Comprehension of jet physics from the analysis of *Swift* Gamma-Ray Bursts

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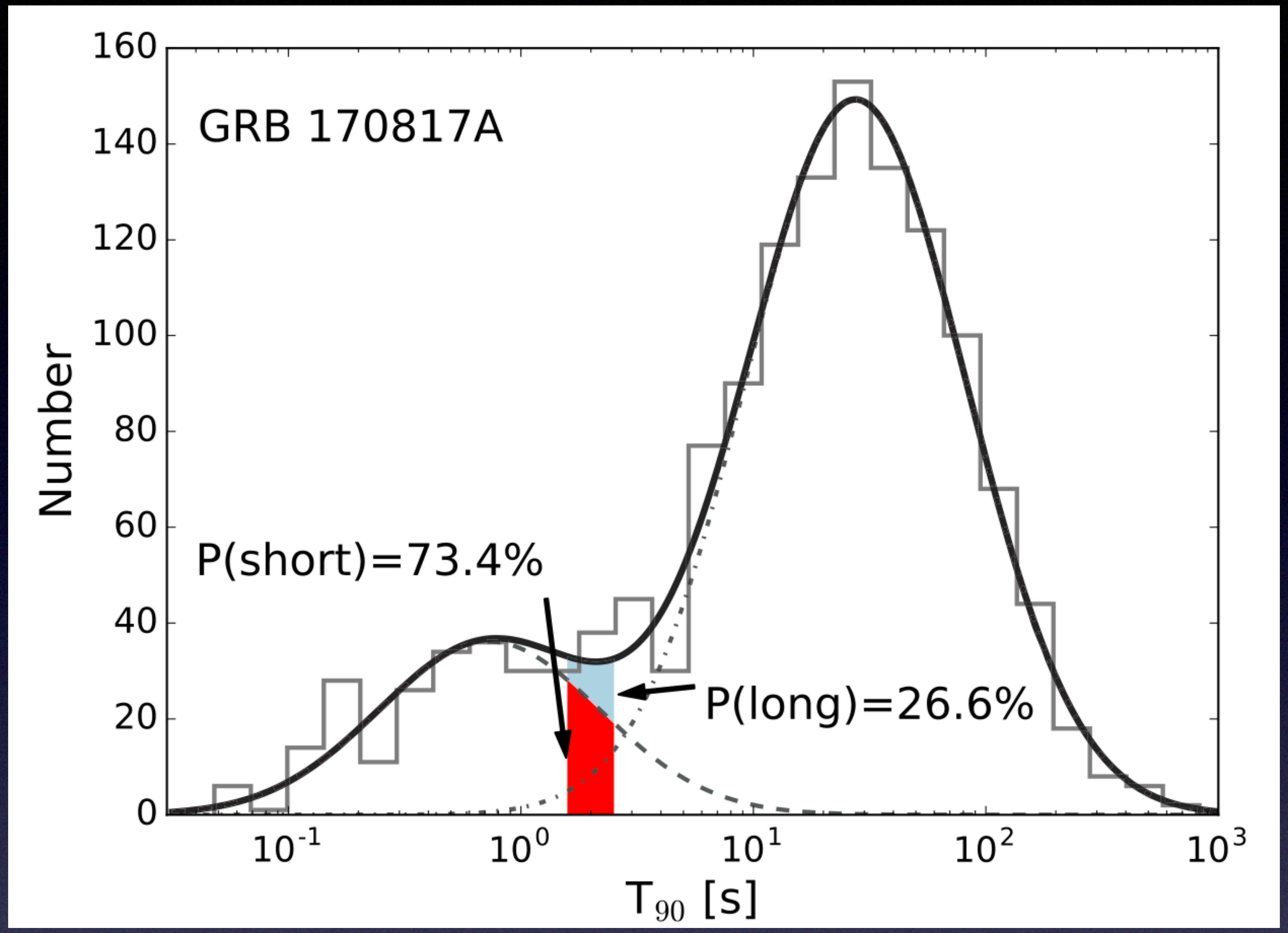
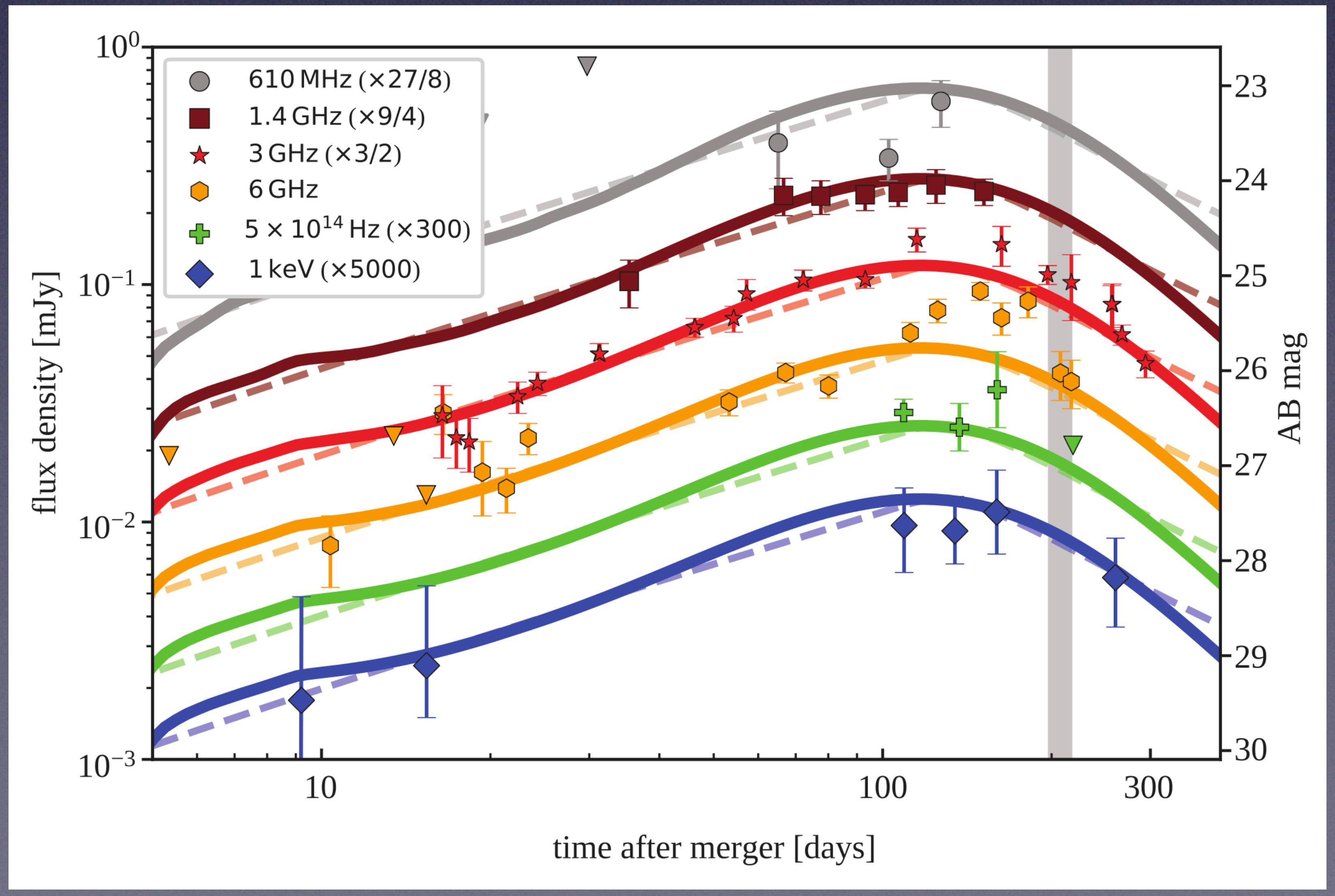
Introduction



Goldstein et al., 2017, ApJL, 848, L14



Ghirlanda et al. 2018

- Need to overcome standard Long-Short classification → Jespersen et al. 2020 → apply t-SNE to Swift-BAT prompt light curves (lc) to obtain a classification map → non-collapsar classification

- “Boosted fireball” model (radiation + geometry) to fit Swift-XRT lc and get a general description → set of parameters that could describe the physics of the sample “mean” SSC model

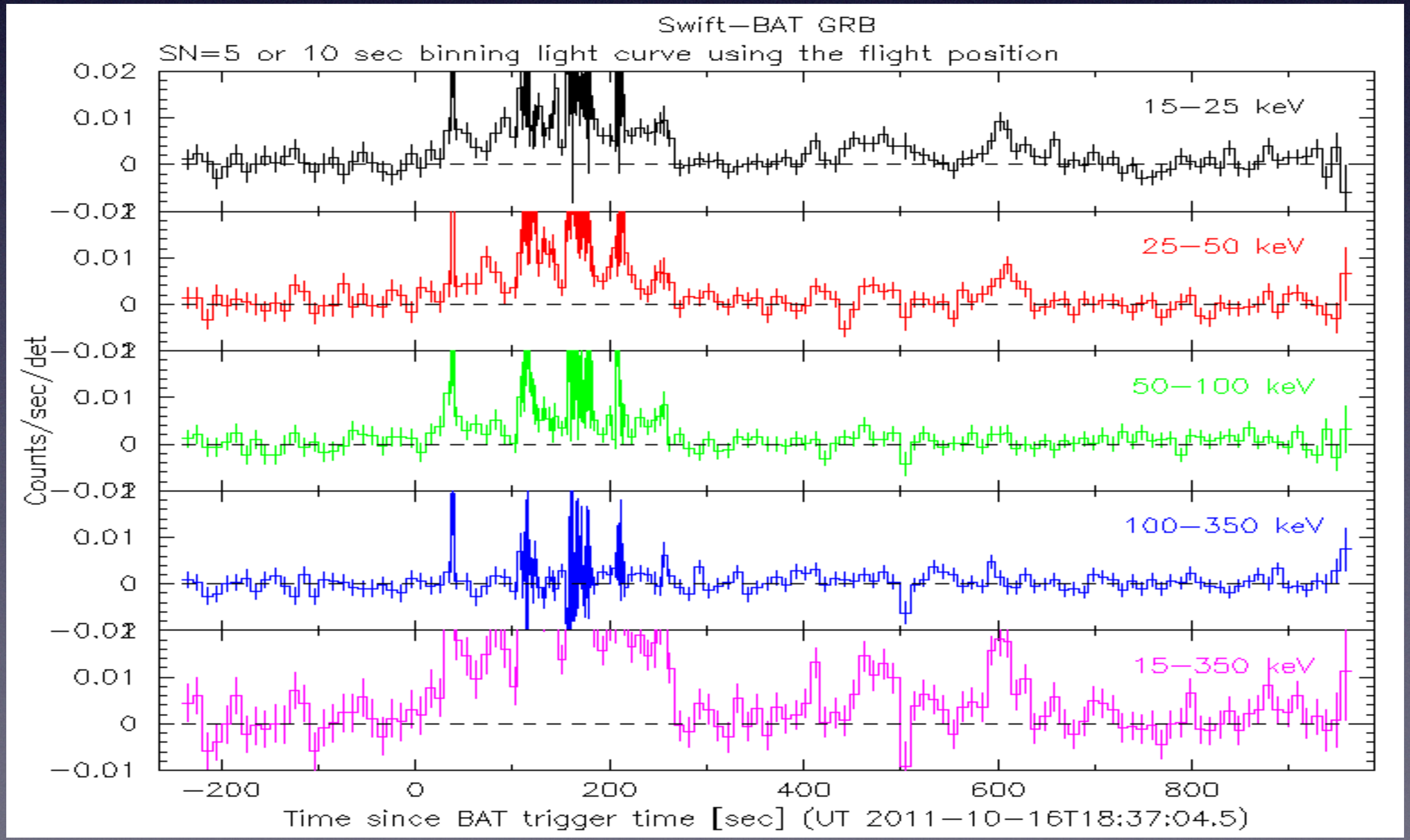
Introduction: analysis strategy

- Prompt phase → use a machine learning algorithm to classify Swift-BAT lc (following https://doi.org/10.3847/2041-8213/ab964d)
  - apply the Discrete Time Fourier Transform (DTFT)
  - use t-Stochastic Neural Embedded Neighbour (t-SNE) to classify the data
  - result: classification maps
- Afterglow phase → fit the lc with "boosted fireball" model + synchrotron model (using https://github.com/NYU-CAL/JetFit)
  - basic cuts applied on the original lc
  - temporal re-bin
  - flare removal technique
  - result: best-fit parameters distributions
- Afterglow phase → "mean" SSC model to describe the multi-wavelength SED of GRB 090510.

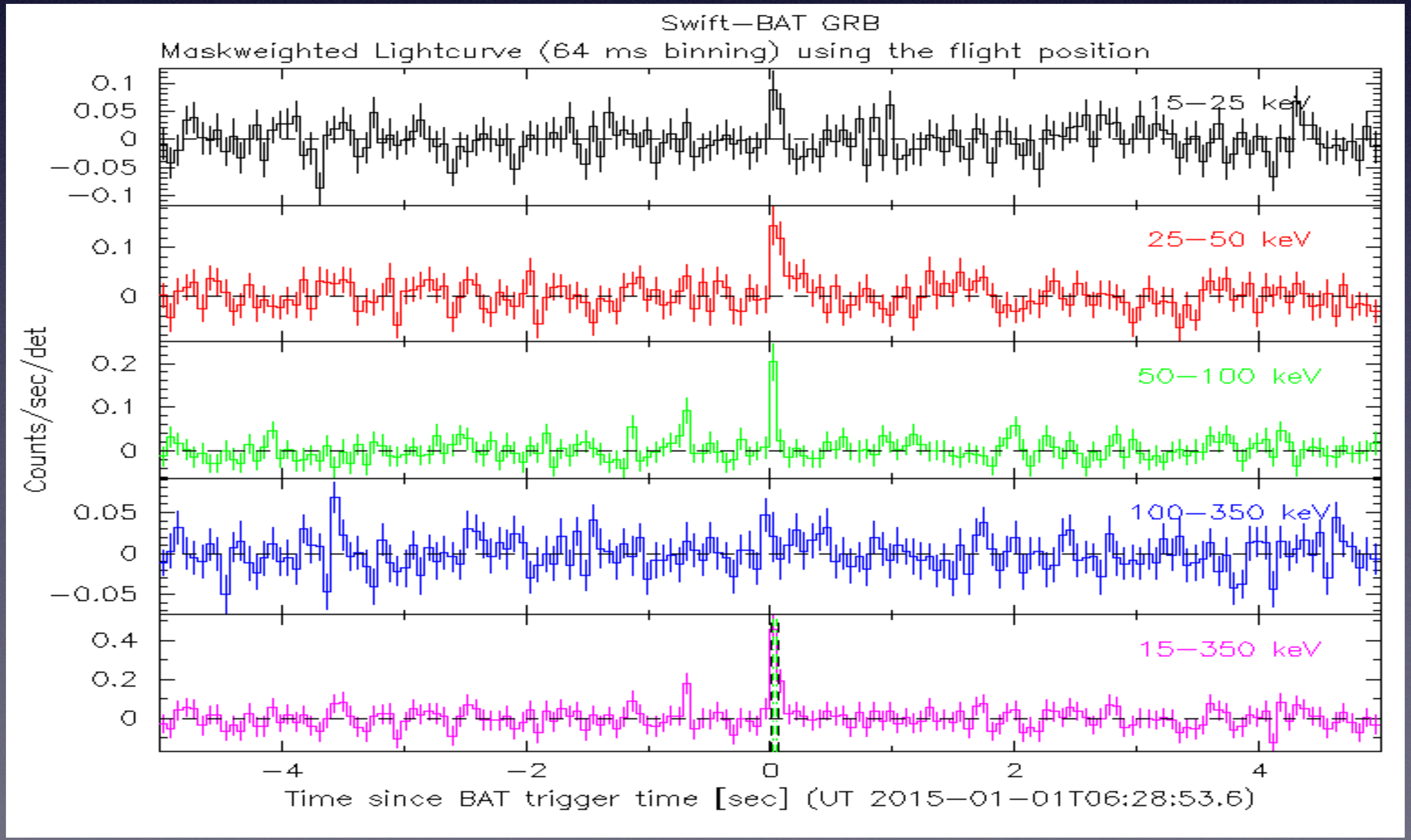
Prompt phase: data preparation

- ~ 1300 Swift-BAT light curves (2005 - 2020) from BAT online GRB catalogue (https://swift.gsfc.nasa.gov/results/batgrbcat/)
- 4 energy energy bands 15-25 keV, 25-50 keV, 50-100 keV, 100-350 keV binned in 64 ms
- t-SNE could distinguish between different morphologies in the light curves and classify the GRBs accordingly

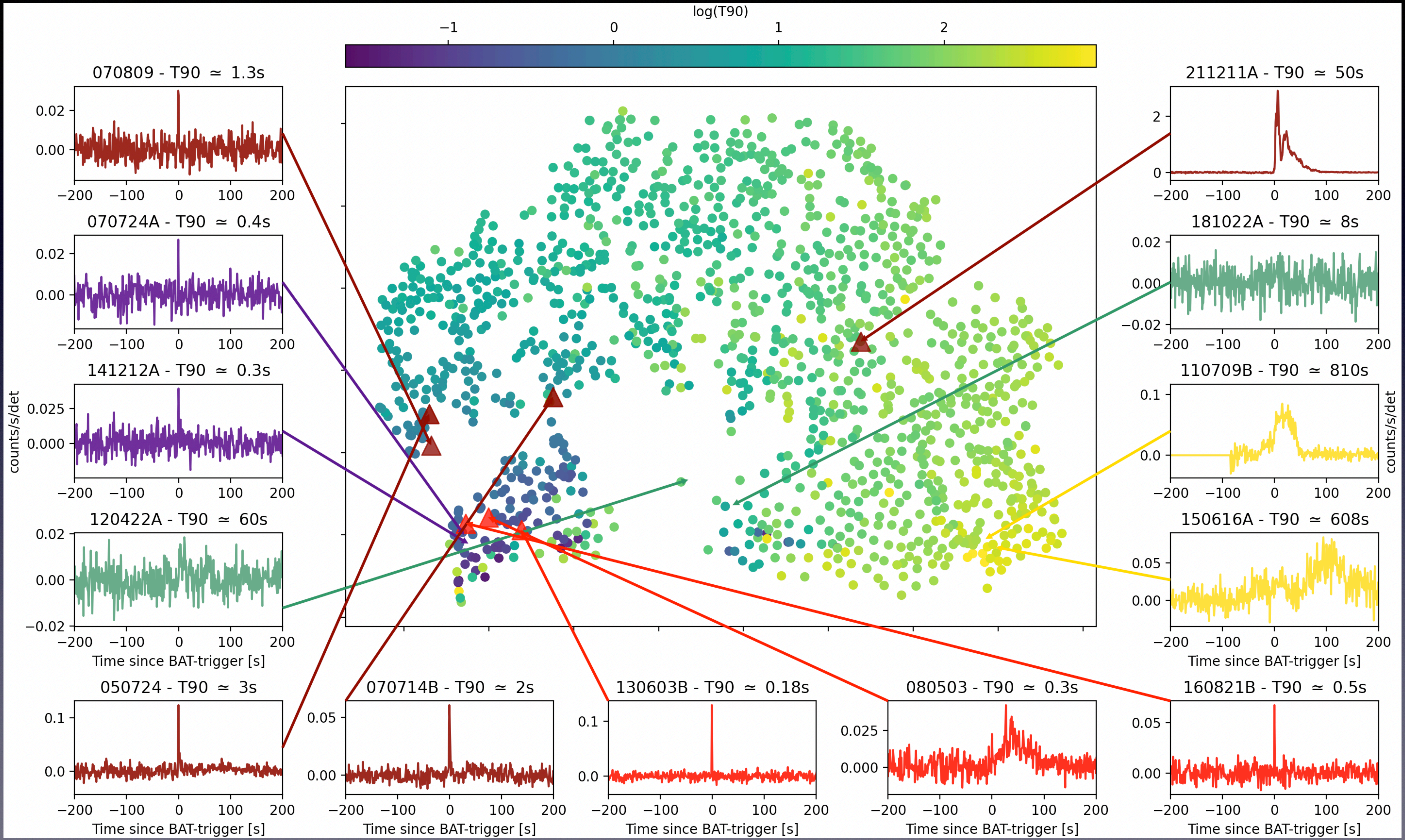
GRB 111016A: T90 ≃ 549 s



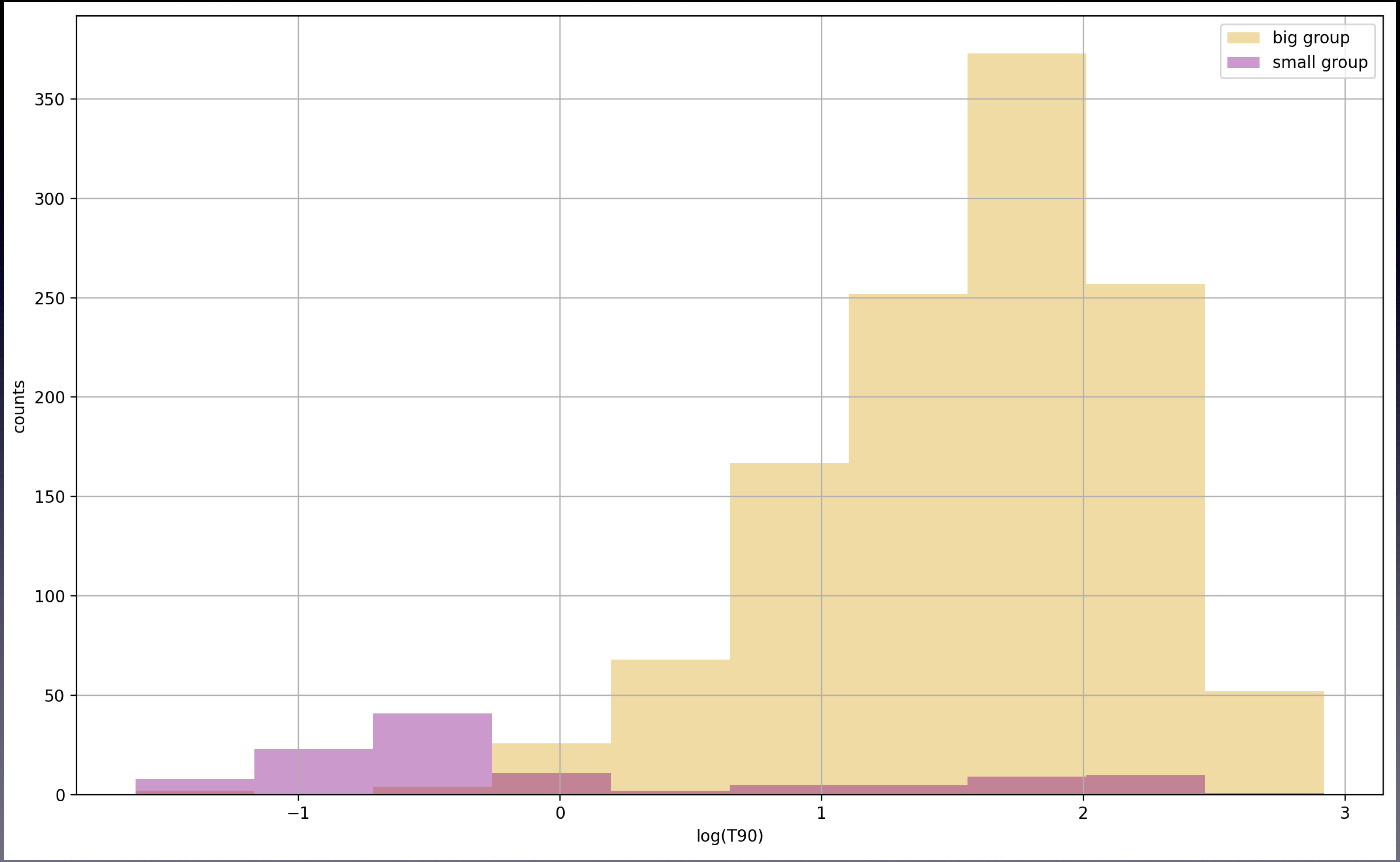
GRB 150101A: T90 ≃ 0.06 s



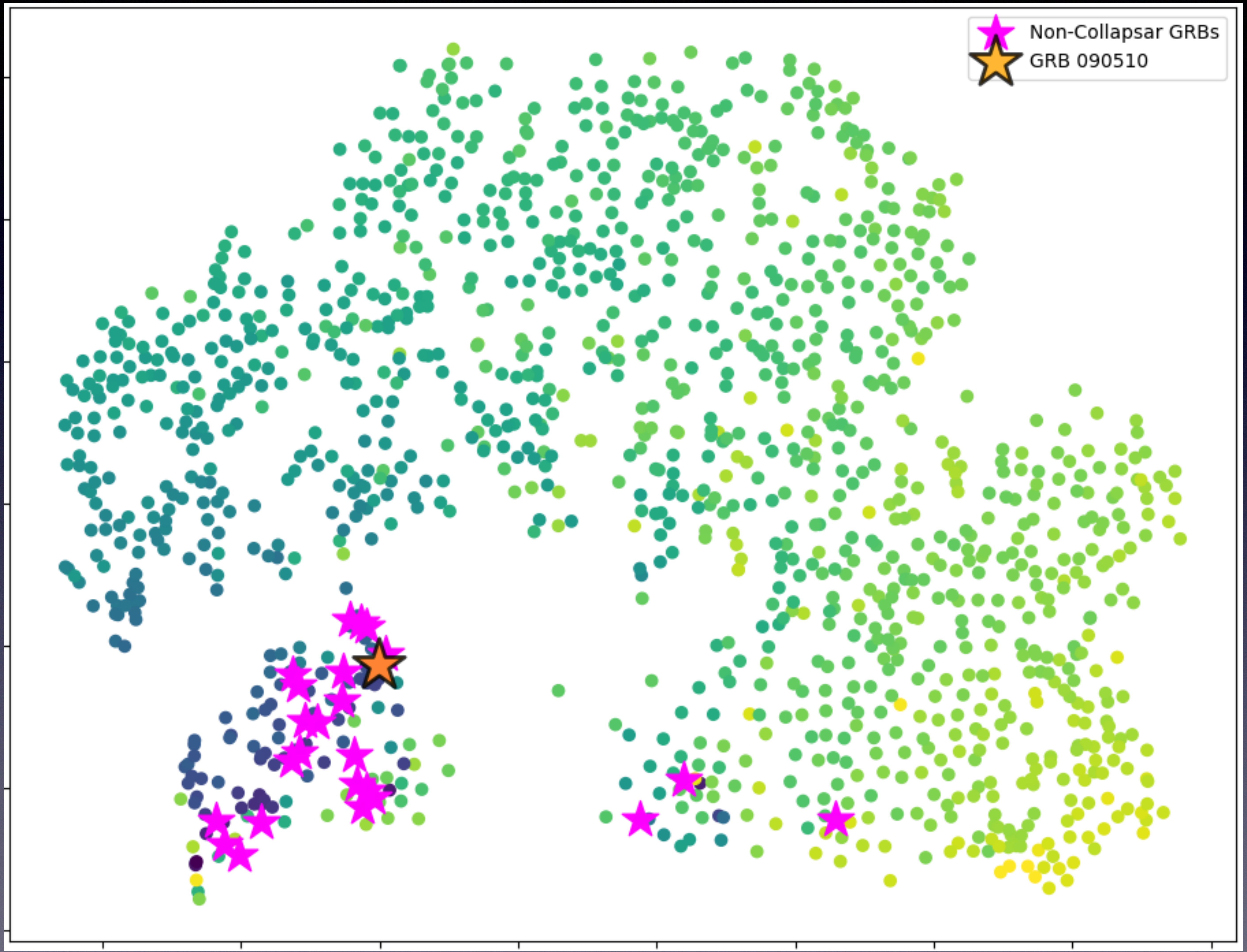
Prompt phase: results



Prompt phase: results



Prompt phase: results



Magenta stars taken from Bromberg et al. 2013, doi: https://iopscience.iop.org/article/10.1088/0004-637X/764/2/179/pdf

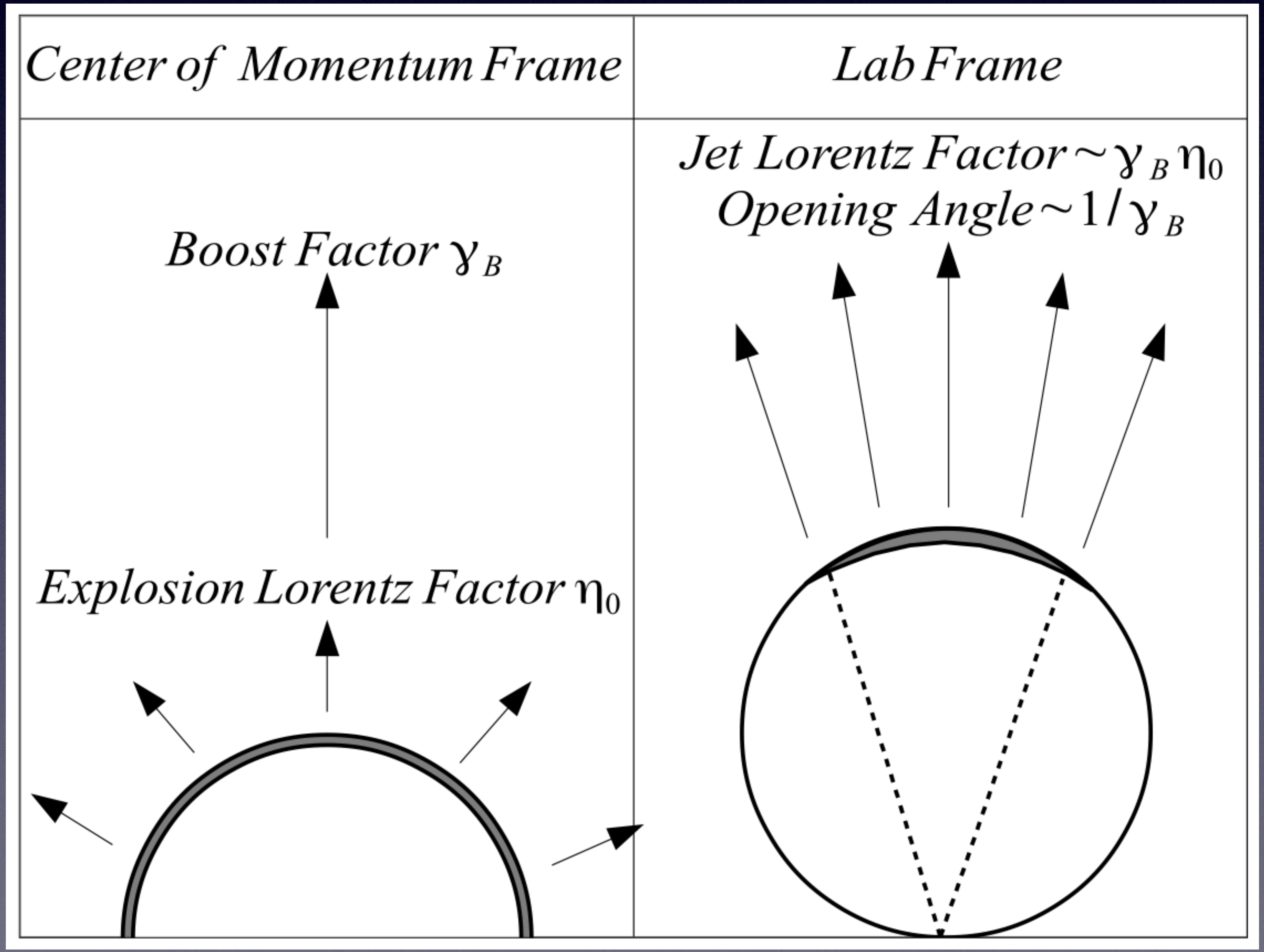
- Bromberg et al. 2013 sub-selection: 27 GRBs with a probability > 90% of having a non-collapsar origin → this could attribute a merger common origin to the small group

GRB	T90(s)	f_NC	z
090510	0.3	0.98 ± 0.20	0.903

f_NC(T90) = probability that a GRB with a given T90 is a Non-Collapsar

Afterglow phase: analysis motivation

- “Boosted fireball” model by Duffell and MacFadyen (doi: https://iopscience.iop.org/article/10.1088/2041-8205/776/1/L9) → XRT GRBs from online catalogue (https://www.swift.ac.uk/xrt_live_cat/) + Simbad catalogue (http://simbad.u-strasbg.fr/simbad/), with known redshift → 430 GRBs



Sketch of the “boosted fireball” model from Duffell and MacFadyen 2013, doi: https://iopscience.iop.org/article/10.1088/2041-8205/776/1/L9

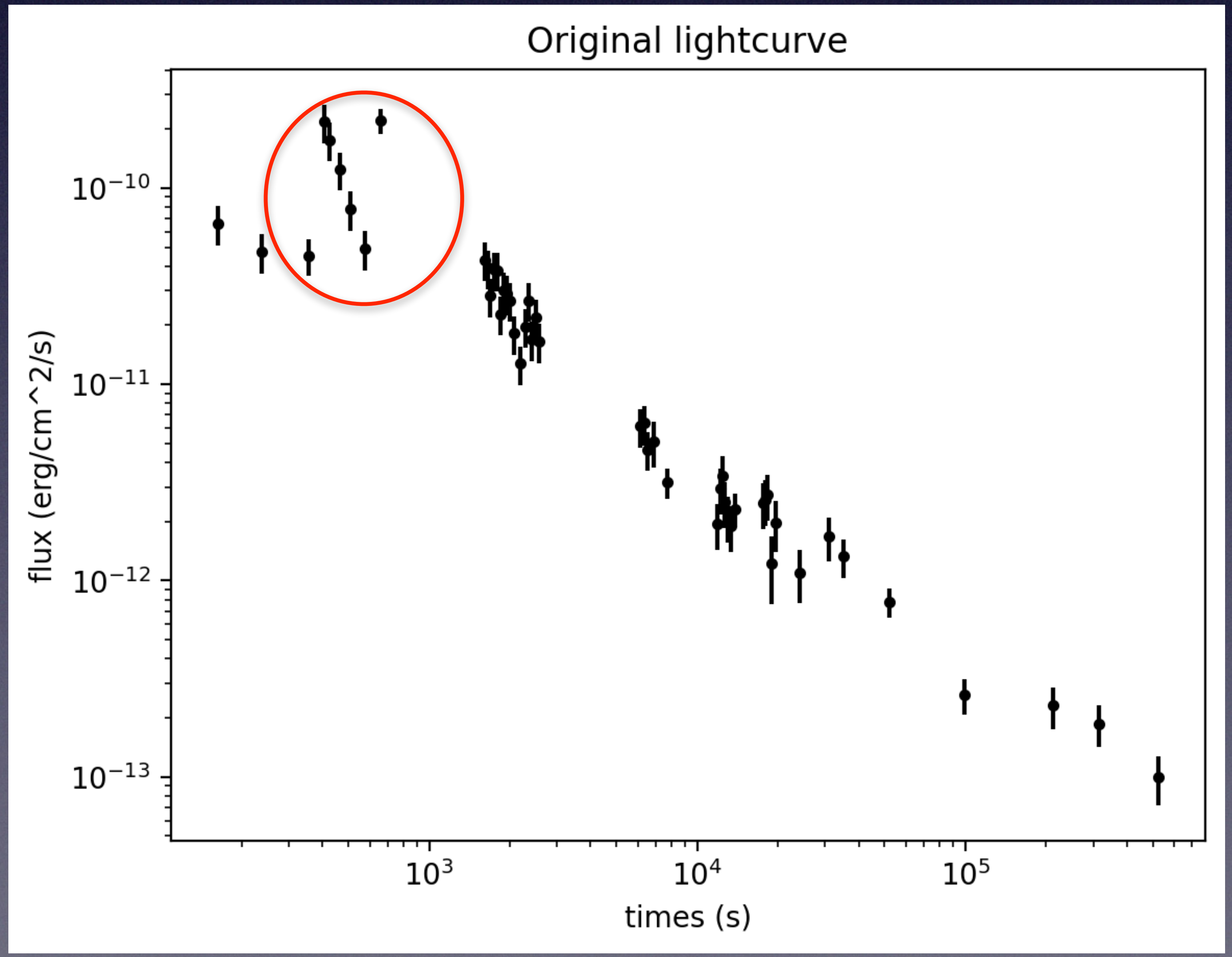
↓

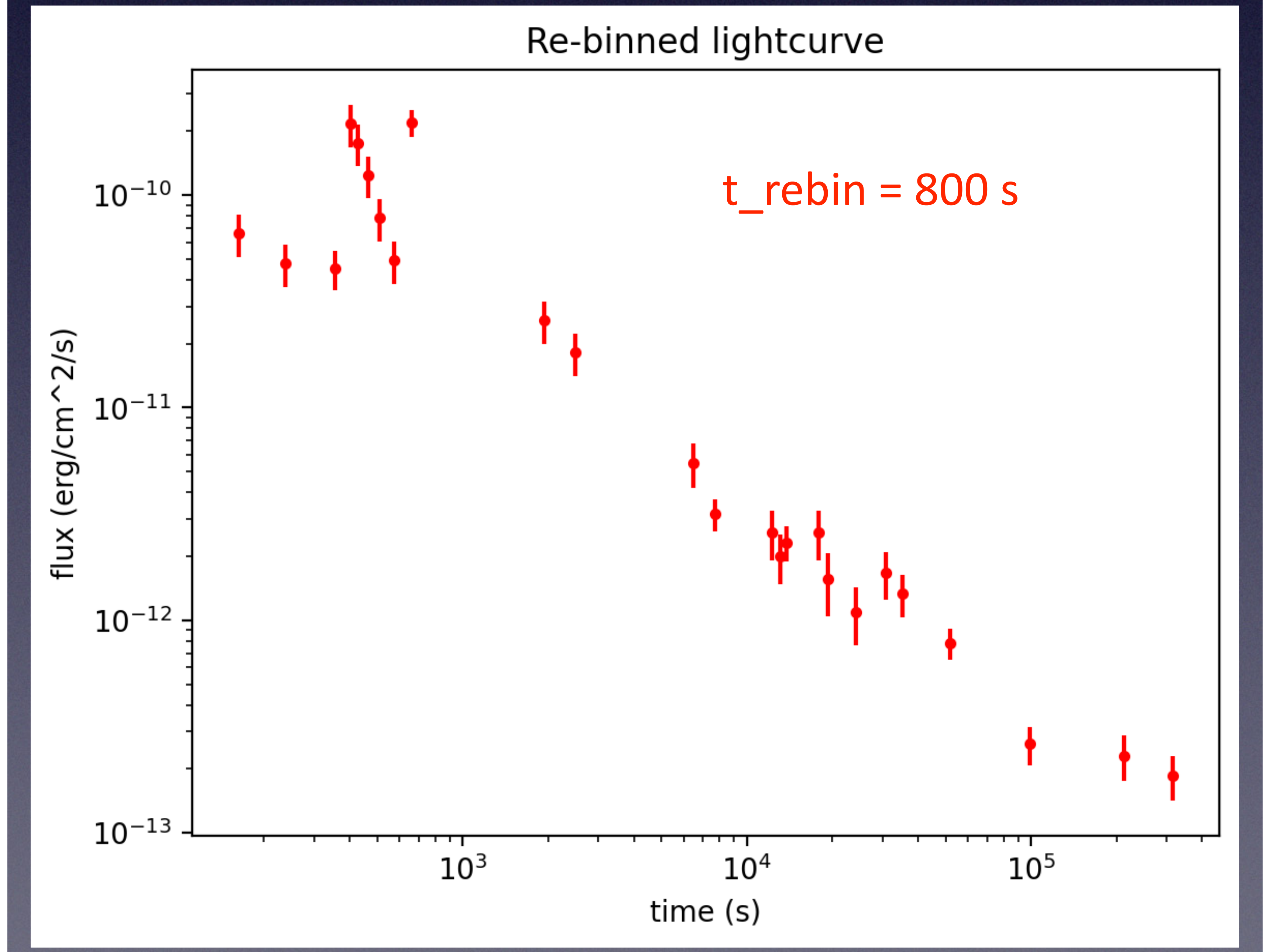
η_0 = Lorentz factor in the c.o.m. frame
γ_B = boosted Lorentz factor in the lab frame

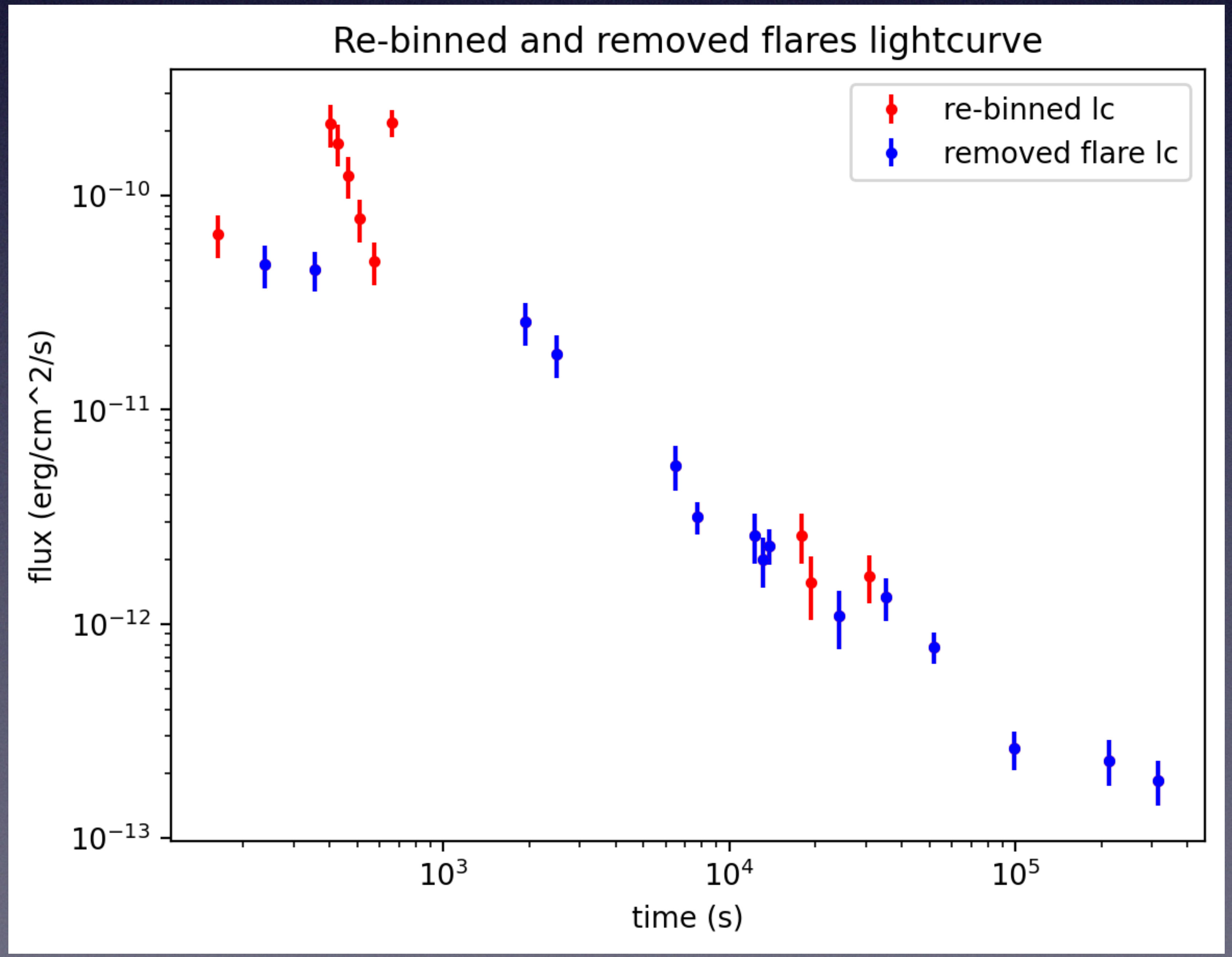
Afterglow phase: analysis procedure

- The model does not describe the flaring activity → new method based on the slopes between points to get rid of the flares

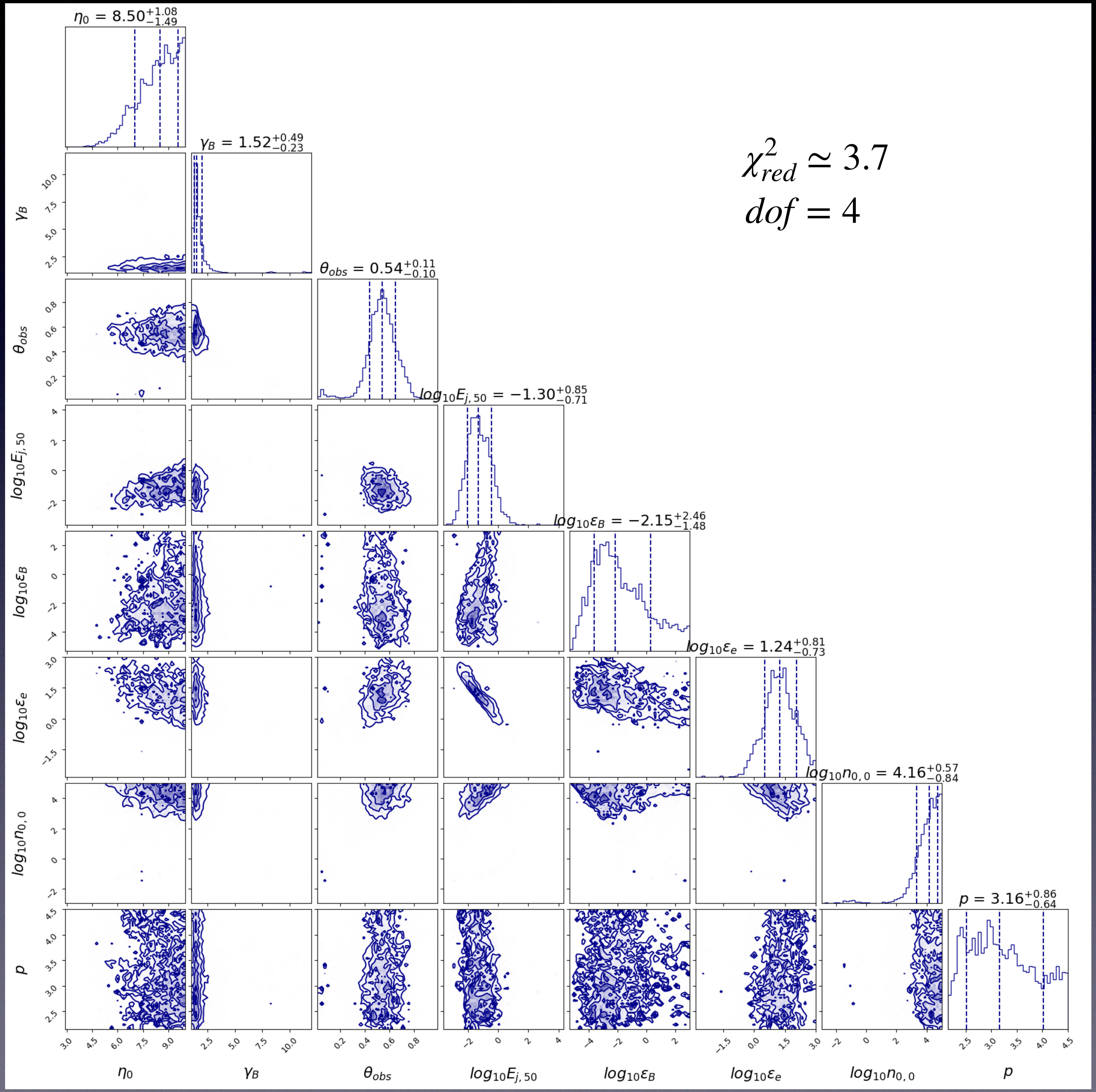
GRB 131103A (data taken from https://www.swift.ac.uk/xrt_live_cat/576562)



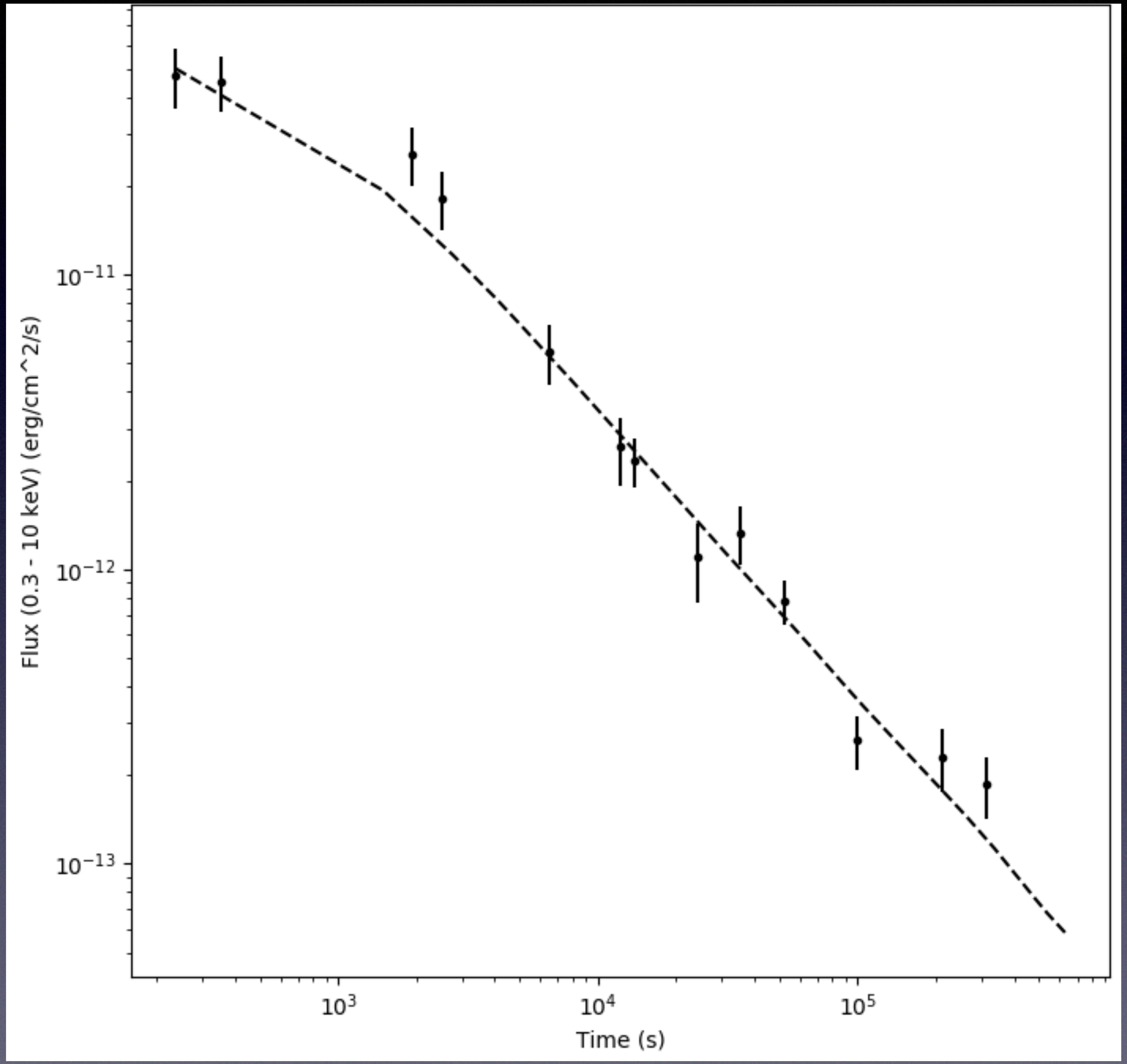




Afterglow phase: results



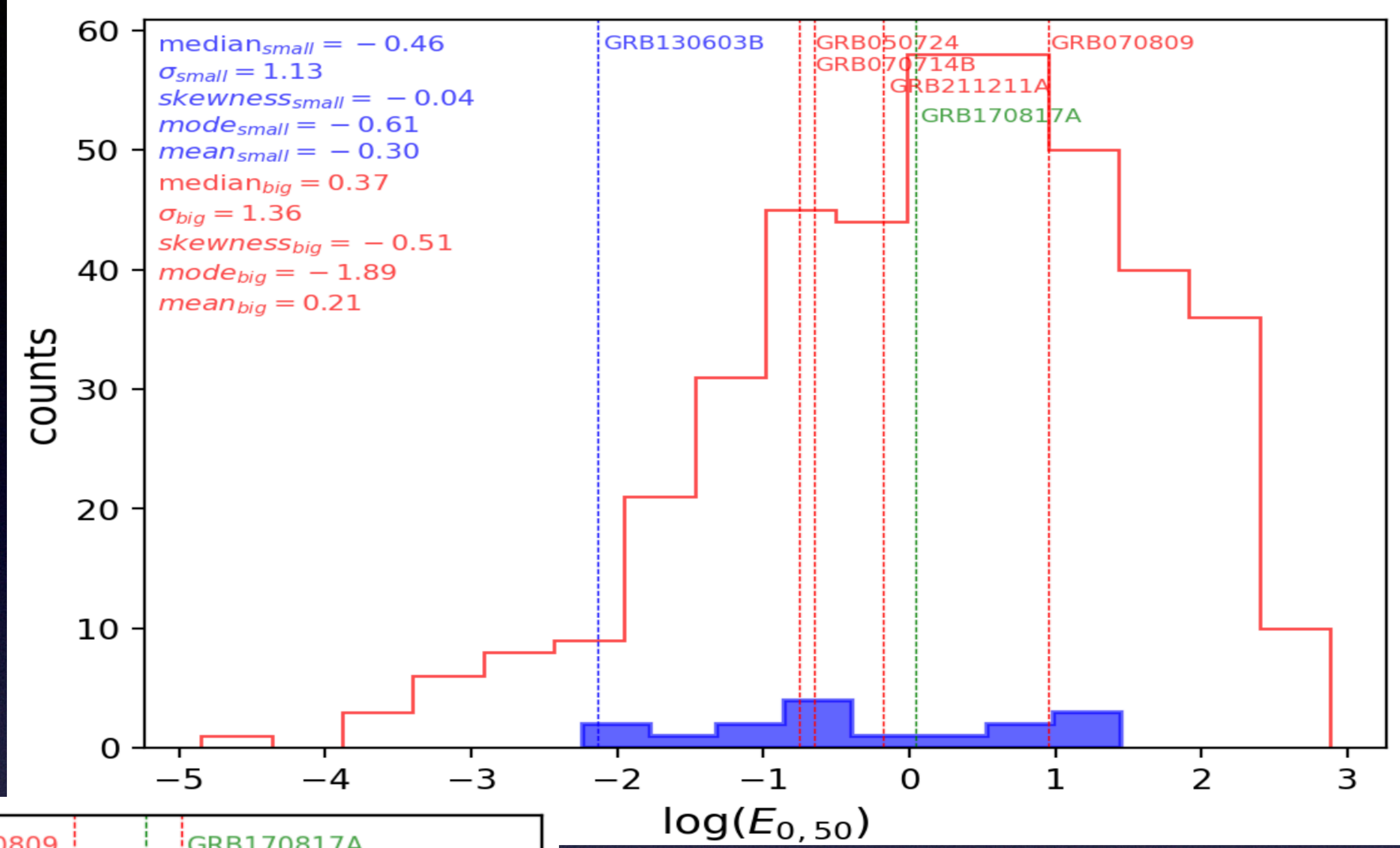
$\chi^2_{red} \simeq 3.7$
$dof = 4$

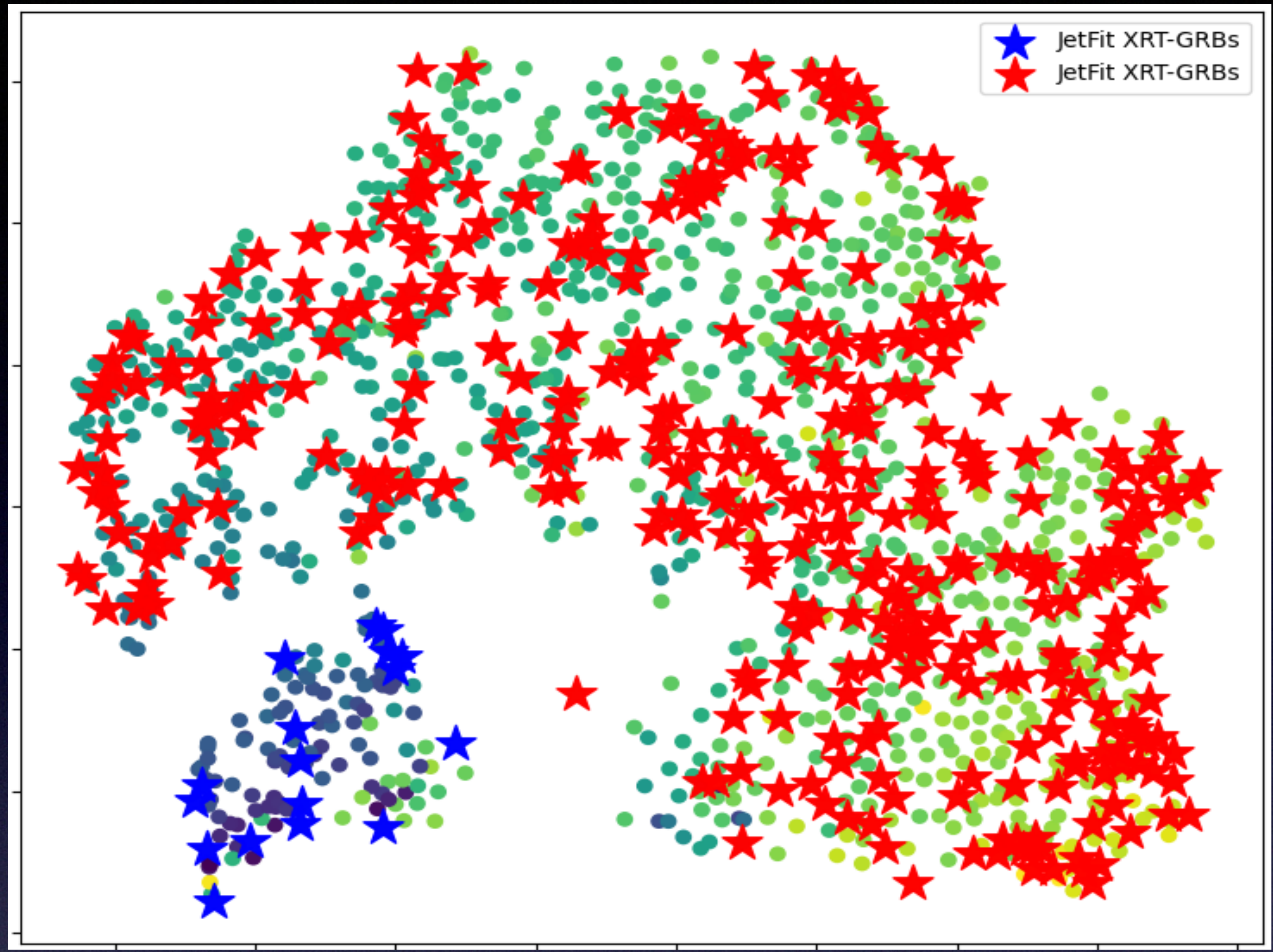


$$\{E_0, n_0, \eta_0, \gamma_B, p, \epsilon_e, \epsilon_B, \xi_N, z, d_L, \theta_{obs}\}$$

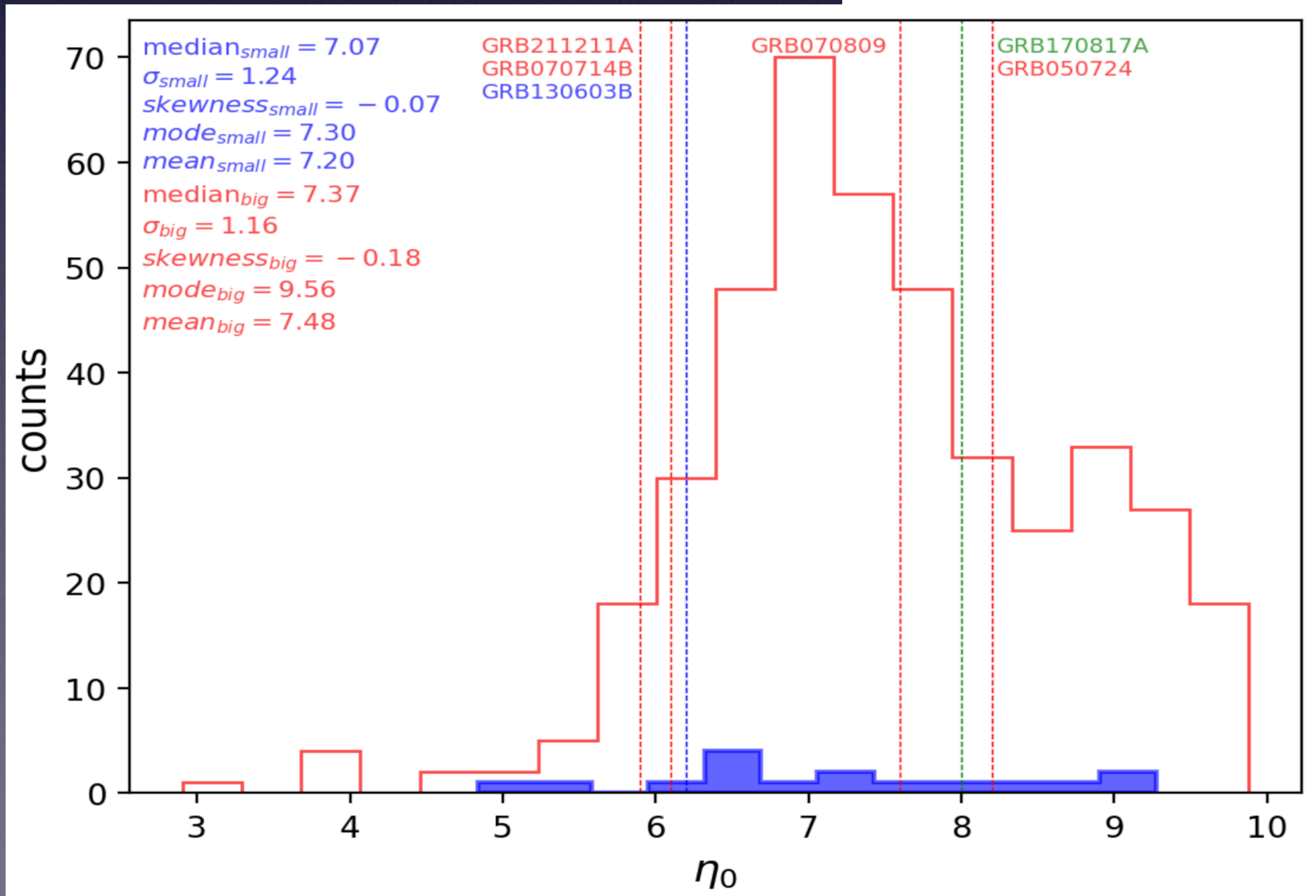
Afterglow phase: results

Explosion Energy

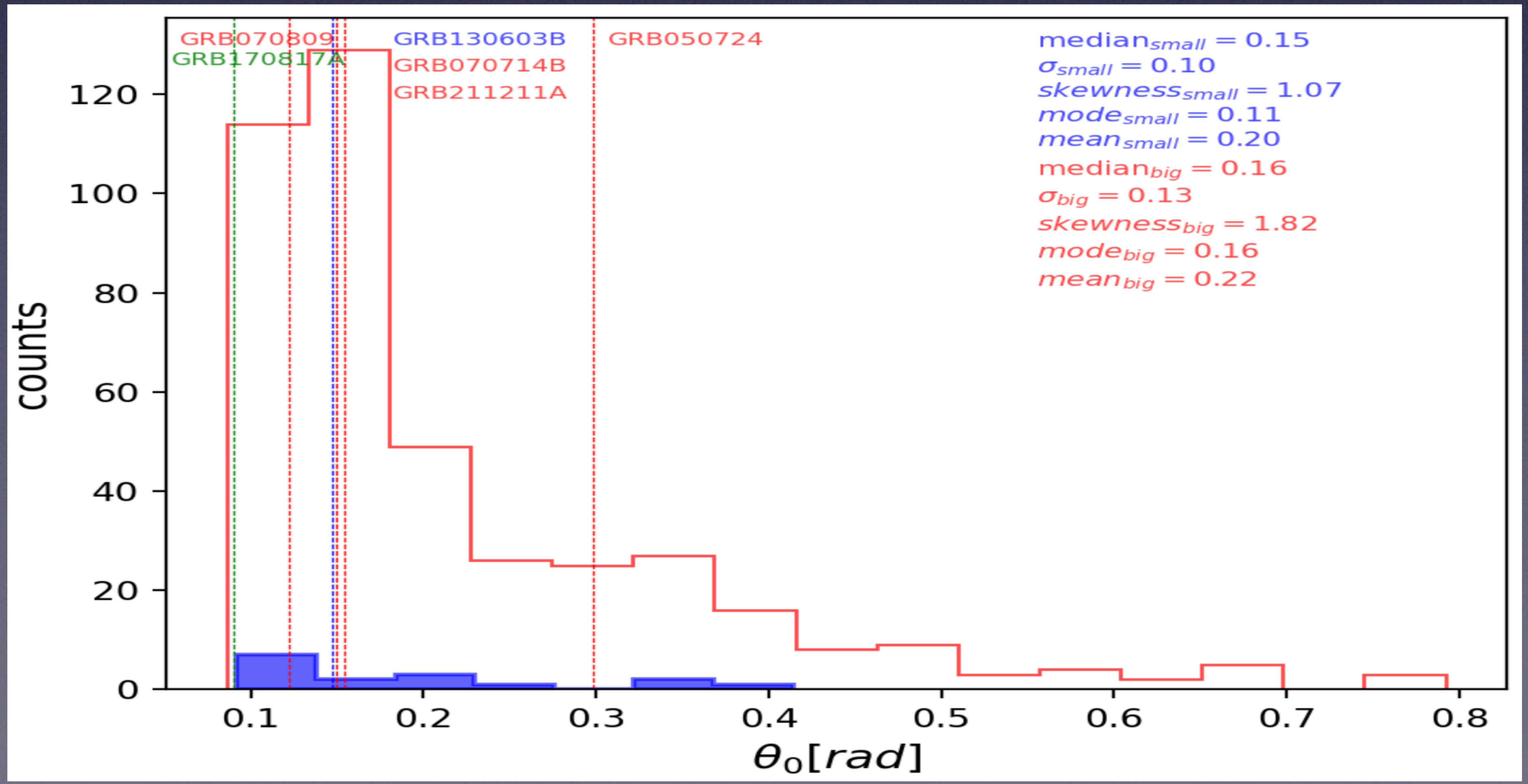




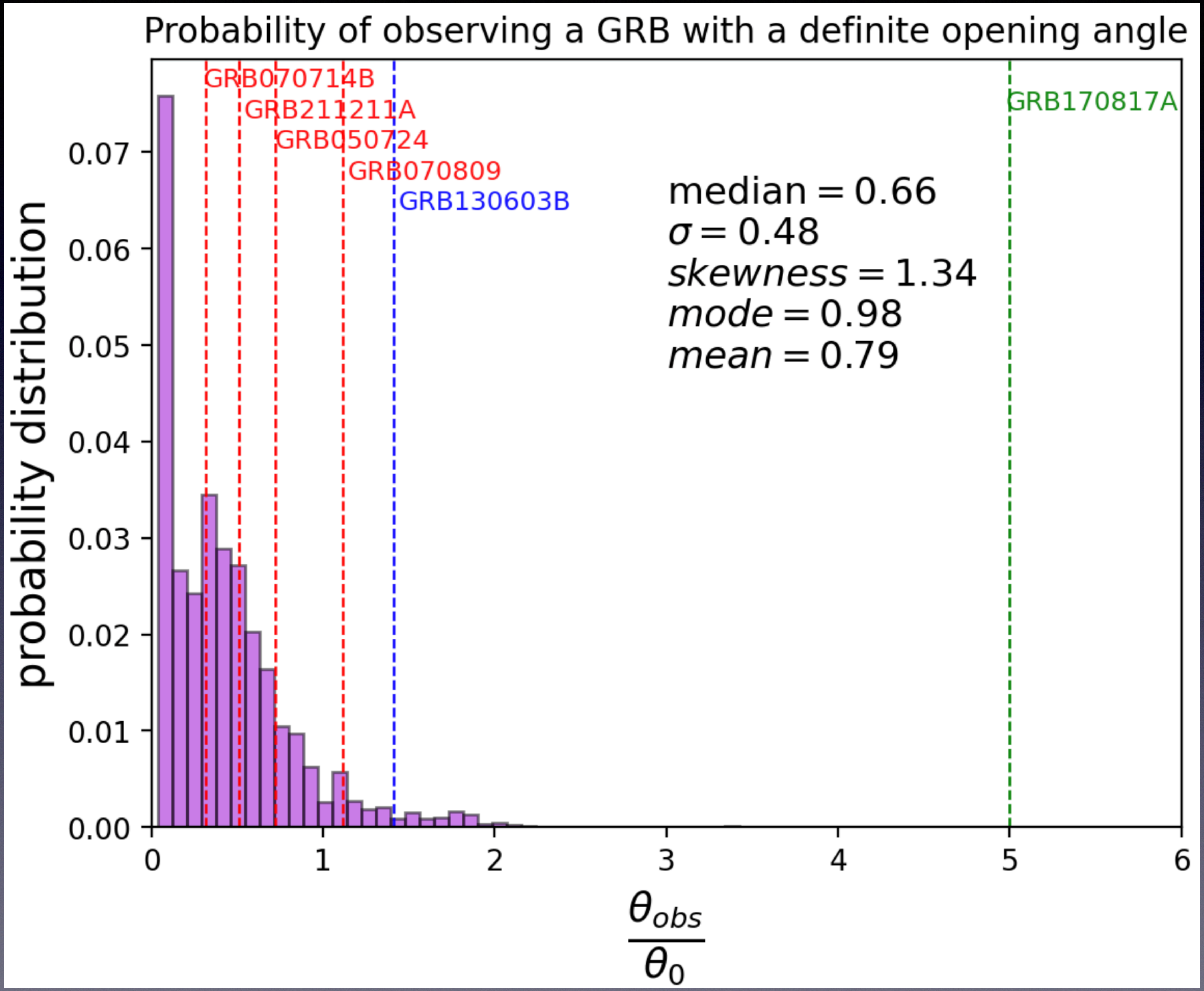
Explosion Lorentz factor



Jet opening angle



Afterglow phase: results



- Distribution of $\frac{\theta_{obs}}{\theta_0}$ weighted by the solid angle → distribution probability of observing a GRB with a jet opening angle equal to θ_0
- The highest probability to observe a GRB with a jet opening angle θ_0 is associated to on-axis GRBs

SSC model: afterglow theory

- Leptonic scenario
- Spherical standard fireball
- To find the SSC flux, we have to resolve (numerically)

Inverse Compton Jones's kernel (Jones 1968)

$$f_c(\gamma,\nu_i,\nu) = \frac{\nu}{4\gamma^2\nu_i}\left[2q\ln q + 1 + q - 2q^2 + \frac{1}{2}\frac{(\Gamma q)^2}{1+\Gamma q}(1-q)\right]$$

$$\Gamma = \frac{4\gamma h\nu_i}{m_e c^2}$$

$$q = \frac{\nu}{4\gamma^2\nu_i(1 - h\nu/\gamma m_e c^2)}$$

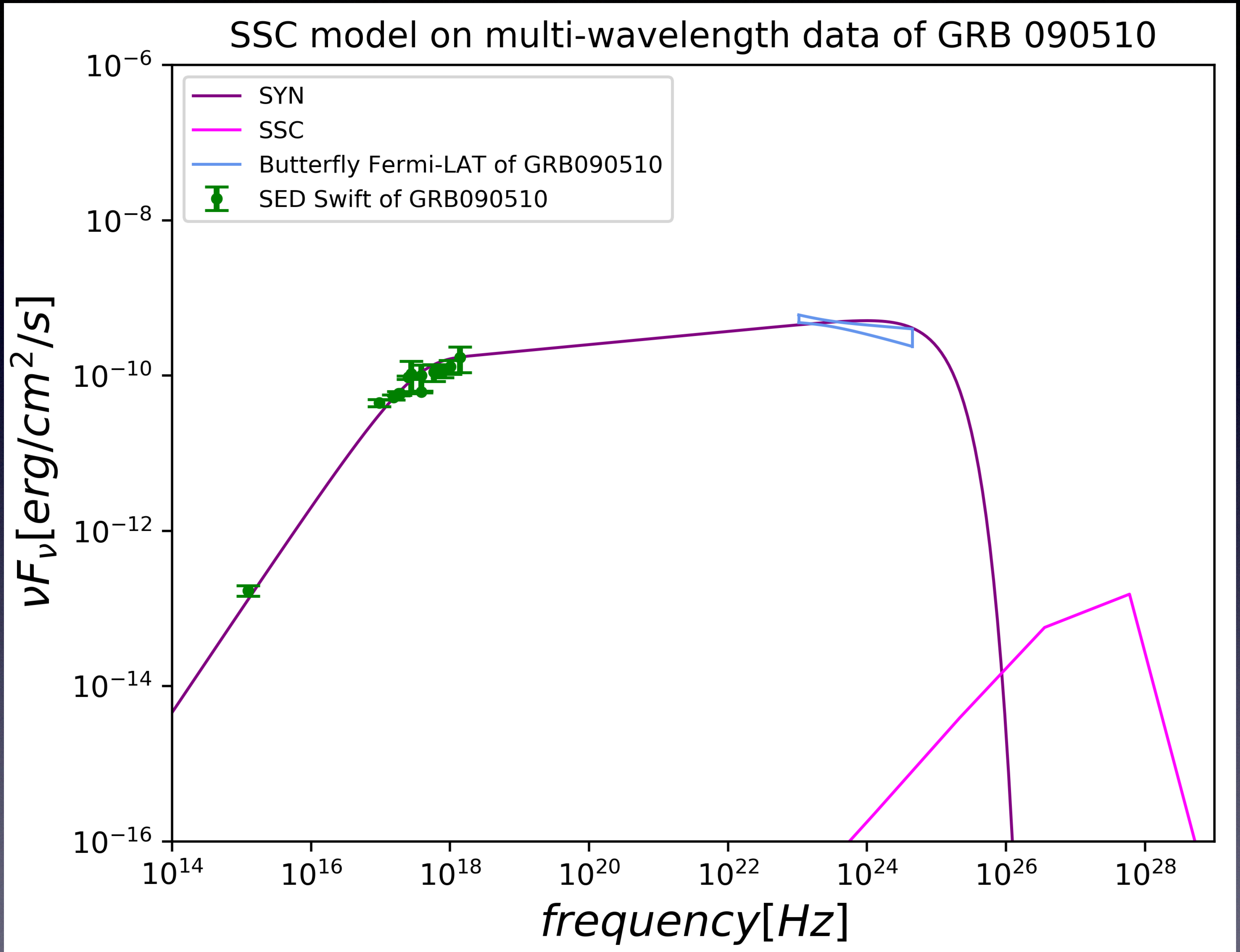
$$P_{ssc}(\nu,\gamma) = 8\pi r_e^2 ch \int_{\nu_i^{min}}^{\nu_i^{max}} f_c(\gamma,\nu_i,\nu)\frac{u_{syn}(\nu_i)}{h\nu_i}d\nu_i$$

$$N(\gamma) \propto \begin{cases} \gamma^{-p}, & \text{if} \quad \gamma_m < \gamma < \gamma_c \\ \gamma^{-p-1}, & \text{if} \quad \gamma_c < \gamma . \end{cases}$$

$$j_{ssc}(\nu) = \frac{1}{4\pi}\int_{\gamma_{min}}^{\gamma_{max}} n(\gamma)P_{ssc}(\nu,\gamma)d\gamma$$

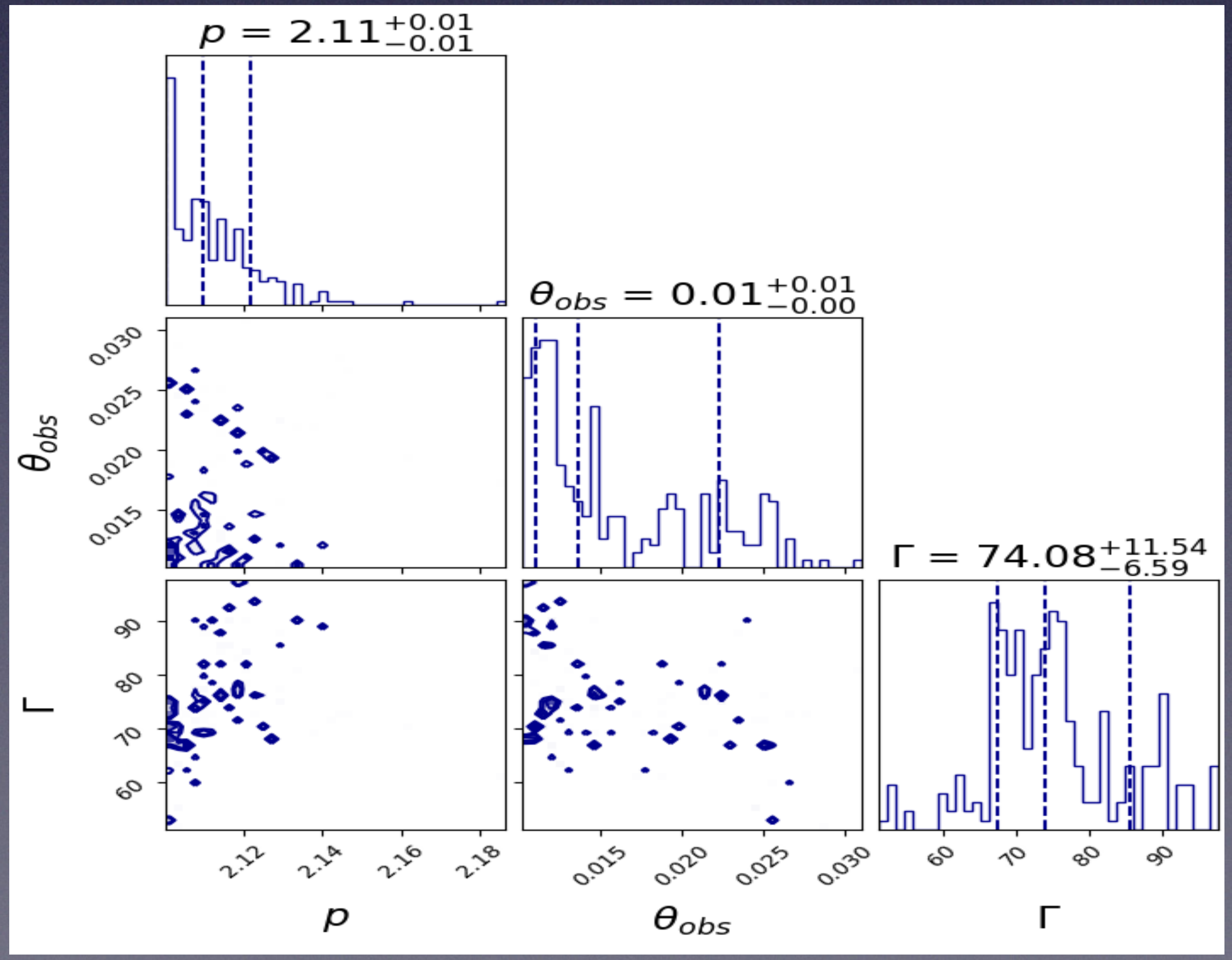
For details see Blumenthal & Gould 1970, Rybicki & Lightman 1979

SSC model: fit of GRB 090510



data taken from De Pasquale et al. 2010, doi: https://iopscience.iop.org/article/10.1088/2041-8205/709/2/L146

- GRB 090510 belongs to the small group in the non-collapsar classification
- GRB 090510: $T90 = 0.30 \pm 0.07$s, $z = 0.903 \pm 0.003$
- PL distribution of electrons
- Slow cooling approximation
- $\Gamma_{bulk} = 80$, $p = 2$, $\theta_{obs} = 0.01$ rad as a starting point for the fit



Summary and conclusions

- This analysis represents a comprehensive study of afterglow and prompt phase of typical Swift GRBs.
- Classification with t-SNE could provide an interesting instruments to distinguish between two classes but:
  - still depends on T90
  - not so useful for kilonova classification
- With JetFit we obtained a general description of our GRBs afterglow sample to use as a starting point for the construction of a simple SSC model.
- The “mean” SSC model that can describe the multi-wavelength SED of GRB 090510 could be used in future for simple parameters estimation of non-collapsar GRBs but…
  - the model does not account for important things as the evolution of bulk Lorentz factor, radius of the source and magnetic field
  - no gamma-gamma pair production

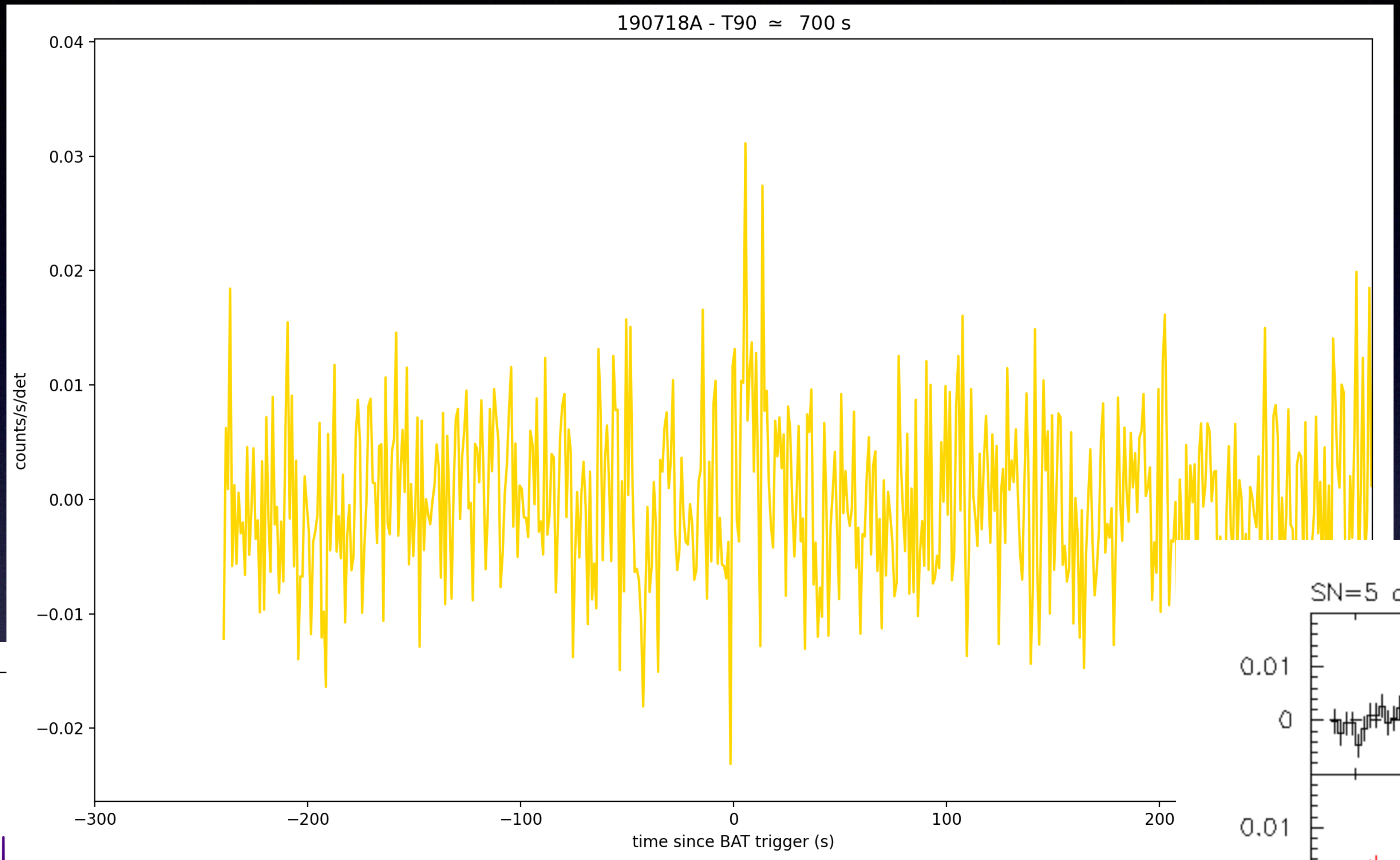
Back up slides

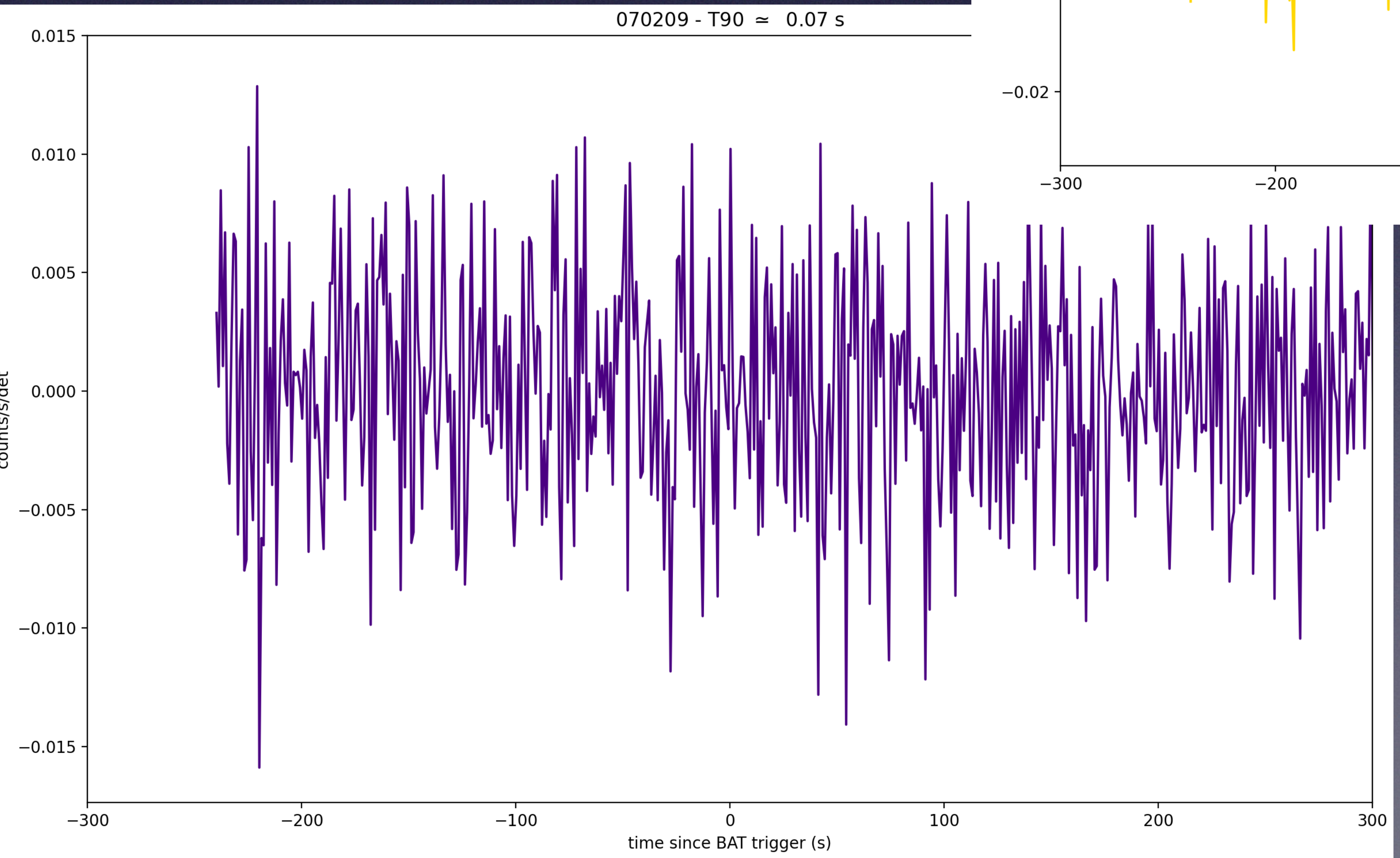
Prompt phase: analysis procedure

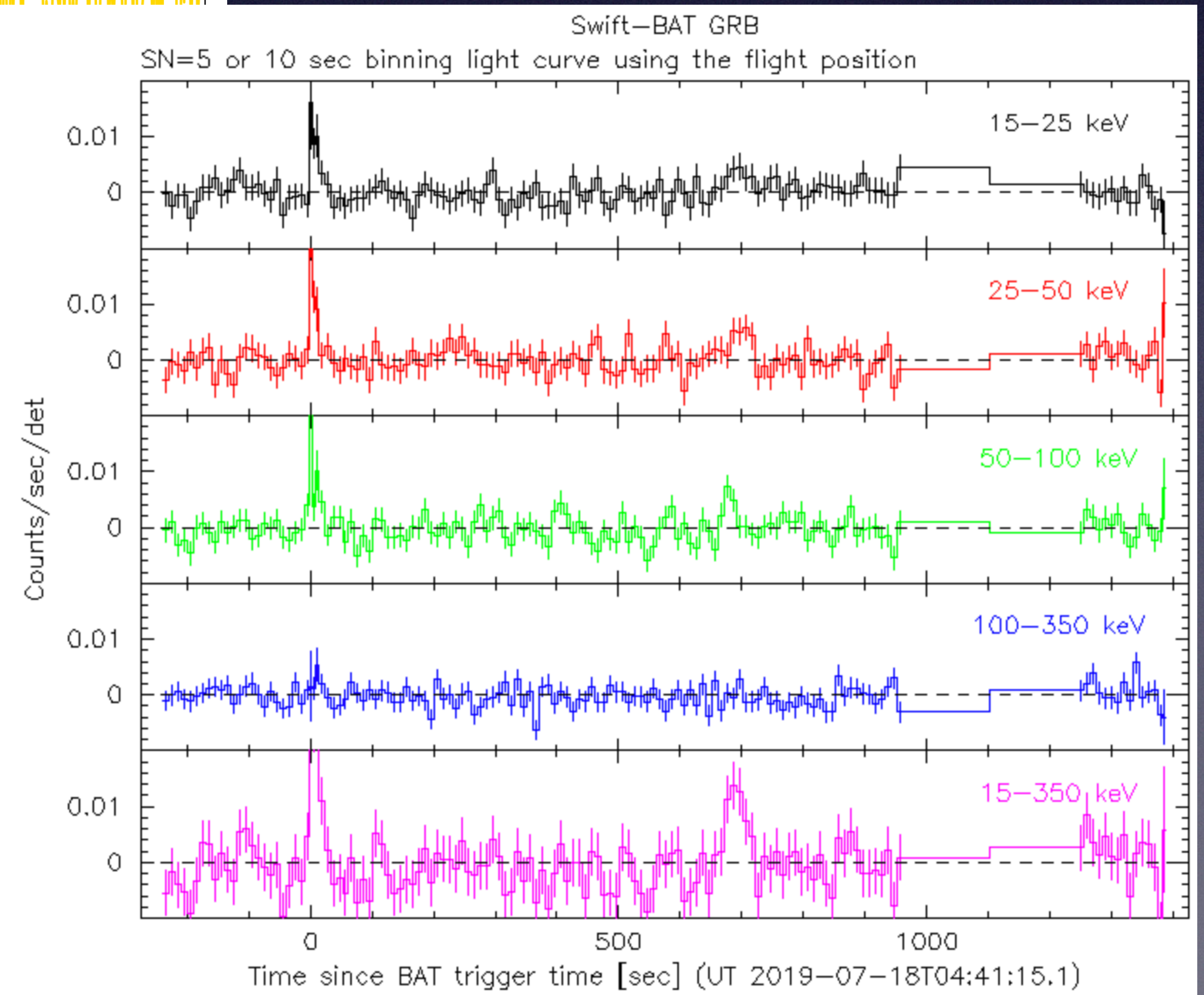
- Standardisation of the light curve → zero-pad of the data file done using the longest GRB in the sample
- select, for each GRB, the data points that are contained in the interval T90-10%(T90) and T90+10%(T90)
- normalise all the channels for the total integral of the flux
- select the channel with the lowest energy (15-25 keV) and apply the DTFT to the padded channel normalised by its total number of points
- get the modules of the Fourier transforms ending up with a final vector (one for each GRB)
- apply t-SNE to the modules of the DTFT and repeat this procedure for each GRB of the sample

Prompt phase: classification

- GRB070209, short but belongs to the biggest group; GRB190718A, long but belongs to the smallest group

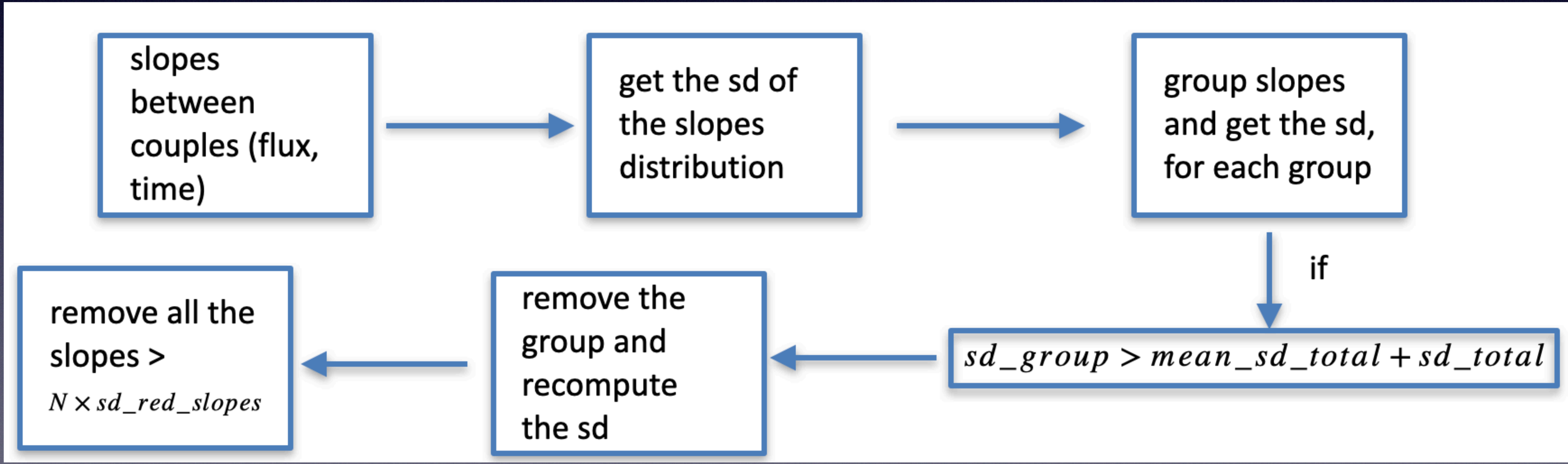






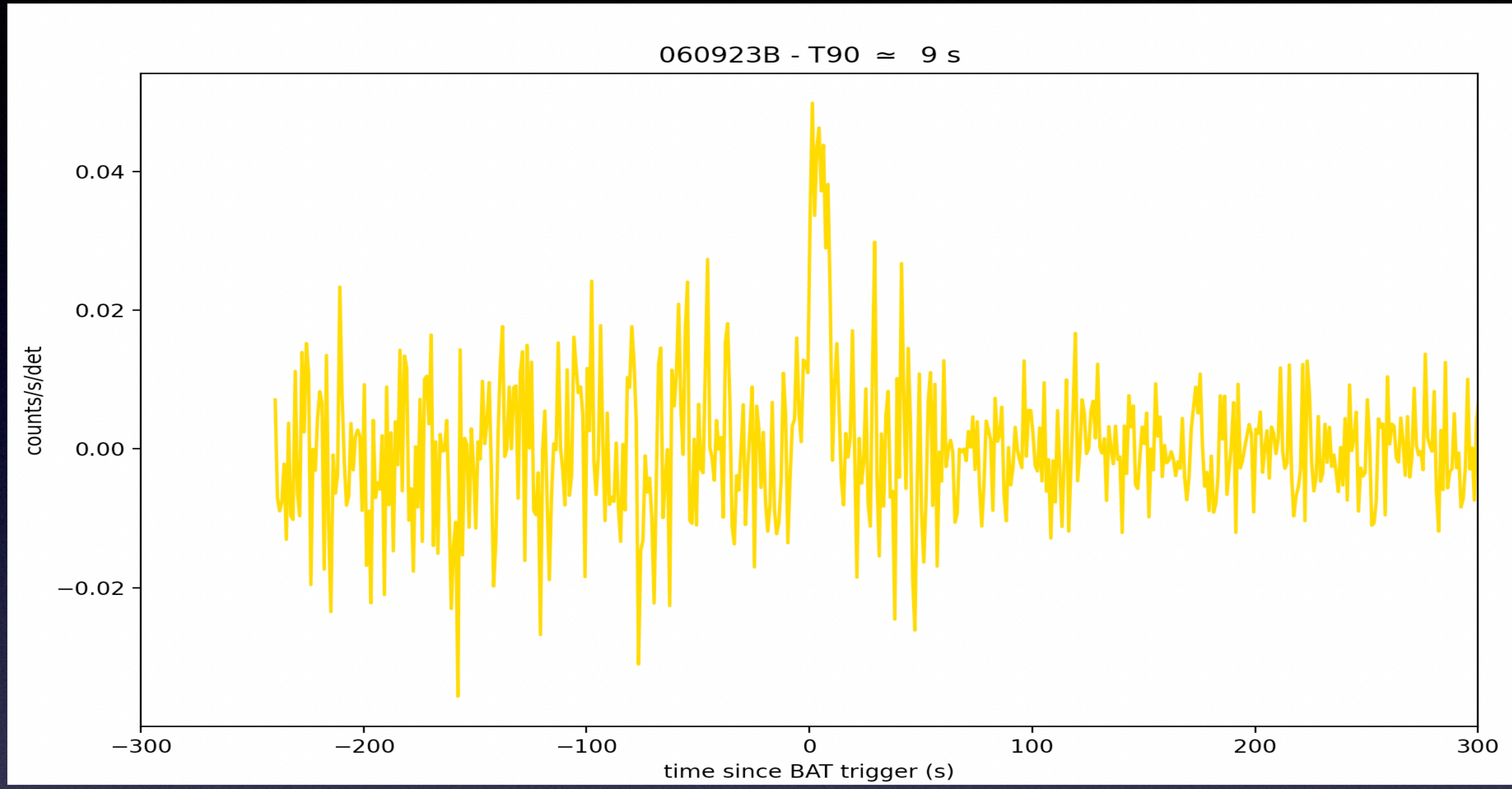
Afterglow phase: data preparation

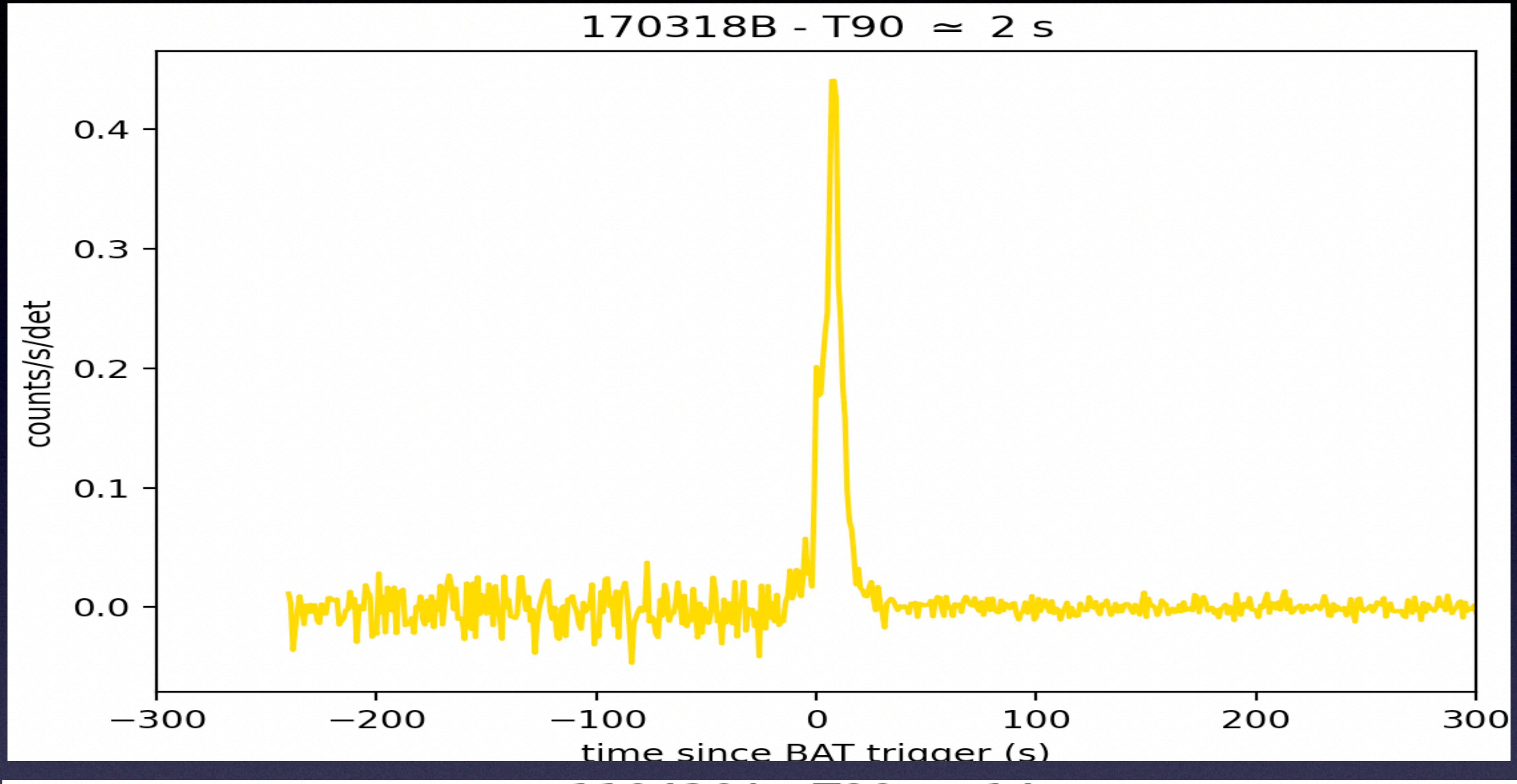
- Since the “boosted fireball” model does not describe the possible flaring activity that is present in the typical XRT light curve, we develop a new analysis procedure that tries to get rid of this data behaviour
- Re-bin time procedure to “smooth” the light curve and make the fit more effective

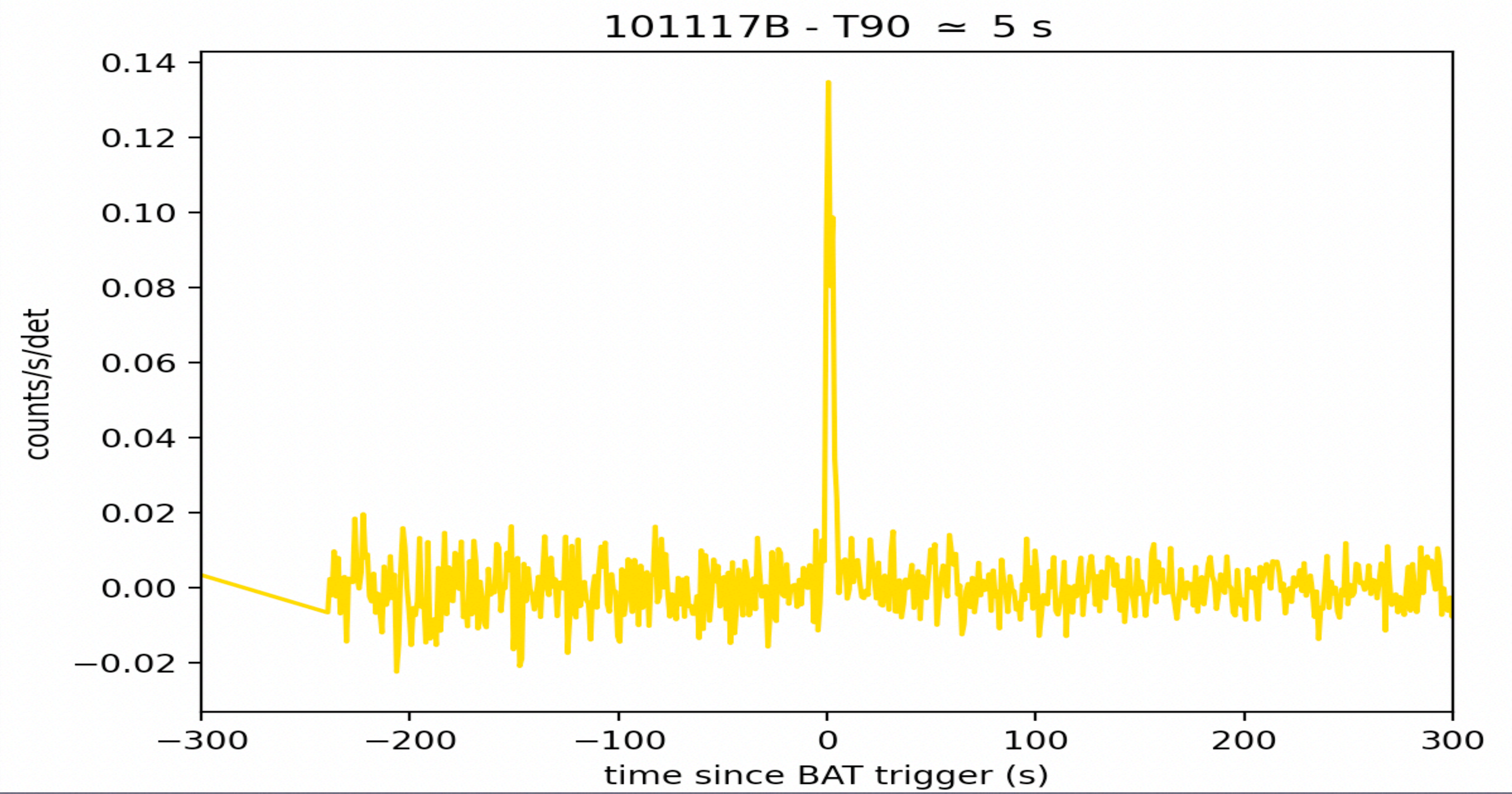


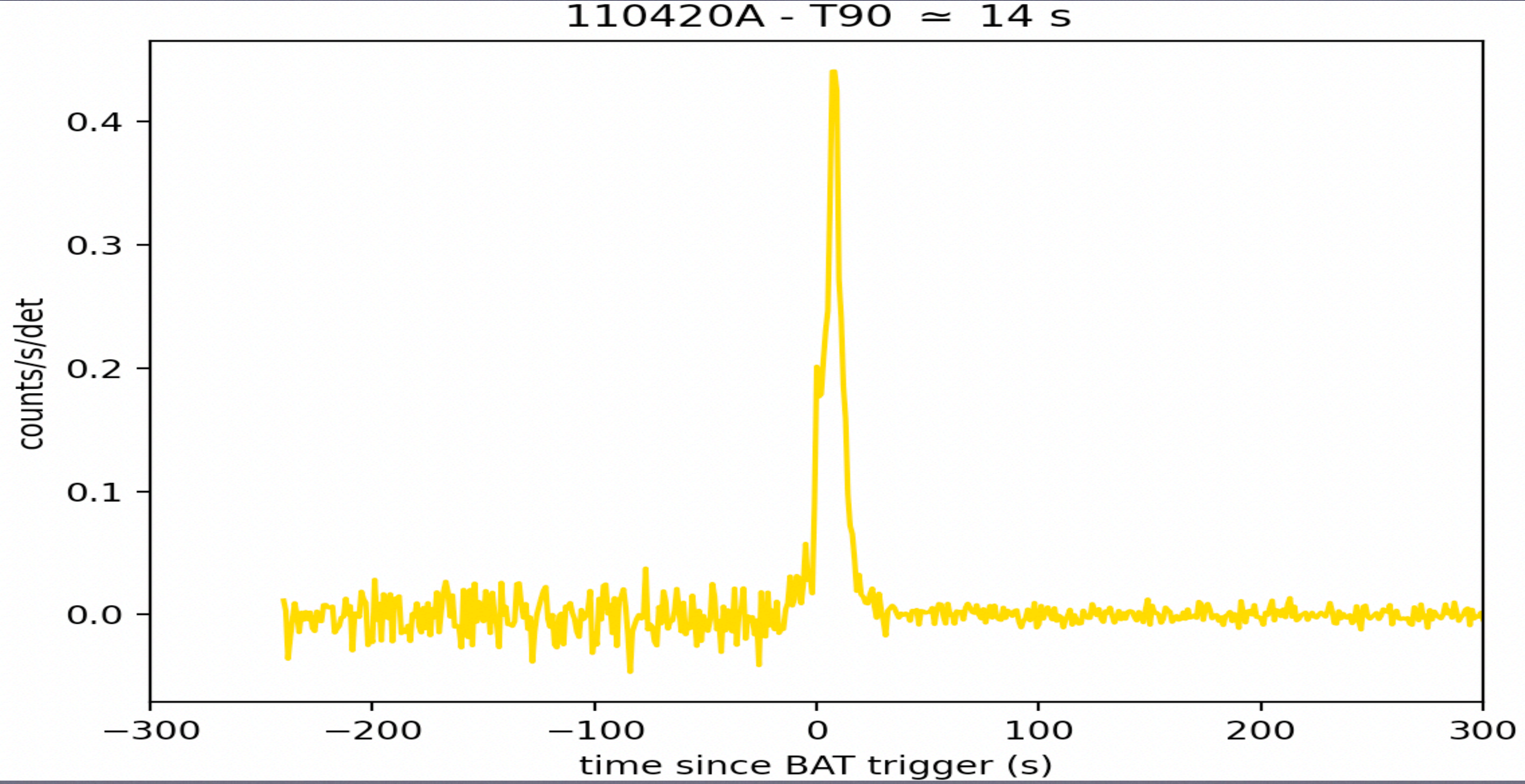
Prompt phase: classification

- Some of the long GRBs classified by t-SNE in the small group









Prompt phase: classification

- Some of the short GRBs classified by t-SNE in the big group