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M. G. Dainotti, B. De Simone, K. M. Islam, K. Kawaguchi, T. J. Moriya, T. Takiwaki, N. Tominaga, A. Gangopadhyay

Biagio De Simone

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The Quest for New Correlations in the Realm of the Gamma-Ray Burst—Supernova Connection

M. G. Dainotti^{1,2,3} , B. De Simone^{4,5} , K. M. Islam⁶ , K. Kawaguchi⁷ , T. J. Moriya^{1,2,8} , T. Takiwaki^{1,2} , N. Tominaga^{1,2,9,10} , and A. Gangopadhyay¹¹ 

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Visiting



6th February 2023

The extreme Universe viewed in very-high-energy gamma rays 2022

bdesimone@unisa.it

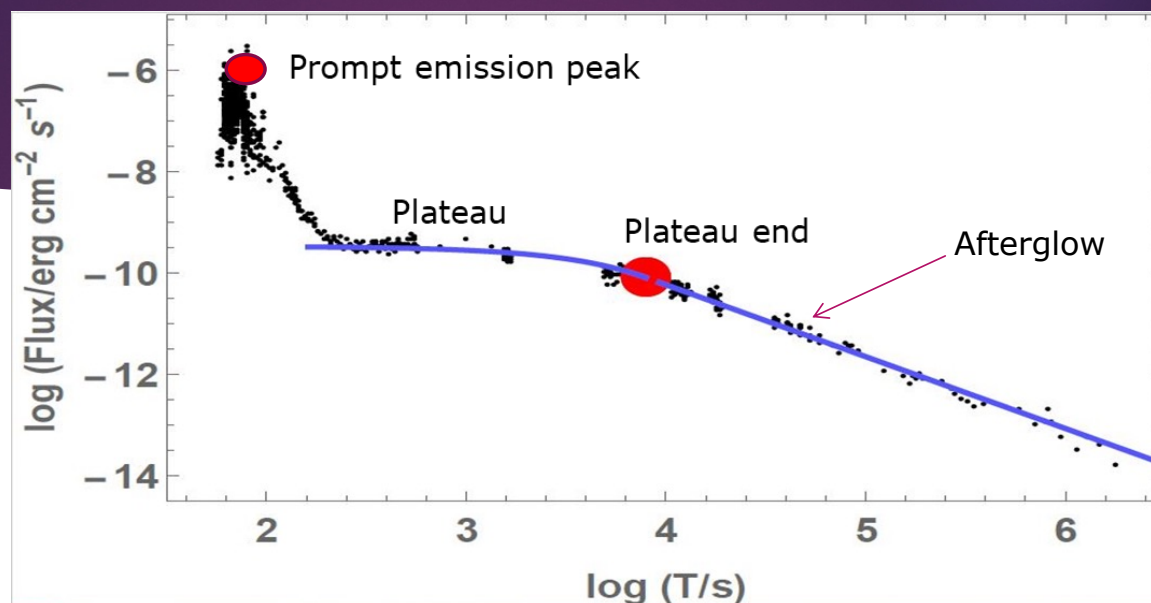
Outline of the talk

1. Introduction to Gamma-ray Bursts (GRBs)
2. The GRB and SN correlations
3. Introduction to Supernovae Ib/c (SNe Ib/c) and GRB-SNe connection
4. Outline of the research
5. The metrics and the fitting procedure
6. Results: the GRB optical plateau luminosity vs the SN peak time
7. Discussion and conclusions

What are Gamma Ray Bursts?

Plateau emission

An important feature observed in the 42% of Swift satellite GRBs (flattening of the afterglow)



A well-sampled GRB light curve (LC) observed Swift instruments (2004-ongoing).

The blue line is the phenomenological Willingale model (R. Willingale et al. 2007)

- ▶ Gamma Ray Bursts (GRBs) are flashes of high energy photons in the sky (typical duration is few seconds).
- ▶ Cosmological origin accepted (furthest GRBs observed $z \sim 9.4 - 13.14$ 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.

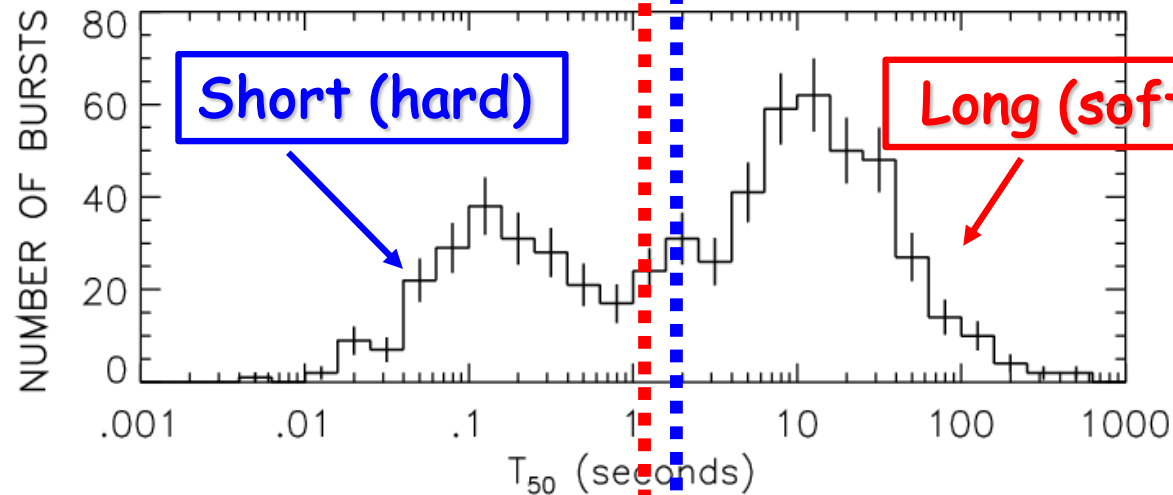
Short vs Long GRBs

4

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

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)



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

Short GRBs $\rightarrow T_{90} < 2 \text{ s}$

Long GRBs $\rightarrow T_{90} > 2 \text{ s}$

Short GRBs $\rightarrow T_{90} < 5 \text{ s}$

Long GRBs $\rightarrow T_{90} > 5 \text{ s}$

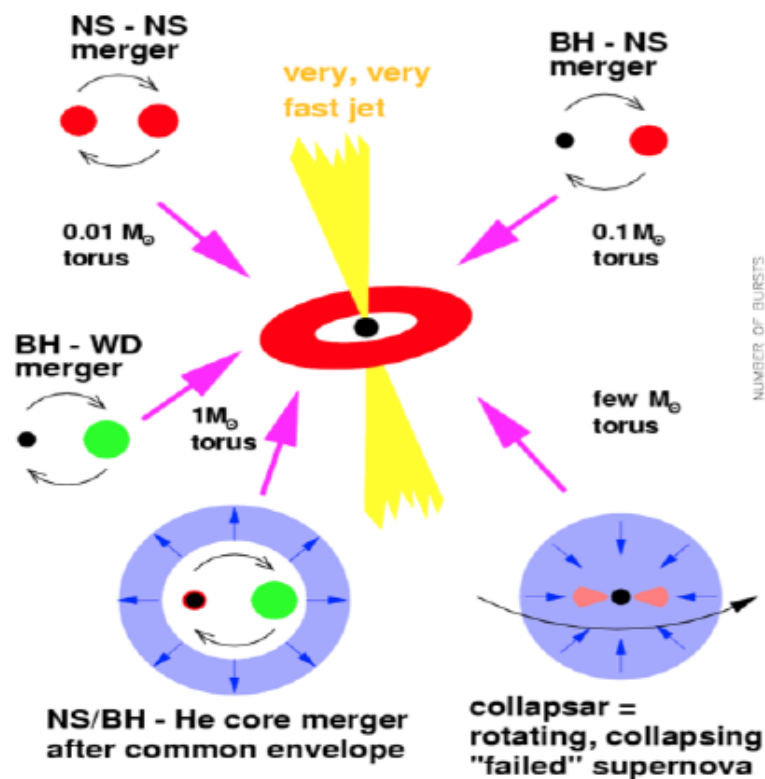
C. Kouveliotou et al., 1996, AIP Conf. Proc., 384, 42.
W. S. Paciesas et al., 1999, ApJS, 122, 465.

J. P. Norris & J. T. Bonnell 2006, intermediate class of GRBs with mixed properties.
O. Bromberg et al. 2013, ApJ, 764, 179 $T_{90} = 0.8 \text{ s}$ in Swift data

GRB progenitors

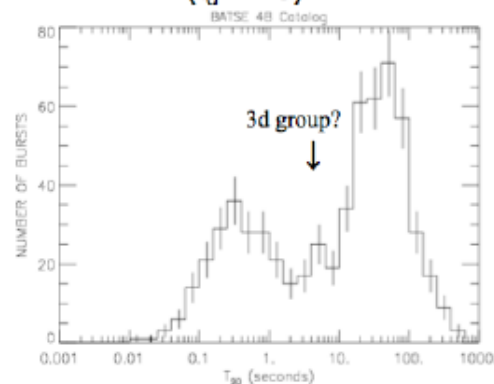
GRB: standard paradigm

Hyperaccreting Black Holes



Bimodal distribution of t_g duration

← ↓ Short
($t_g < 2$ s)



→ ↑ Long
($t_g > 2$ s)

Why are GRBs potential cosmological tools?

Because They...

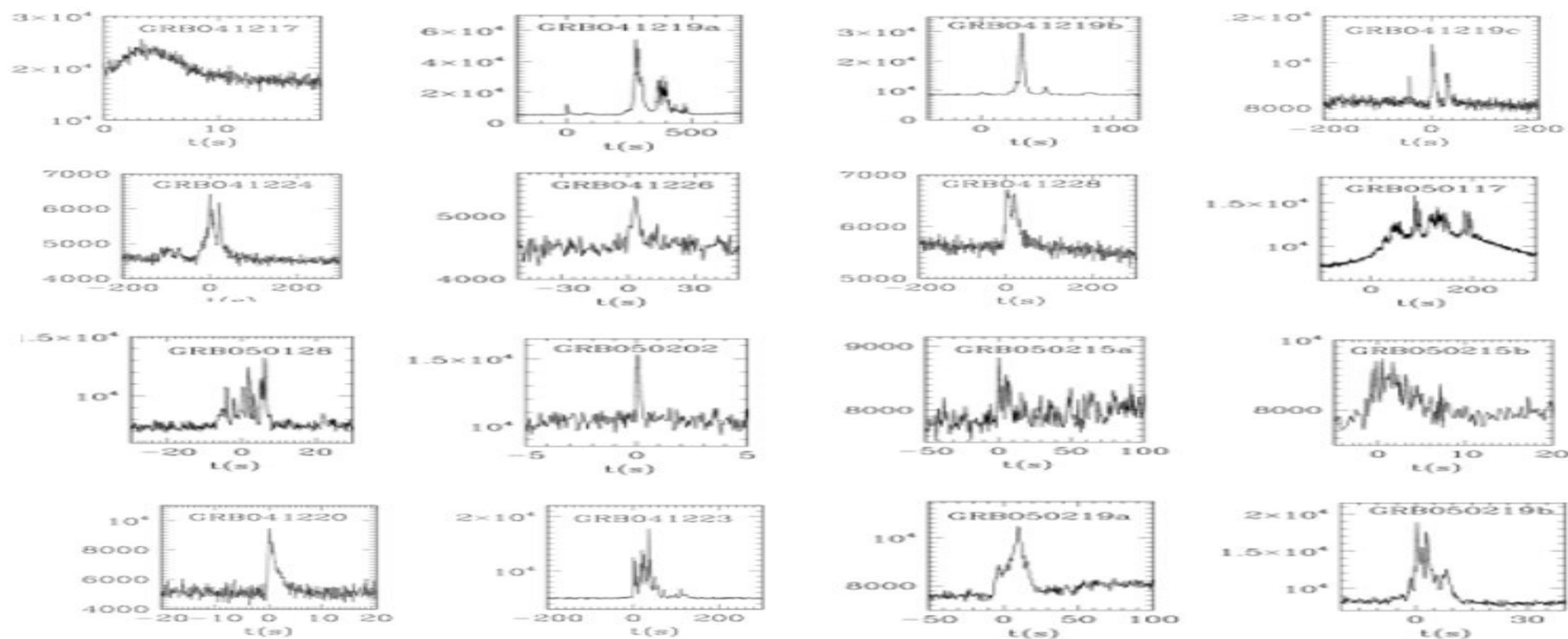
- ▶ Can be probes of the early evolution of the Universe.
- ▶ Are observed beyond the epoch of reionization.
- ▶ Allow us to investigate Pop III stars.
- ▶ Allow us to track the star formation.
- ▶ Are much more distant than Supernovae (SNe) Ia ($z_{obs}^{SNe Ia} \leq 2.26$) and quasars ($z_{obs}^{quasars} \leq 7.54$).

But They...

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

GRBs LCs vary widely

“If you've seen one GRB, you've seen one GRB” -> standardization is challenging



Swift lightcurves taken from the Swift repository

What are standard candles?

Standard candles: astrophysical object/phenomena with a fixed intrinsic luminosity or a well-known relation between the luminosity and other observable parameter(s), this(these) latter being not dependent on luminosity

E.g.: *Cepheids, Supernovae Type Ia*

Standardizable candles: **Gamma-ray Bursts (GRBs), Gamma-ray Bursts associated to Supernovae (GRB-SNe), Quasars, Supernovae Type II**

How to build a standard candle: GRB correlations

To build a standard candle from GRBs, correlations are needed!

GRB-GRB parameters

- *Amati et al. 2002 (Ep-Eiso)*
- *Yonetoku et al. 2004 (Ep-Lpeak)*
- *Ghirlanda et al. 2004 (Ep-Egamma)*
- *Oates et al. 2012 (brightness-decay rate for UVOT GRBs)*
- *Tsutsui & Shigeyama 2013 (scaling law)*

- *Dainotti et al. 2008, 2016, 2020b, 2022 (time-luminosity of plateau-end in X-rays, optical, and radio together with the 3D extension including the peak luminosity)*

Amati, Ghirlanda, Tsutsui, and Dainotti relations hold also for GRB-SNe

For GRB standardization, possible reliable candidates are the T_a - L_a and L_{peak} - L_a 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.

Dainotti 2D relation and Oates relation

$L_a - T^*_{aX}$ & $L_a - L_{pX}$ confirming the reliability after bias correction
L200s-alpha in optical

2008 2010 2011 2015

Dainotti 3D relation

$(L_a - T^*_{aX} - L_{pX})$
(reliable after bias correction)

2016 2017

Dainotti 2D relation

(probing this unbiased relation also in the optical and radio)

2020 2021 2022

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



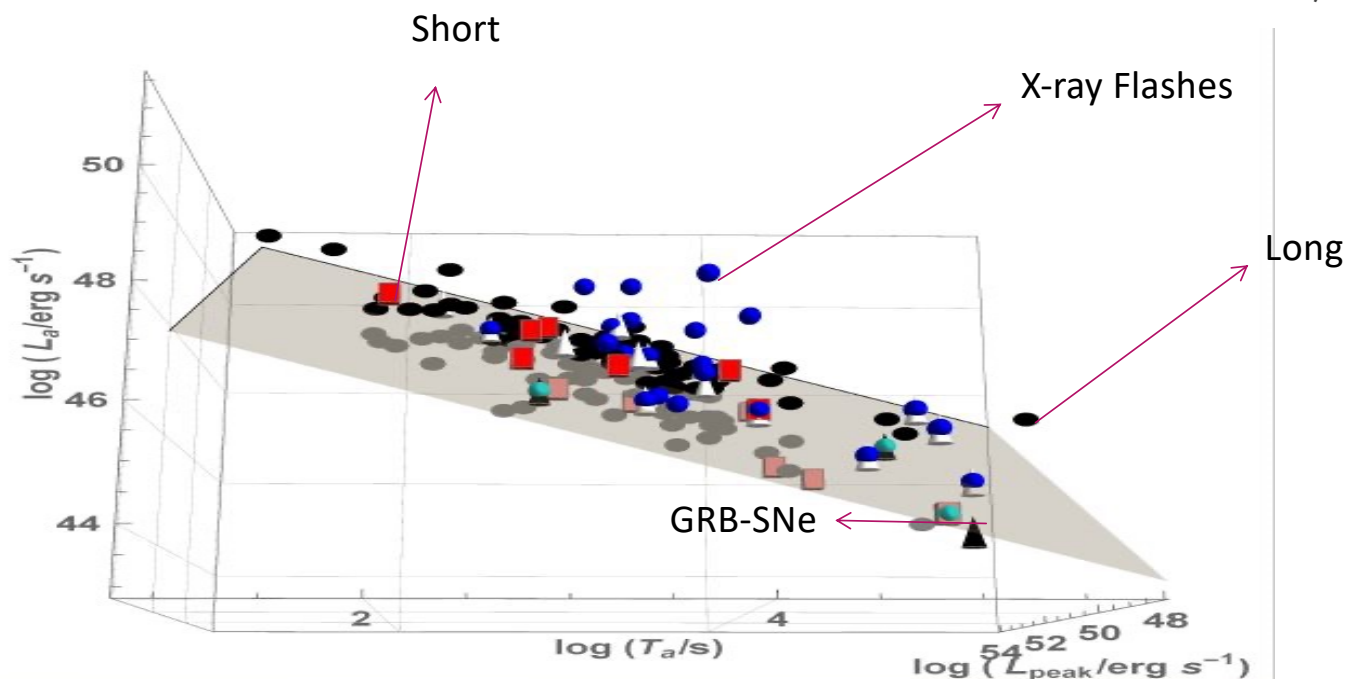
Press release by NASA:

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, σ_{int} of 24 %.



GRB and SNe correlations so far

GRB(prompt)-SN parameters

- Li et al. 2006a (Ep-SN bolometric magnitude)
- Lü et al. 2018 (Ep-SN nickel mass)

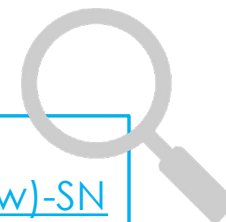
SN-SN parameters(*)

- Cano 2014 (s-k)

(*) in the case of SNe associated with GRBs

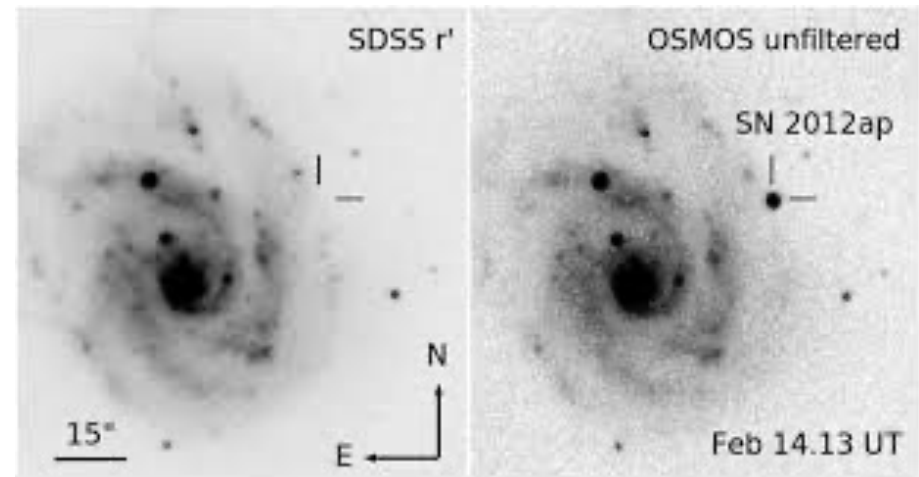
GRB(afterglow)-SN parameters correlations(?)

*Missing in the
previous literature*



A quick introduction to SNe Ib/c

- **SNe Ib/c** = SNe that appear in the core-collapse of massive stars
- No silicon lines but hydrogen in their spectra
- SNe Ib show the helium lines, while SNe Ic not
- Broad-lined SNe Ic (SNe Ic-BL): these have Fe II $\lambda 5169$ widths that are $\sim 9,000 \text{ km s}^{-1}$ broader than SNe Ic (Cano et al. 2017)



The GRB-SN connection!

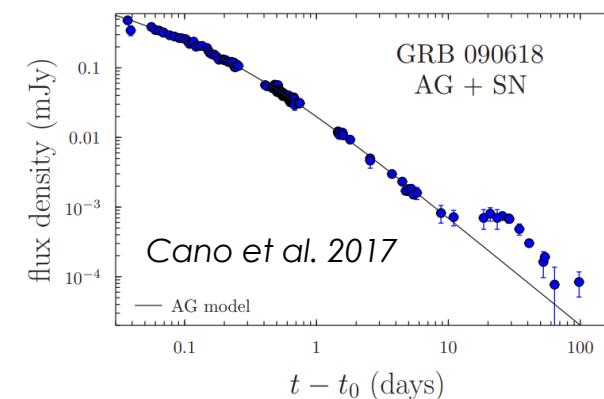
- Long GRBs associated with SNe Type Ib/c
- Believed to arise from the collapse of massive stars (Wolf-Rayet)
- We can see only a fraction of them (2-7%) due to instrumental biases (Rossi et al. 2021), up to a redshift $z \cong 1$

Hjorth & Bloom 2012 classes scheme:

A,B -> spectroscopical evidences+bump

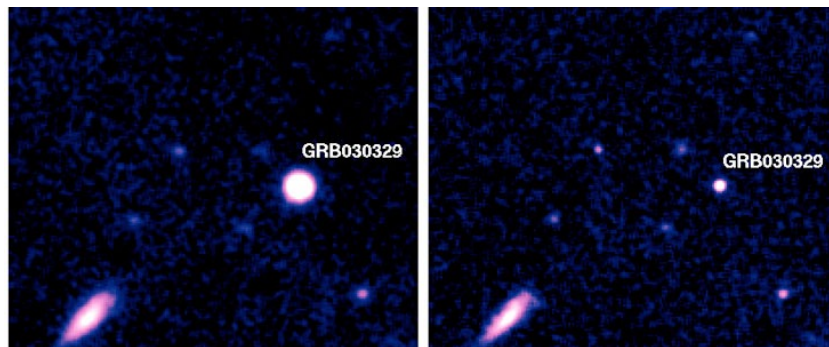
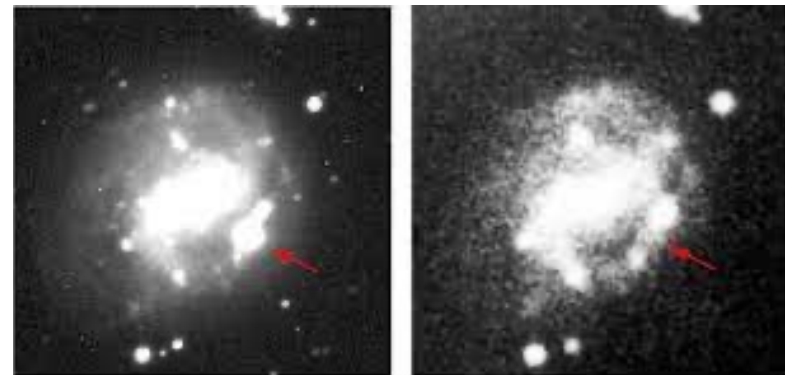
C,D -> intermediate

E -> bump of low significance



(A bit of) History of GRB-SNe...

The first (and most famous) GRB-SN event is the GRB 980425/SN 1998bw (Galama et al. 1998), used as the template for the light curves of SN associated to GRBs (redshift $z = 0.0087$, a very close one!)



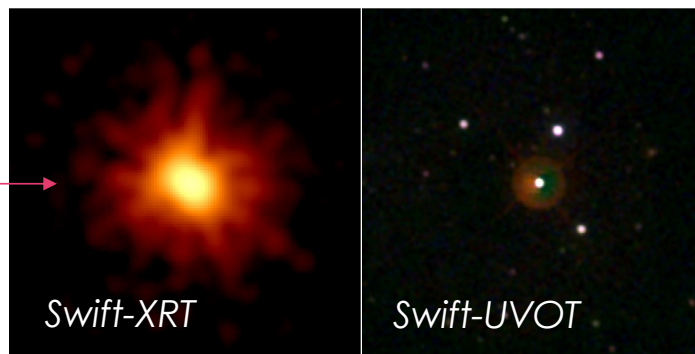
The association between GRBs and SNe was then confirmed with later events, such as the GRB 030329/SN 2003dh (redshift $z = 0.1687$)

...and also high-energy events

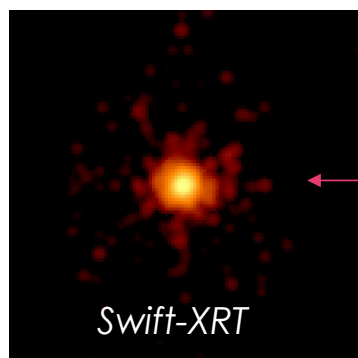
GRB 080319B

$E_{\gamma, \text{iso}} = 1.3 \times 10^{54} \text{ erg}$

Racusin et al. 2008



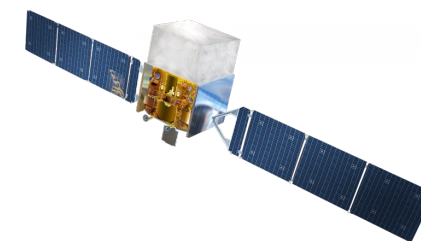
*Both observed by
Fermi-LAT*



GRB 130427A/SN 2013cq

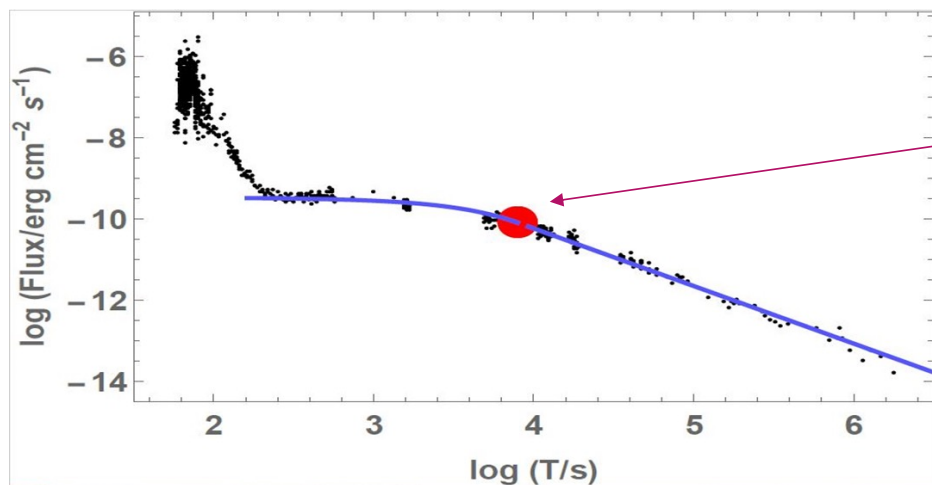
$E_{\gamma, \text{iso}} = 8.5 \times 10^{53} \text{ erg}$

De Pasquale et al. 2016



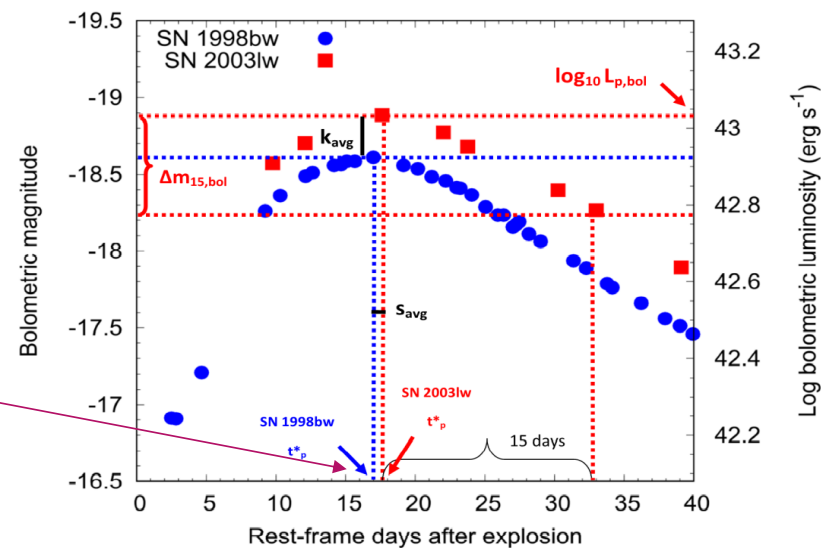
20 MeV-300 GeV

The parameters of interest



GRB $L_{a,opt}$: optical end-of-plateau
luminosity (erg/s)

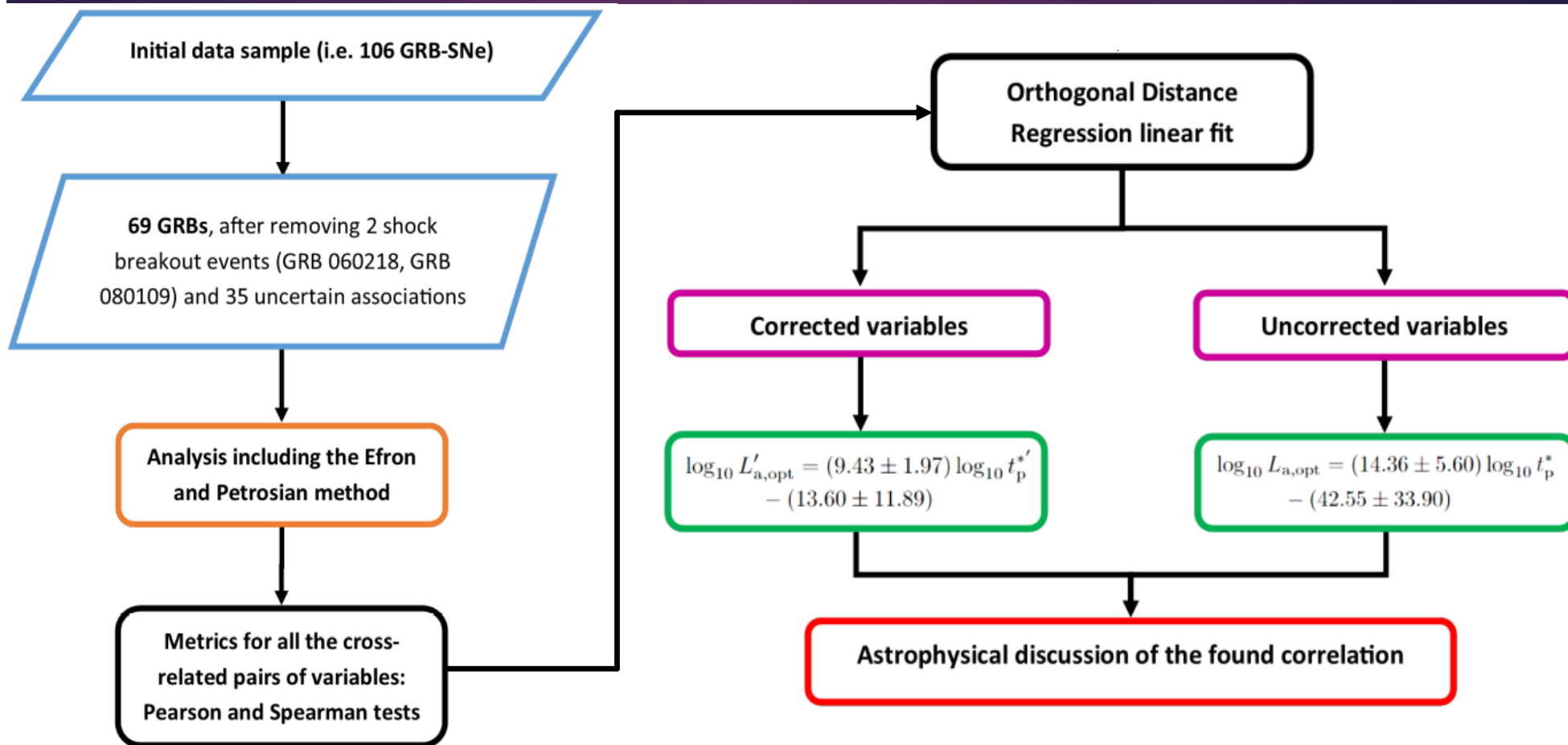
SN t_p^* : the rest-frame peak time of SN (s)



The GRB-SNe sample and the methods

- Sample: the collection of the most complete catalog of GRB-SNe events so far observed (from 1991 to February 2021)
- For the first time, the presence of the afterglow properties -> a feature more regular than the GRB prompt variables!
- A reliable statistical method for the correction of selection biases or redshift evolution: the **Efron and Petrosian method** (EP method, Efron & Petrosian 1992)

Outline of the research

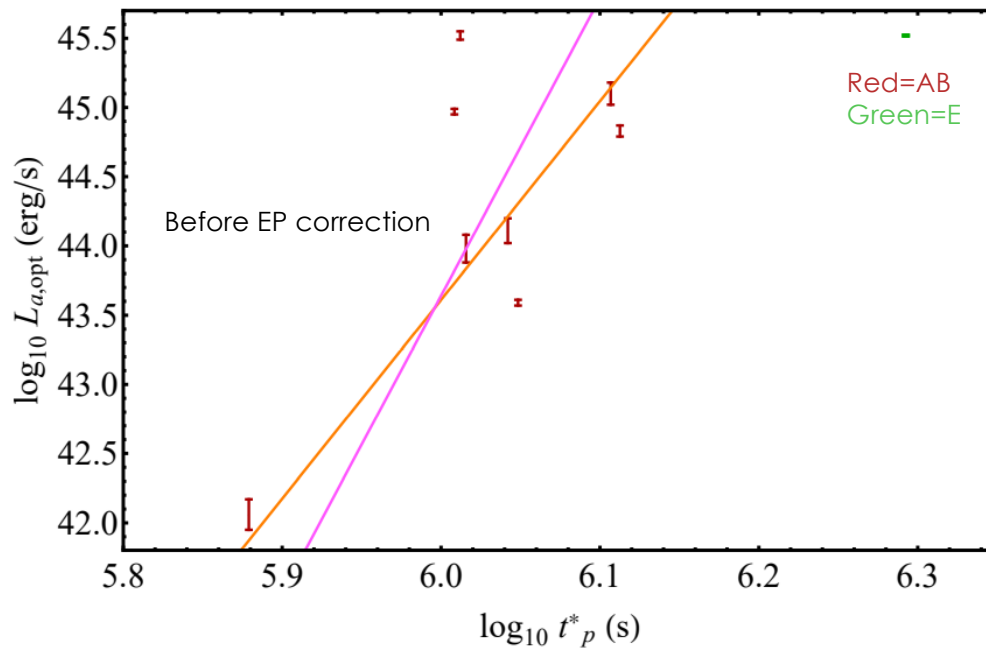


The metrics and the fitting

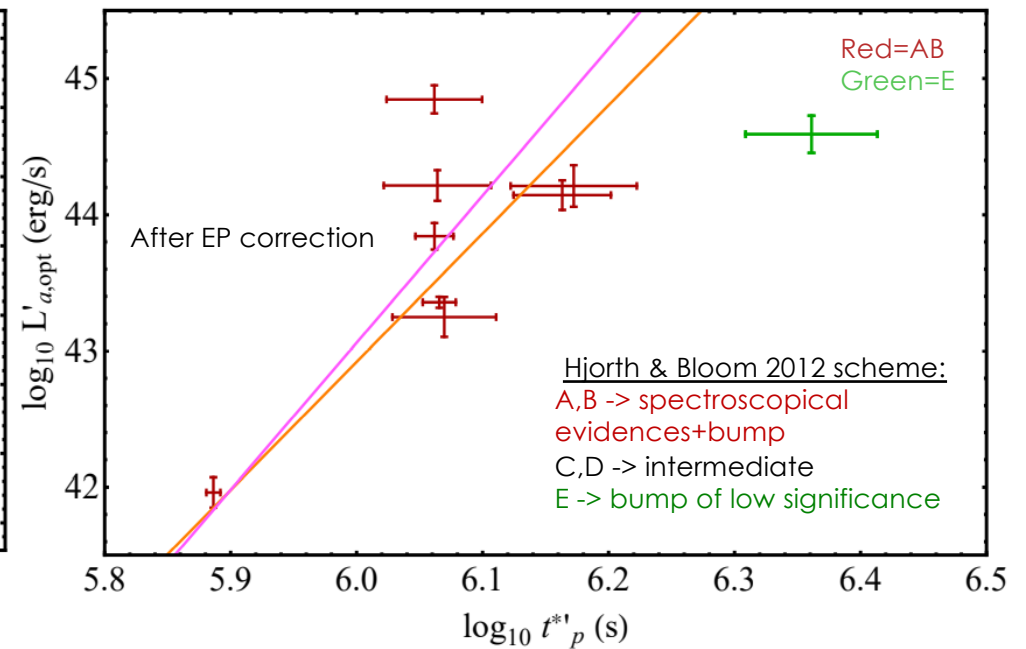
- We tested 91 possible bidimensional correlations (cross-relating GRB and SN parameters)
- We investigated the correlations that fulfill I) or II)
 - I) The Pearson correlation coefficient $|r| > 0.50$ and its p-value $P_p < 0.05$
 - II) The Spearman rank coefficient $|\rho| > 0.50$ and its p-value $P_\rho < 0.05$
- If I) or II) is fulfilled, we fit the correlation with the **Orthogonal Distance Regression** method (Boggs & Donaldson 1989) -> uncertainties both on dependent and independent variable

The results: $\log_{10} L'_{a,opt}$ vs $\log_{10} t_p^{*}$

M. G. Dainotti et al 2022 ApJ 938 41



| Fitting without the EP method | | | |
|-------------------------------|--|------|----------------|
| Sample | ODR method | r | P _P |
| Full | $(14.36 \pm 5.60)x + (-42.55 \pm 33.90)$ | 0.70 | 0.04 |
| AB only | $(21.50 \pm 8.82)x + (-85.36 \pm 53.14)$ | 0.70 | 0.05 |



| Fitting with the EP method | | | |
|----------------------------|--|------|----------------|
| Sample | ODR method | r | P _P |
| Full | $(9.43 \pm 1.97)x + (-13.60 \pm 11.89)$ | 0.71 | 0.03 |
| AB only | $(10.80 \pm 1.98)x + (-21.74 \pm 11.93)$ | 0.75 | 0.03 |

Future perspectives: GRB 221009A/SN 2022xiw A brand new event!








































GRB 221009A: «the trigger that triggered the HEA community»

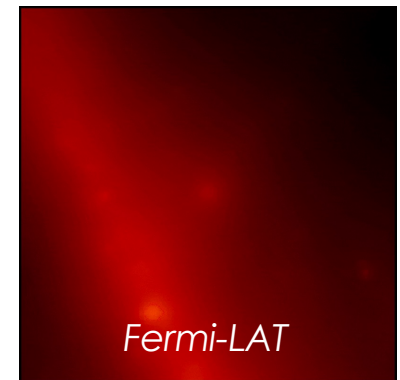
($E_{\gamma, \text{iso}} = 2 \times 10^{54}$ erg \leftrightarrow de Ugarte Postigo et al. 2022)

Observations of the associated SN

GCN: 32670,32769,32780,32800,32802,32808,32818,32828,32850,32921

The optical light curve of GRB 221009A: the afterglow and detection of the emerging supernova SN 2022xiw

M. D. FULTON ¹ S. J. SMARTT ^{2,1} L. RHODES ² M. E. HUBER ³ A. V. VILLAR ^{4,5,6} T. MOORE ¹
S. SRIVASTAV ¹ A. S. B. SCHULTZ ³ K. C. CHAMBERS ³ L. IZZO ⁷ J. HJORTH ⁷ T.-W. CHEN ^{8,9}
M. NICHOLL ¹⁰ R. J. FOLEY ¹¹ A. REST ^{12,13} K. W. SMITH ¹ D. R. YOUNG ¹ S. A. SIM ¹ J. BRIGHT,²
Y. ZENATI ¹³ T. DE BOER,³ J. BULGER,³ J. FAIRLAMB,³ H. GAO ³ C.-C. LIN ³ T. LOWE,³ E. A. MAGNIER ³
I. A. SMITH,³ R. WAINSCOT ³ D. A. COULTER ¹¹ D. O. JONES,¹⁴ C. D. KILPATRICK ¹⁵ P. MCGILL ¹¹
E. RAMIREZ-RUIZ ¹¹ K.-S. LEE ¹⁶ G. NARAYAN ^{17,18} V. RAMAKRISHNAN ¹⁶ R. RIDDEN-HARPER ¹⁹ A. SINGH,²⁰
Q. WANG ¹³ A. K. H. KONG ²¹ C.-C. NGEOW ²² Y.-C. PAN,²² S. YANG ²³ K. W. DAVIS ¹¹ A. L. PIRO,²⁴
C. ROJAS-BRAVO ¹¹ J. SOMMER ^{25,1} AND S. K. YADAVALLI ^{4,5,6}



Fulton et al. 2023
arXiv:2301.11170

Building the most complete catalog of optical GRBs with redshift (527 events!)

Do you wish to join with

- ▶ lightcurves
- ▶ new ideas
- ▶ and tools?

Contact me at
bdesimone@unisa.it

GRB-SNe: discussion and conclusions

- We cross-related 91 bidimensional correlations among GRB and SN parameters after their correction for bias or redshift evolution
- The brightest GRB plateaus are accompanied by the most delayed SNe; the peak time of a SN is proportional to the diffusion time (Khatami & Kasen 2019) which is related to the width of the LC
- To confirm this correlation, future observations are needed (Subaru, KISO telescopes)



Thank you for your attention! Any comments or questions?

Biagio De Simone

"The extreme Universe viewed
in very-high-energy gamma
rays 2022"

6th February 2023
Kashiwa Campus, Tokyo (JP)

bdesimone@unisa.it