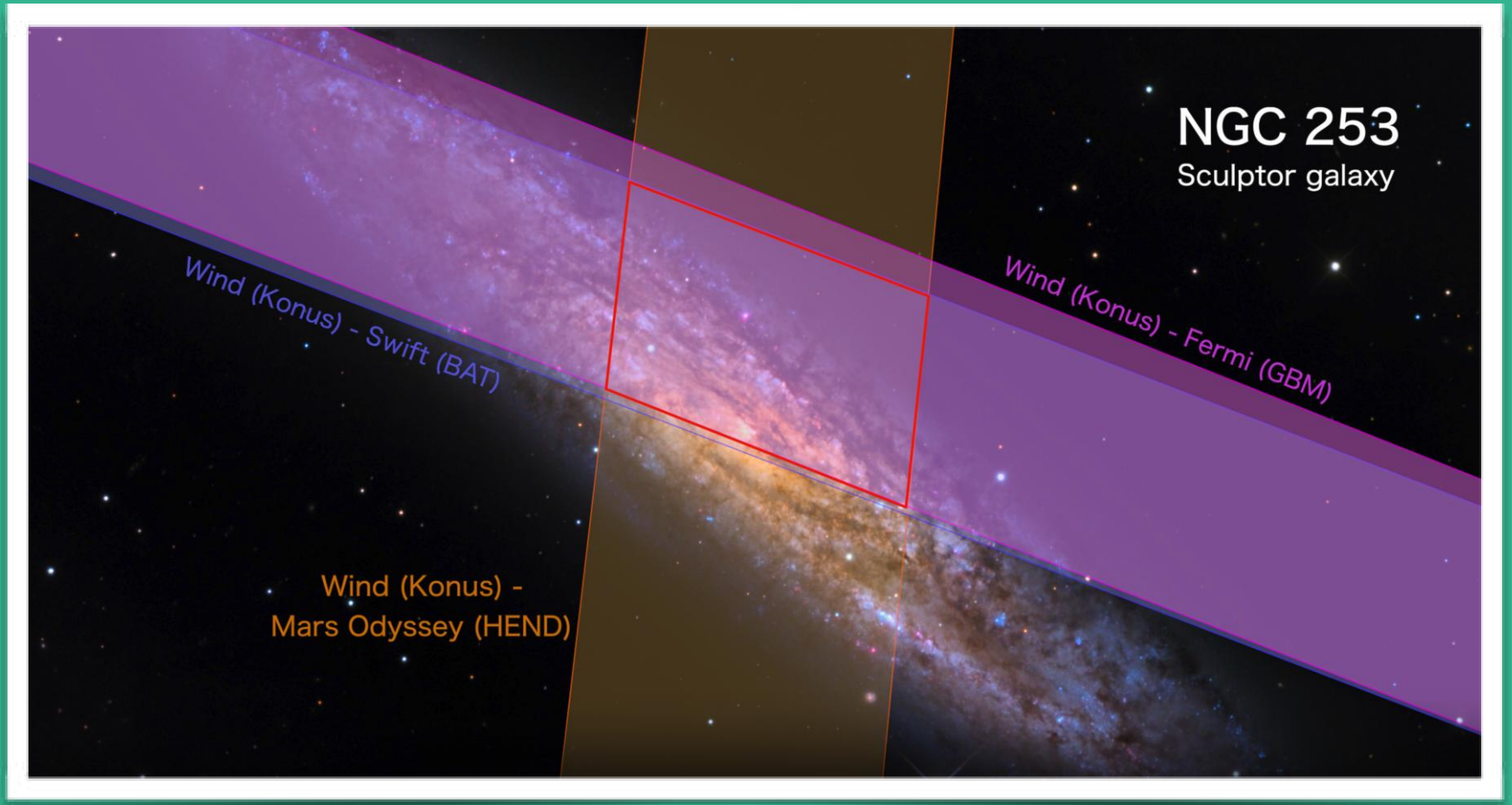
New Understandings of Gamma-ray Burst Origins & Mechanisms

Binbin Zhang
Nanjing University

The 32nd Texas Symposium on Relativistic Astrophysics
12/14/2023

Very recent new-type GRBs



GRB 200415A
GRB 231115A
+MGF
Yang, J+ 2020
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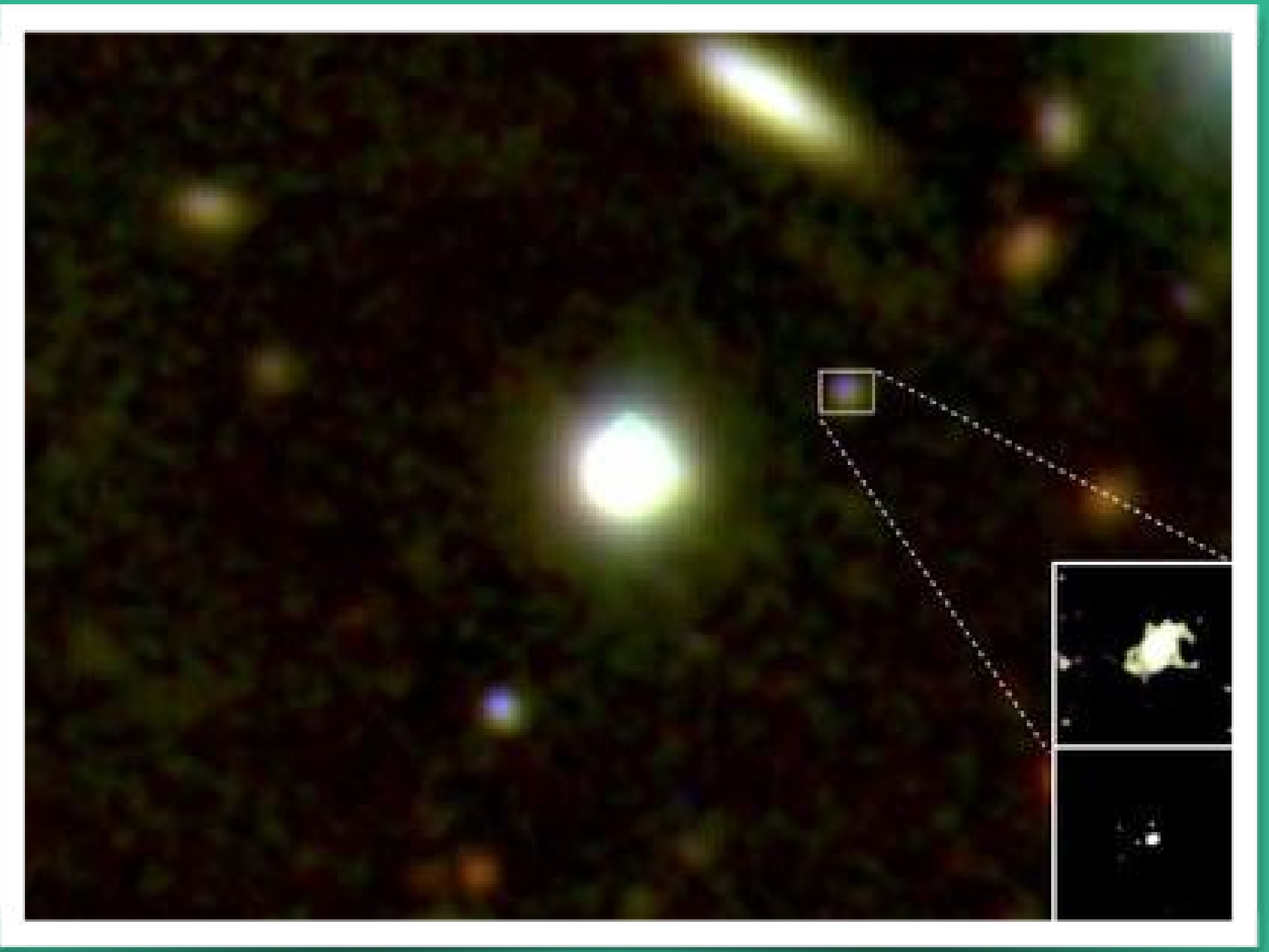

GRB 200826A
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Tomás +2021
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GRB 211211A
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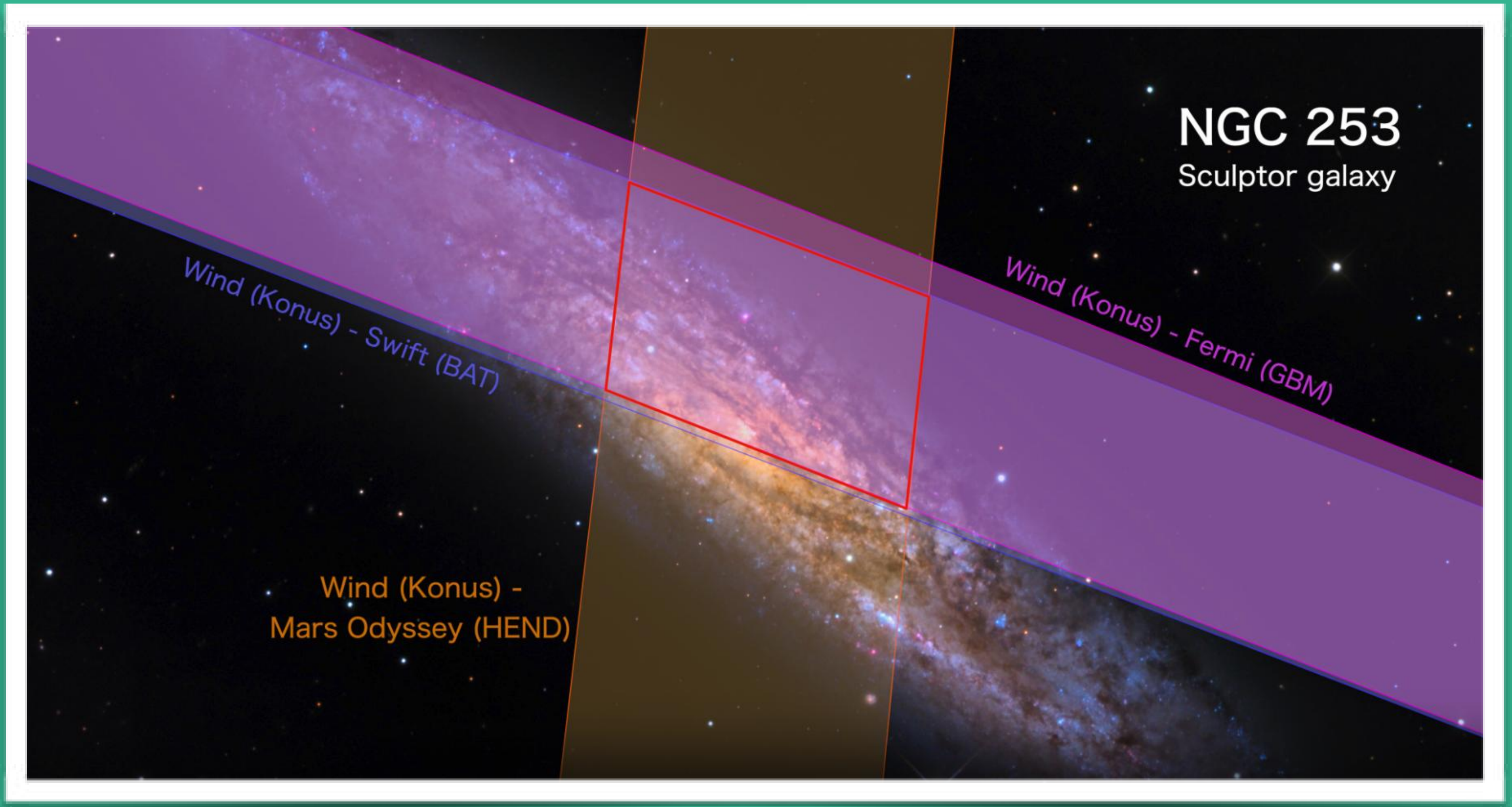

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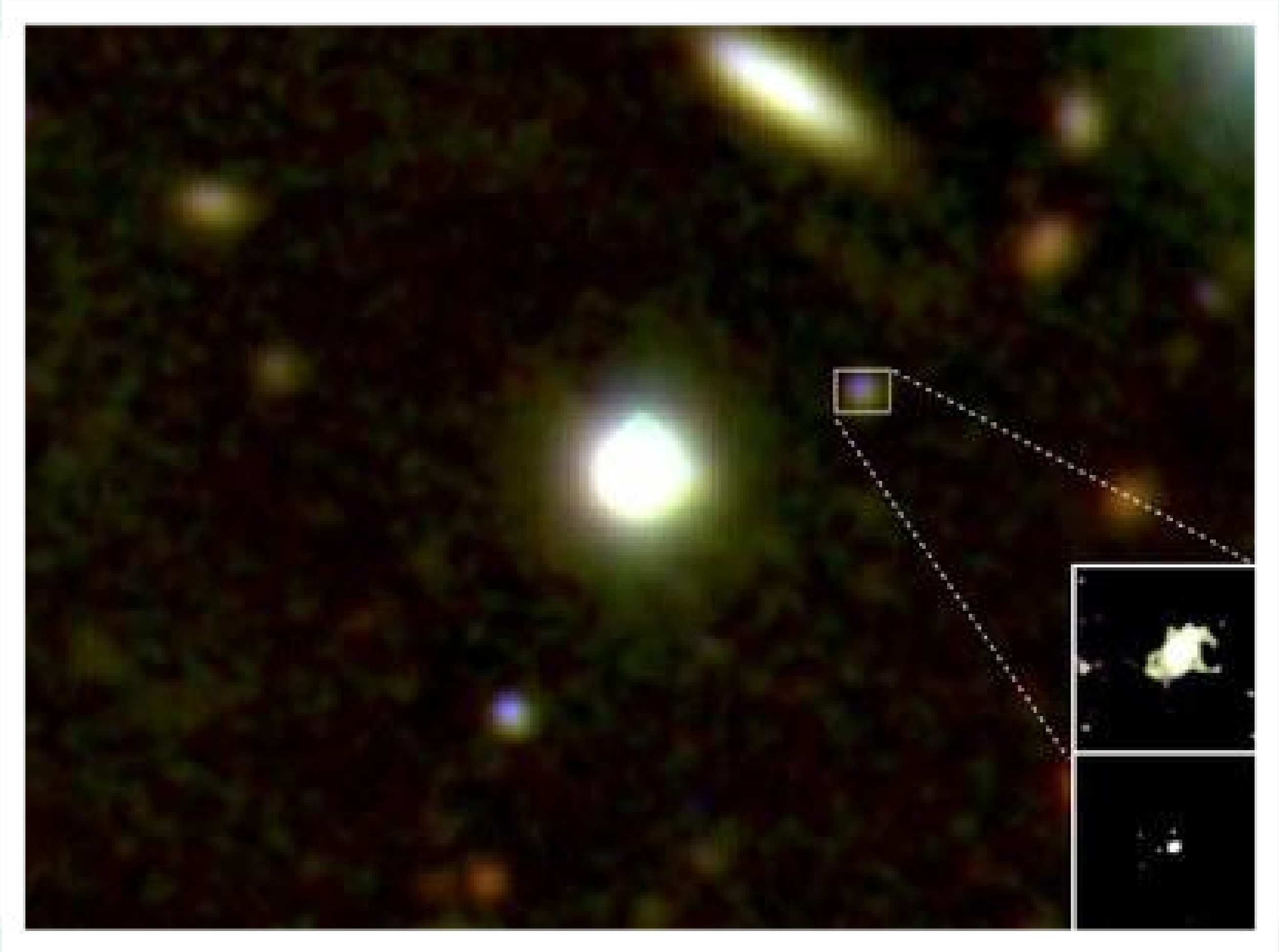

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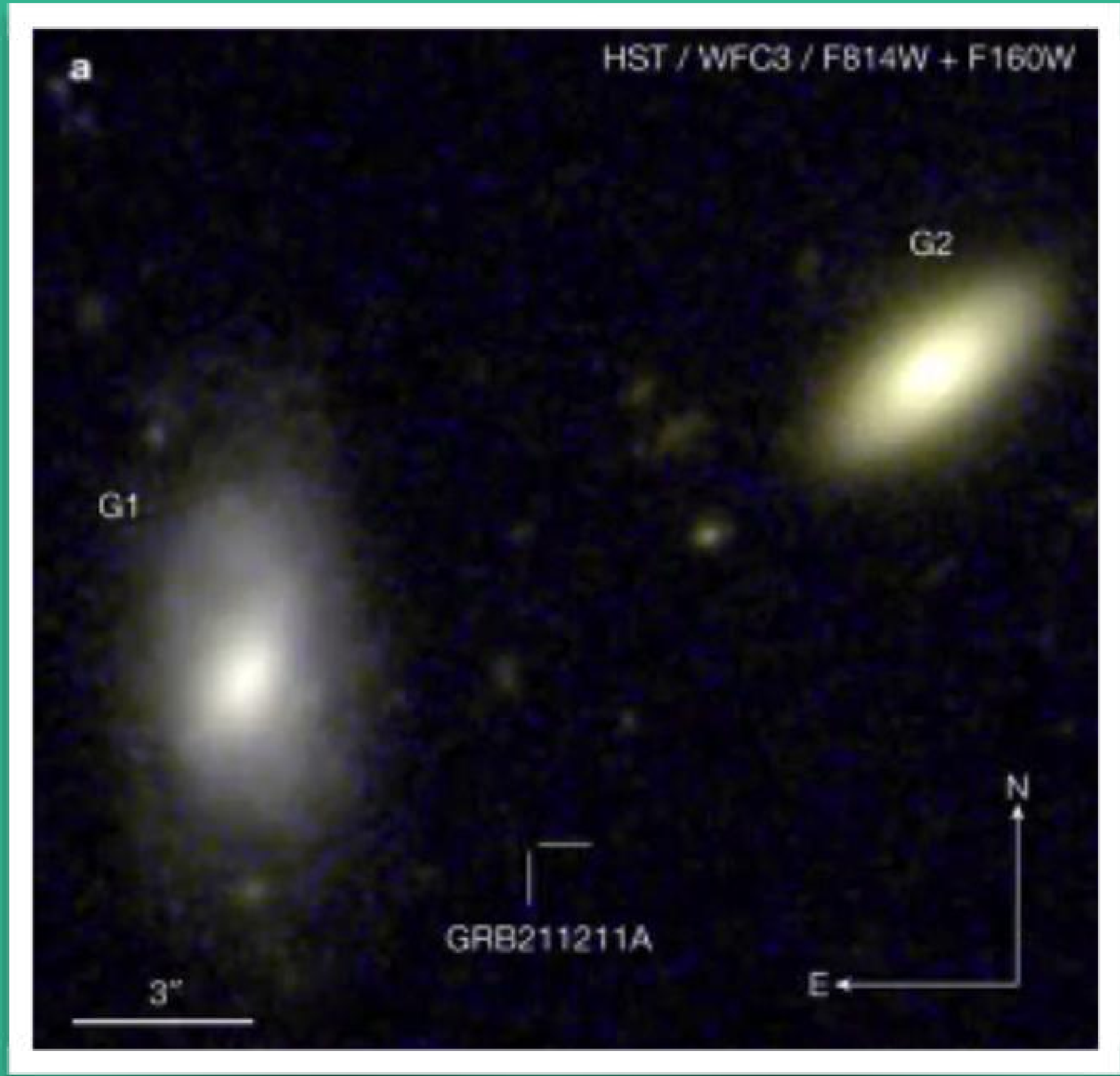

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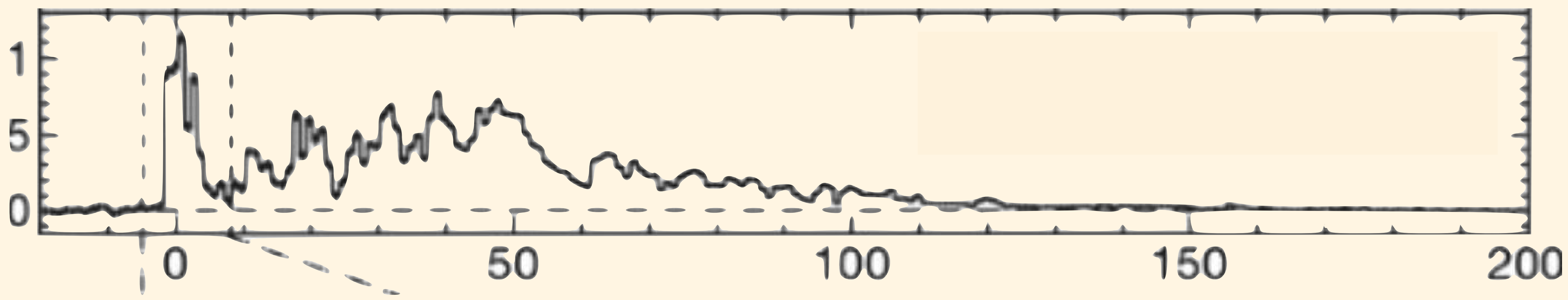
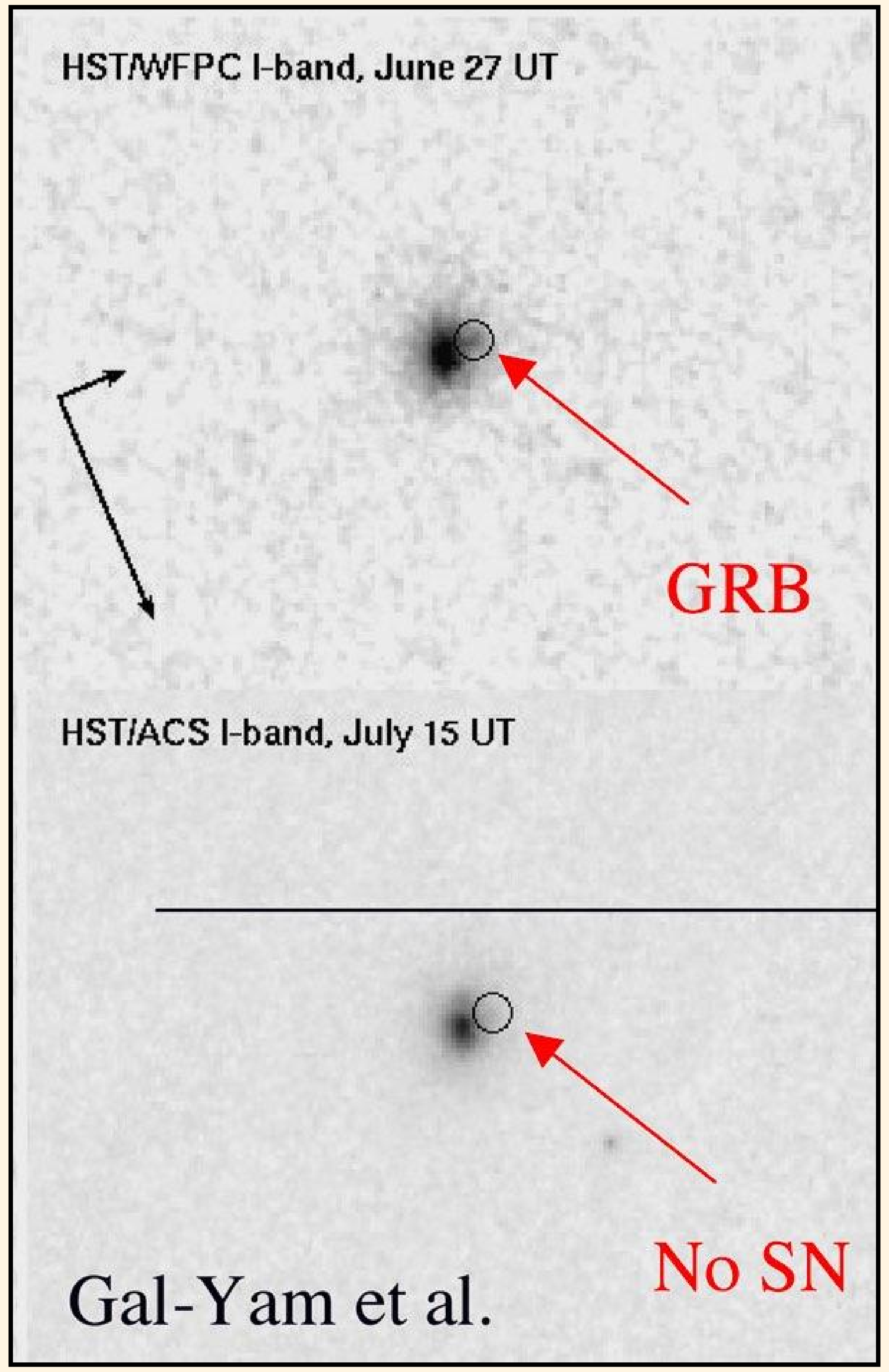
A (not-very-recent) new-type GRB 060614

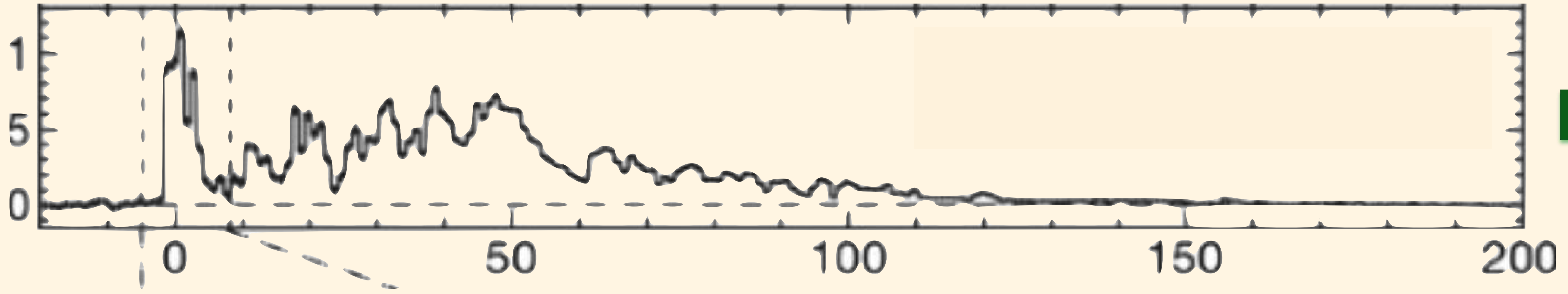


GRB 060614

- 6-s peak + 100-s tail
- no SN (so: merger)



A (not-very-recent) new-type GRB 060614 and efforts to explain it in the standard models

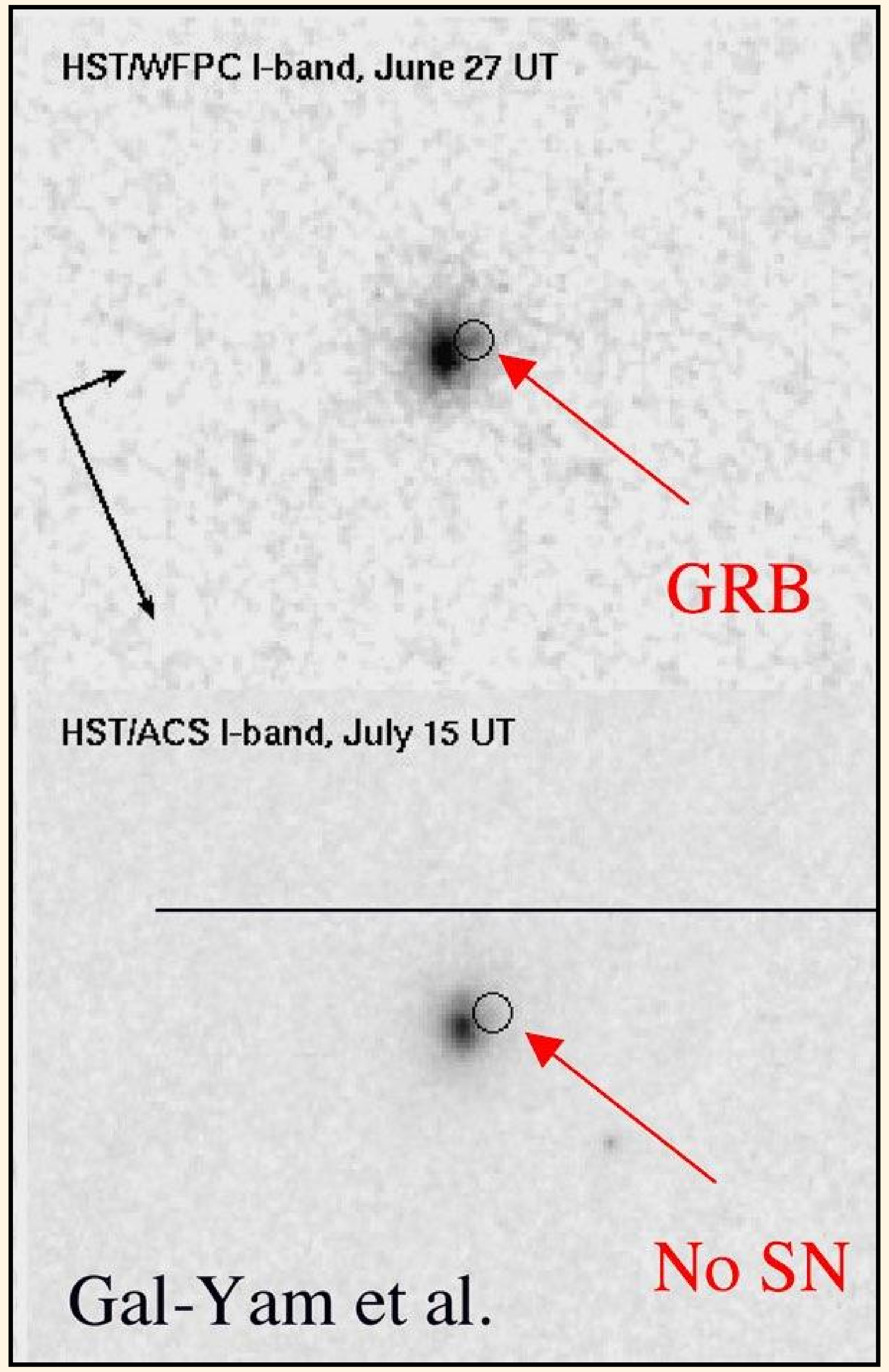


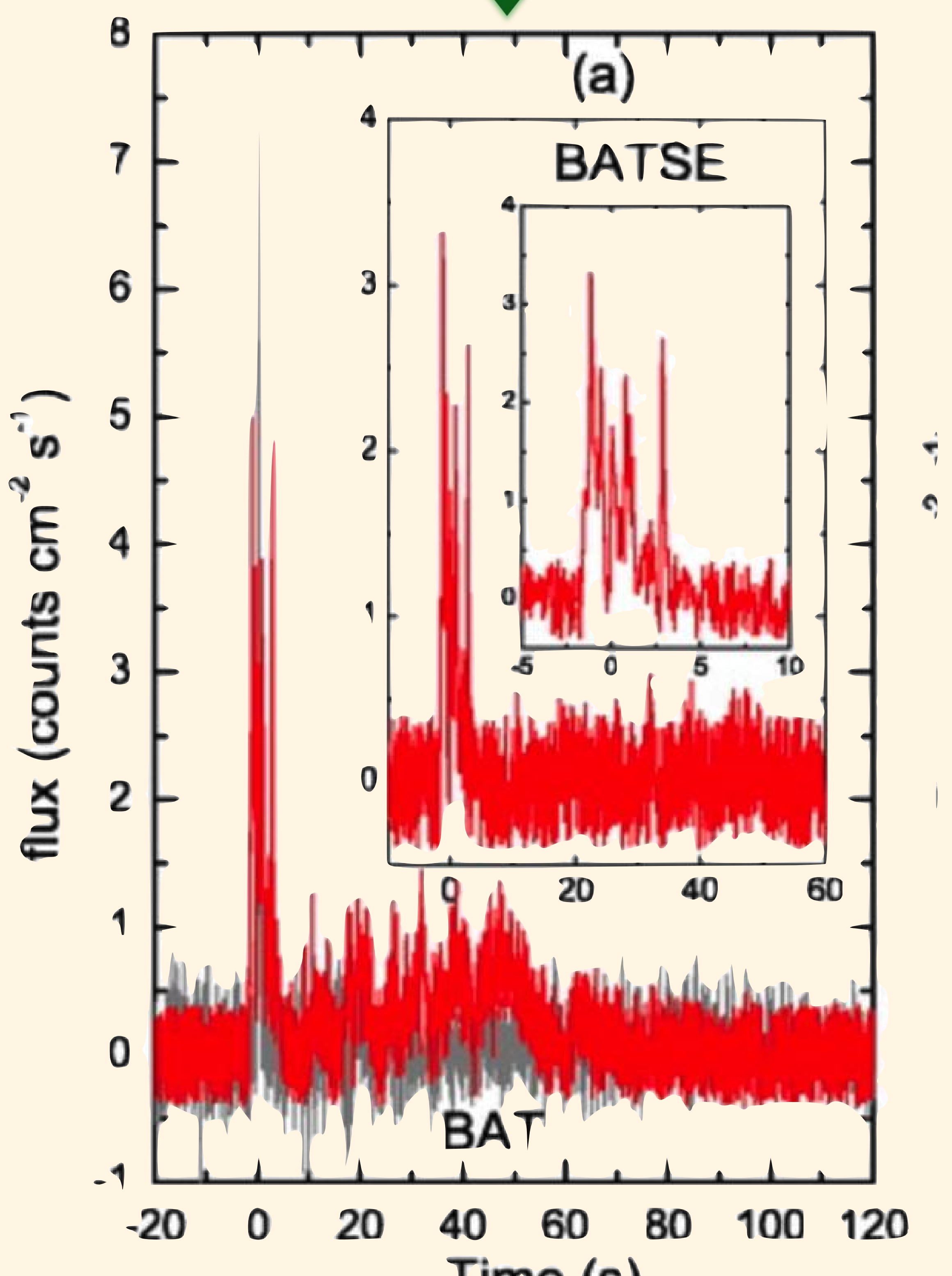
"Making a Short Gamma-Ray Burst from a Long One"

Zhang, B, Zhang, B.-B. et al. 2017, ApJL.

GRB 060614

- 6-s peak + 100-s tail
- no SN (so: merger)
- an evolving softer tail
- instrumental effects





Why were we so obsessed with making a merger event shorter?

because we do not have so much freedom in the central engine time scale *(if it is accretion powered)*:

$$t_{dur} \sim t_{acc} \geq t_{ff} \sim \left(\frac{3\pi}{32G\rho}\right)^{1/2}$$

For NS: $\rho = 10^{14} gcm^{-3}; t_{ff} \sim 0.2ms$

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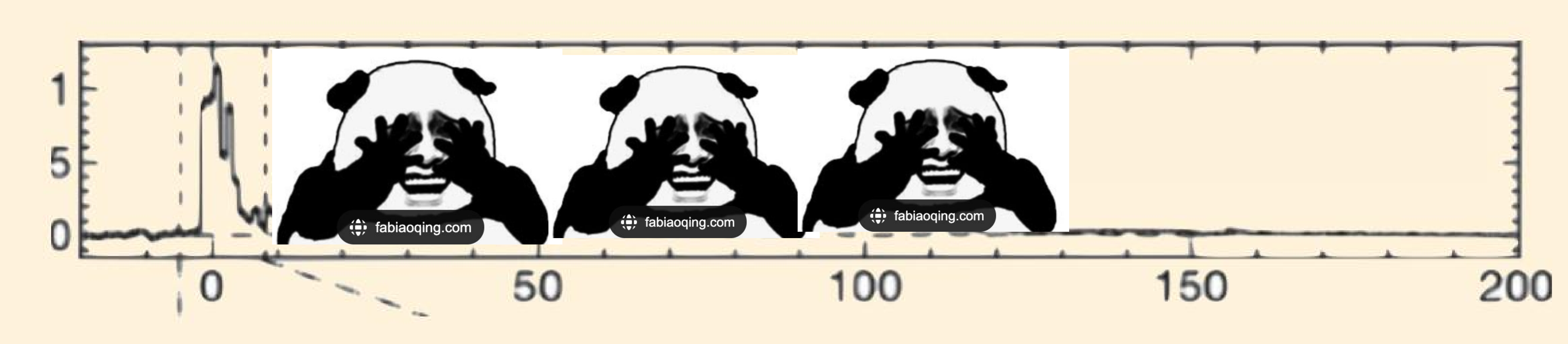

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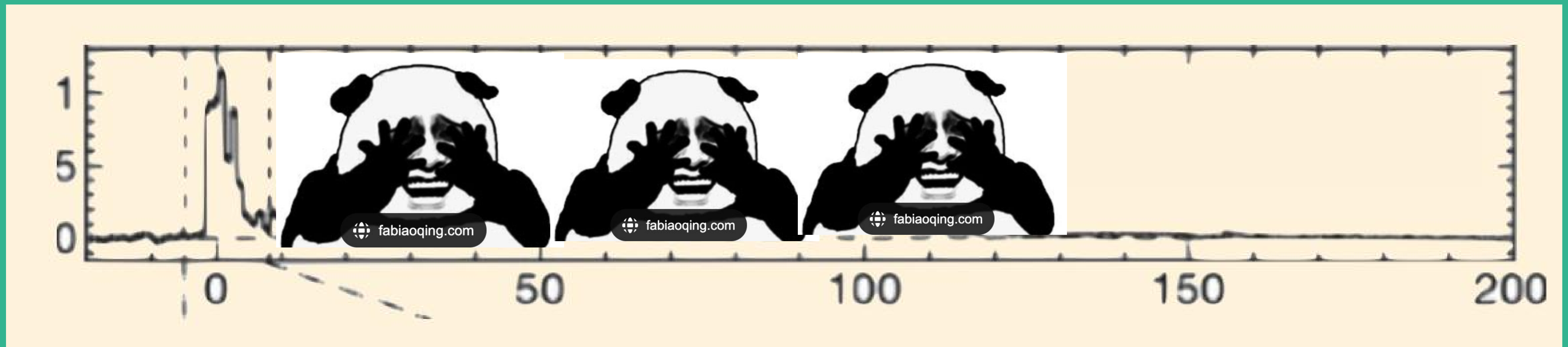
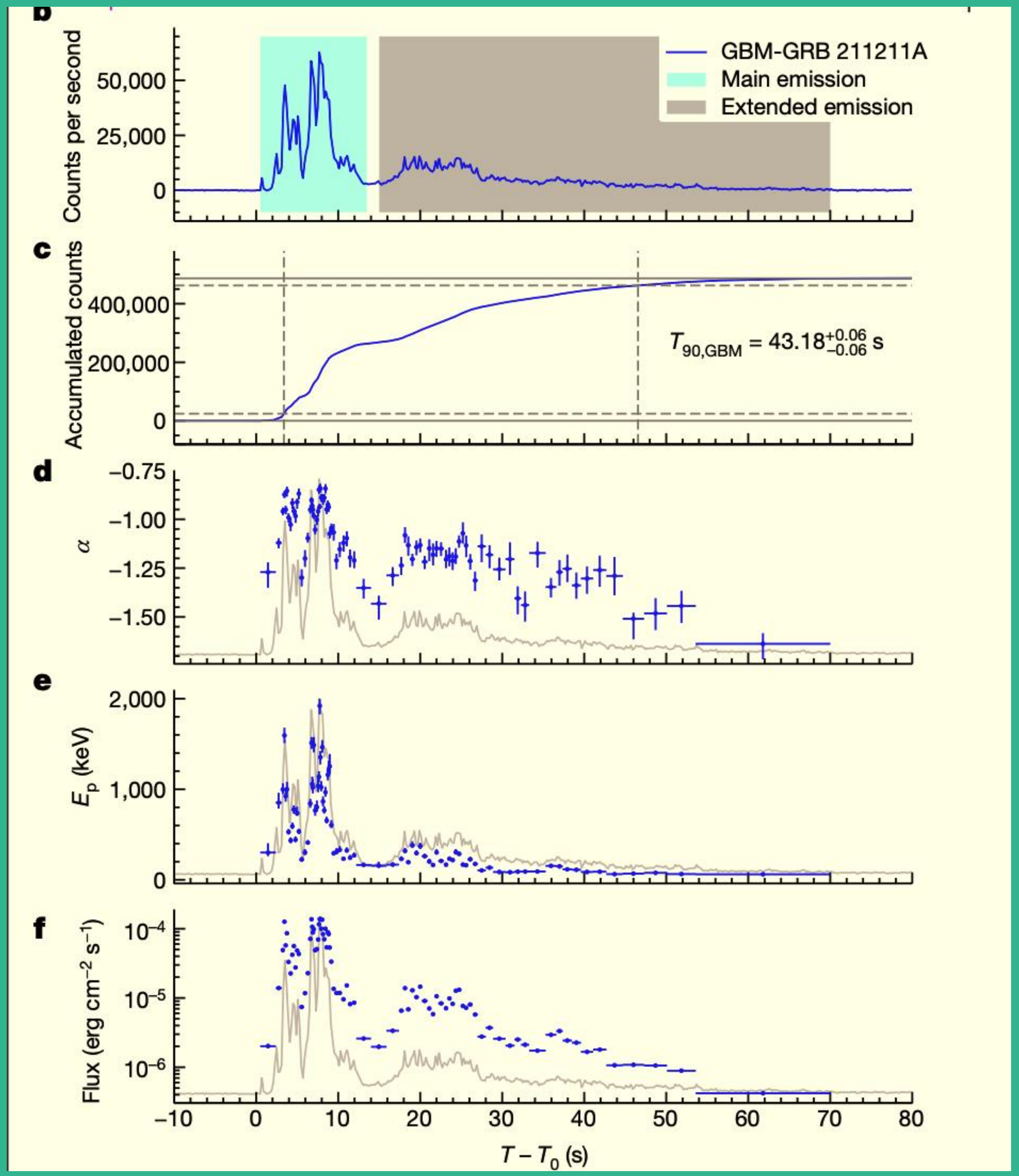


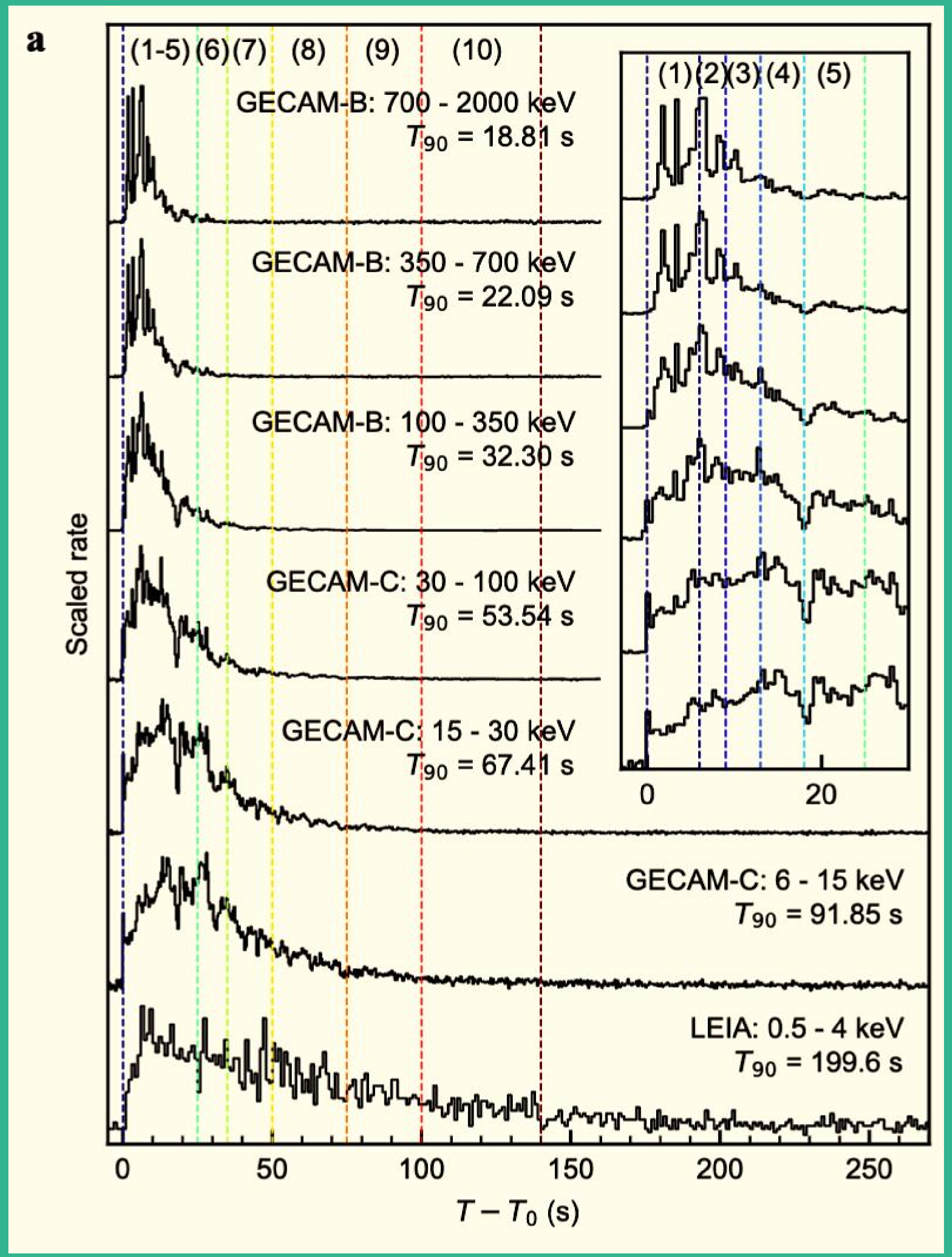
GRB 060614

But we can't ignore EE for these two (significant HE till EE):



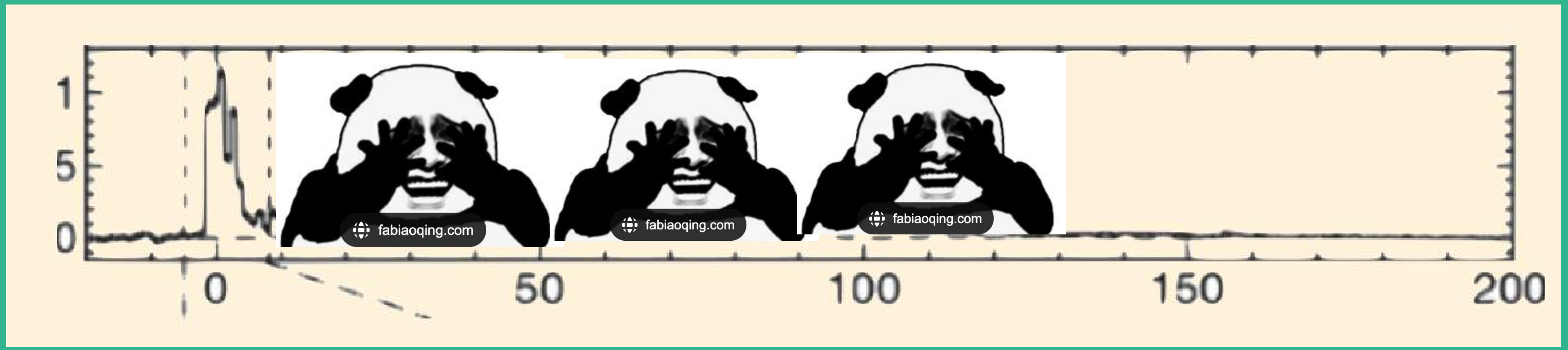
GRB 211211A

(Yang, et al. 2022, Nature)



GRB 230307A

(Sun, et al. 2023, Nature submitted)



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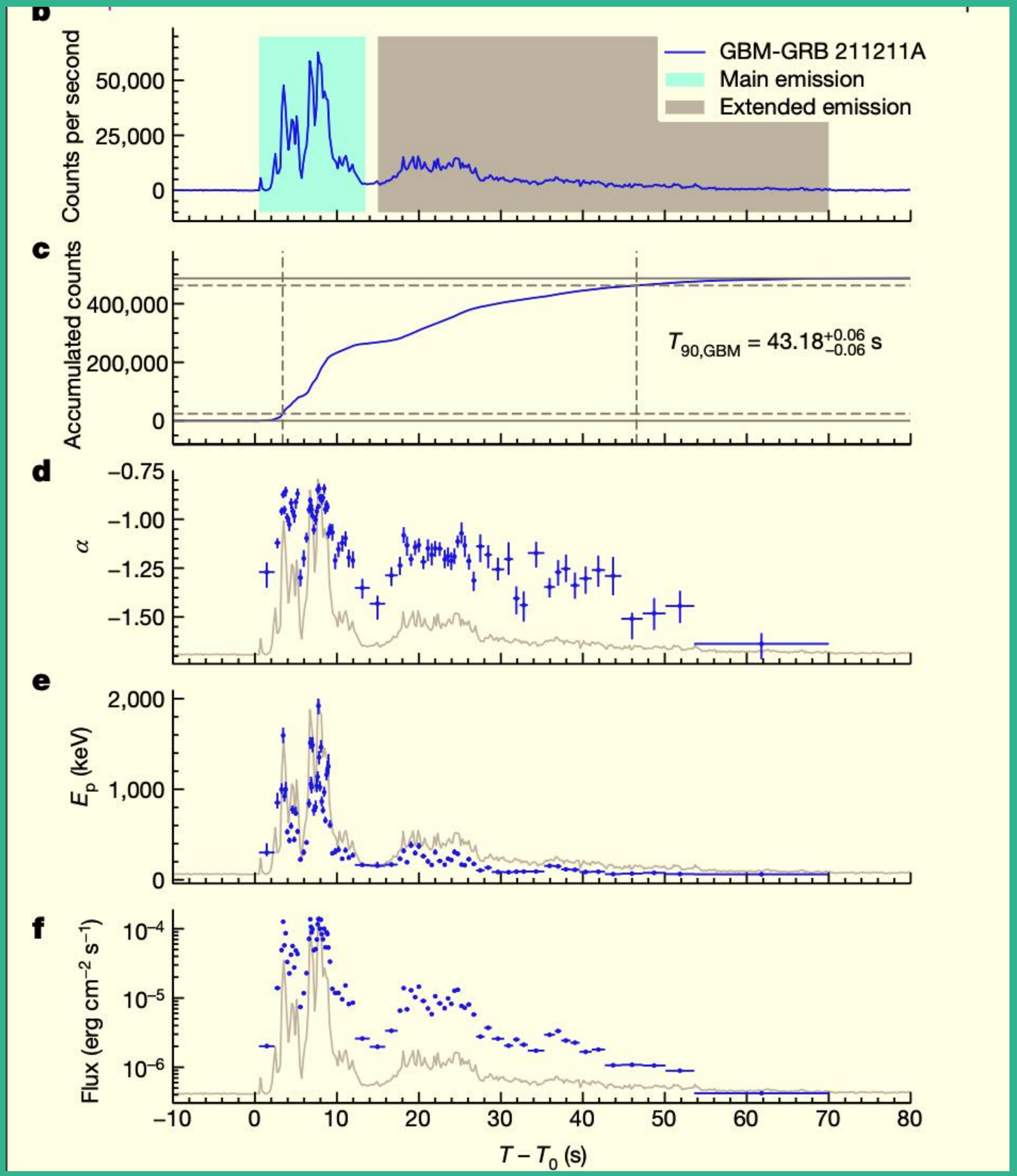

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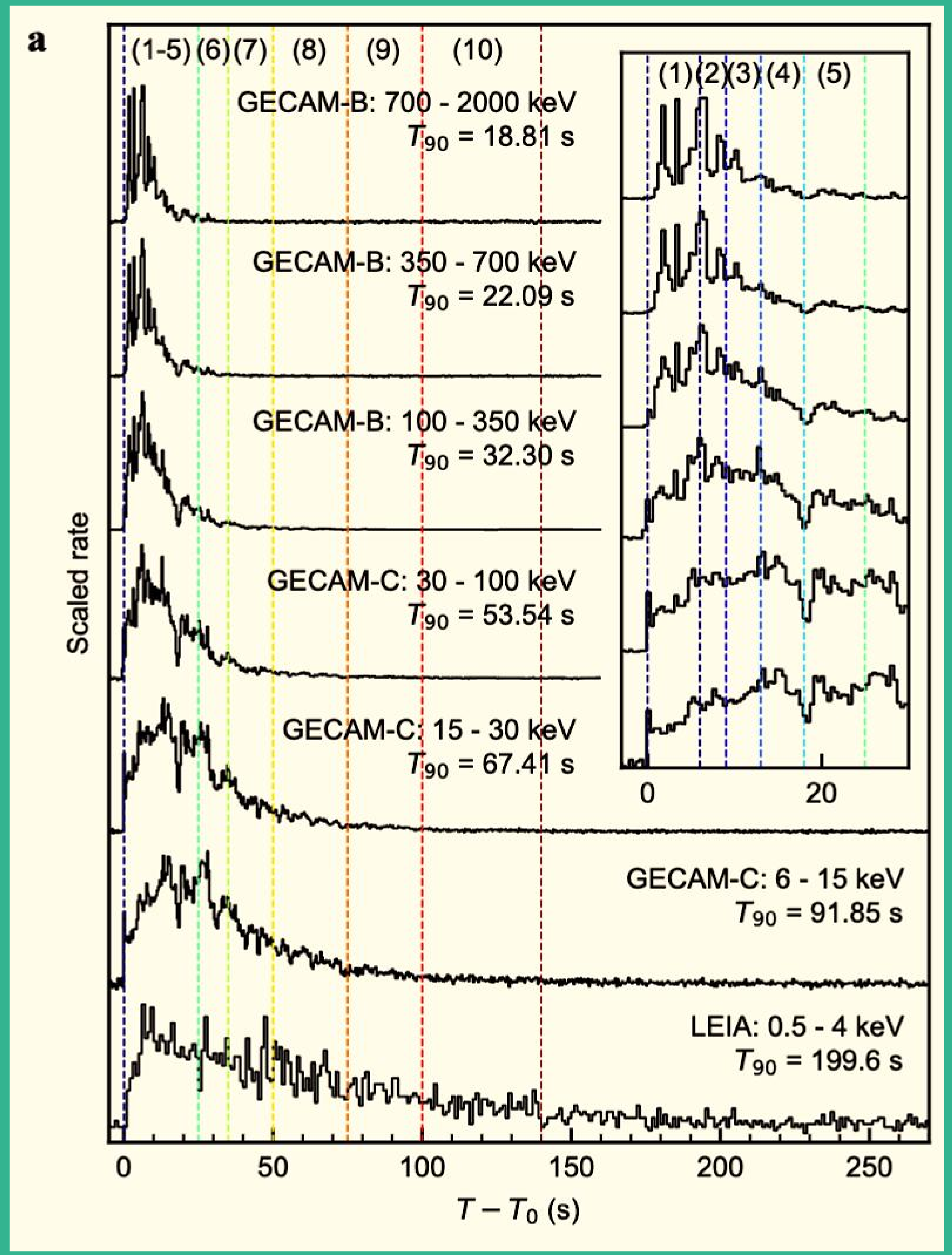

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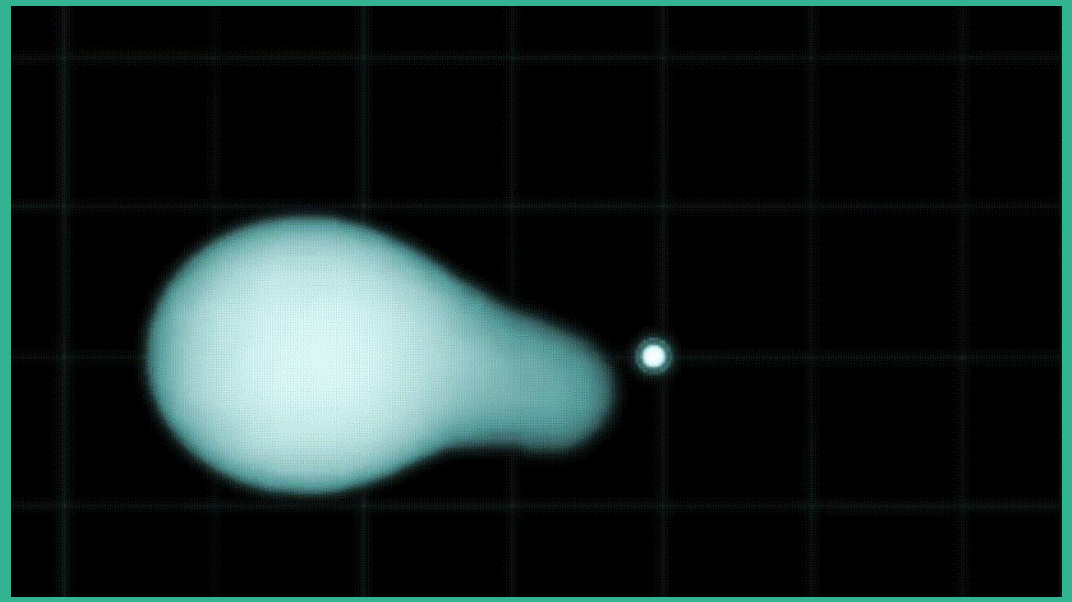
$$t_{dur} \geq 10s$$

$$t_{ff} \sim \left(\frac{3\pi}{32G\rho}\right)^{1/2}$$

$$\rho = 10^{6-7} g cm^{-3} \sim \rho_{WD}$$

NS+WD merger as origin for oddball GRBs *(211211A, 230307A)*



- rare NS-WD combination : requires $q=m_{WD}/m_{NS}\sim1$; produces a magnetar; neutron-rich wind launched during AIC of the WD to the NS.
- ME – initial accretion phase (few sec)
- EE – magnetic bubbles (Kluźniak & Ruderman 1998; Ruderman 2000)
- X-ray Plateau – spin-down power of the long lasting central engine
- KN – engine-fed kilonova; energy injection from the magnetar central engine

NS+WD merger as origin for oddball GRBs *(060614, 211211A, 230307A)*

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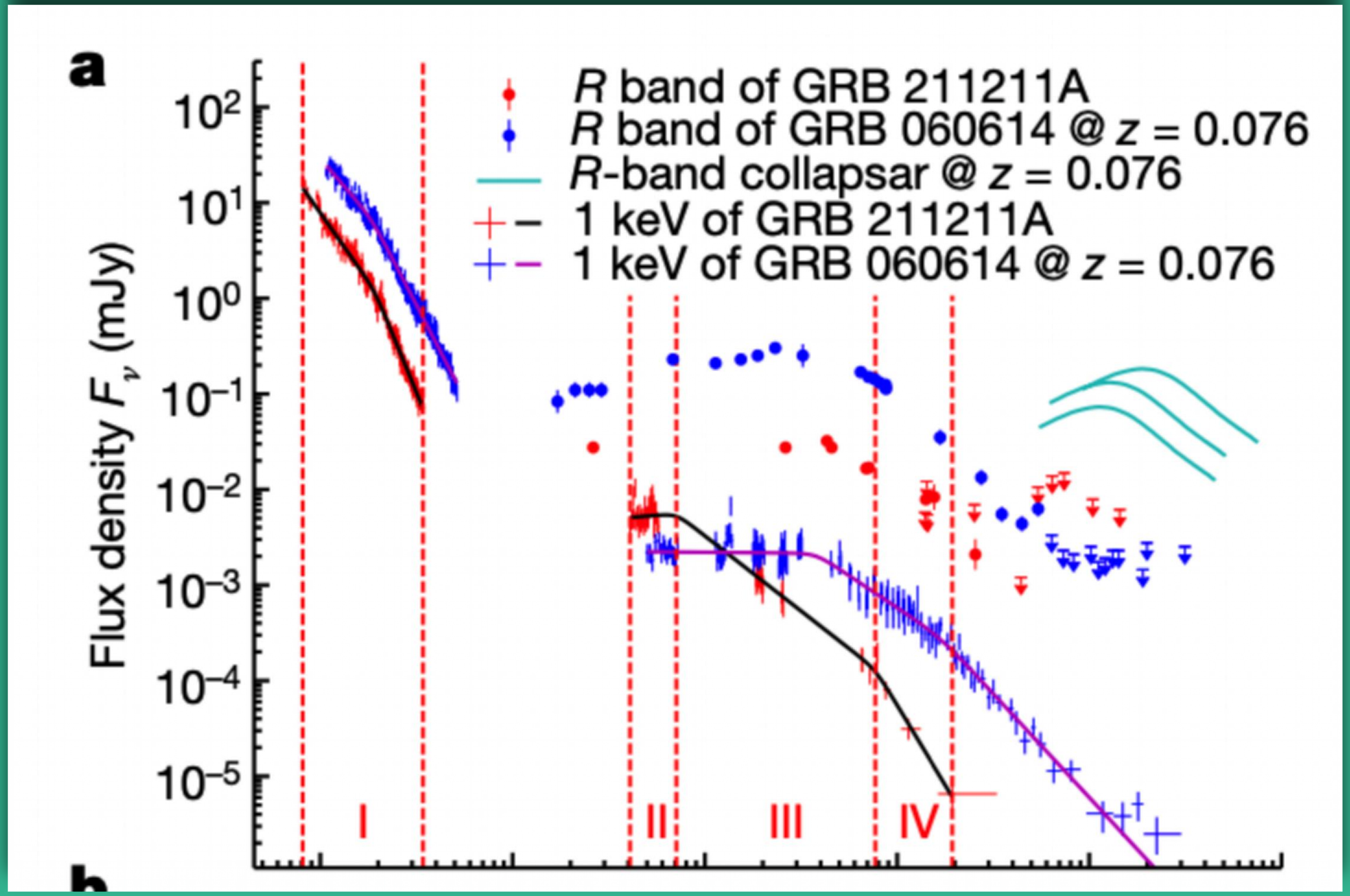

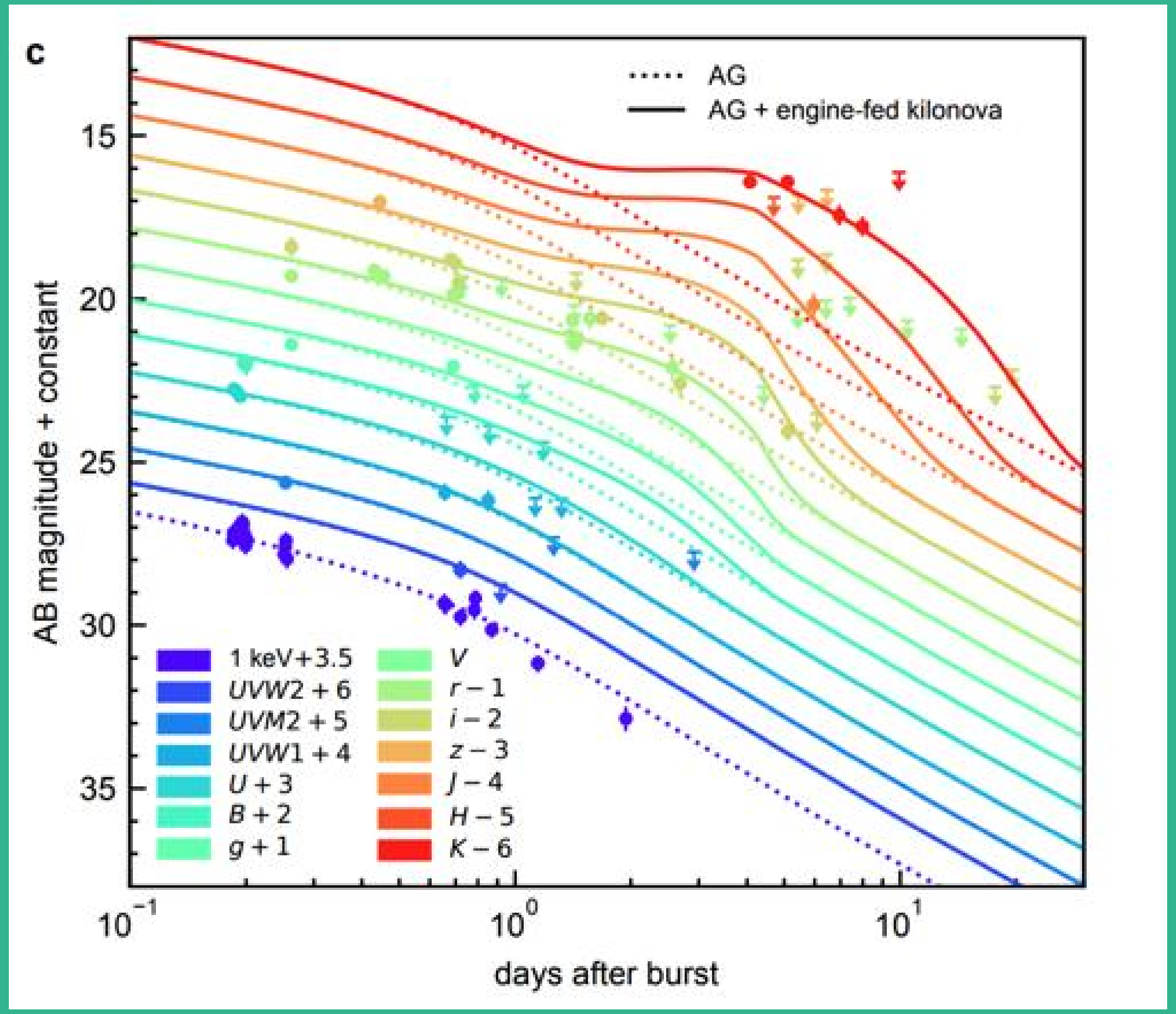

Yang, J. et al. 2022, Nature

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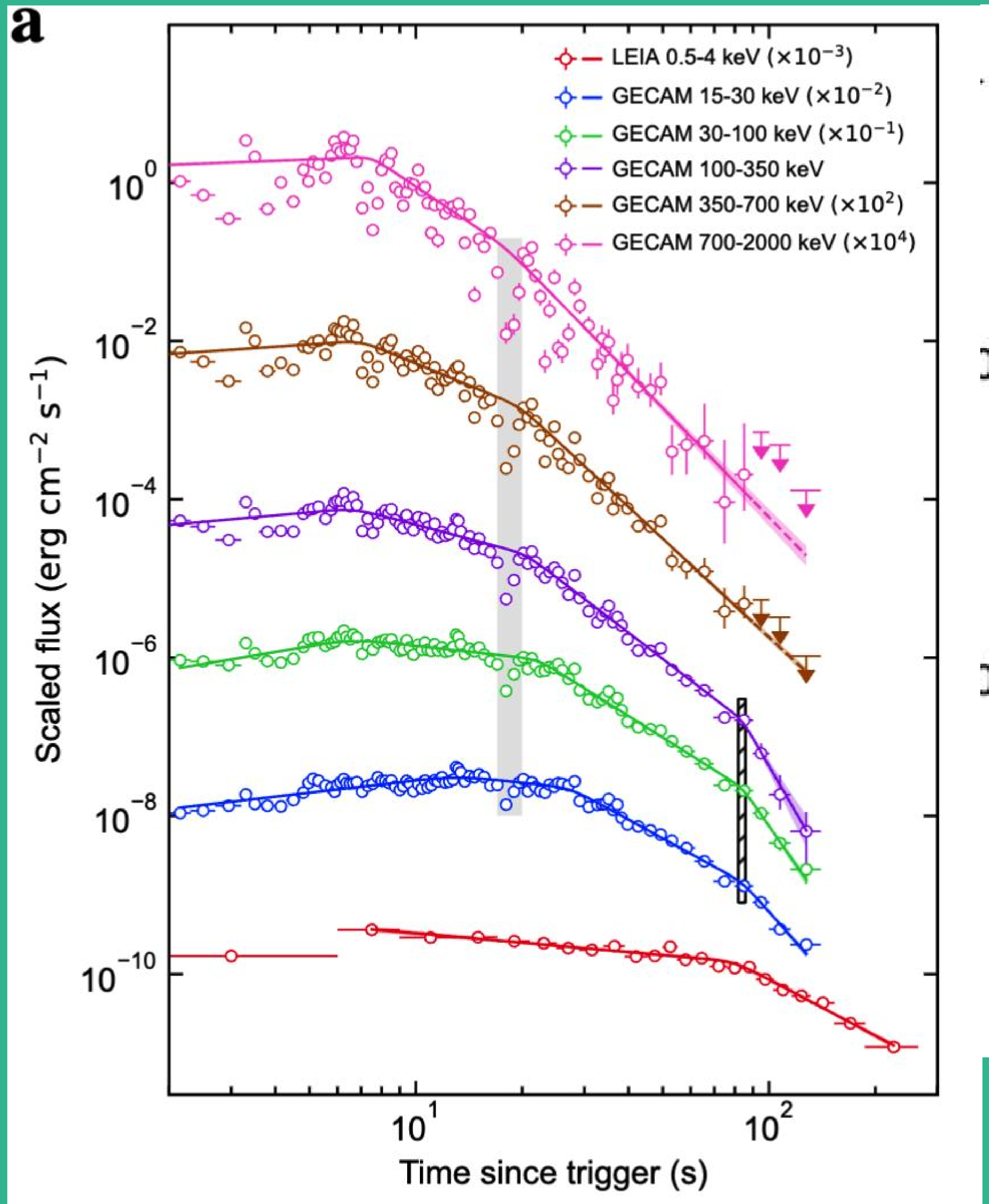
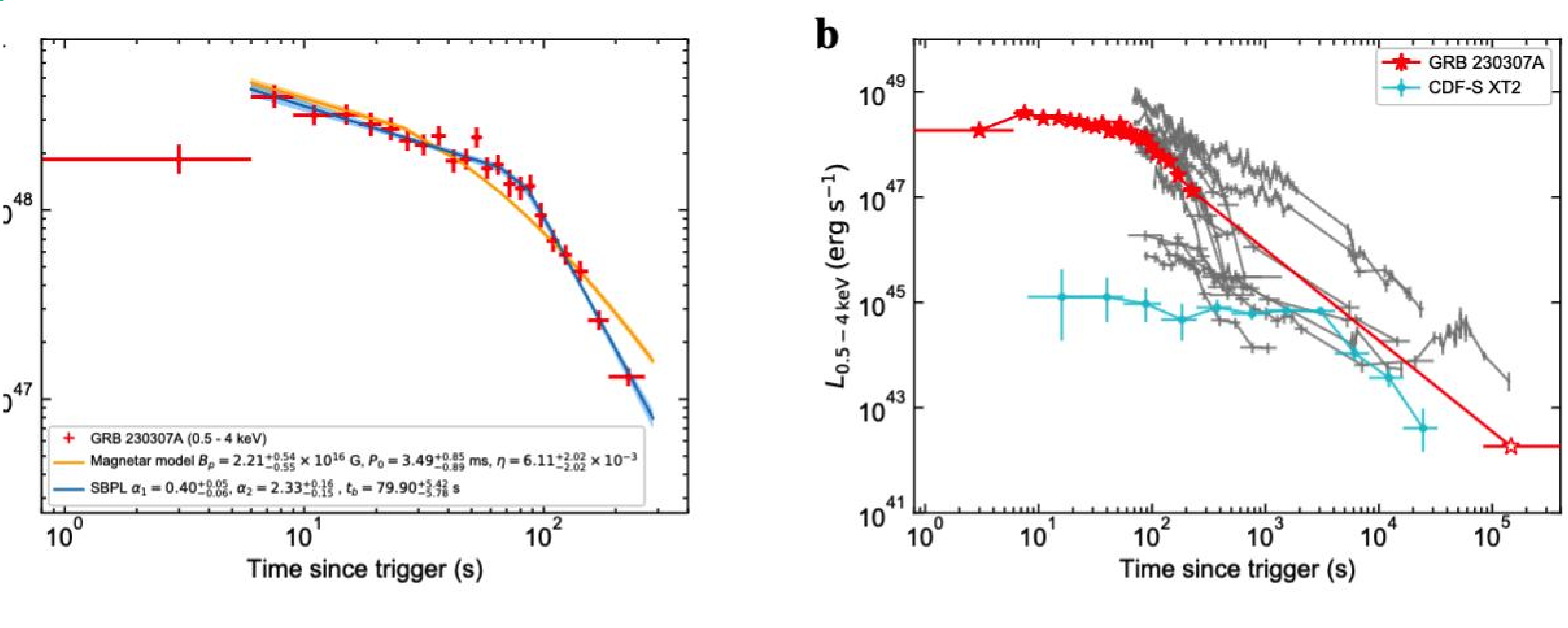
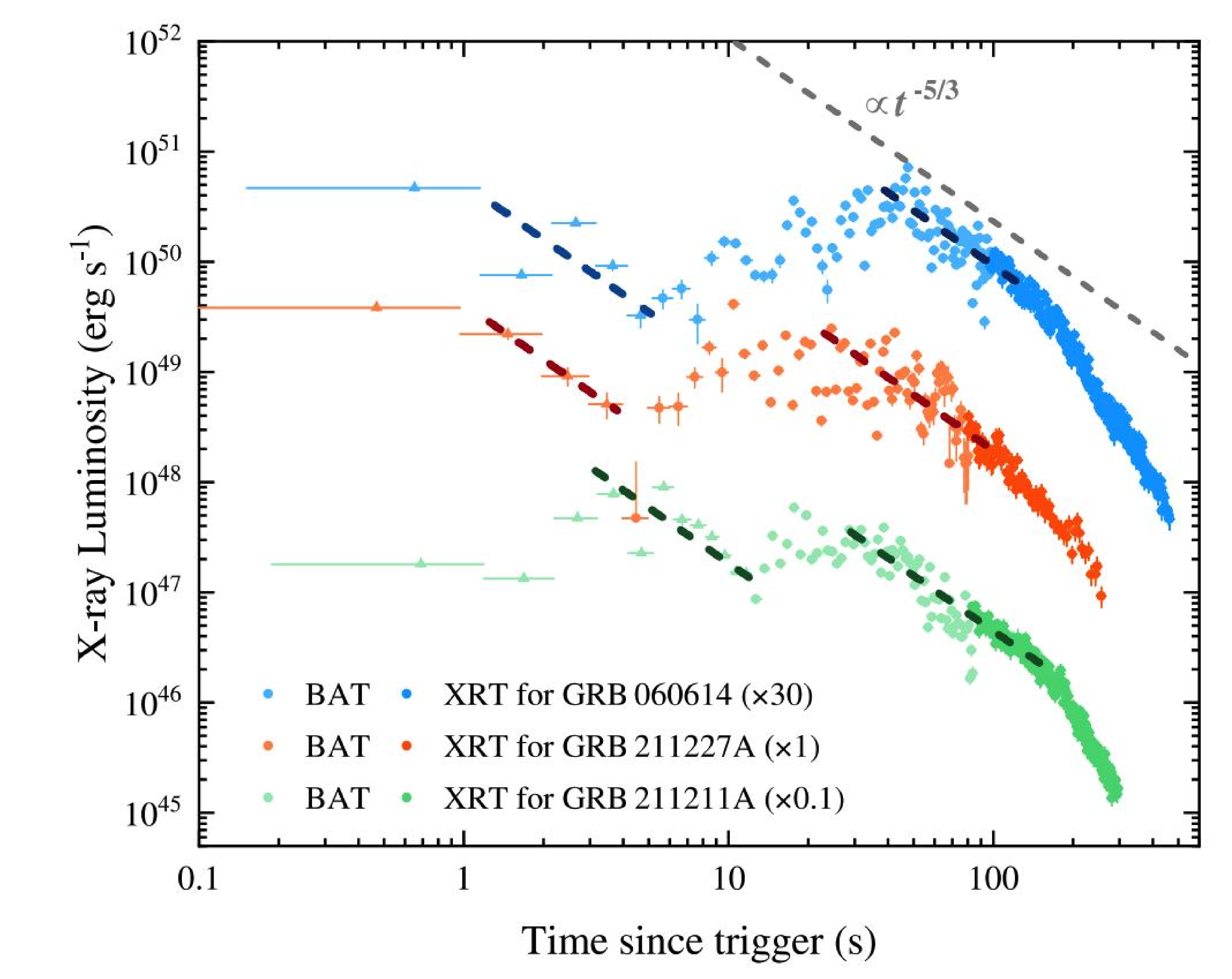
Additional evidence of magnetar emergence in GRB 230307A



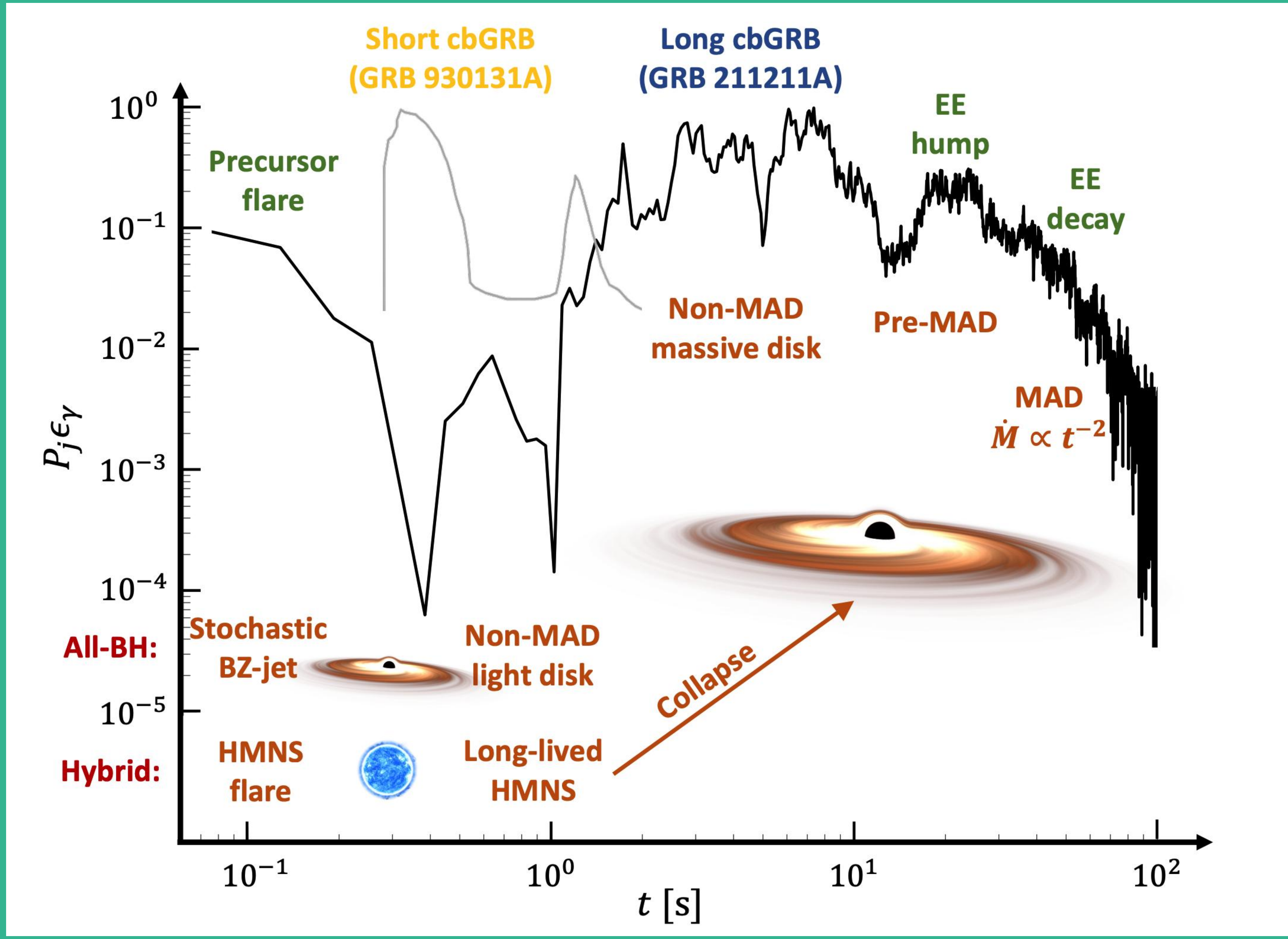


Sun, H. et al, 2023, under revision

Any alternative models?
e.g., NS+BH + fallback+MAD

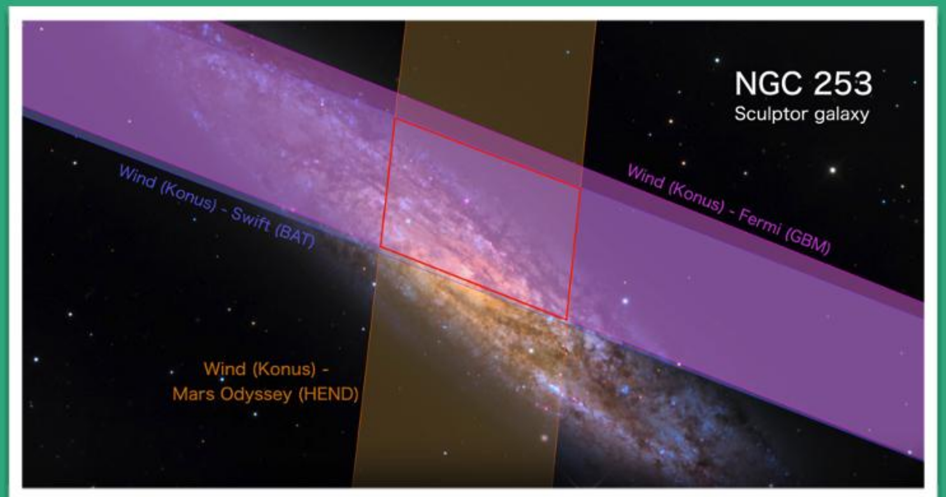


Zhu, J.-P. et al. 2023



Gottlib, O. et al. 2023

But fails on anti-correlation luminosity and duration, X-ray plateau, magnetar



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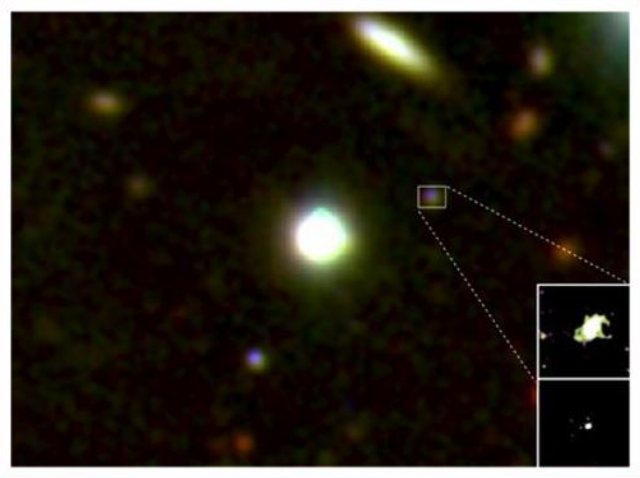

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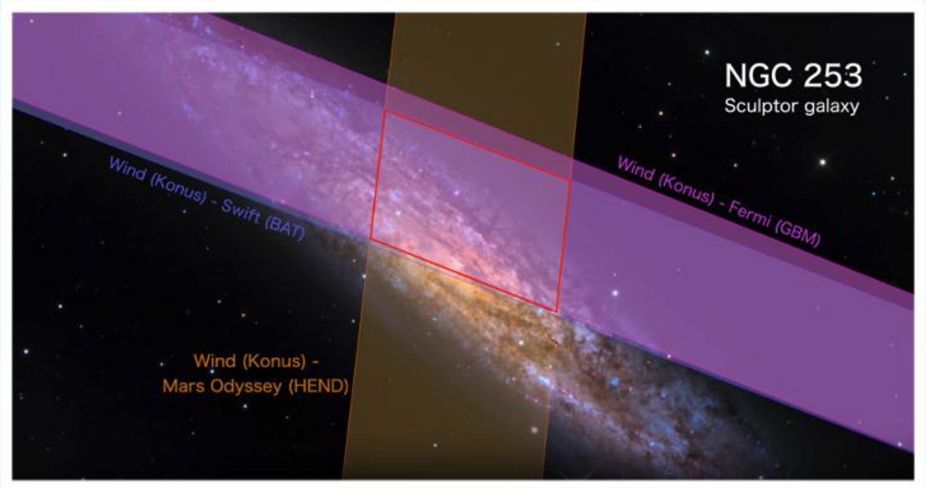
Long-duration Type-I GRBs; probably due to
NS+WD merger

Magnetar GF, non-GRB



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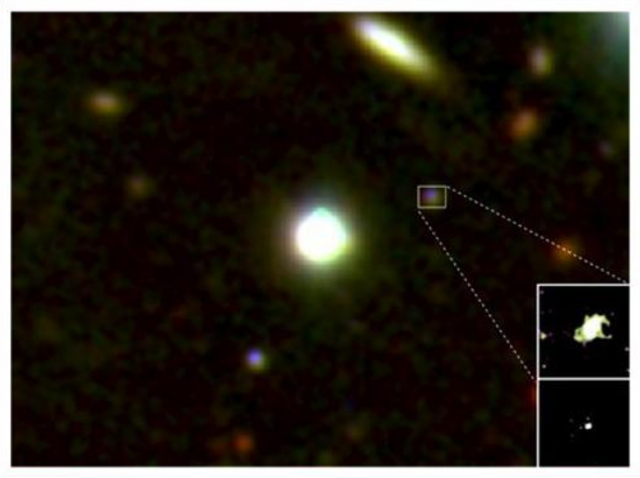

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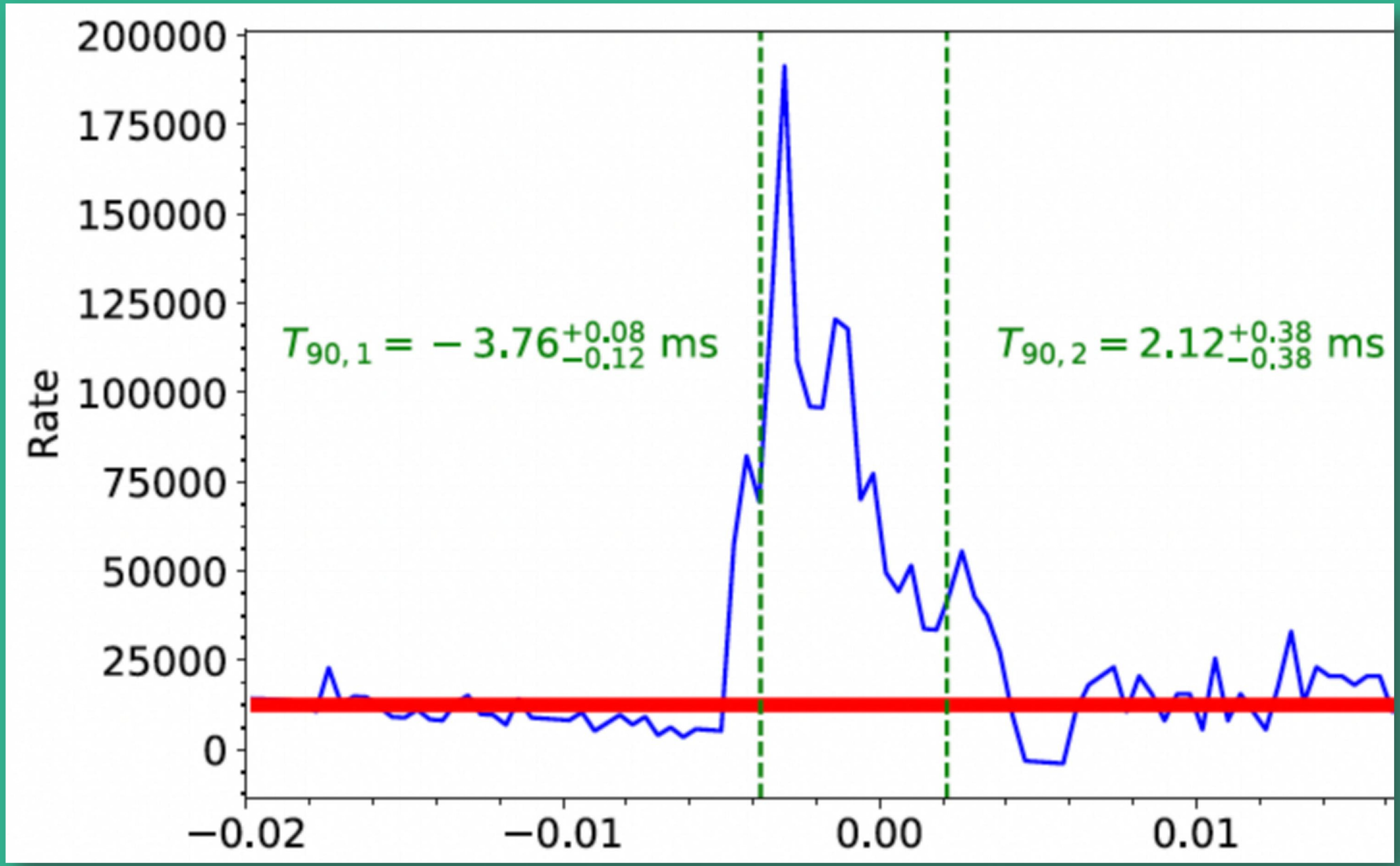
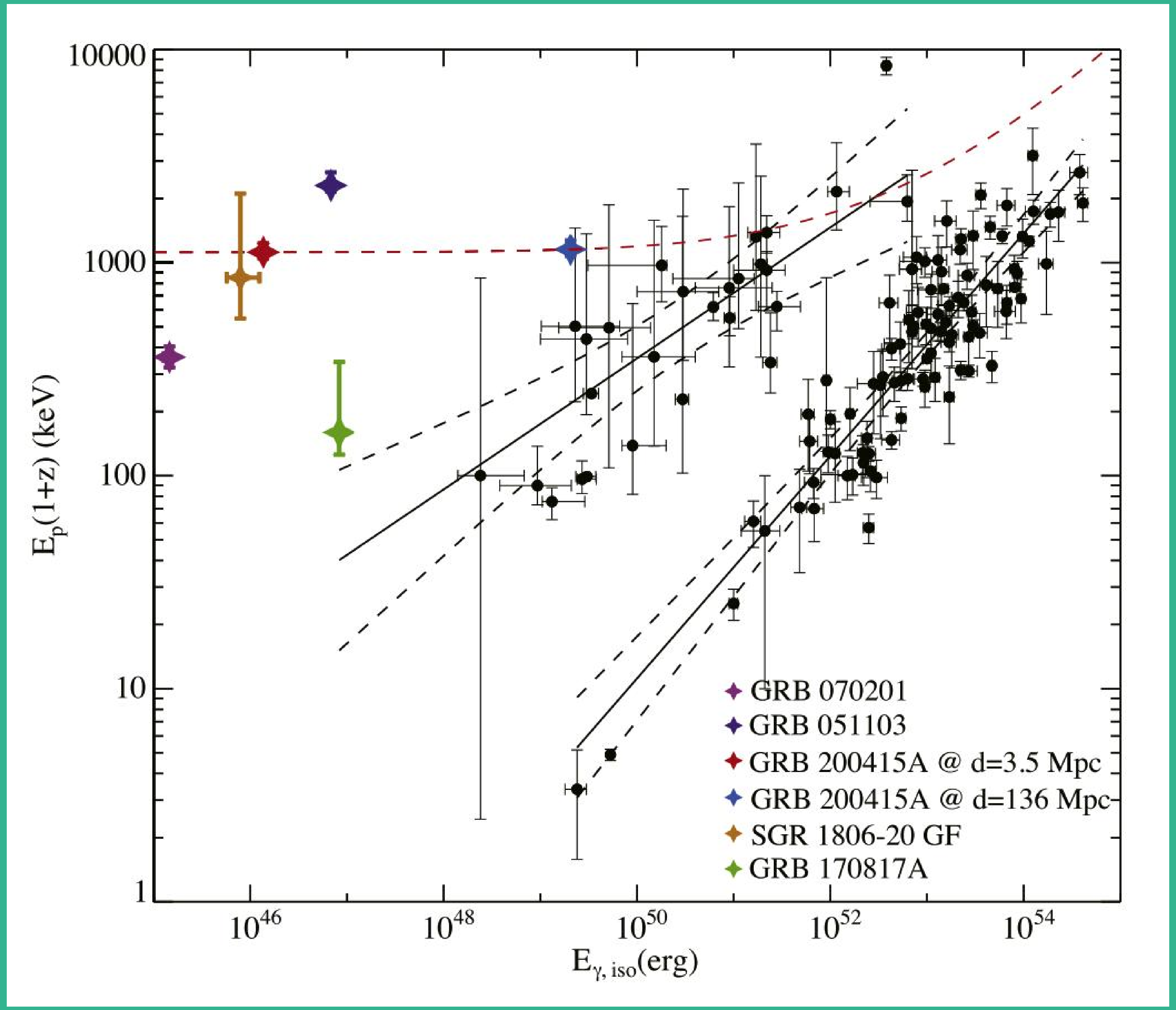
Magnetar GF (non-)GRBs 200415A & 231115A

extremely short, close-by (3.5 Mpc), off-track in Ep-Eiso, no KN





GRB 200415A, Yang, J. et al. 2020 ApJL

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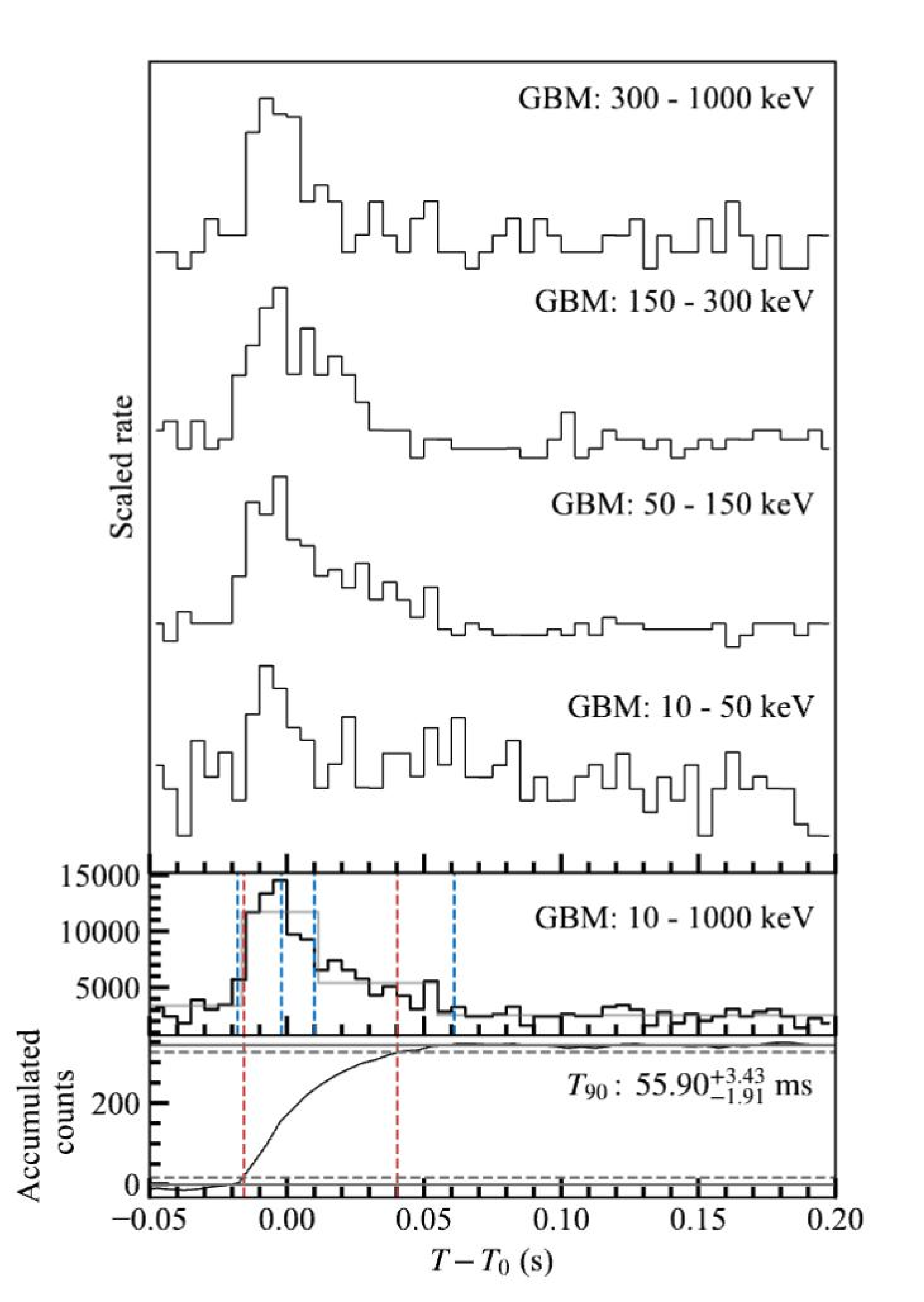
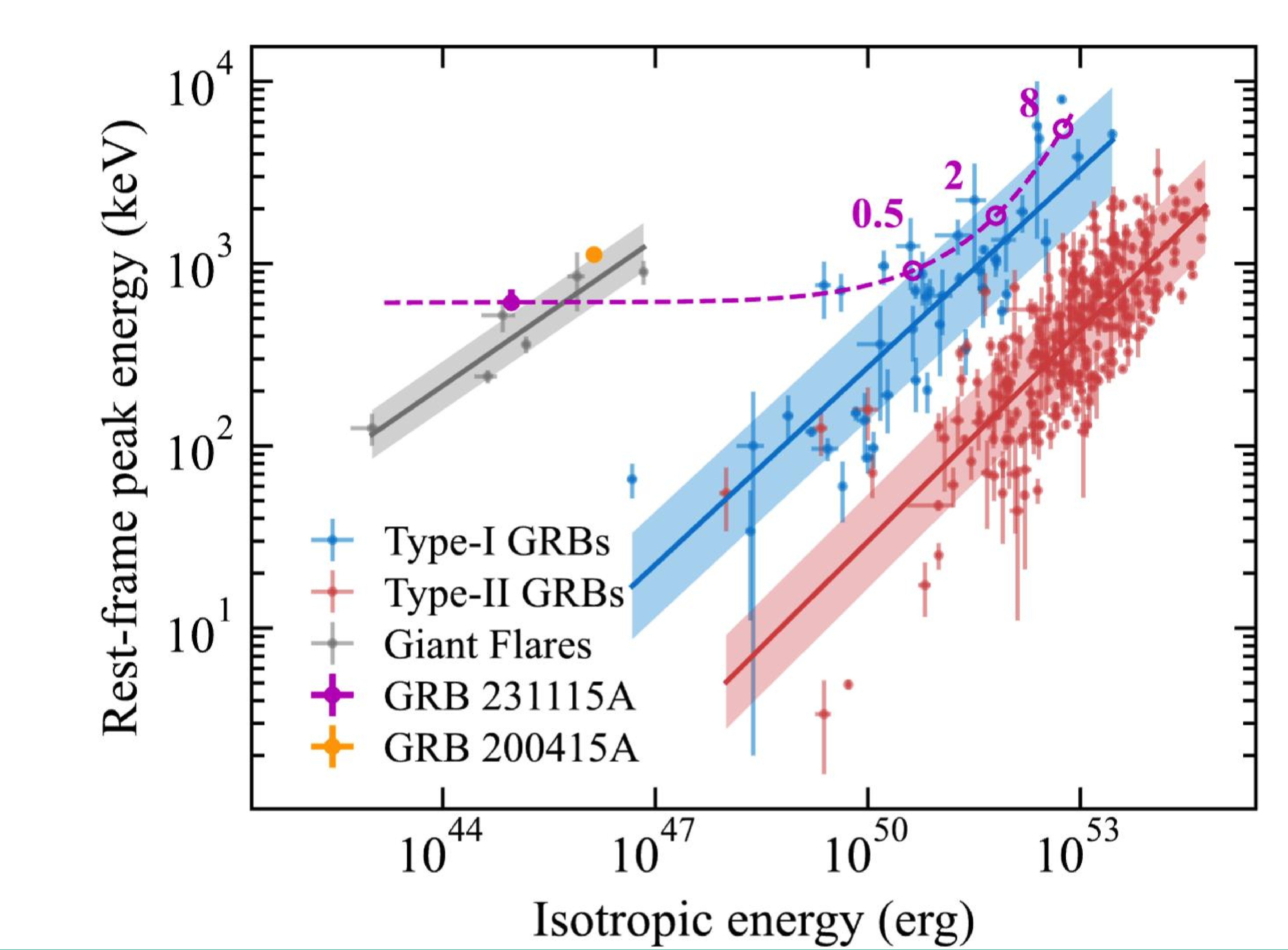




GRB 231115A, Yin, I. Y. et al. 2023 in prep

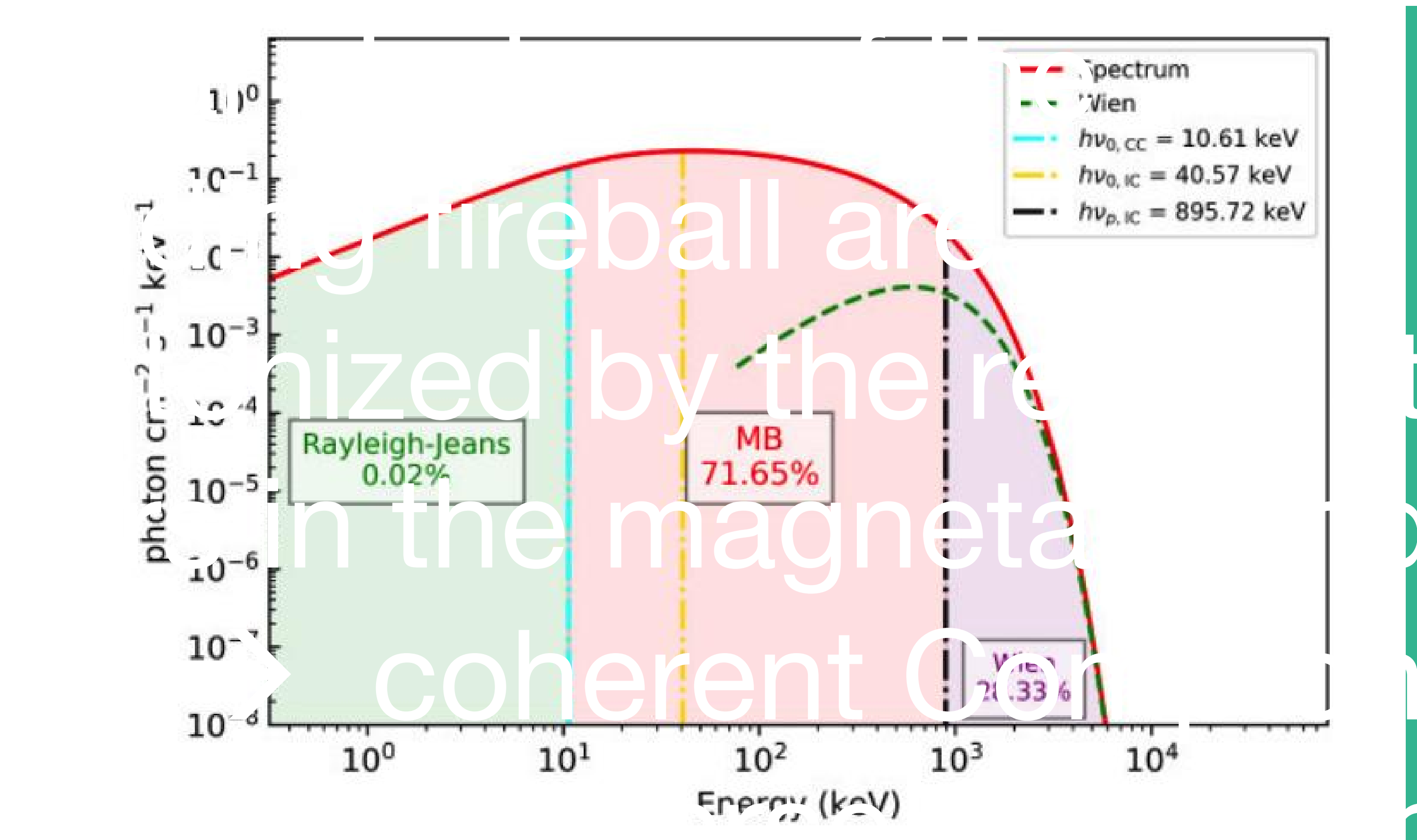
Magnetar GF (non-)GRBs 200415A & 231115A

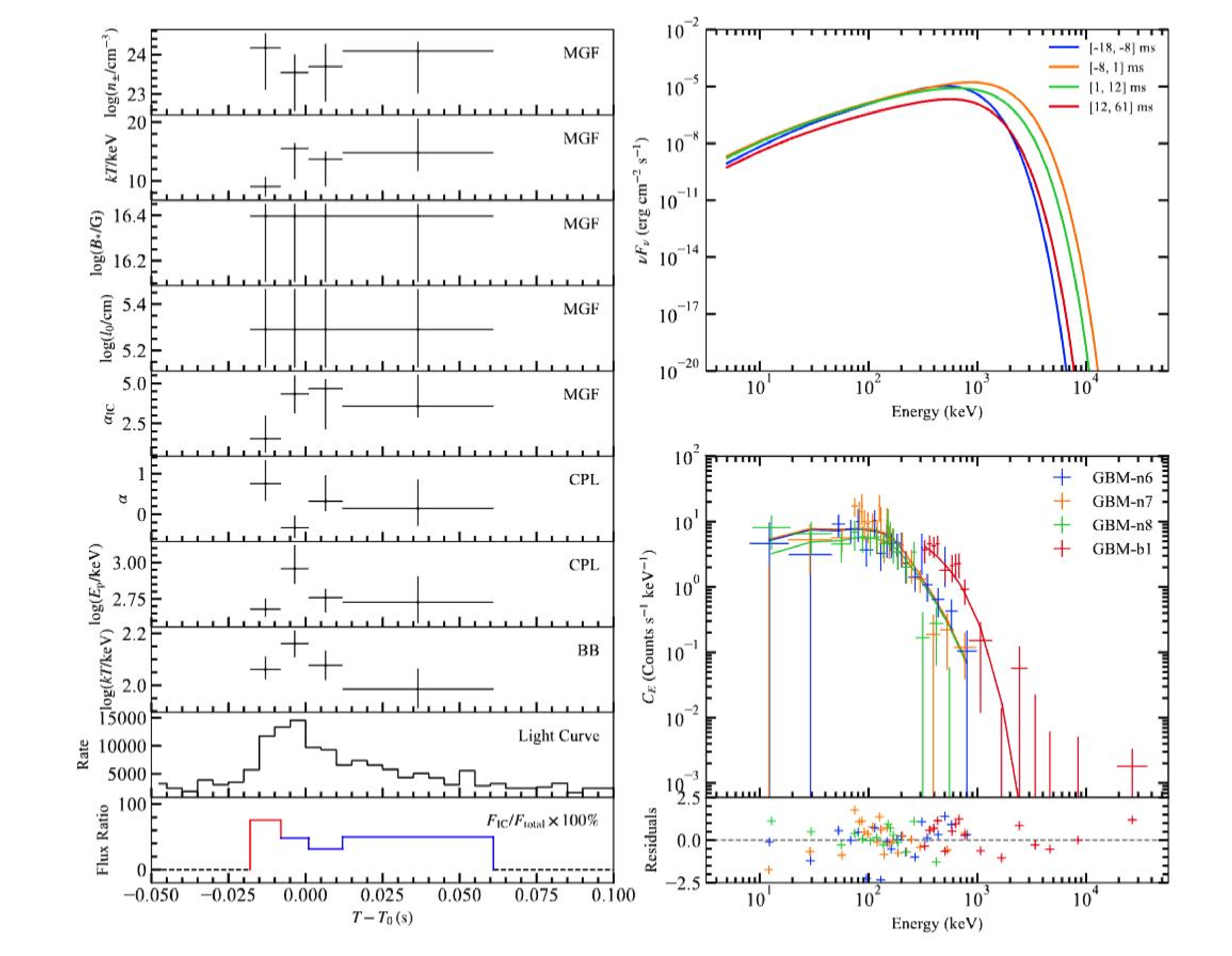
a comptonized fireball bubble

Table 3. Time-integrated and Time-resolved Spectral Fittings of GRB 231115A

Time Intervals	CPL Parameters				BB Parameters		
(t_1, t_2) (s)	α	E_p (keV)	PGSTAT/dof	BIC	kT (keV)	PGSTAT/dof	BIC
(-0.018, 0.061)	$0.16^{+0.21}_{-0.19}$	$605.54^{+84.72}_{-67.84}$	468.89/463	487.32	$119.66^{+8.32}_{-8.12}$	487.51/464	499.79
(-0.018, -0.008)	$0.75^{+0.58}_{-0.42}$	$478.50^{+84.43}_{-54.65}$	321.99/463	340.42	$115.16^{+13.69}_{-9.85}$	322.62/464	334.91
(-0.008, 0.001)	$-0.33^{+0.29}_{-0.24}$	$907.55^{+404.02}_{-193.04}$	336.11/463	354.54	$144.77^{+17.53}_{-16.32}$	349.98/464	362.27
(0.001, 0.012)	$0.32^{+0.64}_{-0.24}$	$573.73^{+83.60}_{-117.56}$	313.13/463	331.56	$119.28^{+16.46}_{-14.31}$	316.62/464	328.91
(0.012, 0.061)	$0.14^{+0.71}_{-0.42}$	$533.27^{+271.80}_{-149.56}$	387.60/463	406.03	$96.61^{+19.32}_{-15.14}$	391.03/464	403.32
Time Intervals	MGF Parameters						
(t_1, t_2) (s)	$\log(n_\pm)$	kT	$\log(B_*)$	$\log(l_0)$	α_{IC}	PGSTAT/dof	BIC
(-0.018, 0.061)	$24.03^{+0.07}_{-0.33}$	$12.73^{+4.51}_{-0.68}$	16.40 (fixed)	5.29 (fixed)	$2.83^{+2.19}_{-0.37}$	467.03/463	485.46
(-0.018, -0.008)	$24.17^{+0.36}_{-1.06}$	$9.04^{+1.64}_{-1.67}$			$1.54^{+1.44}_{-0.85}$	321.00/461	334.35
(-0.008, 0.001)	$23.55^{+0.46}_{-0.98}$	$15.52^{+0.88}_{-5.16}$	$16.40^{+0.05}_{-0.29}$	$5.29^{+0.17}_{-0.16}$	$4.34^{+1.14}_{-1.18}$	336.96/461	350.31
(0.001, 0.012)	$23.70^{+0.57}_{-0.89}$	$13.71^{+1.25}_{-4.57}$			$4.67^{+0.57}_{-2.53}$	314.79/461	328.13
(0.012, 0.061)	$24.09^{+0.24}_{-1.07}$	$14.79^{+5.77}_{-3.08}$			$3.57^{+1.97}_{-0.68}$	387.96/461	401.30

The ... exp... fireball an... Con...nized by the re...tic e$^\pm$ p... in the magneta... regi... coherent C... scattering + inverse Compton





Zhang, J. Z. et al, 2023 MNRAS; GRB 231115A, Yin, I. Y. et al. 2023 in prep.

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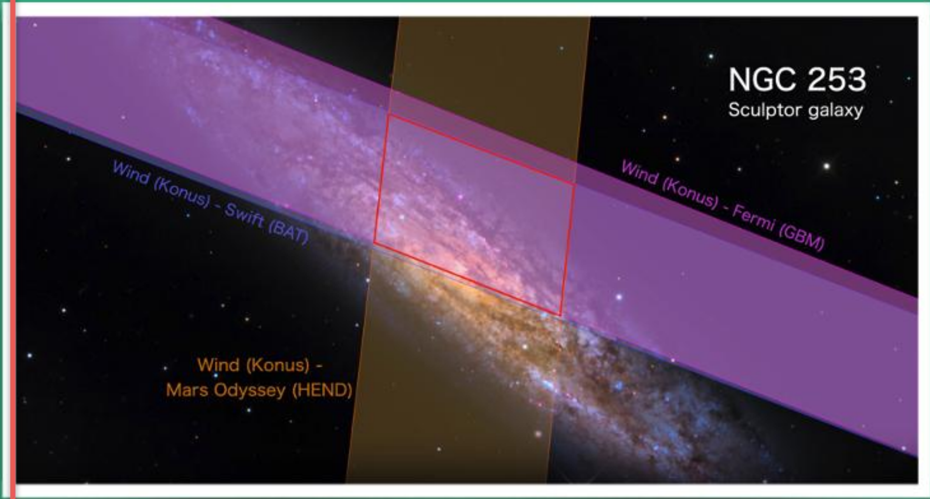

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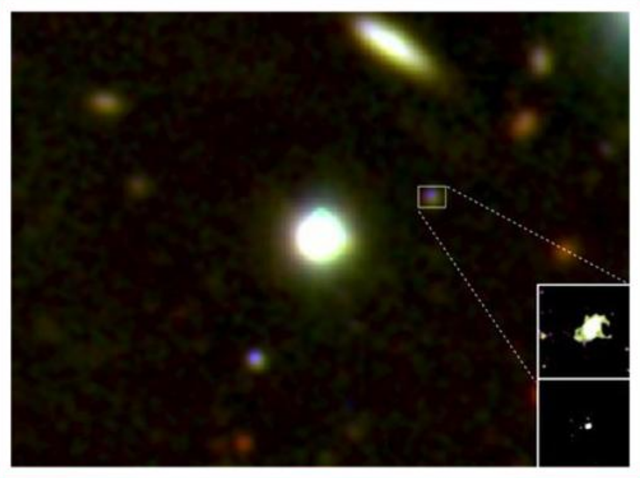

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MGF GRBs are likely from a comptonized fireball bubble

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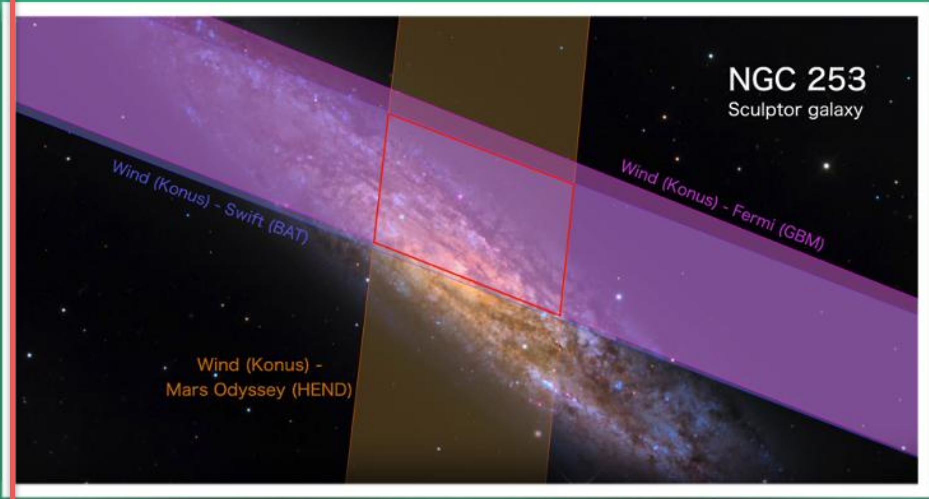

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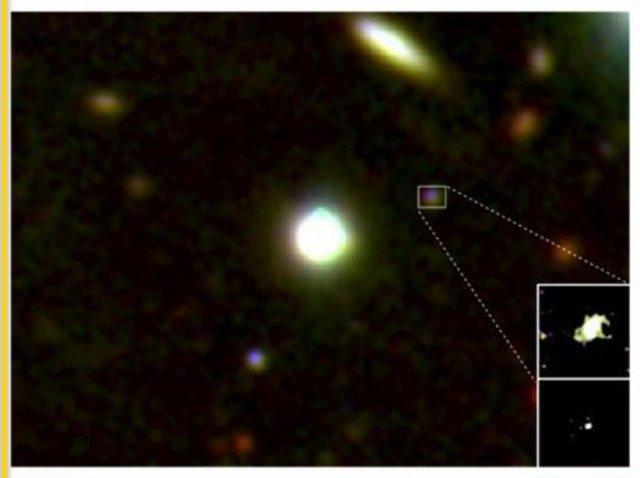

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Short-duration Type-II GRB

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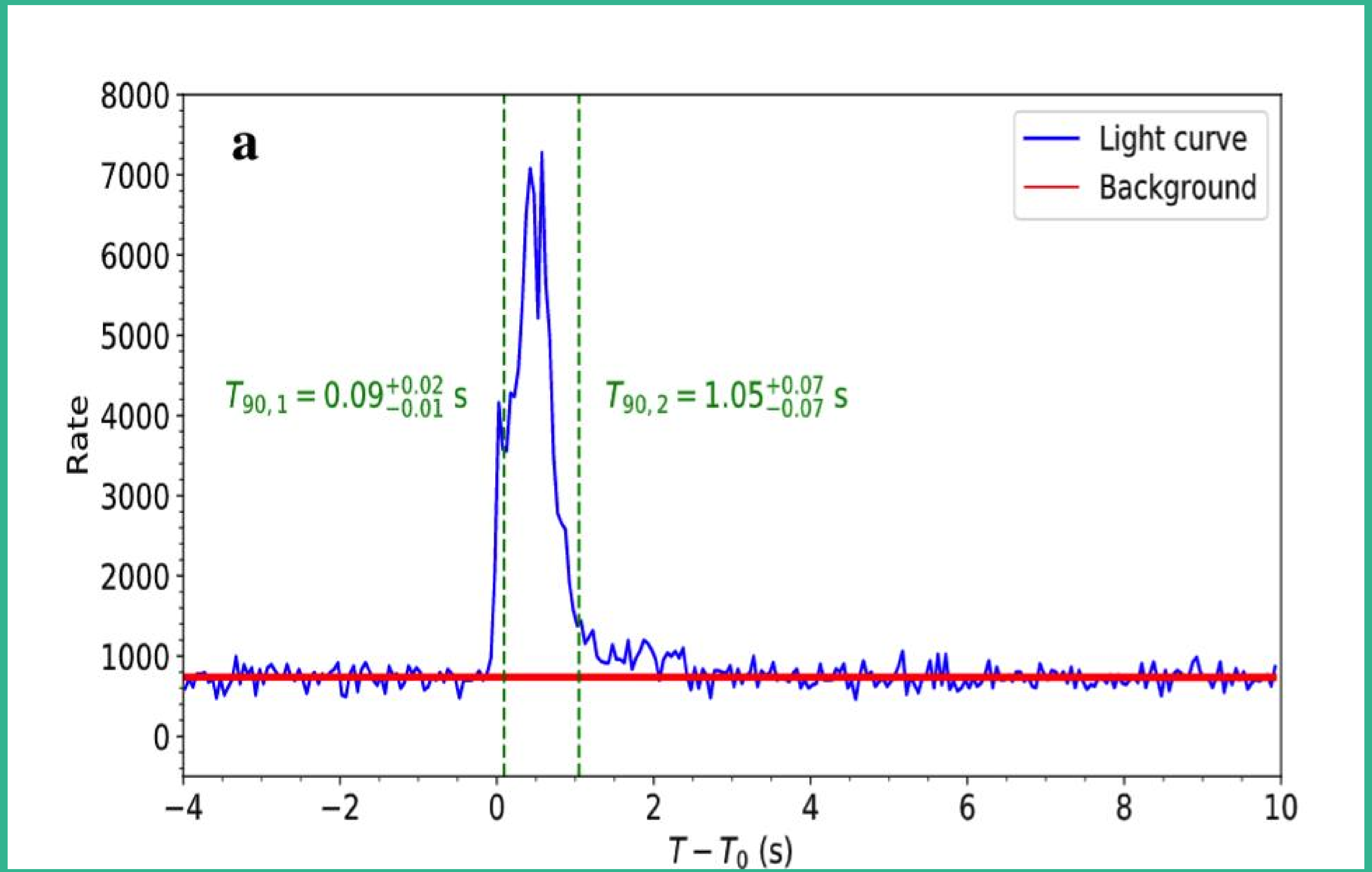
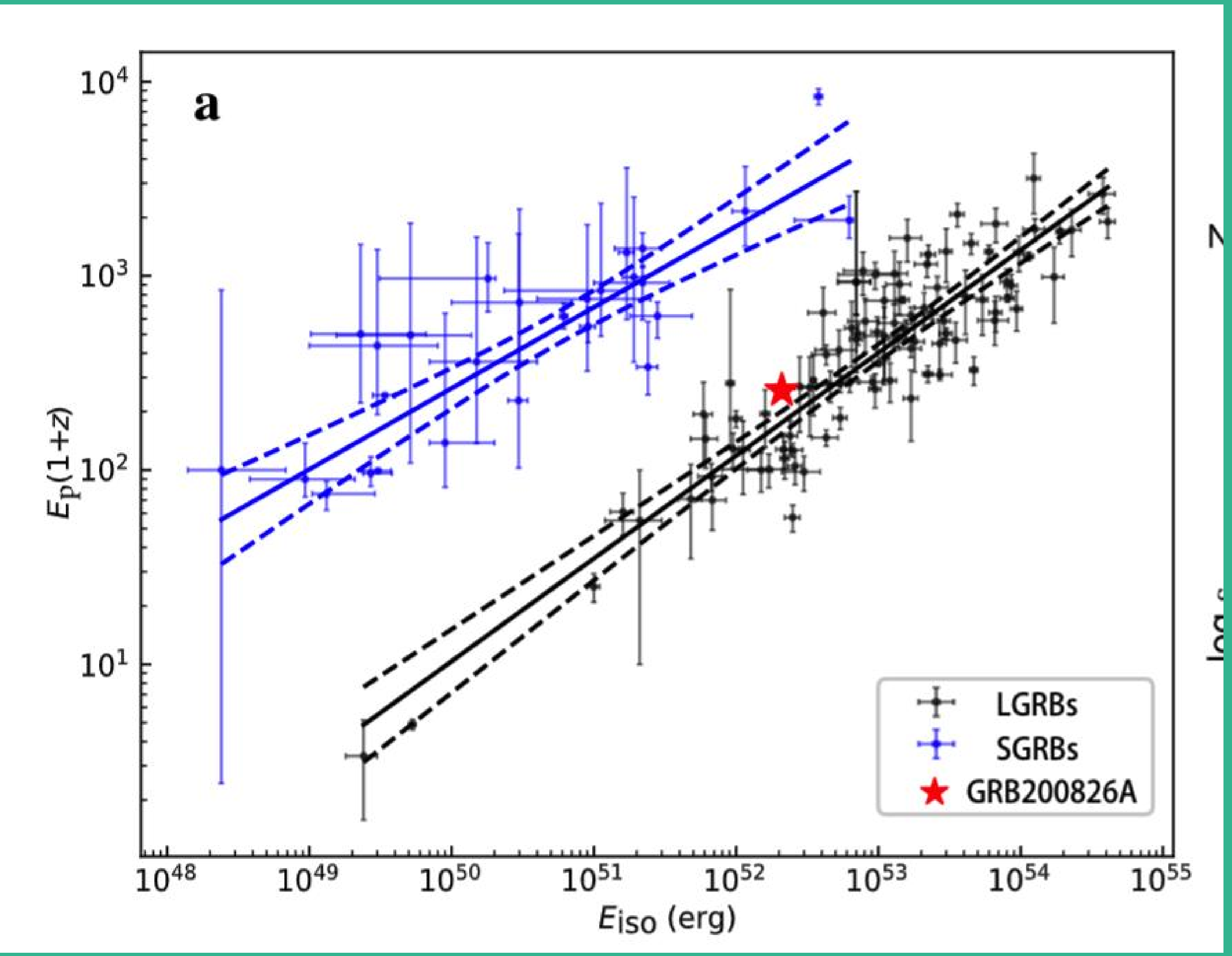
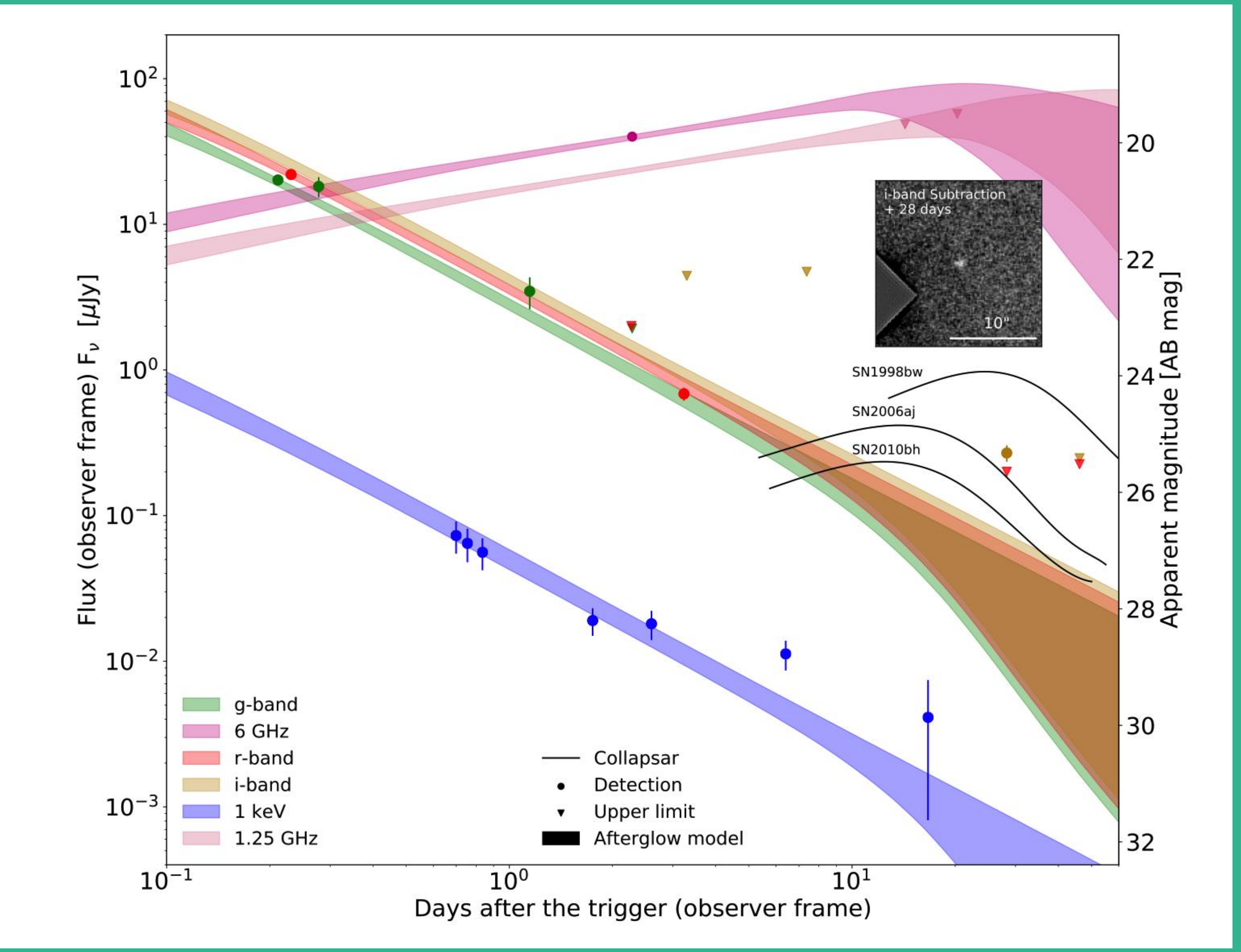


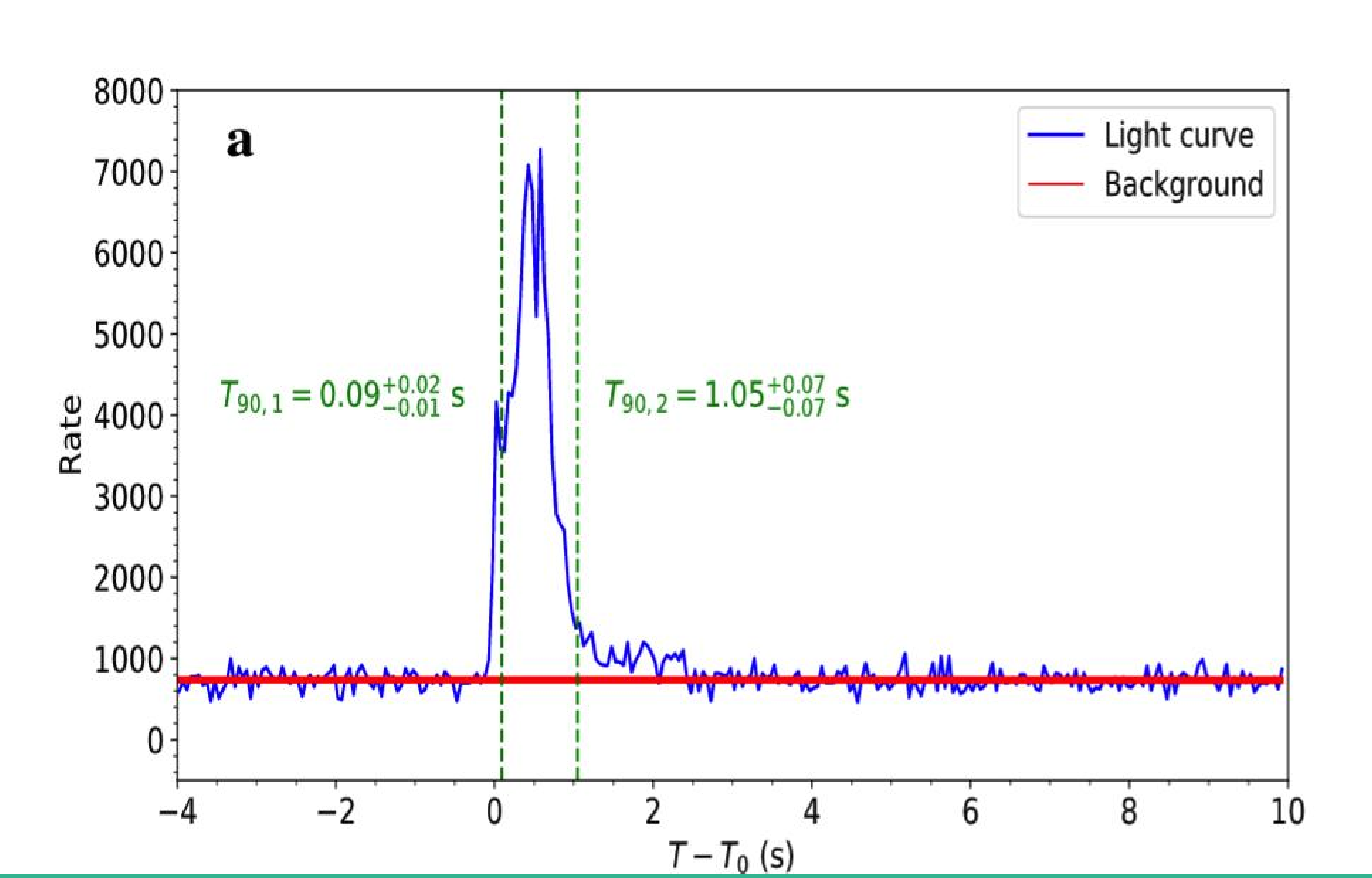




An otherwise perfect collapsar GRB with SN,
except for its extremely bright sharp peak lasting for 1 second
(tip of the iceberg not likely).

Zhang,B.-B et al 2021,Nature Astronomy, Tomas et al.. 2021,Nature Astronomy,

Short-duration Type-II GRB 200826A



challengeable to make it short if it is really accretion powered:

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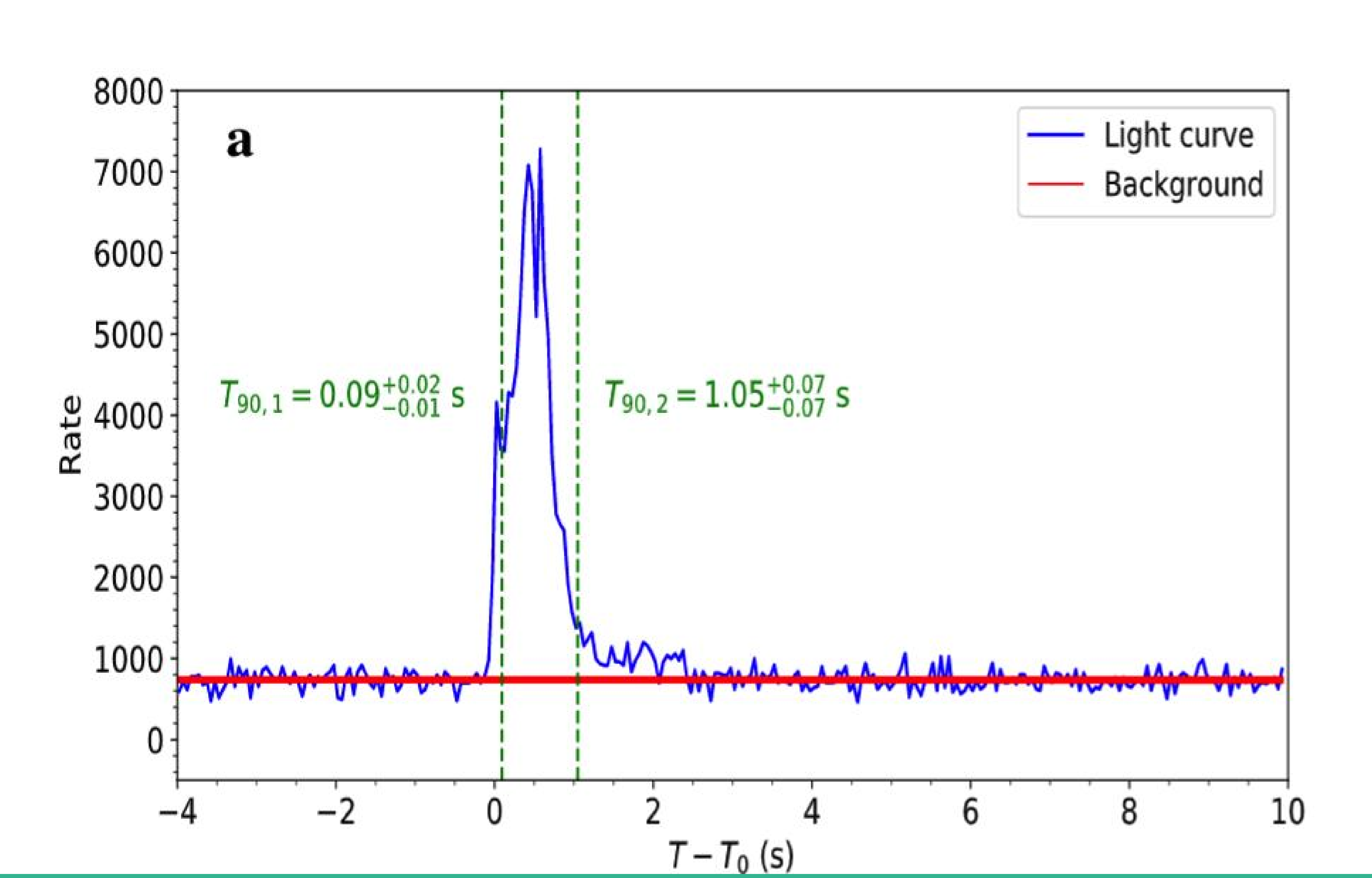

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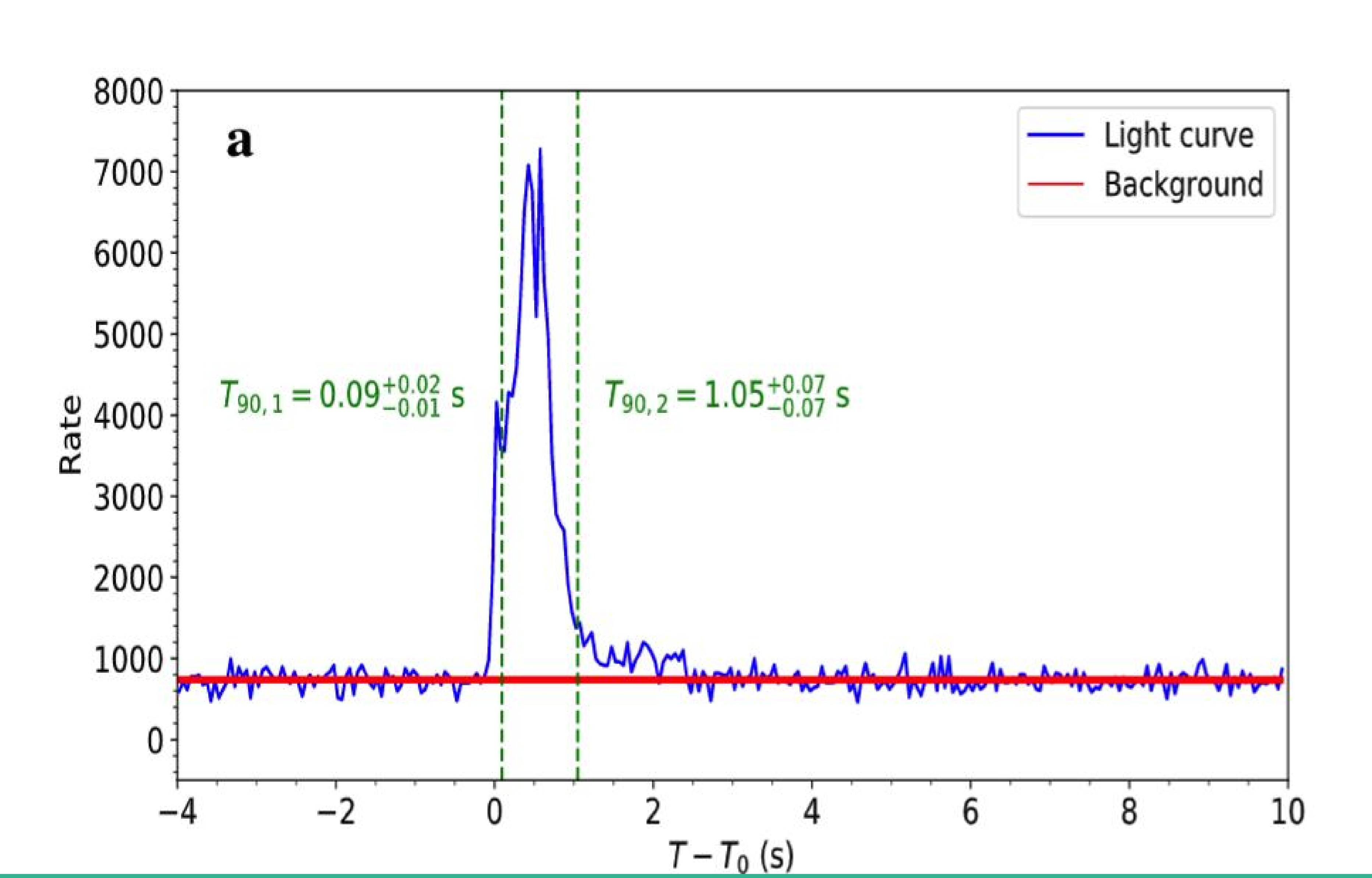
Two options to make a 10-s Collapsar GRB short:

- Increase baryon flavors in the jet (week jet; low S/N)
- Allocate dedicated 9s to facilitate breakout (coincidence).

Short-duration Type-II GRB 200826A

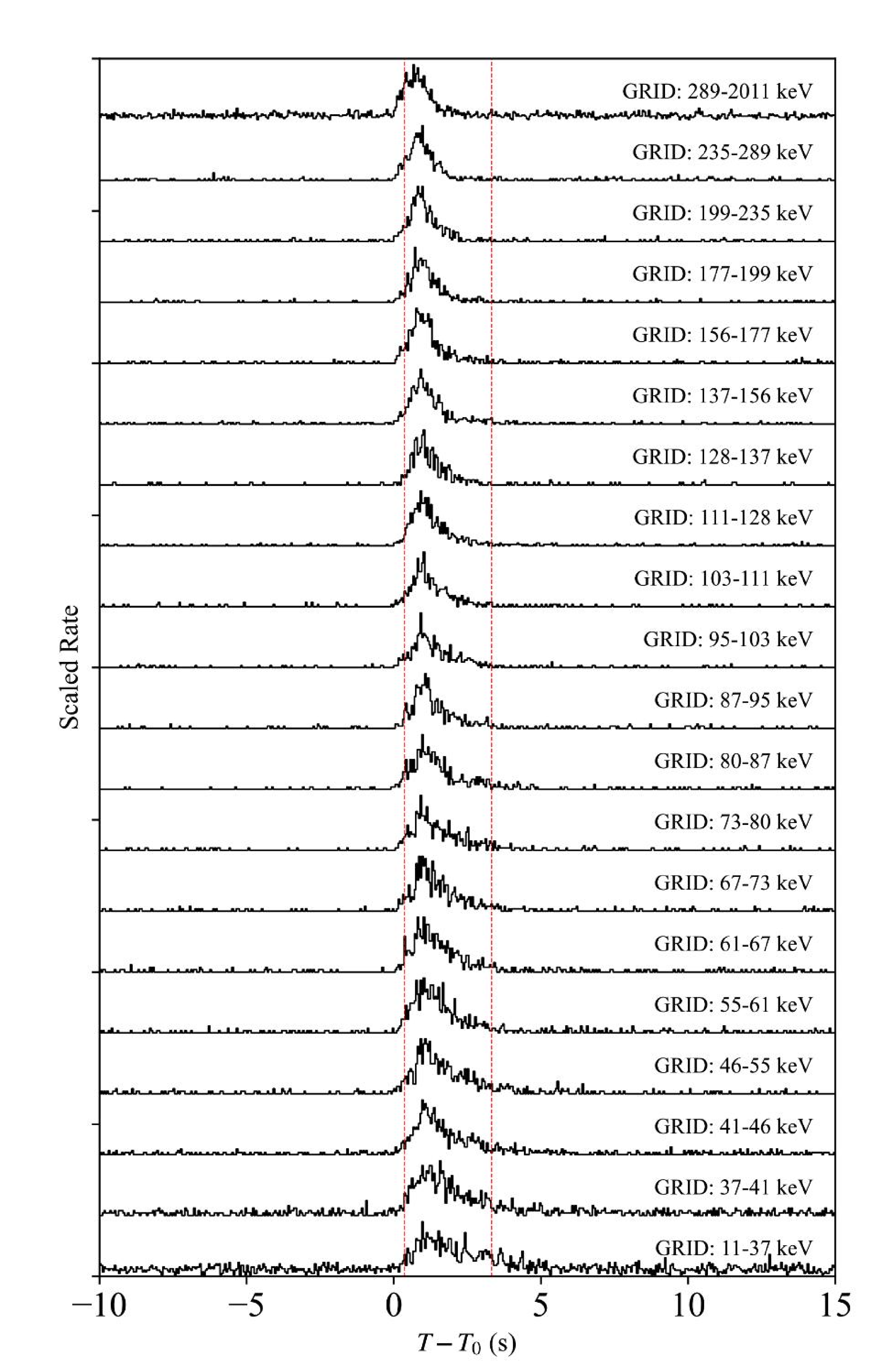


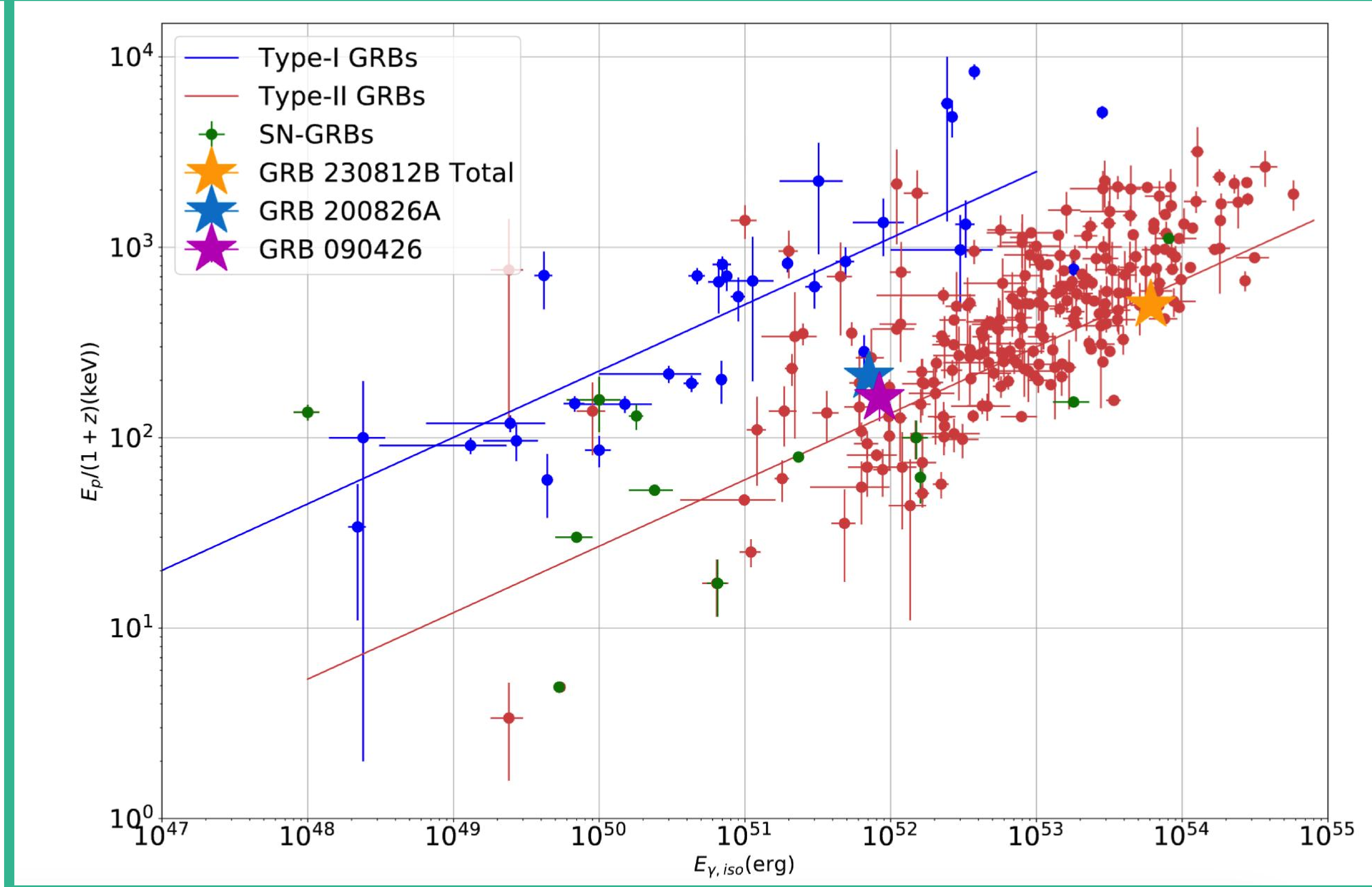
Credit: NASA/GSFC

Two options to make a 10-s Collapsar GRB short:

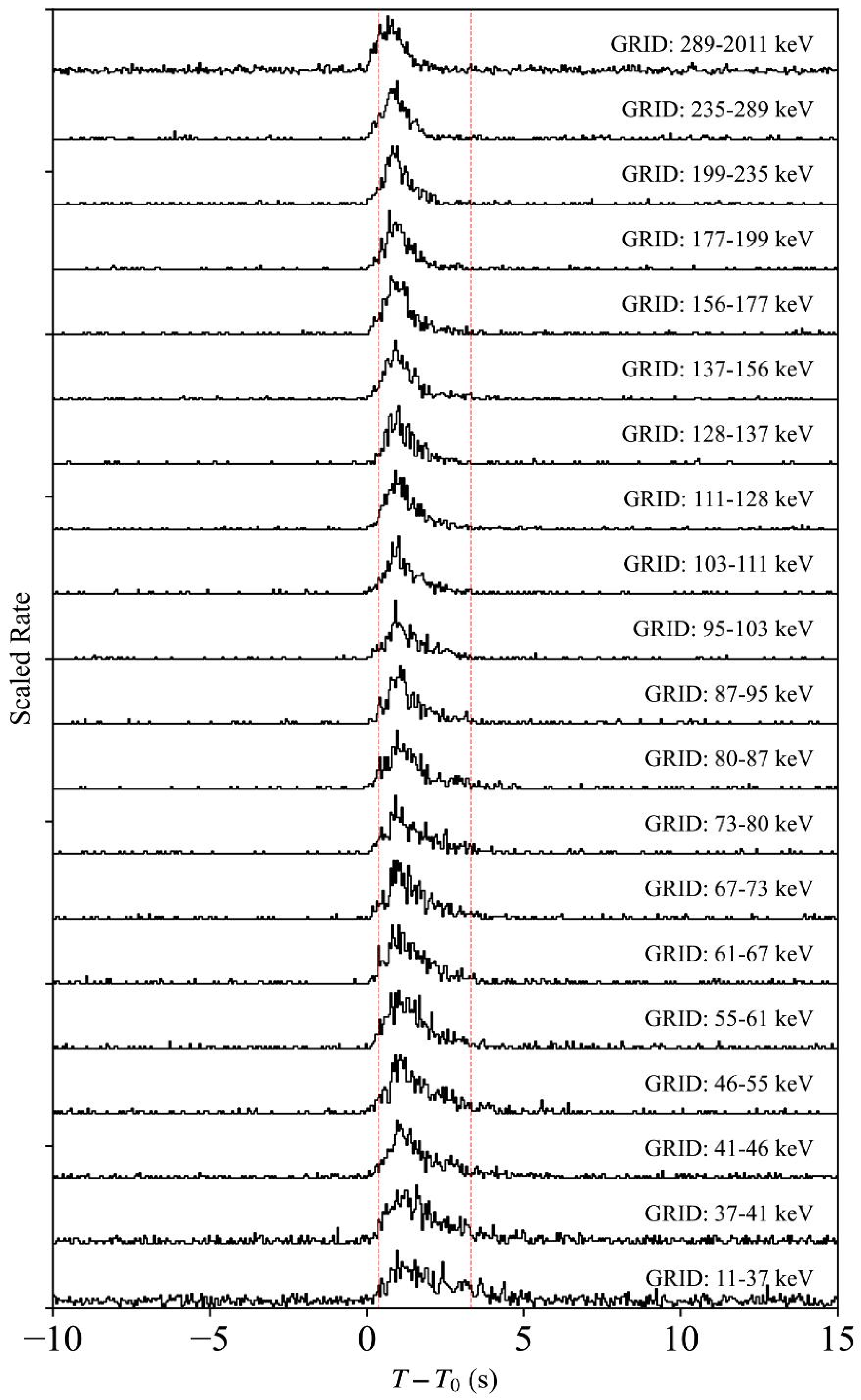
- Increase baryon flavors in the jet (week jet; low S/N)
- Allocate dedicated 9s to facilitate breakout (coincidence).

Short-duration Type-II GRB 230812B





Short-duration Type-II GRB 230812B



Consider an ultra-relativistic thin shell ejected from the GRB central engine, within which the magnetic field is entrained with the ejected material and electrons are accelerated into a power-law distribution with an index of p. Upon injection, the electrons will primarily undergo cooling through synchrotron and adiabatic processes towards lower energies. The continuity equation of electrons is

$$\frac{\partial}{\partial t'}\left(\frac{dN_{\rm e}}{d\gamma_{\rm e}}\right)+\frac{\partial}{\partial\gamma_{\rm e}}\left[\dot{\gamma}_{\rm e}\left(\frac{dN_{\rm e}}{d\gamma_{\rm e}}\right)\right]=Q\left(\gamma_{\rm e},t'\right), \qquad (1)$$

where $Q(\gamma_e, t')$ is the injection rate of electrons, and reads as (we consider the injection rate increases with a power-law in time and ceases at an observed time t_{inj})

$$Q\left(\gamma_{\rm e},t'\right)=\begin{cases} Q_0\left(\frac{t'}{t'_0}\right)^q\gamma_{\rm e}^{-p}, & \gamma_{\rm min}<\gamma_{\rm e}<\gamma_{\rm max} \\ 0, & \text{otherwise} \end{cases}, \qquad (2)$$

The synchrotron cooling and adiabatic cooling rate are given by

$$\dot{\gamma}_{\rm e,tot}=\dot{\gamma}_{\rm e,syn}+\dot{\gamma}_{\rm e,adi}=-\frac{\sigma_{\rm T}B^2{\gamma_{\rm e}}^2}{6\pi m_{\rm e}c}-\frac{2\gamma_{\rm e}}{3(t'+t'_0)}, \qquad (3)$$

The magnetic field decay behavior and synchrotron radiation power in the co-moving frame are

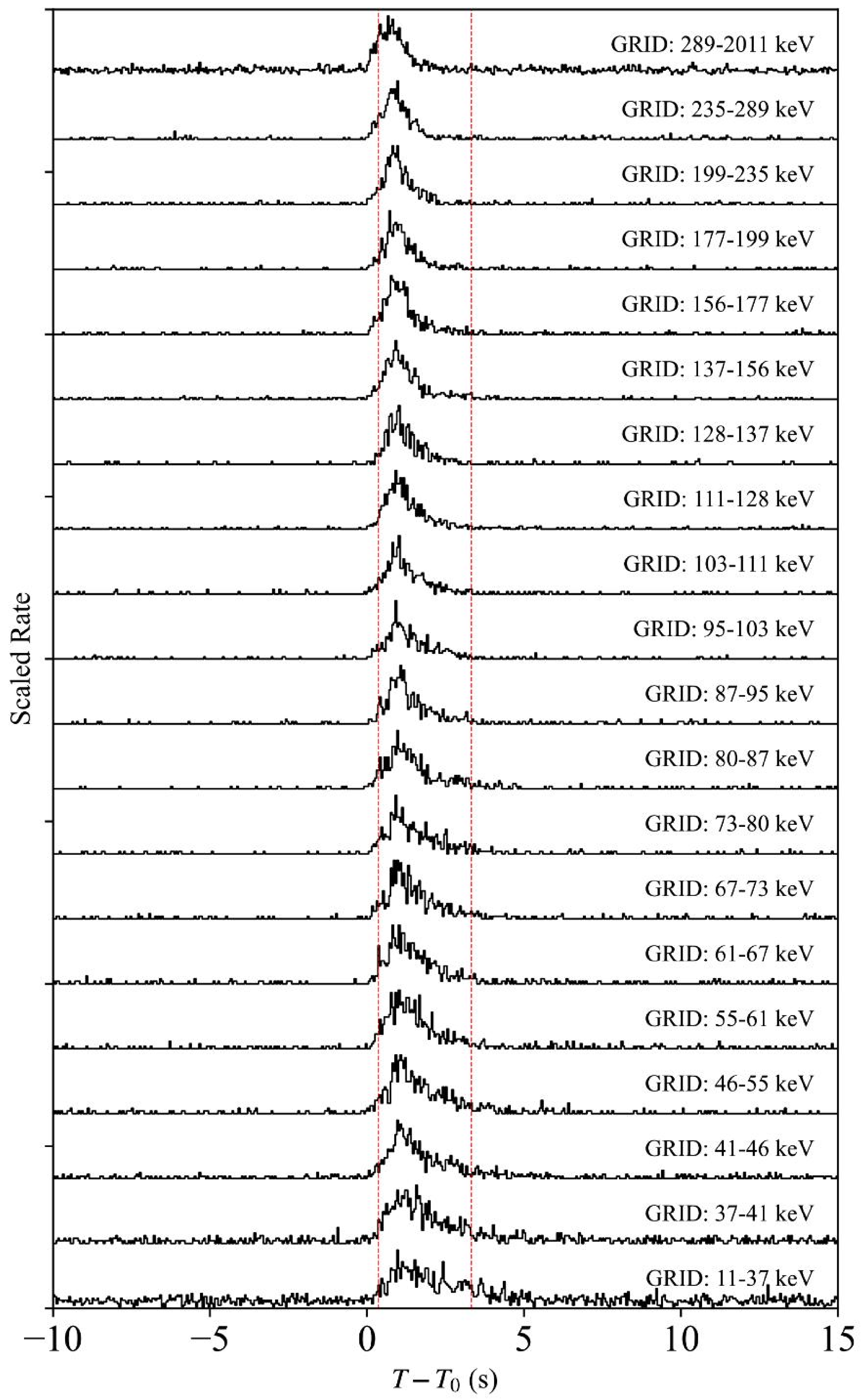
$$B=B_0\left(\frac{t'}{t'_0}\right)^{-\alpha_{\rm B}}, \qquad (4)$$

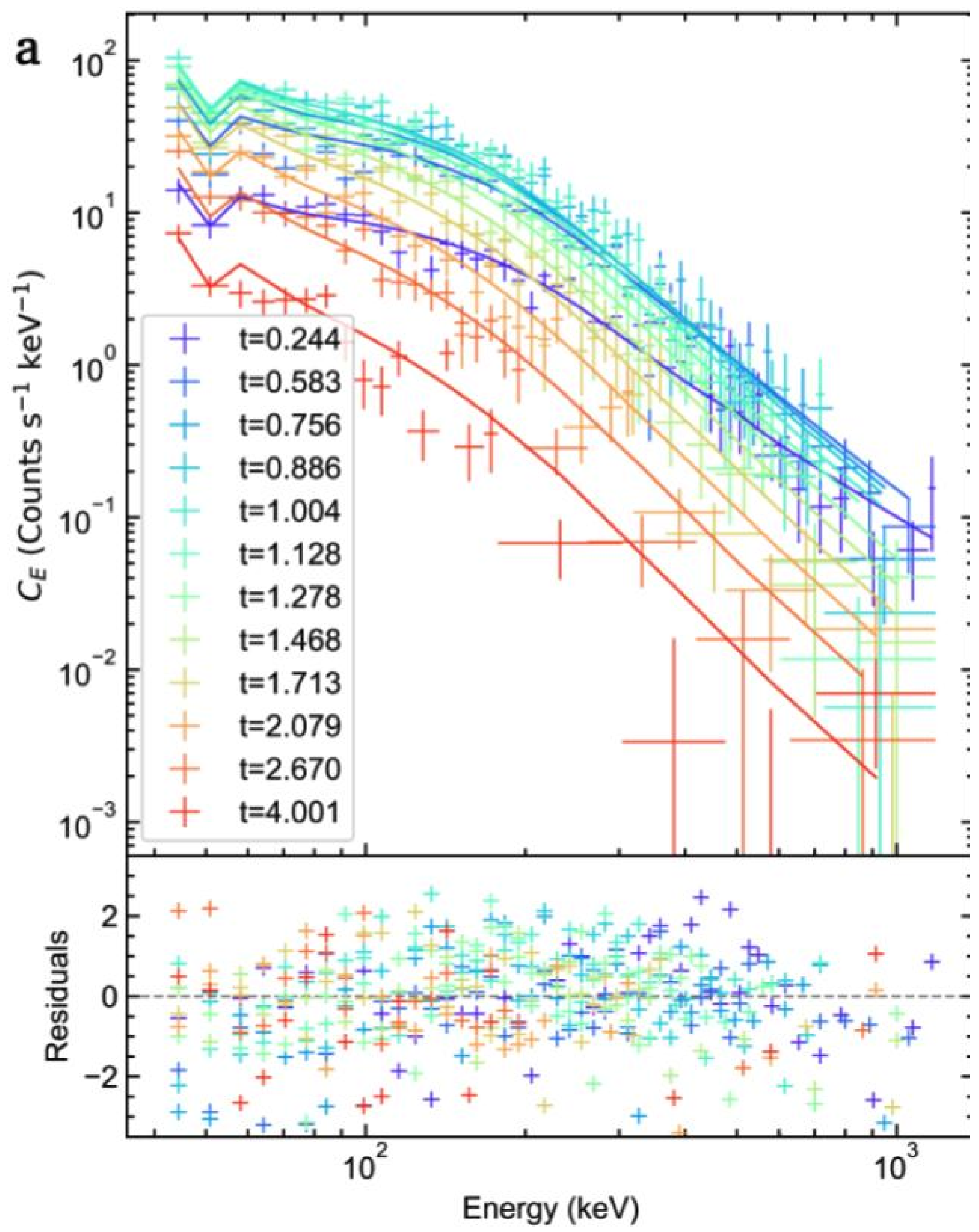
$$P'\left(\nu'\right)=\frac{\sqrt{3}q_{\rm e}^3B}{m_{\rm e}c^2}\int_{\gamma_{\rm min}}^{\gamma_{\rm max}}\left(\frac{dN_{\rm e}}{d\gamma_{\rm e}}\right)F\left(\frac{\nu'}{\nu'_{\rm c}}\right)d\gamma_{\rm e}, \qquad (5)$$

respectively. Considering the equal-arrival-time surface effect, the observed specific flux can be obtained by

$$F_{\nu_{\rm obs}}=\frac{1+z}{4\pi D_{\rm L}^2}\int_{t_0}^{t_{\rm e}}\frac{c}{2R}\frac{P'\left(\nu'\left(\nu_{\rm obs}\right)\right)}{\Gamma^3(1-\beta_\Gamma cos\theta)^2}dt, \qquad (6)$$

Short-duration Type-II GRB 230812B, typical sync.

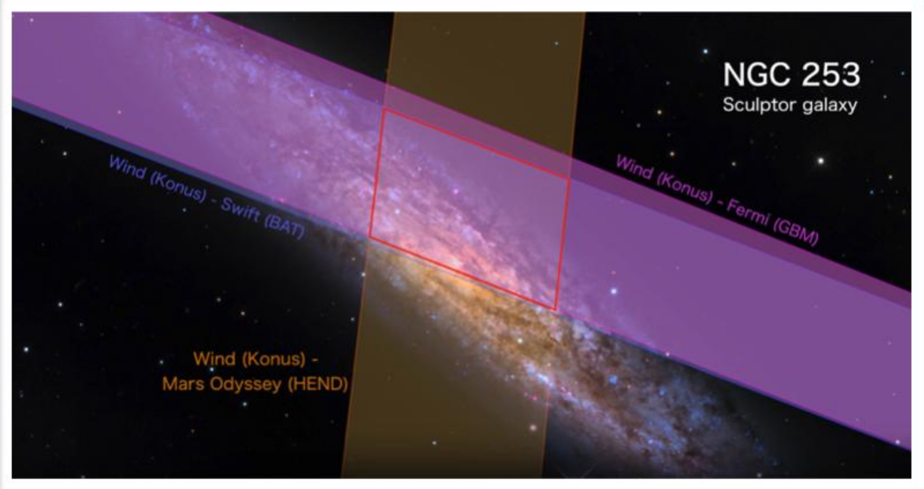




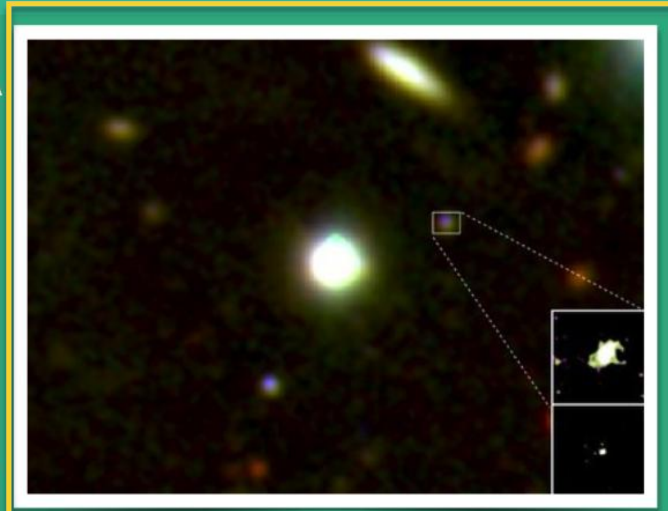
Parameters	Prior bounds	Best fitting results
$log(B_0/G)$	[0, 3]	$2.663^{+0.107}_{-0.114}$
α_B	[1, 2]	$1.945^{+0.033}_{-0.046}$
$log\gamma_{min}$	[4, 7]	$5.174^{+0.007}_{-0.012}$
$log\Gamma$	[1.2, 3]	$2.547^{+0.066}_{-0.069}$
p	[1.5, 3.5]	$3.487^{+0.008}_{-0.012}$
t_{inj}/s	[-1.5, 2]	$0.86^{+0.011}_{-0.01}$
q	[0, 10]	$2.121^{+0.054}_{-0.045}$
$log(R_0/cm)$	[12, 16]	$14.26^{+0.117}_{-0.161}$
$log(Q_0/s^{-1})$	[31, 156]	$48.117^{+0.213}_{-0.217}$

γ'_e

Energy (keV)



GRB 200415A
+MGF
Yang, J+ 2020
Roberts+2021
Eric+2021
Svinkin+2021
Castro-Tirado+2021



GRB 200826A
+SN
Zhang,BB+ 2021
Tomás +2021
Amati+ 2021
Rossi +2022

GRB 211211A
+KN
Yang, J+2022
Troja+2022
Rastinejad+2022
Alessio+2022

GRB 230307A
+KN
Sun,H+2023
Yang,YH+2023
Gillanders+2023
Levan+2023
Dichiara+2023

Magnetar GF, non-GRB

Short-duration Type-II GRB

Long-duration Type-I GRBs

Towards a more physical classification

Towards a more physical classification

Criterion	Merger/ Type I	Core-collapse/Type II
Duration	usually short, but can have extended emission	usually long, can be short (tip of iceberg)
Spectrum	on average hard (soft tail)	on average soft
Spectral Lag	usually short	usually long, can be short
$E_{\gamma,iso}$	on average low	on average high
$E_p - E_{\gamma,iso}$	on short GRB track	on long GRB track
$L^p_{\gamma,iso}$ −lag	usually off Norris relation	usually on the relation
SN/KN association	KN	SN
Medium type	usually low-n ISM	wind or usually high-n ISM
$E_{K,iso}$	on average low	on average high
Jet angle	on average wide	on average narrow
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Host galaxy type	elliptical, early, or late	usually late
SSFR	from low to high	usually high
Offset	outskirts or "hostless"	well inside
z-distribution	on average low z	on average high z
GW association	BH-NS, NS-NS, WD-NS?	collapsar?

Zhang,B., Zhang,B.-B., et al 2007, 2009

○ **Peculiar Core-Collapse Type-II GRB**

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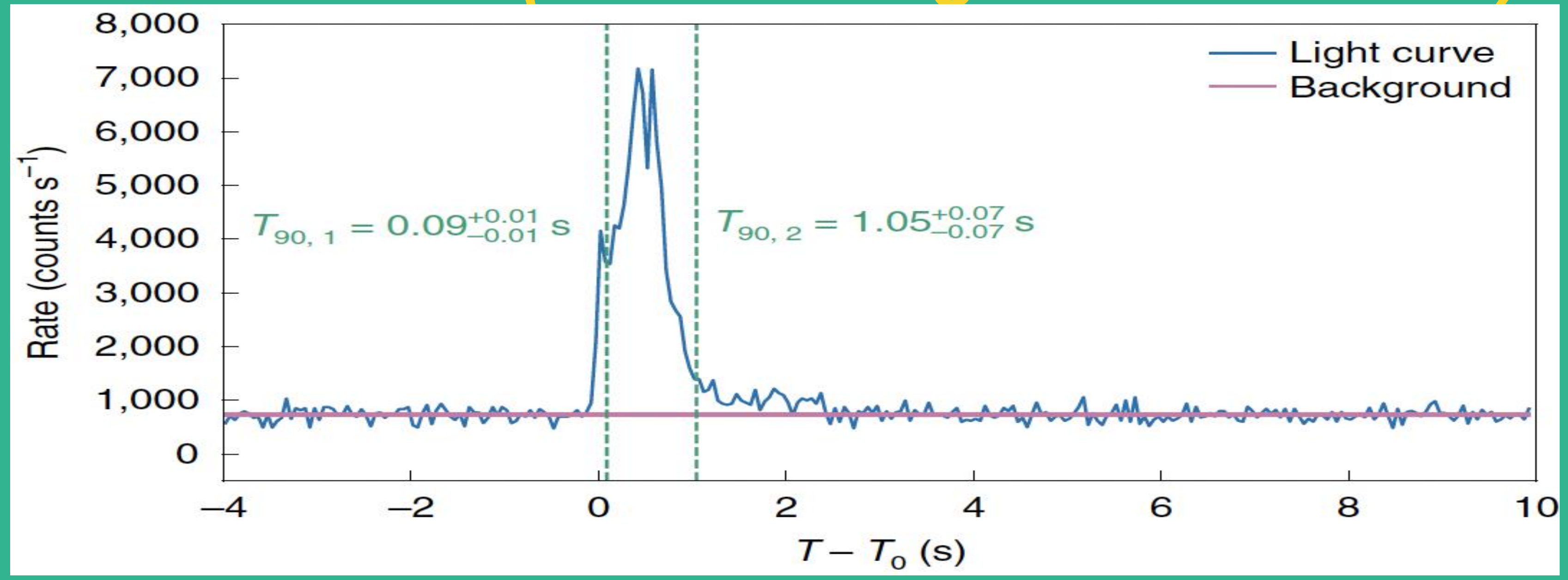
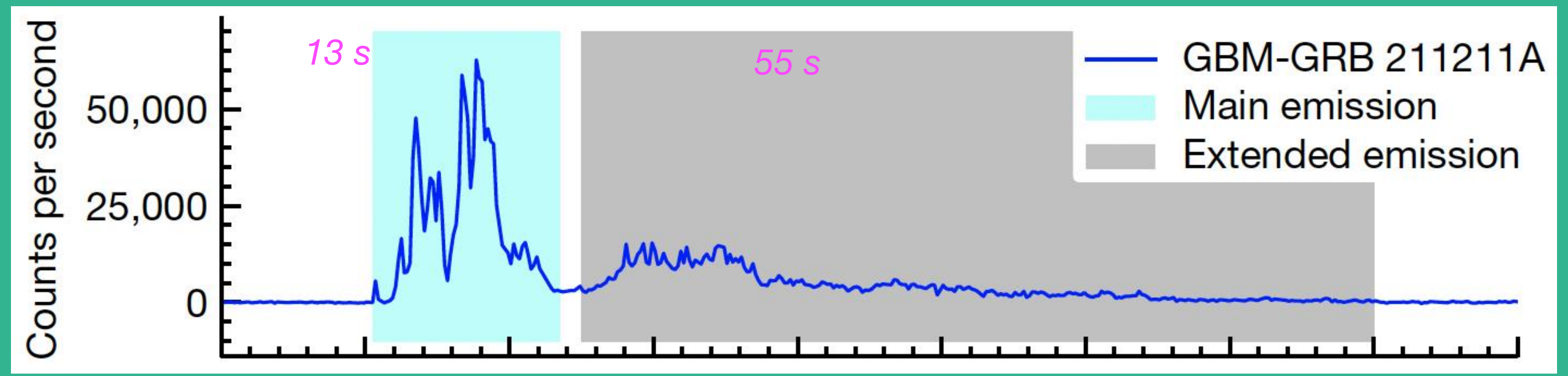


○ **Peculiar Merger Type-I GRB**

GRB 211211A (Jun Yang et al. 2022 Nature)

GRB 230307A (HUi Sun et al, submitted)



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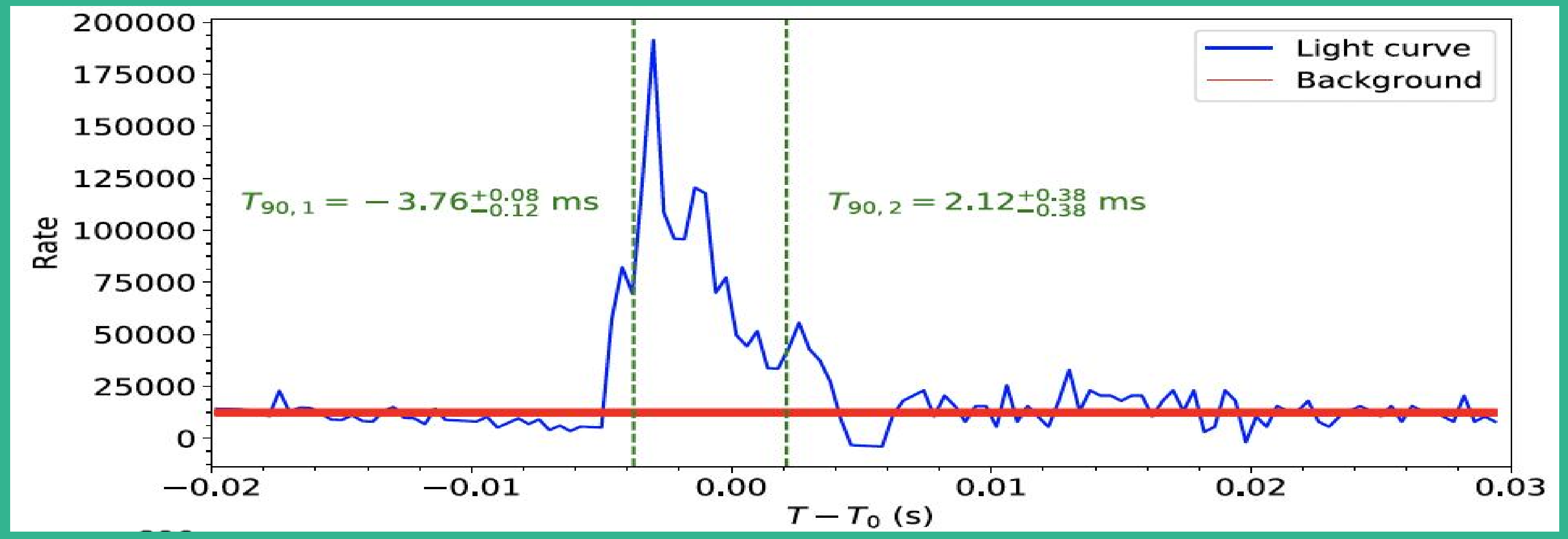

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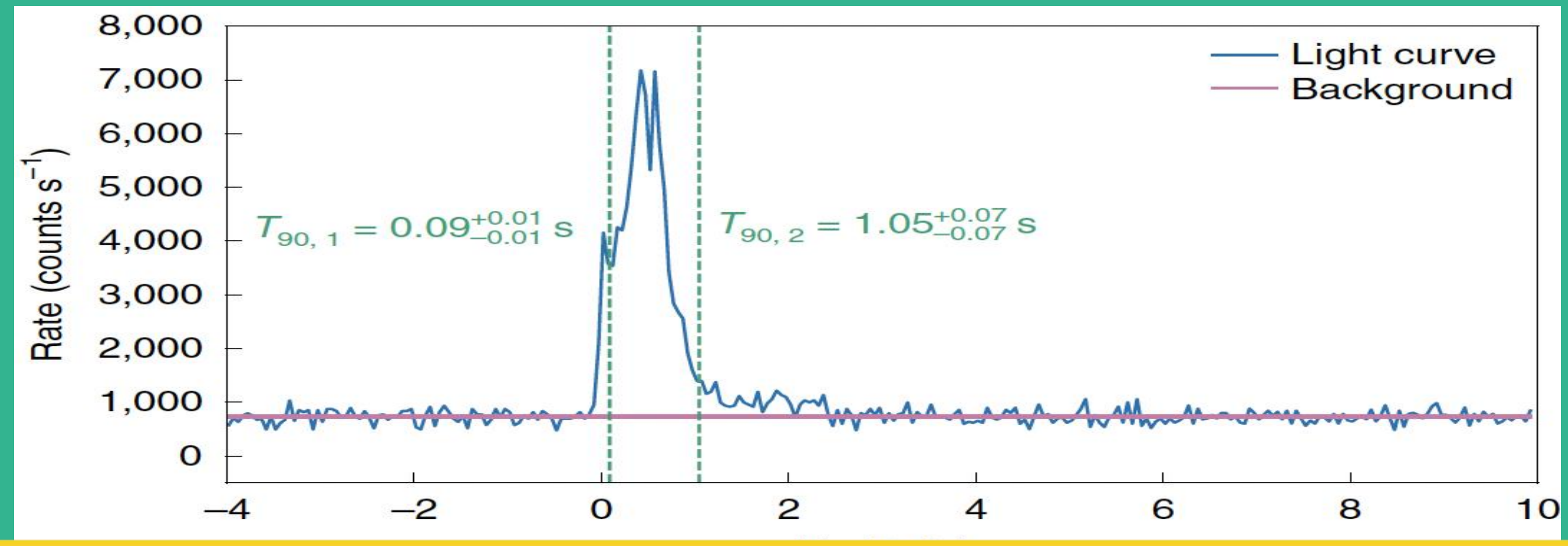

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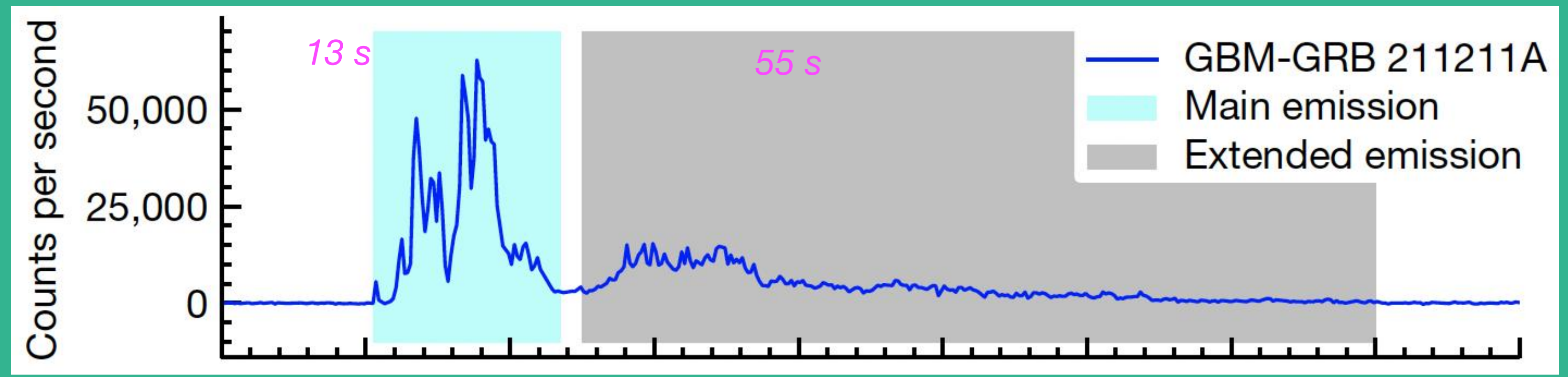

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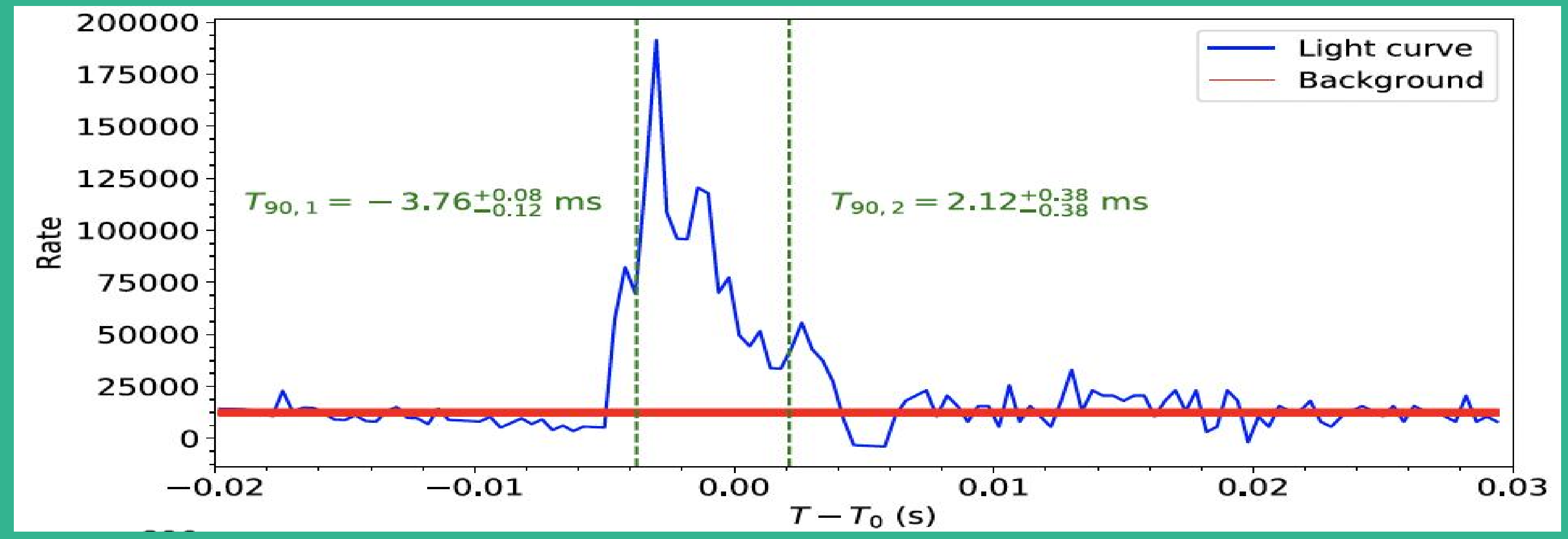

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Merger/ Core-collapse/

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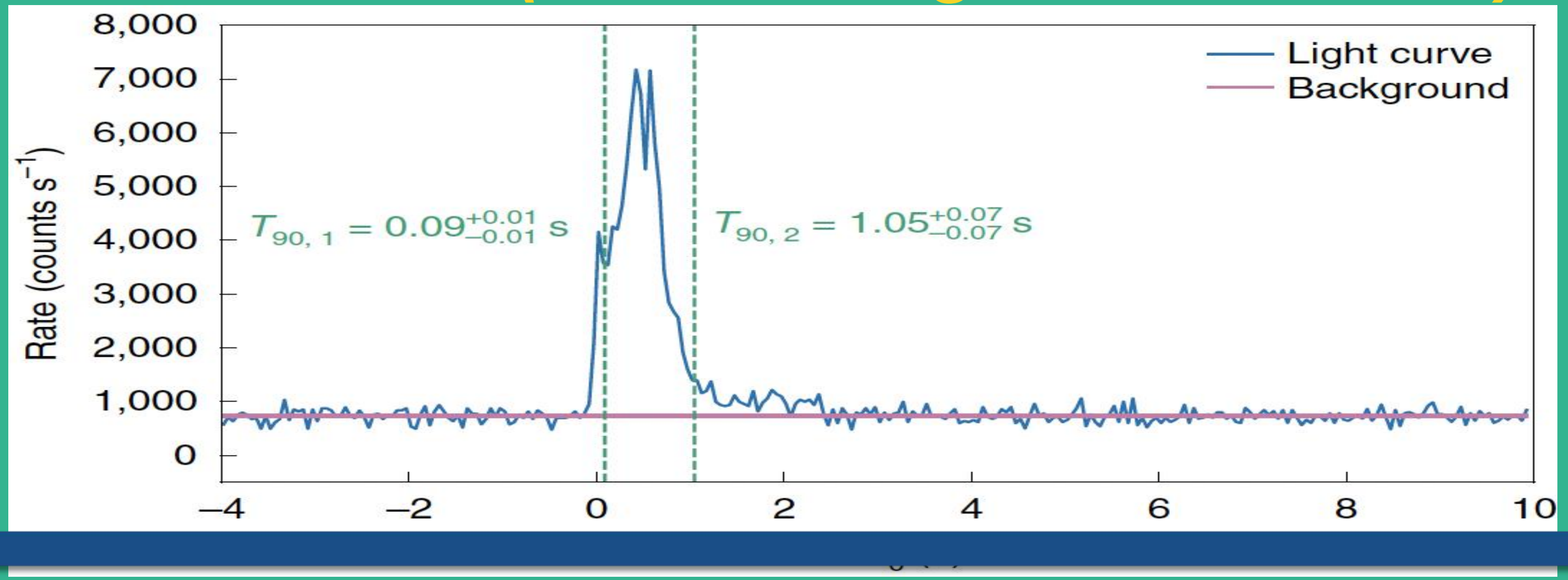

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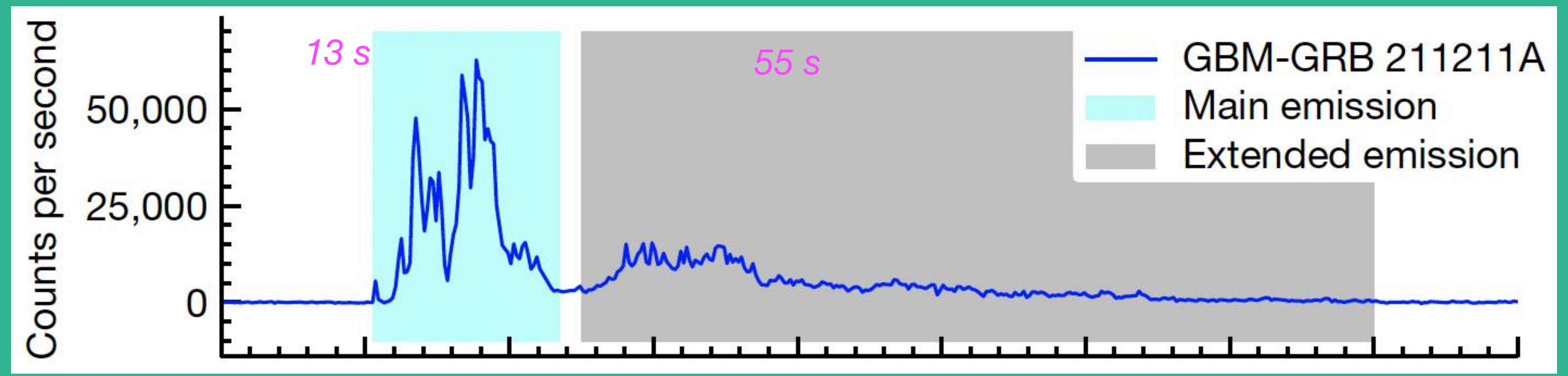

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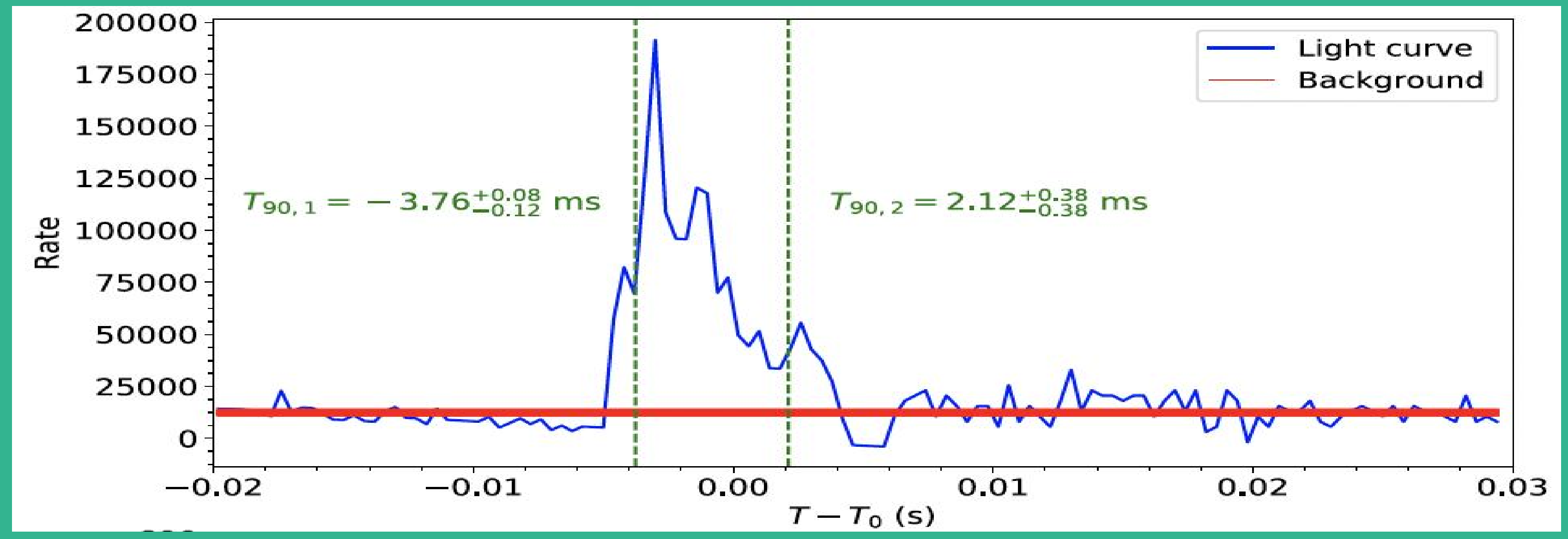

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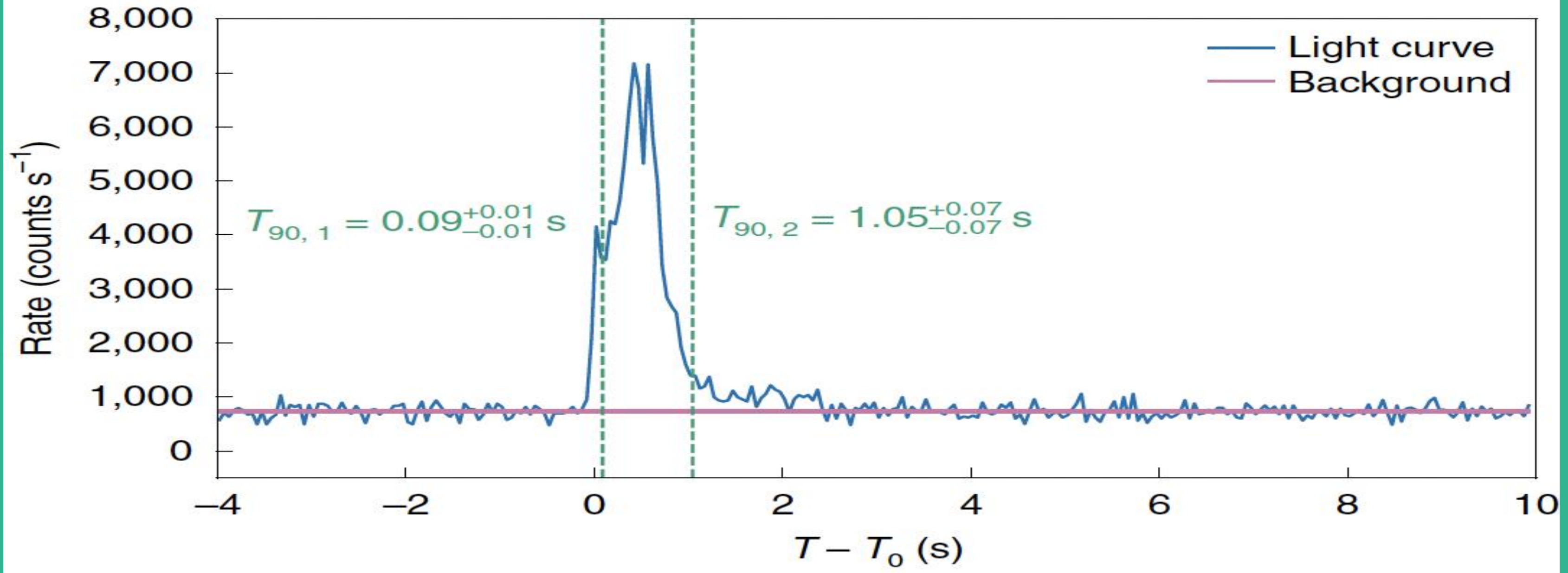

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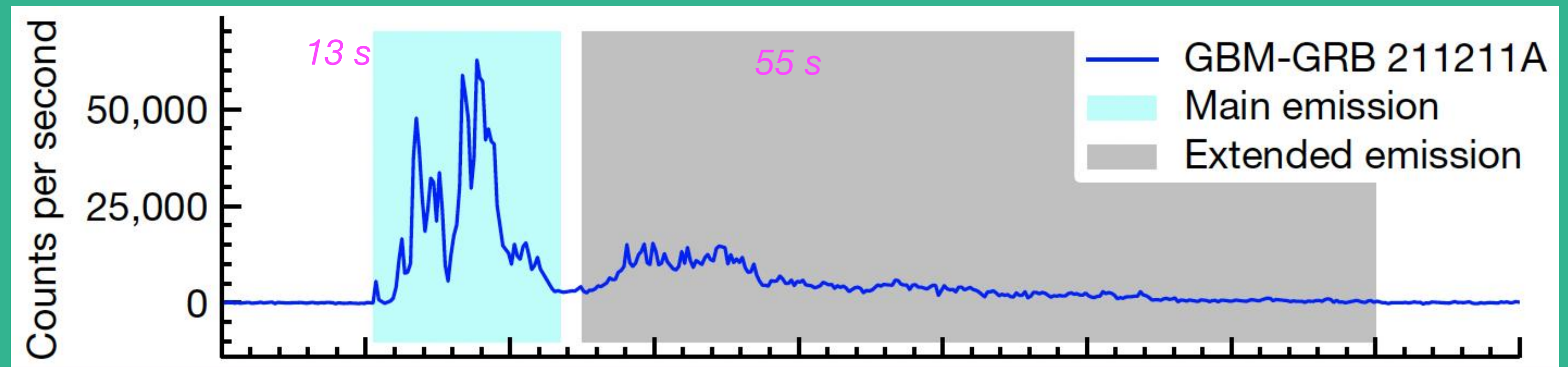

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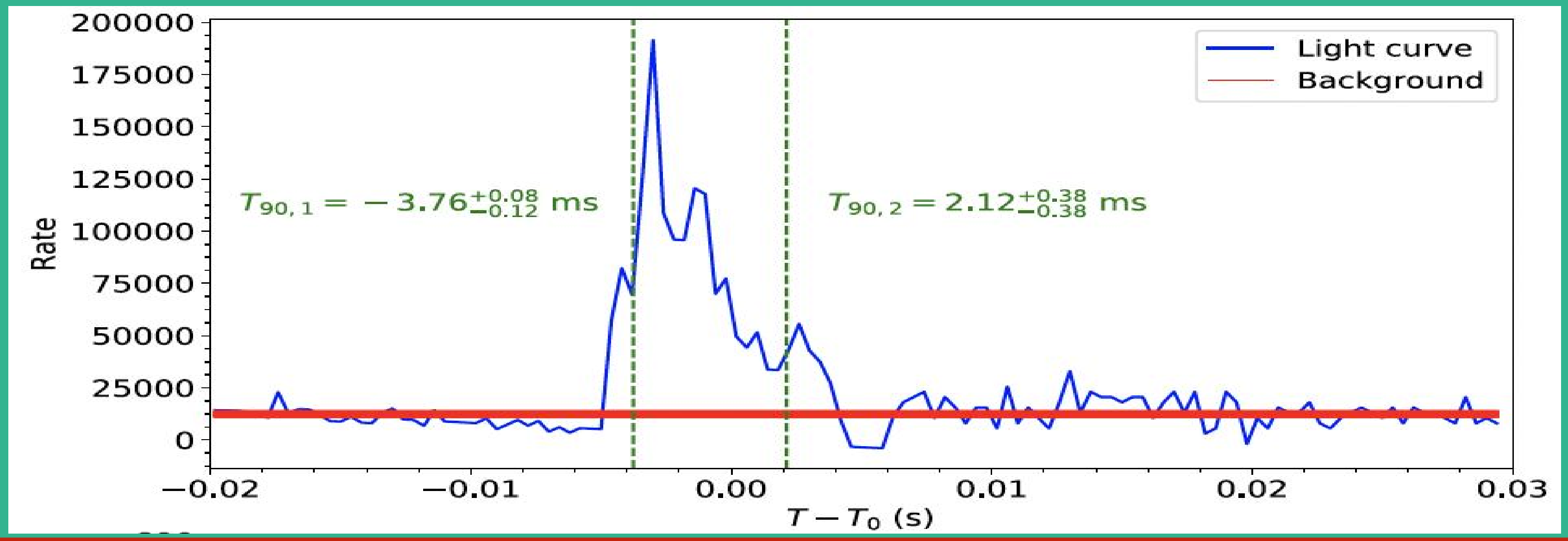

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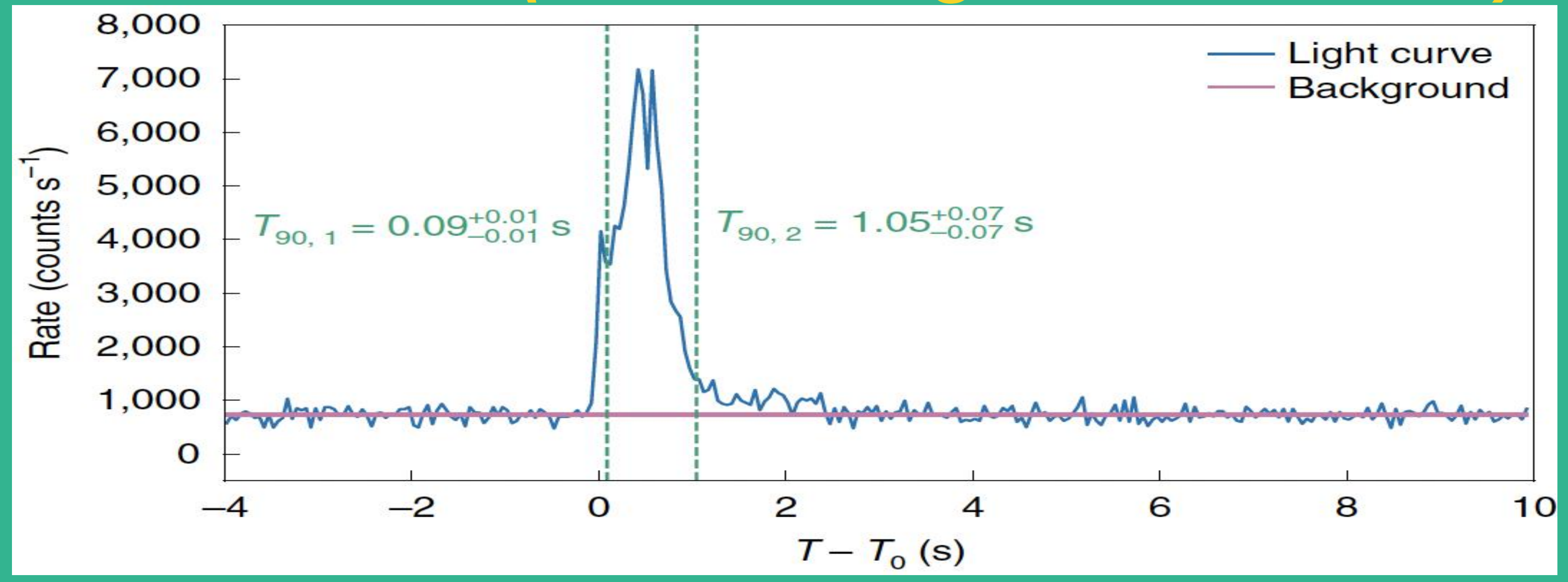

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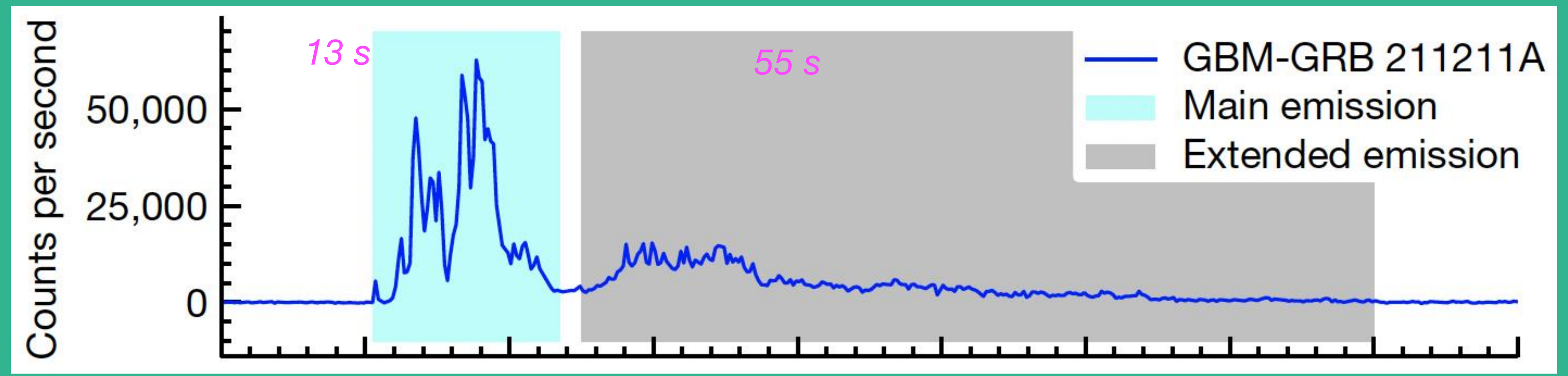

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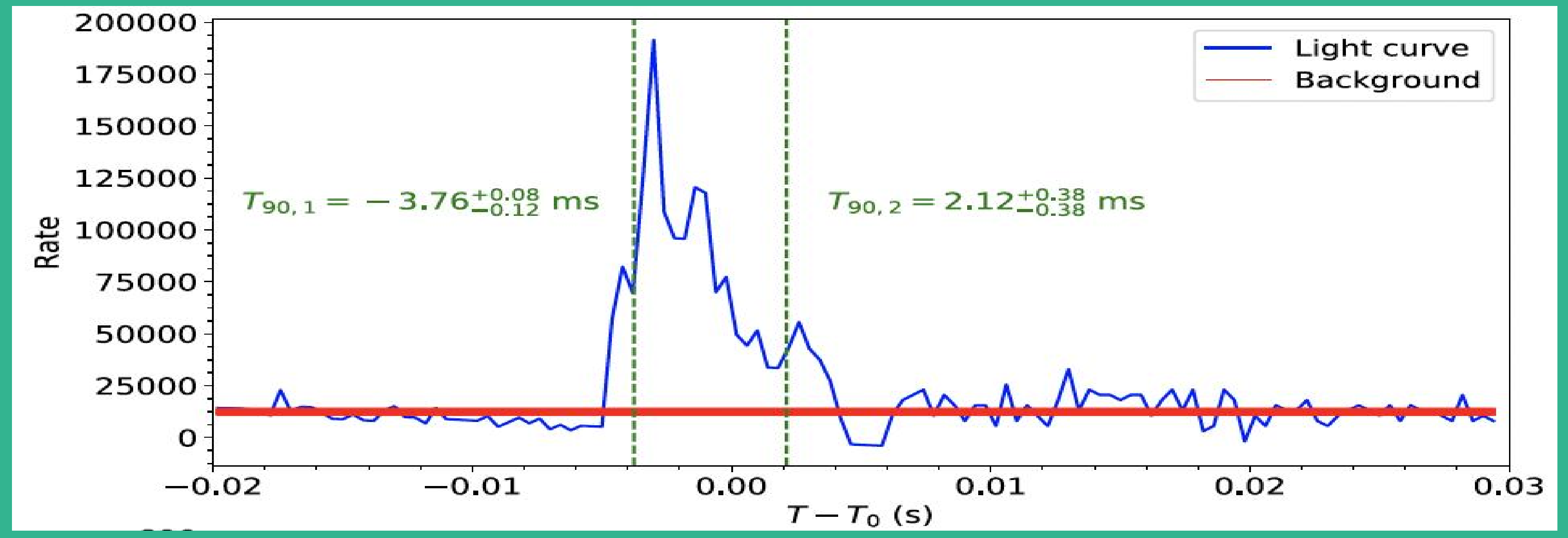
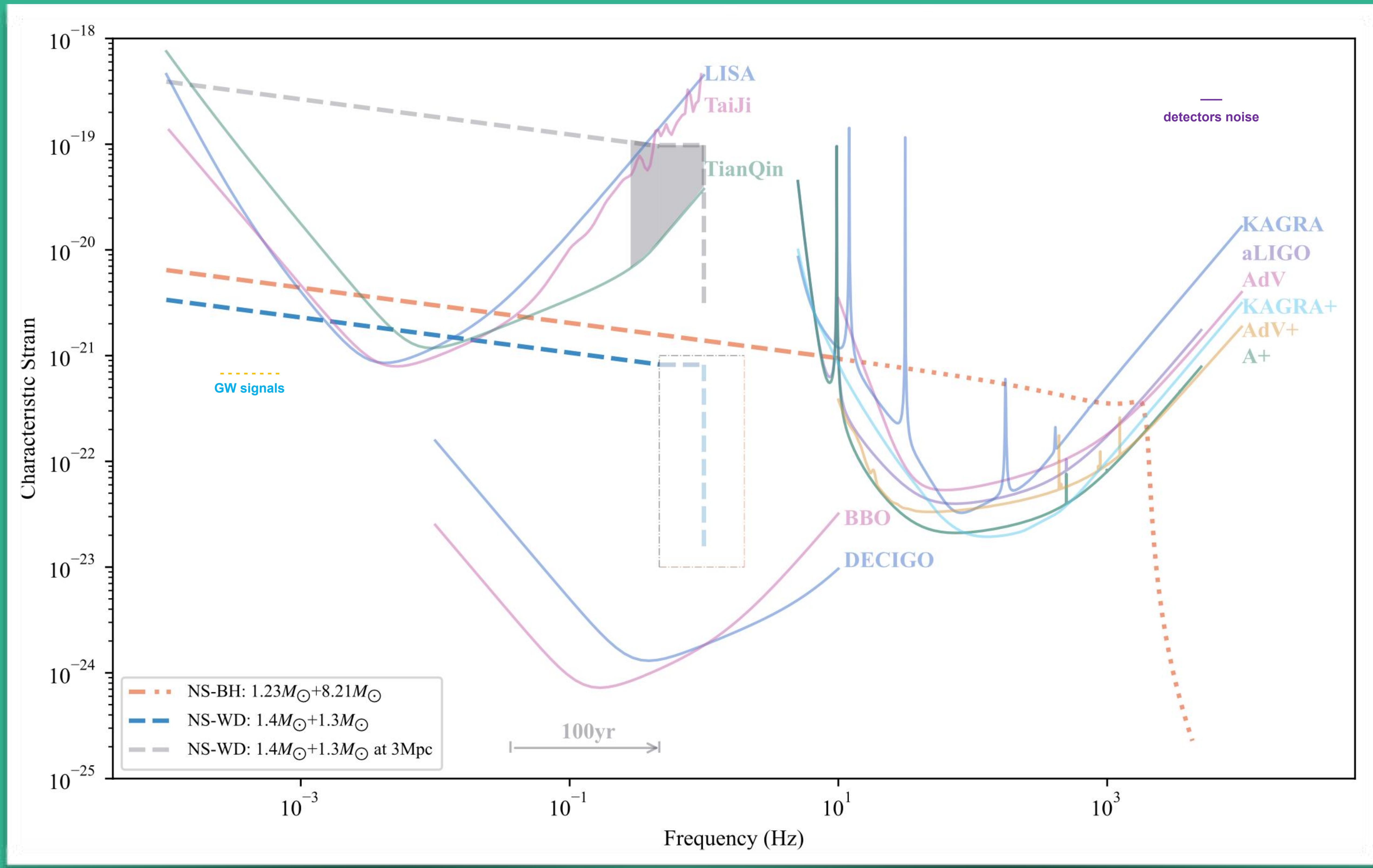


GRB 211211A-like Events and How GWs May Tell Their Origins

- NS-BH merger : detectable by ground-based detectors
- NS-WD merger: detectable by decihertz space GW detectors
- NS-WD merger: detectable by millihertz space GW detectors at ~ 3 Mpc (LISA, Taiji and TianQin)



Yin, I. H, et al. 2023, ApJL in press, arXiv:

New Types of Gamma-ray Bursts Push our New Understandings about their Origins & Mechanisms

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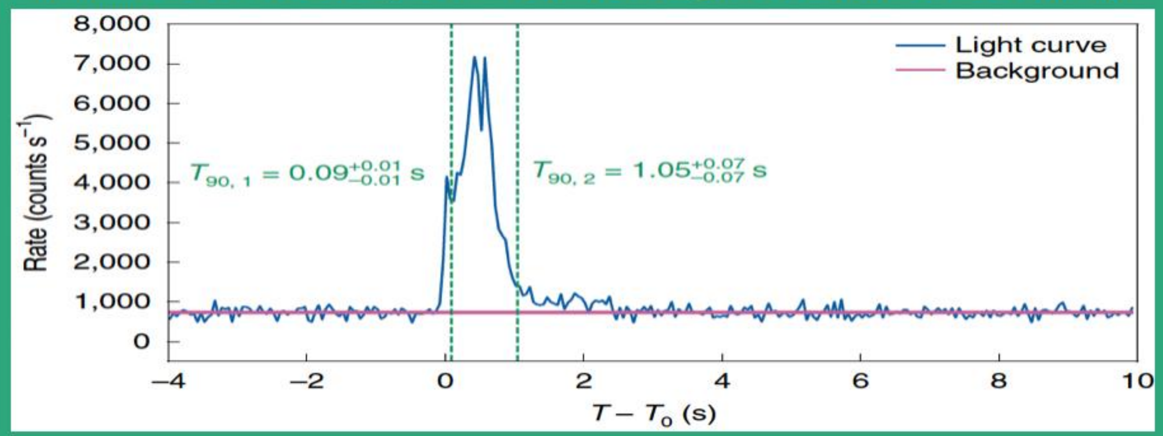

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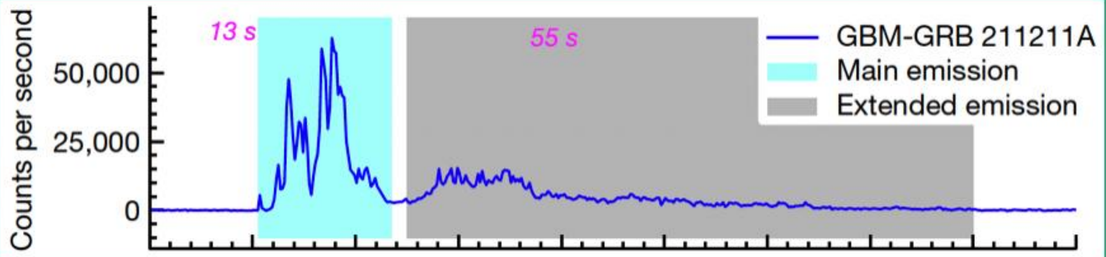

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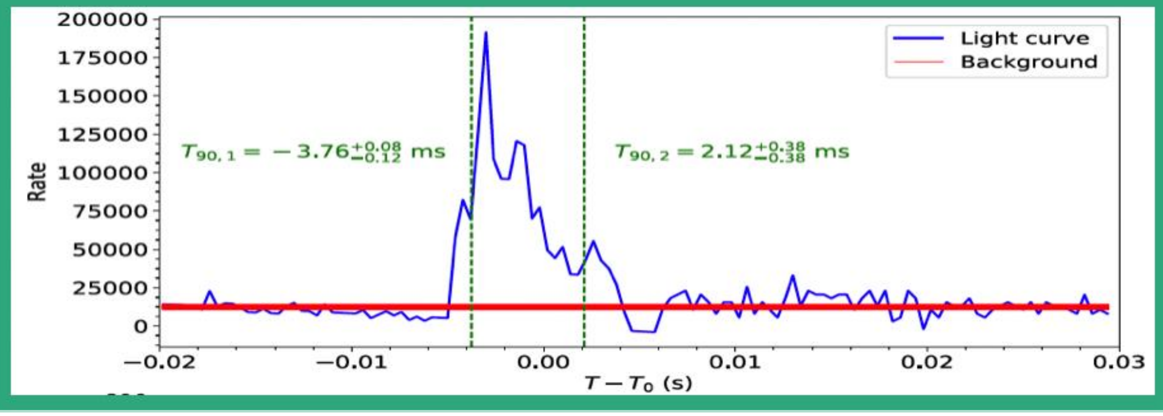

Let's expecting more news, when we meet again!

The 3rd Nanjing GRB Conference

May 21-25, 2024 , Suzhou, China

New transients,
New missions,
New ideas.

Since the 2nd Nanjing GRB conference held in 2019, significant strides have been made in the field of Gamma-Ray Bursts. The detection of several distinctive GRBs, including the unprecedented "Brightest of All Time" GRB 221009A, has been continuously driving this vigorous field. In May 2024, we will gather once again in the beautiful city of Suzhou with the aim of summarizing and discussing the recent progress, both in the fronts of new observations and theoretical modeling. It will also highlight the initiatives and the results of some existing, newly launched or anticipated space/ground-based missions/telescopes, with a strong focus on their connections to multi-messenger astrophysics.

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