New insights in the realm of the Gamma-ray Burst - Supernovae correlations

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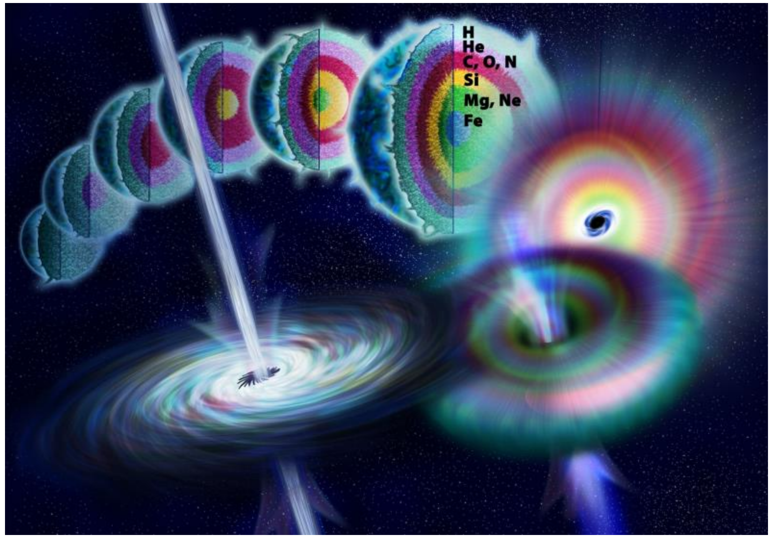

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Istituto Nazionale di Fisica Nucleare

MG17 PESCARA 7-12 JULY 2024
SEVENTEENTH MARCEL GROSSMANN MEETING
ON RECENT DEVELOPMENTS IN THEORETICAL AND EXPERIMENTAL GENERAL RELATIVITY, ASTROPHYSICS AND RELATIVISTIC FIELD THEORIES

11th July 2024
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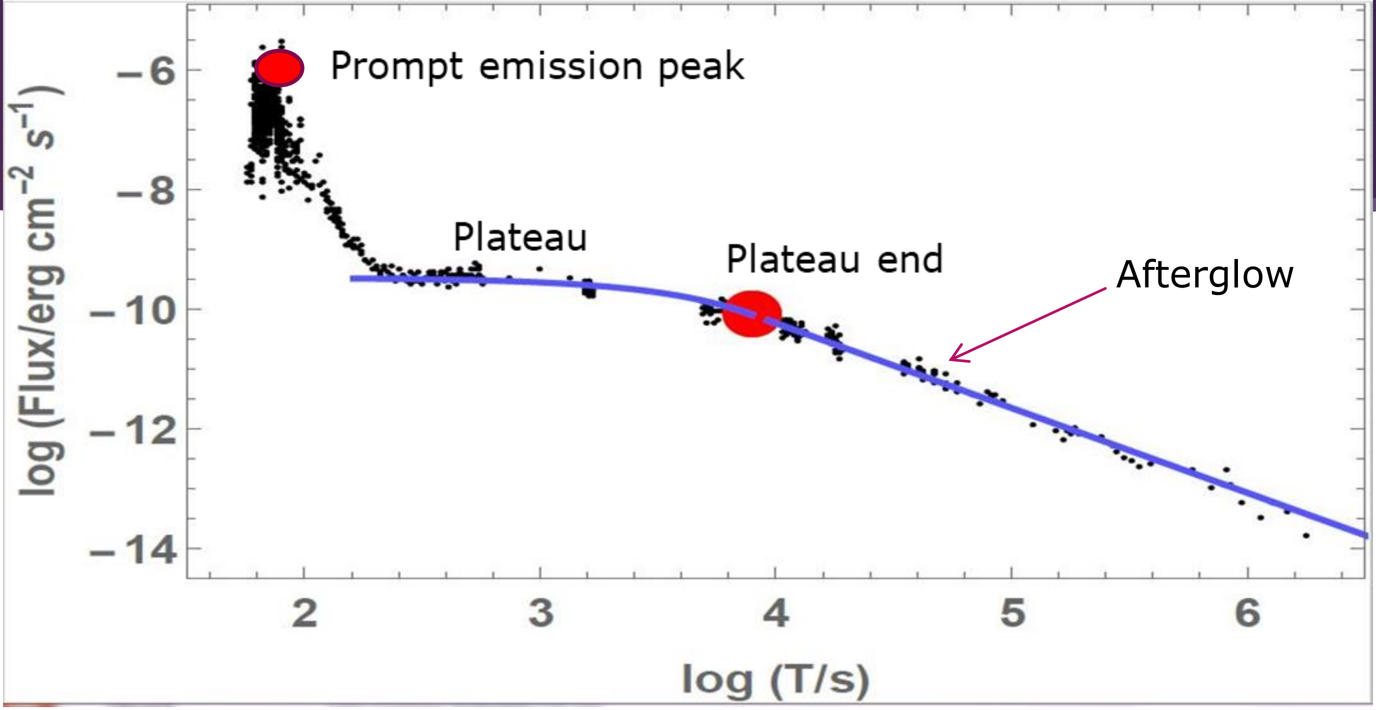
Outline of the talk

1. Introduction to Gamma-ray Bursts (GRBs)
2. The GRB and SN correlations
3. Introduction to 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 ~ 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.

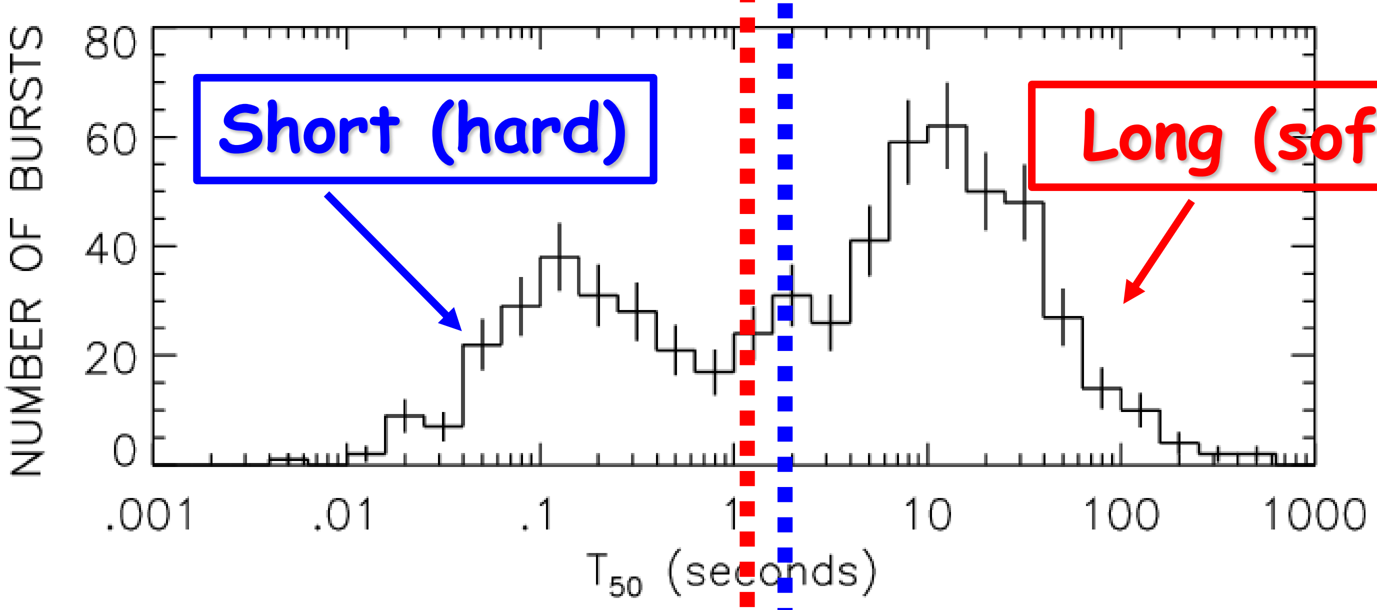
Short vs Long GRBs

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)



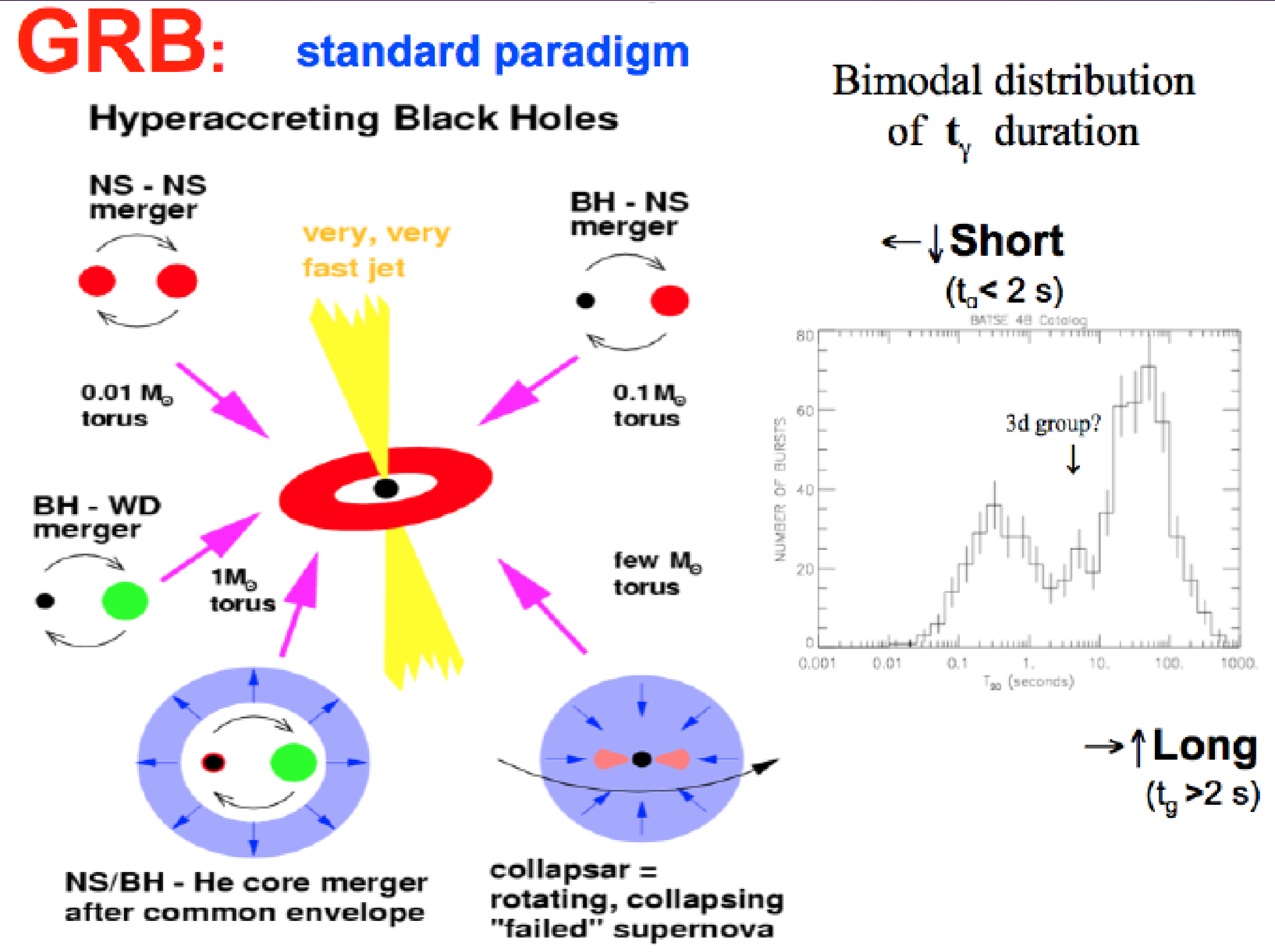
Short GRBs -> $T_{90}<2$ s　　Long GRBs -> $T_{90}>2$ s

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

GRB progenitors



Why are GRBs potential cosmological tools?

Because They…

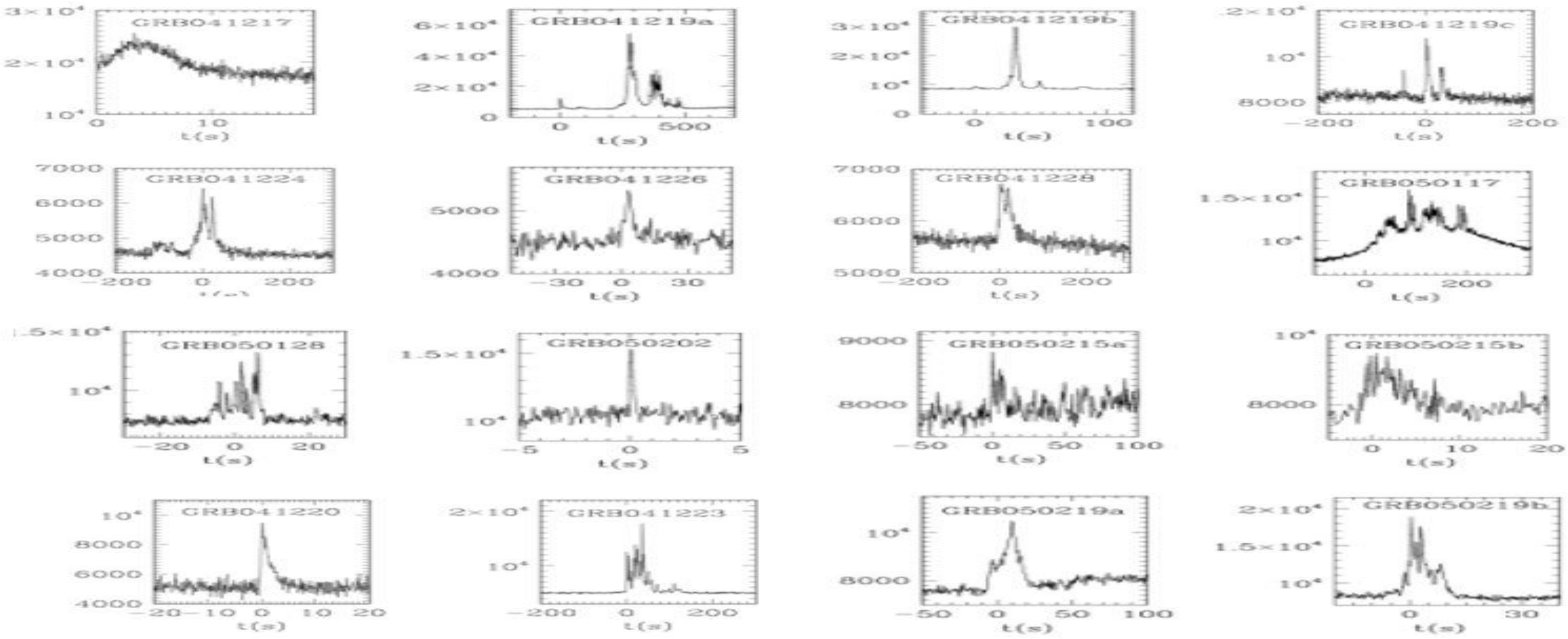
- Can be probes of the early evolution of the Universe.
- Are observed beyond the epoch of reionization.
- Allow us to investigate Pop III stars.
- Allow us to track the star formation.
- Are much more distant than Supernovae (SNe) Ia ($z_{obs}^{SNe\ Ia} \leq 2.26$) and quasars ($z_{obs}^{quasars} \leq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

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 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.

2008 – 2015	2016 – 2017	2020 – 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)

2008 2010 2011 2015 | 2016 2017 | 2020 2021 2022

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)

GRB(afterglow)-SN parameters correlations(?)

Missing in the previous literature

SN-SN parameters(*)

- Cano 2014 (s-k)

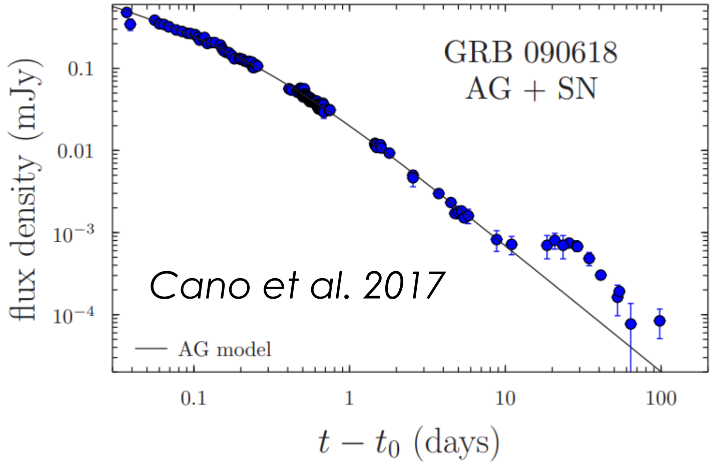
(*) in the case of SNe associated with GRBs

The GRB-SN connection!

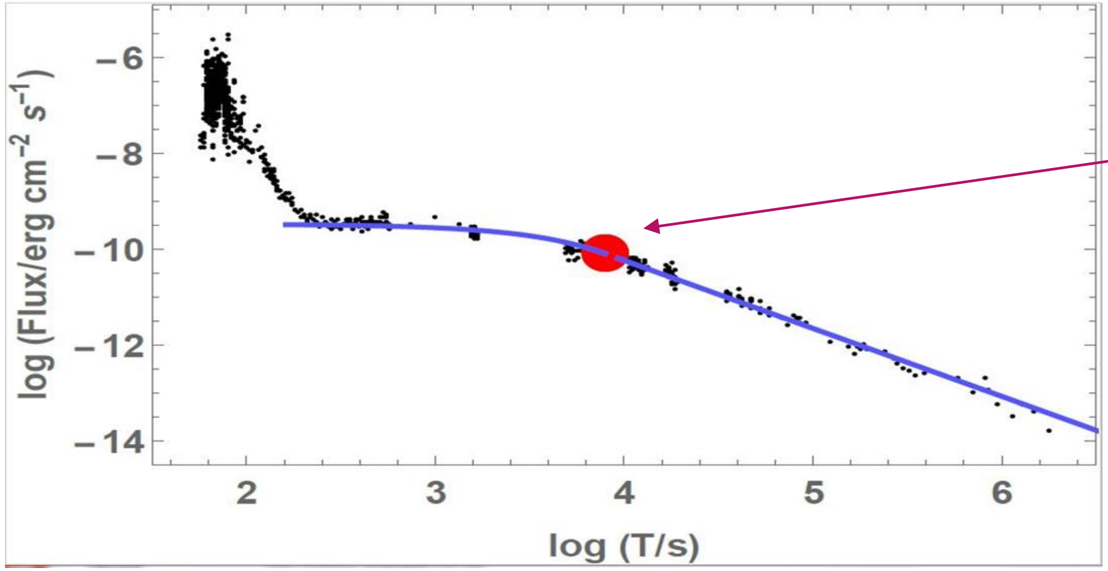
- Long GRBs associated with SNe Type Ib/c
- Believed to arise from the collapse of massive stars (Wolf-Rayet)
- We can see only a fraction of them (2-7%) due to instrumental biases (Rossi et al. 2021), up to a redshift $z \cong 1$

<u>Hjorth & Bloom 2012 classes scheme:</u>

A,B -> spectroscopical evidences+bump
C,D -> intermediate
E -> bump of low significance

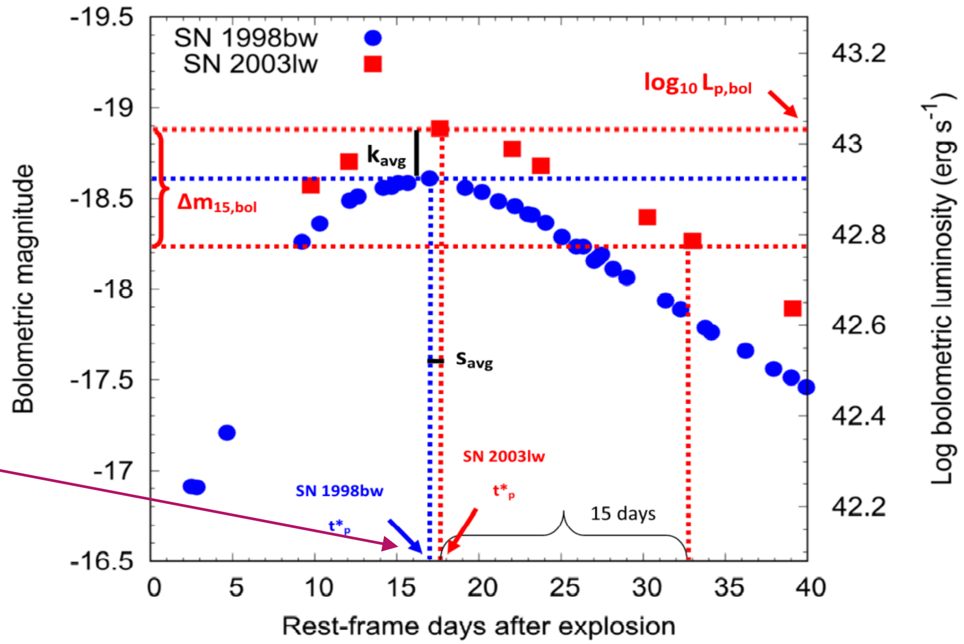


The parameters of interest



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

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



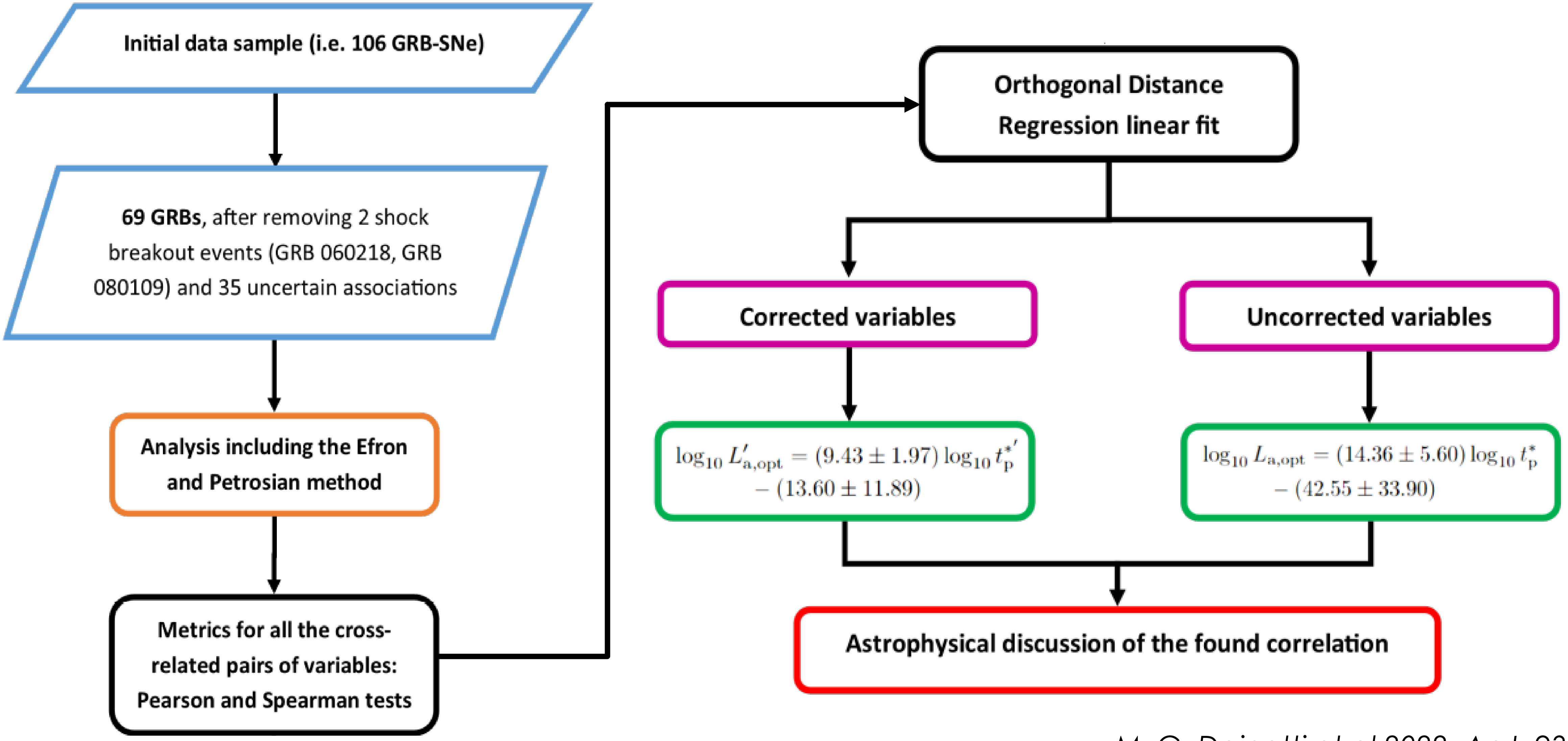
The GRB-SNe sample and the methods

- 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



M. G. Dainotti et al 2022, ApJ, 938, 41

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)

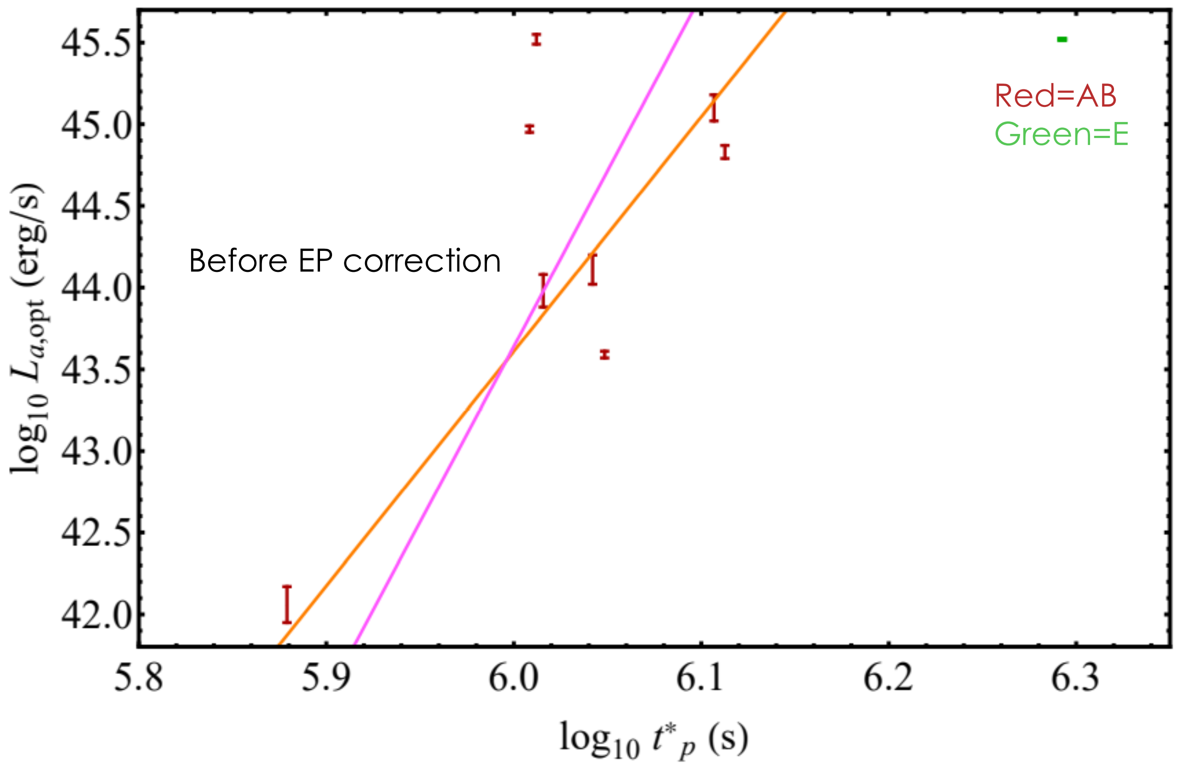
I) The Pearson correlation coefficient $|r| > 0.50$ and its p-value $P_P < 0.05$

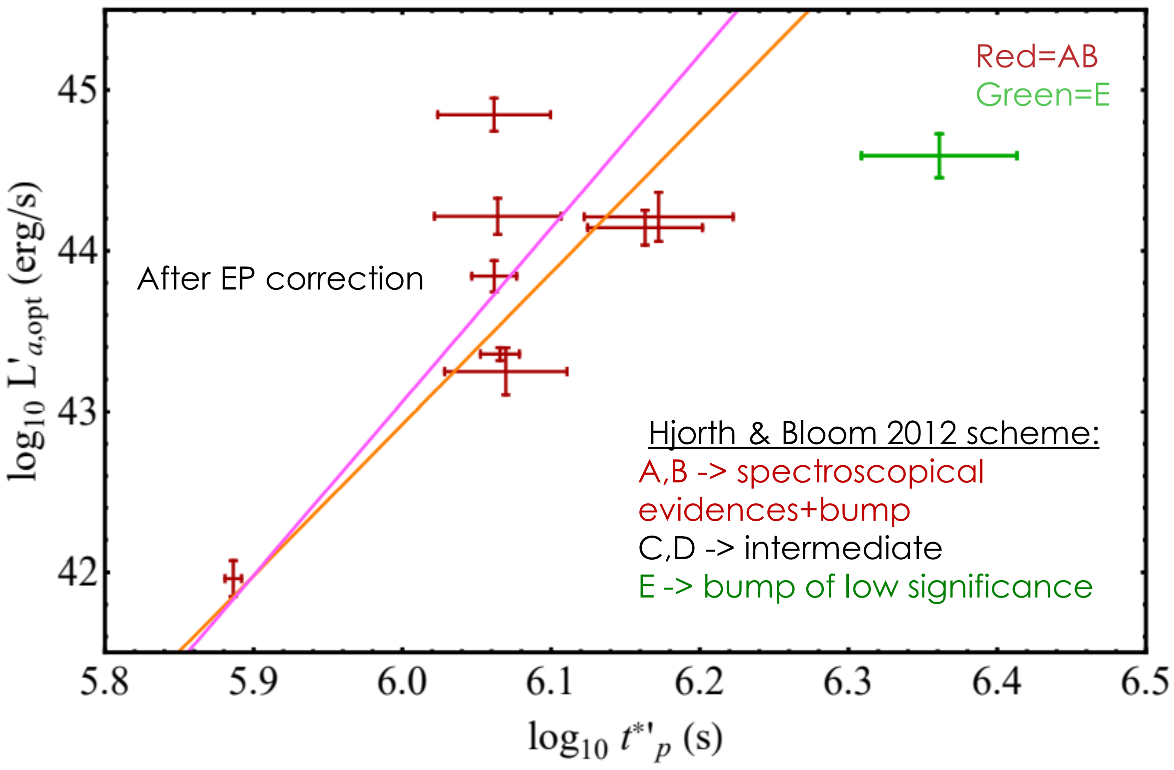
I) The Spearman rank coefficient $|\rho| > 0.50$ and its p-value $P_\rho < 0.05$

- 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 $\log_{10} t_p^{*\prime}$

M. G. Dainotti et al 2022 ApJ 938 41



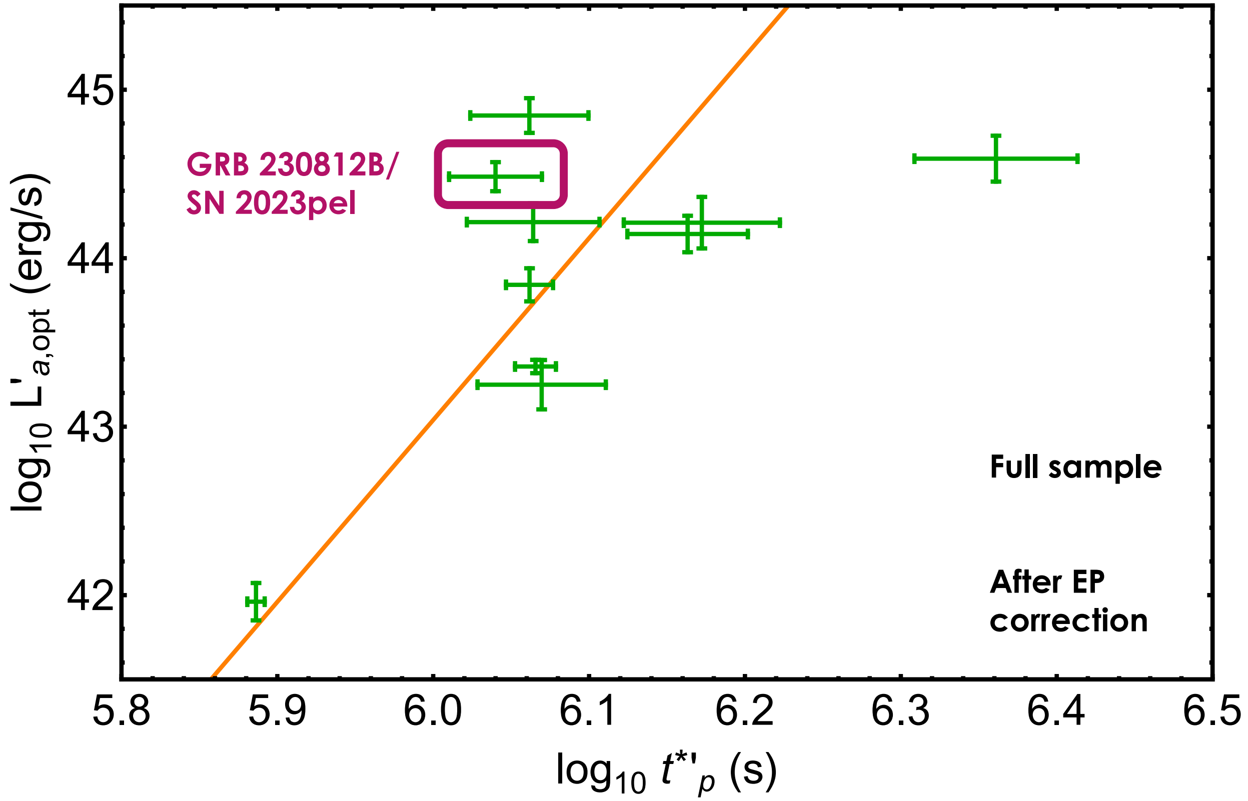


Fitting without the EP method			
Sample	**ODR method**	**r**	$\mathbf{P_P}$
Full	$(14.36 \pm 5.60)x + (-42.55 \pm 33.90)$	0.70	0.04
AB only	$(21.50 \pm 8.82)x + (-85.36 \pm 53.14)$	0.70	0.05

Fitting with the EP method			
Sample	**ODR method**	**r**	$\mathbf{P_P}$
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

Testing the $\log_{10} L'_{a,opt}$ *vs* $\log_{10} t_p^{*\prime}$ relation with a new GRB

... but still more data are needed!



<u>**NEW! GRB 230812B/SN 2023pel**</u>

GRB optical plateau luminosity from
Gokul P. Srinivasaragavan et al 2024 ApJL 960 L18

Rest-frame SN peak time from
T. Hussenot-Desenonges et al 2024 MNRAS 530 1 1-19

Adding this GRB/SN:

$$r = 0.638$$
$$P_P = 0.047$$

$$\log_{10} L'_{a,opt}\ (\mathrm{erg/s}) = (10.7959 \pm 1.98594) \log_{10} t^{*\prime}_p\ (\mathrm{s}) + (-21.7362 \pm 11.9328)$$

More data, more correlations research… The most complete catalog of optical GRBs with redshift (535 events!)

Follow *Ridha Fathima Mohideen Malik* talk tomorrow!

Do you wish to join this project?

Contact us at
bdesimone@unisa.it, maria.dainotti@nao.ac.jp

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 (e.g. Subaru, KISO telescopes…)
- The future research for GRB-SNe correlations could involve more models (like 3D relations)

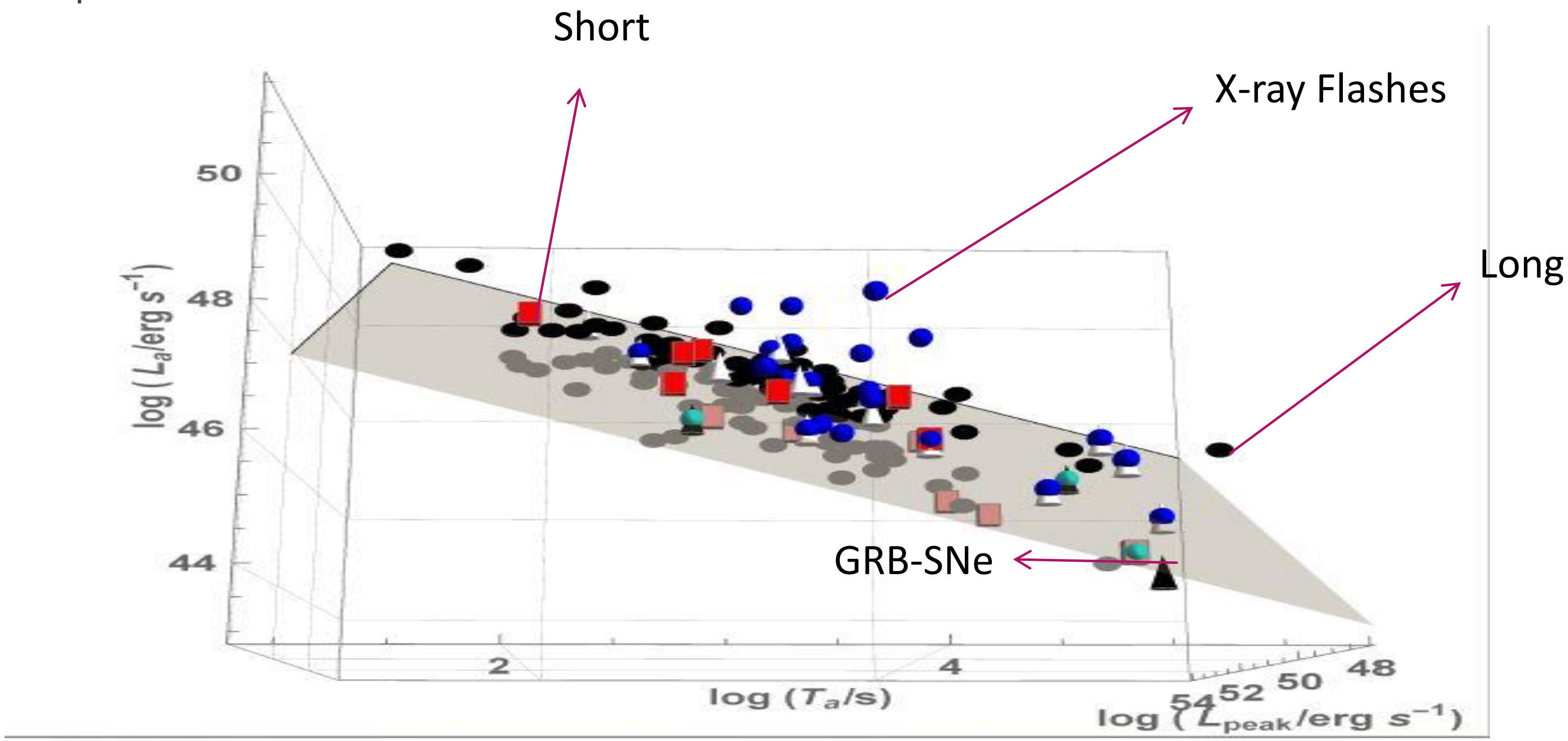

Thank you for your attention!
Any comments or questions?

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.

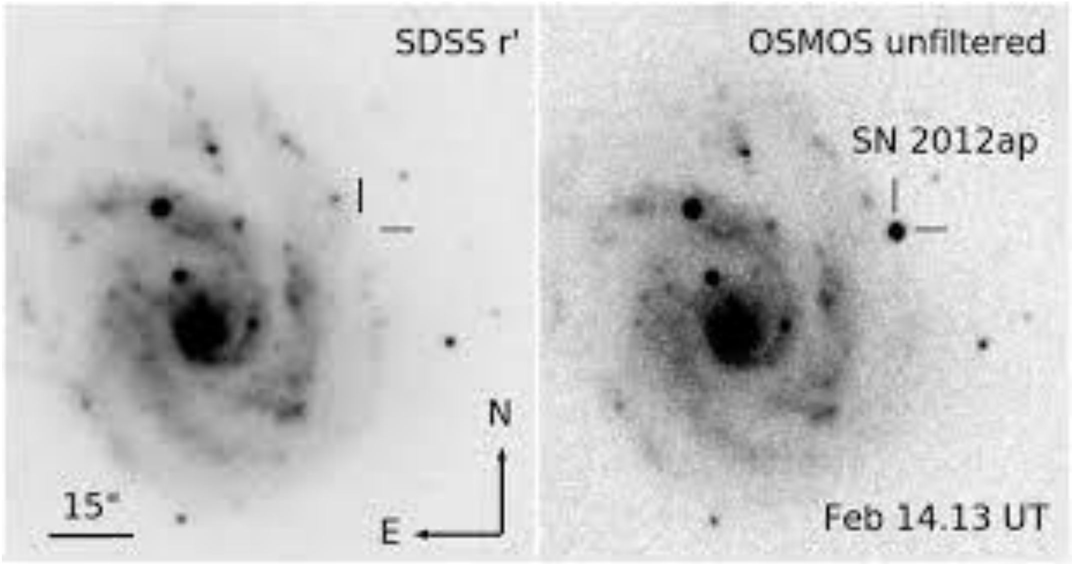
M. G. Dainotti, S. Postnikov, X. Hernandez, M. Ostrowski, 2016, ApJL, 825L, 20

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



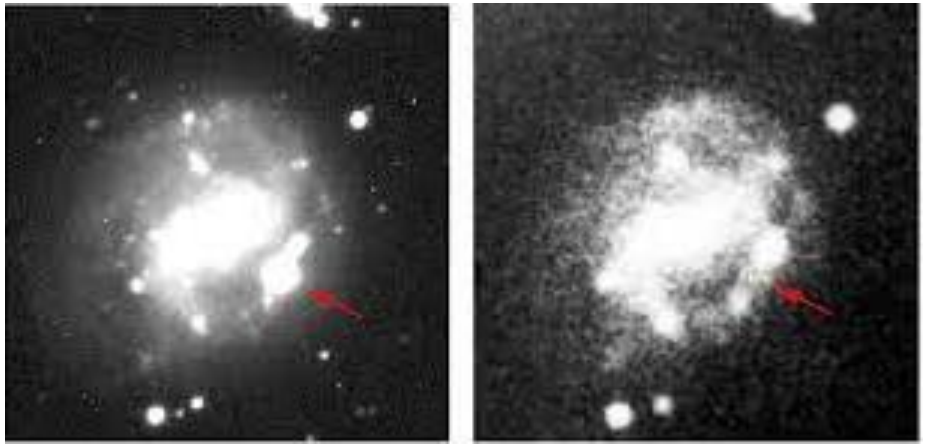
A quick introduction to SNe Ib/c

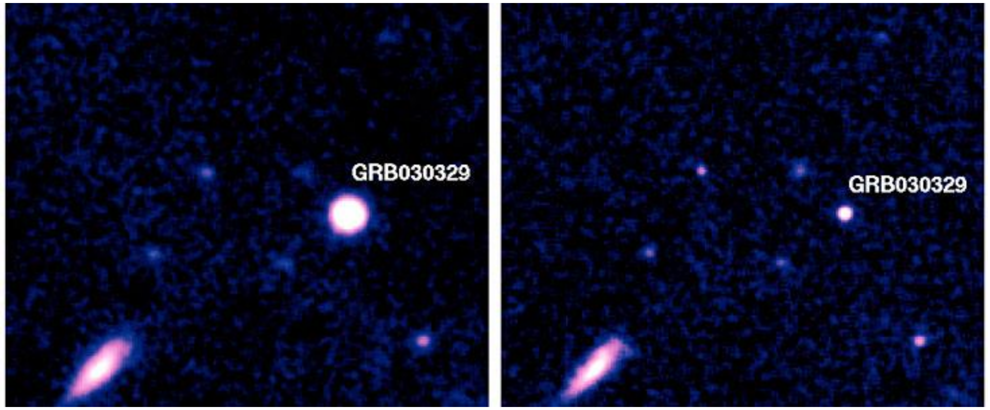
- **SNe Ib/c =** SNe that appear in the core-collapse of massive stars
- No silicon lines but hydrogen in their spectra
- SNe Ib show the helium lines, while SNe Ic not
- Broad-lined SNe Ic (SNe Ic-BL): these have Fe II λ5169 widths that are ~ 9, 000 km s−1 broader than SNe Ic (Cano et al. 2017)



(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!)





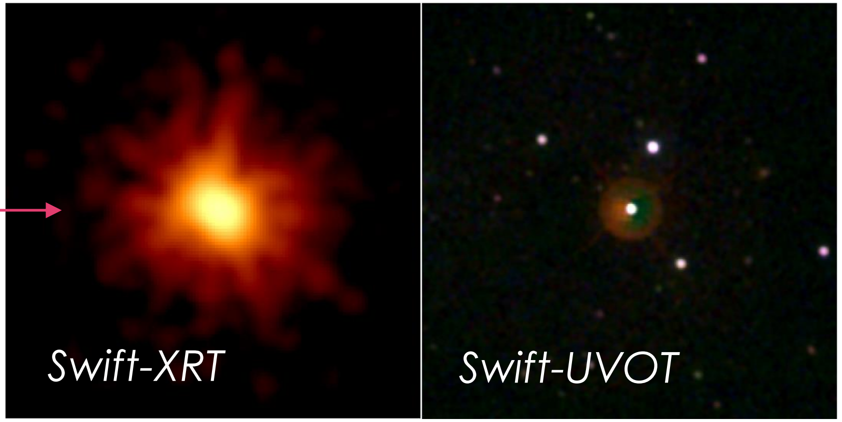
The association between GRBs and SNe was then confirmed with later events, such as the GRB 030329/SN 2003dh (redshift $z = 0.1687$)

…and also high-energy events

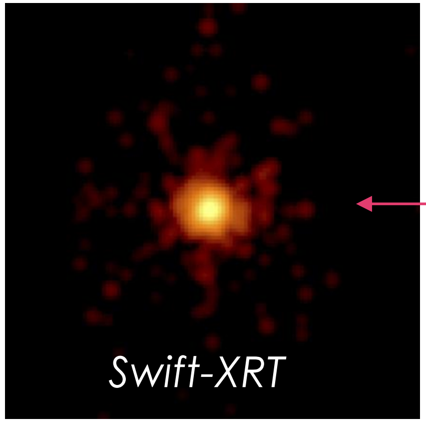
GRB 080319B

Eγ,iso= 1.3×10^54 erg

Racusin et al. 2008



Both observed by Fermi-LAT



GRB 130427A/SN 2013cq

Eγ,iso= 8.5×10^53 erg

De Pasquale et al. 2016

20 MeV-300 GeV

How to build the GRB-SNe catalog

From **106** possible associations, we reduced to **69** GRB-SNe confirmed events with

- The removal of spurious associations given by a spatial and temporal coincidence of GRB and SN signals (106-**35=71** candidate GRB-SNe events)
- Removal of two shock-breakout events, GRB 060218 and GRB 080109 - the *failed jet mechanism* is different from the GRB-SNe engine (**71-2=69 confirmed GRB-SNe**)

The SN classes in $\log_{10} L'_{a,opt}$ vs $\log_{10} t_p^{*\prime}$

M. G. Dainotti et al 2022 ApJ 938 41

AB graded events:

- **GRB 030329/SN 2003dh (Ic/Hypernova)**
- **GRB 081007A/SN 2008hw (Ic)**
- **GRB 091127/SN 2009nz (Ic-BL)**
- **GRB 100316D/SN 2010bh (Ic)**
- **GRB 101219B/SN 2010ma (Ic)**
- **GRB 111209A/SN 2011kl (Superluminous SN)**
- **GRB 130702A/SN 2013dx (Ic)**
- **GRB 130831A/SN 2013fu (Ib/c)**

→

- **4 SNe Type Ic**
- **1 SN Type Ic/Hypernova**
- **1 SN Type Ic broad-lined**
- **1 Superluminous SN**
- **1 SN Type Ib or Ic**

E graded event:

- **GRB 111228A**

→

- **1 GRB with a bump in the LC associated with the SN**

First feasibility study for the potential use of the KISO Telescope

- 27% of observations-100 nights observed by KISO
- 50% will be happening during the night.
- 70% will be visible, 30% will occur in the Southern Hemisphere.
- Fraction of GRBs with optical plateaus 102/267=0.38%.
- Probability of observing all optical GRBs =0.5*0.7*0.27=0.094
- Probability of observing optical GRBs with plateaus=0.5*0.7*0.27*0.38= 0.036

What could we observe with the KISO observatory?

- From Swift, Fermi, and IPN 229 GRBs are observed each year.
- 8 GRBs with plateaus, 22 GRBs per year
- Based on the probability 20 years of observations (1997-2016)

KN	XRR and XRFs	GRB-SNe	Long	Short	Ultra Long	Gold
0.2	13	5.6	7.5	2	0.88	1.5

Let's correct the parameters!

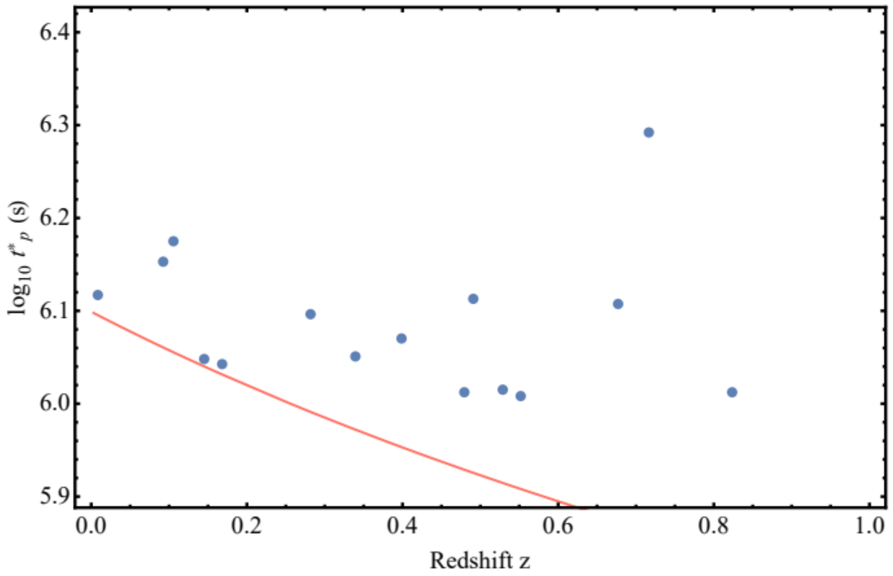
EP method: a modification of the Kendall-tau statistics

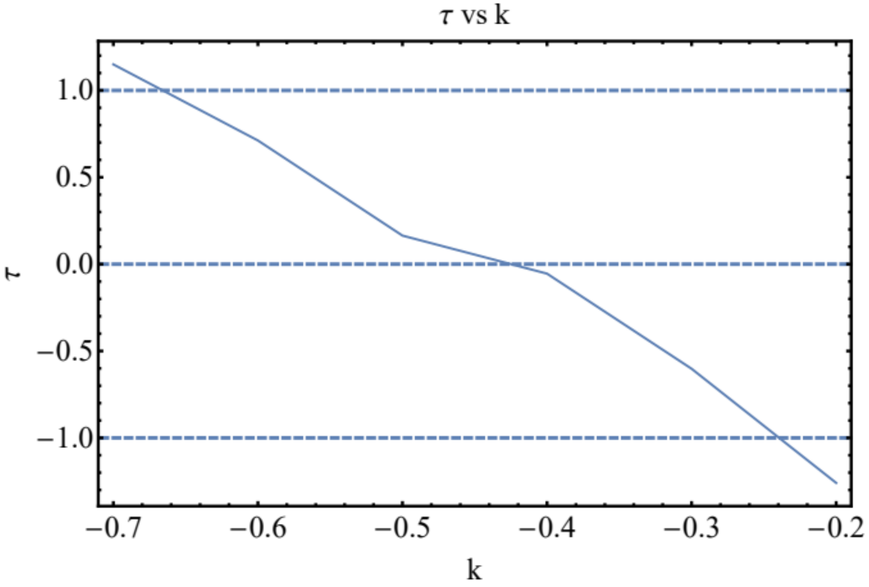
M. G. Dainotti et al 2022, ApJ, 938, 41

$$\tau = \frac{\sum_i (\mathcal{R}_i - \mathcal{E}_i)}{\sqrt{\sum_i \nu_i}}$$

$\mathcal{R}_i$ = rank of the variable, $\mathcal{E}_i = \frac{1}{2}(i+1)$ = expected value

$\nu_i = \frac{1}{12}(i^2+1)$ = variance





Local variable

$x' = x/g(z)$

$g(z) = (1+z)^k$

k: evolutionary slope

We take the k s.t. $\tau = 0$ (no correlation between t^*_p and z)

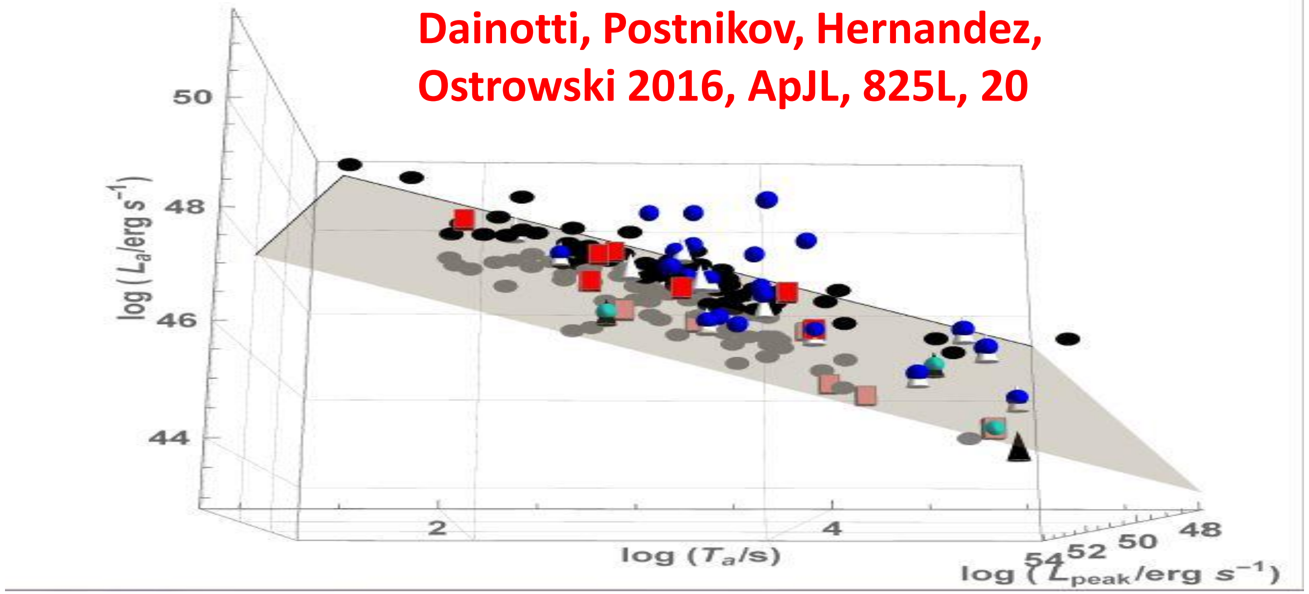
EP method applied on t^*_p (M. G. Dainotti et al 2022, ApJ, 938, 41)

HOW TO MAKE A STANDARD CANDLE:

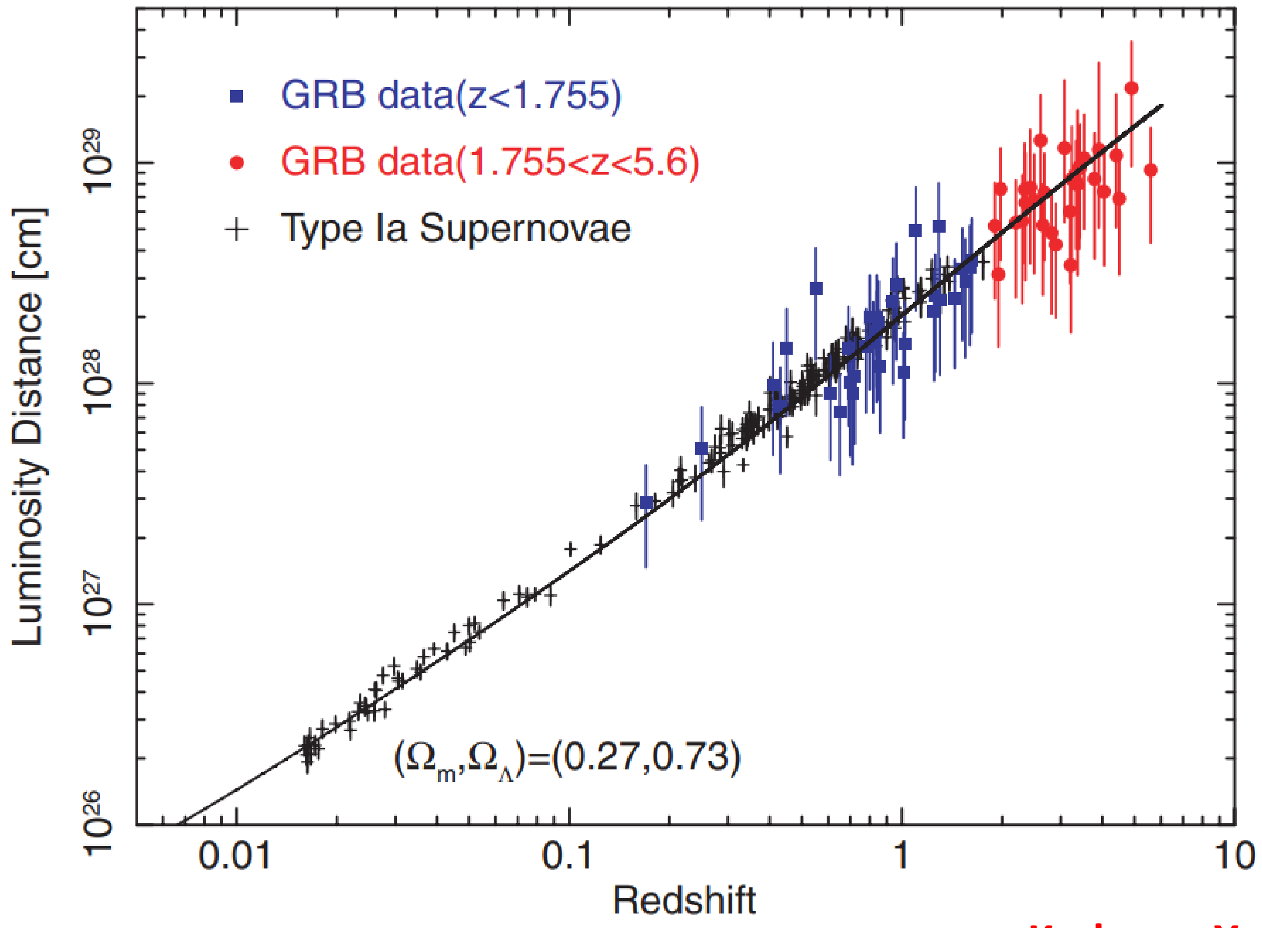
- BUILDING RELATIONS AMONG RELEVANT PHYSICAL PROPERTIES
- E.G. THE PLATEAU PROPERTIES OF GRBs SEEM TO LEAD TOWARDS STANDARD CANDLES
- HOW CAN THESE RELATIONS BE USED IN COSMOLOGY? THEY LINK THE LUMINOSITY OF GRBs TO THE OTHER PHYSICAL PARAMETERS

Dainotti, Postnikov, Hernandez, Ostrowski 2016, ApJL, 825L, 20

The Dainotti 3D relation links the X-rays peak prompt luminosity – the X end-of-plateau luminosity and the end-of-plateau time



CORRELATIONS AS MODEL-INDEPENDENT CALIBRATORS



If $L = a + bX$, L is the luminosity
If X independent of L then we can build the standard candle!

Yonetoku relation (Lpeak-Epeak)
cosmology-independent calibration

$$\left(\frac{L_p}{10^{52}\ \mathrm{erg\,s^{-1}}}\right) = (1.31 \pm 0.67) \times 10^{-4} \left(\frac{E_p}{1\ \mathrm{keV}}\right)^{1.68\pm0.09}$$

Kodama, Yonetoku, et al. 2008
MNRAS 391 L1-L4

GRB 221009A/SN 2022xiw
A brand new event!

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

($E_{\gamma,iso}$= 2×10^54 erg <-> *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

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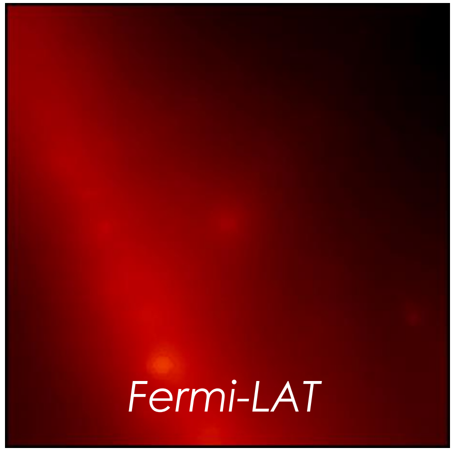

Fulton et al. 2023
arXiv:2301.11170

The most complete catalog of optical GRBs with redshift (535 events!)

Do you wish to join with

- light curves
- new ideas
- and tools?

Contact us at

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