Maria Giovanna Dainotti

The GRB fundamental plane correlation: building an optical catalog

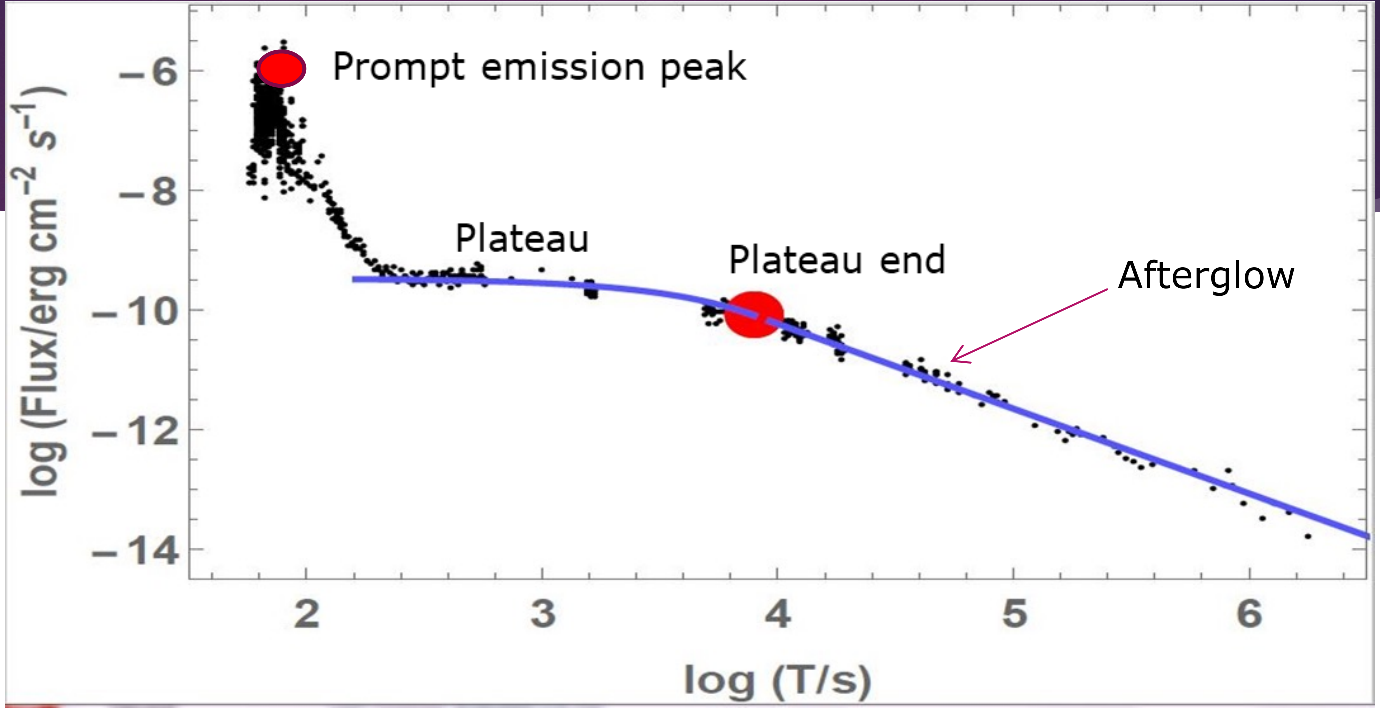
2th February 2023, Subaru Meeting

国立天文台
NAOJ
National Astronomical Observatory of Japan

Outline of the talk

1. Introduction on Gamma Ray Bursts
2. The 3D fundamental plane involving the plateau emission and its interpretation
3. Gamma Ray Bursts as cosmological tools
4. Details on the ongoing project → The most complete catalog of optical GRBs with redshift
5. Conclusions

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 – 13.14 billions of light-years).
- Extremely energetic and short: the greatest amount of energy released in a short time (not considering the Big Bang).
- X-rays and optical and radio radiation observed after days/months (afterglows), distinct from the main γ-ray events (the prompt emission).
- Observed spectrum non thermal.
- GRBs are important for their energy emission mechanisms.

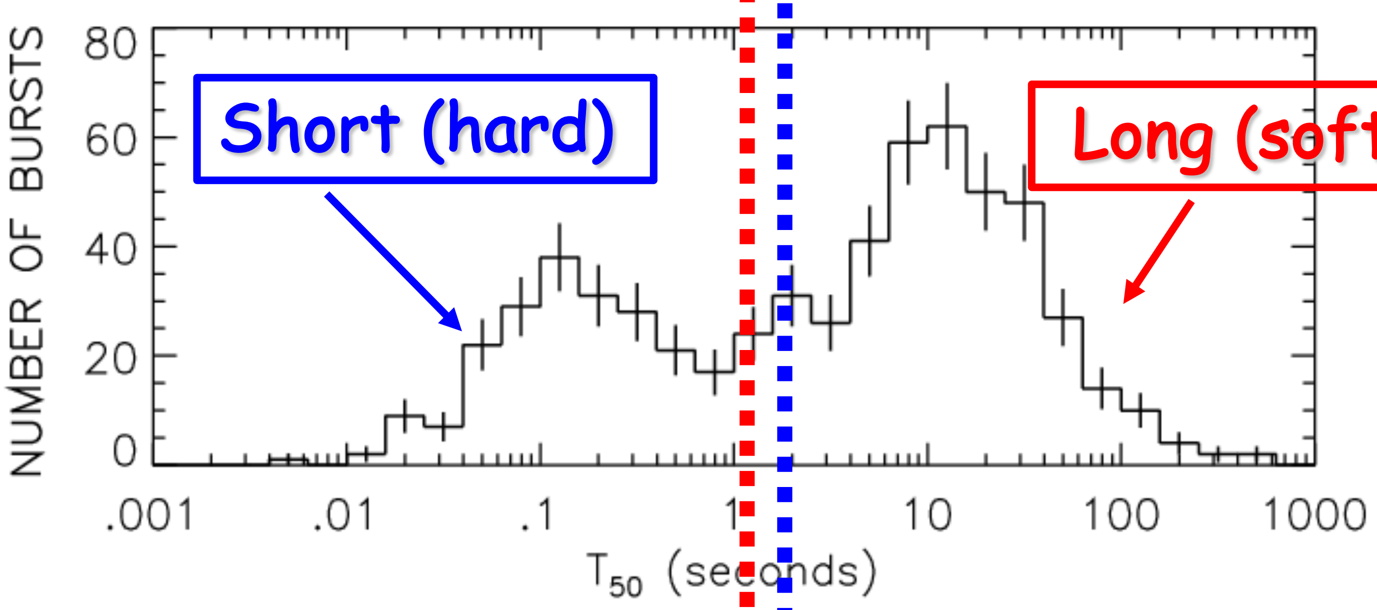
Short vs Long GRBs

compact object mergers
(NS-NS, NS-BH)

core collapse of
massive stars
($M > 30\ M_{sun}$)

BATSE definition
HR=S3/(S1+S2)

S3=100 to 300 keV
(channel 3)
S2= 50-100 KeV
(channel 1)
S1=25 to 50 keV
(channel 1)



Short GRBs -> T_{90}<2 s   Long GRBs -> T_{90}>2 s

Short GRBs -> T_{90}<5 s   Long GRBs -> T_{90}>5 s

C. Kouveliotou et al., 1996, AIP Conf. Proc., 384, 42.
W. S. Paciesas et al., 1999, ApJS, 122, 465.

J. P. Norris & J. T. Bonnell 2006, intermediate class of GRBs with mixed properties.
O. Bromberg et al. 2013, ApJ, 764, 179 T90=0.8s in Swift data

Why are GRBs potential cosmological tools?

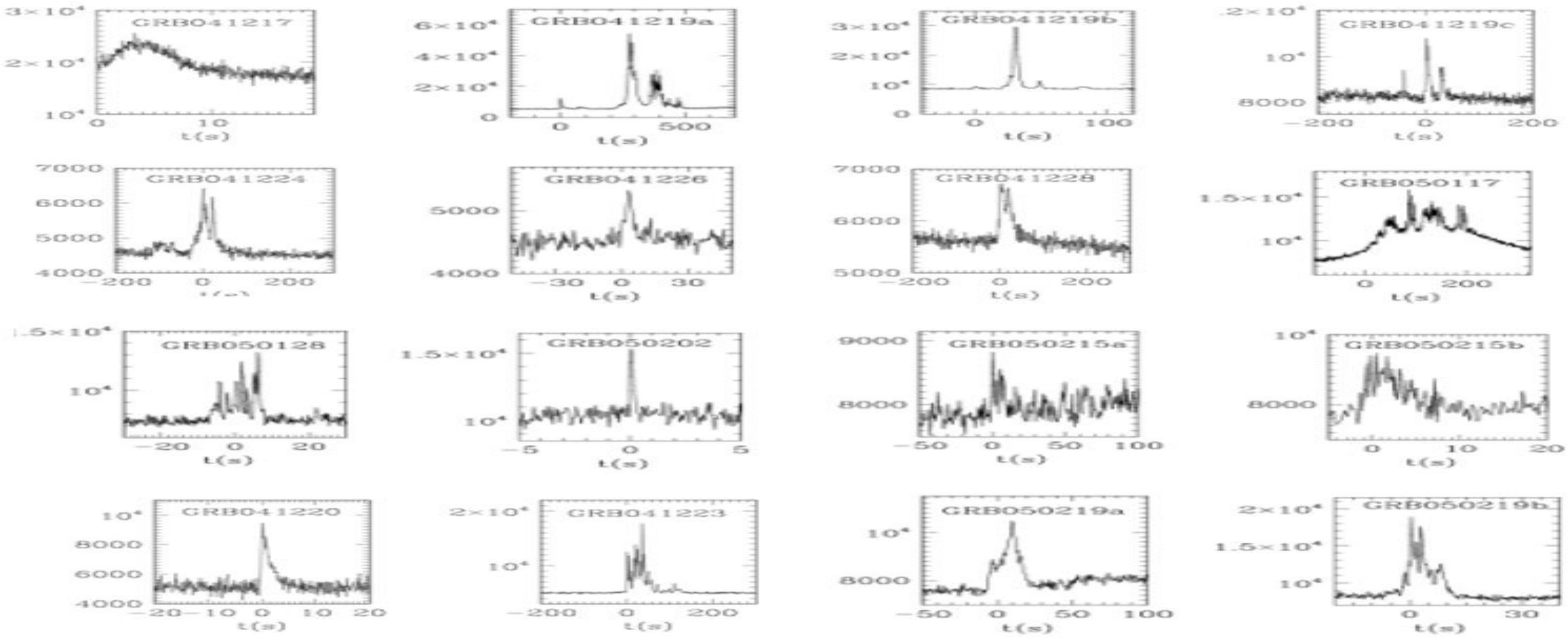
Because They…

- 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 ($z=2.26$) 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

GRB zoo

Which GRB class works best as a standard candle?

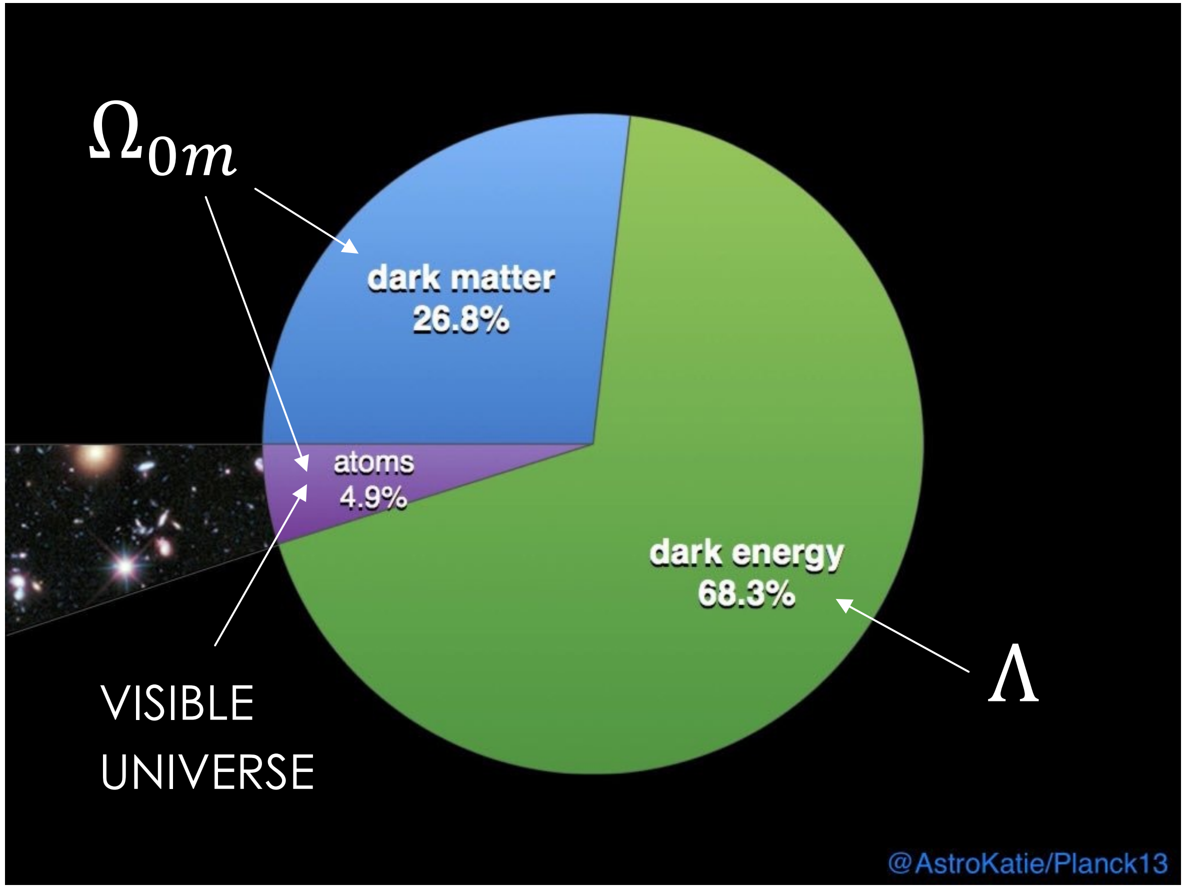
Class	Duration of prompt emission	X-ray fluence/ γ-ray fluence	Presence of supernovae or optical bumps
X-ray flashes	>2 s	>1	In some cases
GRB-SNe	>2 s	<1	Yes
Short	<2 s	<1	No
Short Extended Emission	<10 s	<1	In one case
Long	>2 s	<1	No
Ultra-Long	>2000s	<1	yes

Alone, none of these classes are standard candles (but I have good news for you later!).

Now the drive is to standardize them.

What are the cosmological parameters that we can infer with GRBs?

H_0 (Hubble constant), Ω_{0m} (total matter density), $\Omega_{0\Lambda}$ (dark energy density), w (equation of state parameter)



ΛCDM MODEL IS BASED ON THE PRESENCE OF THE «**COLD DARK MATTER**» (CDM, NOT DIRECTLY VISIBLE) AND THE «COSMOLOGICAL CONSTANT»

Ω_{0m} DESCRIBES THE TOTAL MATTER DENSITY (DARK MATTER + BARYONS) OF THE UNIVERSE

Λ IS THE COSMOLOGICAL CONSTANT THAT DESCRIBES THE ENERGY OF VOID, RESPONSIBLE FOR THE EXPANSION OF THE UNIVERSE

w IS THE PARAMETER OF THE EQUATION OF STATE FOR THE UNIVERSE ($w = -1$ IN THE ΛCDM MODEL)

H_0 IS A CONSTANT THAT DESCRIBES THE UNIVERSE EXPANSION RATE IN THE ΛCDM MODEL

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

Together with the correlations found so far between prompt properties of GRB (Yonetoku, Amati, Ghirlanda, Tsutsui) a lot of new interesting correlations emerged when the GRBs afterglow was considered.

An important feature observed in the 42% of Swift satellite GRBs is the plateau emission, namely a flattening of the afterglow LC.

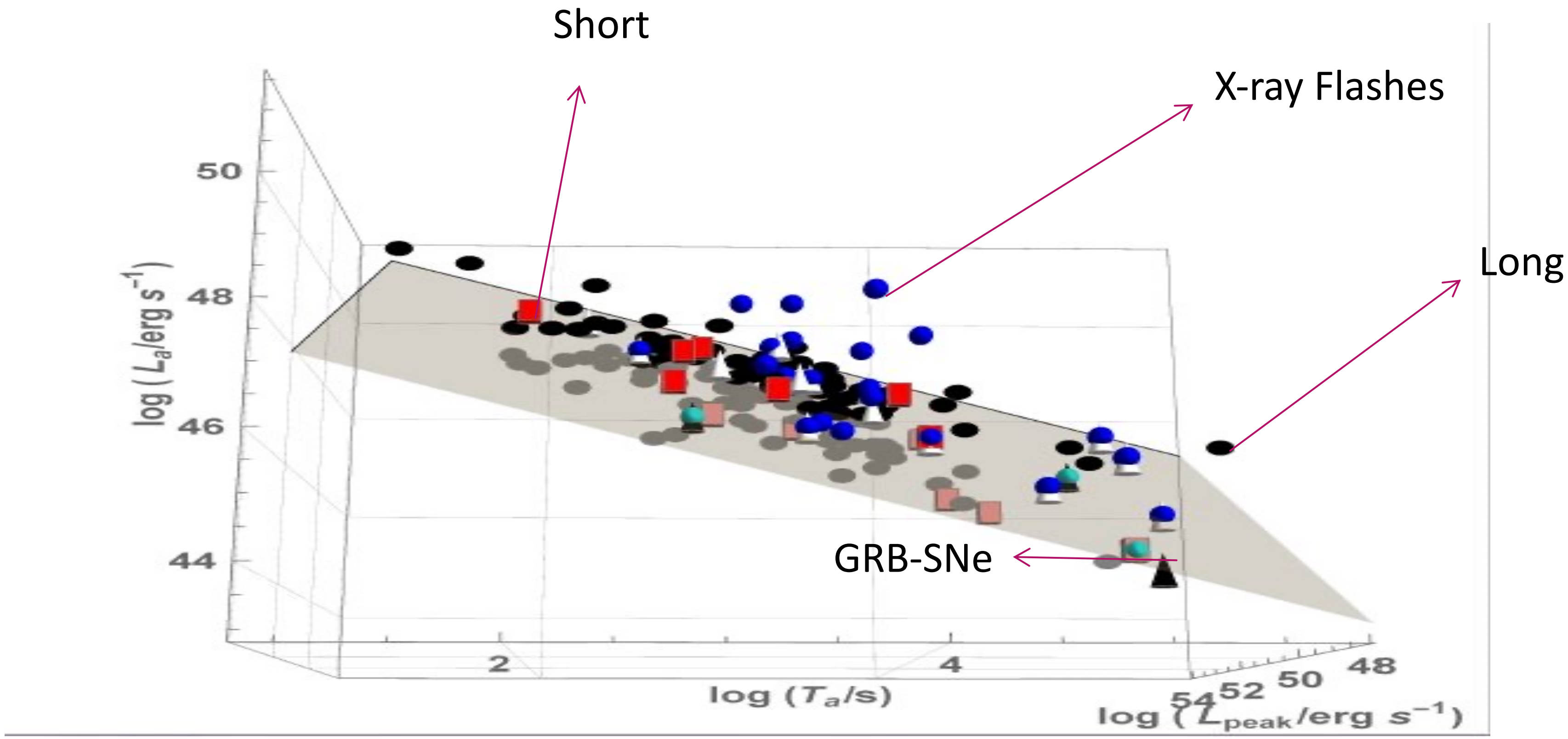
2008 2010 2011 2015	2016 2017	2020 2021 2022
Dainotti 2D relation and Oates relation LaX - T*aX & LaX-LpX confirming the reliability after bias correction L200s-alpha in optical	**Dainotti 3D relation** (LaX - T*aX - LpX) (reliable after bias correction)	**Dainotti 2D relation** (probing this unbiased relation also in the optical and radio)

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

Press release by NASA:
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, 20

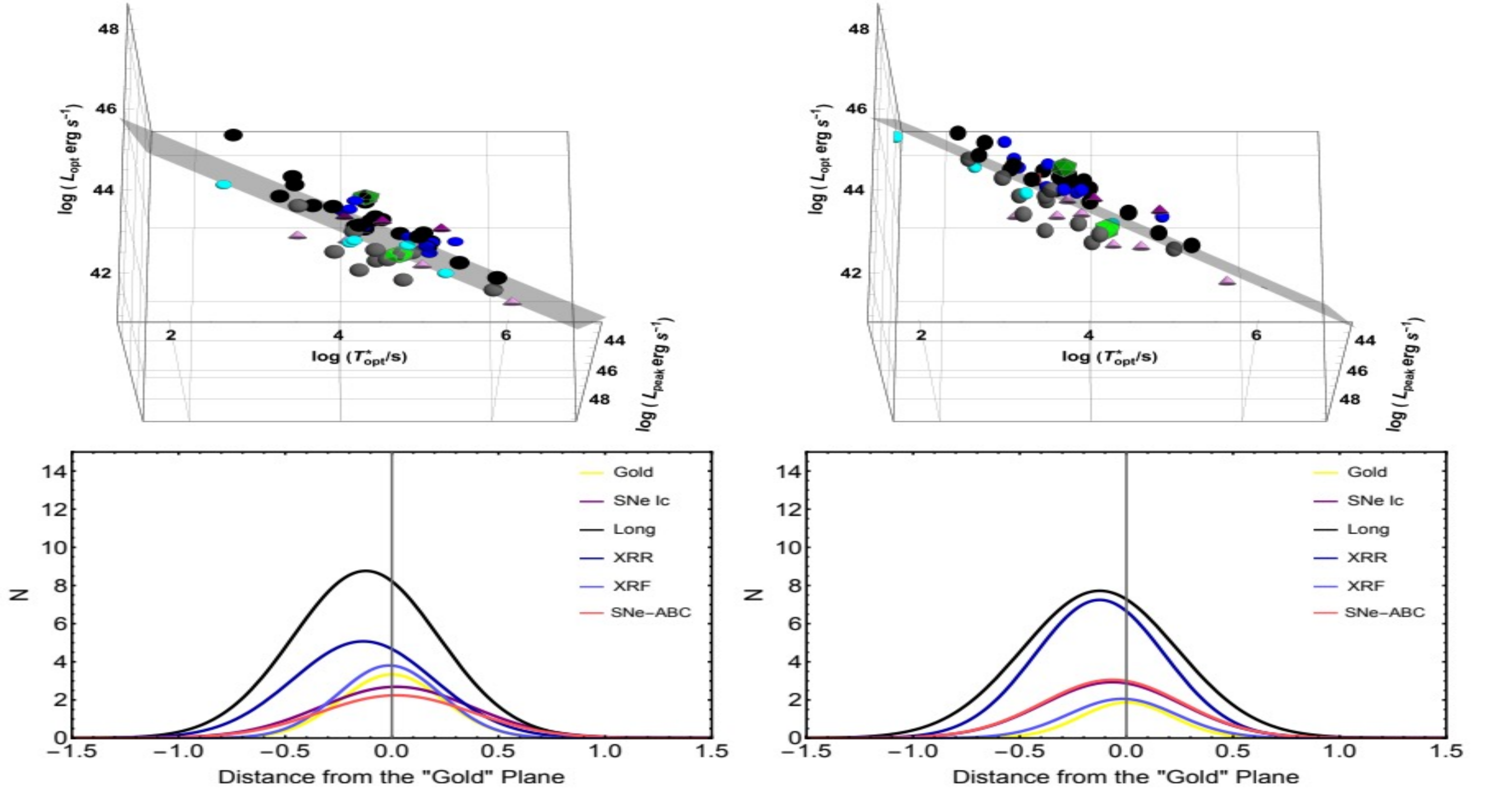


Figure 5. Upper panels: 58 GRBs in the $L^{(\prime)}_{\rm opt} - T^{(*/\prime)}_{\rm opt} - L^{(\prime)}_{\rm opt}$ parameter space with the fitted plane parameters in Table 2, including LGRBs (black circles), SGRBs (red cuboids), GRB-SNe Ic (purple cones), XRFs and XRRs (blue spheres), and ULGRBs (green 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.

- Black→Long
- Gold→ Gold
- 12 Blue→ XRF, XRR
- Green->UL
- 4 Red→ Short
- 1 Red → Short-KN
- 8 Orange→ GRB-SNe Ib/c

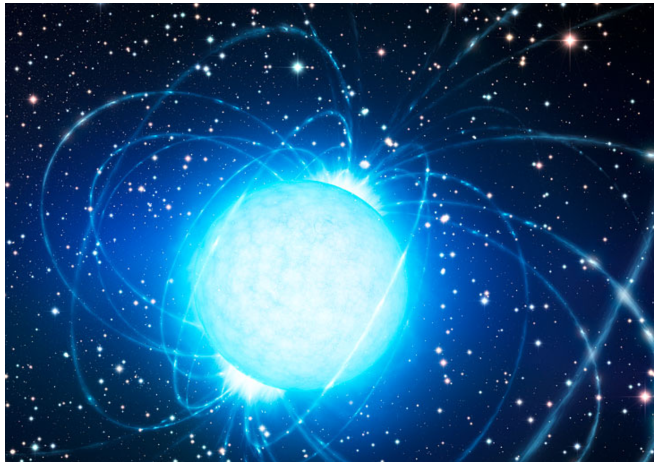
The physical interpretation of the plateau

The GRB plateau emission can be described through two models:

Fallback accretion onto a black hole

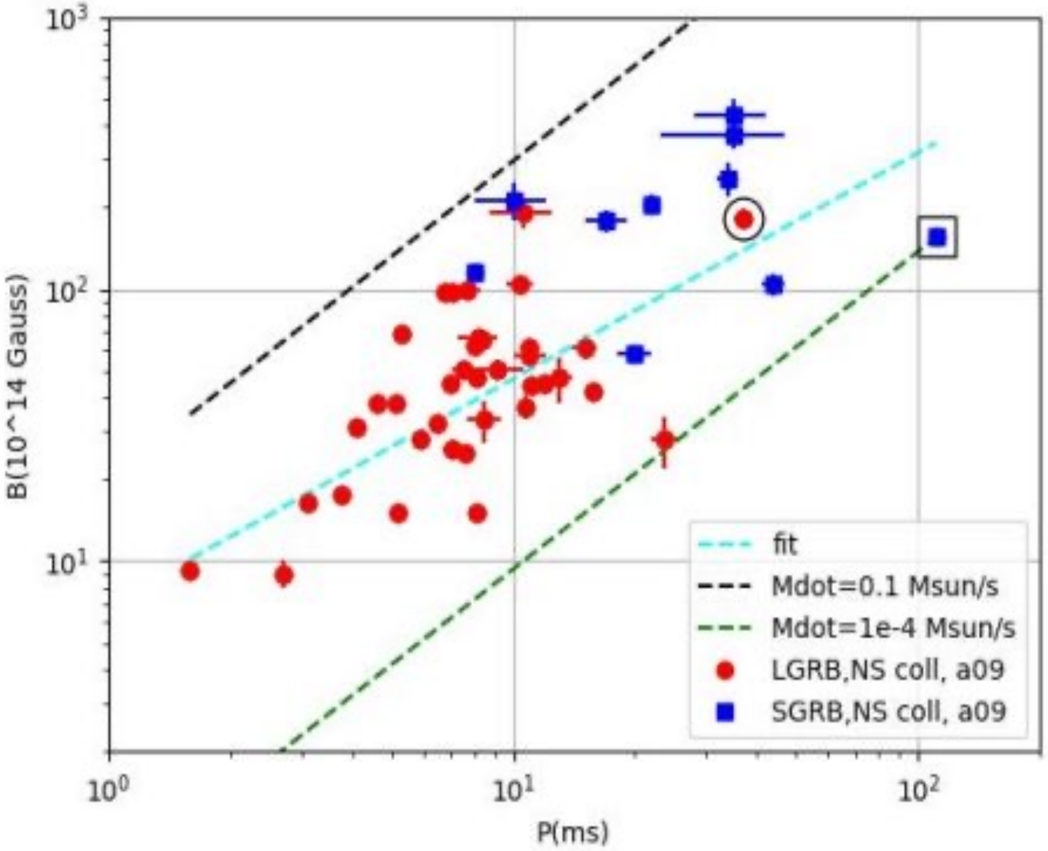
P. Kumar, et al., 2008, MNRAS, 388, 4, 1729-1742

Spinning down of a magnetar



A. Rowlinson, et al., 2014, MNRAS, 443, 2, 1779-1787

Two different classes within the magnetar scenario



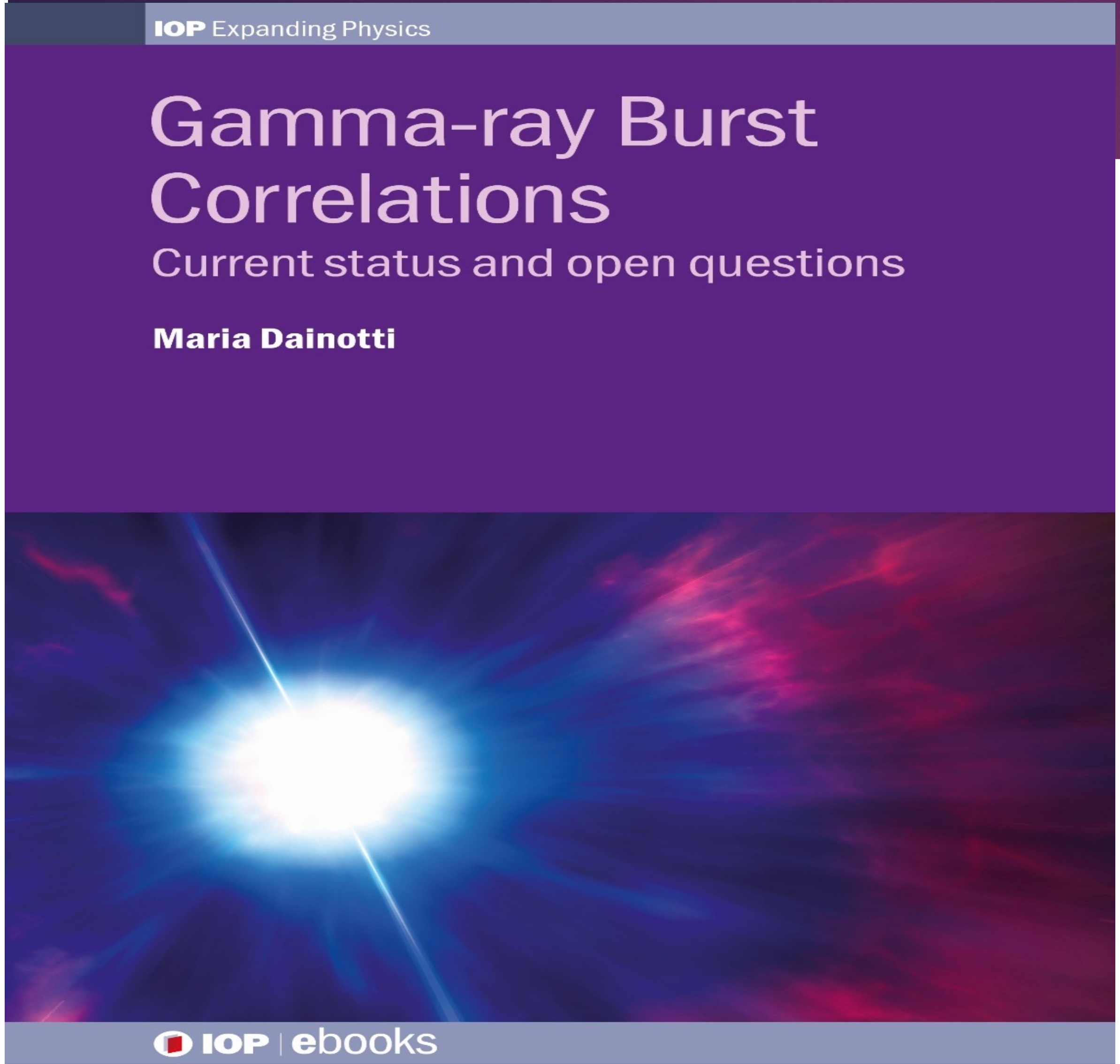
G. Stratta, M. G. Dainotti, S. Dall'Osso, X. Hernandez, G. De Cesare, 2018, ApJ, 869, 155

- The spin-down luminosity of the magnetar is entirely beamed within **ϴjet** (=jet opening angle)
- The long GRB 070208 (circle) and the peculiar GRB 060614A (square).

- Previous literature: S. Dall'Osso et al. 2011, M. G. Bernardini et al. 2012, 2013, 2015, **A. Rowlinson et al. 2014 including Dainotti, N. Rea et al. 2015 (including Dainotti)**, **P.** Beniamini et al. 2017, P. Beniamini & R. Mochkovitch 2017.

- Within the external shock model (G. Srinivasagaravan, M. G. **Dainotti et al. 2020**, D. Warren et al. 2017).

For a more a complete review see



A series of review papers:

Dainotti, M.G., & del Vecchio, R., "Gamma Ray Burst afterglow and prompt-afterglow relations: An overview", NAREV, 77, 23 (2017).

Dainotti, M.G., del Vecchio, R. & Tarnopolski, M., "Gamma Ray Burst Prompt correlations" Advances in Astronomy, vol. 2018, id. 4969503.

Dainotti & Amati, "Gamma Ray Burst selection effects in prompt correlations: an overview", PASP, 30, 987, 051001 (2018b).

Conclusions I: towards standard candles

- The 3D correlation for the gold sample has a σ_{int} 54% smaller than the long GRBs for the Lx-Ta correlation.

↓

It is the tightest three parameter correlation including the plateau phase.

- The statistical difference of the planes of short and long GRBs

↓

a difference in the B, P diagram of the magnetars.

- It also holds for Fermi-GBM bursts.

Are you ready for the BIG news?

The fundamental plane relation for new classes: Ambushing the standard candle in its own nest

M. G. Dainotti, A. Lenart, G. Sarracino, S. Nagataki, S. Capozziello, N. Fraija, 2020, ApJ, 904, 2, 97, 13

- **The platinum sample:** a subset of the gold sample obtained after removing gold GRBs with at least one of the following features:
  - Tx is inside a large gap of the data, and thus has a large uncertainty.
  - A small plateau duration <500 s with gaps after it. This could mean that the plateau phase is longer than the one observed.
  - Flares and bumps at the start and during the plateau phase.
  - It reduces the scatter of 31%, σint=0.22.

Press release distributed by the AAS, issued by Jagiellonian, Space Science Institute, and by INAF (Italian National Astrophysics Institute) and interview by INAF.

The fundamental plane relation for new classes

M. G. Dainotti, et al., 2020, ApJ, 904, 2, 97, 13

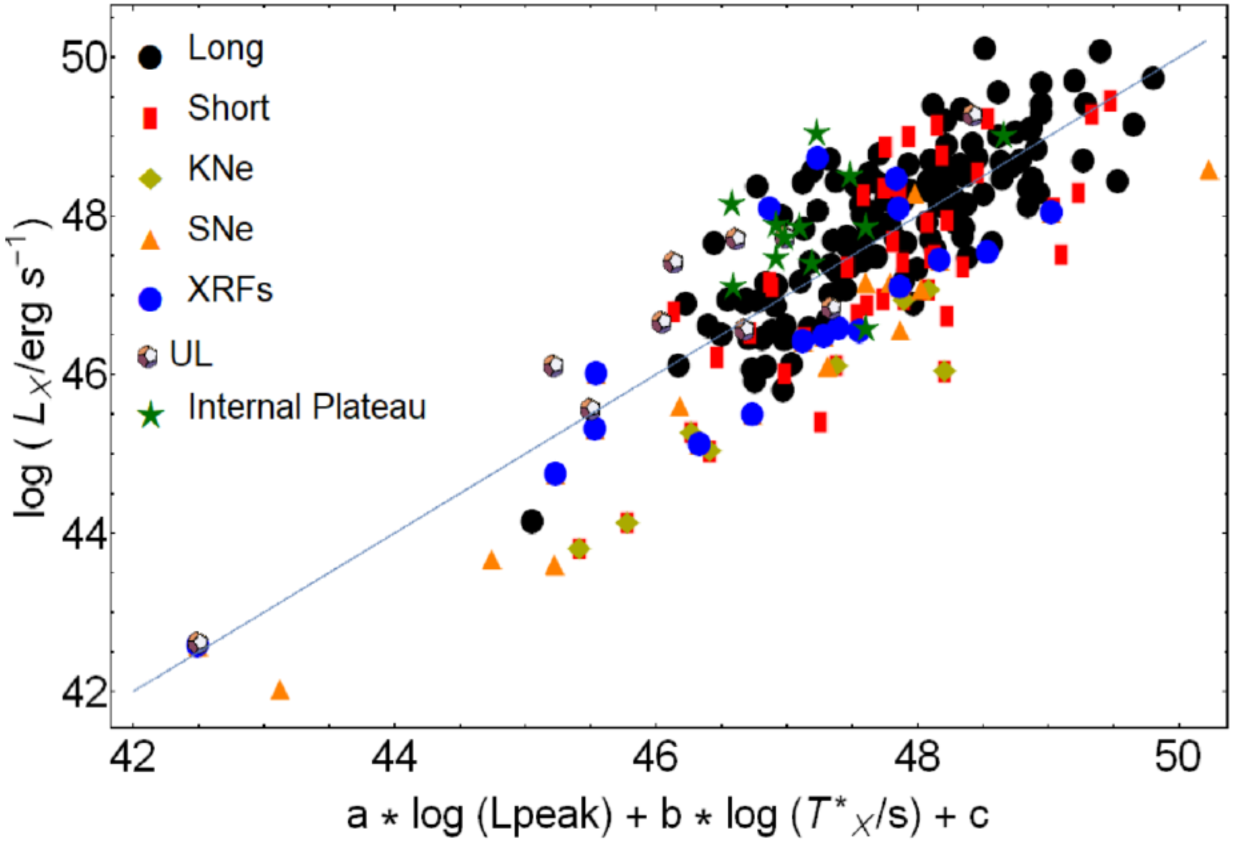


Figure 1. The 2D projection of the $L_X - T^*_X - L_{peak}$ relation for the 222 GRBs of our sample, with a plane fitted including LGRBs (black circles), SGRBs (red rectangles), KN-SGRBs (dark yellow rhombuses), SN-LGRBs (orange triangles), XRFs (blue circles), ULGRBs (dodecahedrons), and GRBs with internal plateaus (green stars).

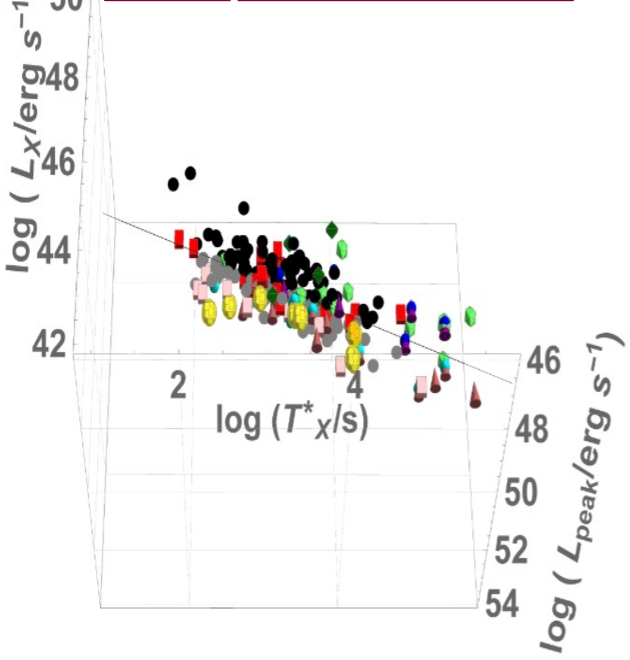
- KNe are transient objects which are derived by the mergers of two neutron stars.
- Several KN have been associated with short GRBs.
- All cases are presented in A. Rossi et al. 2020.

- The temporal power-law (PL) decay index of the plateau, α_i: a very steep decay, $\alpha_i \geq 3$ for L. Li et al. (2018) and $\alpha_i \geq 4$ for N. Lyons et al. (2010), indicates the internal origin of the plateau (R. Willingale, et al., 2007) related to the magnetar.

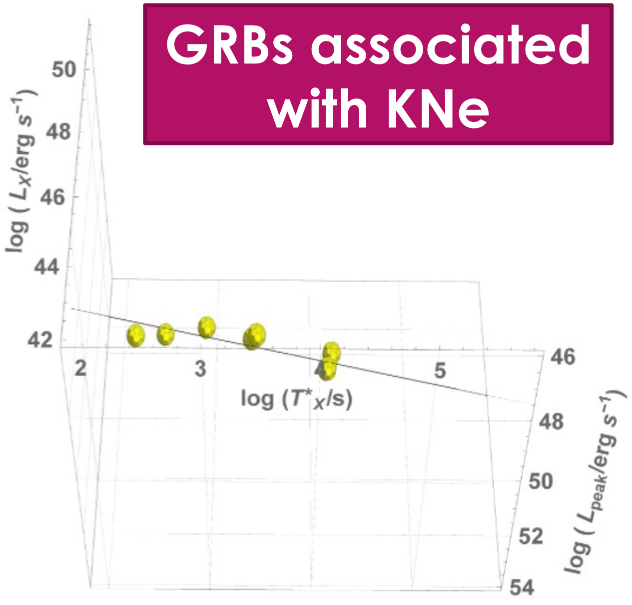
3D fundamental plane relations for different samples: the whole, GRBs associated with KNe and SGRB and KNe.

M. G. Dainotti et al. 2020, ApJ, 904, issue 2, 97, 13

All GRBs with plateaus



GRBs associated with KNe



SGRBs and SGRBs-KNe

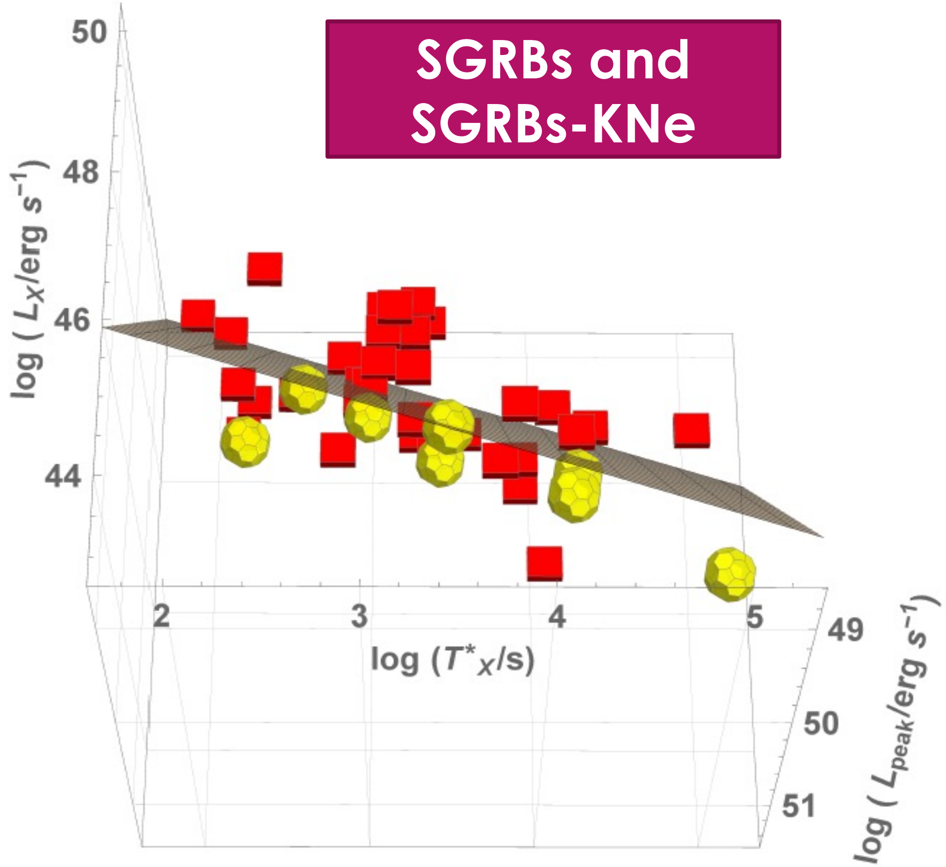


Figure 2. left panel: 222 GRBs in the $L_X - T^*_X - L_{peak}$ parameter space, with a fitted plane including SN-LGRBs (purple cones), XRFs (blue spheres), SGRBs (red cuboids), LGRBs (black circles), ULGRBs (green dodecahedrons), KN-SGRBs (yellow truncated icosahedrons) and GRBs with internal plateau (dark green diamonds). Darker colors indicate GRBs above the plane, while lighter colors GRBs below the plane. This figure shows the edge on projection. right panel shows the same fitting, but with only the KN-SGRB.

Figure 8. The $L_X - T^*_X - L_{peak}$ relation for the SGRB sample with separated KN-SGRB cases. We note here that all the KN-SGRBs fall below the best-fitting plane.

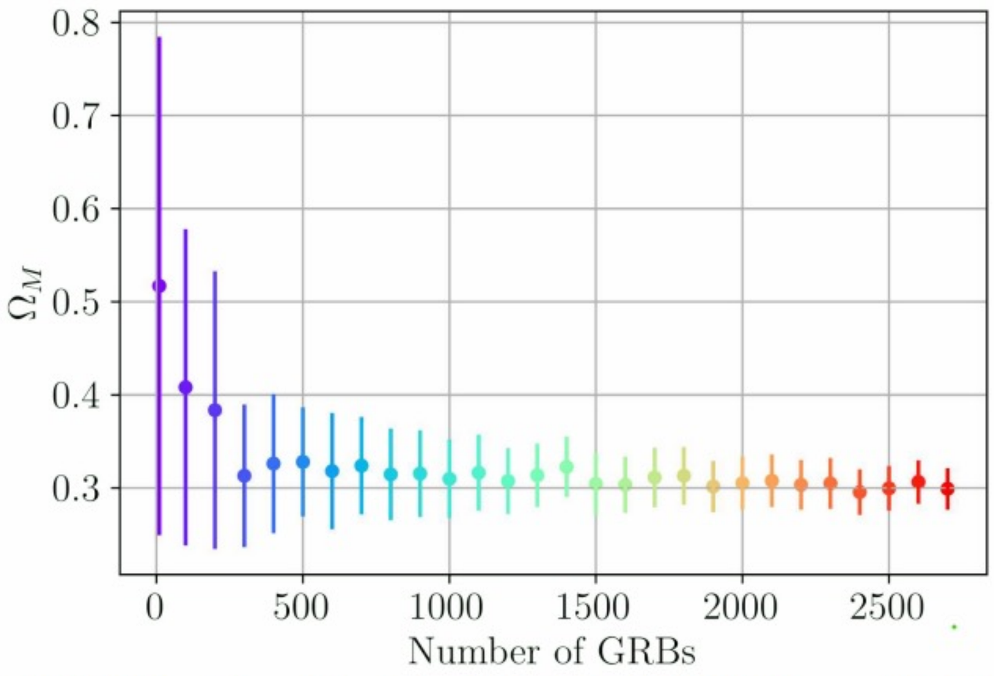
Conclusions II: towards standard candles

- New samples: the Gold Sample and Platinum.
  - Gold: reduced σ by 54% compared to the 2D Lx-Ta relation.
  - Platinum: reduces σ in the updated sample of the 3D relation by 31.3%.
- GRBs-KNe sample has a comparable σ compared to the Platinum.
- z-scores → SGRB-KNe, SGRB and SN-LGRBs have a different plane compared to the gold.
- SGRB-KNe are always below the SGRB fundamental plane
- These results are confirmed once evolution effects are accounted for.
- Luminosity-time holds for optical and may → standardize candles
- Match between theory and observations → smaller scatter for fundamental plane

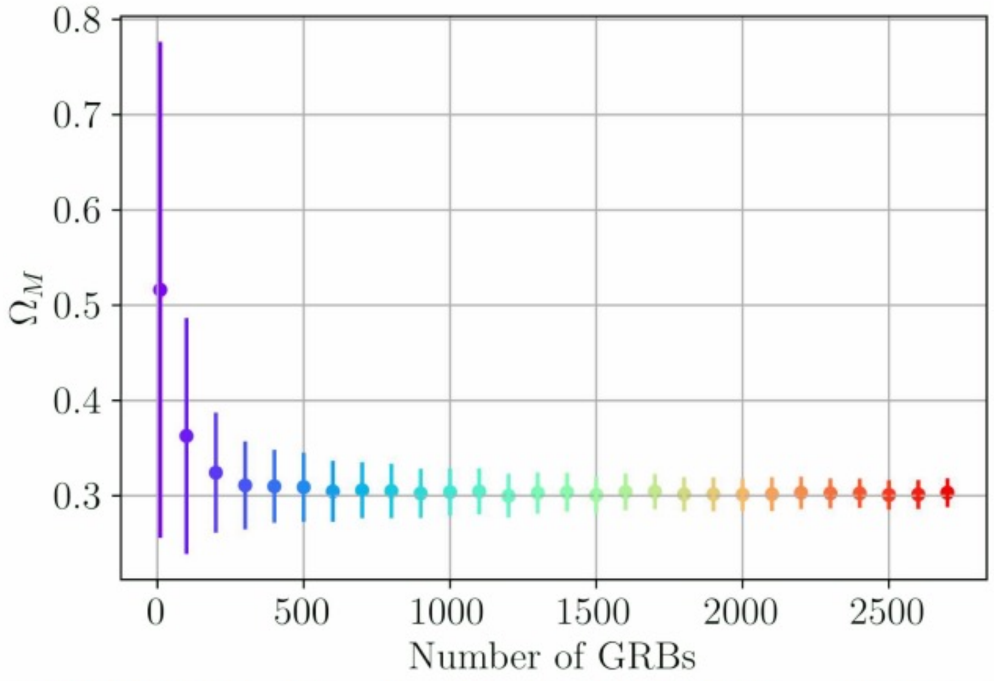
Now, are you ready for GRB-cosmology?

THE PRECISION ON Ω_M WITH GRBs

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



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



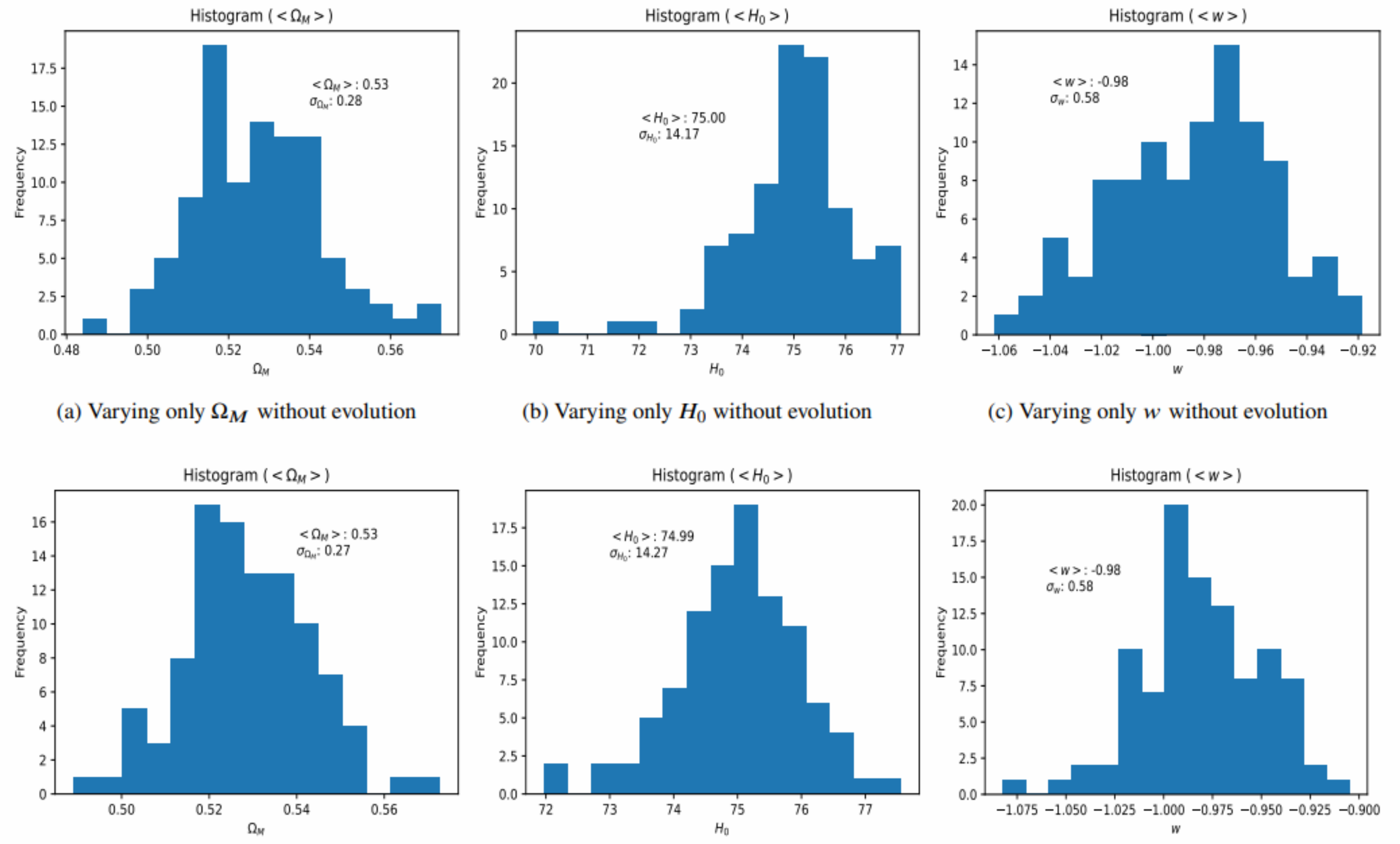
(b) OPTICAL | Simulation Results for the Full OPT Base with Halved Errors

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	With Machine learning (ML), errors on the parameters halved (n=2), and Lightcurve reconstruction (LCR)
134	Betoule et al. 2014 precision $\sigma\Omega_M = 0.042$	2026	
390	Scolnic et al. 2018 precision $\sigma\Omega_M = 0.022$	2042	

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

The latest cosmological results with GRBs only



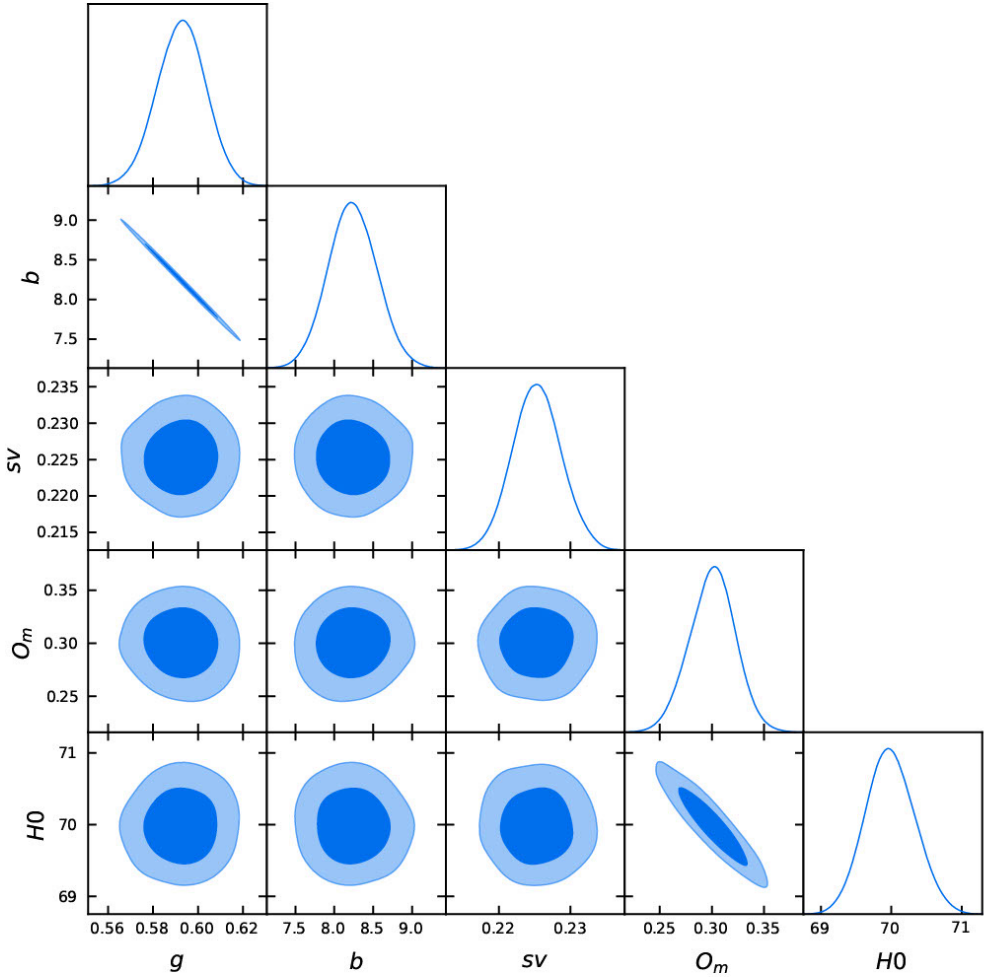
(a) Varying only Ω_M without evolution
(b) Varying only H_0 without evolution
(c) Varying only w without evolution
(d) Varying only Ω_M with fixed evolution
(e) Varying only H_0 with fixed evolution
(f) Varying only w with fixed evolution

M. G. Dainotti, A. Lenart, et al., 2022, MNRAS, 518, 2, 2201-2240

Results from QSO cosmology

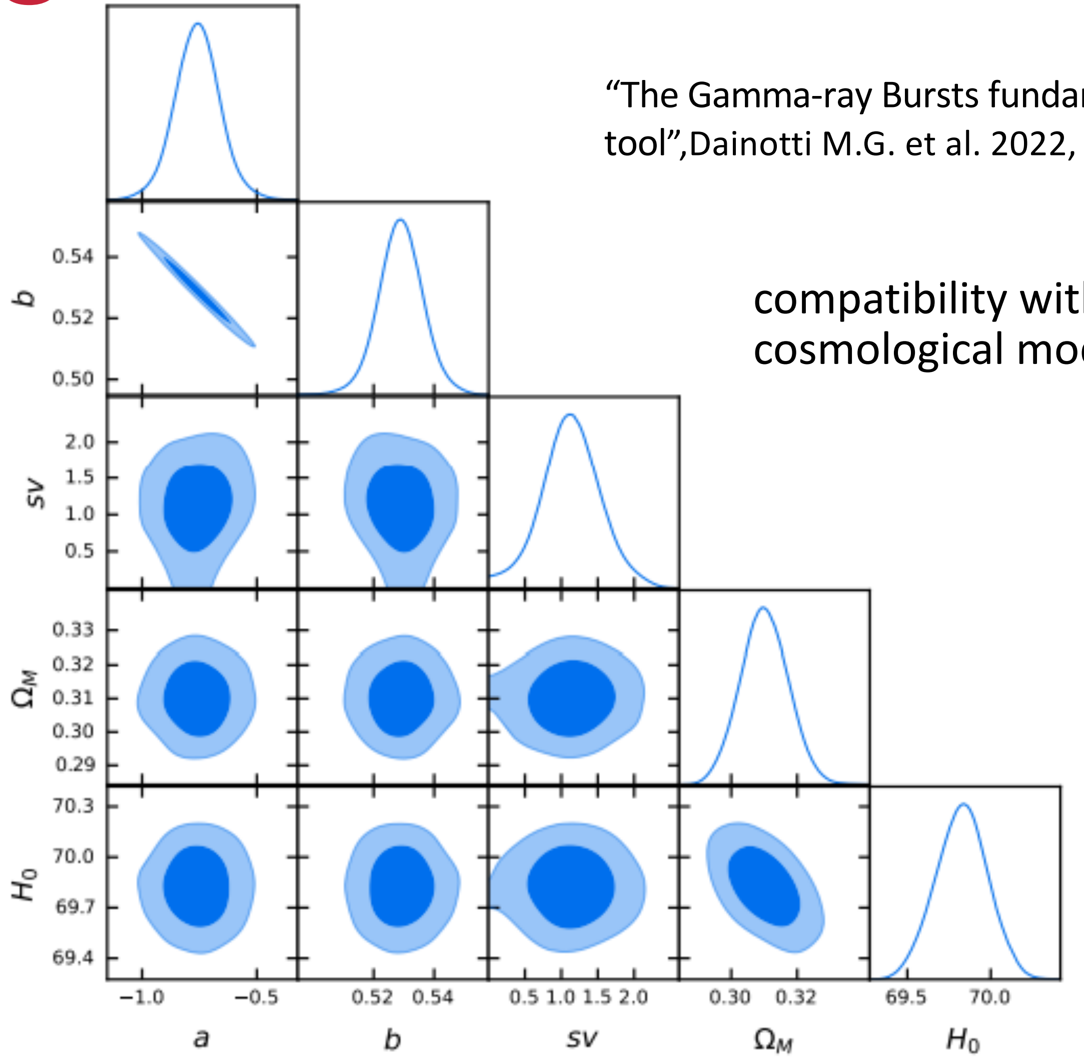
- QSOs+SNe Ia:

compatibility with standard cosmological model



"A bias-free cosmological analysis with quasars alleviating $H0$ tension", Lenart A.L., Bargiacchi G. et al. 2022, accepted in ApJS

Combining GRBs + SNe Ia + BAO



"The Gamma-ray Bursts fundamental plane correlation as a cosmological tool",Dainotti M.G. et al. 2022, MNRAS

compatibility with standard cosmological model

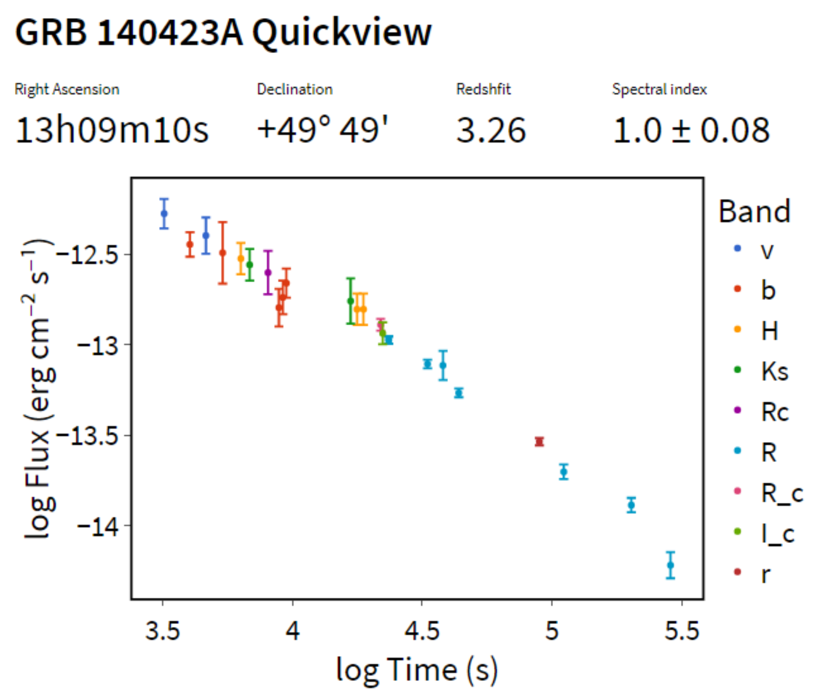
What else do we need for GRB cosmology?

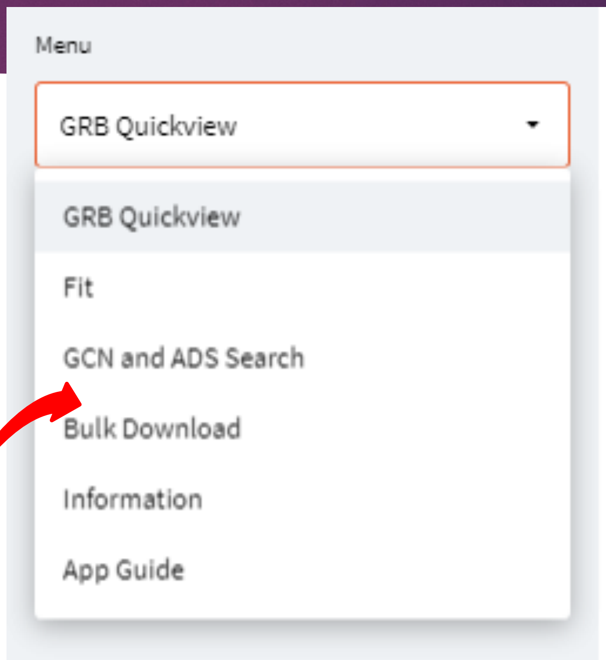
Reliable correlations and **Increase the sample size**

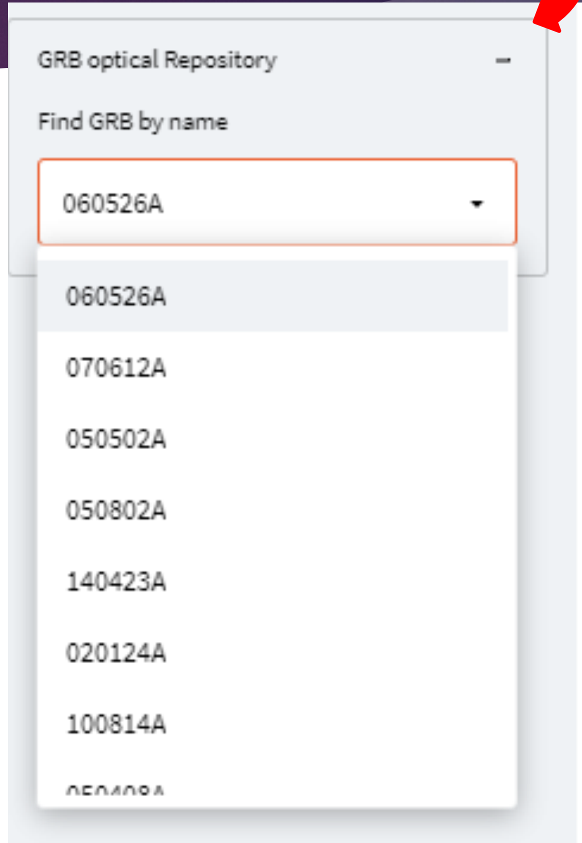
How?

Building a web-tool containing the largest GRB optical catalogue to date (including SUBARU and KISO observations)

524 optical GRBs with well-determined redshifts







<u>The menu list of the options provided</u>

M. G. Dainotti, the RATIR Collaboration, Oates, R. Fathima, D. Levine, B. De Simone, A. Chakraborty, Y. Niino, N. Tominaga, T. Moriya, T. Takiwaki, et al., 2022 (supported by the Exploratory Research Grant)

Pipeline for building the GRB catalog

Data collection — from GCNs, papers, ATel, private communications etc…

Uniforming the data files — rescaling the magnitudes after shift in AB system and Galactic extinction correction

Automatized fitting of the light curves — with 8 models

Conversion from magnitudes to fluxes — flux normalized to R Cousins (R_c) band

First step: collection of 524 GRBs

140423A_arXiv_gcn_mag.txt - Blocco note

File Modifica Visualizza

```
Time(s) Mag MagErr Filter System Observatory/Telescope GalExtCorr Source
164.96 13.66 0.02 I Johnson KAIT n arXiv2008.02445
262.96 13.77 0.02 I Johnson KAIT n arXiv2008.02445
360.96 13.98 0.02 I Johnson KAIT n arXiv2008.02445
458.96 14.37 0.02 I Johnson KAIT n arXiv2008.02445
561.96 14.5 0.02 I Johnson KAIT n arXiv2008.02445
661.96 14.65 0.03 I Johnson KAIT n arXiv2008.02445
762.96 14.82 0.02 I Johnson KAIT n arXiv2008.02445
865.96 15.02 0.03 I Johnson KAIT n arXiv2008.02445
965.96 15.21 0.04 I Johnson KAIT n arXiv2008.02445
1064.96 15.38 0.04 I Johnson KAIT n arXiv2008.02445
1167.96 15.56 0.05 I Johnson KAIT n arXiv2008.02445
1267.96 15.71 0.05 I Johnson KAIT n arXiv2008.02445
1367.96 15.84 0.05 I Johnson KAIT n arXiv2008.02445
1468.96 16.21 0.09 I Johnson KAIT n arXiv2008.02445
1570.96 16.19 0.07 I Johnson KAIT n arXiv2008.02445
```

Information provided

Midtime of the observation after the satellite trigger (s), magnitude with 1σ error, filter, magnitude system, telescope, corrected for galactic extinction?(y/n), source of data (arXiv,GCN,…)

+ Equatorial coordinates, spectral index, redshift

Correct for Galactic extinction
Shift into AB system

We correct the reddening on magnitudes via the **Schafly et al. (2011) dust map**

or, if the filter is not available in Schafly

↓

ASIAGO Database (ADPS)

↓

We correct for the Galactic extinction

↓

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

Time duplicates removal

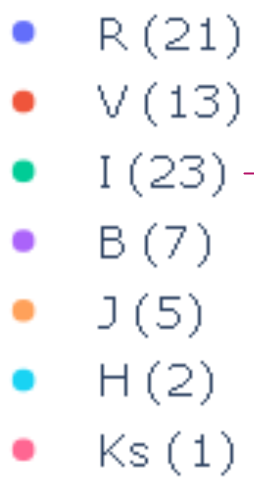
We remove the points with least numerous filter

Removal of time duplicate magnitudes

(if their $\log_{10} t$ values are equal up to the 2nd digit)

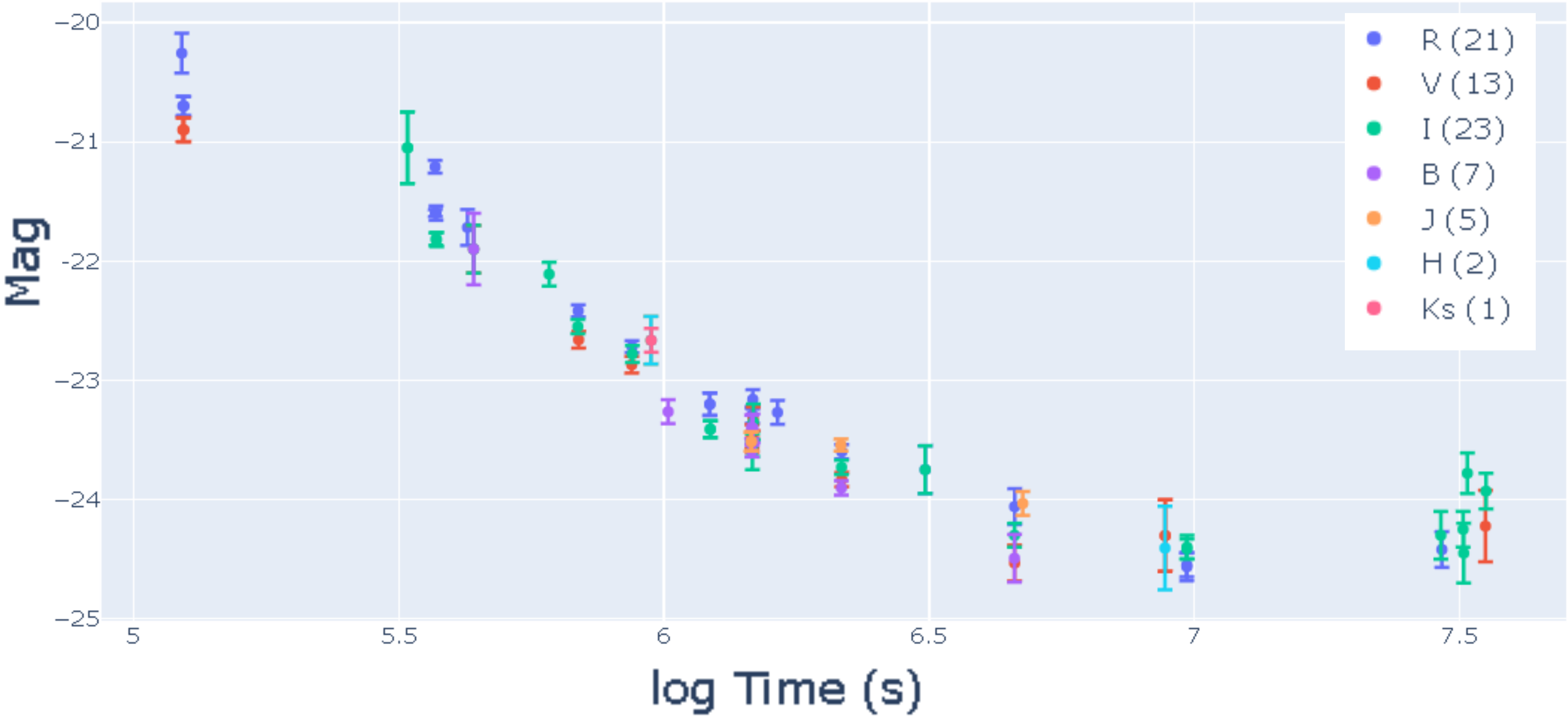
Before the rescaling (coincident times)

E.g. GRB 000911A



Most numerous

After the rescaling factor (coincident times)



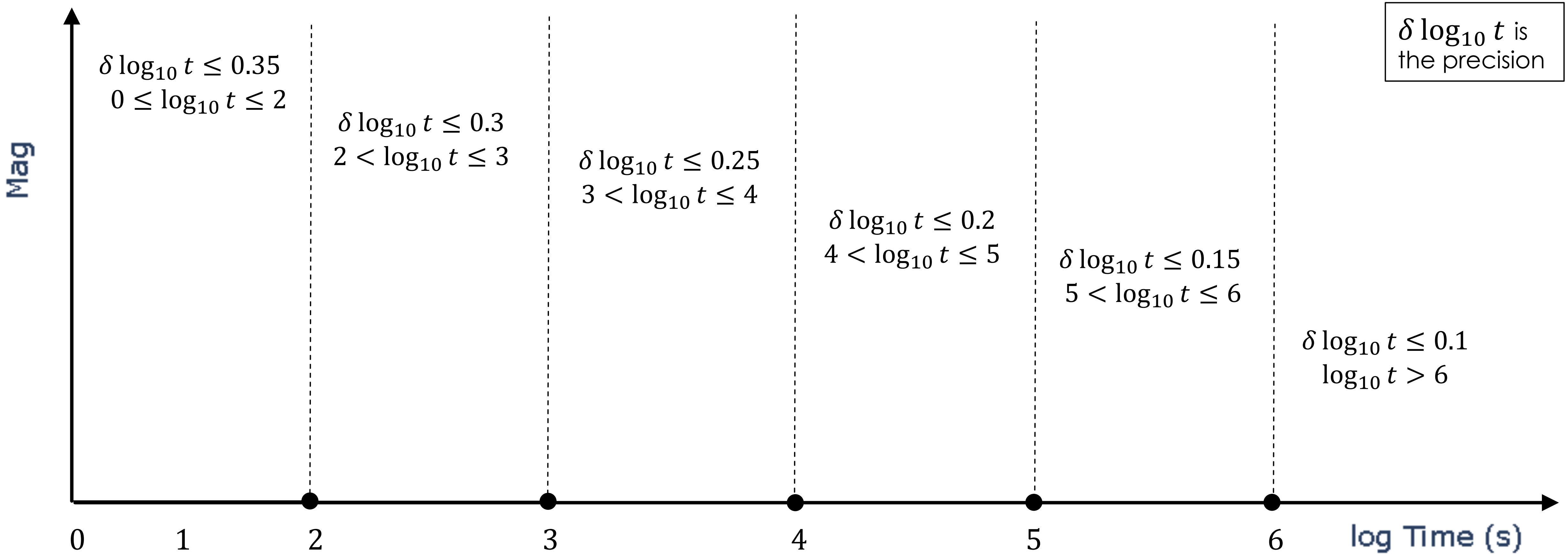
E.g. GRB 000911A

If we have

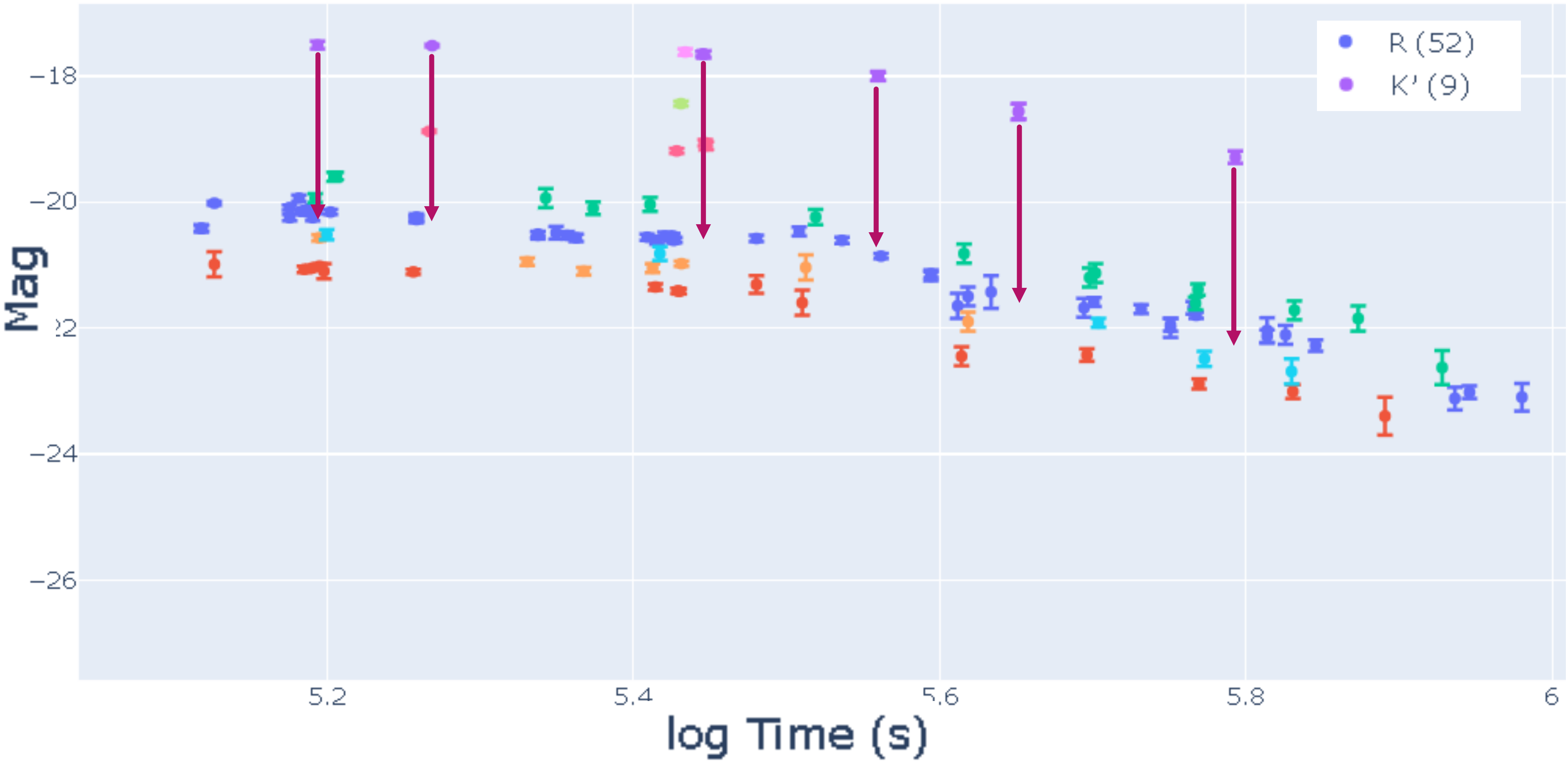
$\log_{10} t\,(\mathrm{I}) = \log_{10} t\,(\mathrm{B})$

Rescaling factor = difference between the magnitudes

The division of the light curve for the rescaling with no coincident times



Before rescaling (not coincident times)



E.g. rescaling K' to R

$$5 < \log_{10} t \leq 6$$
$$\delta \log_{10} t \leq 0.15$$

If we have

$$|\log_{10} t\,(\mathrm{K}') - \log_{10} t\,(\mathrm{R})| \leq 0.15$$

their magnitude difference (the purple arrow) is the <u>rescaling factor</u>

Average between all the $K' - R$ rescaling factors within each interval

After rescaling (not coincident times)

K' are rescaled to R only if K' are close to an R point at least of $\delta \log_{10} t$ and their magnitudes are not compatible in 1σ

After rescaling, <u>removal of time duplicate magnitudes</u>

(if their $\log_{10} t$ values are equal up to the 2nd digit)

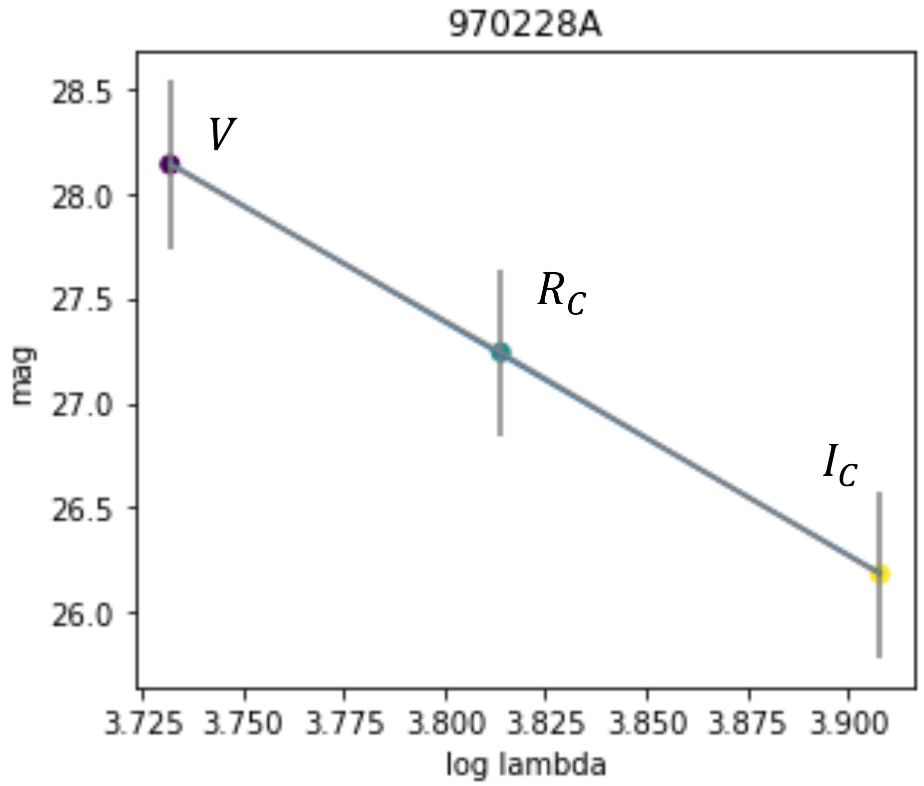
The spectral analysis

If the optical spectral index (β) is not present in literature, we perform a spectral analysis

Identifying duplicate magnitudes (exact same time or following the $\delta \log_{10} t$ criterion when no coindent times are present)

Fitting magnitude vs log10 wavelength (Angstroms)

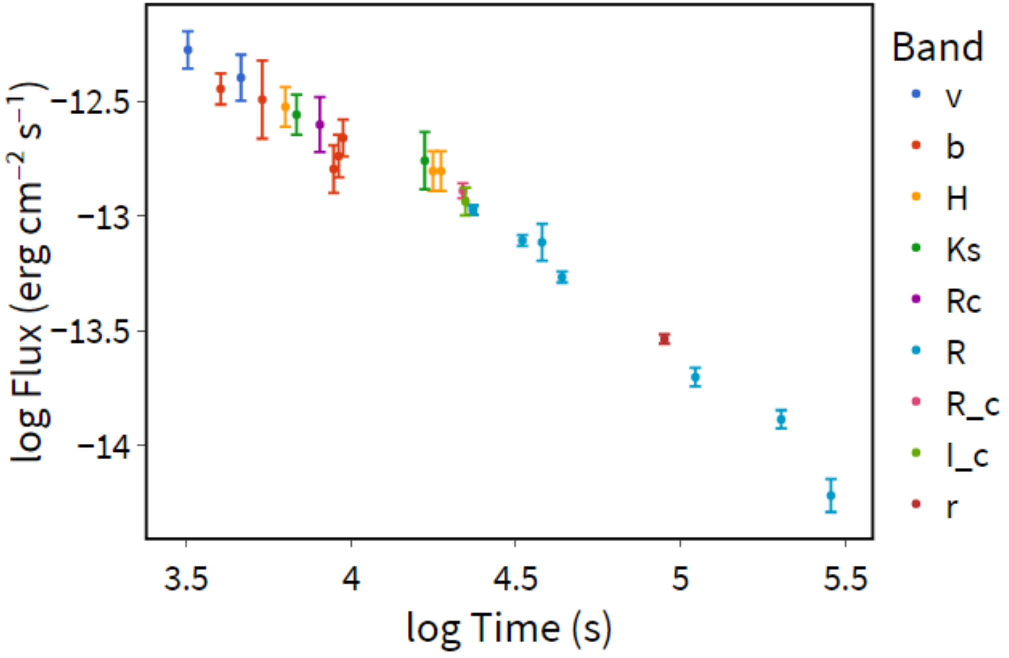
Fitting slope/2.5 = β



Converting from magnitudes to fluxes

GRB 140423A Quickview

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



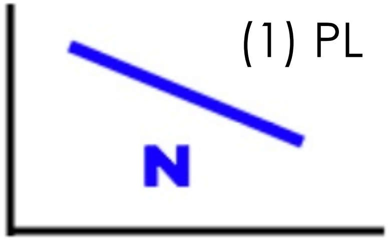
$$\text{Flux} = \lambda_R f_X \left(\frac{\lambda_X}{\lambda_R}\right)^{-\beta} (10)^{-m/2.5}$$

λ_R: wavelength of the R_c band
λ_X: wavelength of the X filter
f_X: flux in the X filter
m: magnitude (ext.corr., AB sys.)
β: spectral index

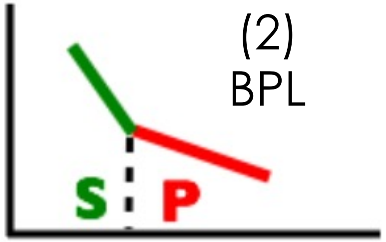
$$\sigma = |\text{Flux}|\sqrt{\left(\frac{\sigma_m}{2.5}\log 10\right)^2 + \left(\sigma_\beta \log\left(\frac{\lambda_X}{\lambda_R}\right)\right)^2}$$

Fitting the light curve models

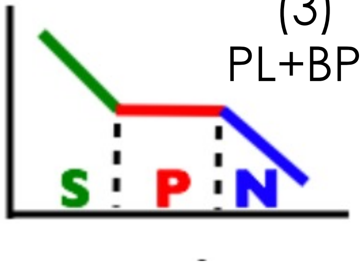
(1) Power law (PL), (2) Broken power law (BPL), (3) PL+ BPL, (4) PL+ BPL+PL, (5) Willingale function (W07, Willingale et al. 2007), (6) W07 + PL, (7) W07 + BPL, and (8) W07 + BPL + PL



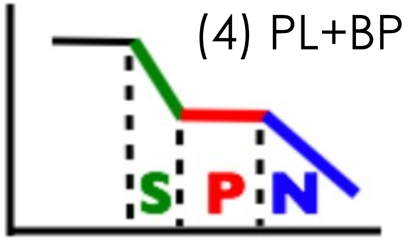
(1) PL



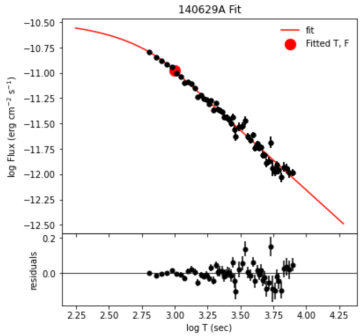
(2) BPL



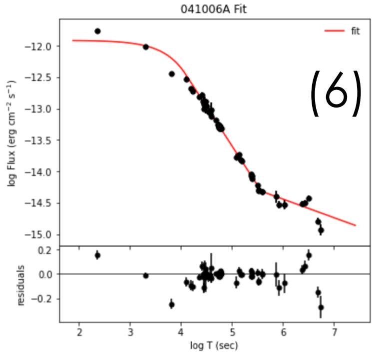
(3) PL+BPL



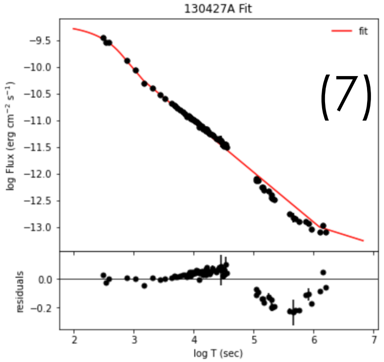
(4) PL+BPL+PL



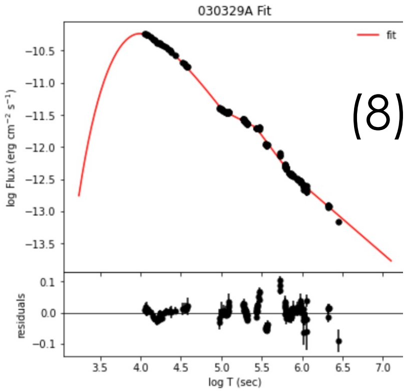
(5) W07



(6) W07+ PL



(7) W07+BPL



(8) W07+BPL+PL

Figures for (1), (2), (3), and (4) from Zaninoni et al. 2013

Similar to Roming et al. 2009, 2017

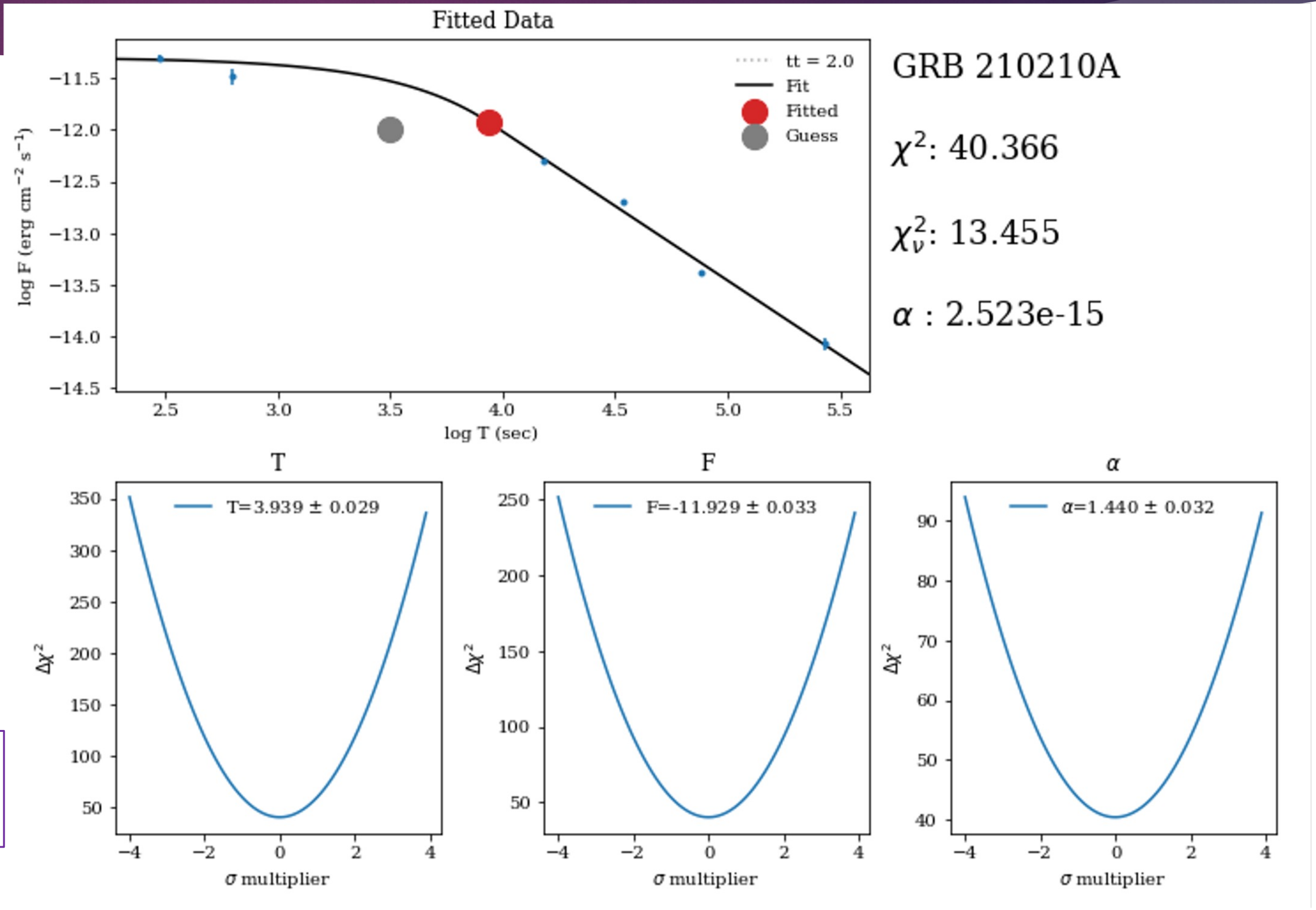
Fitting the Lightcurves

User Inputs Guess:

- Plateau start (tt)
- Time, Flux at end of Plateau (T, F)
- Temporal power-law decay index (α)
- Initial rise timescale (t)

$$f(t) = \begin{cases} F_c \exp\left(\alpha_c - \frac{t\alpha_c}{T_c}\right) \exp\left(-\frac{t_c}{t}\right) & \text{for } t < T_c \\ F_c \left(\frac{t}{T_c}\right)^{-\alpha_c} \exp\left(-\frac{t_c}{t}\right) & \text{for } t \geqslant T_c \end{cases},$$

A fitting example of GRB 210210A through the Willingale model



HOW THE WEB-APP LOOKS LIKE

Menu

GRB Quickview

GRB optical Repository

Find GRB by name

060526A

Gamma-ray Coordinates Network(GCN)

Enter GCN Number

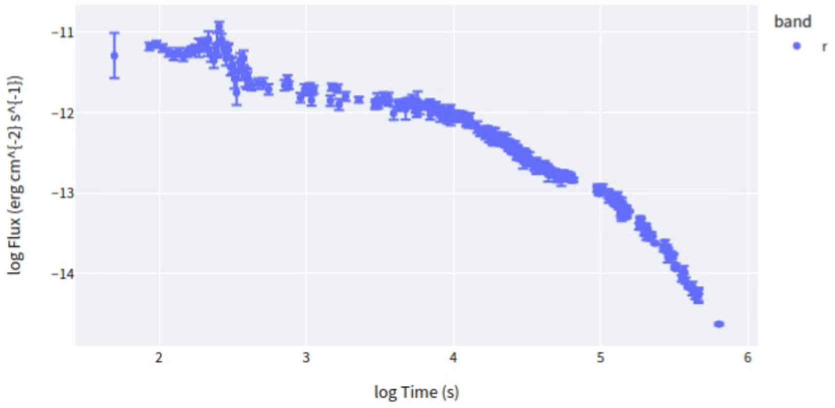
-

Gamma Ray Bursts Optical Repository

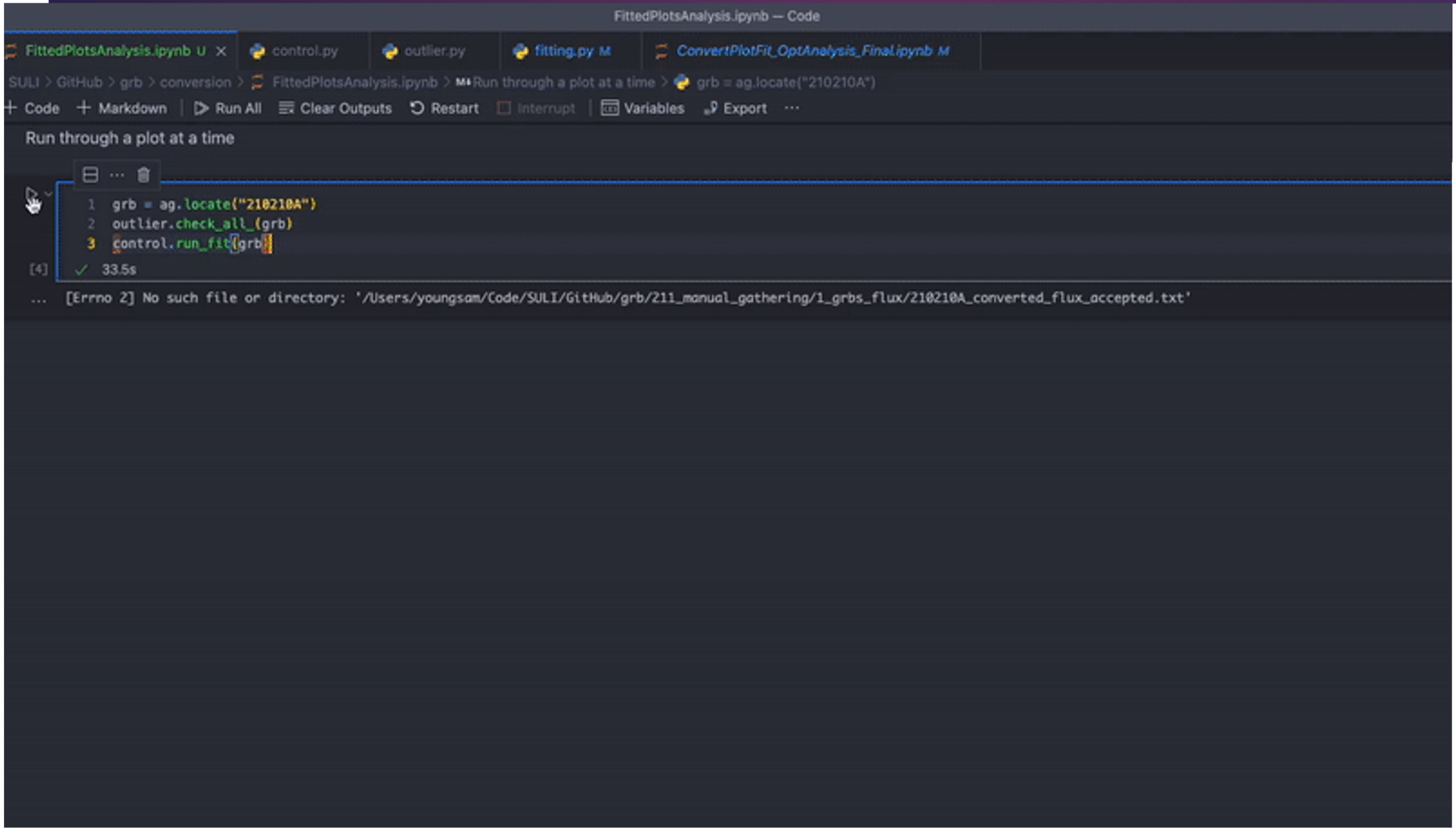
GRB 060526A Quickview

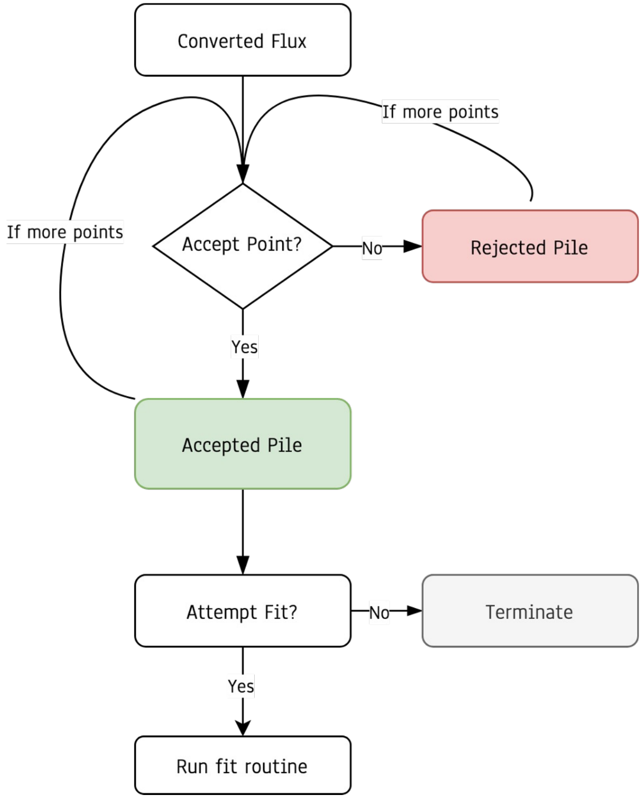
Right Ascension	Declination	Redshfit
15h31m23s	+00° 15'	3.21

Raw Data



If you want to discard points by youserlf: the end-user's process





A data catalog to perform GRB population studies, morphology, models and properties classification

- 42238 data points collected!
- 524 lightcurves gathered
- We are working on for
  - On-the-fly conversion from fitted flux to *luminosity*
  - Ability to download magnitude and flux data files in uniform format
  - Automatic plots with the embedded fitting, both Bayesian (MCMC) and χ^2 for LCs and spectra
  - Web scraper for automatizing data collection (ongoing)
  - Packaging for release to the scientific community

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

M. G. Dainotti, The RATIR Collaboration, R. Fathima, B. De Simone, D. Levine, Y. Niino, Oates, Cenko et al., 2022
(supported by Exploratory Reseach Grant)

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