A Stochastic Approach To Reconstruct Gamma Ray Burst Light Curves

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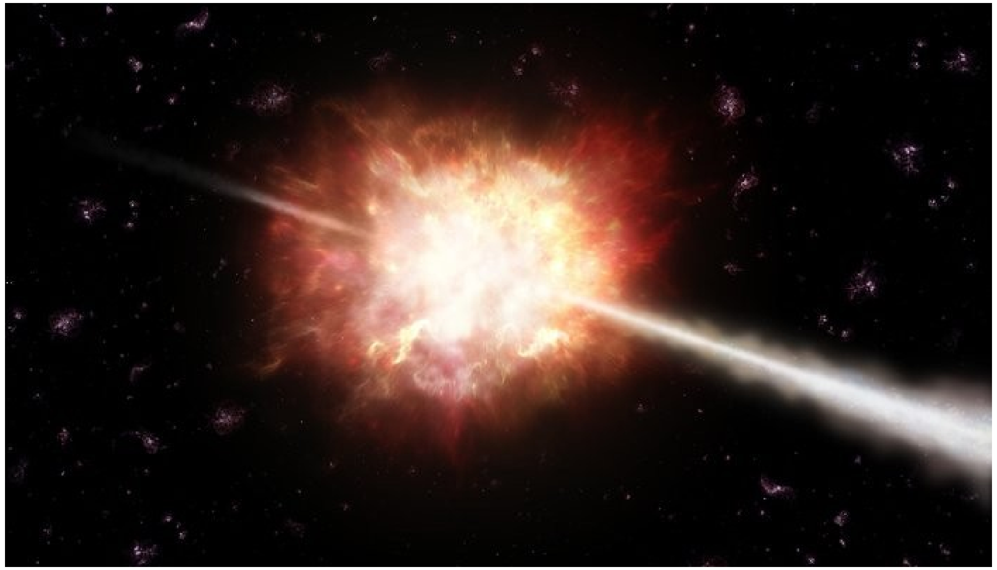
GAMMA RAY BURSTS (GRB) – INTRODUCTION

- Highly energetic outbursts of EM radiation
  - Occurring during supernovae explosion
  - During the merging of compact binary objects (NS-NS, NS-BH).

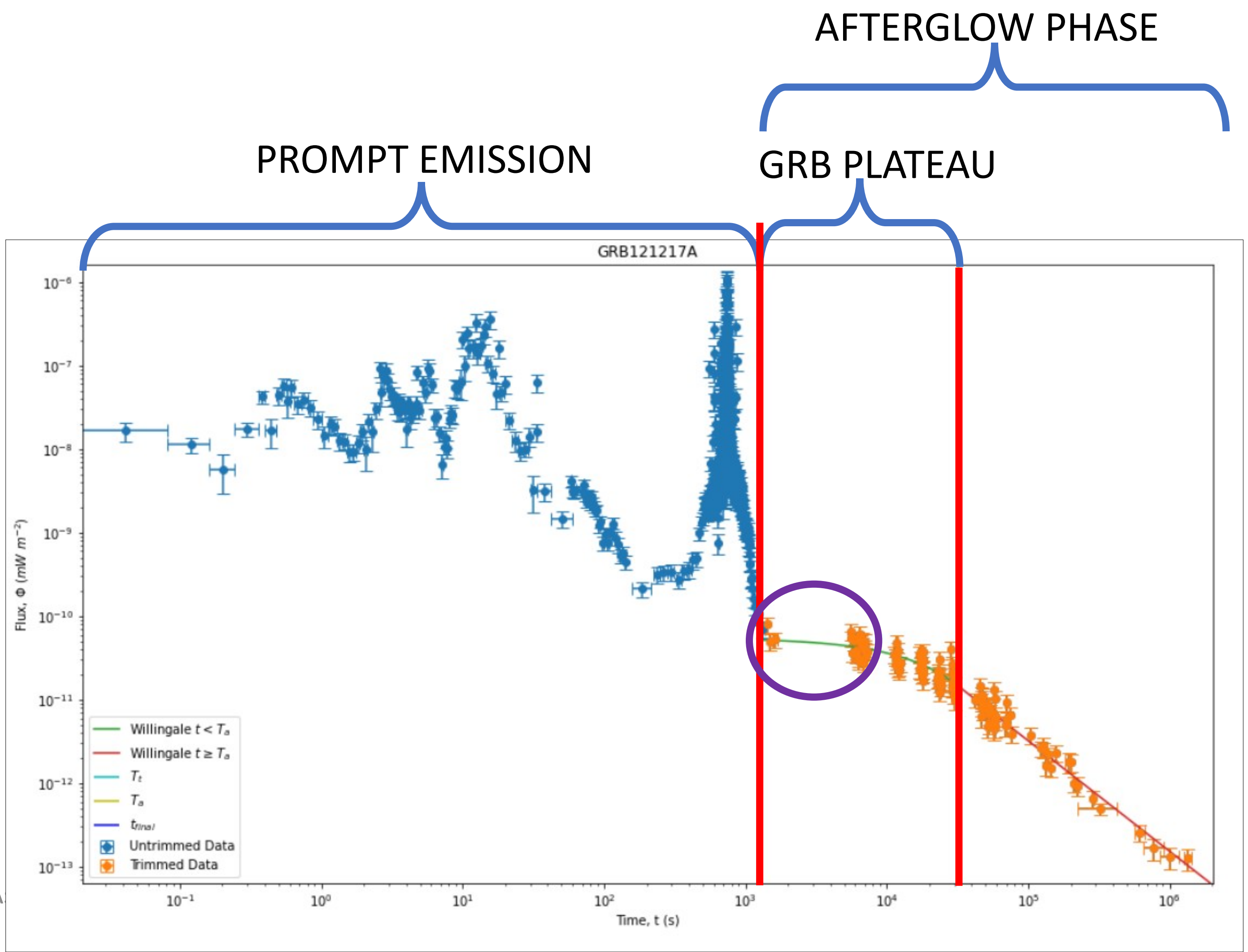
- One of the most luminous events in the universe.
- Observed at great distances (as far as redshift $z = 9.4$).
- Useful for cosmological applications.



Artistic depiction of a GRB.
Credit: ESO/A. Roquette

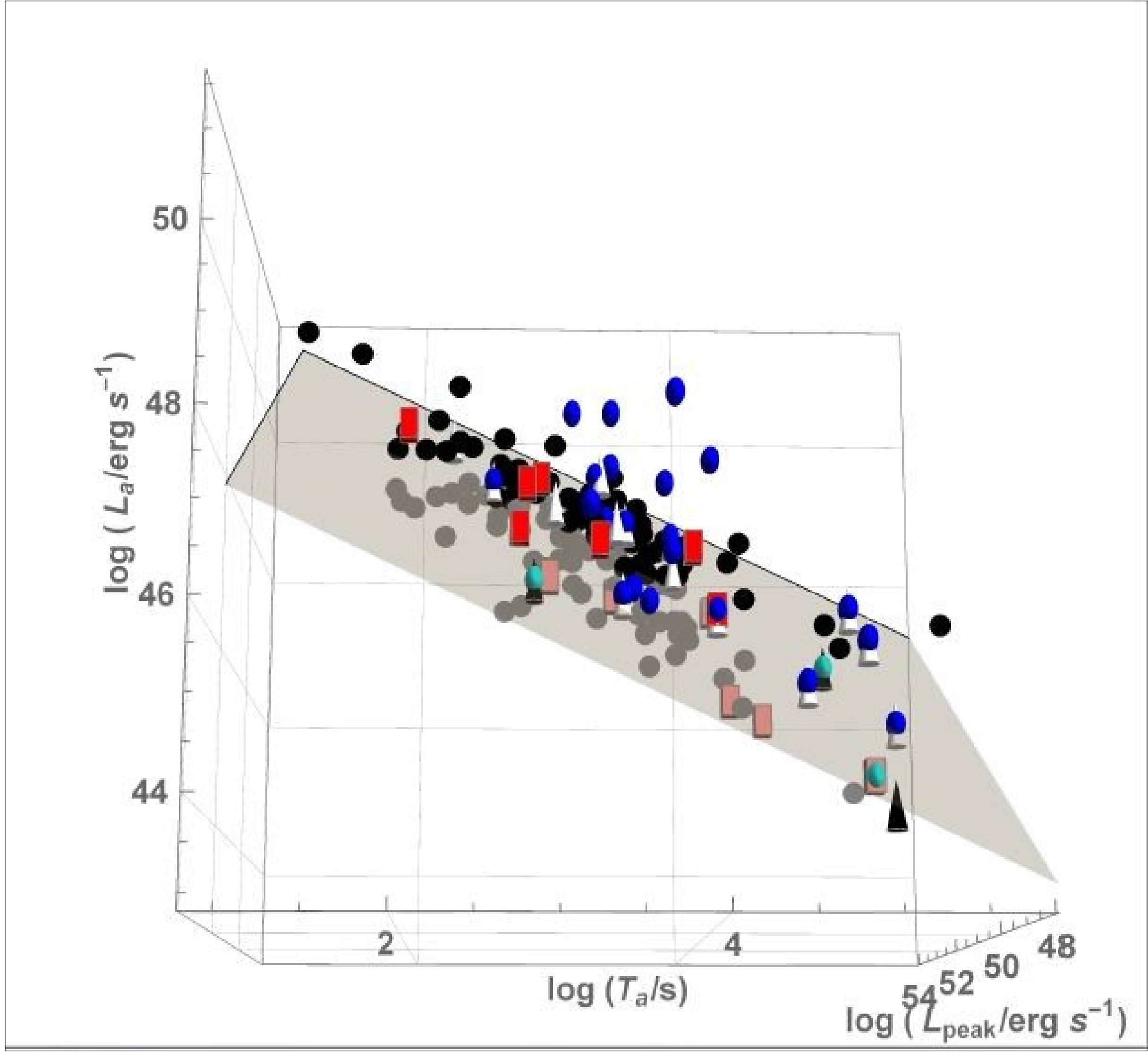
AIM & MOTIVATION

- We want to better study the plateau emission, flat part of GRB lightcurve.
- Plateau emission is generally explained via the dipole radiation of newly born neutron star.
- Thus, it is grounded in fundamental physics.
- However, such studies are hindered by temporal gaps in the plateau emission, which can arise due to:
  - Orbital periods of satellites
  - Lack of fast follow-up
  - Atmospheric turbulence
  - Intrumental errors.



AIM & MOTIVATION

- Thus, we want to reconstruct the lightcurve of GRBs in the plateau region.
- This can help us obtain better estimates on plateau parameters.
- These have been used to build relevant plateau parameter correlations, to be used as cosmological tools (The Dainotti relations).
- Also these estimates can be used for better machine learning models!

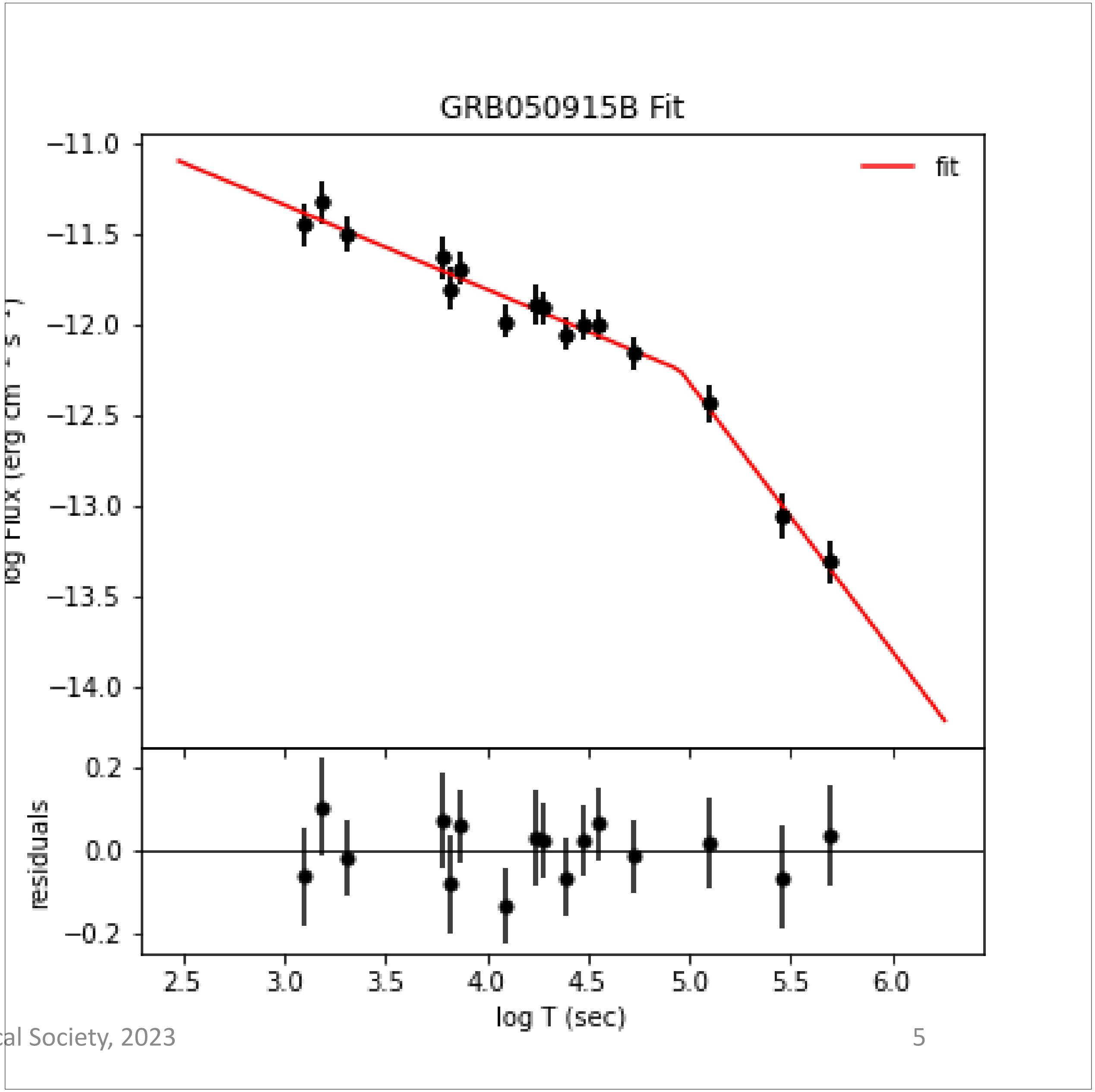


M. G. Dainotti, S. Postnikov, X. Hernandez, M. Ostrowski, 2016, ApJL, 825L, 20

HOW TO STUDY THE PLATEAU?

- GRB plateau emissions are typically studied using:
  - Broken powerlaw (BPL)
  - Smooth broken powerlaw (SBPL)
  - Willingale model (W07)

- A typical GRB afteglow lightcurve with plateau feature
- Red line is a BPL fit



OBJECTIVE

- Reconstruct the plateau emission of GRB LCs using two methods:

1. Model dependant reconstruction:
   a) Willingale reconstruction
   b) Broken powerlaw reconstruction

2. Model independent reconstruction:
   a) Gaussian Process

A brief overview of Willingale model, BPL model and Gaussian Process

THE WILLINGALE ET AL. 2007 (W07) MODEL

- The W07 phenomenological model can be described as:

$$f(t) = \begin{cases} F_i \exp\left(\alpha_i \left(1 - \frac{t}{T_i}\right)\right) \exp\left(-\frac{t_i}{t}\right) & \text{for } \; t < T_i \\ F_i \left(\frac{t}{T_i}\right)^{-\alpha_i} \exp\left(-\frac{t_i}{t}\right) & \text{for } \; t \geq T_i, \end{cases}$$

- $\mathbf{T_i}$ and $\mathbf{F_i}$ are the times and fluxes, respectively.
- Either at the end of the prompt ($\mathbf{T_p}$, $\mathbf{F_p}$).
- Or at the end of the **plateau** emission ($\mathbf{T_a}$, $\mathbf{F_a}$).
- The temporal decay index **after the plateau** is denoted by $\boldsymbol{\alpha_a}$ (shown generally as α_i).

THE BROKEN POWERLAW MODEL

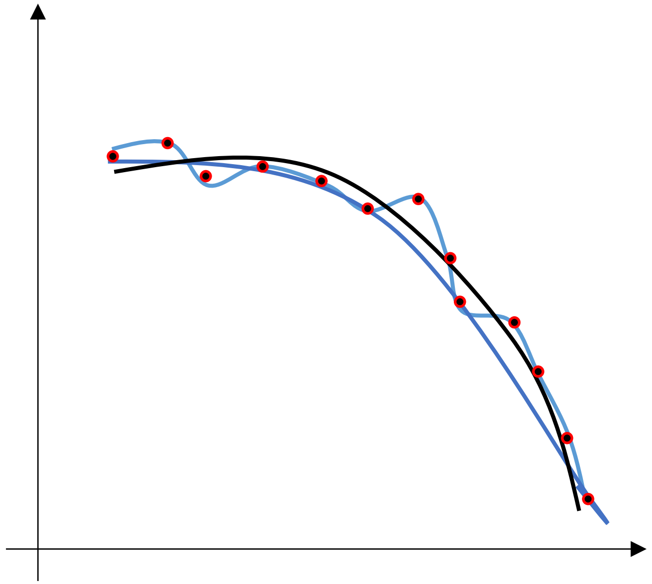
- The BPL model can be described as:

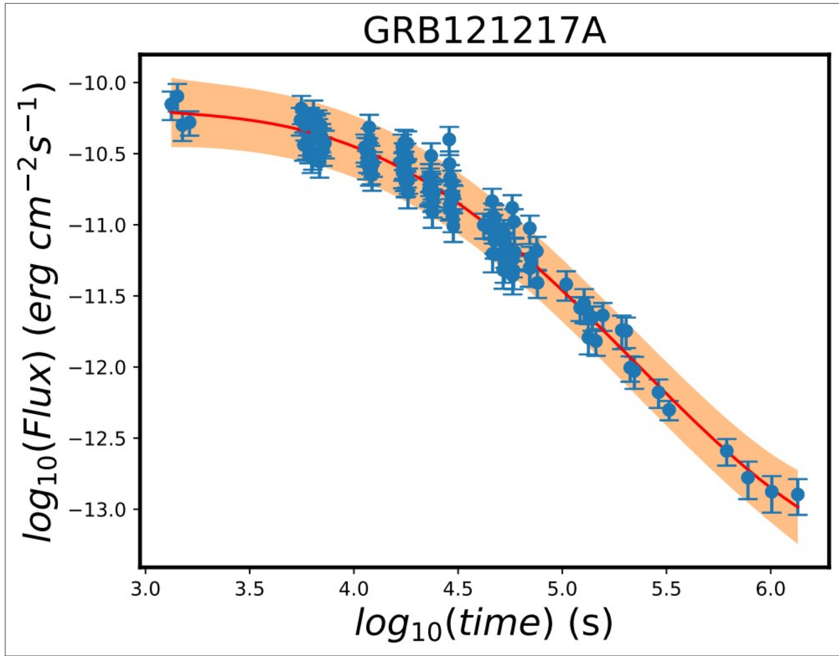
$$f(t) = \begin{cases} F_i \left(\frac{t}{T_i}\right)^{-\alpha_1} & \text{for } \; t < T_i \\ F_i \left(\frac{t}{T_i}\right)^{-\alpha_2} & \text{for } \; t \geq T_i, \end{cases}$$

- $\mathbf{T_i}$ and $\mathbf{F_i}$ are the times and fluxes at the end of the plateau.
- $\boldsymbol{\alpha_1}$ and $\boldsymbol{\alpha_2}$ are the slopes of the LC before and after the break.

THE GAUSSIAN PROCESS (GP)

- GP is a generic supervised learning method designed for regression problems.
- Based on the properties of Gaussian distributions
- GP fits multiple functions to a given set of data points.
- Then it assigns a weight to each of the function based on their fit statistics.
- This results in a confidence region within which GP predicts the results (orange band).
- We use the Radial Basis Function + white noise kernel for our analysis.





Methodology of LCR

MODEL DEPENDANT RECONSTRUCTION

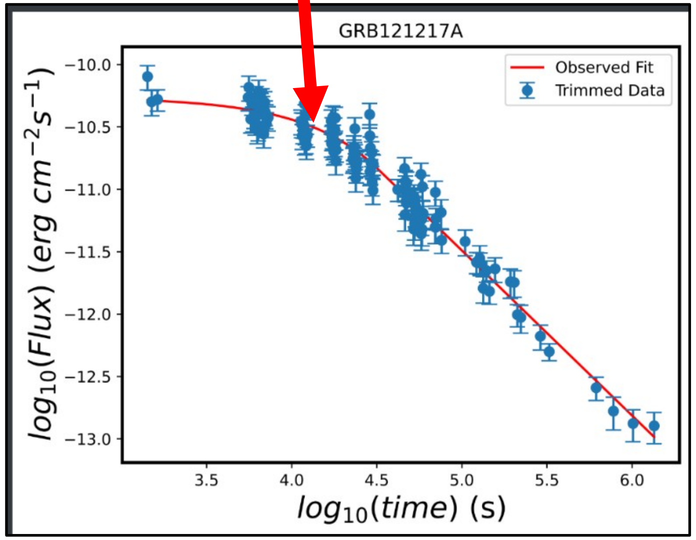
Fit W07/BPL model on original GRBs.

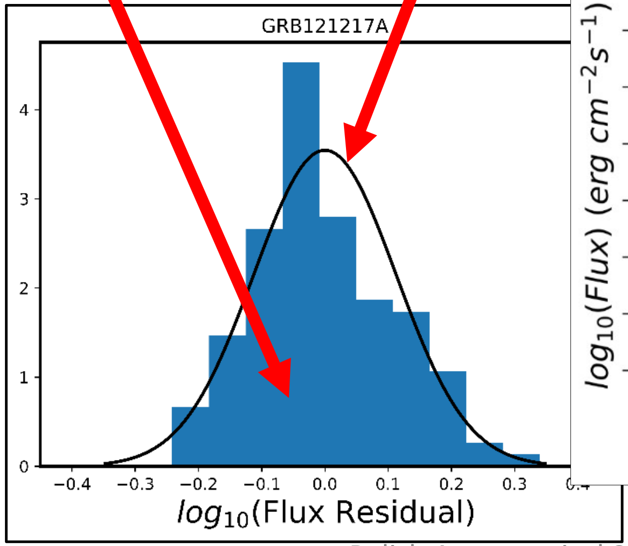
Produce Flux Residual Histogram "Original flux points – Flux on W07/BPL line"

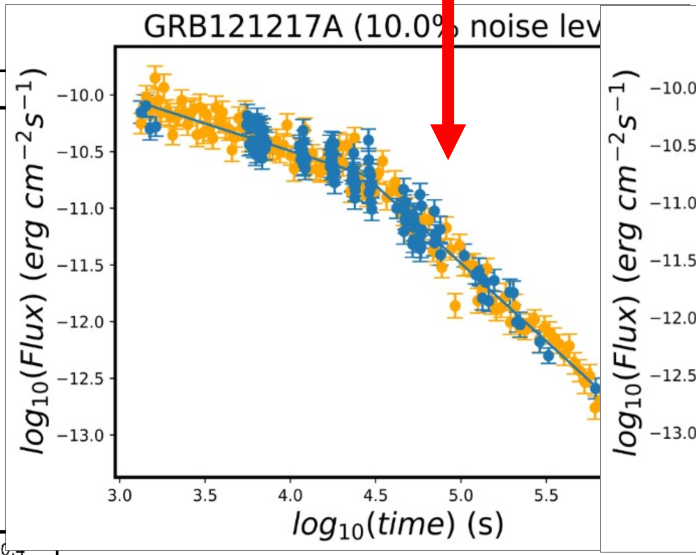
Fit Gaussian Distribution on the Flux Residual Histogram.

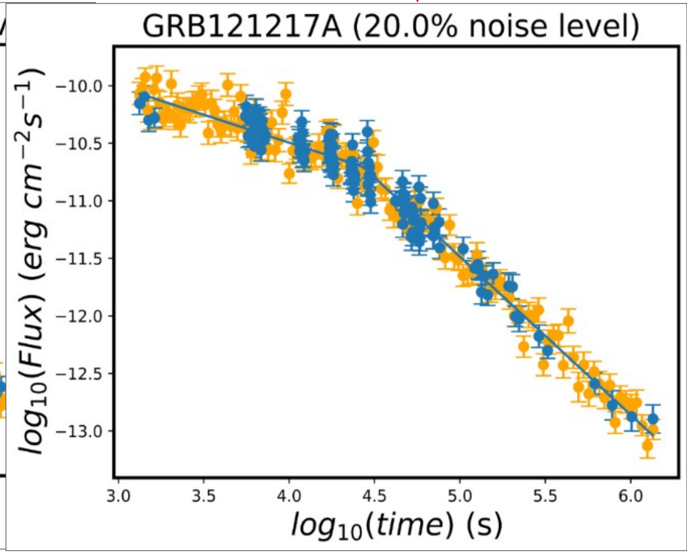
To reconstruct the LC draw new flux points from the W07/BPL fit.

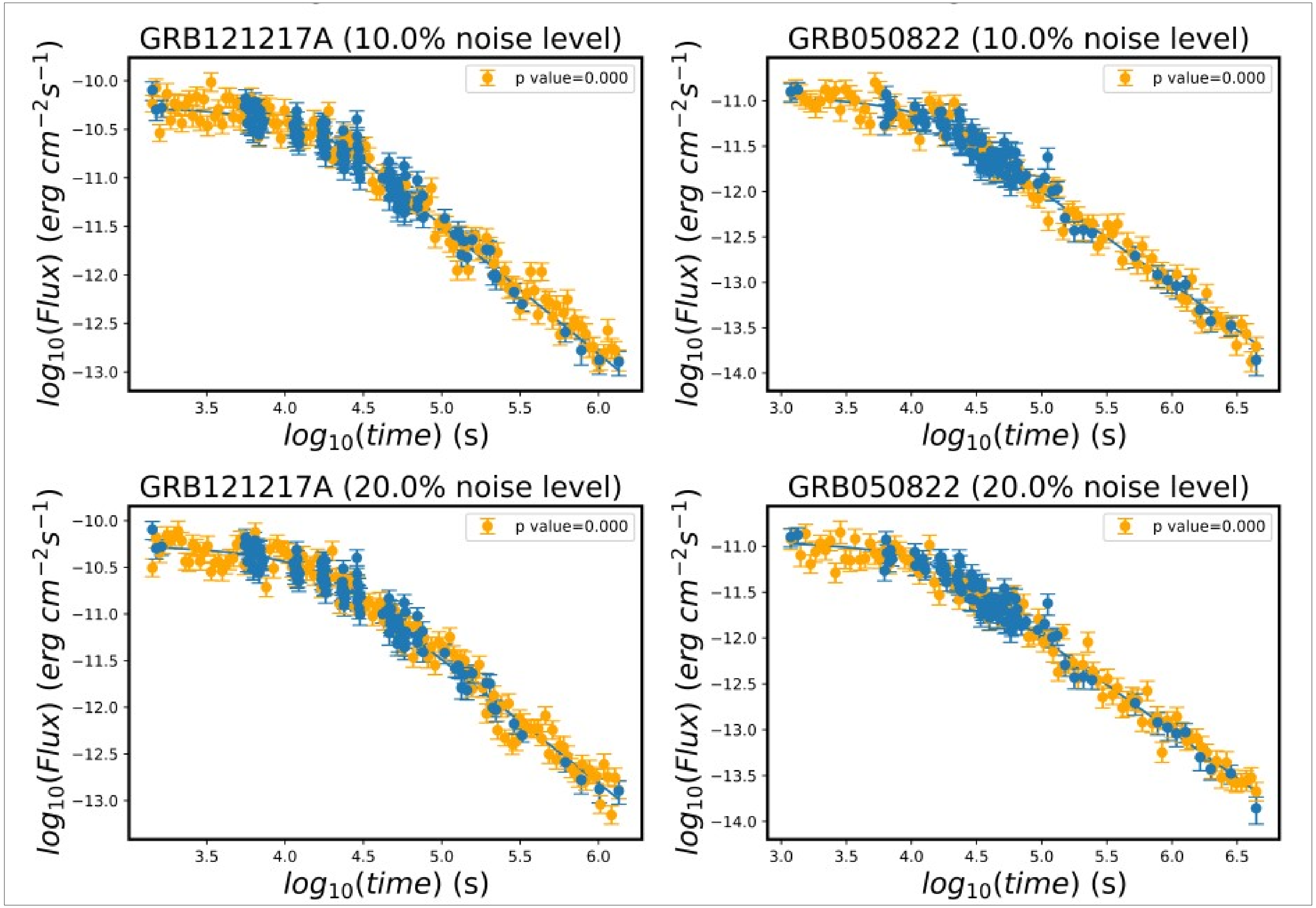
Apply a noise value to the new flux point drawn from the flux residual gaussian fit. The noise can be increased by 10 or 20%











Adding noise:

$$\log_{10} F_t^{\text{recon}} = \log_{10} f(t) + (1+n) \times RV_{\mathcal{N}}$$

n = noise parameter
(0.1, 0.2 and so on)

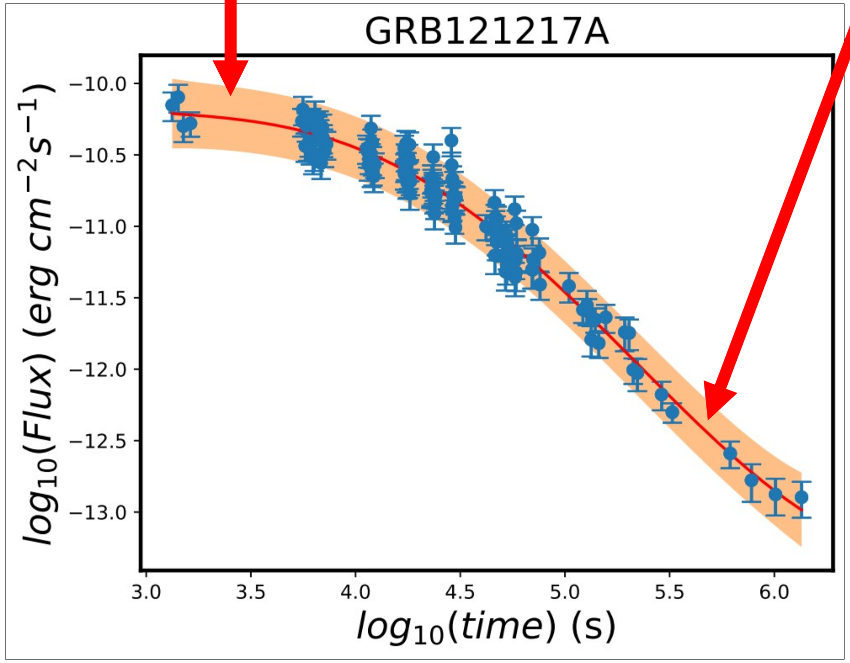
MODEL INDEPENDANT RECONSTRUCTION

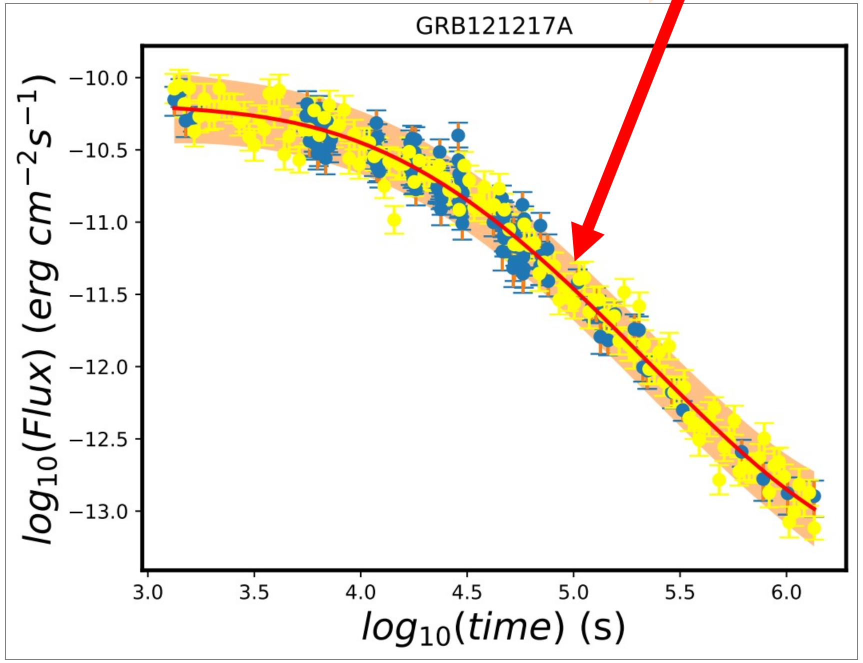
Fit the GP function (orange band)

Derive the best GP fit (red line)

Perform 100 MCMC simulation of the reconstructed LC

Pick one flux value at random at equal time intervals





METRICS FOR RESULTS

- Refit the W07 and BPL model on the reconstructed GRB
- Check how the individual parameters have changed.
  - For W07: T_a, F_a, α_a
  - For BPL: T_a, F_a, α_1, α_2
- Compare the **error fractions (EF)** of the parameters before and after reconstruction.
- The error fractions are defined as (for W07):

$$EF_{\log(Ta)} = \left| \frac{\Delta \log(T_a)}{\log(T_a)} \right|$$

$$EF_{\log(F_a)} = \left| \frac{\Delta \log(F_a)}{\log(F_a)} \right|$$

$$EF_{\alpha_a} = \left| \frac{\Delta \alpha_a}{\alpha_a} \right|$$

RESULTS FOR W07 RECONSTRUCTION

Table showing error fractions before and after reconstruction.
Last three columns show the relative percentage decrease in the W07 parameter error fractions. As we can see, a majority of them show a decrease.

GRB ID	$EF_{\log_{10}(T_i)}$	$EF_{\log_{10}(F_i)}$	EF_{α_i}	$EF_{\log_{10}(T_i)}$ RC	$EF_{\log_{10}(F_i)}$ RC	EF_{α_i} RC	$\%_{\log_{10}(T_i)}$	$\%_{\log_{10}(F_i)}$	$\%_{\alpha_i}$
				10% noise					
050712	0.019	0.005	0.044	0.014	0.004	0.027	-26.67	-24.96	-38.04
050318	0.011	0.006	0.046	0.008	0.004	0.033	-22.91	-24.05	-28.62
050416A	0.024	0.005	0.018	0.016	0.003	0.012	-31.24	-33.54	-34.85
050607	0.021	0.005	0.044	0.016	0.004	0.027	-22.62	-22.79	-39.18
050713A	0.01	0.003	0.018	0.008	0.002	0.011	-16.21	-14.31	-36.35
050822	0.011	0.003	0.026	0.007	0.002	0.015	-31.06	-35.46	-43.07
050824	0.025	0.006	0.094	0.015	0.003	0.056	-40.7	-38.45	-40.27
050826	0.029	0.019	0.131	0.026	0.016	0.196	-9.54	-15.21	49.99
050915B	0.036	0.008	0.115	0.025	0.005	0.068	-29.03	-34.25	-40.92
051016A	0.033	0.006	0.051	0.021	0.004	0.024	-36.11	-28.49	-53
051109A	0.012	0.005	0.016	0.006	0.002	0.01	-51.32	-58.89	-33.99
051221A	0.02	0.005	0.051	0.015	0.004	0.033	-27.39	-28.33	-34.6
060105	0.004	0.001	0.007	0.003	0.001	0.003	-16.2	-14.1	-54.34
060108	0.024	0.006	0.071	0.018	0.004	0.047	-26.39	-30.58	-33.59
060109	0.014	0.005	0.057	0.008	0.003	0.025	-40.63	-45.09	-56.2
060124	0.008	0.004	0.012	0.006	0.003	0.007	-28.27	-29.34	-42.7
060218	0.028	0.014	0.082	0.014	0.005	0.065	-50.59	-63	-20.77
060306	0.012	0.003	0.024	0.009	0.002	0.017	-22.76	-28.7	-29.23
060418	0.018	0.005	0.03	0.01	0.003	0.01	-43.68	-32.48	-66.37
060421	0.041	0.01	0.087	0.022	0.006	0.039	-46.03	-40.58	-55.27

RESULTS FOR BPL RECONSTRUCTION

Table here showing error fractions before and after reconstruction, for 10% noise level. Last four columns show the relative percentage decrease in the BPL parameter error fractions. Similar to the W07 reconstruction, a majority of them show a decrease.

GRB ID	$EF_{\log_{10}(T_i)}$	$EF_{\log_{10}(F_i)}$	EF_{α_1}	EF_{α_2}	$EF_{\log_{10}(T_i)}$ RC	$EF_{\log_{10}(F_i)}$ RC	EF_{α_1} RC	EF_{α_2} RC	$\%_{\log_{10}(T_i)}$	$\%_{\log_{10}(F_i)}$	$\%_{\alpha_1}$	$\%_{\alpha_2}$
				10% noise								
GRB050712	0.031	0.031	0.155	0.056	0.022	0.008	0.158	0.033	-30.6	-28.48	2.15	-39.97
GRB050318	0.011	-0.007	0.075	0.047	0.009	0.005	0.058	0.038	-20.09	-23.11	-23.14	-19.47
GRB050416A	0.038	-0.01	0.078	0.023	0.029	0.007	0.056	0.013	-23.52	-22.5	-28.03	-40.54
GRB050607	0.036	-0.011	0.15	0.053	0.03	0.01	0.166	0.03	-16.39	-11.78	10.48	-43.15
GRB050713A	0.015	-0.006	0.043	0.019	0.012	0.004	0.039	0.013	-18.58	-18.89	-9.77	-34.12
GRB050822	0.012	-0.004	0.223	0.024	0.01	0.004	0.164	0.014	-14.58	-14.2	-26.57	-42.26
GRB050824	0.026	-0.006	0.276	0.105	0.015	0.004	0.223	0.057	-40.25	-30.63	-19.2	-46.1
GRB050826	0.008	-0.004	0.328	0.064	0.005	0.002	0.226	0.039	-33.14	-35.02	-30.9	-38.46
GRB050915B	0.021	-0.006	0.085	0.13	0.012	0.004	0.057	0.069	-43.28	-33.53	-32.4	-46.8
GRB051016A	0.089	-0.025	0.327	0.048	0.047	0.013	0.2	0.024	-47.27	-48.27	-38.99	-49.86
GRB051109A	0.011	-0.005	0.136	0.015	0.009	0.003	0.049	0.01	-21.7	-24.17	-63.81	-31.43
GRB051221A	0.021	-0.007	0.082	0.058	0.016	0.006	0.067	0.038	-23.99	-23.82	-18.86	-34.93
GRB060105	0.007	-0.002	0.011	0.011	0.003	0.002	0.011	0.003	-51.9	-34.29	8.85	-68.73
GRB060108	0.026	-0.008	0.147	0.075	0.019	0.006	0.113	0.048	-26.83	-25.54	-23.34	-36.11
GRB060109	0.01	-0.003	0.347	0.047	0.007	0.003	0.271	0.022	-26.18	-9.85	-22.03	-54.26
GRB060124	0.014	-0.008	0.034	0.019	0.011	0.007	0.027	0.01	-17.7	-16.08	-21.58	-47.95
GRB060218	0.013	-0.005	0.582	0.064	0.01	0.004	0.811	0.042	-22.2	-21.99	39.27	-34.22
GRB060306	0.075	-0.026	0.395	0.024	0.018	0.006	0.107	0.018	-76.3	-78.27	-72.97	-24.73

RESULTS FOR GP RECONSTRUCTION

Here we show the results from the GP reconstructed LC refitted with W07 and BPL.

GRB ID	$EF_{\log_{10}(T_i)}$	$EF_{\log_{10}(F_i)}$	EF_{α_i}	$EF_{\log_{10}(T_i)}$ RC	$EF_{\log_{10}(F_i)}$ RC	EF_{α_i} RC	$\%_{\log_{10}(T_i)}$	$\%_{\log_{10}(F_i)}$	$\%_{\alpha_i}$
				GP (W07)					
050712	0.019	0.005	0.044	0.012	0.003	0.028	-34.01	-31.09	-36.97
050318	0.011	0.006	0.046	0.008	0.004	0.031	-26.66	-27.68	-32.19
050416A	0.024	0.005	0.018	0.016	0.003	0.011	-32.44	-34.04	-38.46
050607	0.021	0.005	0.044	0.017	0.004	0.028	-18.58	-19.62	-36.98
050713A	0.01	0.003	0.018	0.008	0.002	0.011	-18.81	-15.29	-35.28
050822	0.011	0.003	0.026	0.008	0.002	0.015	-29.98	-33.14	-43.56
050824	0.025	0.006	0.094	0.015	0.003	0.056	-39.2	-37.19	-40.83
050826	0.029	0.019	0.131	0.02	0.012	0.156	-32.22	-36.64	19.63
050915B	0.036	0.008	0.115	0.024	0.005	0.068	-34.36	-37.46	-41.29
		0.006	0.051	0.024	0.005	0.025	-25.01	-17.02	-51.08
		0.005	0.016	0.007	0.002	0.009	-41.5	-49.53	-40.98
		0.005	0.051	0.013	0.004	0.033	-33.79	-32.68	-34.76
		0.001	0.007	0.003	0.001	0.003	-23.04	-20.31	-52.2
		0.006	0.071	0.018	0.004	0.047	-23.29	-28.84	-33.57
		0.005	0.057	0.008	0.003	0.025	-40.9	-44.23	-55.74
		0.004	0.012	0.005	0.003	0.007	-34.32	-34.36	-45.13
		0.014	0.082	0.013	0.005	0.062	-54.56	-65.62	-24.38
		0.003	0.024	0.01	0.002	0.018	-19.95	-26.66	-26.92
		0.005	0.03	0.009	0.003	0.01	-48.49	-37.4	-67.46
		0.01	0.087	0.032	0.008	0.046	-21.65	-20.75	-46.81

GRB ID	$EF_{\log_{10}(T_i)}$	$EF_{\log_{10}(F_i)}$	EF_{α_1}	EF_{α_2}	$EF_{\log_{10}(T_i)}$ RC	$EF_{\log_{10}(F_i)}$ RC	EF_{α_1} RC	EF_{α_2} RC	$\%_{\log_{10}(T_i)}$	$\%_{\log_{10}(F_i)}$	$\%_{\alpha_1}$	$\%_{\alpha_2}$
						GP (BPL)						
050712	0.031	-0.011	0.155	0.056	0.02	0.008	0.114	0.035	-36.96	-31.16	-26.56	-36.7
050318	0.011	-0.007	0.075	0.047	0.009	0.005	0.057	0.037	-21.44	-24.84	-25.07	-22.08
050416A	0.038	-0.01	0.078	0.023	0.03	0.008	0.054	0.013	-22.17	-20.55	-30.49	-41.1
050607	0.036	-0.011	0.15	0.053	0.033	0.01	0.265	0.03	-9.03	-6.18	76.48	-44.07
050713A	0.015	-0.006	0.043	0.019	0.012	0.005	0.038	0.013	-19.09	-17.92	-10.82	-33.81
050822	0.012	-0.004	0.223	0.024	0.011	0.004	0.126	0.014	-13.12	-10.96	-43.37	-40.74
050824	0.026	-0.006	0.276	0.105	0.016	0.004	0.257	0.056	-36.37	-29.54	-6.94	-47.22
050826	0.008	-0.004	0.328	0.064	0.009	0.004	0.387	0.068	18.19	10	18.16	6.79
050915B	0.021	-0.006	0.085	0.13	0.017	0.005	0.068	0.085	-19.3	-12.5	-19.55	-34.08
051016A	0.089	-0.025	0.327	0.048	0.055	0.016	0.123	0.029	-38.03	-36.85	-62.33	-38.73
051109A	0.011	-0.005	0.136	0.015	0.009	0.004	0.043	0.01	-17.46	-18.84	-67.92	-33.14
051221A	0.021	-0.007	0.082	0.058	0.015	0.005	0.062	0.038	-29.47	-27.45	-24.21	-34.37
060105	0.007	-0.002	0.011	0.011	0.004	0.002	0.012	0.004	-47.21	-29.55	16.34	-66.73
060108	0.026	-0.008	0.147	0.075	0.02	0.006	0.13	0.05	-21.43	-19.39	-11.85	-33.82
060109	0.01	-0.003	0.347	0.047	0.008	0.003	0.249	0.022	-22.93	-1	-28.48	-52.56
060124	0.014	-0.008	0.034	0.019	0.012	0.007	0.026	0.009	-15.57	-14.13	-24.78	-49.47
060218	0.013	-0.005	0.582	0.064	0.011	0.004	0.551	0.045	-16.69	-15.08	-5.28	-29.79
060306	0.075	-0.026	0.395	0.024	0.017	0.005	0.092	0.019	-77.62	-79.69	-76.75	-20.34
060418	0.066	-0.034	0.11	0.029	0.031	0.015	0.068	0.01	-52.96	-55.91	-38.76	-64.8
060421	0.092	-0.038	0.557	0.082	0.053	0.02	0.177	0.051	-43.01	-46.22	-68.23	-37.96

We see a decrease in the error fractions here as well!

OVERALL RESULTS

Taking an average over 218 reconstructed LCs, we see an overall decrease in the error fraction of all the parameters.

Reconstruction process	$\%^{avg}_{\log_{10}(T_a)}$	$\%^{avg}_{\log_{10}(F_a)}$	$\%^{avg}_{\alpha_a}$	$\%^{avg}_{\alpha_1}$	$\%^{avg}_{\alpha_2}$
W07 reconstruction (10%)	-33.33	-35.03	-43.32	-	-
W07 reconstruction (20%)	-29.49	-31.24	-40.57	-	-
BPL reconstruction (10%)	-33.3	-30.78	-	-14.76	-43.9
BPL reconstruction (20%)	-29.88	-27.2	-	-1.7	-41.1
Gaussian process (W07)	-24.9	-27.9	-41.5	-	-
Gaussian process (BPL)	-15.02	-11.91	-	-25.10	-35.92

CONCLUSIONS

Here we have proposed a relatively simple reconstruction technique for GRB LCs. This can lead to severe advantages such as:

- Discovery of plateau features in GRB LCs, which otherwise may remain undetected.
- Better classification of GRBs according to their morphology with increased accuracy.
- Better GRB correlation using plateau emission, leading to reduced scatter on cosmological parameters.

With the GP reconstruction, this method can be generalized to different LC morphologies (with flares and bumps).

All the reconstructed LCs and the new parameters are freely available along with the publication.

Scan for the paper

Thank you!

Contact