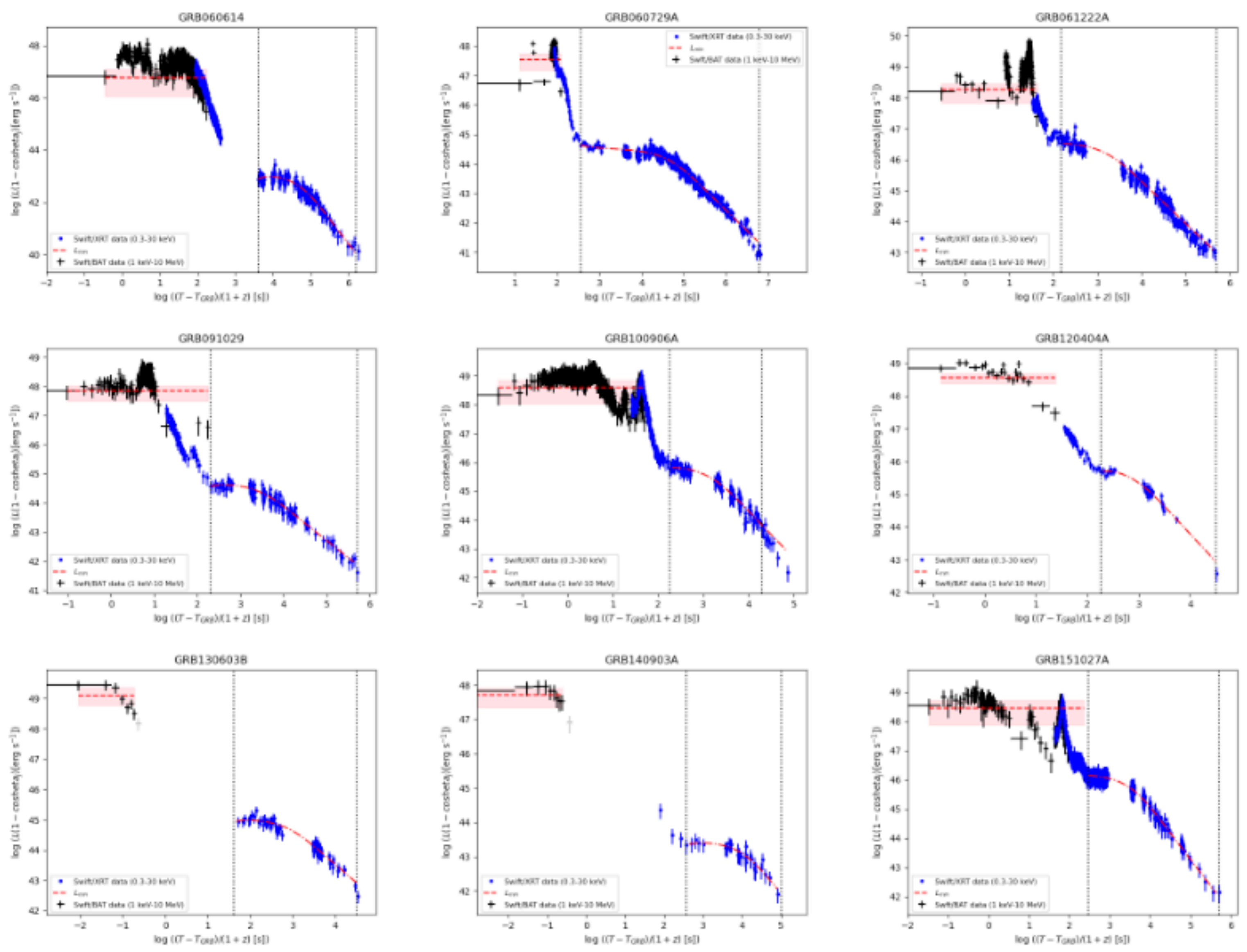


The events with / without plateau, including the faintest ones ("inconclusive"), have similar redshift and energy distribution, suggesting that the lack of plateau evidence is not due to biases against distant or faint events

Guglielmi+2024







$$\kappa = L_{\rm min}/L_{\rm sd} \approx 1.2\times10^5 \epsilon P^{5/3} \left(R_6 M_{1.4}^{2/3}\right)^{-1} (\xi/0.5)^{7/2}$$

EE events with k>30 are incompatible with harbouring a magnetar

Bernardini+2015

Dall'Osso, Stratta et al. 2023