GRB 221009A: the B.O.A.T. Burst that Shines in Gamma Rays

http://arxiv.org/abs/2409.04580

Nicola Omodei (Stanford University)
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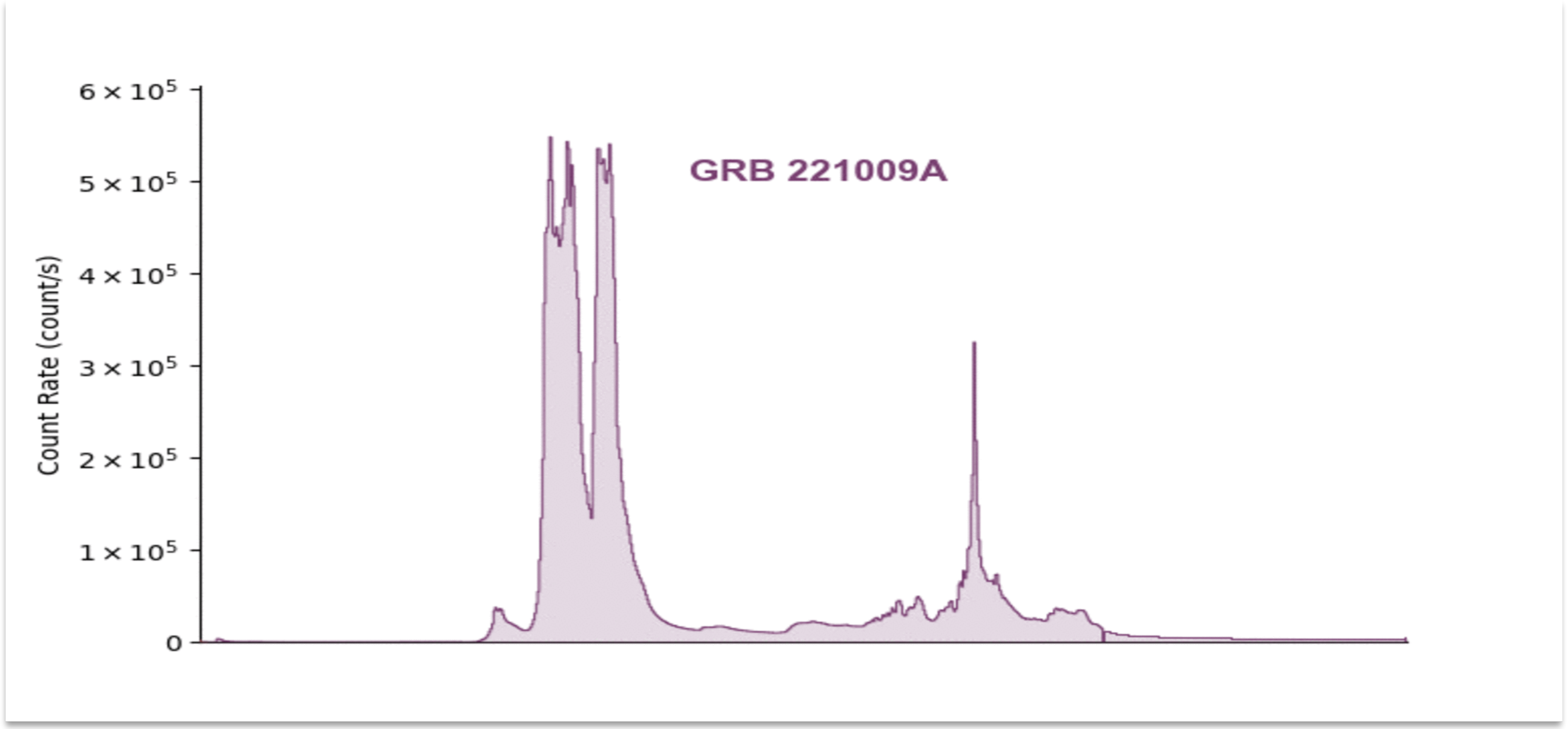
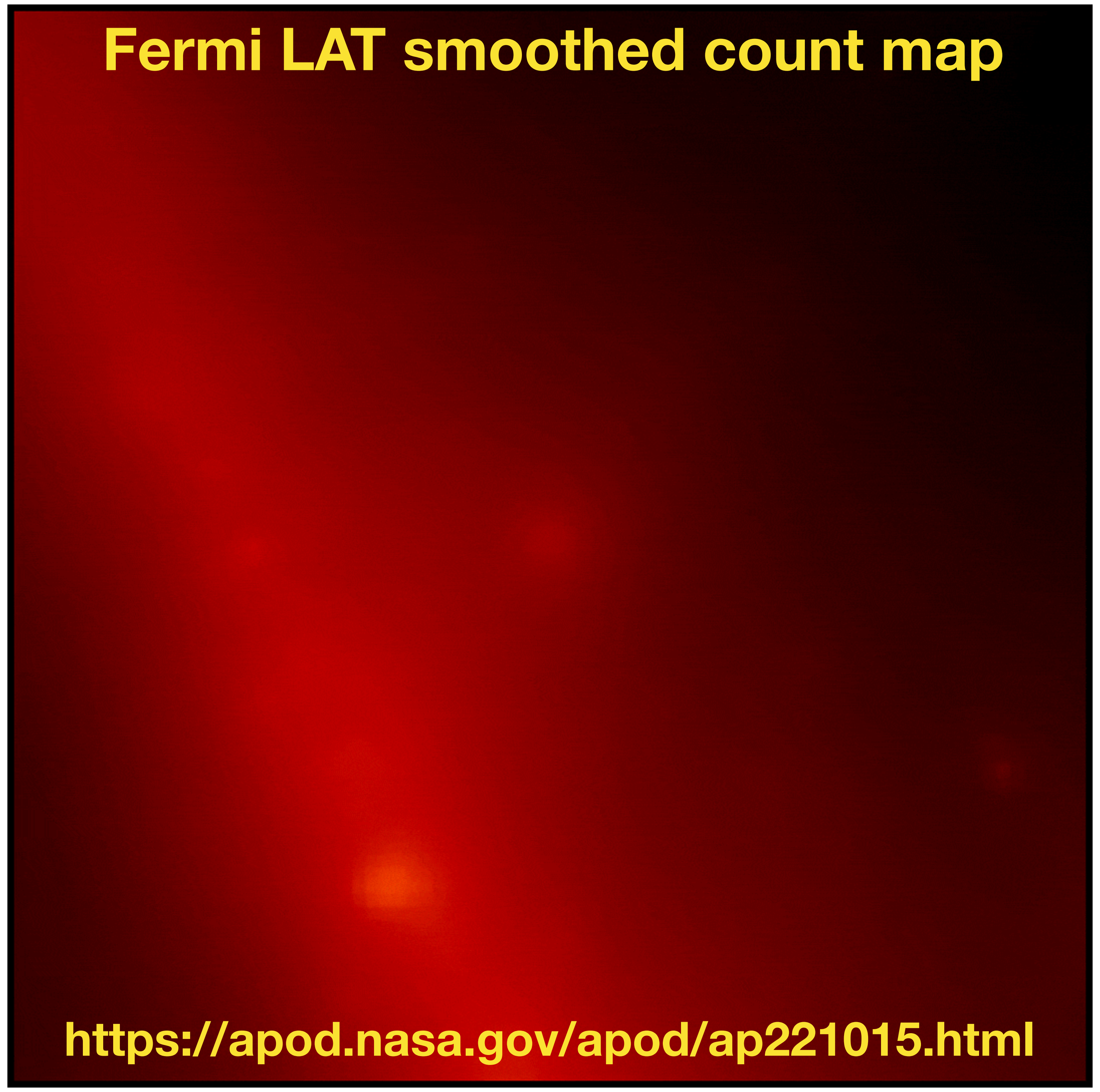
on behalf of the Fermi LAT collaboration
(Special thanks to Sunny & Yoni!)

GRB+CE2024

B.O.A.T.: The Brightest Of All Time

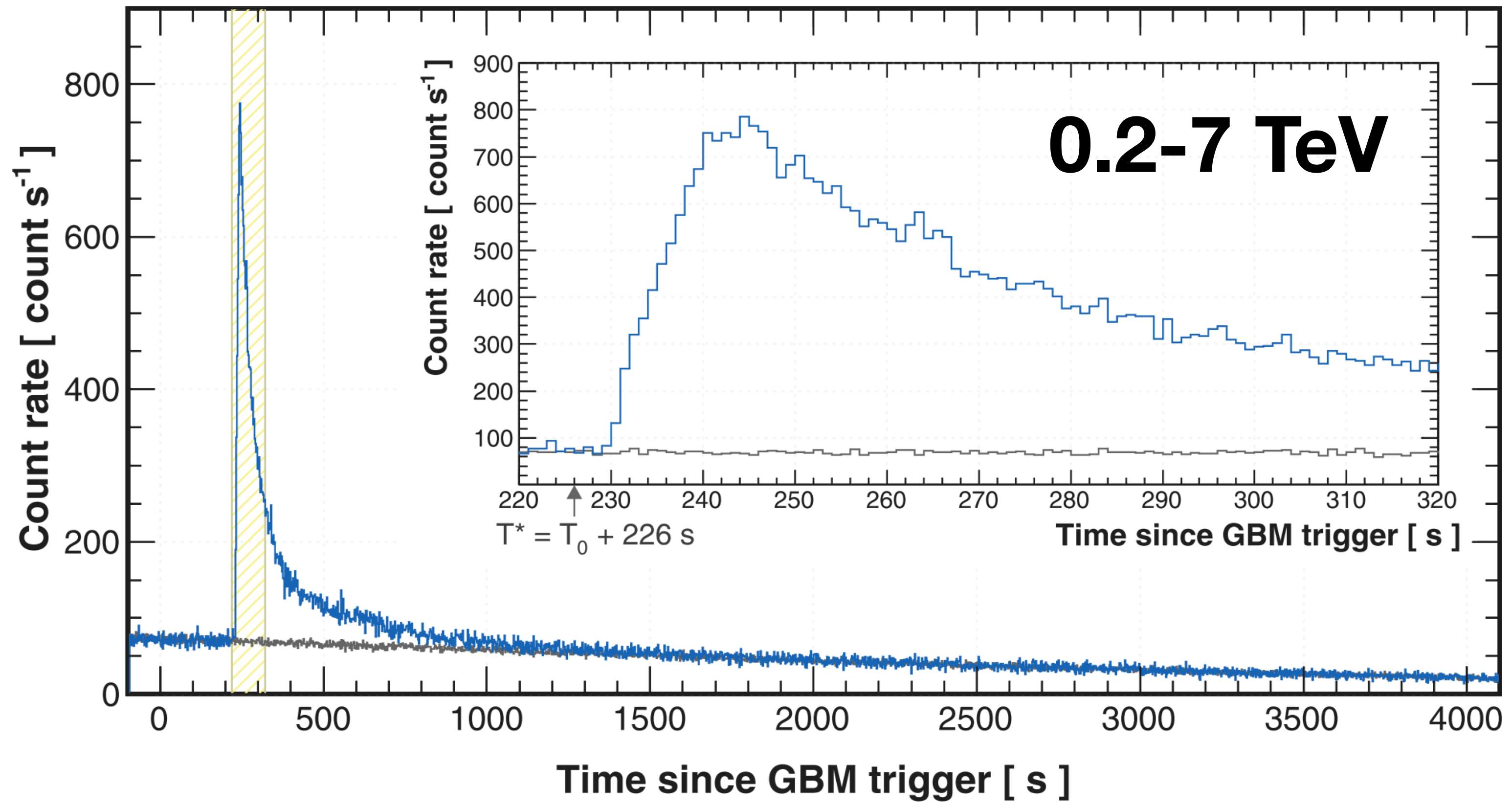
- **GRB221009A was an extraordinary event**
  - **A burst as energetic (~10^{55} erg) and as close to Earth (z=0.151) as 221009A is thought to be a once-in-10,000-year event (Burns et al). The B.O.A.T. is the Brightest Of All Time**



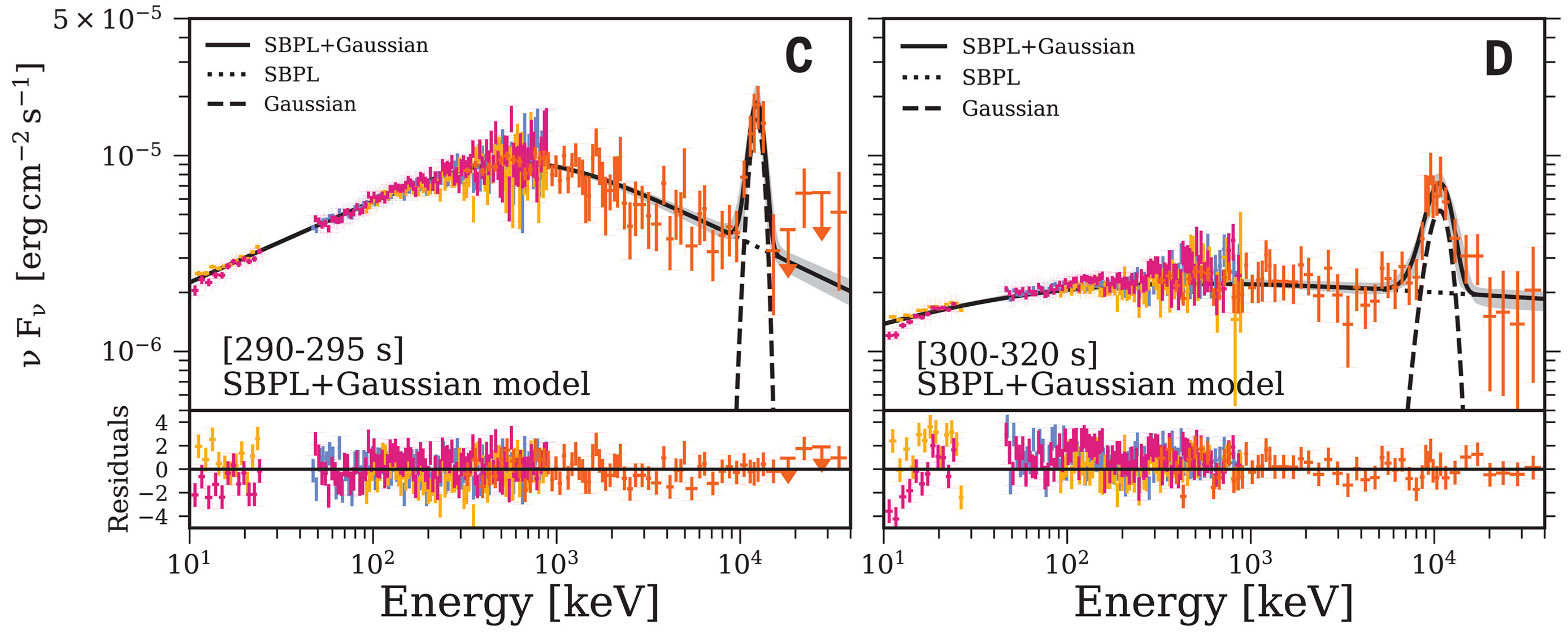


Few remarkable observations

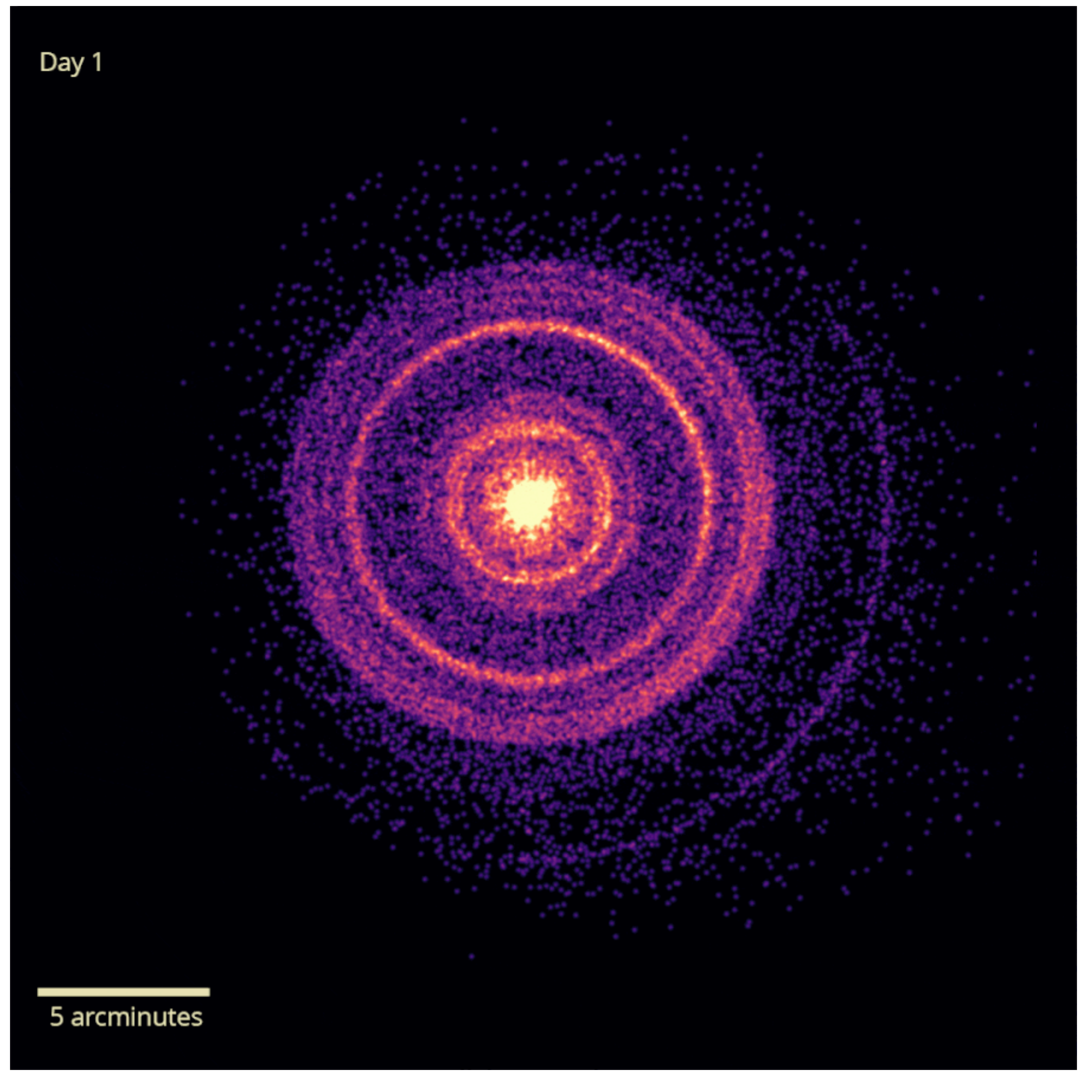
- **LHAASO detection of the TeV afterglow**
  - LHAASO Collaboration, 2023



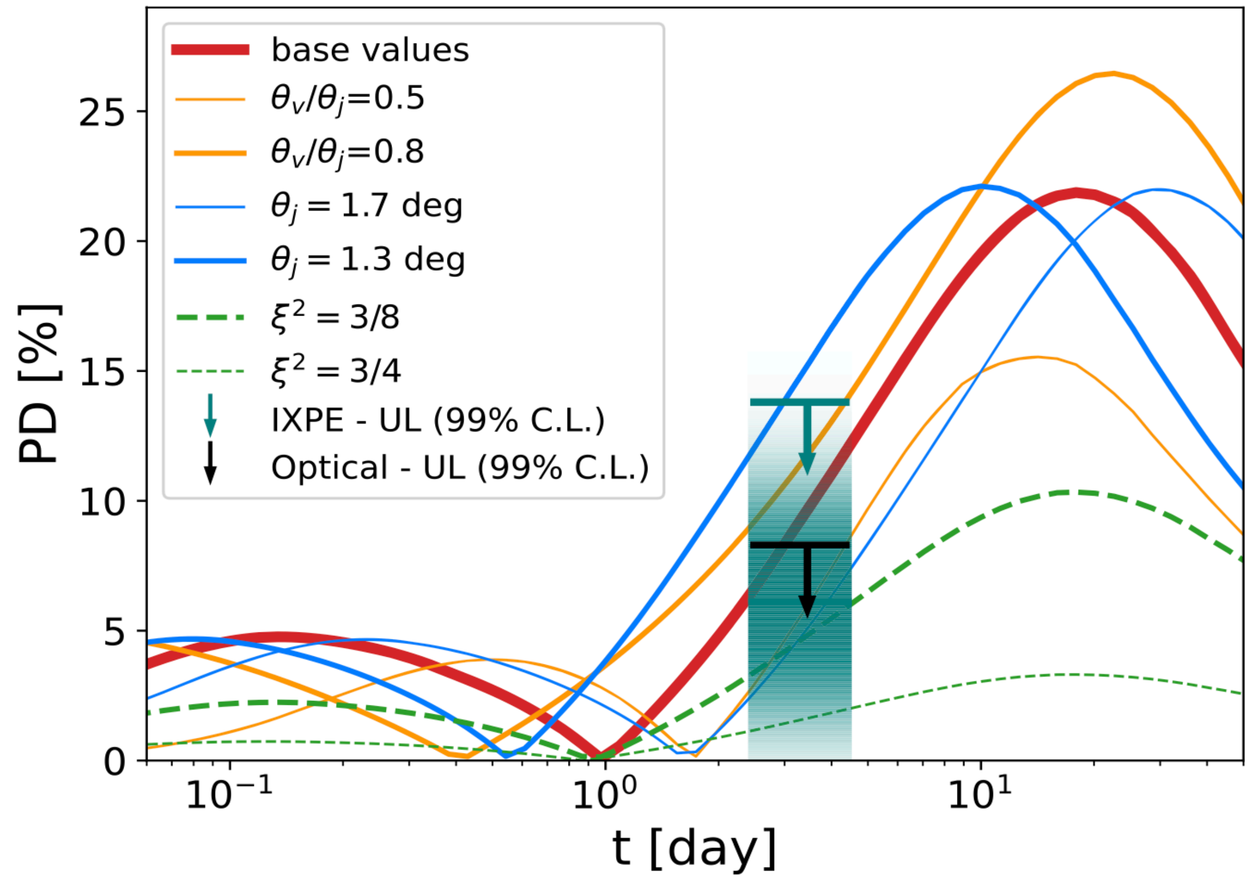
- **A MeV emission line in its spectrum**
  - Ravasio et al. 2024



- **Dust scattering rings visible in Swift and XMM and IXPE**
  - Williams at al. 2023
  - Tiengo et al, 2023



- **X-ray polarization UL on both prompt and afterglow**
  - IXPE collaboration (Negro et al. 2023)



Nicola Omodei – Stanford/KIPAC

Connect-the-dots game…

- I want to present the observations of GRB 221009A by Fermi LAT with minimal interpretation and, like in a “connect-the-dots” game, leave it to you to draw most of the conclusions—taking full advantage of this fantastic workshop!

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Ok… then I asked : "Can you draw a connect-the-dot game that when the dots are connected a boat appears?"

Connect-the-dots game…

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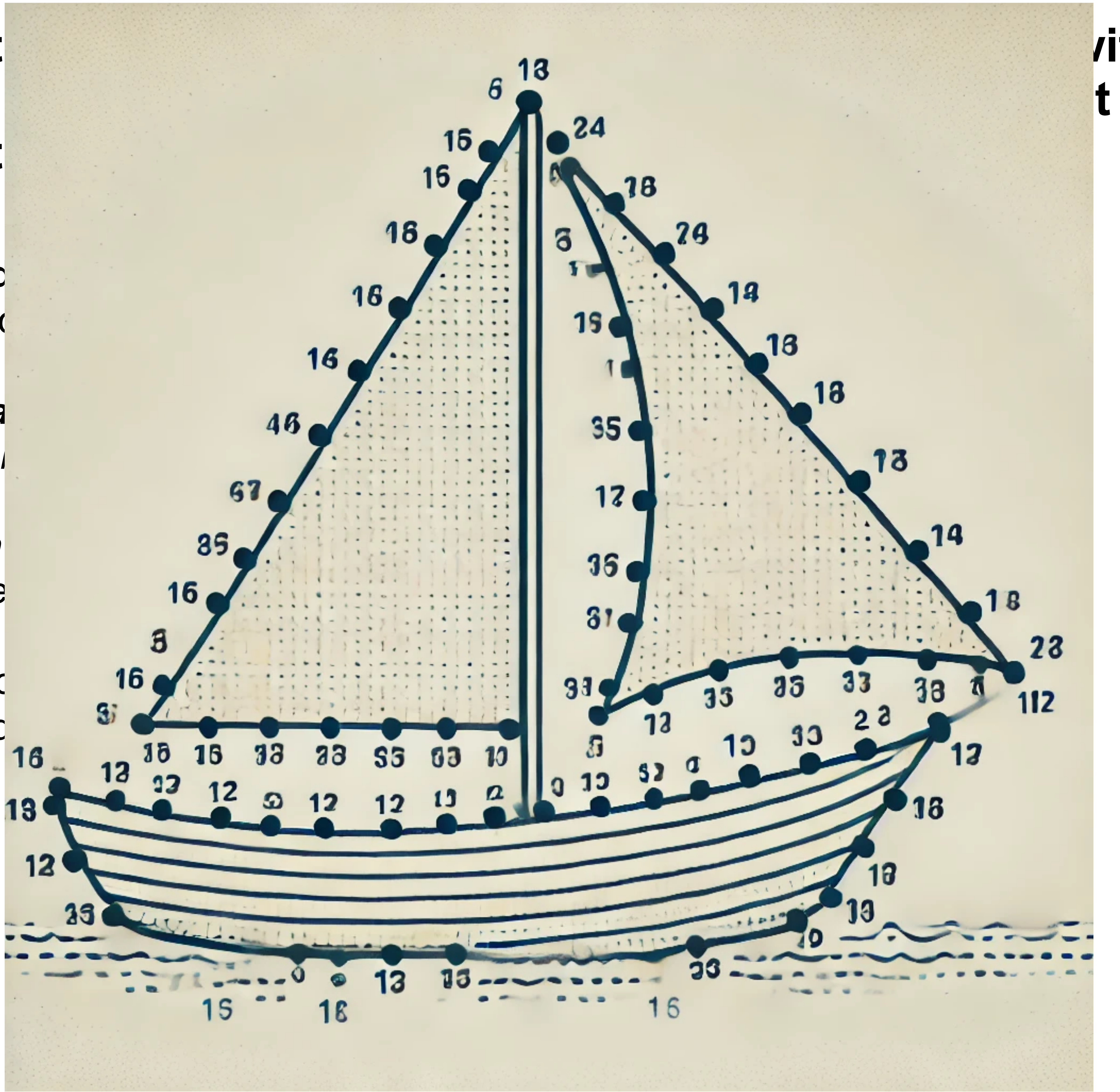

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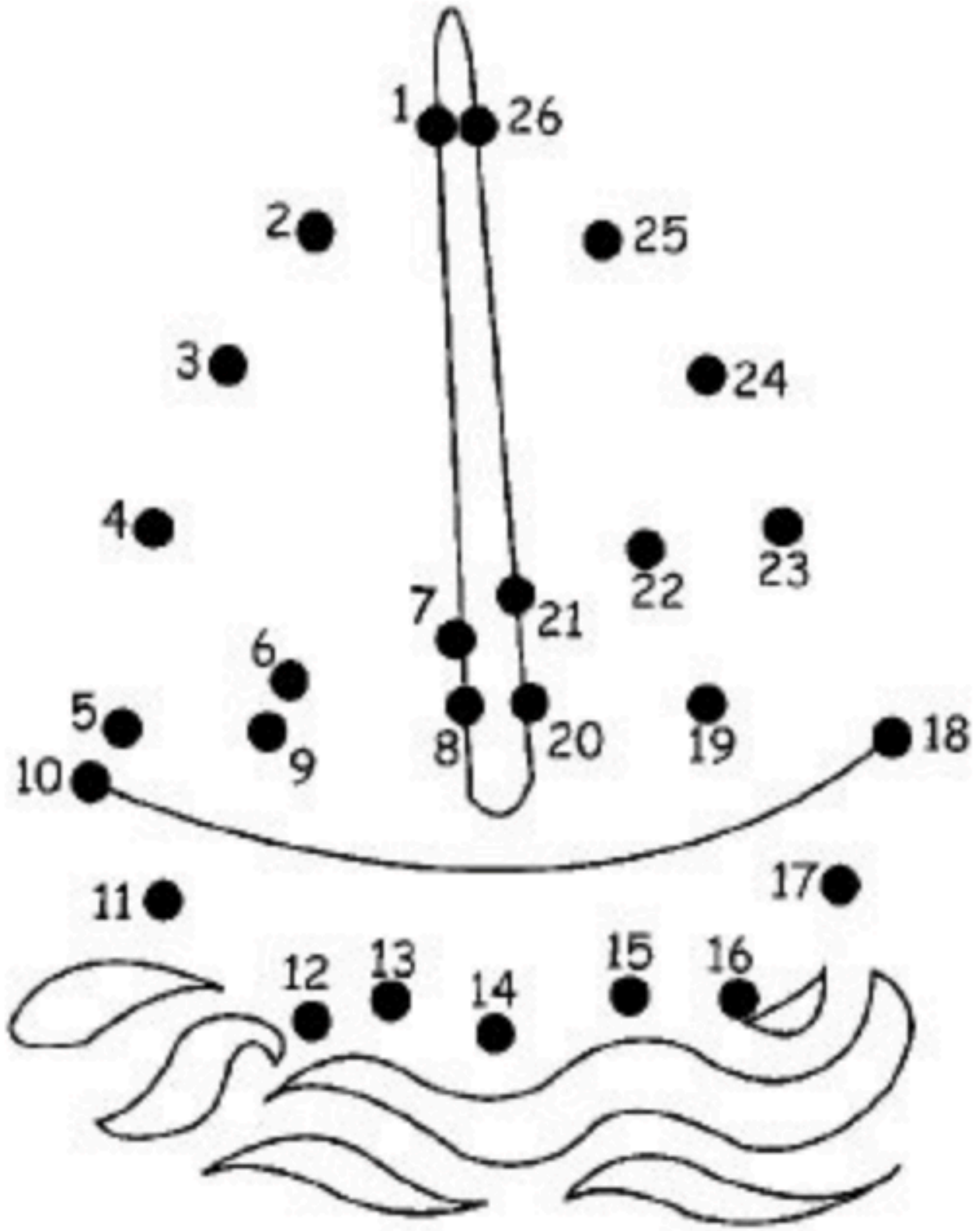

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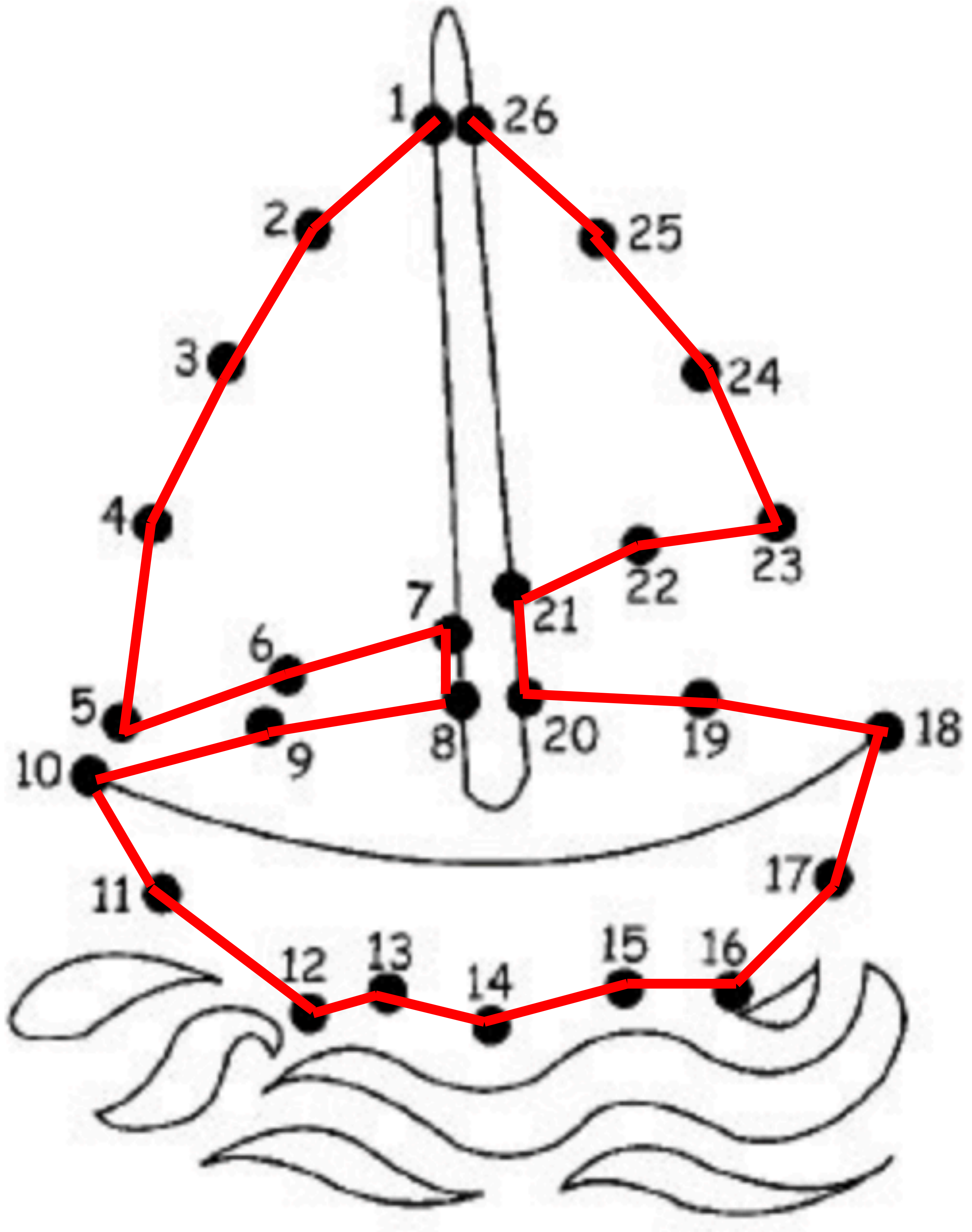
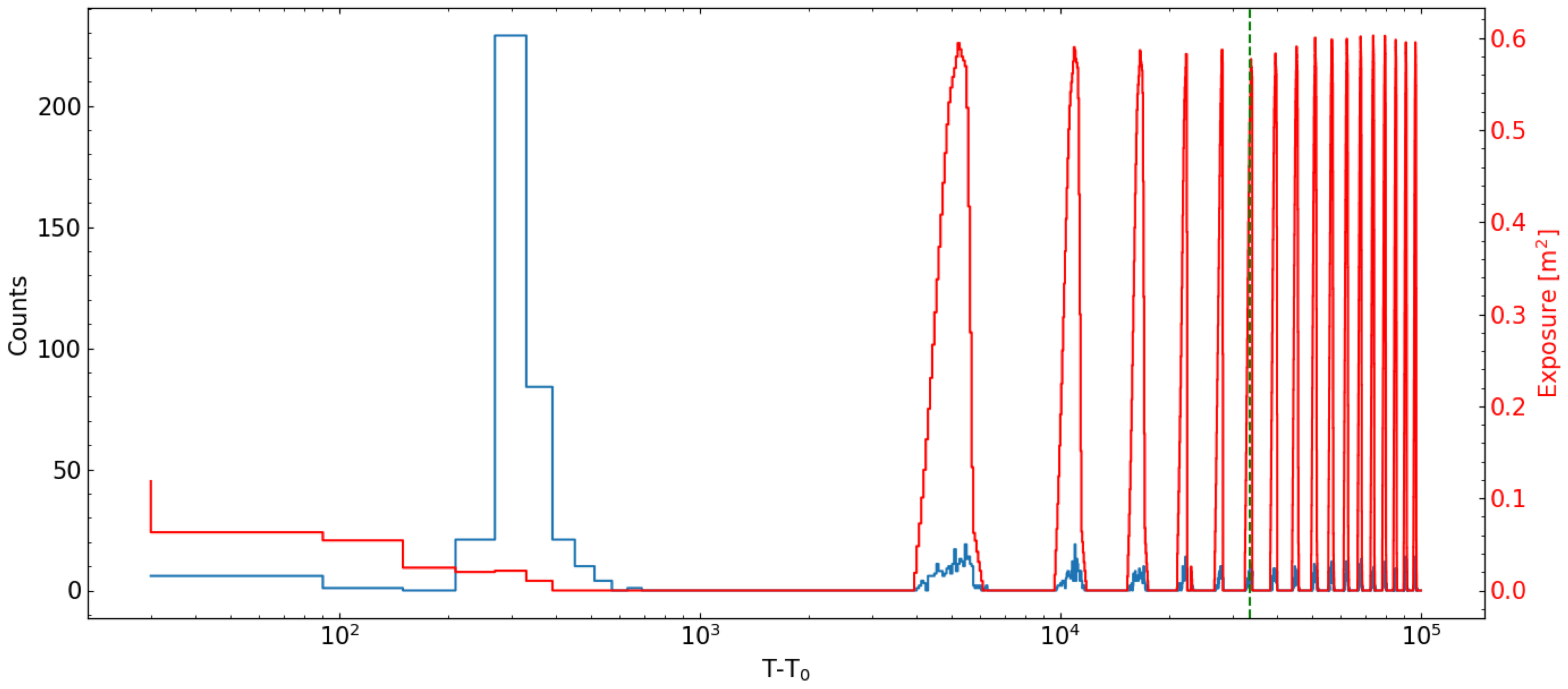
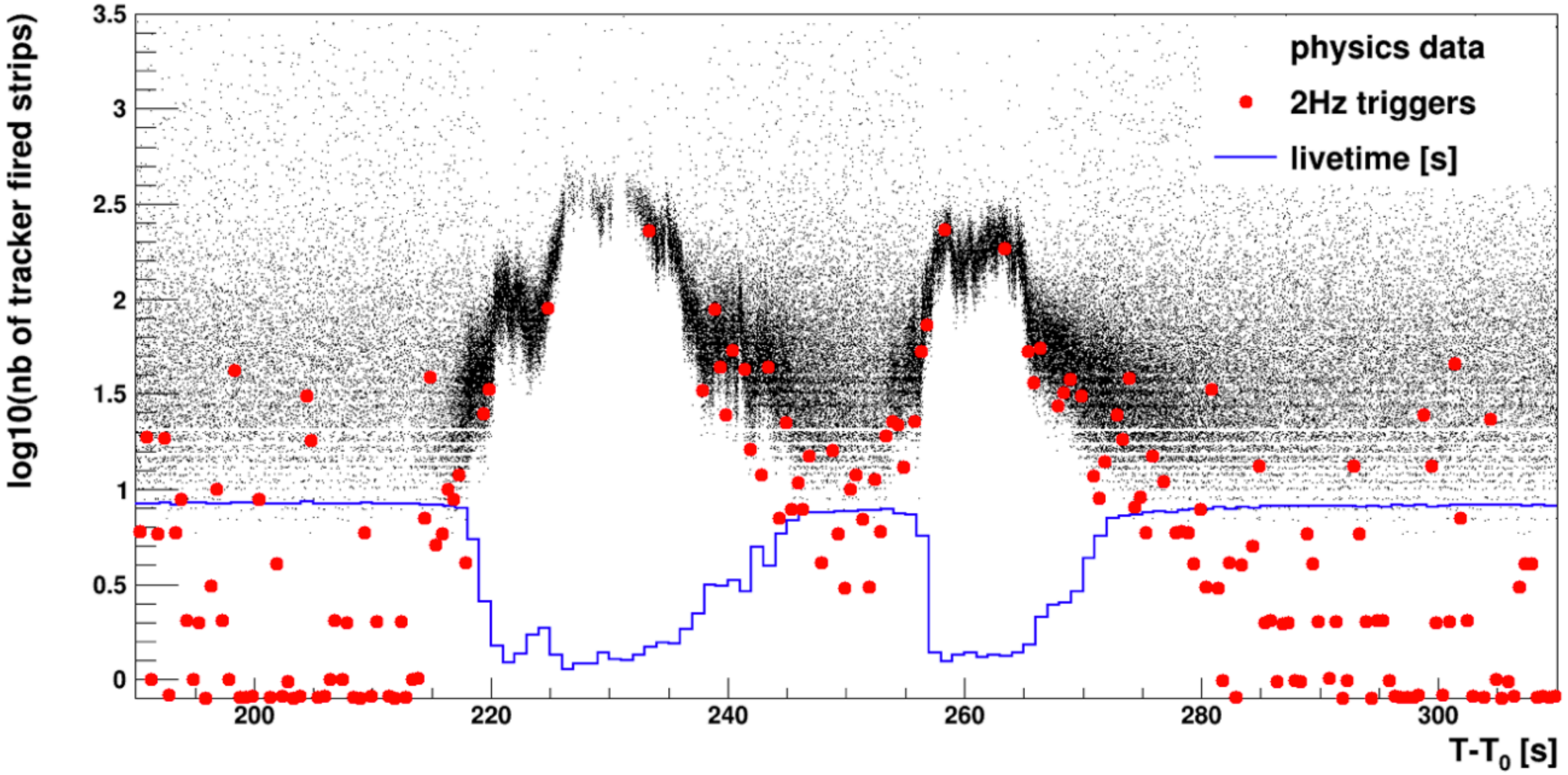


Fermi LAT observations, and Bad Time Interval (BTI)

- GRB 221009A was at large incident angle (~70˚) at the time of the GBM trigger and quickly left the LAT field of view. Re-entered ~4ks later
  - Low exposure during the prompt phase
  - Afterglow well sampled
- Effects in the LAT due to high flux of hard X rays
  - Extra "hits" in the tracker
  - Decrease of the live time due to extra veto in the ACD
  - The energy can be overestimated by up to 300 MeV
- We fix the problem!
  - Developed a modified energy estimator and use the Earth limb to calibrate the flux measurement during the BTI
  - Details here: http://arxiv.org/abs/2409.04580





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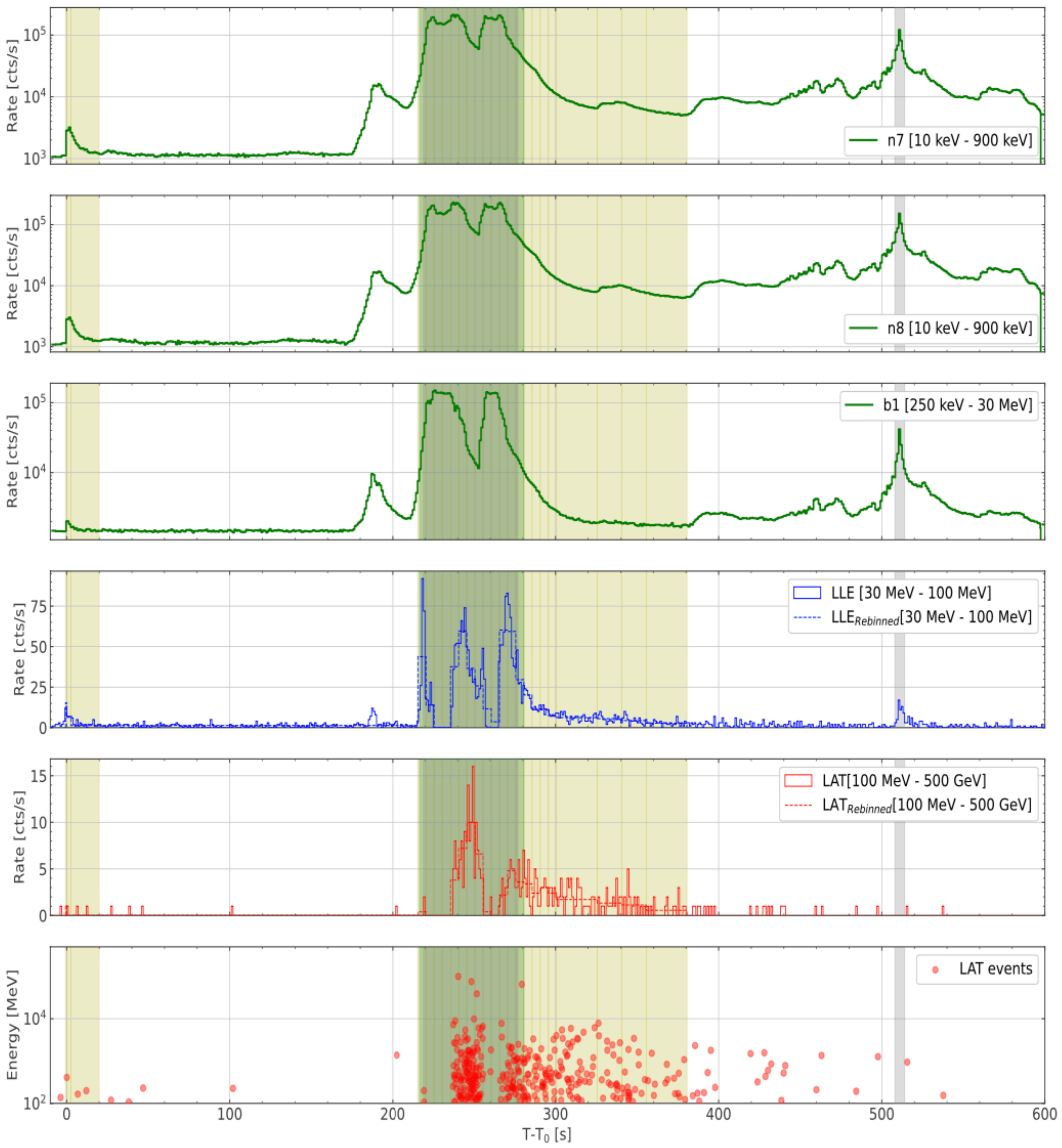
Fermi composite light curve



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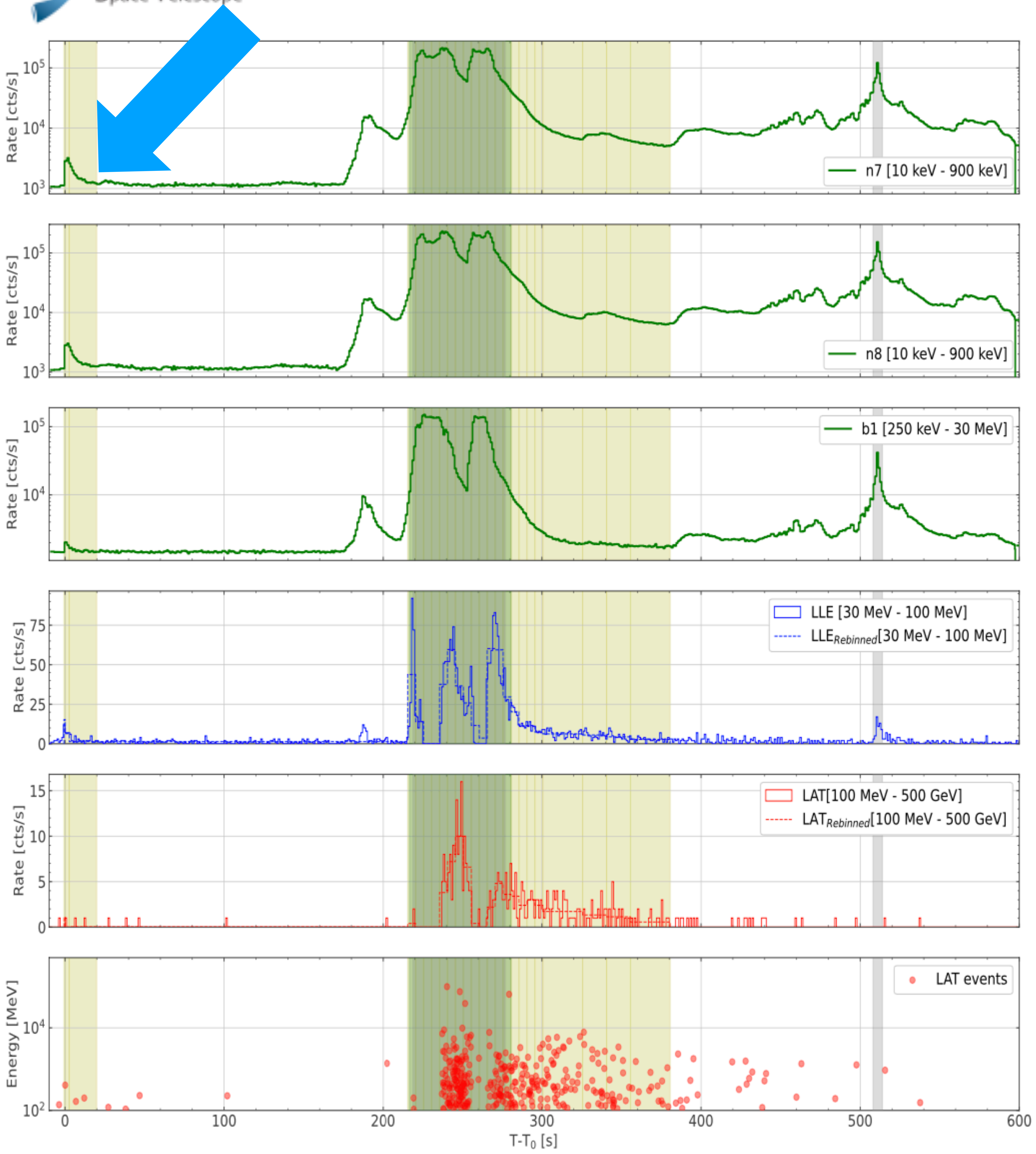

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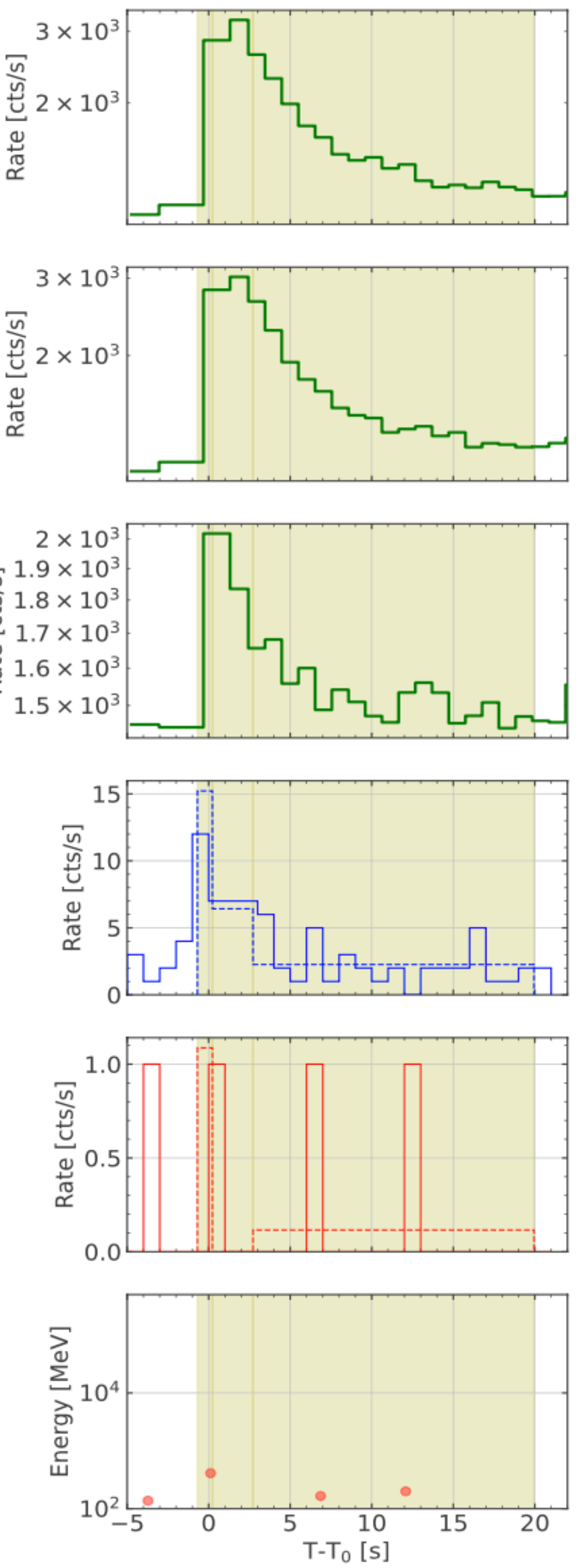

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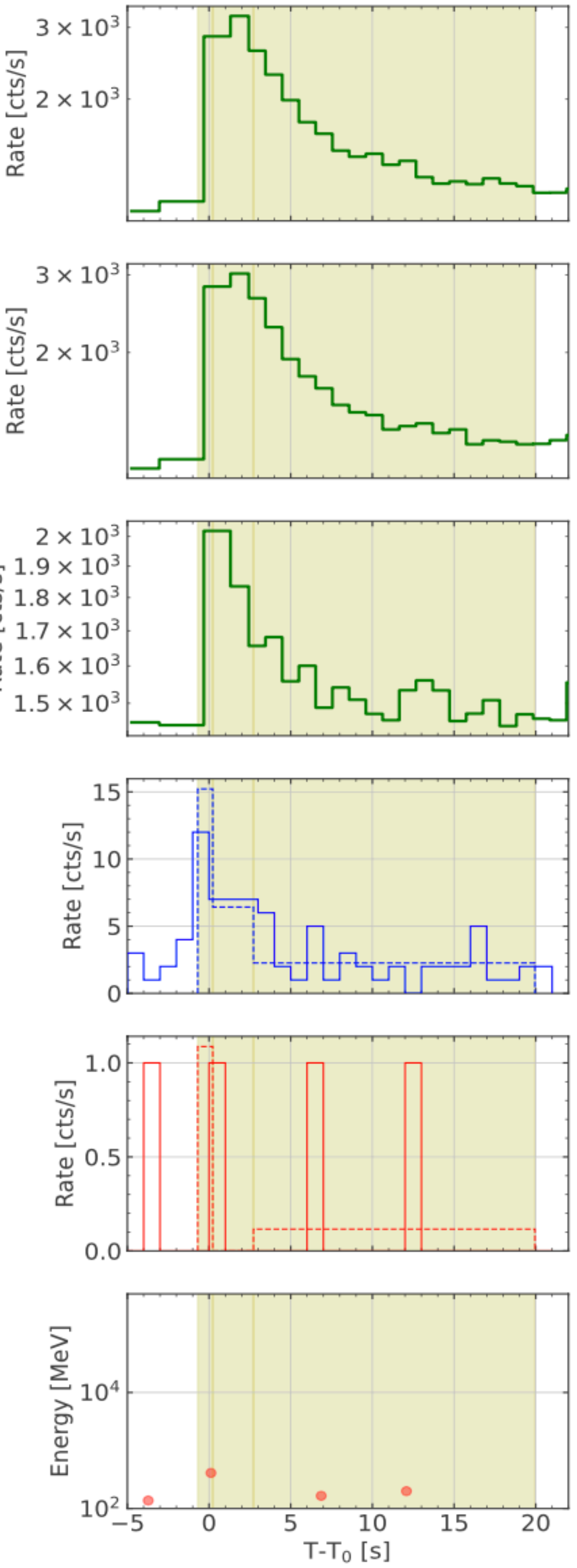

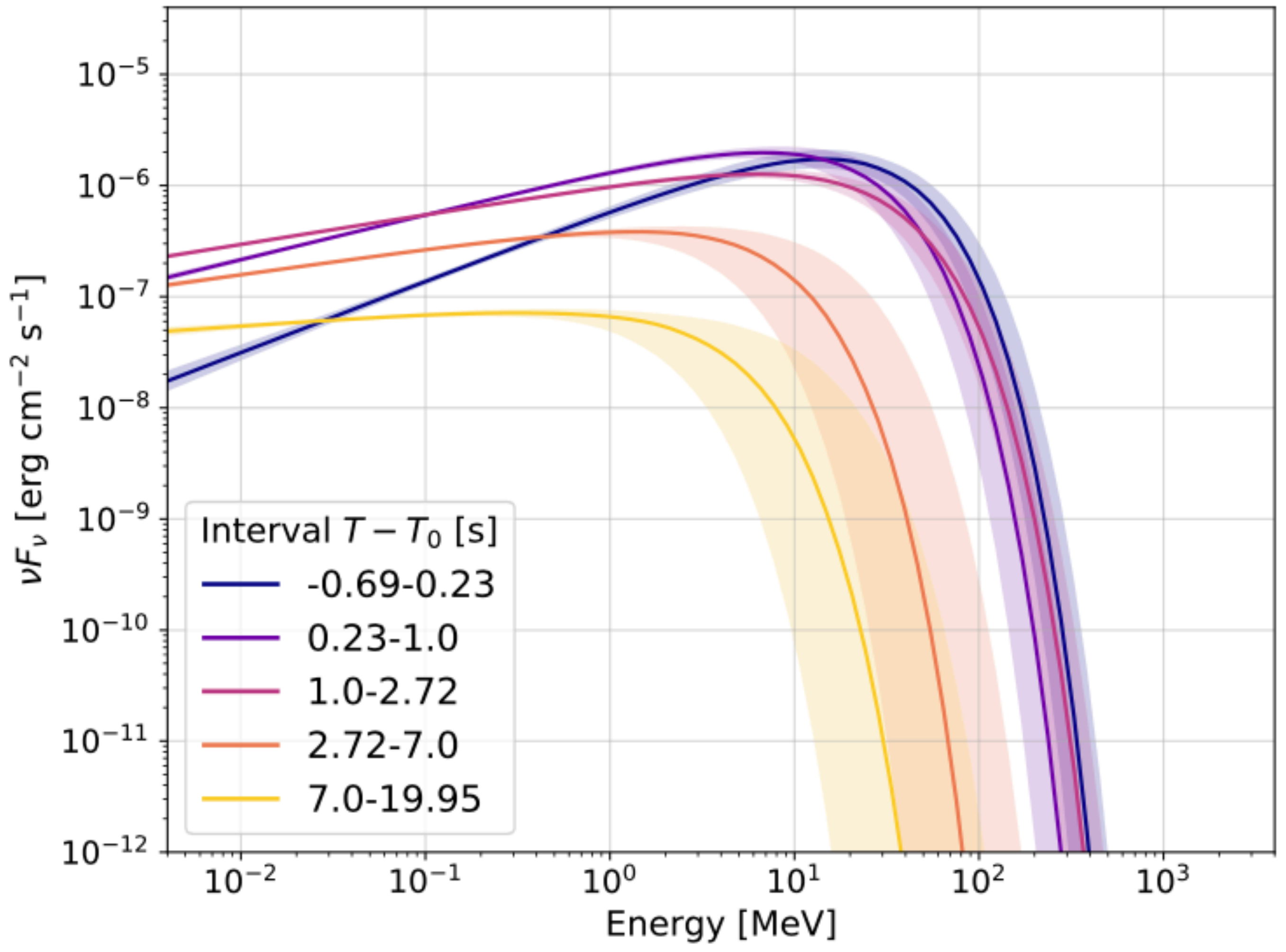

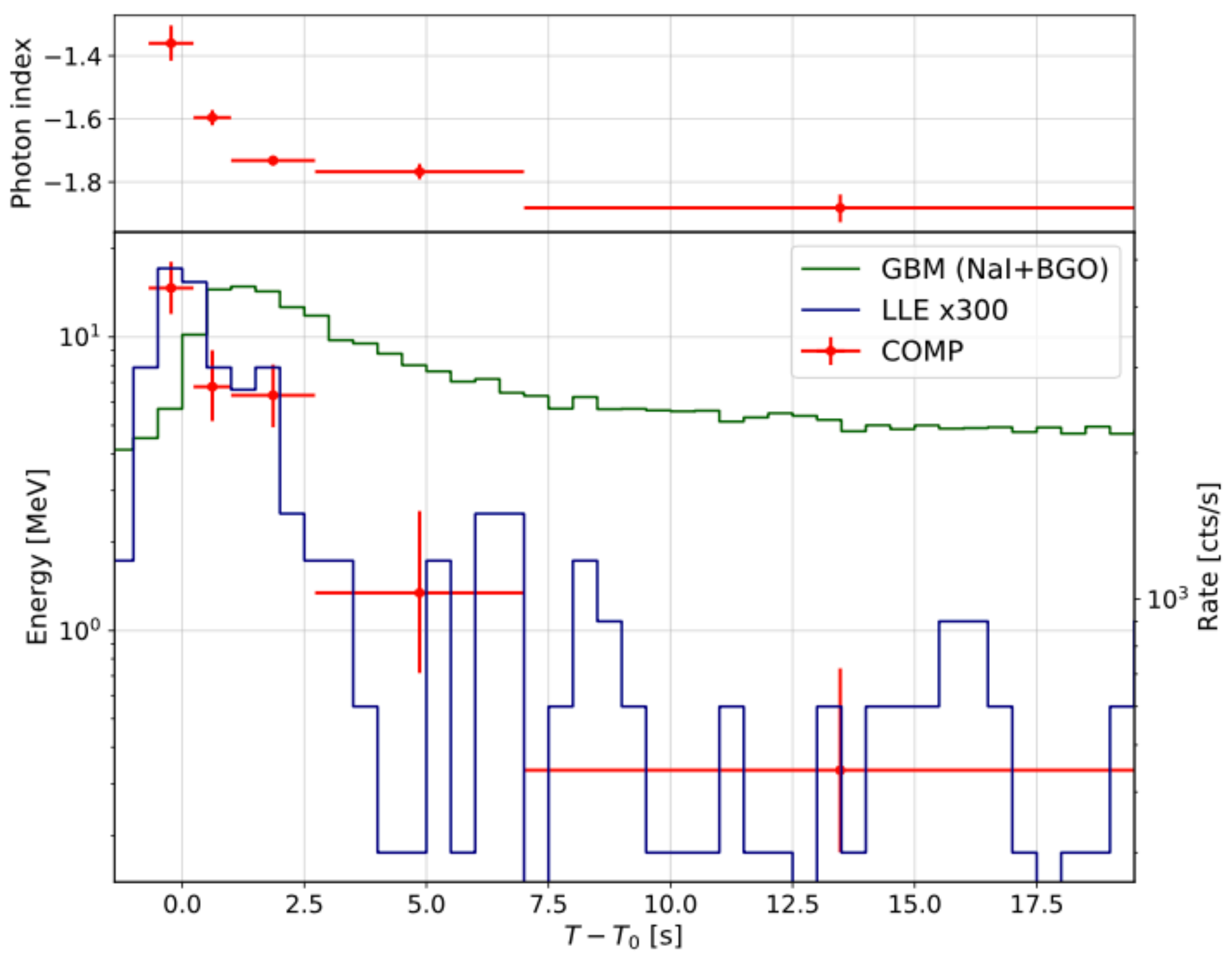

- <u>Triggering pulse</u>: Combining GBM and LAT data and using ThreeML for fitting.
  - Powe law with exp. cut off is preferred in all intervals

- ☆ Cut off at very high energy (15 MeV)
- ☆ High-energy light curve precedes the low energy LC (like GRB 130427A, indicative of synchrotron emission)
- ☆ Softening of the spectrum (–1.36 → –1.88)
- ☆ Peak energy "cools down" (15 MeV → 0.33 MeV)

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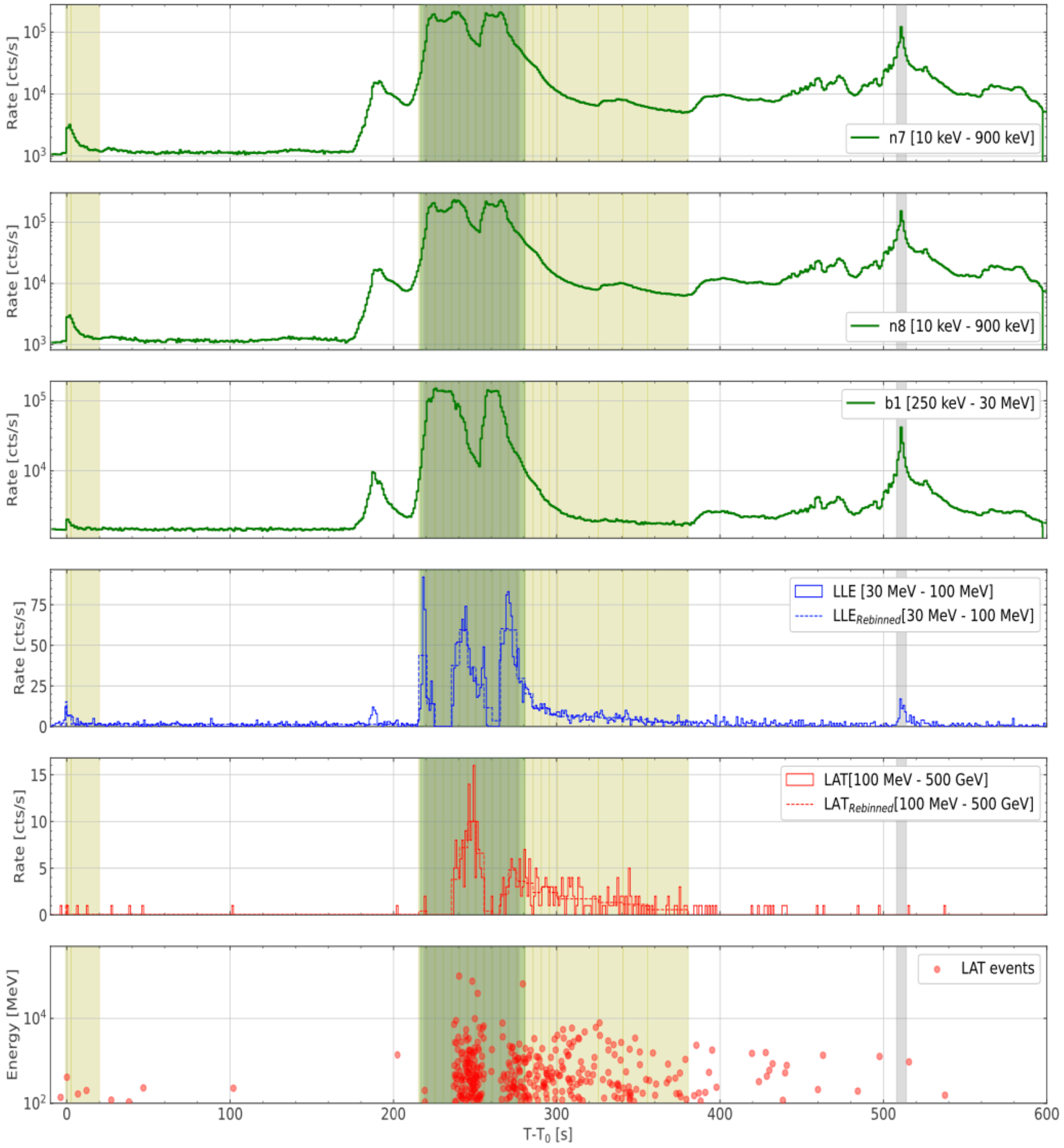

- <u>Prompt emission</u>: Extremely high flux of Hard X-rays increased the noise in all LAT subsystems
  - The LAT was not designed for this!
- BTI definition:
  - T<216.6 and T>280.6: LAT data OK!
  - [216.6-280.6] <u>NOT USABLE with standard analysis</u>
  - <u>We used the results of the template fitting</u>
    - Appendix A of our paper (http://arxiv.org/abs/2409.04580) entirely dedicated to describe this analysis.

☆ During the BTI: LAT shows a single peak as opposed as the two peaks from the GBM.

☆ Flux maximum in the BTI (important for measuring the energetics!)

☆ 4 event >10 GeV arrive during BTI (highest at 99.4 GeV, breaking the GRB130427A record)

☆ Gamma-gamma opacity => Lower limit for the bulk Lorentz factor: $\Gamma \sim 500$

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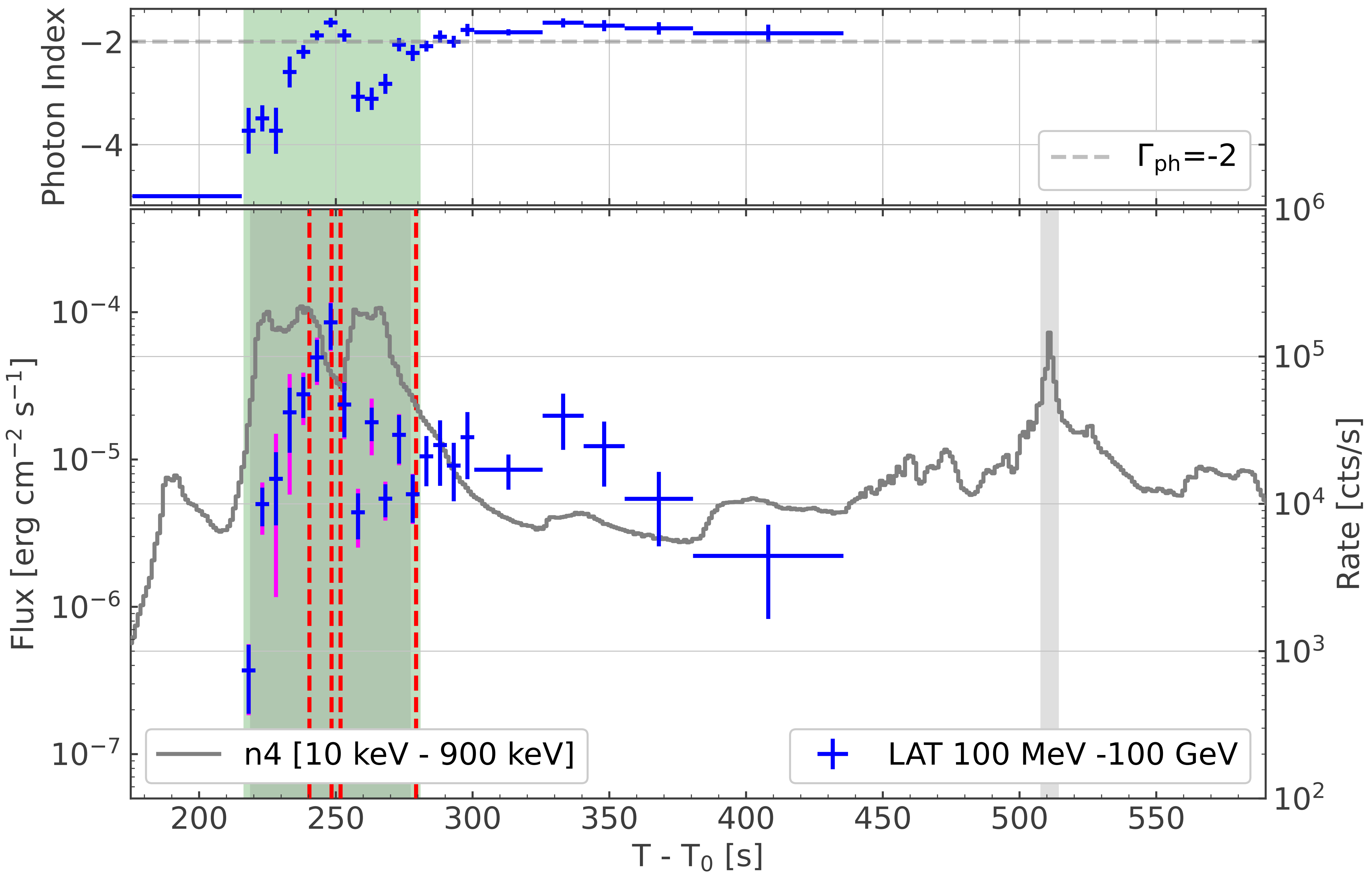

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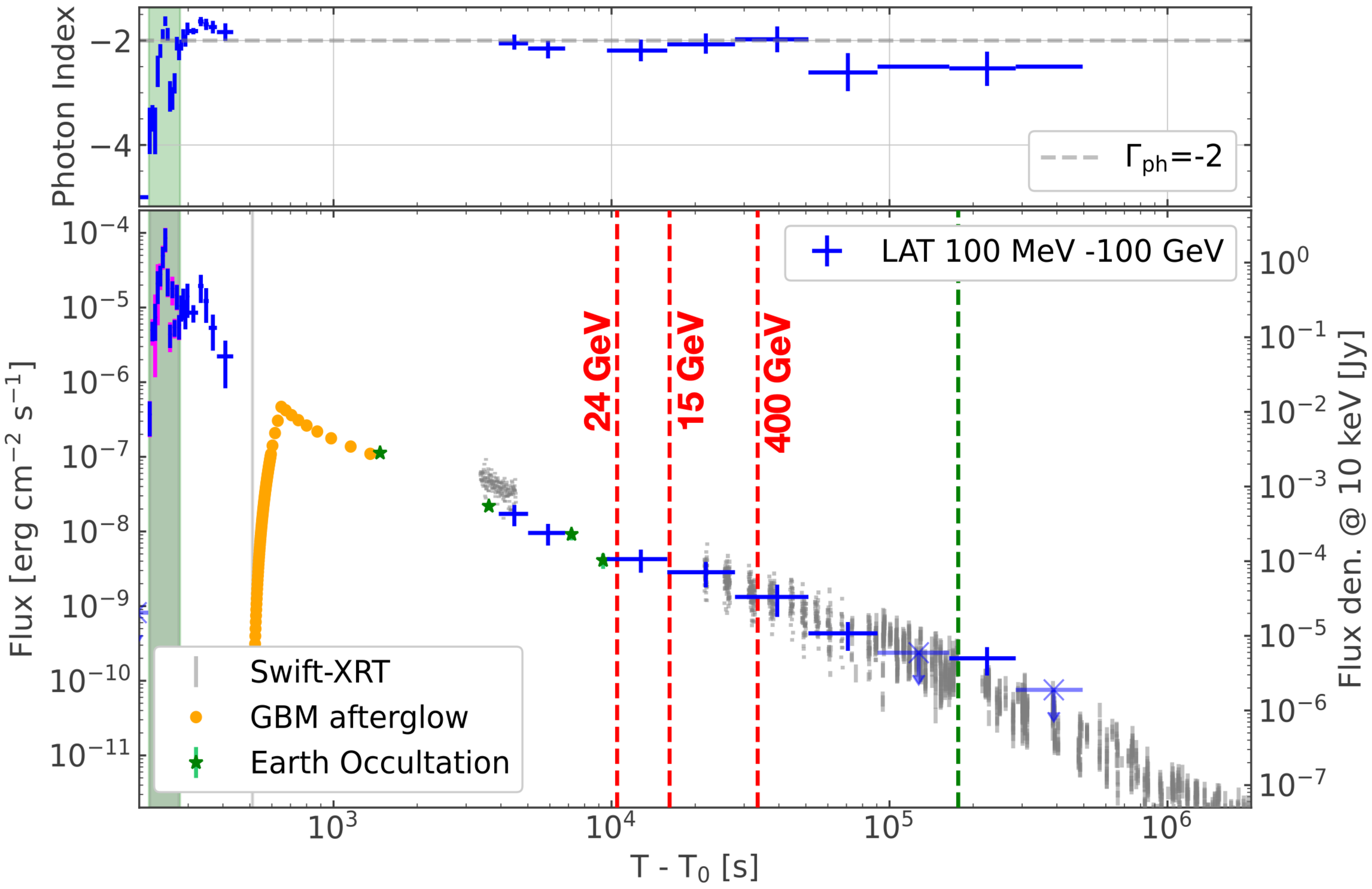
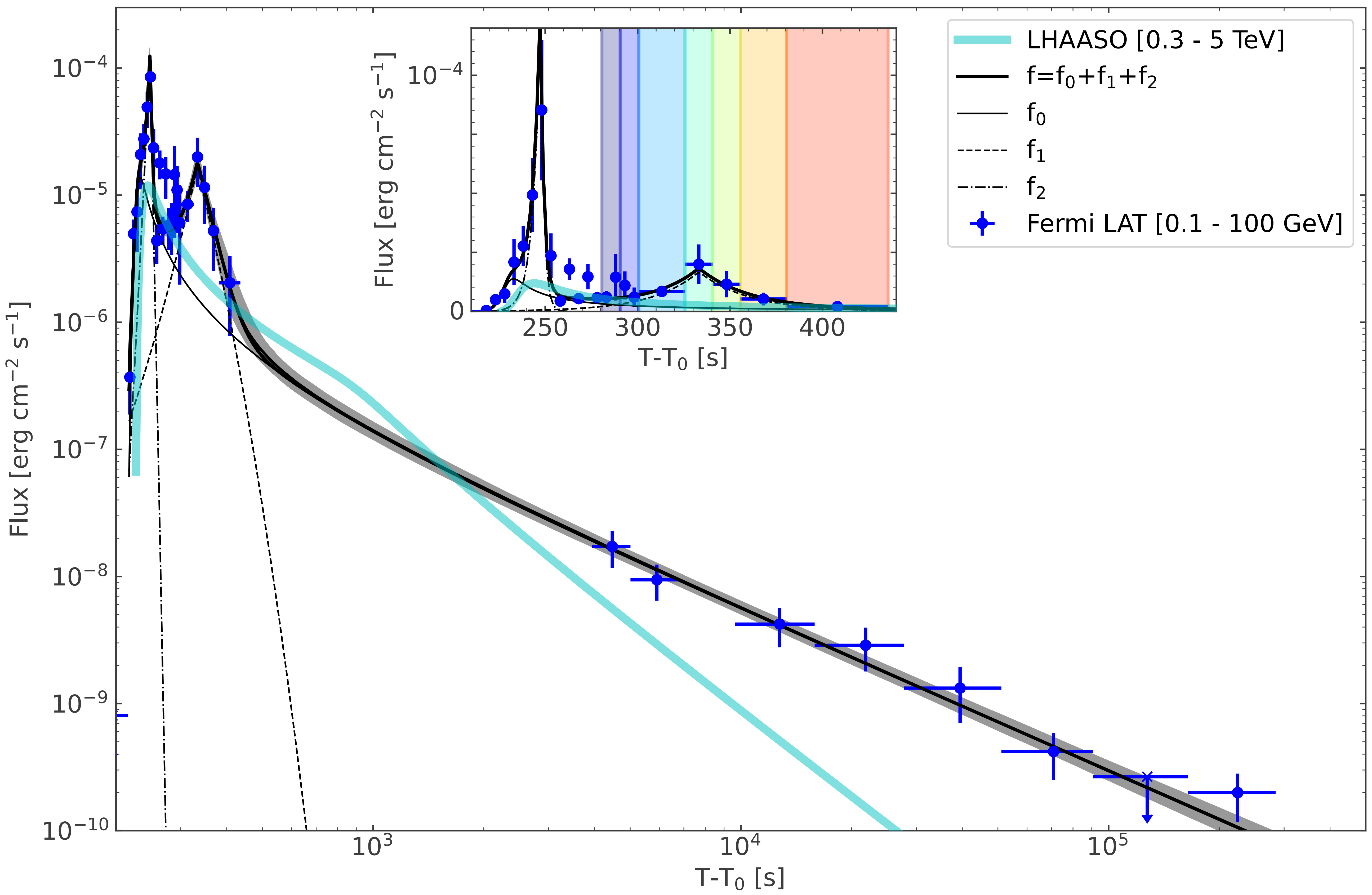
The afterglow phase



- **After the gap due to Earth occultation, flux decays as a power law, with constant spectral index (typical of GeV-detected afterglow)**
- **Estimated duration: 176ks (2 days, <u>new record!</u>)**
- **3 events >10 GeV, one at 400 GeV! (<u>New record!</u>)**

T-T_0 (s)	Energy (GeV)	Prob.	Conv. type.	Ang. Sep. (°)
Prompt				
240.336	99.3	–	Back	0.70†
248.427	75.2	1.000	Back	0.05
251.724	38.9	1.000	Back	0.25
279.342	65.0	1.000	Front	0.19
Extended				
10475.104	24.4	0.998	Front	0.10
16176.428	14.7	0.993	Front	0.16
33552.966	397.7	1.000	Back	0.02

Temporal evolution of the 0.1-100 GeV light curve



- **LHAASO-WCDA detector light curve (0.3- 5 TeV) is displayed but not used in the fit.**
- **Best fitting model: f0+f1+f2**
  - **Overall, the FS model cannot explain the pulses during the prompt emission, so it is a subdominant component at early time**
  - **At late time, emission dominated by the FS model.**
  - **The FS component is very similar to the LHAASO measured flux**
- **From the peak time of the FS light curve, we can estimate the bulk Lorentz factor (Nappo et al. 2014, Ghirlanda et al. 2018):** $\Gamma \sim 250 \pm 10 \; (\mathrm{wind, s=2}), \Gamma \sim 520 \pm 40 (\mathrm{ISM, s=0})$
- **If we assume the derivation from Sari & Piran 99 (same as in the LHAASO paper) we obtain** $\Gamma \sim 440 (\mathrm{ISM, s=0})$ **as in their paper.**
- **Integrating the light curve, we can also estimate the energy released (0.1-100 GeV):** $E_{iso} \sim 2 \times 10^{53} \mathrm{erg}$

Afterglow model from Nakar & Piran 2004

$$f_0(T) = K\left(\frac{1}{2}\left(\frac{T-T_{on}}{\tau}\right)^{-\xi\alpha_1} + \frac{1}{2}\left(\frac{T-T_{on}}{\tau}\right)^{-\xi\alpha_2}\right)^{-\frac{1}{\xi}}$$

Pulse model from model from Norris et al. 2005 (also adopted by Hakkila and Preece, 2014)

$$f_i(T) = K_i \begin{cases} \exp\left(\frac{T-T_{p,i}}{\tau_i}\right), & \text{for } T < T_{p,i}, \\ \exp\left(\frac{T_{p,i}-T}{\xi_i \tau_i}\right), & \text{for } T > T_{p,i}, \end{cases}$$

Measurement of the bulk Lorentz factor

	f_0	f_0+f_1	$f_0+f_1+f_2$	$f_0+f_1+f_2+f_3$
K_0 [erg cm^{-2} s^{-1}]	$(1.8 \pm 0.3)\times10^{-5}$	$(1.6 \pm 0.3)\times10^{-5}$	$(1.3 \pm 0.3)\times10^{-5}$	$(1.1^{+0.4}_{-0.2})\times10^{-5}$
α_1	3.0 (fix)	3.0 (fix)	3.0 (fix)	3.0 (fix)
α_2	-1.35 ± 0.03	-1.31 ± 0.04	-1.27 ± 0.05	$-1.25^{+0.06}_{-0.05}$
ξ	2(fix)	2(fix)	2(fix)	2(fix)
τ [s]	20 ± 2	18^{+3}_{-2}	17^{+4}_{-3}	15^{+4}_{-3}
T_{on} [s]	213 ± 1	214 ± 1	215 ± 2	215 ± 2
K_1 [erg cm^{-2} s^{-1}]	-	$(1.7^{+1}_{-0.6})\times10^{-5}$	$(1.7^{+0.6}_{-0.5})\times10^{-5}$	$(1.7^{+0.7}_{-0.4})\times10^{-5}$
$T_{p,1}$ [s]	-	330 ± 10.0	333 ± 2	333 ± 2
τ_1 [s]	-	22^{+10}_{-8}	25^{+9}_{-6}	25^{+8}_{-5}
ξ_1	-	$1.1^{+1}_{-0.6}$	1.1 ± 0.4	$1.0^{+0.4}_{-0.3}$
K_2 [erg cm^{-2} s^{-1}]	-	-	$(1.2^{+0.7}_{-0.4})\times10^{-4}$	$(1.2^{+0.6}_{-0.4})\times10^{-4}$
$T_{p,2}$ [s]	-	-	247.4 ± 0.9	247.3 ± 0.9
τ_2 [s]	-	-	4^{+2}_{-1}	4^{+2}_{-1}
ξ_2	-	-	$0.5^{+0.3}_{-0.2}$	$0.5^{+0.3}_{-0.2}$
K_3 [erg cm^{-2} s^{-1}]	-	-	-	$(1.1^{+4}_{-0.9})\times10^{-5}$
$T_{p,3}$ [s]	-	-	-	263^{+3}_{-2}
τ_3 [s]	-	-	-	$0.6^{+0.2}_{-0.1}$
ξ_3	-	-	-	3^{+3}_{-1}
BIC	69.2	64.9	62.6	71.2
Δ_{BIC}	0	-4.3	-2.3	6.3
T_p	21^{+3}_{-2}	23 ± 4	18^{+4}_{-3}	17 ± 4
Γ (wind)	240 ± 7	237 ± 10	250 ± 10	$250.0^{+20.0}_{-10.0}$
Γ (ISM)	490 ± 20	480 ± 30	520 ± 40	$530.0^{+50.0}_{-40.0}$
Fluence [erg cm^{-2}]	$(1.4 \pm 0.1)\times10^{-3}$	$(2.2 \pm 0.3)\times10^{-3}$	$(2.6 \pm 0.4)\times10^{-3}$	$(2.7 \pm 0.4)\times10^{-3}$
E_{iso} [erg]	$(9 \pm 0.8)\times10^{52}$	$(1 \pm 0.2)\times10^{53}$	$(2 \pm 0.3)\times10^{53}$	$(2 \pm 0.3)\times10^{53}$

- **From the peak of the FS light curve we can estimate the bull Lorentz factor:**

$$\Gamma = \left[\left(\frac{(17-4s)}{16\pi(4-s)}\right)\left(\frac{E_K}{n_0 m_p c^{5-s}}\right)\right]^{\frac{1}{8-2s}}\left(\frac{T_p}{1+z}\right)^{-\frac{3-s}{8-2s}}$$

Nappo et al. 2014, Ghirlanda et al. 2018

  – $\Gamma \sim 250(\mathrm{wind}, s=2), \Gamma \sim 520(\mathrm{ISM}, s=0)$

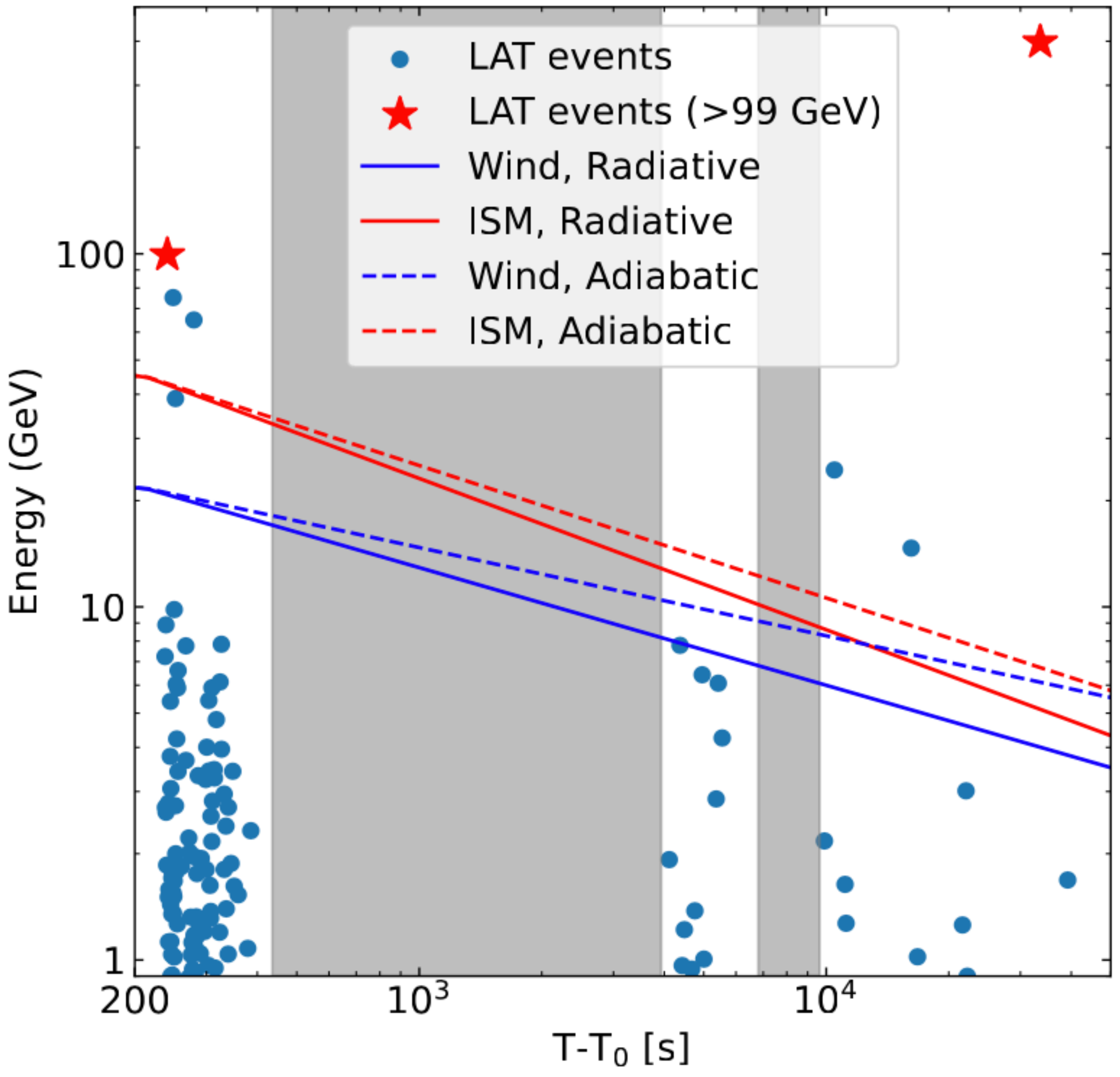
- **If we assume the derivation from Sari Piran '99 (same as in the LHAASO paper) we obtain**
  – $\Gamma \sim 440(\mathrm{ISM}, s=0)$ **as in their paper.**
- **Integrating the light curve, we can also estimate the energy released in the 0.1-100 GeV band:**
  – $E_{iso} \sim 2\times10^{53}$erg

Maximum synchrotron energy

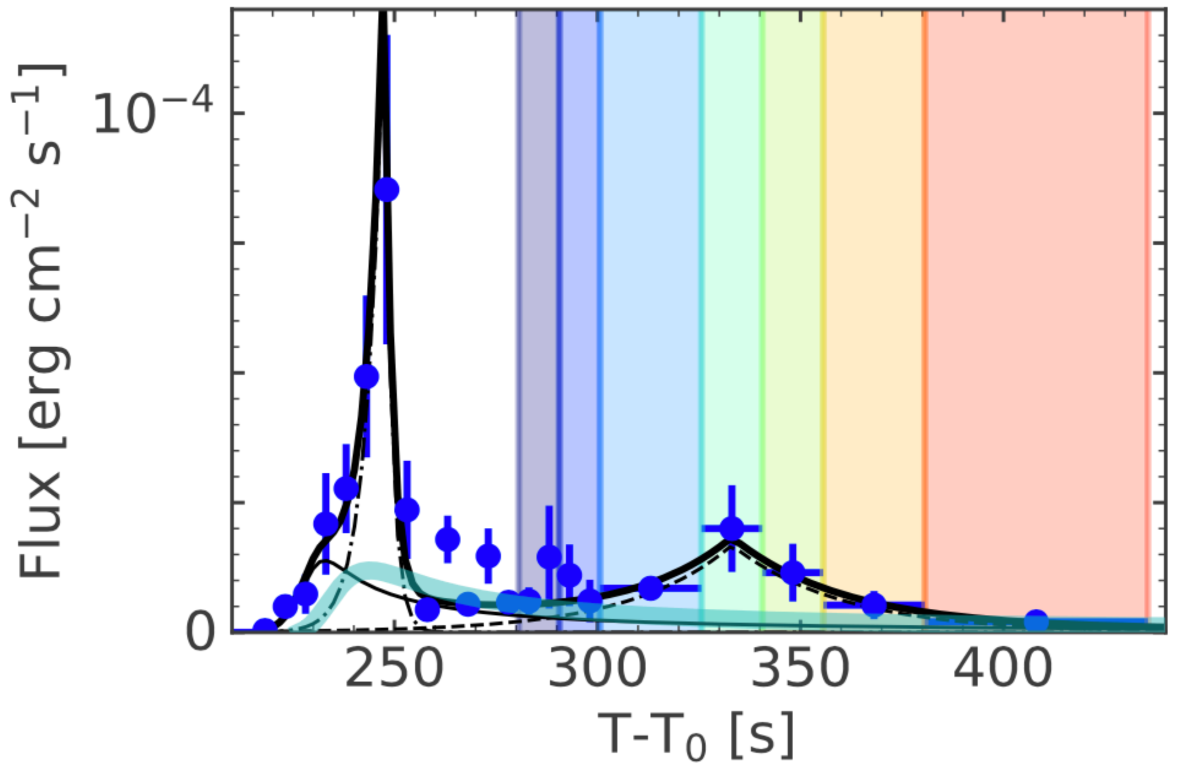
- **From the two values of Gamma (wind and ISM), we can compute the maximum energy of synchrotron emission (cooling=acceleration)**
- $\mathrm{E}_{\mathrm{max,syn}} \sim (100\mathrm{MeV}) \times \Gamma/(1+\mathrm{z})$**, and for (g=0, rad. g=1, adiab.)**

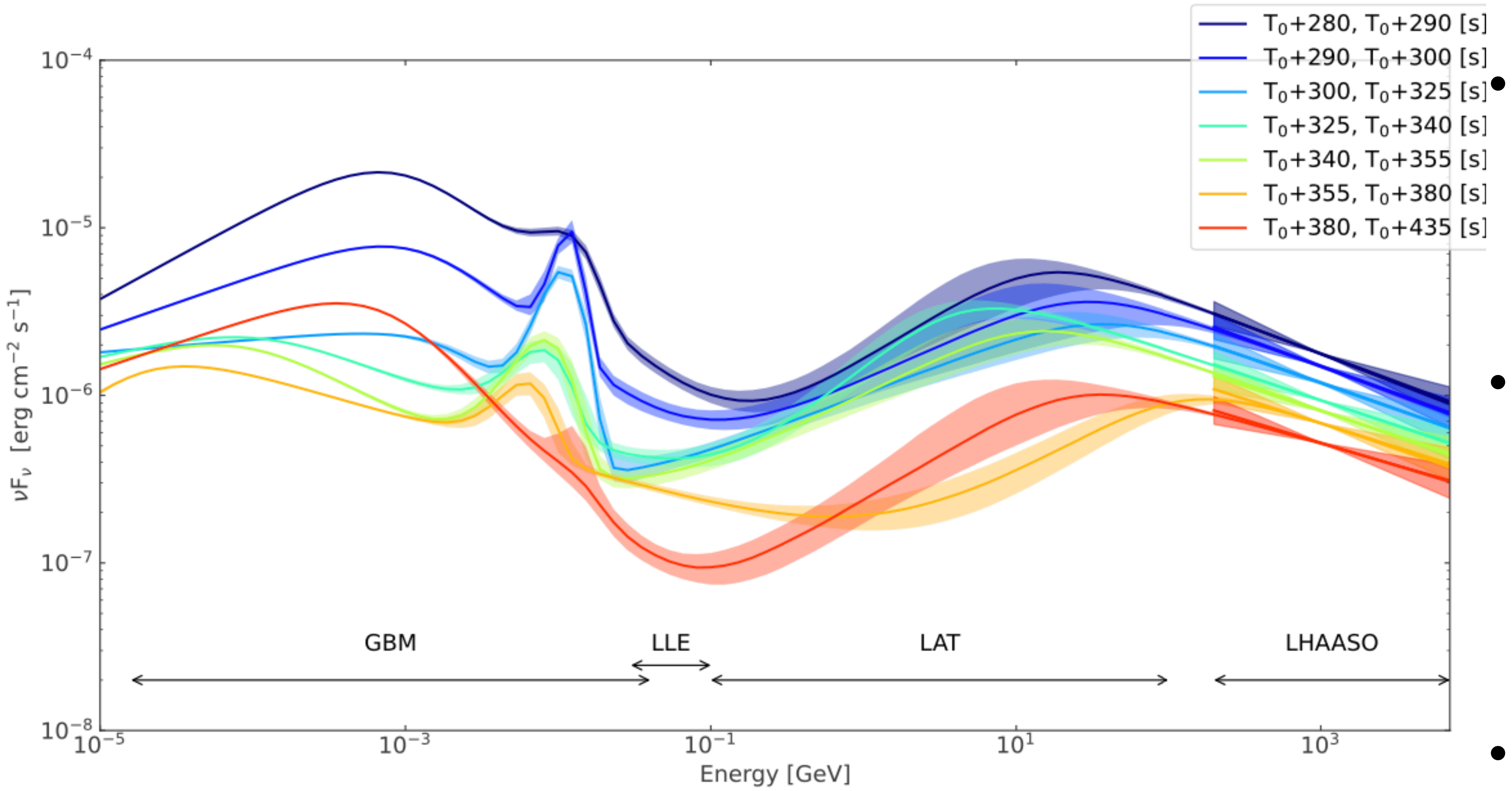
$$\Gamma(T) \sim \Gamma_0 \left(\frac{T+T_p}{T_0+T_p} \right)^{-(3-s)/(7+g-2s)}$$

- **LAT high-energy events are not compatible with pure synchrotron emission**



Fermi - LHAASO spectral fit





- From the LHAASO paper we sample their best fit model (flux and spectral index) to generate spectra during 7 LAT time intervals. We then use 3ML to perform a join likelihood fit.
- We tested several models, using *multinest* as Bayesian sampler (up to 11 free parameters). We use the Bayesian evidence to discriminate between models (Jeffreys' scale)

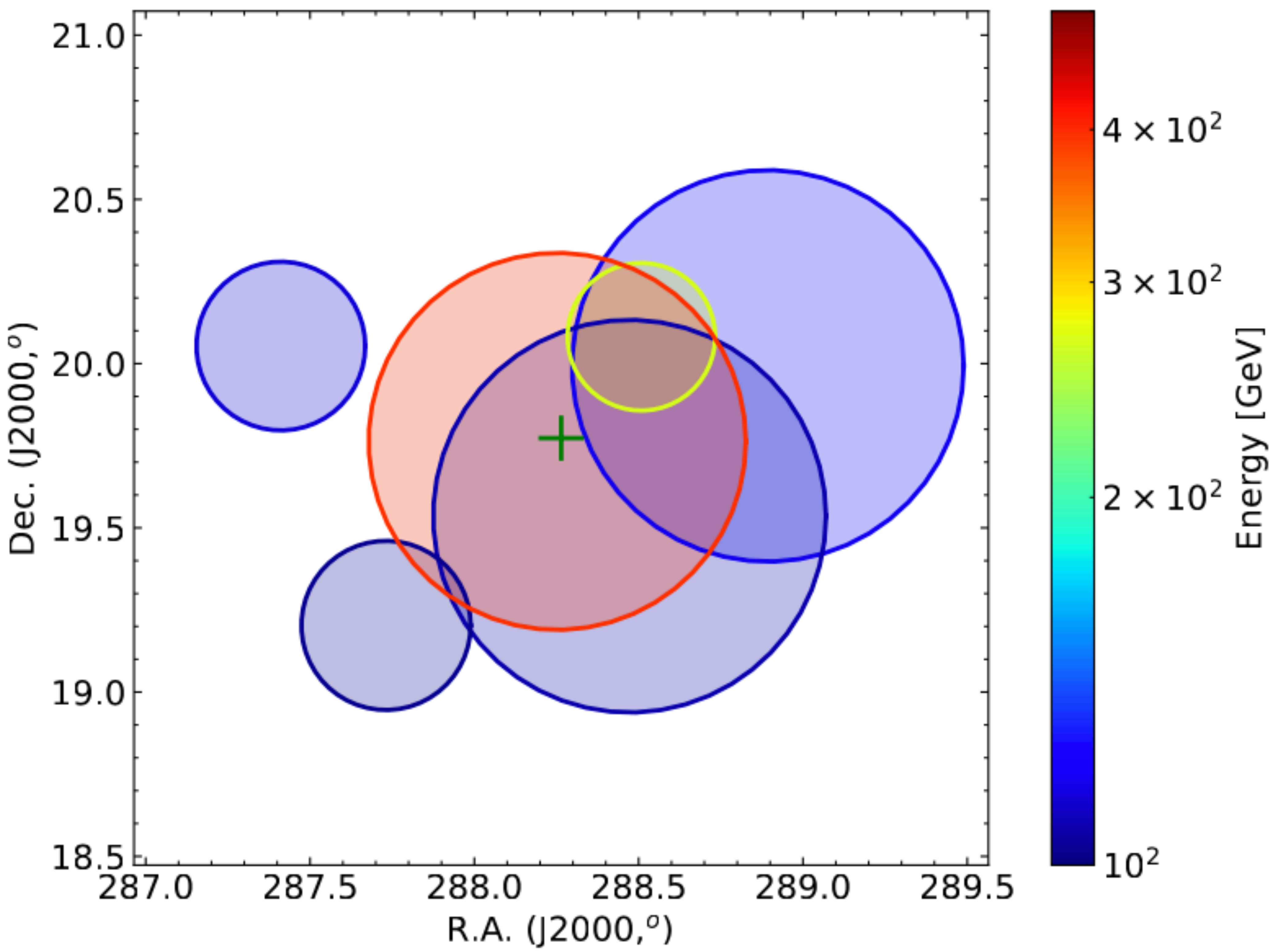
Interval (s from T$_0$)	SBPL	SBPL+G	SBPL+PL	SBPL+G+PL	SBPL+SBPL	SBPL+G+SBPL	Gaussian Line	Break at high energy
280.6–290.6	413.0	413.1	155.4	143.8	10.9	0.0	Strong	Strong
290.6–300.6	156.0	155.9	91.4	73.2	18.9	0.0	Strong	Strong
300.6–325.6	161.5	144.4	146.1	118.7	26.5	0.0	Strong	Strong
325.6–340.6	137.8	137.9	88.9	89.0	30.8	0.0	Strong	Strong
340.6–355.6	203.4	203.5	72.9	69.8	5.6	0.0	Strong	Strong
355.6–380.6	186.2	185.9	63.9	61.1	2.7	0.0	Moderate	Strong
380.6–435.6	472.6	472.7	173.7	173.9	0.4	0.0	Not required	Strong

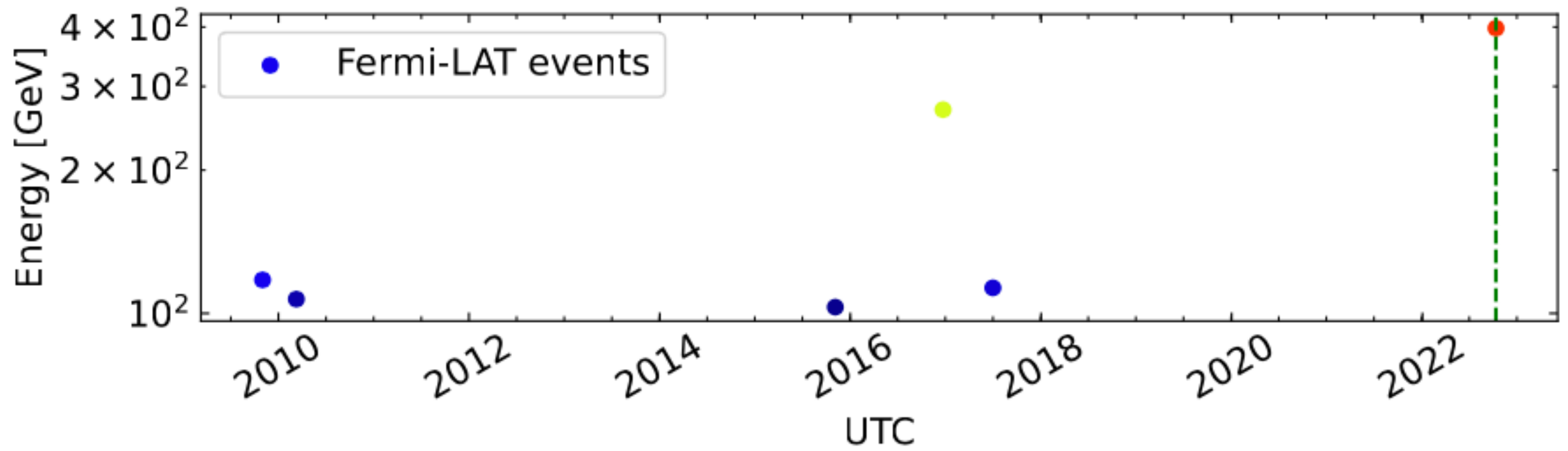
Table 6. Decrement of the Bayesian evidence ($\Delta \log Z$) with respect the best fit model.

- Gaussian line (already discovered by Ravasio et al.):
  - Hard to soft evolution (12 MeV-> 5 MeV)
  - 511 keV $e^+ e^-$ annihilation line shifted by Γ~20 decelerating to Γ~10
    - Spine-sheer jet model
    - Off axis motion
  - LLE data increases the significance of the MeV line (analysis performed by S. Lesage).

400 GeV event

UTC (s)	Energy (GeV)	R.A. (J2000, ^{o})	Dec. (J2000, ^{o})	Conv. type.	Ang. Sep. ^{o}
2009-11-01 06:21:03.90	117.6	288.9	20.0	Back	0.63
2010-03-10 17:30:57.05	107.1	288.5	19.5	Back	0.31
2015-11-04 12:22:50.10	103.1	287.7	19.2	Front	0.76
2016-12-21 08:42:19.47	268.1	288.5	20.1	Front	0.38
2017-06-30 08:24:03.47	113.1	287.4	20.0	Front	0.85
2022-10-09 22:36:17.96	397.7	288.2	19.8	Back	0.02





- **We can compute the probability to have 1 event when [N background] are observed using Li & Ma formalism:**

N signal	N background	probability
1	5	1.6×10^{-4} (3.6)
1	1	4.5×10^{-5} (3.9)
1	0	9.3×10^{-6} (4.3)

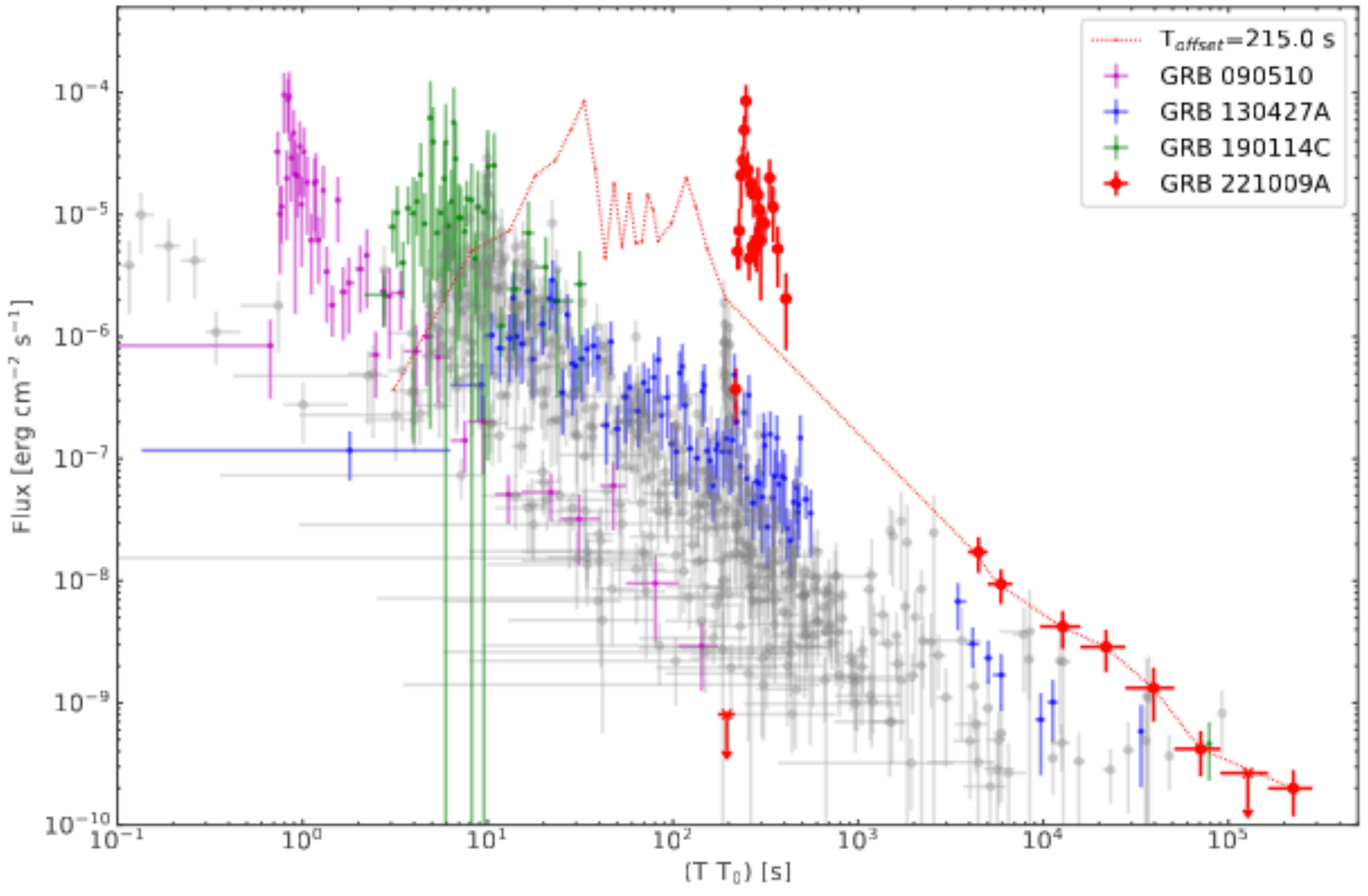
- **If the photon comes from the GRB, we can also compute the probability to obtain 1 or more event above 400 GeV (or 360 GeV) from the extrapolation of the spectrum <100GeV:**

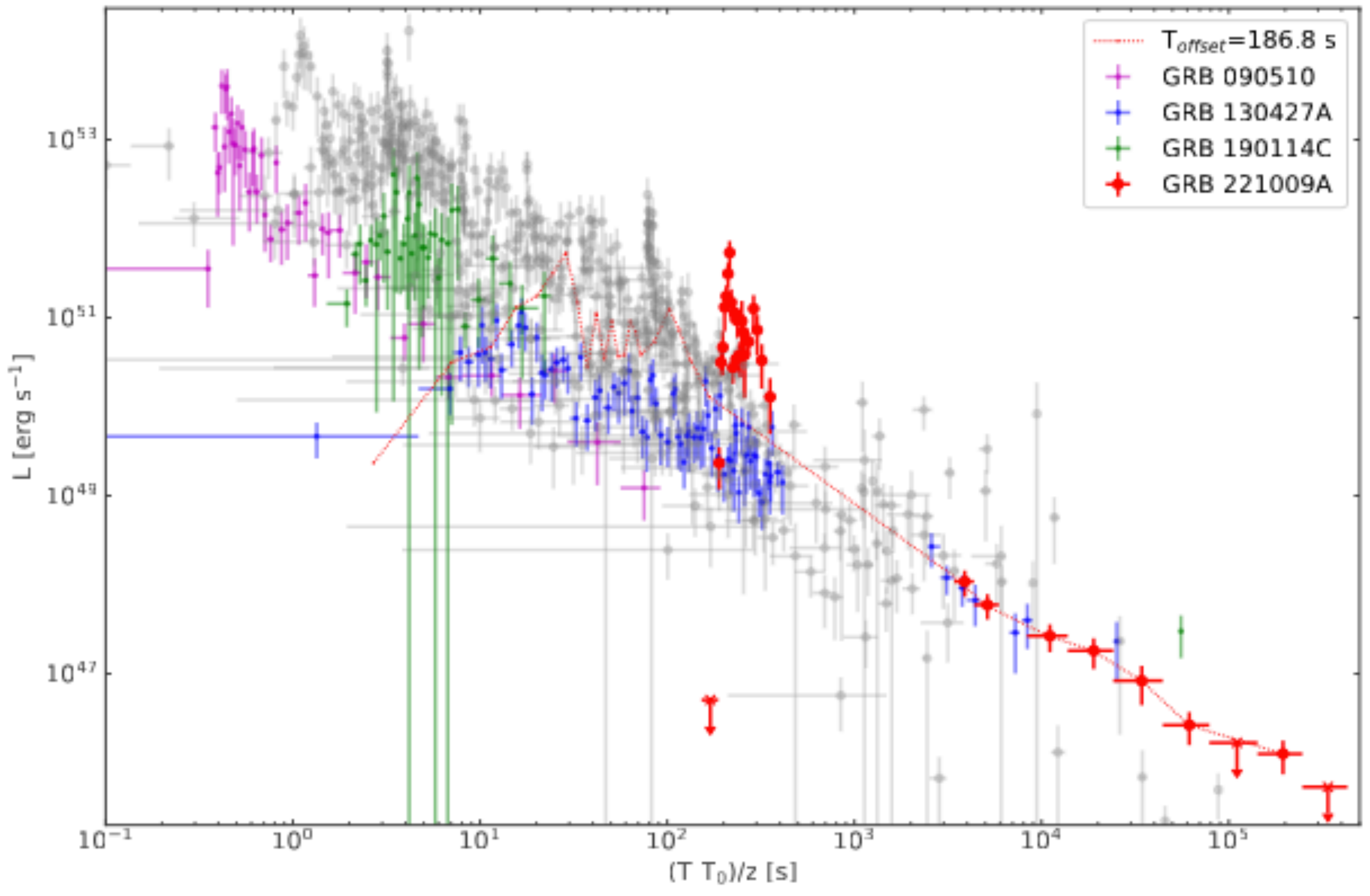
E threshold	probability
400	4.3×10^{-6} (4.4) – 5.8×10^{-4} (3.2)
360	7.3×10^{-6} (4.3) – 1.0×10^{-5} (3.1)

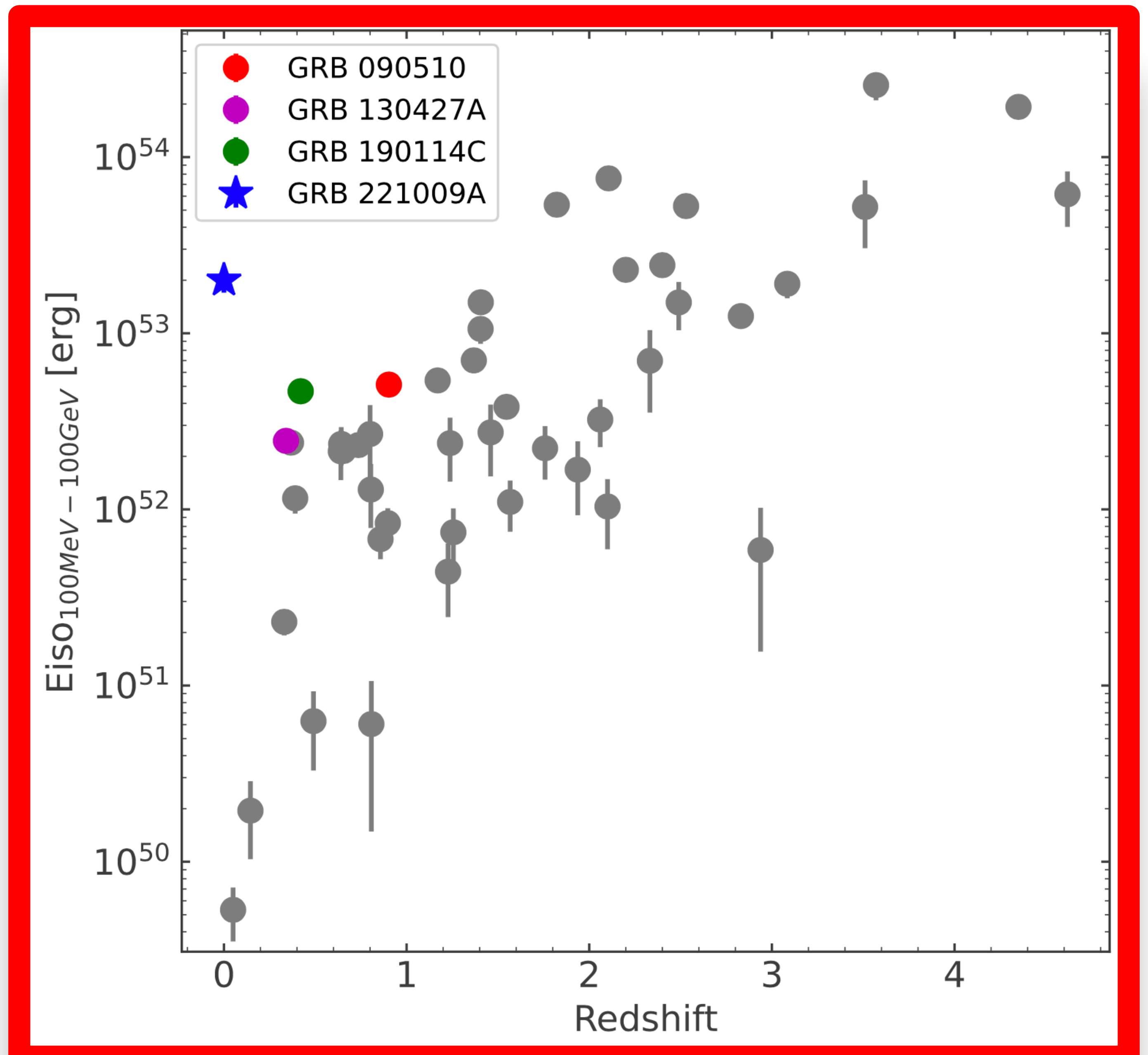
- **EM cascade from TeV photons interacting with the EBL:**
  - **Assuming a 30 TeV primary photon, would require a B~2×10^{-18}, not compatible with B>3×10^{-16} G from non-detection of halos around blazars (Ackermann et al. 2018)**

Let's put GRB 221009A in the context of other LAT GRBs

- **Exceptionally fluent, but not quite exceptional in terms of E_{iso}**
  - **Very close, comparable to high redshift LAT detected GRBs => extremely rare!**
  - **Geometric extrapolation of the total fluence and peak flux distributions, GRB 221009A appears to be a once-in-10,000-year event (Burns et al. 2023)**
  - **Probability to observe one in the Fermi lifetime $\sim 10^{-3}$: should we revise what we know about GRB population?**







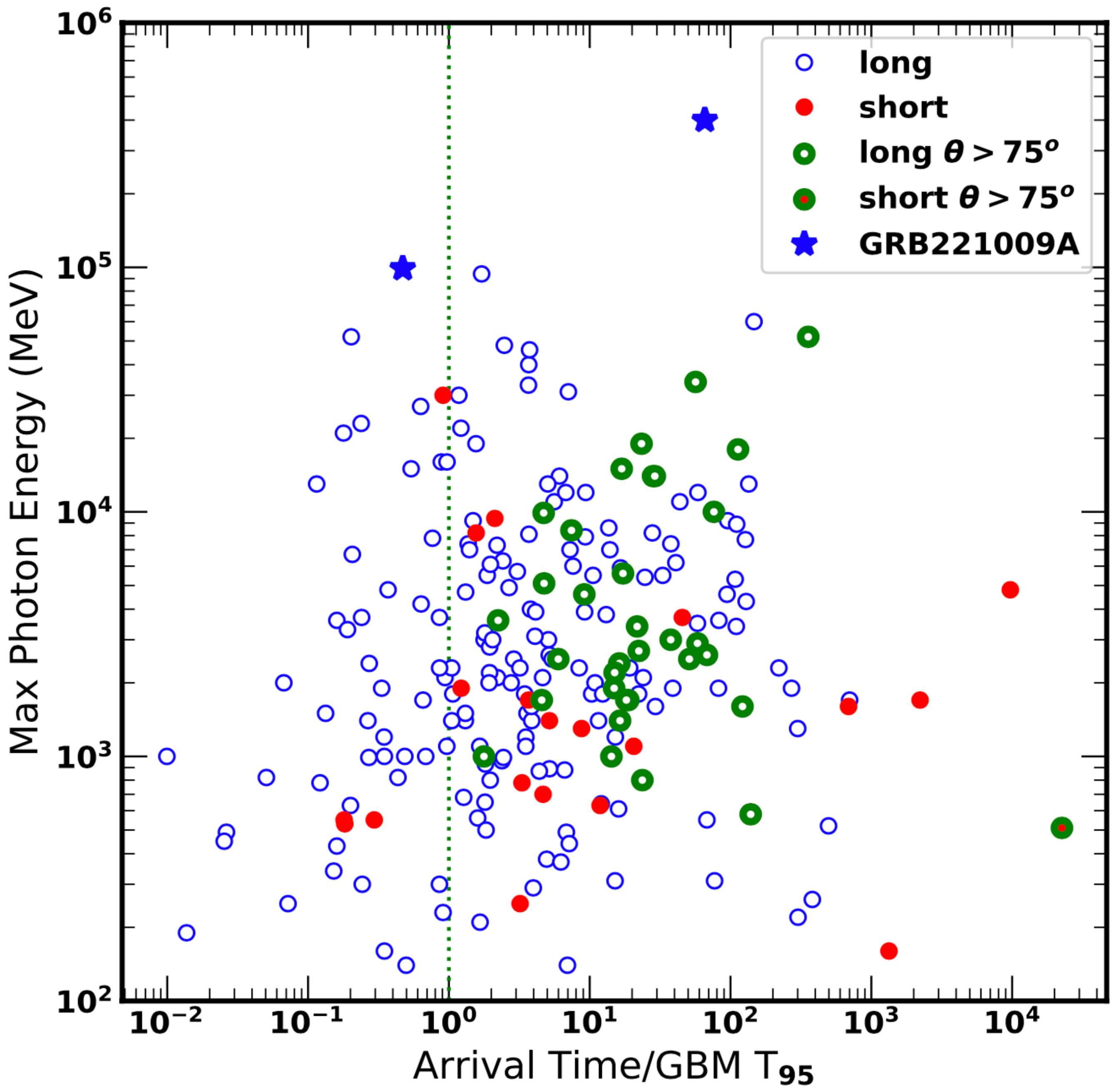
Conclusion

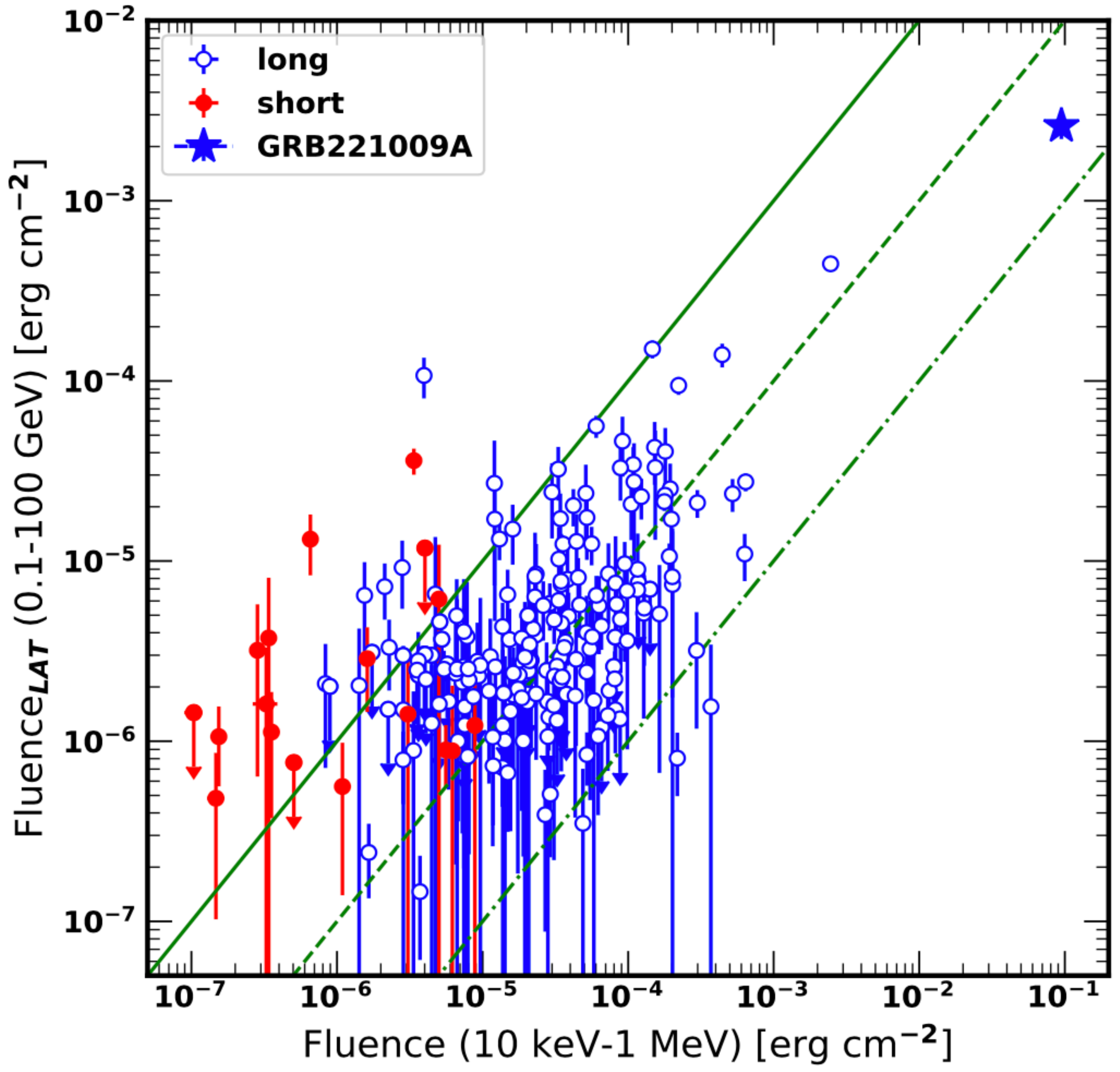
- GRB 221009A is the brightest GRB ever detected by the LAT (and by many other instruments)
  - Complex event, required a lot of non standard analysis!
  - During the BTI: we provided a reliable measurement of the flux
  - Many records have been broken… (Fluence, high-energy events, duration)
    - High E_{iso}, especially considering its proximity: Incredibly rare event!
- What did we learn?
  - Triggering pulse (precursor?):
    - Seen at high energy (uncommon)
    - Very high-energy cut off, high-energy precedes low-energy: synchrotron?
  - Prompt:
    - Gamma factor ~ 250-500, depending on the environment.
    - "Simultaneous" prompt and afterglow, with pulses on top of smooth afterglow model
    - Afterglow model well synchronized with LHAASO-WCDA light curve
    - Synchrotron + SSC + gaussian line preferred model
  - Afterglow:
    - intriguing 400 GeV event at 33ks after the trigger (although not firmly associated with the burst)
  - ChatGPT sucks at connect-the-dots game…
- Paper under review, available on the arXiv: http://arxiv.org/abs/2409.04580

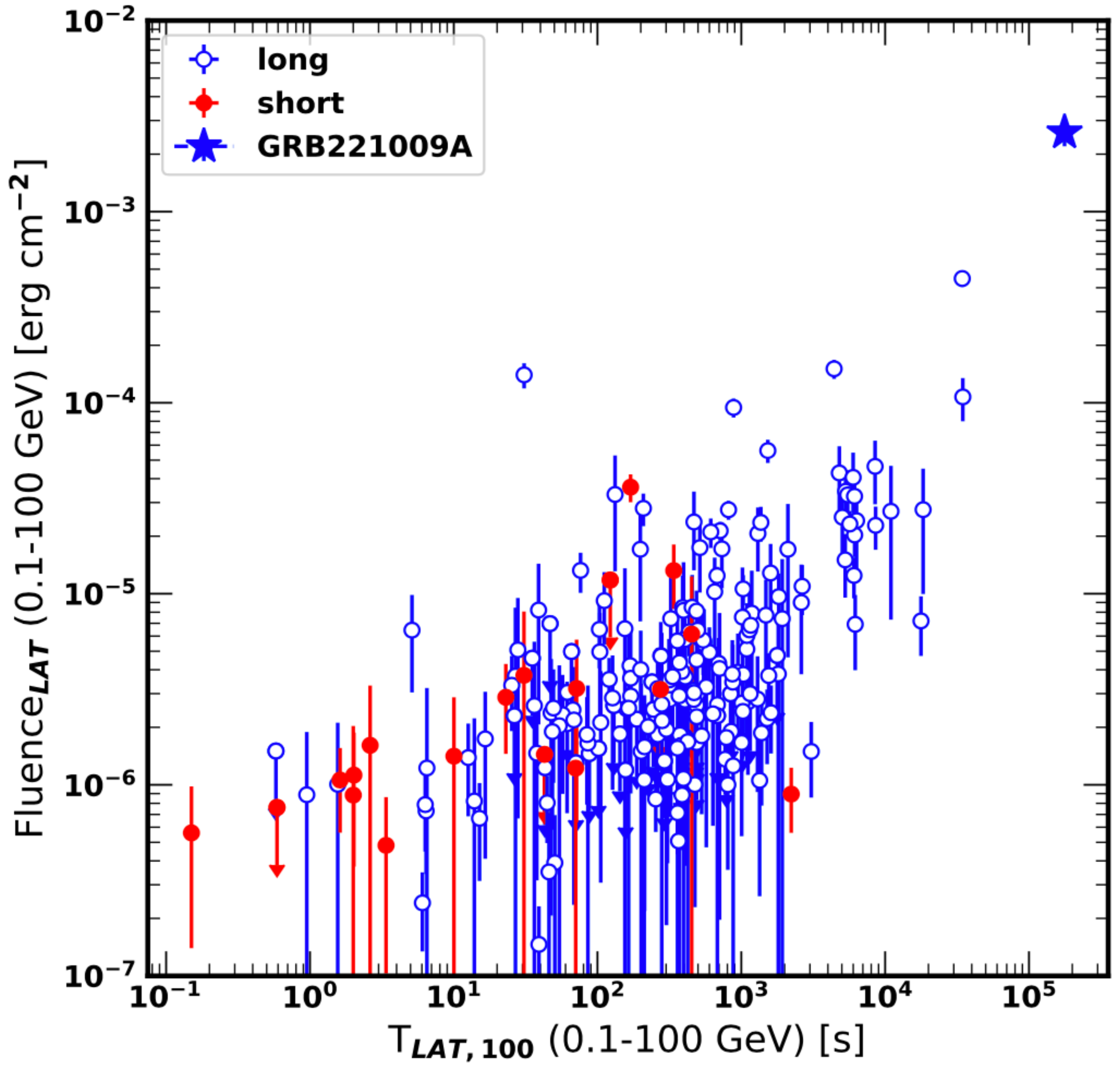
Back up slides

Let's put GRB 221009A in the context of other LAT GRBs

- **Highest photons detected by the LAT**
  - at 99.3 GeV during the prompt phase, 400 GeV during the afterglow)
- **Highest fluence**
  - 10^{-2} erg/cm^2 (>1 order of magnitude brighter than the previous record holder.
- **Longest duration**
  - 2 days

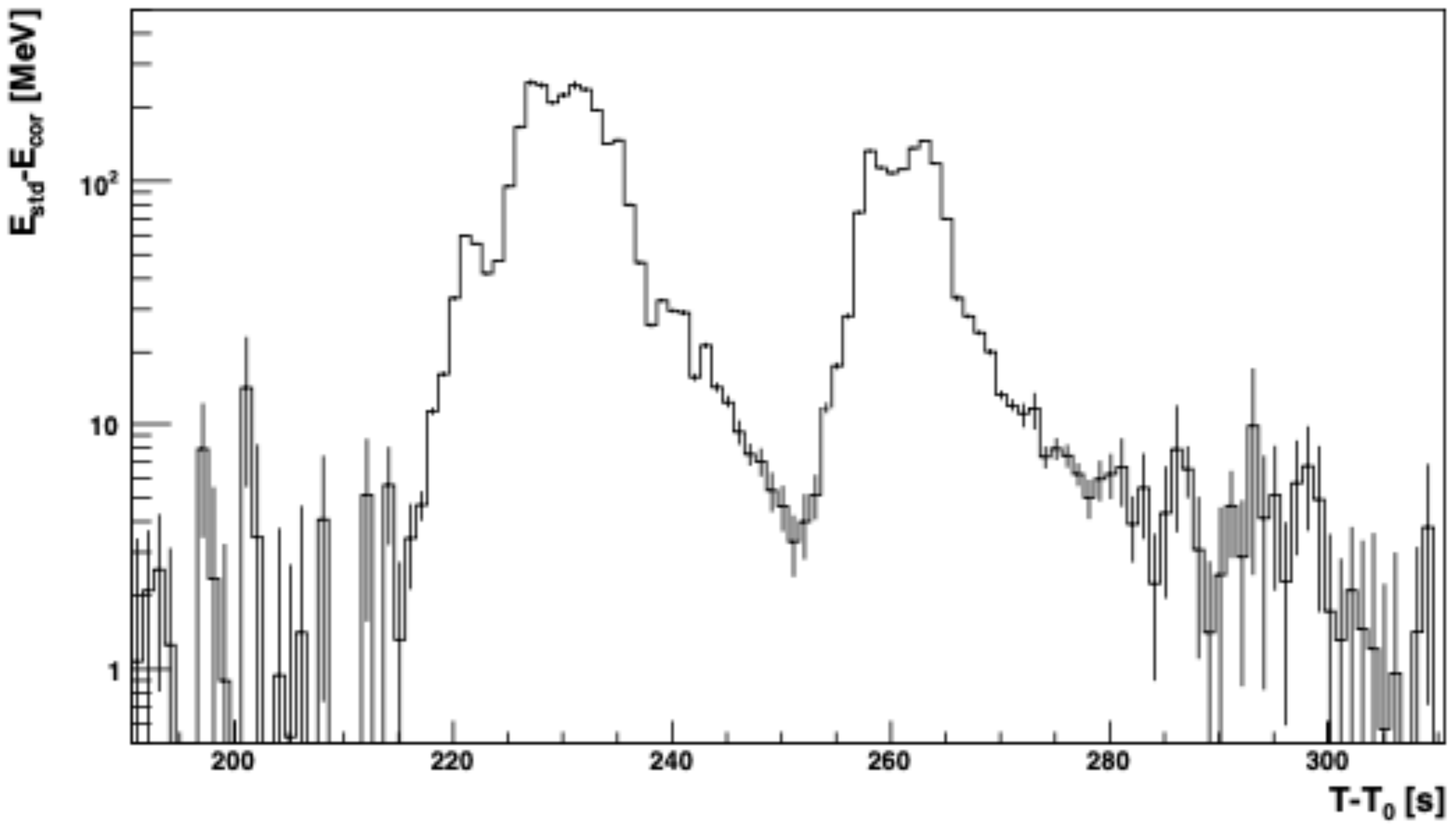




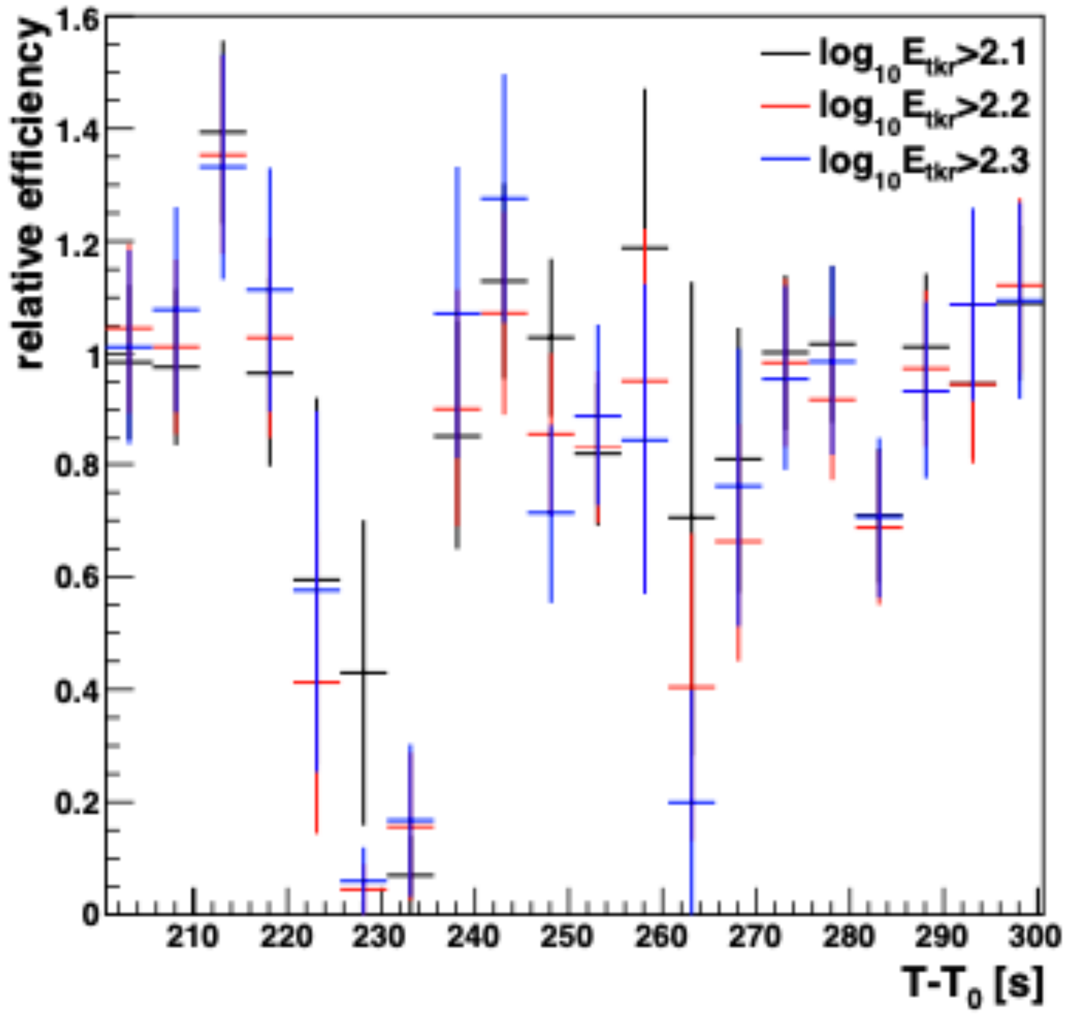


How we fixed the problem

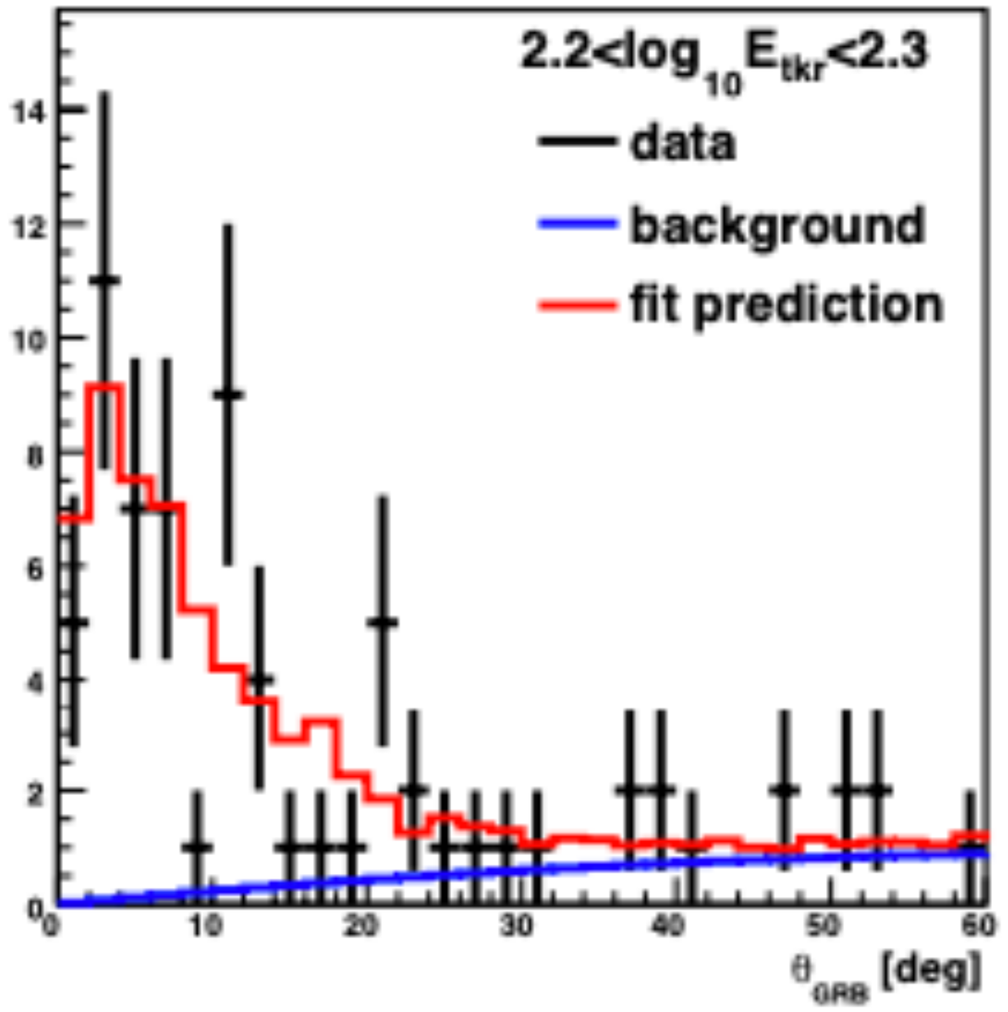
1. Developed a modified energy estimator using only the strips around the event track;
2. We use Earth-limb data to constrain the selection efficiency;
3. We use the information in the top corner of the tracker and the information in the bottom ACD to define the boundaries of the BTI [T_0+216.6 – T_0+280.6];
4. We perform Monte Carlo simulations to estimate the selection effective area as a function of time, as well as the false positive rate due to the LE background;
5. We apply a template fit approach to derive the HE emission light curve.



Difference between standard and modified energy estimator vs Time



Efficiency vs Time



Example of spatial template fitting for one energy bin

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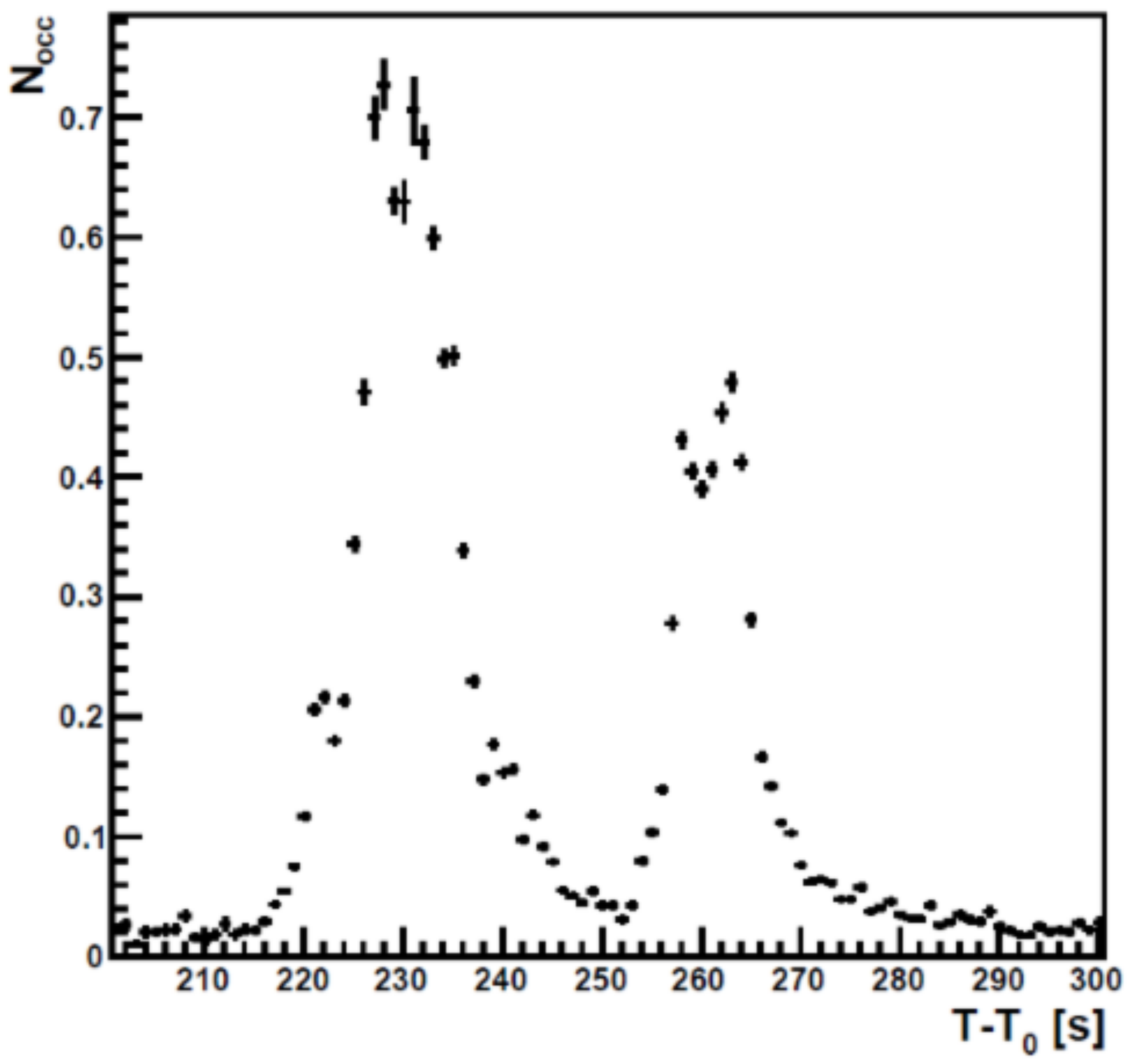
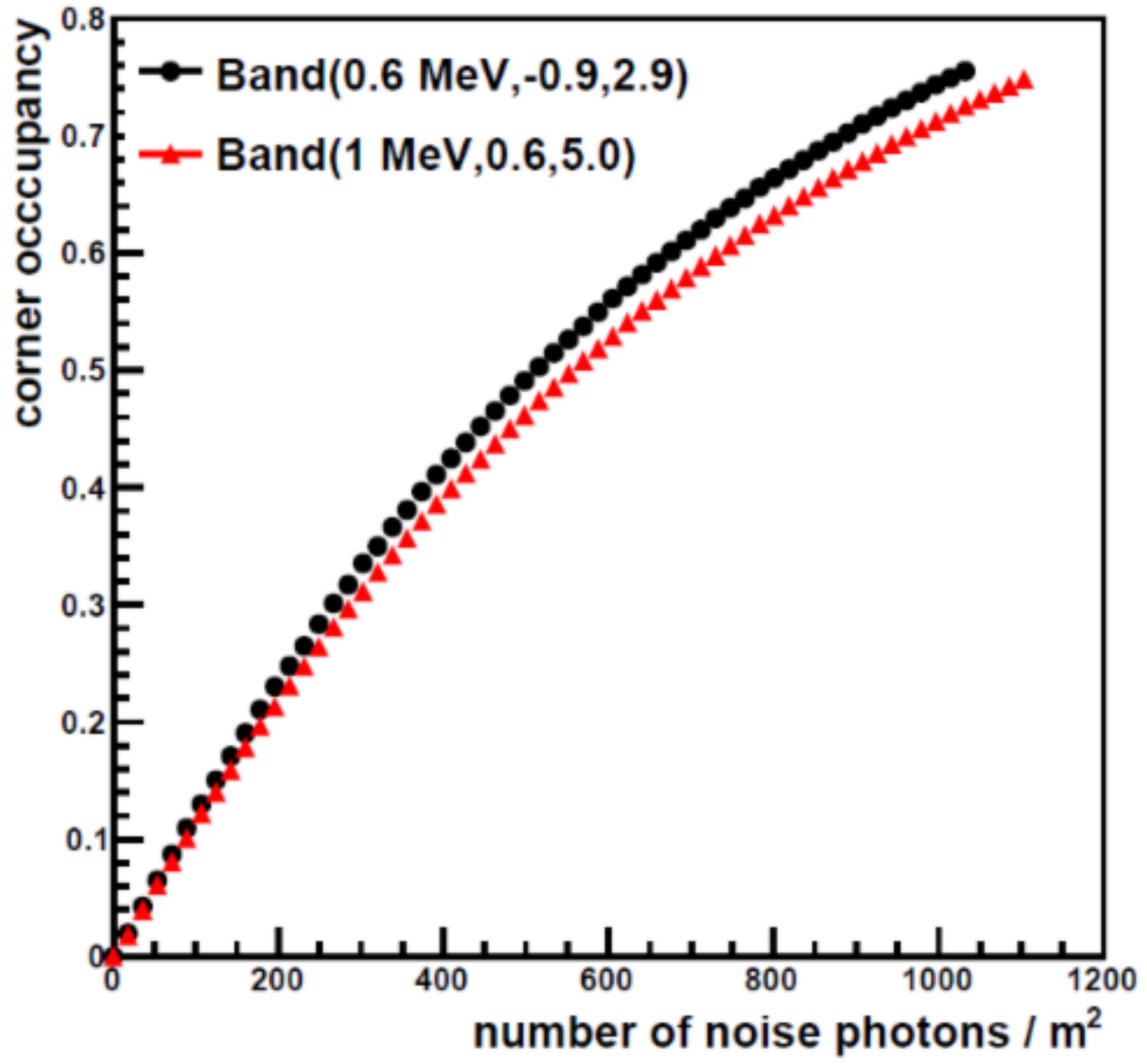
Extra noise estimation

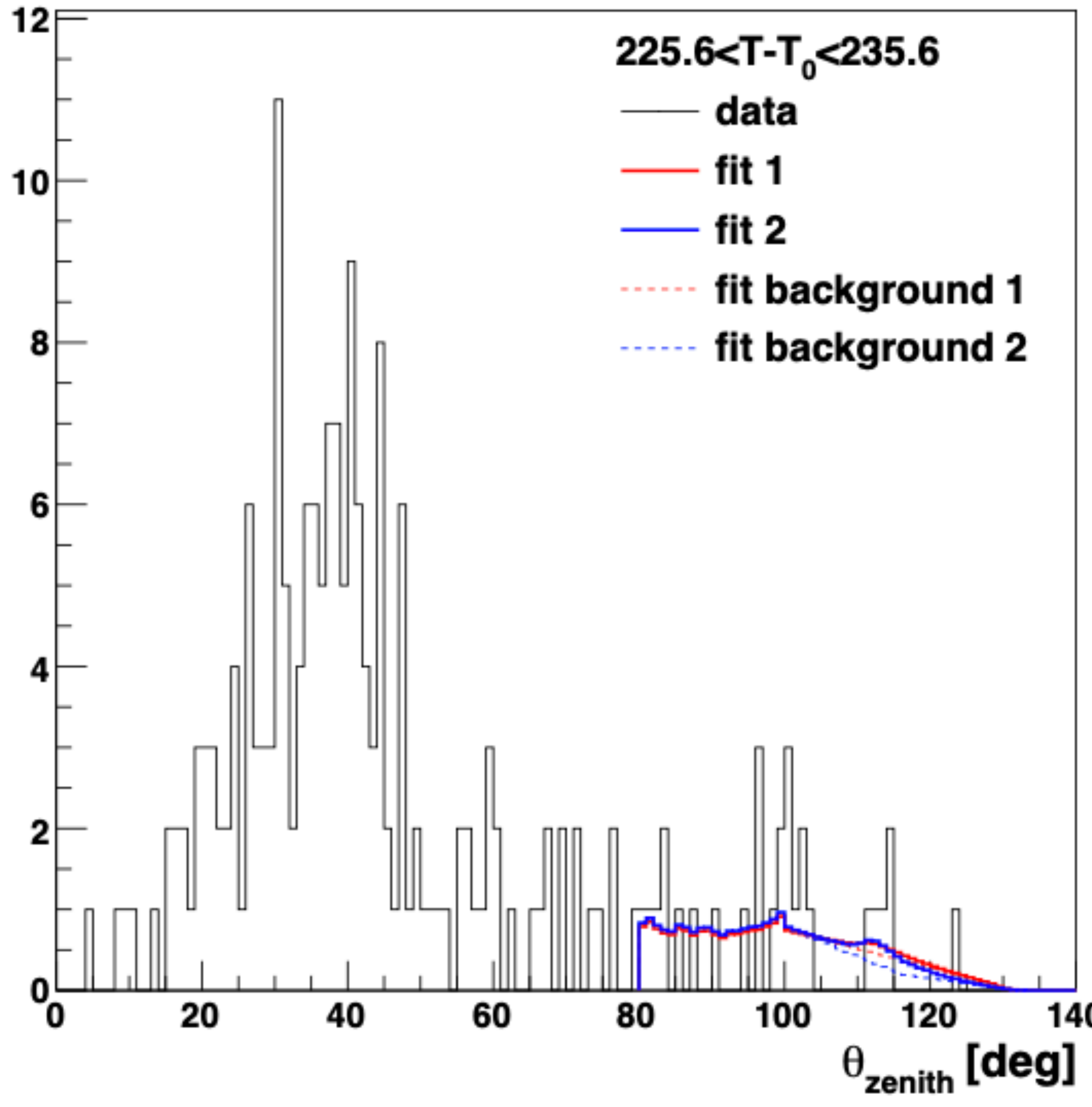
- We use some tracker-related quantities (i.e. the average fraction of events with at least a fired strip in the corner planes) to monitor the extra noise as a function of time
- We use simulations to translate this quantity into the flux of low energy photons. At the maximum of P1: ~900 photons/m²/10μs [0.1-30 MeV]

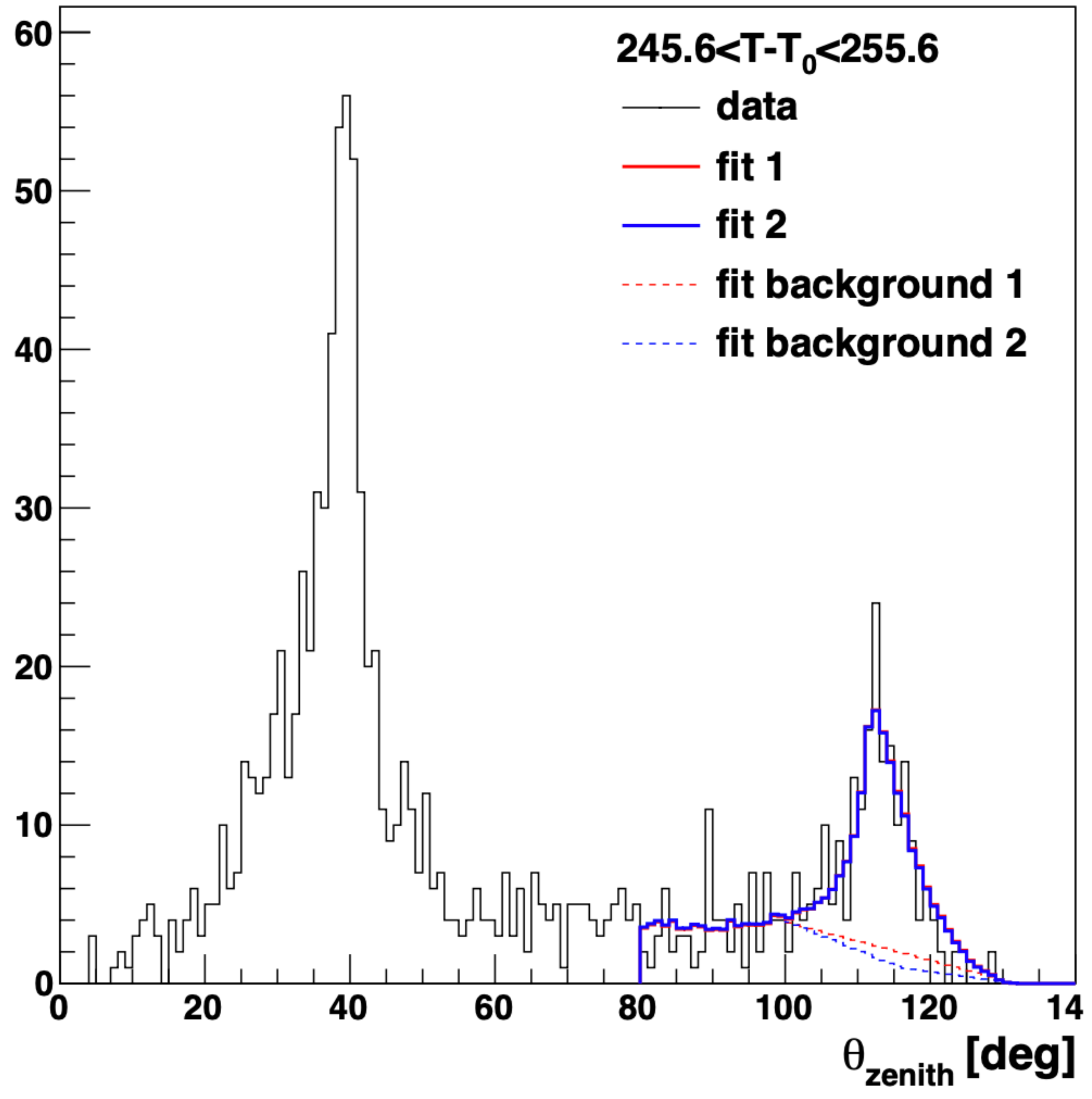


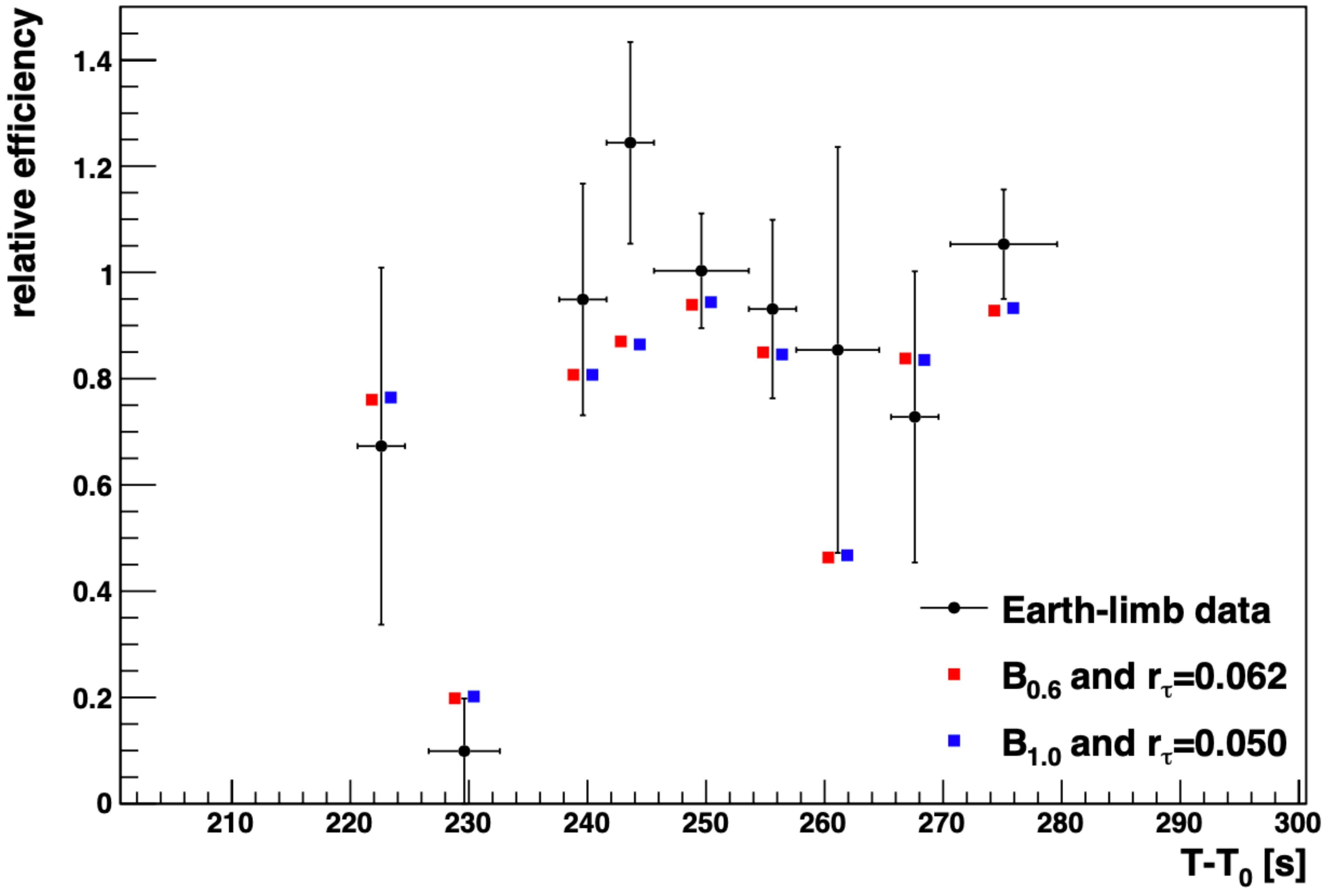


Using the Earth limb to estimate the efficiency

- The Earth limb is a bright source, visible in the LAT data at θzenith ~ 113. It offers a calibration source to estimate the trigger and on-board filter efficiency;
- Template fitting (piece-wise linear function + 2 gaussians)
- Estimate the <u>relative efficiency</u> with respect to a reference interval (T0+600.6, T_0+650.6)







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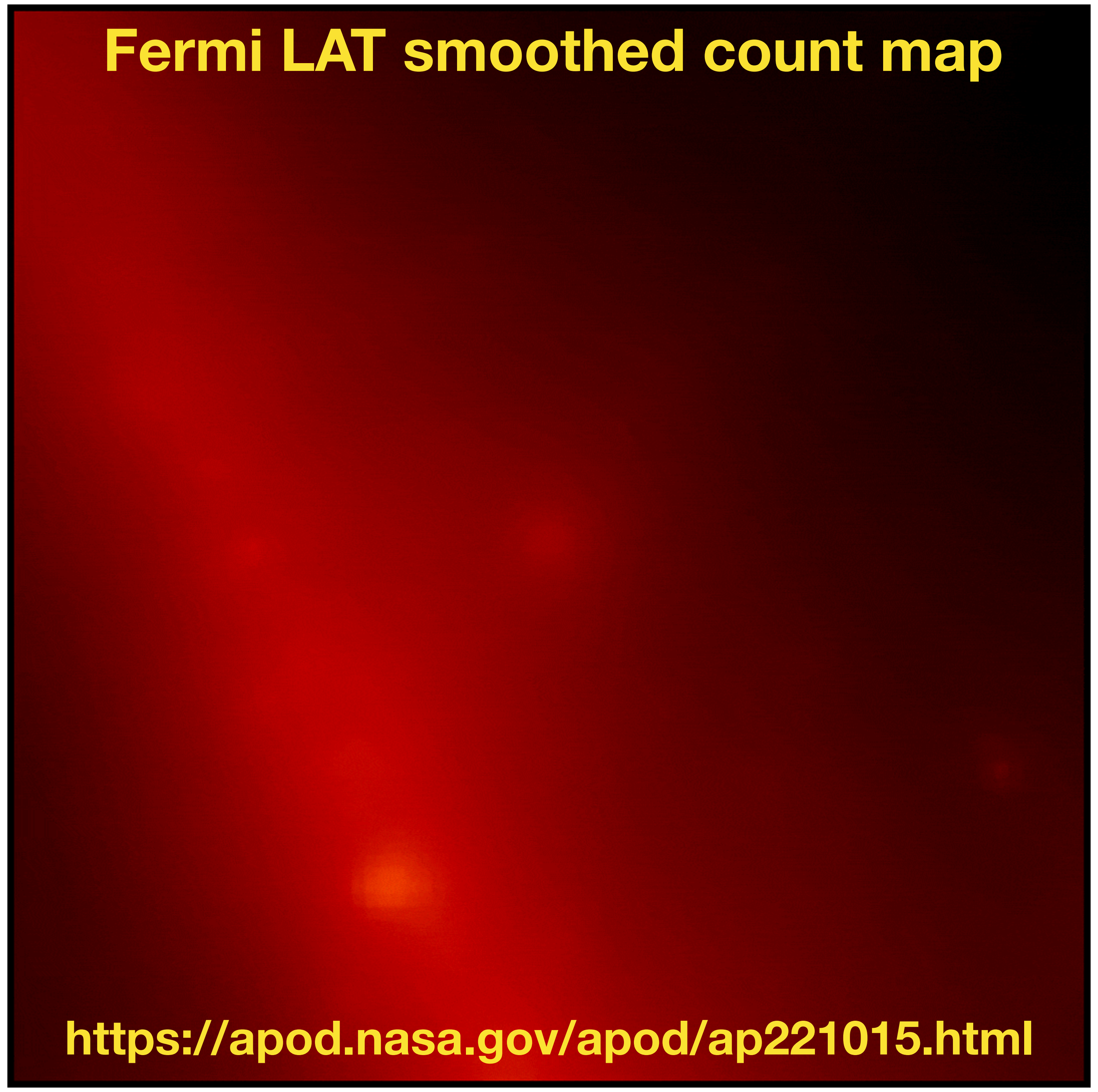
The BOAT timeline

- **Oct.9 2022**
  - 13:16:60 UT (T_0) Fermi-GBM trigger 221009553 (no prompt GCN notices)
  - 14:10:17 UT (T_0+3200s) Swift trigger (GCN after 20min - **Swift J1913.1+1946**)
  - 20:54:36 UT Fermi-GBM reports that trigger 221009553 is superbright+long **GRB 221009A** → location consistent with Swift → **same event!!!**
  - 21:45:05 UT Fermi-LAT reports HE emission (E_{max}: 8 GeV @766 s post Swift trigger)
- **Oct.10, 2022**
  - X-shooter/VLT reports redshift **z = 0.151**
  - Fermi-LAT reports refined analysis (Duration >25ks and E_{max}: **99 GeV** @T_0+240s)
  - IceCube reports neutrino UL (no detection)
  - Konus/WIND reports highest GRB fluence in 28 years of operation
- **Oct.11, 2022**
  - LHAASO reports **>500 GeV** emission within T_0+2000s (>100σ) + **18 TeV** photon (10σ)
  - Swift/XRT reports complex system of bright expanding dust-scattering rings
  - HAWC reports upper limits 8 hours after trigger (See Lucia Tian presenation
- **Oct.12, 2022**
  - Carpet-2 reports **250 TeV** photon-like air shower
- **Oct.14, 2022**
  - Xia et al. report **400 GeV** photon observed by Fermi-LAT at T_0+0.4 d



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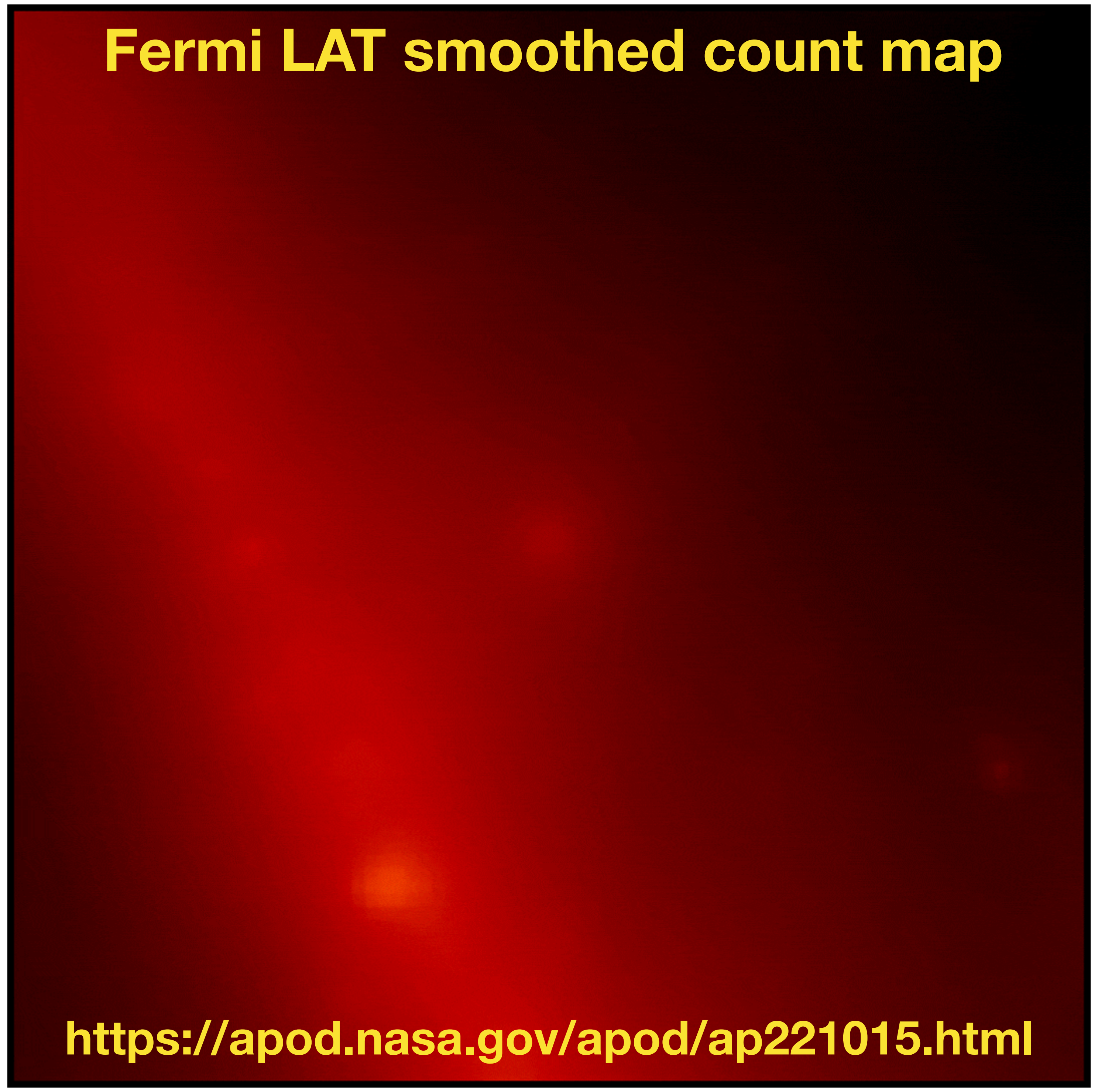

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