Maria Giovanna Dainotti

Reducing the uncertainties by 35% for cosmological applications

国立天文台
NAOJ
National Astronomical Observatory of Japan

Bari, INFN, 23th of September 2025

Monthly Notices
of the Royal Astronomical Society

JOURNAL ARTICLE ACCEPTED MANUSCRIPT

An optical gamma-ray burst catalogue with measured redshift PART I: Data release of 535 gamma-ray bursts and colour evolution

M G Dainotti, B De Simone, R F Mohideen Malik, V Pasumarti, D Levine, N Saha, B Gendre, D Kido, A M Watson, R L Becerra, S Belkin, S Desai, A C C do E S Pedreira, U Das, L Li, S R Oates, S B Cenko, A Pozanenko, A Volnova, Y-D Hu, A J Castro-Tirado, N B Orange, T J Moriya, N Fraija, Y Niino, E Rinaldi, N R Butler, J d J G González, A S Kutyrev, W H Lee, X Prochaska, E Ramirez-Ruiz, M Richer, M H Siegel, K Misra, A Rossi, C Lopresti, U Quadri, L Strabla, N Ruocco, S Leonini, M Conti, P Rosi, L M T Ramirez, S Zola, I Jindal, R Kumar, L Chan, M Fuentes, G Lambiase, K K Kalinowski, W Jamal

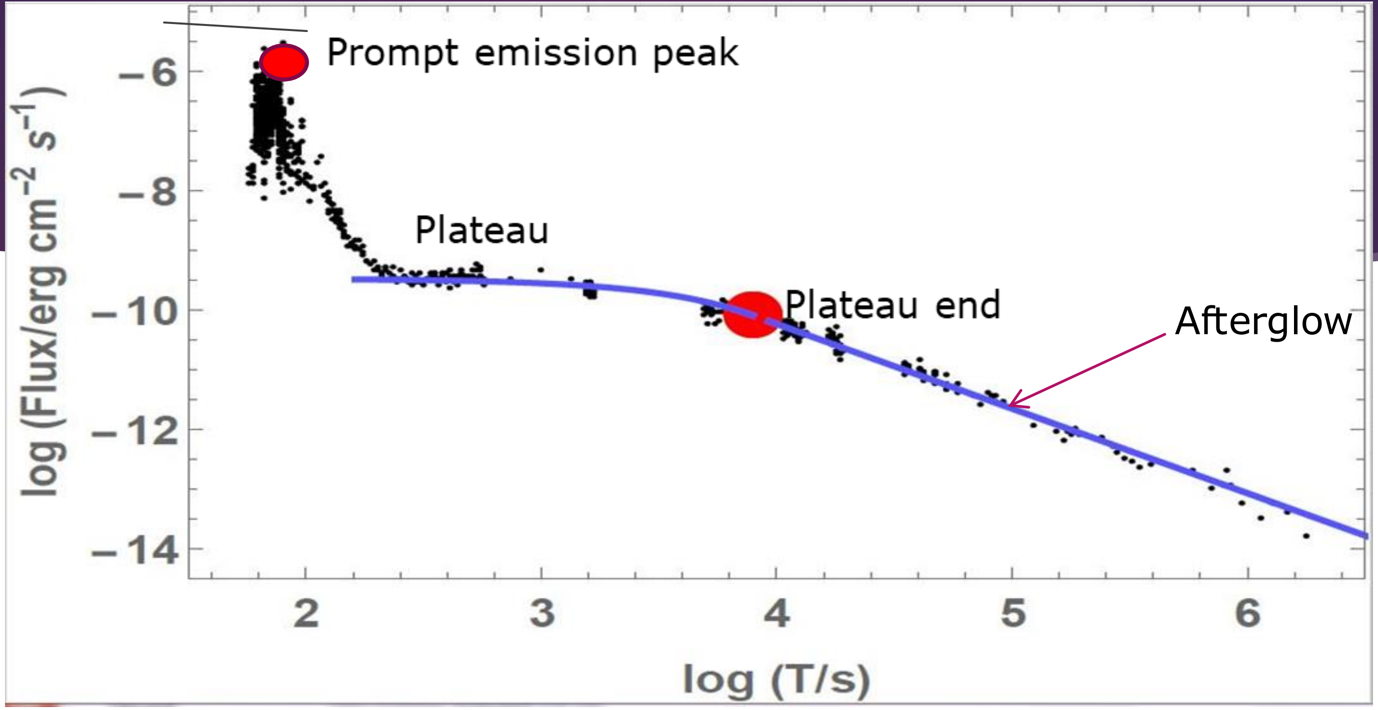
Author Notes

Monthly Notices of the Royal Astronomical Society, stae1484,
https://doi.org/10.1093/mnras/stae1484
Published: 21 June 2024

Outline

- Introduction to GRBs and why we need this catalogue
- The importance for GRB cosmology and the correlations
- Steps involved in compiling the catalogue
- Colour evolution analysis
- Rescaling
- Introducing the GRBLC webtool

GRB phenomenology



Important features of a well-sampled GRB light curve observed by Burst Alert Telescope+ X-Ray Telescope +Swift (2004-ongoing). The blue line is the phenomenological Willingale model (R. Willingale et al. 2007)

- Flashes of high energy photons in the sky (typical duration is few seconds).
- Cosmological origin accepted (furthest GRBs observed z ~ 9.4).
- Extremely energetic and short: the greatest amount of energy released in a short time.
- X-rays, optical and radio observed after days/months (afterglows), distinct from the main γ-rays.

Why are GRBs potential cosmological tools?

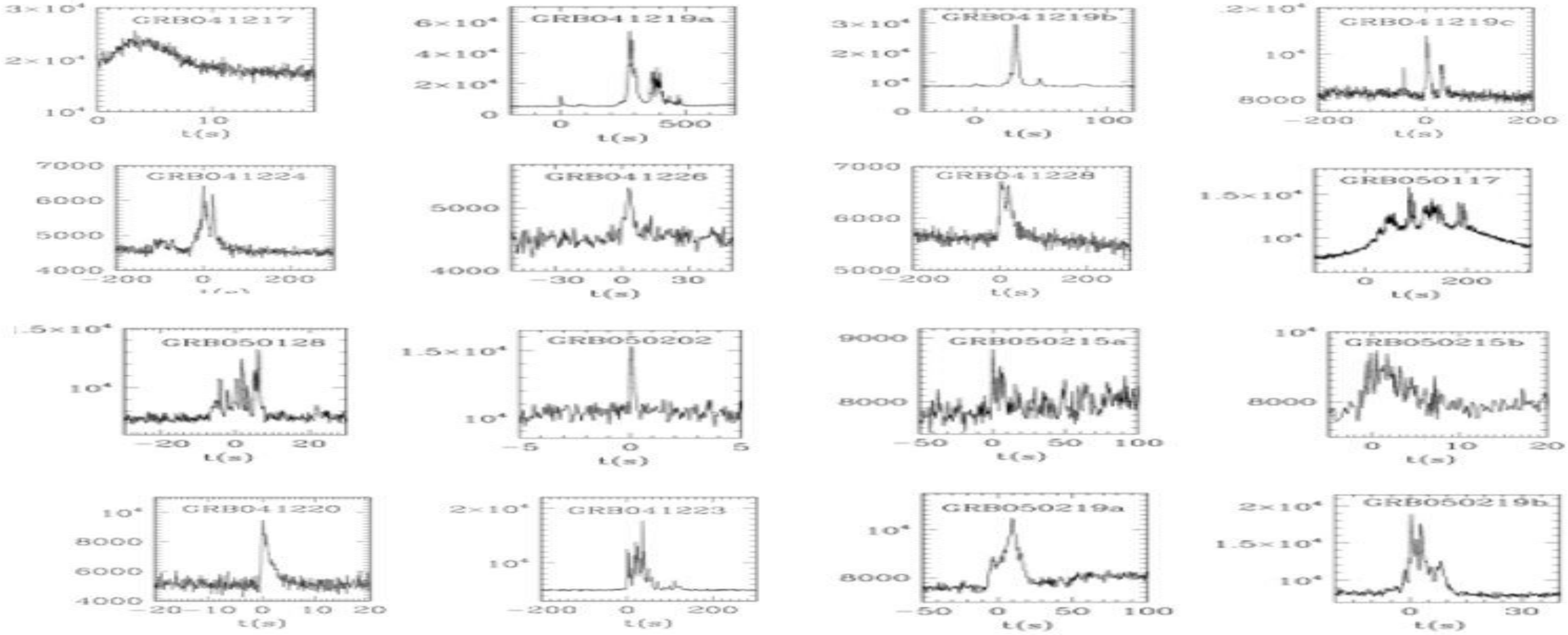
Because They…

- Can be probes of the early evolution of the Universe.
- Are observed beyond the epoch of reionization.
- Allow us to investigate Pop III stars.
- Allow us to track the star formation.
- Are much more distant than Supernovae (SNe) Ia ($z=2.9$) and quasars ($z=7.54$).

But They…

- Don't seem to be standard candles with their isotropic prompt luminosities spanning over 8 order of magnitudes (we need standard candles!)

For 20 years, we’ve been struggling: how to use GRBs as standard candles?
Challenge: Light curves vary widely - “if you've seen one GRB, you've seen one GRB”



Swift lightcurves taken from the Swift repository

For GRB standardization, possible reliable candidates are the Ta-La and Lpeak-La correlations

Prompt correlations of GRB discovered by Yonetoku, Amati, Ghirlanda, Tsutsui
An important feature observed in the 42% of Swift satellite GRBs is the plateau emission, namely a flattening of the afterglow LC.

Afterglow correlations

2008–2015	2016–2017	2020–2022
Dainotti 2D and Oates relation LaX - T*aX & LaX-LpX confirming the reliability after bias correction L200s-alpha in optical (Oates et al. 2012)	**Dainotti 3D relation** (Lax - T*ax - Lpx) (reliable after bias correction)	**Dainotti 2D and 3D relation in radio and optical** (probing these to be unbiased relation)

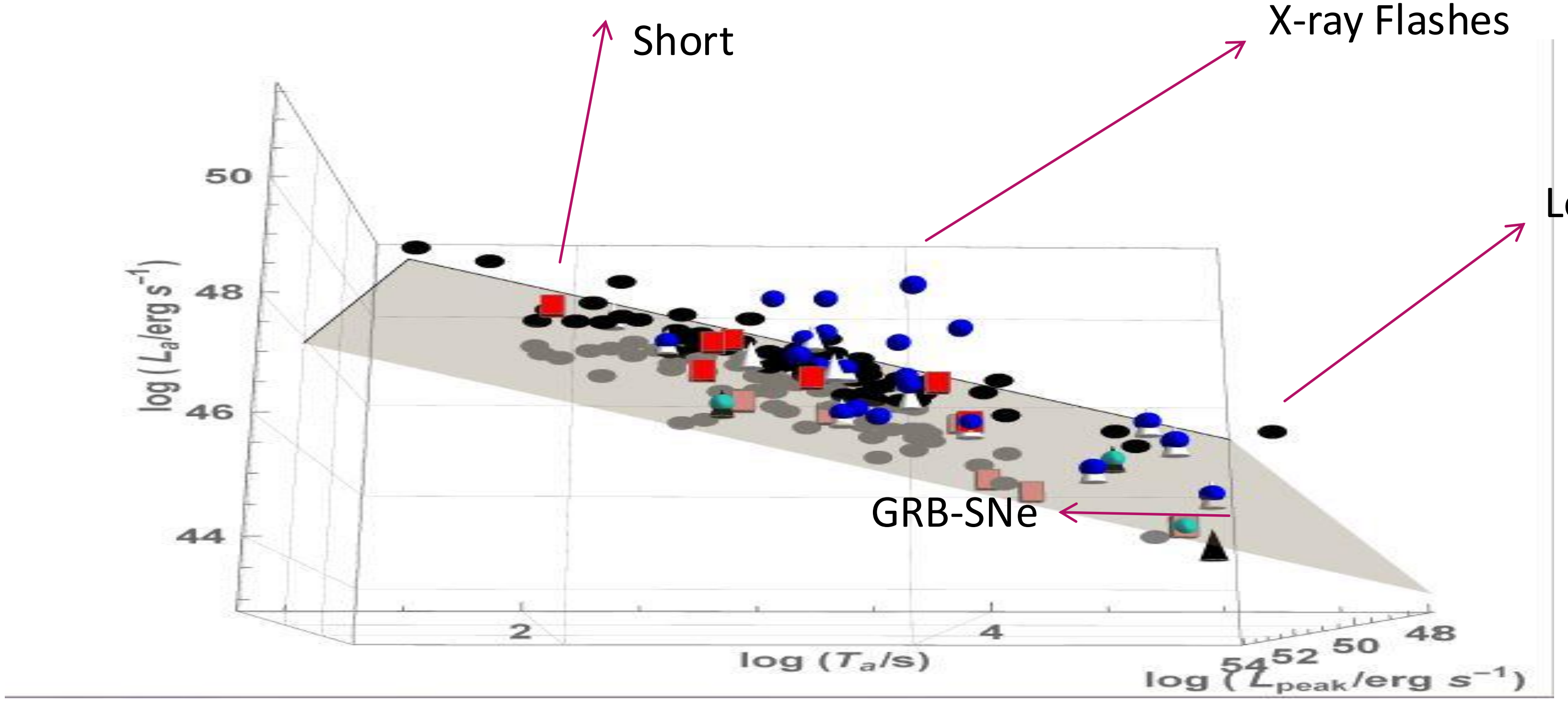
2008 2010 2011 2015 | 2016 2017 | 2020 2021 2022

THE EXTENSION OF THE LX-TA AND LX-LPEAK CORRELATIONS GIVEN THEIR INTRINSIC NATURE

Press release by NASA and press conference at the AAS June 2016:
https://swift.gsfc.nasa.gov/news/2016/grbs_std_candles.html
Mention in Scientific American, Stanford highlight of 2016, INAF Blogs, UNAM gaceta, and many online newspapers took the news

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

- the 3D Lpeak-Lx-Ta correlation **is intrinsic** and it has a reduced scatter, σint of 24 %.



The 3D correlation in optical exists for 58 GRBs !!!

M. G. Dainotti, et al., 2022c, ApJS, 261, 2, 25. Press release from NAOJ

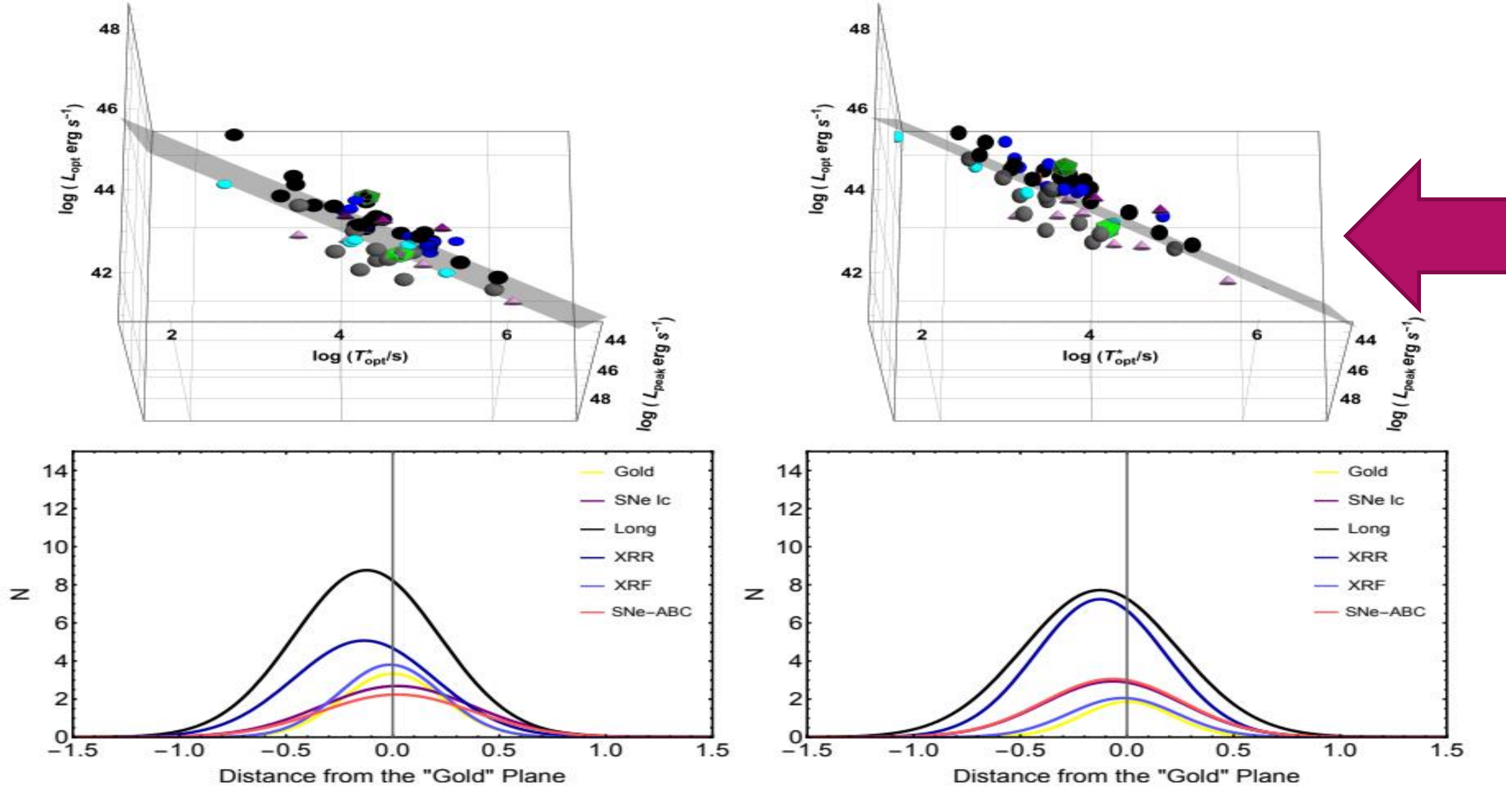


Figure 5. Upper panels: 58 GRBs in the $L^{(\prime)}_{\rm opt} - T^{(*/\prime)}_{\rm opt} - L^{(\prime)}_{\rm opt}$ parameter space with the fitted plane parameters in Table 2, including LGRBs (black circles), SGRBs (red cuboids), GRB-SNe Ic (purple cones), XRFs and XRRs (blue spheres), and ULGRBs (green icosahedrons). The left and right panels display the 3D correlation with and without any correction for both redshift evolution and selection biases, respectively. Lower panels: the distances of the GRB of each class indicated with different colors from the Gold fundamental plane, which is taken as a reference, with and without correction for redshift evolution and selection biases, respectively.

Correcting for evolution

- **Long=31**
- **Gold→ 6**
- **XRF=4**
- **XRR=19**
- **GRB-SNe Ib/c-> 9**
- **SNe Ib/c (ABC)->7**

What do we need for GRB cosmology?

New or tighter Reliable correlations

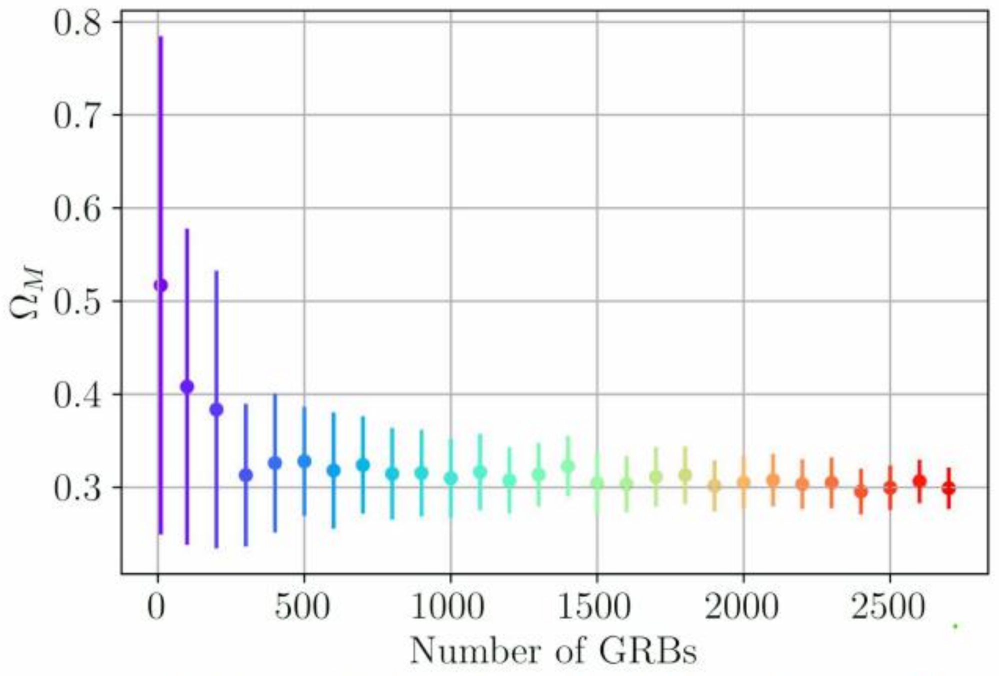
Increase the sample size, having a cosmology independent approach via low-z probes

Physical interpretation, connection with theory In the quest for the standard set

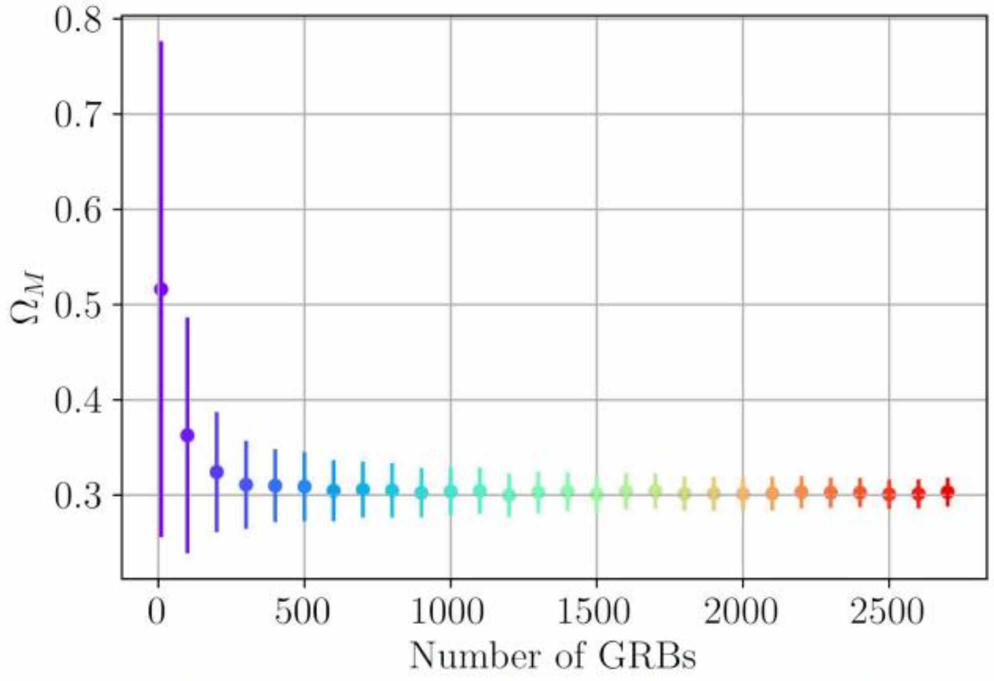
How?

THE PRECISION ON Ω_M WITH GRBs A FEW YEARS AGO

M. G. Dainotti, V. Nielson, et al., Sarracino, 2022, MNRAS, 514, 2, 1828-1856



(a) OPTICAL | Simulation Results for the Full OPT Base with Undivided Errors



(b) OPTICAL | Simulation Results for the Full OPT Base with Halved Errors

How many GRBs with optical plateaus are needed to achieve the SNe Ia precision?

When?

How?

67 → Conley et al. 2011 precision $\sigma\Omega_M = 0.10$ — Now

134 → Betoule et al. 2014 precision $\sigma\Omega_M = 0.042$ — 2026

390 → Scolnic et al. 2018 precision $\sigma\Omega_M = 0.022$ — 2042

With Machine learning (ML), errors on the parameters halved (n=2), and Lightcurve reconstruction (LCR) and redshift inference and with the catalog

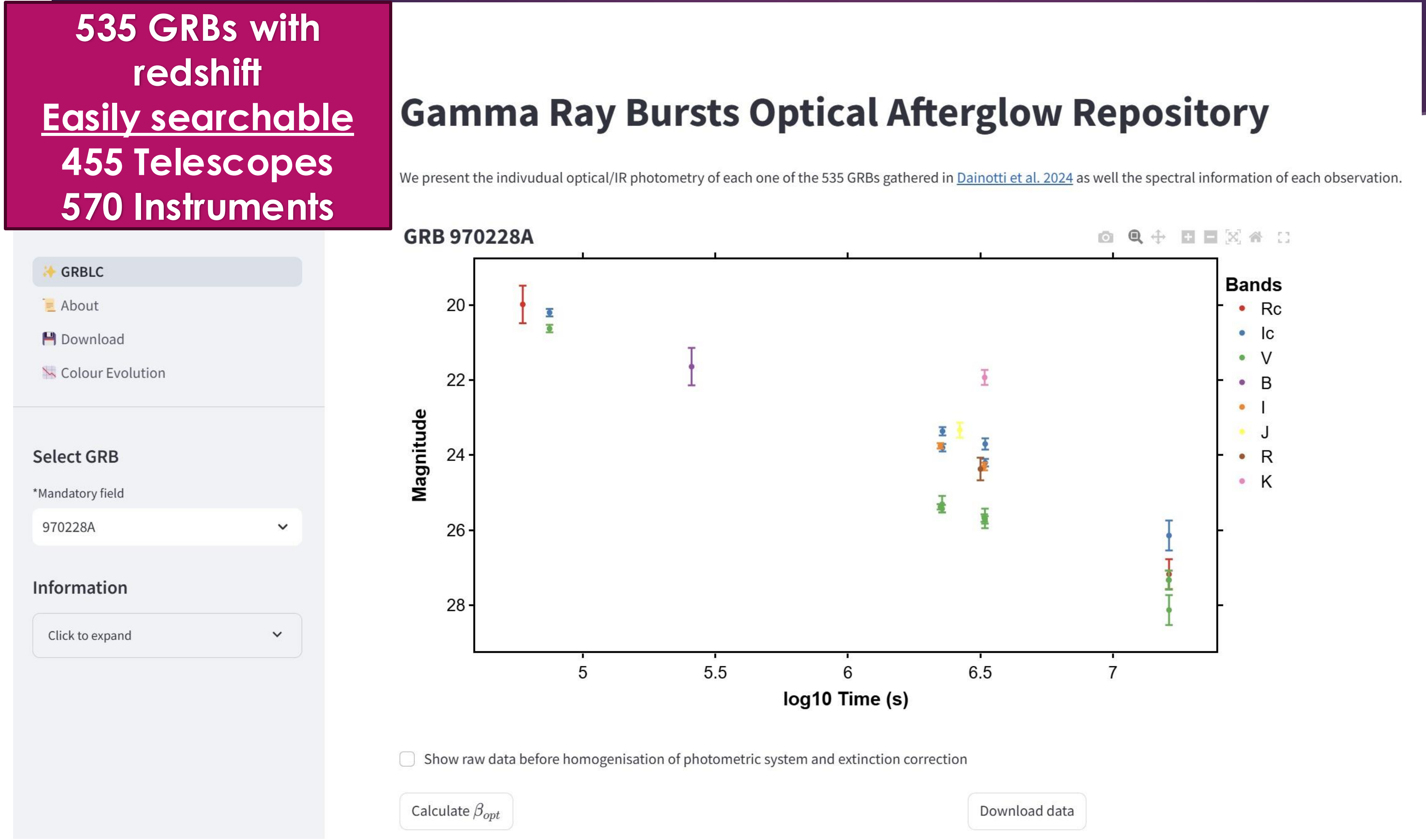
Worry not: we should not wait 18 years!

M. G. Dainotti, et al. 2022, MNRAS, 514, 2, 1828-1856

The largest GRB Optical Repository: GRB LC package affiliated with NAOJ

Dainotti et al., including Y. Niino, **T. Moriya, …,** 2024, MNRAS, 2024, 533, 4023.

535 GRBs with redshift
<u>Easily searchable</u>
455 Telescopes
570 Instruments

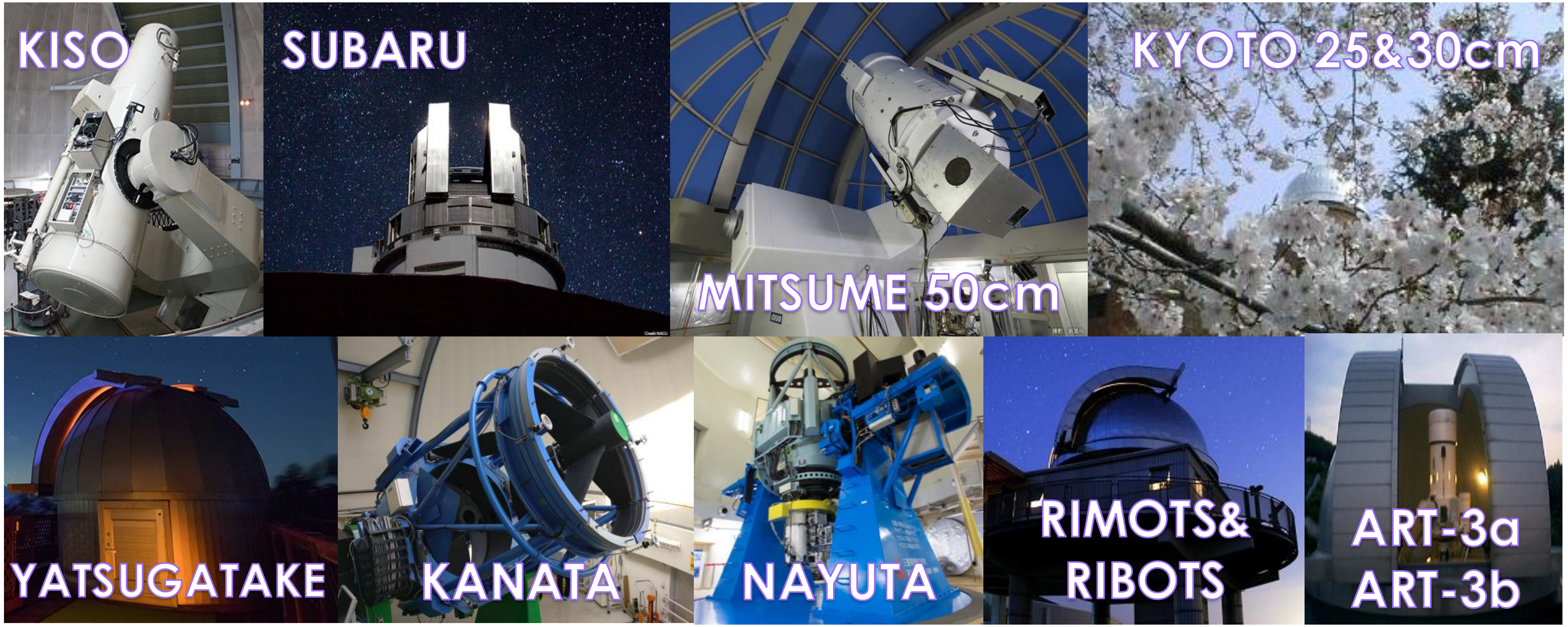


- **Large to small apertures: 14 GRBs from Subaru, 1 from Kiso at z=3.6, and other Japanese Telescopes.**
- **Re-calibration**
- **GRBs observed by Kiso (Dainotti, PI) since 2022.**
- **Joint KISO and SVOM.**
- **<u>Product: accessible via web-app</u>**
- **<u>ERG, 2022, part II</u>**

535 GRBs with determined redshfift Swift-UVOT + 570 instruments!

AND MORE …

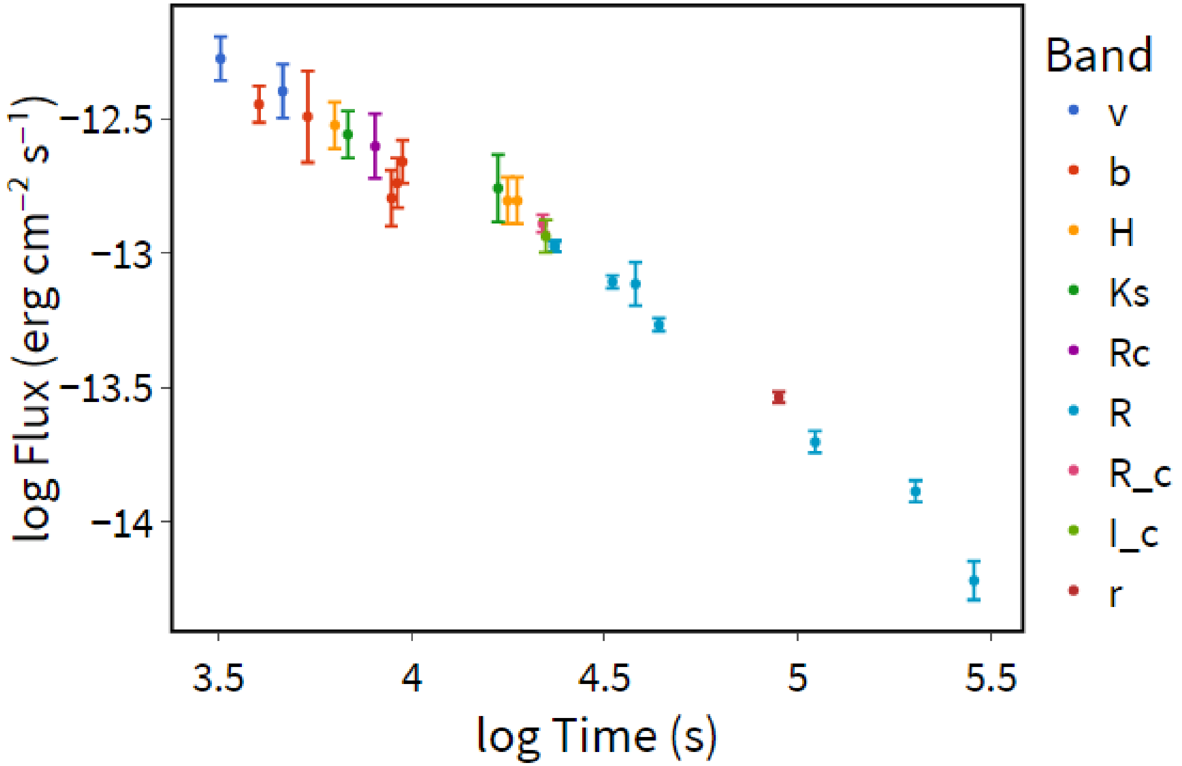
Japanese telescopes in our catalogue



FUTURE PERSPECTIVE: 33 new GRBs with known redshifts (up to end of January 2025)

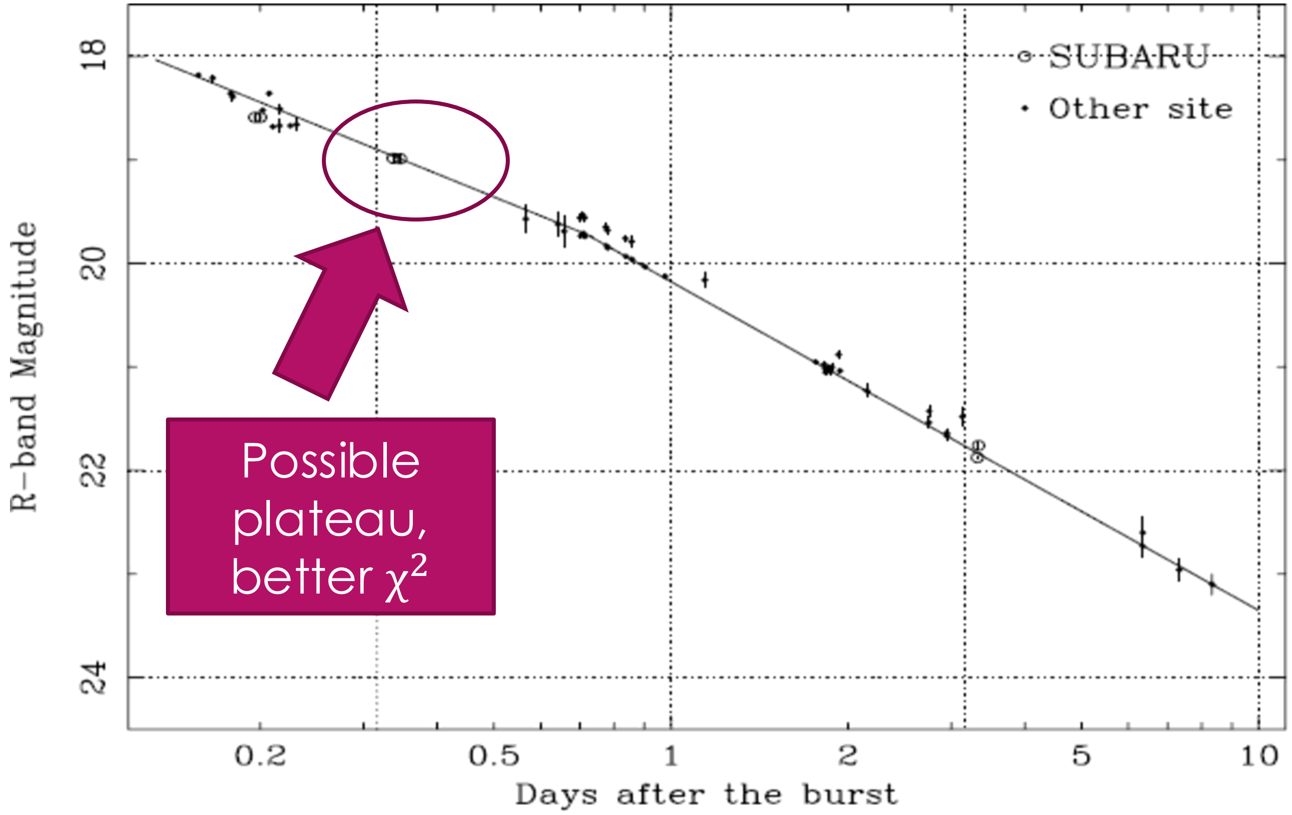
GRB 140423A Quickview

Right Ascension	Declination	Redshfit	Spectral index
13h09m10s	+49° 49'	3.26	1.0 ± 0.08



The importance of the SUBARU Telescope and the 1.05 meters Kiso Telescope in Nagano for the current study

GRB 010222 (J. Watanabe, et al., 2001, PASJ, 53, 4, 25)



The SUBARU Telescope helps to

- fill the gap in the optical light curves,
- provide spectra,
- redshift determination.
- identify new plateaus,
- reduce uncertainties in the error bars.

Why do we need an optical catalogue of GRBs?

GRB morphology
- Emerging of features (e.g. plateau emission and KN properties)

Population studies
- Beyond the long-short dichotomy and for correlation studies

Machine learning
- Light curve reconstruction
- Redshift estimation

Towards the early universe…
- Population III stars cosmology

The community needs a uniform format for data sharing and GCN for GRB optical data

Pipeline for building the GRB catalogue

- **Data collection**: GCNs, papers, ATel, private communications etc…
- **Homogenising sample**: shifting in AB system and applying Galactic extinction correction and, where possible, the K-correction and host galaxy correction
- **Colour evolution and rescaling**: Fitting of the rescaling factors vs log10 time
- **Division into three groups**: Agreement and Disagreement with literature, Undetermined by us

Homogenising the sample

Correct for galactic reddening
using Schafly et al. (2011) dust map or ASIAGO database (ADPS)

$$mag_{AB,gal} = mag^* - A_{\lambda,gal}$$

Transform the magnitudes in the AB system
(overcoming fluctuations of the filters' zeropoint)

$$mag_{AB,gal} = mag^* - A_{\lambda,gal} + shift_{Vega \rightarrow AB}$$

Apply the K-correction (if the spectral index is available)

$$mag_{corr} = mag_{AB,gal} - k$$

Apply the host correction using Pei (1992) extiction curves

$$mag_{corr} = mag_{AB,gal} - k - A_{\lambda,host}$$

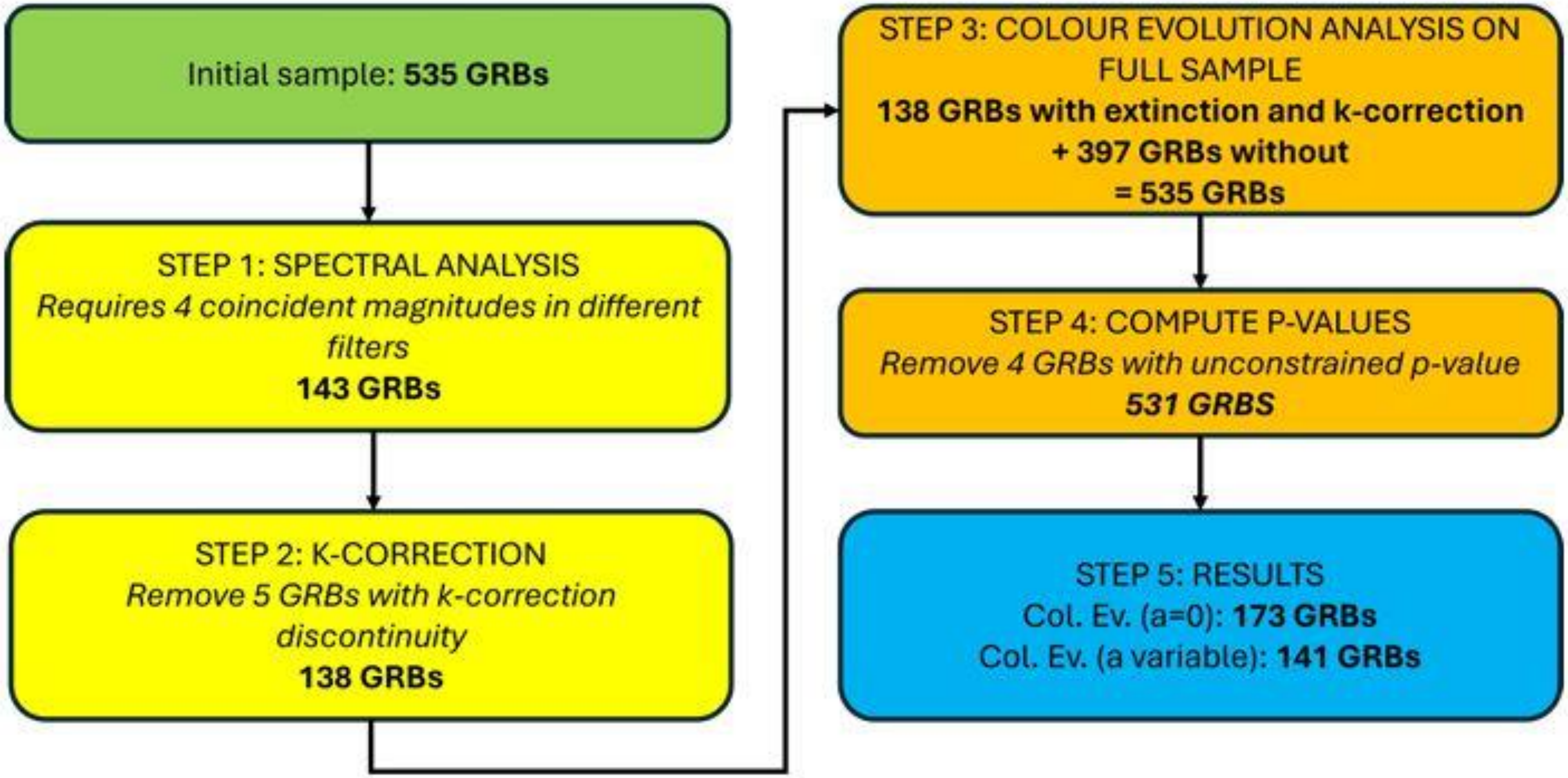
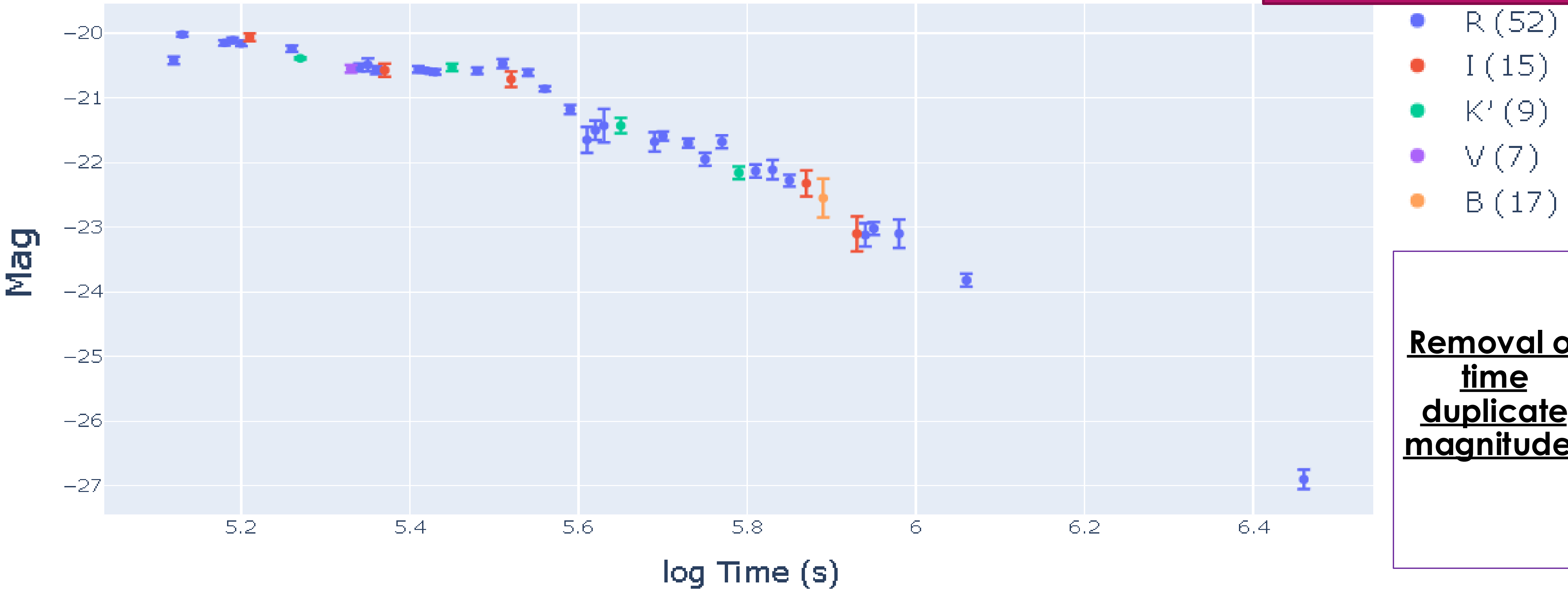


Figure 8. The flowchart of the GRB analysis.

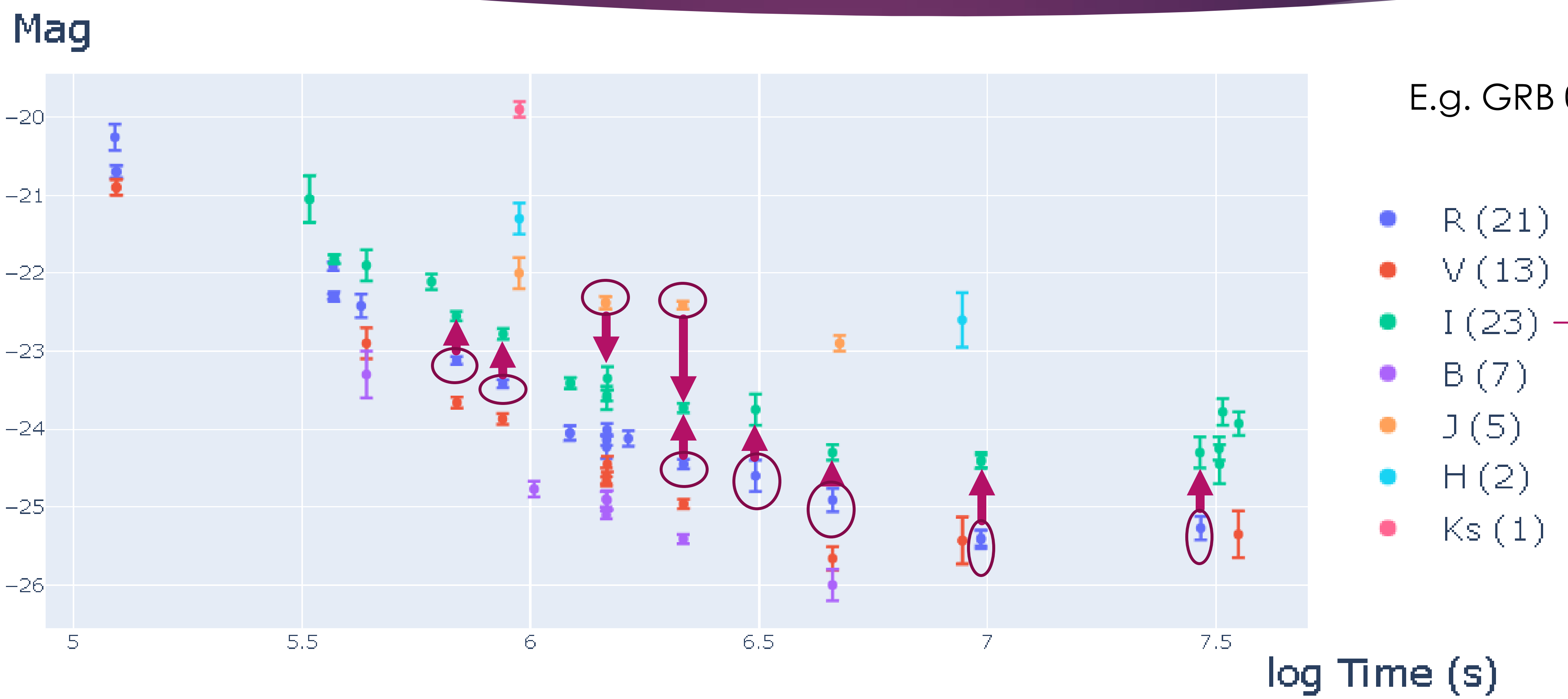
Time duplicates removal
We remove the points with least numerous filter

Occurrences



Removal of time duplicate magnitudes

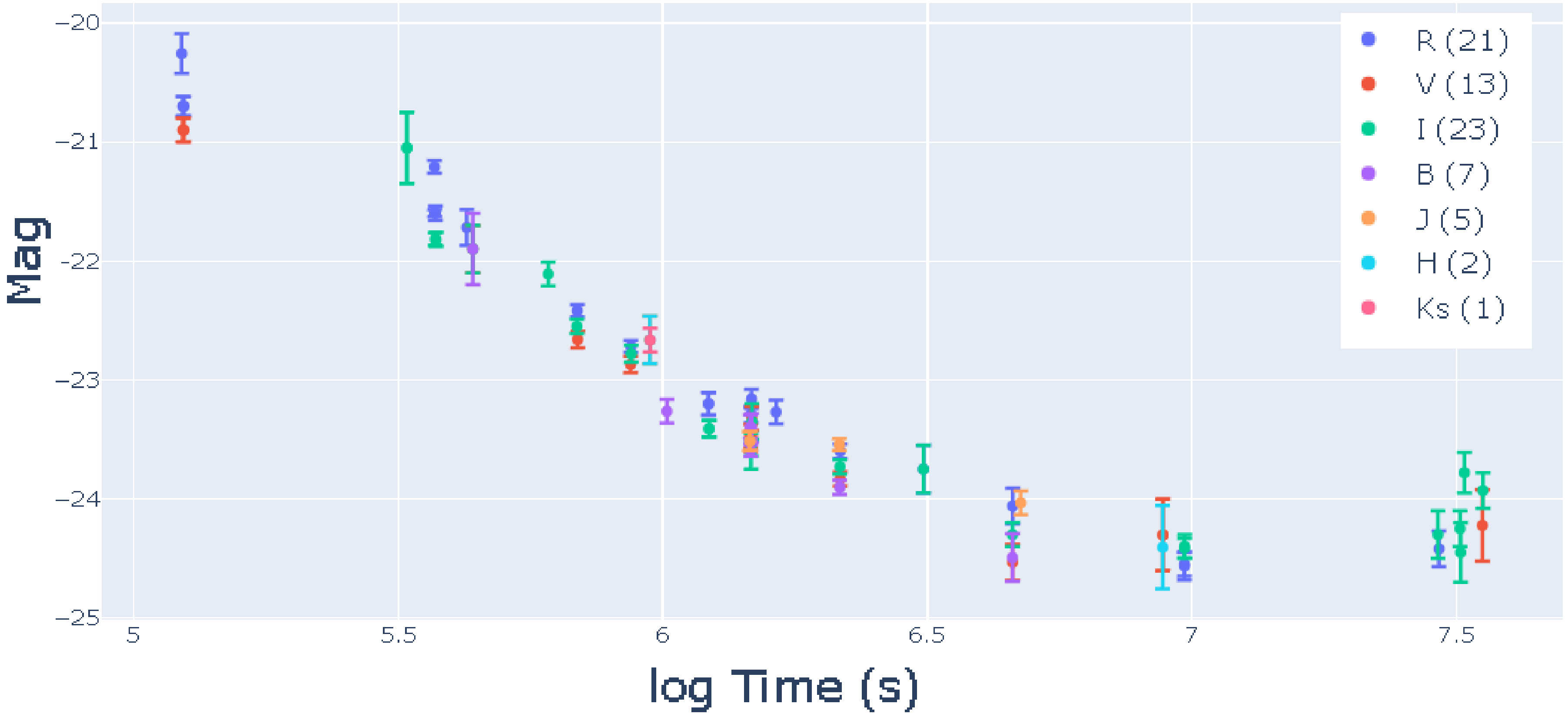
Before the rescaling (coincident times)



E.g. GRB 000911A

Most numerous

After the rescaling factor (coincident times)



E.g. GRB 000911A

If
$|tf - ti|/tf < 2.5\%$

tf = final time
ti = beginning time

<u>Rescaling factor = difference between the magnitudes</u>

Providing a uniform format for GRB optical data

- Example data gathered for 050904A

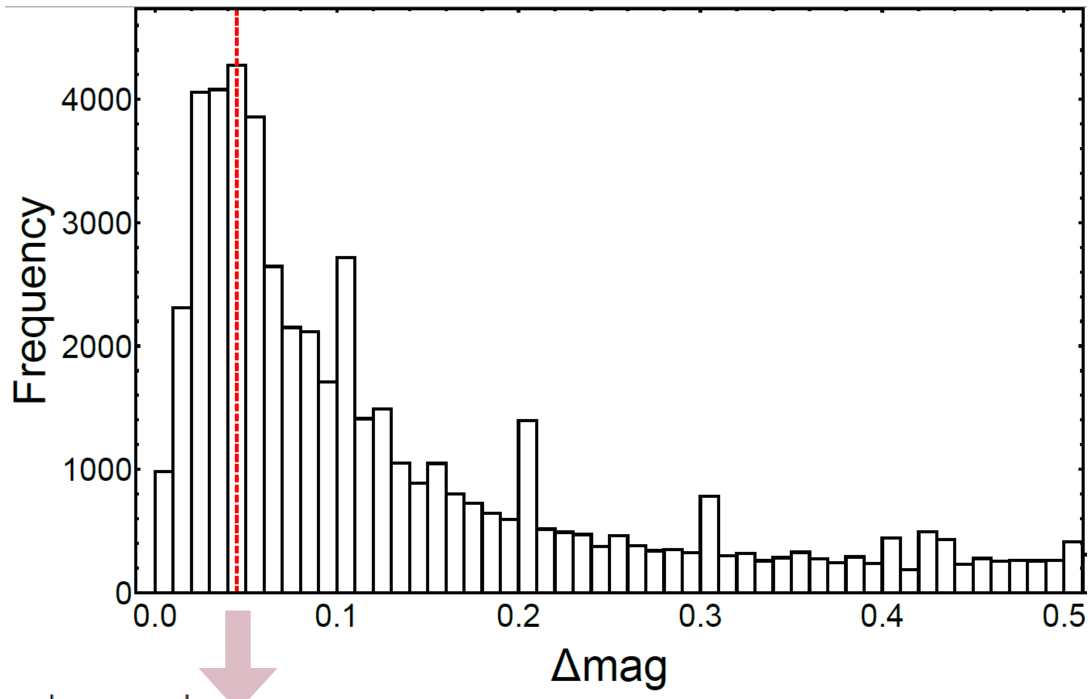
Time(s)	Mag	MagErr	Filter	System	Observatory/Telescope/Instrument	GalExtCorr	Source	Flag
115	17.981	0	R	AB	LSO/TAROT-S(25cm)/ANDOR-IKON-DW-436-N	y	3917	yes/X/Z
519	13.951	0.24	Ic	AB	Calern/TAROT(25cm)/ANDOR-IKON-L936-BEX2-DD	y	Boer2006	no
786.5	15.381	0	Ic	AB	Calern/TAROT(25cm)/ANDOR-IKON-L936-BEX2-DD	y	Boer2006	no
2402	20.698	0	UVW1	AB	NGSO/Swift/UVOT	y	3923	no
2481.5	20.812	0	UVW2	AB	NGSO/Swift/UVOT	y	3923	no

The rescaling factor

Given a GRB with magnitudes in the filters f (the most numerous filter) and g (generic), the rescaling factor is at coincident epochs.

$$rf_{f,g} = (\mathrm{mag}_f - \mathrm{mag}_g)_{\mathrm{coincident}}$$

Magnitude errors peak at ~5% (=0.05 mag). The typical decay of a GRB magnitude as 1/time, taking a range of times that deviate by <2.5% as coincident, will have negligible effect on LC evolution



$$\frac{|t_f - t_g|}{t_f} \leq 0.025 \;\rightarrow\; t_f \text{ and } t_g \text{ are coincident}$$

β found for 138 GRBs!

Spectral analysis and k-correction + host galaxy correction

We consider at least 4 different filters at coincident times to estimate the spectral index and the host extinction

$$\frac{|t_f - t_g|}{t_f} \leq 0.025 \ \rightarrow t_f \text{ and } t_g \text{ are coincident}$$

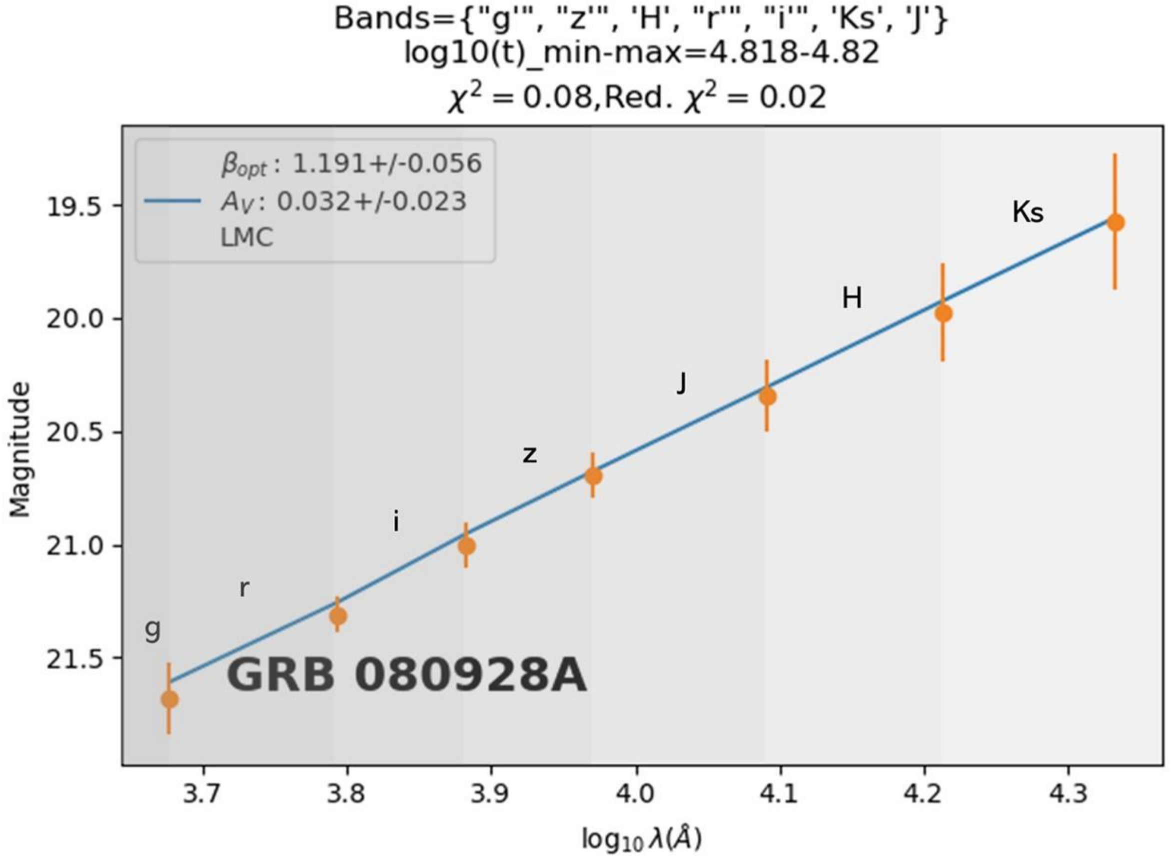
Zaninoni (2013) approach

$$\mathrm{mag}_{\mathrm{AB,gal}}(\lambda) = -\,2.5\beta_{\mathrm{opt}}\log_{10}(\lambda) - 2.5A_V\left(\left[\frac{A_\lambda}{A_V}\right]_{\mathrm{obs}} - \left[\frac{A_\lambda}{A_V}\right]_{1+z}\right) + \mathrm{mag}_0$$

where mag_0 is the magnitude value correspondent to F_0, A_V is the host galaxy extinction in V band, A_λ/A_V is taken from the extinction map reported in Pei (1992) for the three dust models: Milky Way (MW), Large Magellanic Cloud (LMC), and Small Magellanic Cloud (SMC), with $R_V = 3.08, 3.16, 2.93$ respectively

We then correct magnitudes according to k-correction and Pei (1992)

$$mag_{corr} = mag_{AB,gal} - k - A_{\lambda,host}$$



The spectral analysis

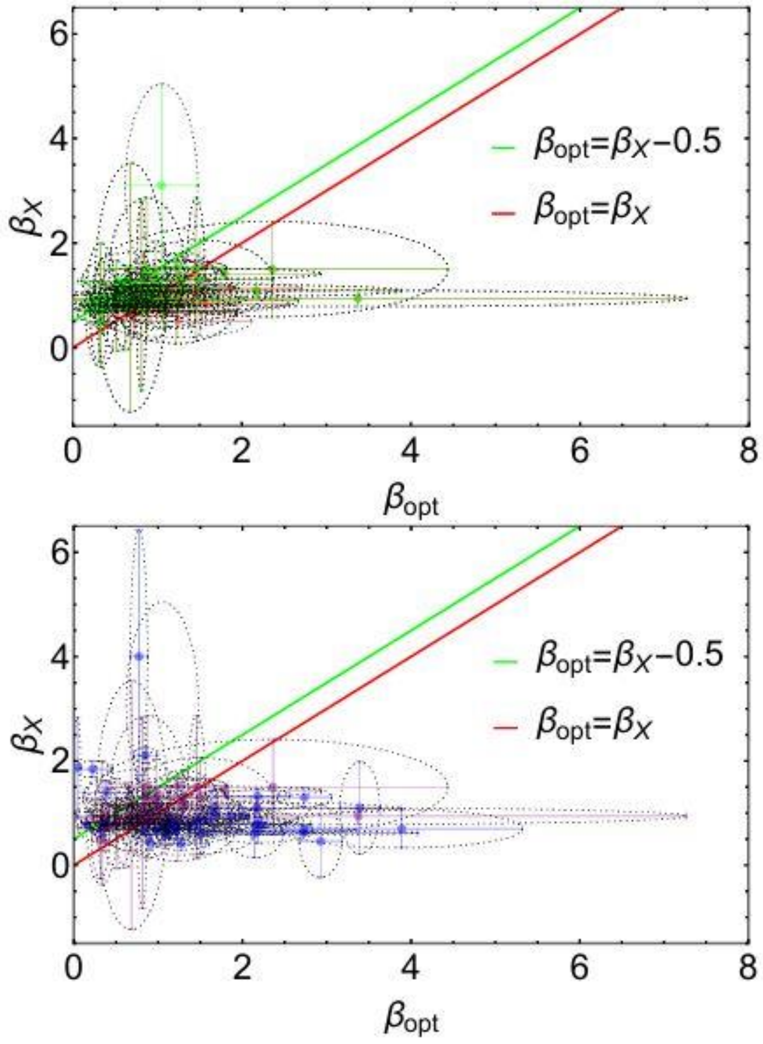
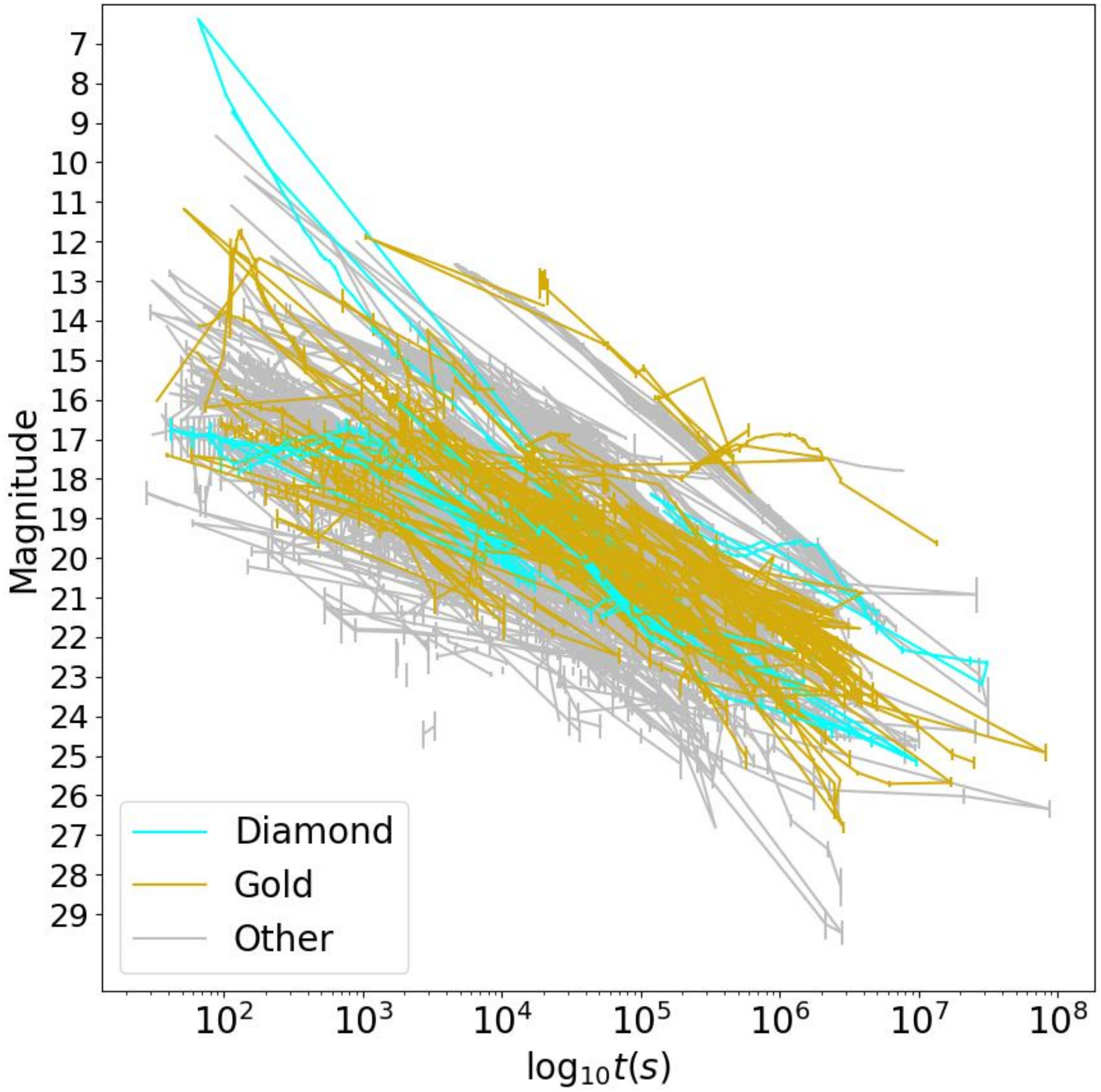


Figure 1. The comparison between the optical spectral indices (in the x-axis) and the X-ray ones (in the y-axis). **Upper panel.** The green data points are the β_{opt}s that follow the $\beta_{opt} = \beta_X - 0.5$ relation (48 cases), while the red ones respect the $\beta_{opt} = \beta_X$ relation (56). The red line is the relation $\beta_{opt} = \beta_X$, while the green line represents $\beta_{opt} = \beta_X - 0.5$. **Lower panel.** The purple data are the GRBs that respect both the relations $\beta_{opt} = \beta_X - 0.5$ and $\beta_{opt} = \beta_X$ (34), while the blue ones do not respect any of the two (43). The color-coding is the same in both panels.

Gold sample: computed βopt in the current analysis and fulfill one of two conditions:
A) the achromatic behaviour, characterized by colour evolution or the absence thereof, aligns with findings from existing literature.
B) if the chromatic behaviour is determined in this work due to an increased data set compared to previous analyses.

Diamond sample: a computed βopt and exhibit no colour evolution.

Kann Plot



Magnitude
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
10^2
10^3
10^4
10^5
10^6
10^7
10^8
$\log_{10} t(s)$
Diamond
Gold
Other

Colour evolution: Fitting $rf_{f,g} = a * \log_{10}(t_f) + b$

using Levenberg–Marquardt algorithm

a set to 0

variable a

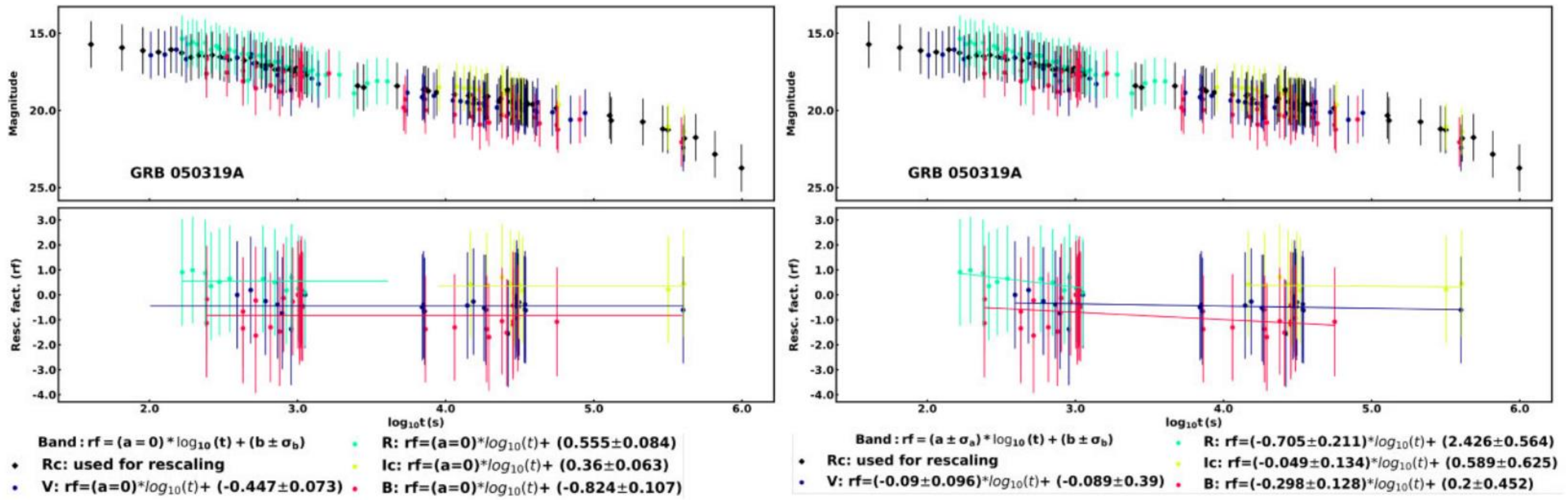
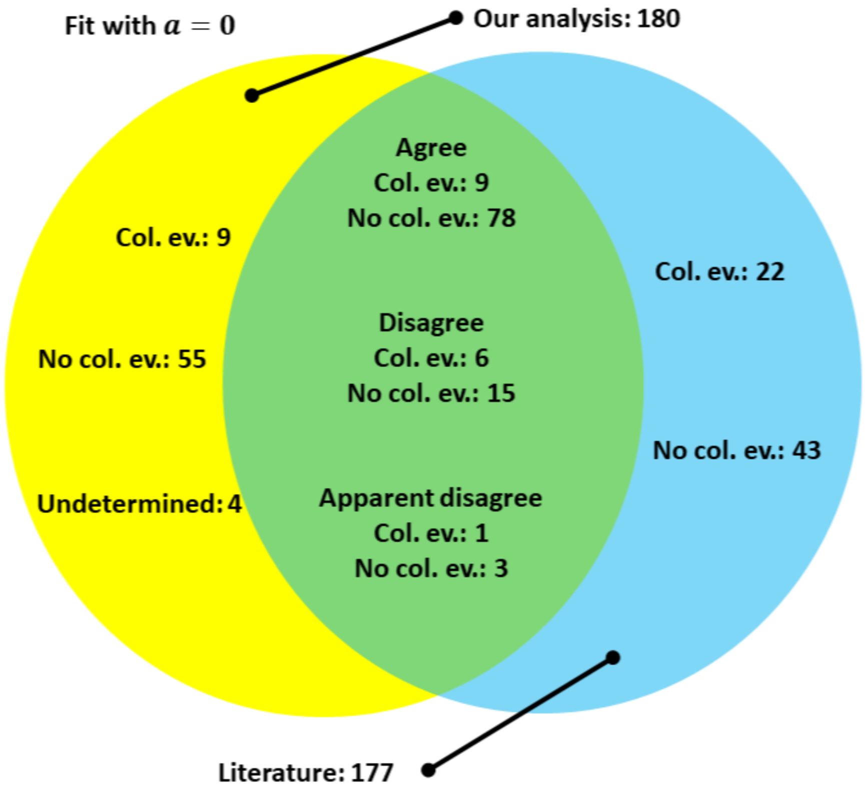
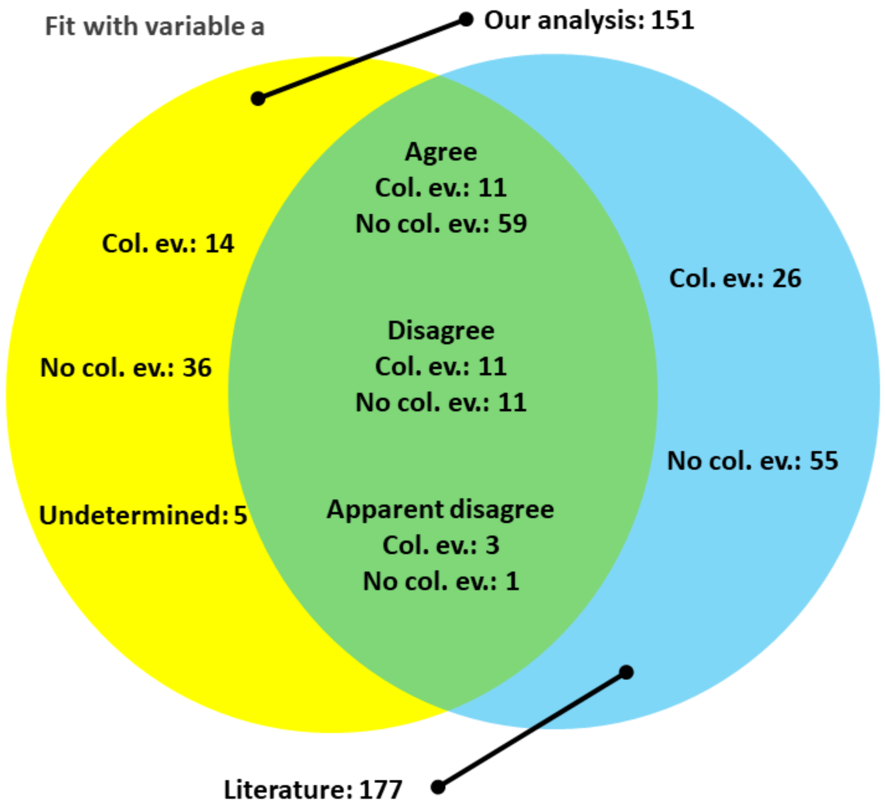


Figure 9. A comparison of the $a = 0$ fitting (left panel) and the variable slope fitting (right panel) for GRB 050319A. For both panels, the upper half shows magnitudes versus times, while in the lower half we report the rescaling factors versus time with their fitting functions.

Colour evolution: Results





Colour evolution: Results

Fit with fixed a=0

Agreement: 84 (49%)

Disagreement: 23 (13%)

Determined only by us: 66 (39%)

Total number: 173

Fit with variable slope

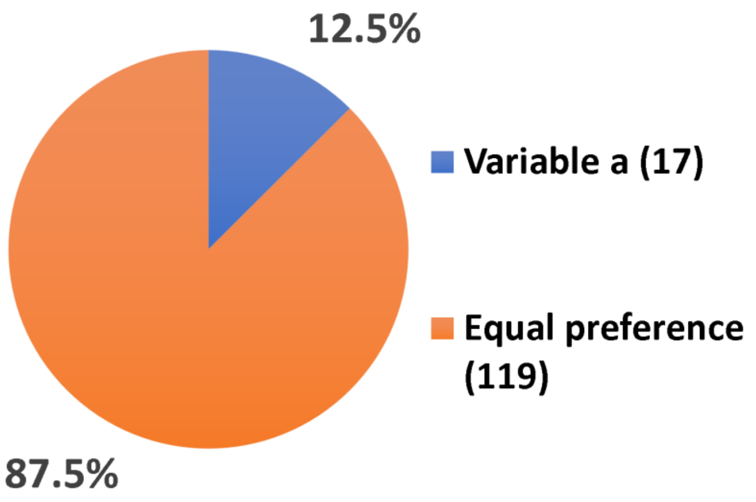
Agreement: 66 (47%)

Disagreement: 24 (17%)

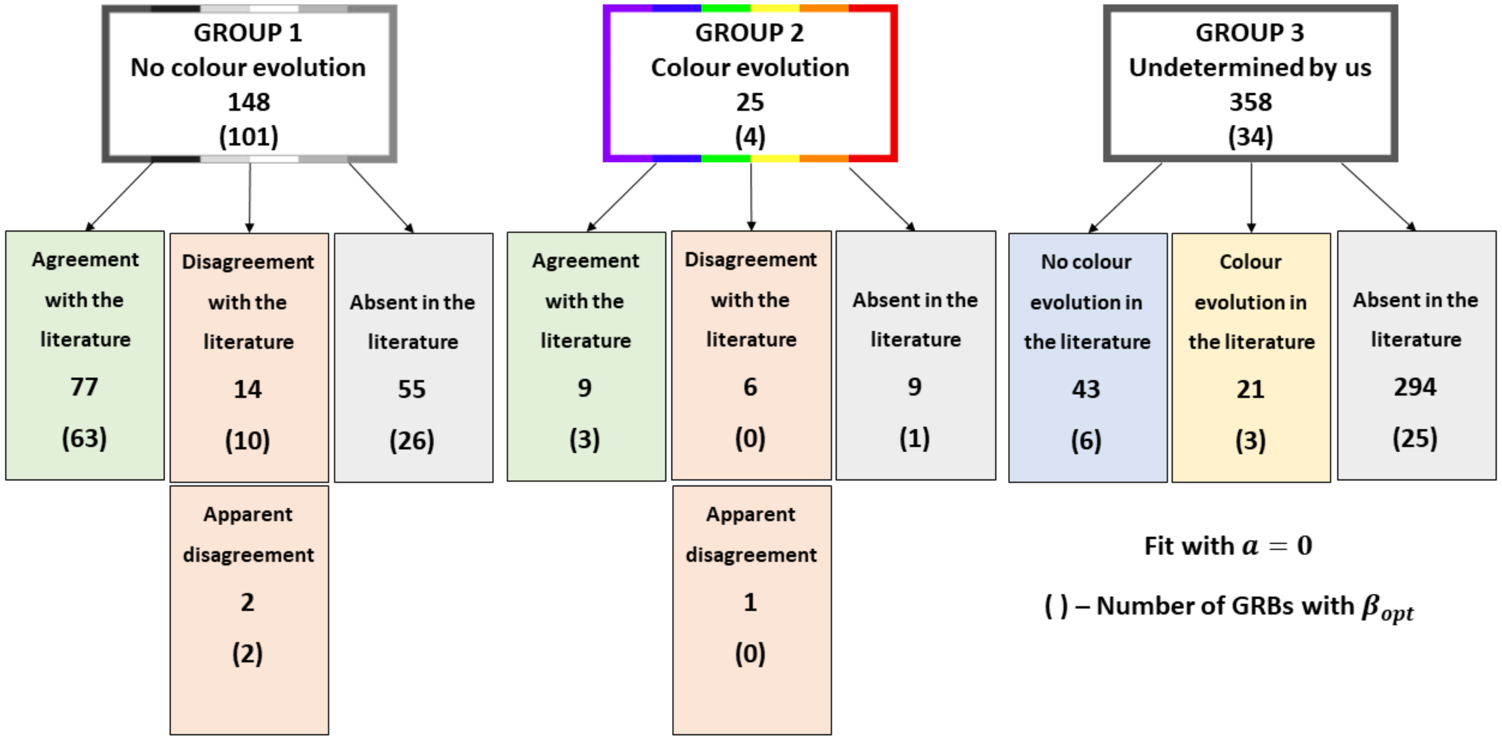
Determined only by us: 51 (36%)

Total number: 141

Best model (BASED ON BIC)



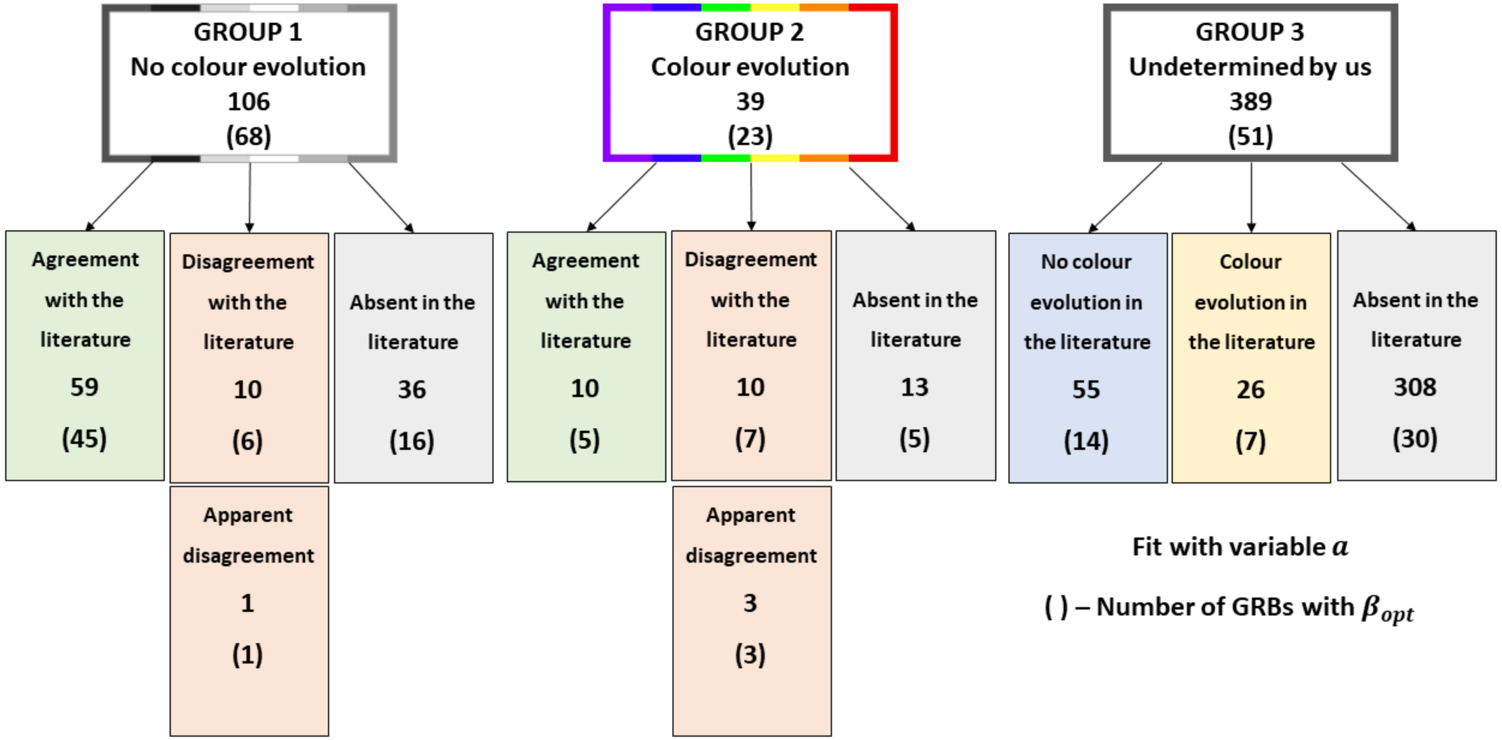
Division of Groups: a=0 model



Fit with $a = 0$

( ) – Number of GRBs with β_{opt}

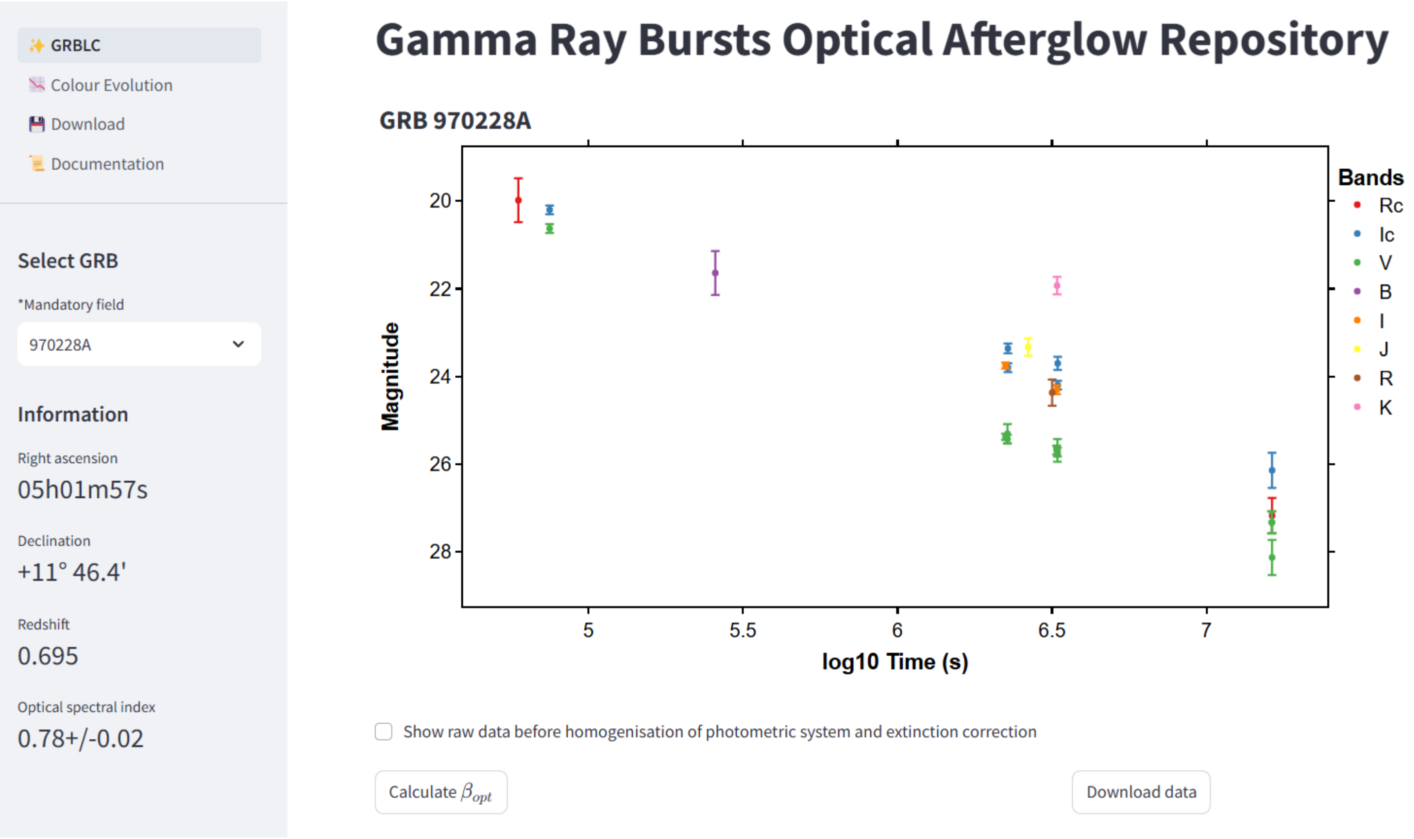
Division of Groups: variable a model



Fit with variable a

( ) – Number of GRBs with β_{opt}

One web-tool to include them all...



grblc-catalog.streamlit.app

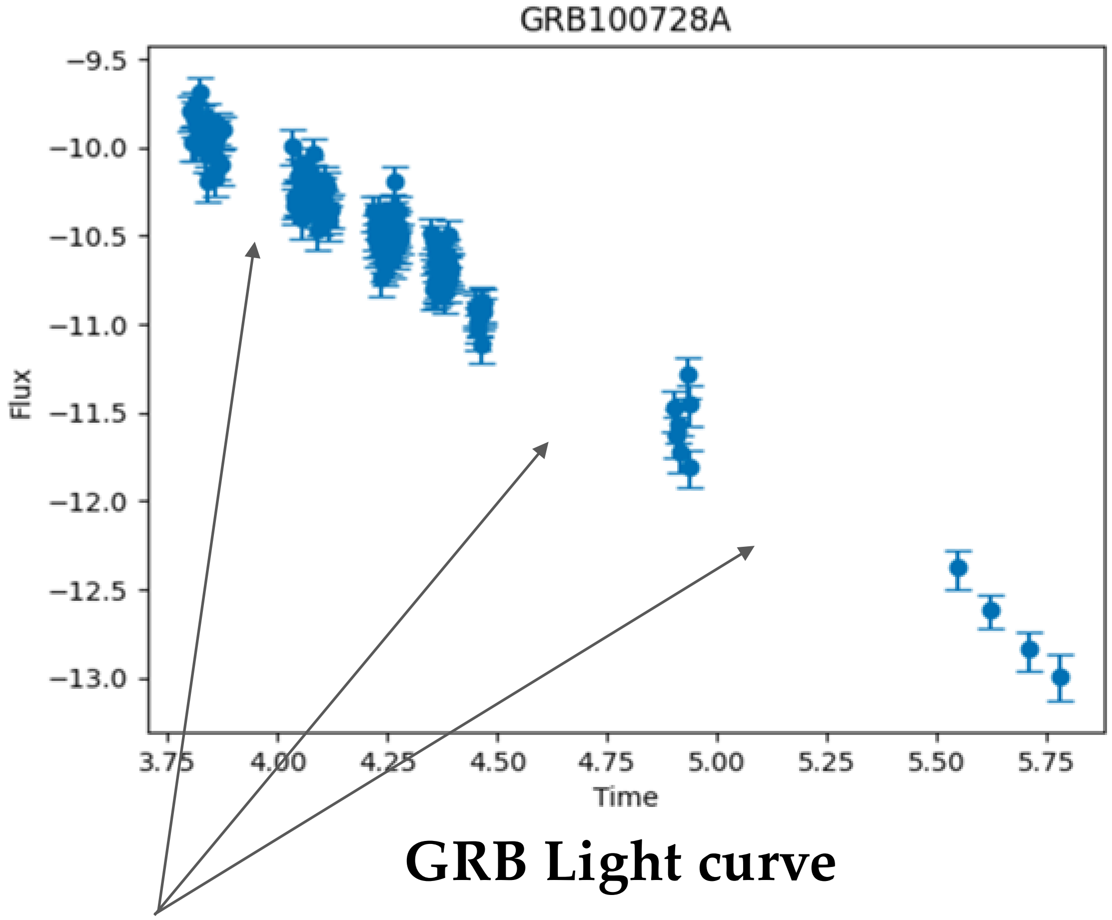
Gamma-Ray Burst Light Curve Reconstruction: A Comparative Machine and Deep Learning Analysis (ApJS accepted, Machanda, Gupta, Dainotti et al.)

Aim:

- To reconstruct the gaps in the Light Curve using ML/ Statistical models.
- Decreasing the uncertainty associated with the W07 parameters.
- We have used 9 models to reconstruct the LCs: **MLP, Bi-MAMBA, GP-RF, Bi-LSTM, CGAN, KAN, Attention UNet, Fourier transform and Sarimax based Kalman filter model.**

Data:

Dataset comprises of **545 GRBs**, originating from the **Swift BAT-XRT repository**. The GRB's have been classified into four distinct classes based on the features of their afterglow emission: Good, Break, Flares/Bumps, Flares/Bumps + Double Break



GRB Light curve

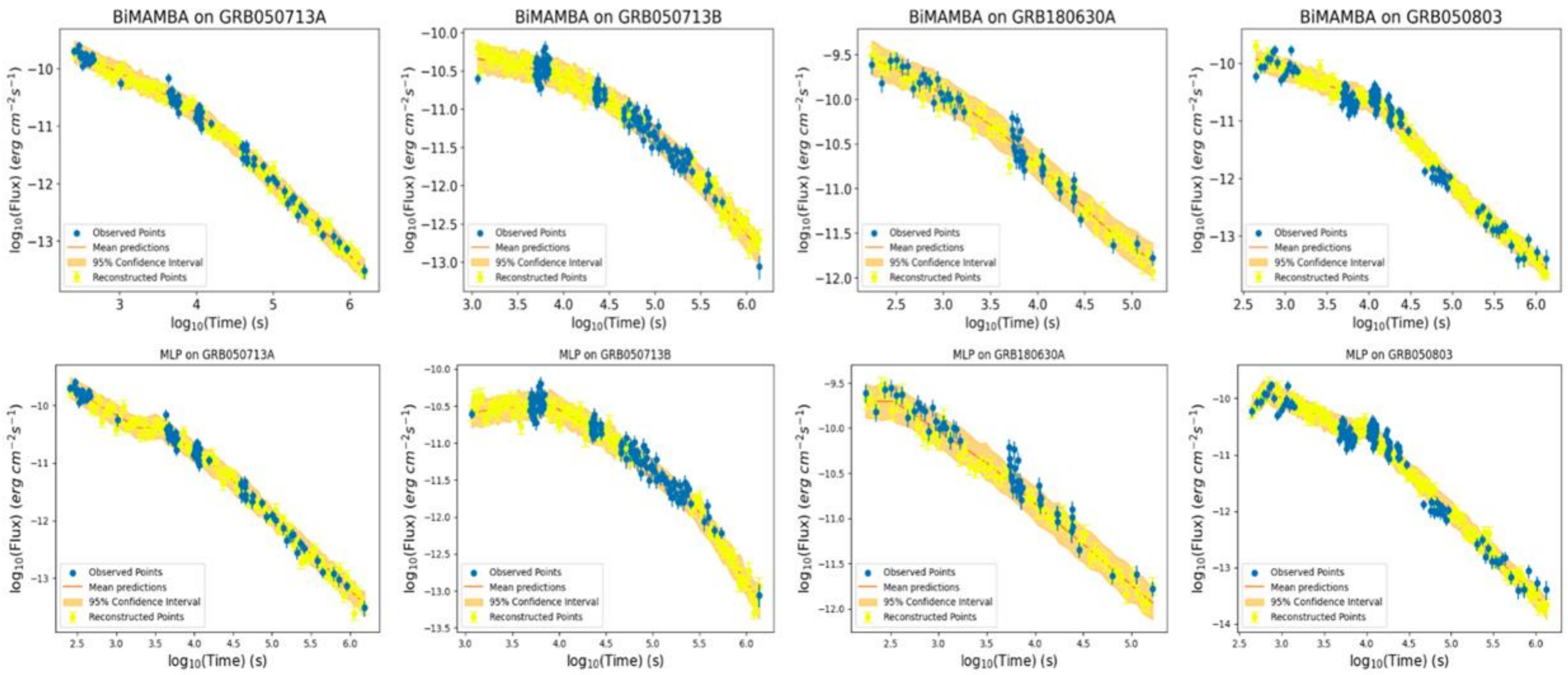
Temporal gaps defined as greater than 0.03 in the time scale.

Gamma-Ray Burst Light Curve Reconstruction Results

- The **Bi-Mamba** model achieves highest uncertainty reduction across all parameters (33.3% for log Ta, 33.6% for log Fa, and 41.9% for α).
- The **MLP model** provides the lowest 5-Fold Test MSE of 0.0275 among deep learning models, making it the best option when prioritizing reconstruction accuracy.
- On comparison with **Dainotti et al. (2023b):**
  Bi-MAMBA slightly outperforms W07, achieving a 43.6% reduction in uncertainty compared to 43.3% with W07, indicating a difference of 0.7% but a noteworthy improvement. Compared to the GP model, Bi-MAMBA outperforms for all three parameters.

Reconstruction Model	Uncertainty Decrease			% Outliers			5 K-Fold CV	
	% log T_a	% log F_a	% α	% log T_a	% log F_a	% α	Train MSE (10^{-1})	Test MSE (10^{-1}) ↓
	545 GRBs							
MLP	-25.9	-28.6	-37.7	3.60	3.30	0.900	0.227	**0.275**
Fourier	-28.8	-27.8	-36.7	3.30	3.50	0.500	**0.0270**	0.339
CGAN	-18.8	-19.1	-24.3	3.60	4.40	3.30	0.260	0.429
Bi-LSTM	-28.4	-28.2	-36.0	3.80	3.60	1.20	0.231	0.532
SARIMAX-based Kalman	-19.3	-24.6	-28.9	4.10	3.70	0.900	0.814	0.825
Bi-Mamba	**-33.3**	**-33.6**	**-41.9**	2.70	2.70	0.700	0.151	1.30
GP-RF	-25.0	-27.5	-34.7	5.60	5.30	2.30	0.0551	1.33
Attention U-Net	-27.5	-28.3	-38.1	3.10	3.10	**0.300**	0.206	1.34
KAN model	-15.5	-25.4	-27.0	7.70	3.50	1.60	0.423	1.74
GP (W07)	-22.8	-23.2	-33.5	3.10	3.30	1.10	8.56	3.63
W07 model (10%)	-24.5	-25.7	-36.2	**2.40**	**2.40**	0.900	-	-
W07 model (20%)	-21.2	-22.9	-34.7	2.80	2.80	1.50	-	-
	218 Good GRBs Dainotti et al. (2023b)							
SARIMAX-based Kalman	-21.4	-26.3	-30.4	2.20	1.80	0.400	0.191	**0.192**
MLP	-24.1	-27.8	-38.9	0.900	0.400	0.400	0.230	0.268
CGAN	-18.3	-20.7	-26.5	1.80	2.30	2.30	0.230	0.383
Fourier	-26.3	-28.2	-38.2	0.900	0.900	**0**	0.0900	0.480
Bi-LSTM	-26.1	-28.0	-37.3	1.30	1.80	1.30	0.210	0.626
Bi-Mamba	-32.7	-34.3	**-43.6**	0.400	0.400	0.400	0.110	0.850
GP-RF	-24.2	-27.8	-37.7	1.30	1.30	0.400	**0.0468**	0.920
Attention U-Net	-26.5	-28.2	-38.1	0.900	0.900	**0**	0.173	1.07
KAN model	-14.6	-25.6	-25.7	5.90	1.30	0.400	0.336	1.61
GP (W07)	-25.6	-27.9	-41.6	0.400	**0**	0	7.66	1.81
W07 model (10%)	**-33.3**	**-35.0**	-43.3	**0**	0	0	-	-
W07 model (20%)	-29.5	-31.2	-40.6	0	0	0	-	-

Results: MLP <u>Multilayer Perceptron Model</u> AND Bi-MAMBA (bi-directional Mamba)



THANK YOU SO MUCH FOR YOUR ATTENTION

Do you wish to join providing

- Lightcurves
- new ideas
- and tools?

Contact me at
maria.dainotti@nao.ac.jp