GRB prompt-afterglow correlations

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GRBs phenomenology

- **Flashes of high energy photons in the sky (typical duration is few seconds).**
- **Cosmological origin accepted**
- **X-rays and optical radiation observed after days/months (afterglows), distinct from the main γ-ray events (the prompt emission).**
- **Observed non thermal spectrum**

Short GRBs -> T_{90}<2 s

Long GRBs -> T_{90}>2 s

Norris et Bonnell 2006, intermediate class of GRBs with mixed properties

Virgili et al. 2011

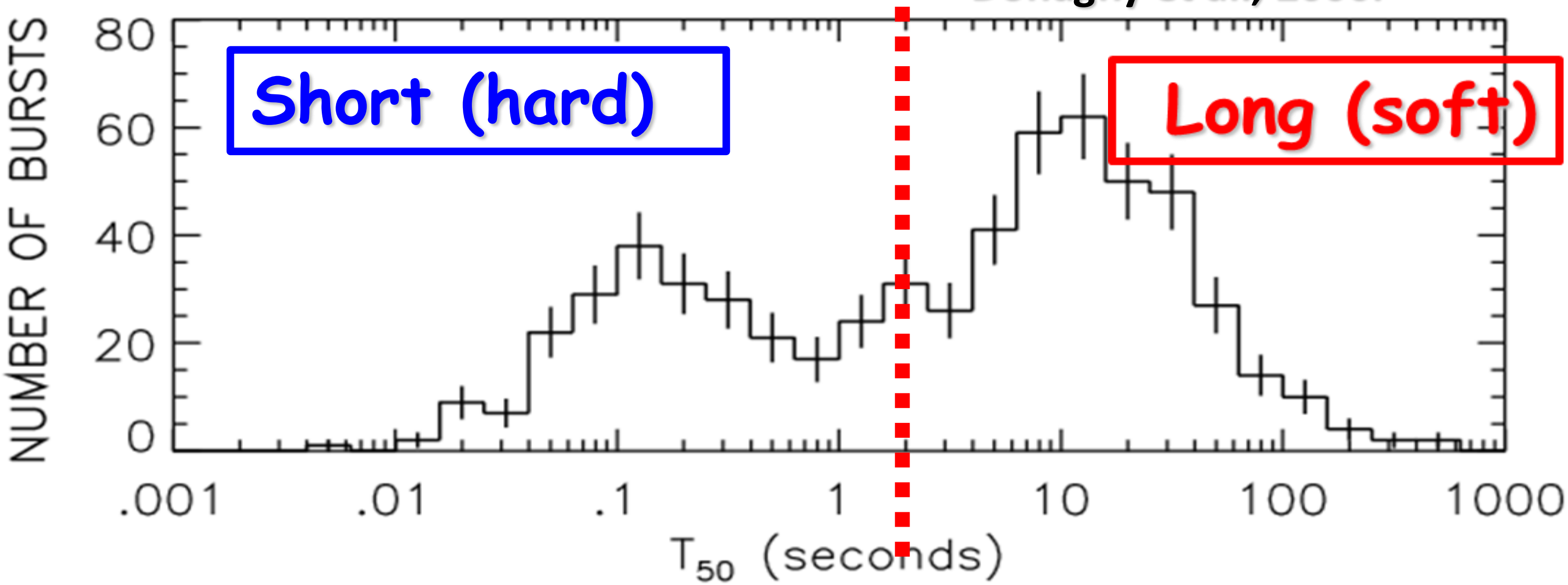
Bromberg et al. 2013, Swift T_{90}<0.8 s

Mazets et al., 1982

Kouveliotou et al., 1996.

Paciesas et al., 1999.

Donaghy et al., 2006.



why GRBs as possible cosmological tools?

Because

They are among the farthest astrophysical observed up to $z=9.46$ (Cucchiara et al. 2011)

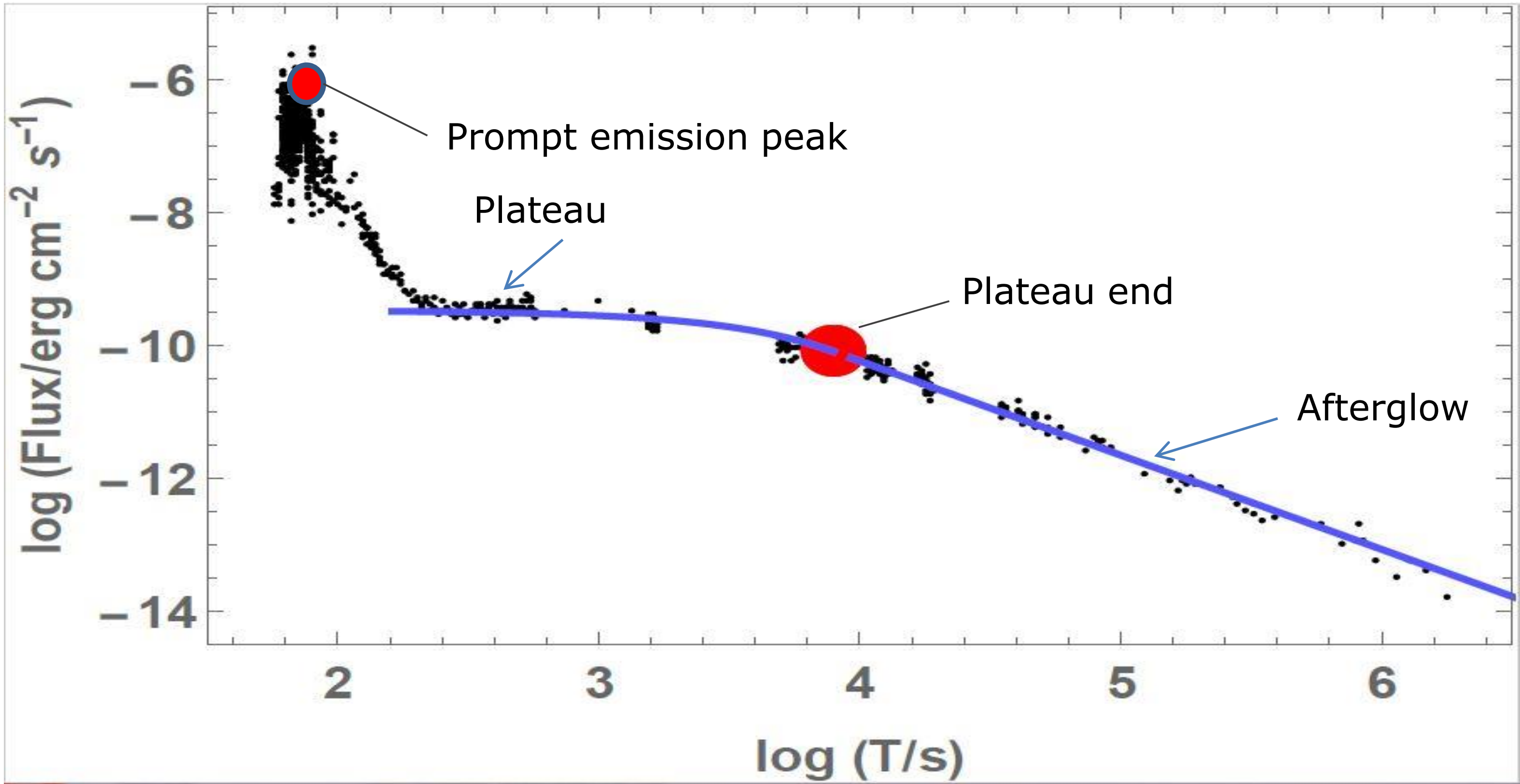
Much more distant than SN Ia ($z=1.914$) and quasars ($z=6$)

BUT

They don't seem to be standard candles with their isotropic prompt luminosities spanning over 8 order of magnitudes

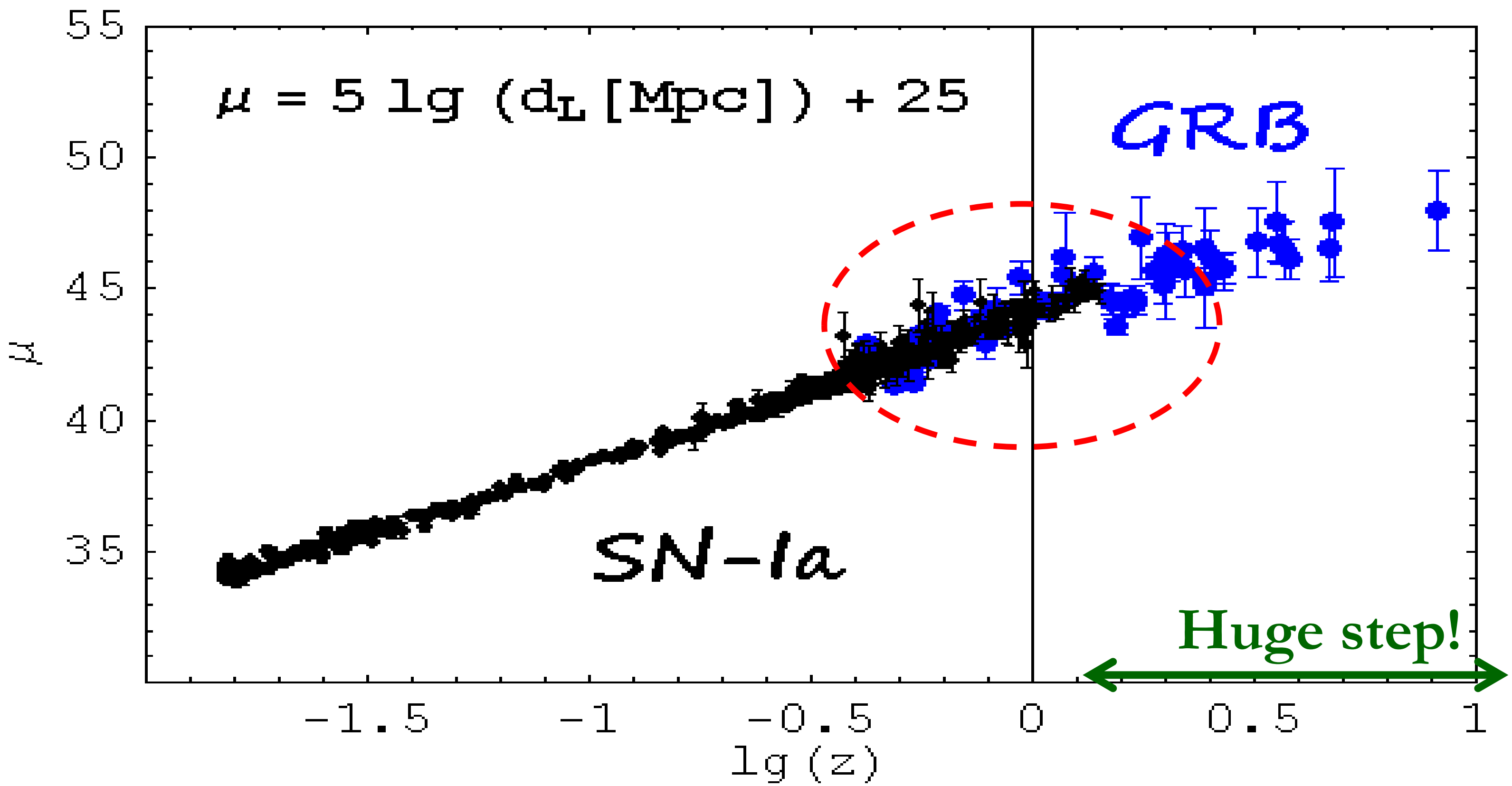
Standard candles: Objects whose luminosities are known or can be derived through relations among relevant properties.

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



GRBs can be detected well beyond supernovae (z=1.94) and quasars (z=6) -- back to less than 1 million years after the Big Bang. For 20 years, we've been trying to figure out how to use GRBs as standard candles, but the light curves vary widely -- "If you've seen one GRB, you've seen one GRB" -- confounding efforts to isolate common properties.

SN-Ia & GRBs, distance ladder



The aim is to find tight correlations so that they can be used as Standardizable candles and useful cosmological tools at high z.

There is more than 2sigma discrepancy between SNe Ia and the Planck Observations (Rigault et al. 2015), so having GRBs as possible probes of determining Ho for the high redshift Universe would be useful.

To identify a species of bird, we might examine different components -- plumage, wing span, and feet – to confirm a match. For example, Type Ia is the favored cosmological probe among SNe.

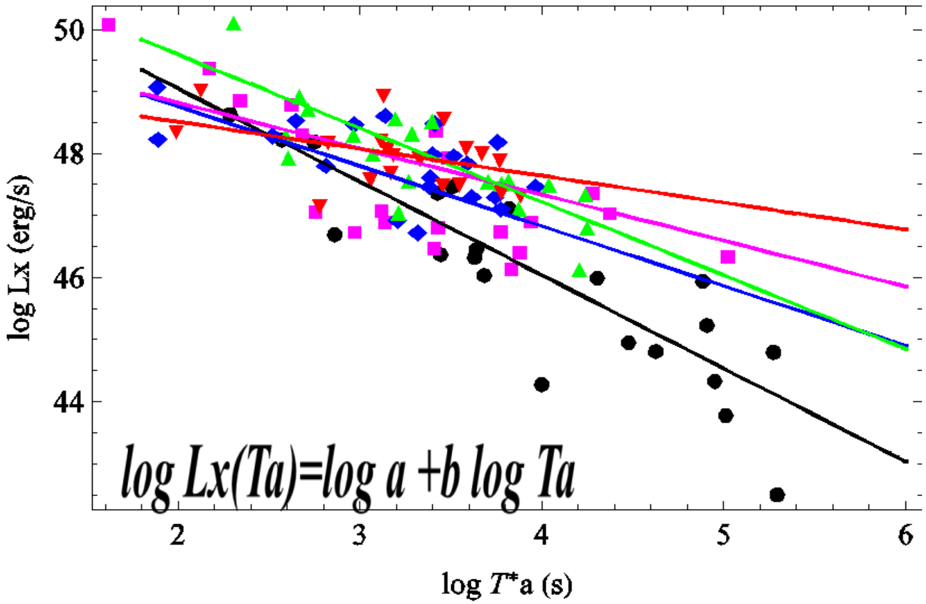
Which GRB category best works as a standard candle?

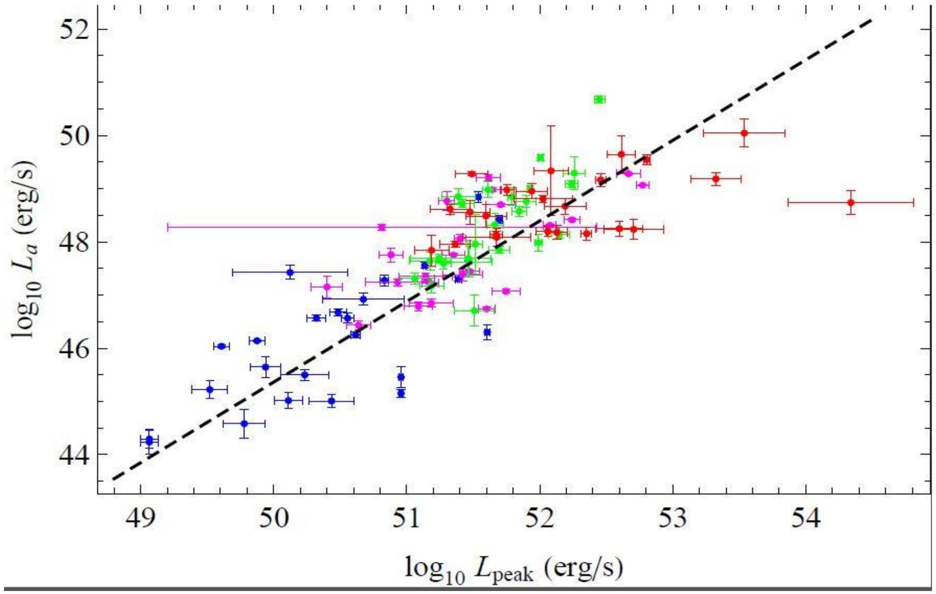
Category	Duration of prompt emission	X-ray fluence/ gamma-ray fluence	Presence of supernovae or optical bumps
X-ray flashes	>2 s	>1	In some cases
GRB-SNe	>2 s	<1	Yes
Short	<2 s	<1	No
Short Extended Emission	<10 s	<1	In one case
Long	>2 s	<1	No
Ultra-Long	**>>2 s**	**<1**	**No**

None of these categories by themselves can work as standard candles

A reliable candidate is the Dainotti relation in the plateau

Dainotti et al. 2013, ApJ, 774, 157





black for $z < 0.89$, magenta for $0.89 \le z \le 1.68$, blue for $1.68 < z \le 2.45$, Green $2.45 < z \le 3.45$, red for $z \ge 3.45$.

Dainotti et al. MNRAS 2015b, 31, 4.
Dainotti et al. 2011b, MNRAS,418,2202.

Firstly discovered in 2008 by Dainotti, Cardone, & Capozziello MNRAS, 391, L 79D (2008) ,

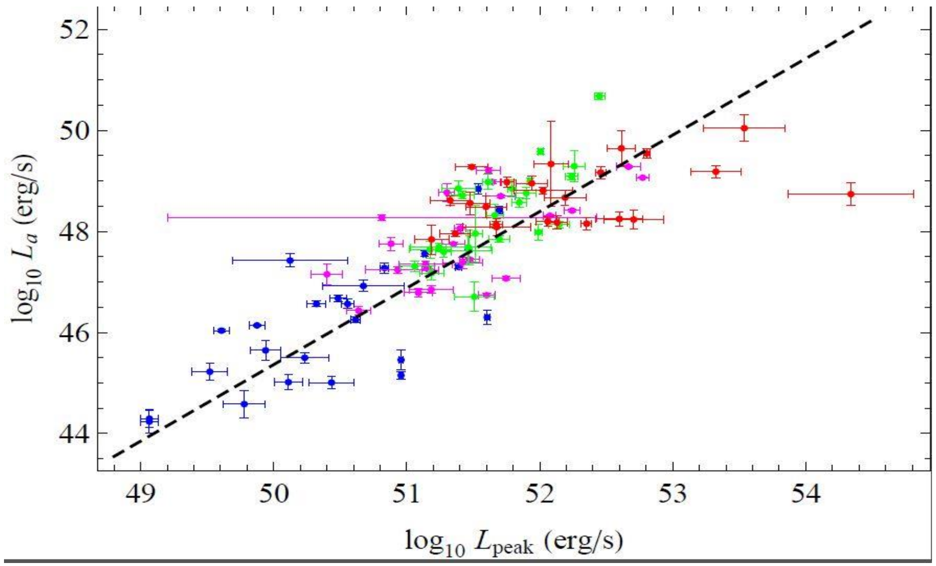
Later updated by Dainotti, Willingale, Cardone, Capozziello & Ostrowski ApJL, 722, L 215 (2010), Dainotti et al. 2011, ApJ, 730, 135

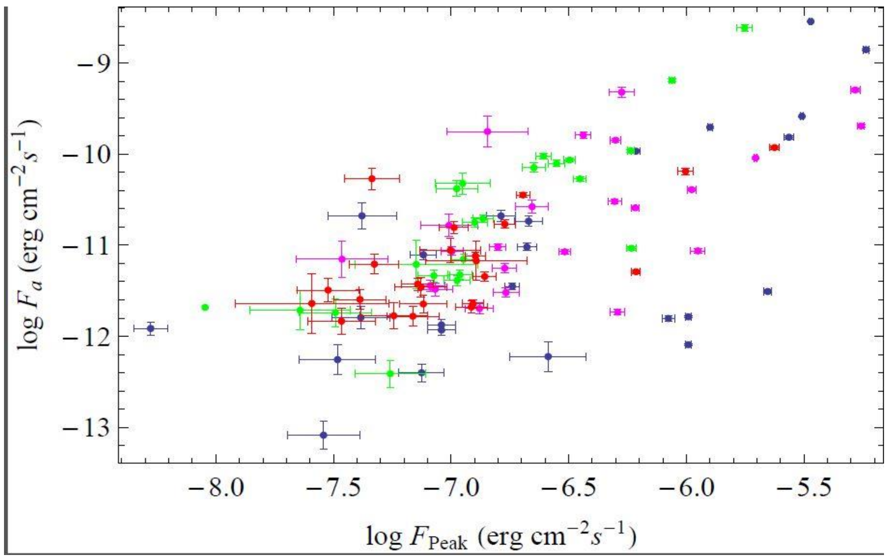
Lx(T*a) vs T*a distribution for the sample of 101 afterglows

Also prompt-afterglow correlations are intrinsic !!!

Dainotti et al. MNRAS 2015b, 31, 4.

Dainotti et al. 2011b, MNRAS,418,2202.

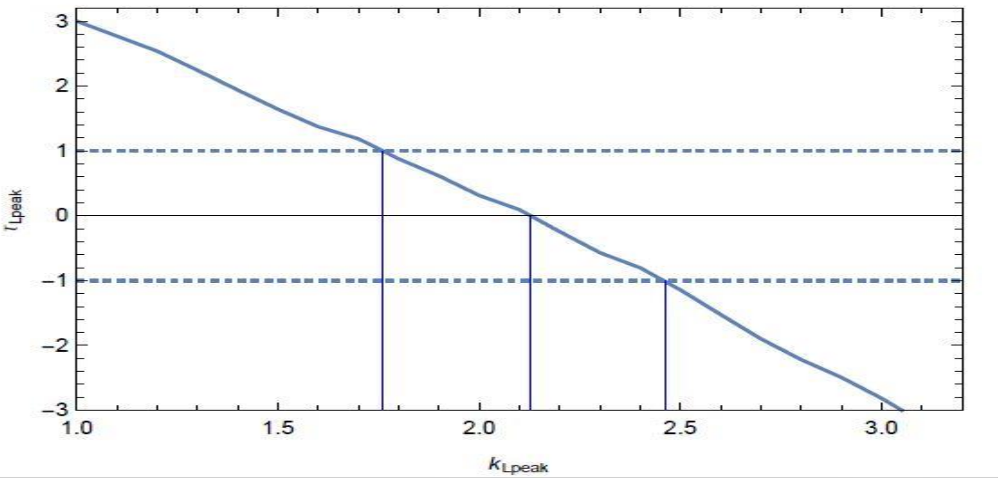




logLa=A+BlogLpeak

A = −14.67 ± 3.46 and B=1.21+0.14−0.13

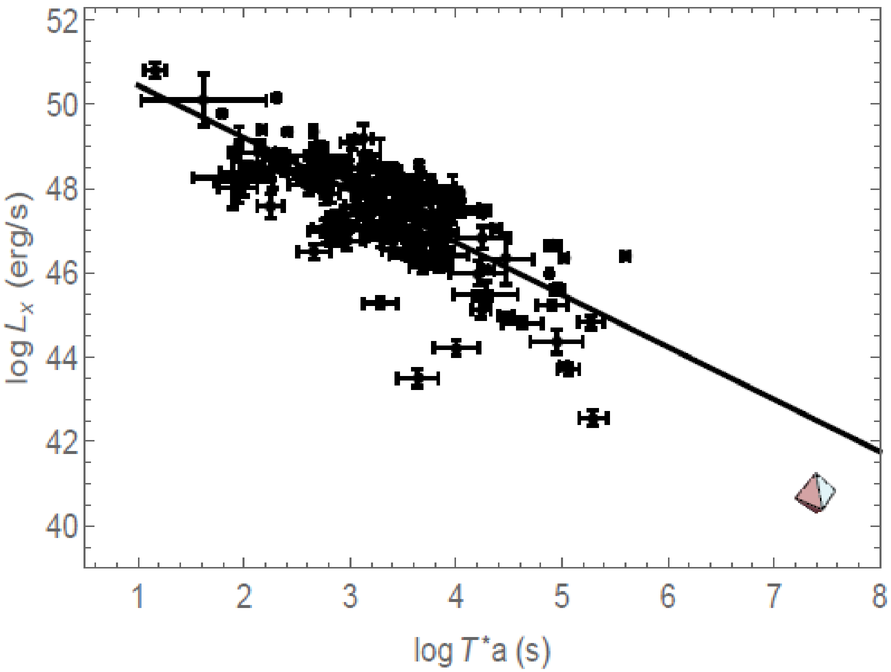
there is a strong evolution in the prompt, 2.13+(0.33,−0.37) consistent with other results, Petrosian et al. 2015,Yonetoku et al. 2005, found a steeper evolution 2.60+/0.15 but still compatible with 1 sigma with this one.

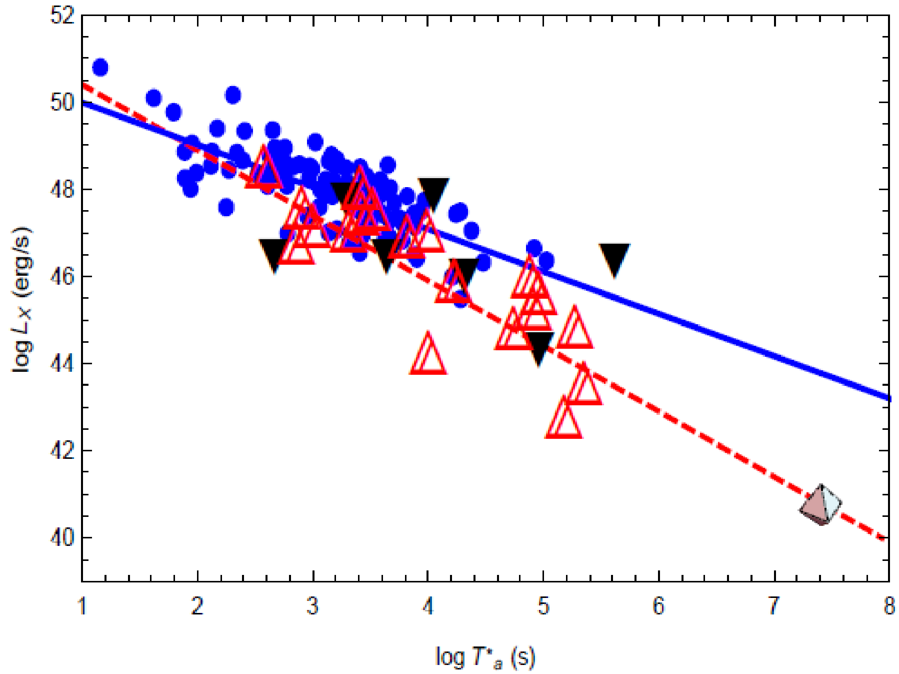


- The correlation La-Ta exists intrinsically!!!
- It can be useful as model discriminator :
- energy injetion model from a spinning-down magnetar *Dall' Osso et al. (2010), Xu & Huang (2011), Rowlinson & Obrien (2011), Rowlinson et al. (2014). In this last paper the intrinsic correlation has been taken into account, Rea et al. 2015, Stratta et al. 2018.*
- Accretion model onto the central engine *Cannizzo & Gerhels (2009), Cannizzo, Gerhels & Troja (2010)*
- The Supercritical Pile Gamma-Ray Burst Model, *Sultana, J., Kazanas, D., Mastichiadis, A. 2013 ApJ, 779, 16S*
- Prior emission model for the X-ray plateau *Yamazaki (2009)*

Looking for a more homogeneous sample for a “Standard GRB set for cosmology”

(Dainotti et al. 2017 A&A, 600A,98)





Long Sample (blue points) for which the SNe is not seen

and GRB-SNe associated (Red triangles)

Conclusions II

- Even though homogeneous observational categories are not separate standard candles they should be separated from the total sample

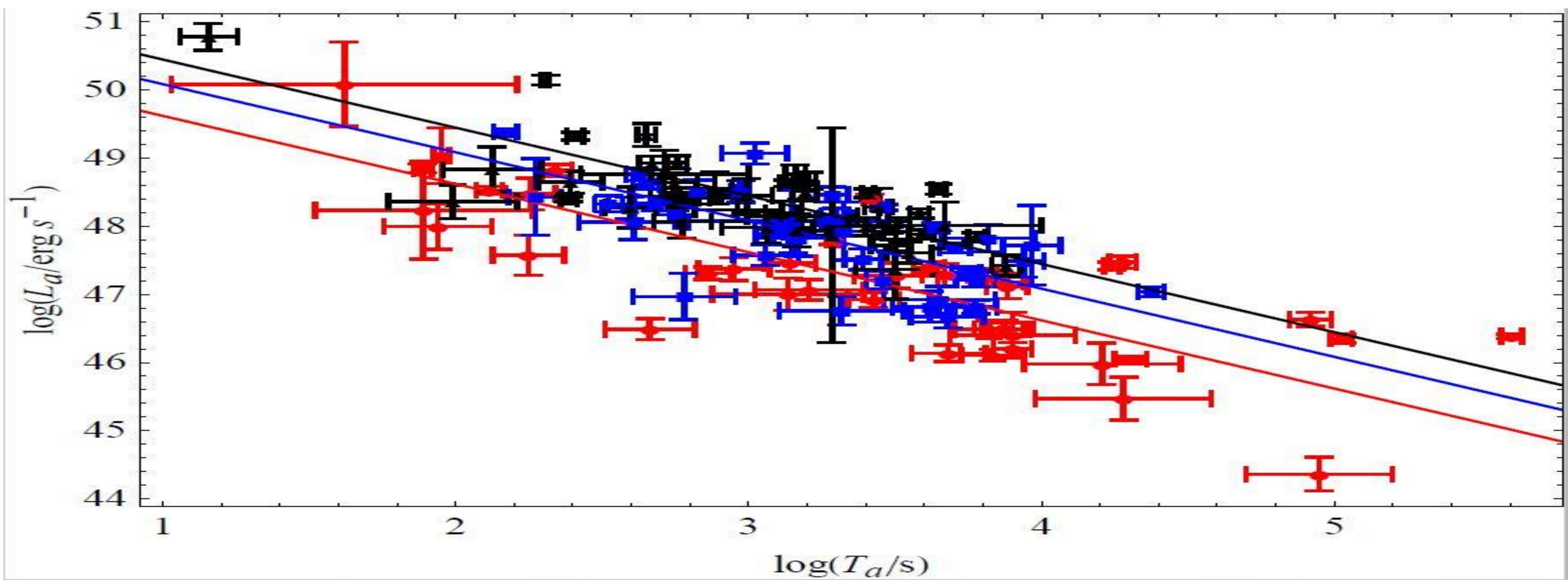
Physical homogeneous categories

Reduction of the scatter in physical relationships

For reviews on GRB relations see

- **Dainotti & del Vecchio 2017, New Astronomy Review, 77,23**
- **Dainotti, M. G.; Del Vecchio, R.; Tarnopolski, M., Advances in Astronomy, 2018 E1D.**
- **Dainotti & Amati, 2018, Publications of the Astron. Society of the Pacific, 130e1001D**

- *To see if La-Ta* correlation is a projection of a more fundamental three dimensional plane
- We plot it as a function of Lpeak, binned into three equally populated ranges :
- 49.9< log *Lpeak*< 51.4 red circles,
- 51.4 <log *Lpeak*< 51.8 blue squares,
- 51.8 < log *Lpeak*< 53.0 black triangles.
- The lines show best fit lines of fixed slope equal to one and free intercept calculated for each *Lpeak* bin. We see a clear monotonic trend of the intercept is determined by the *Lpeak* bin of the subsample.

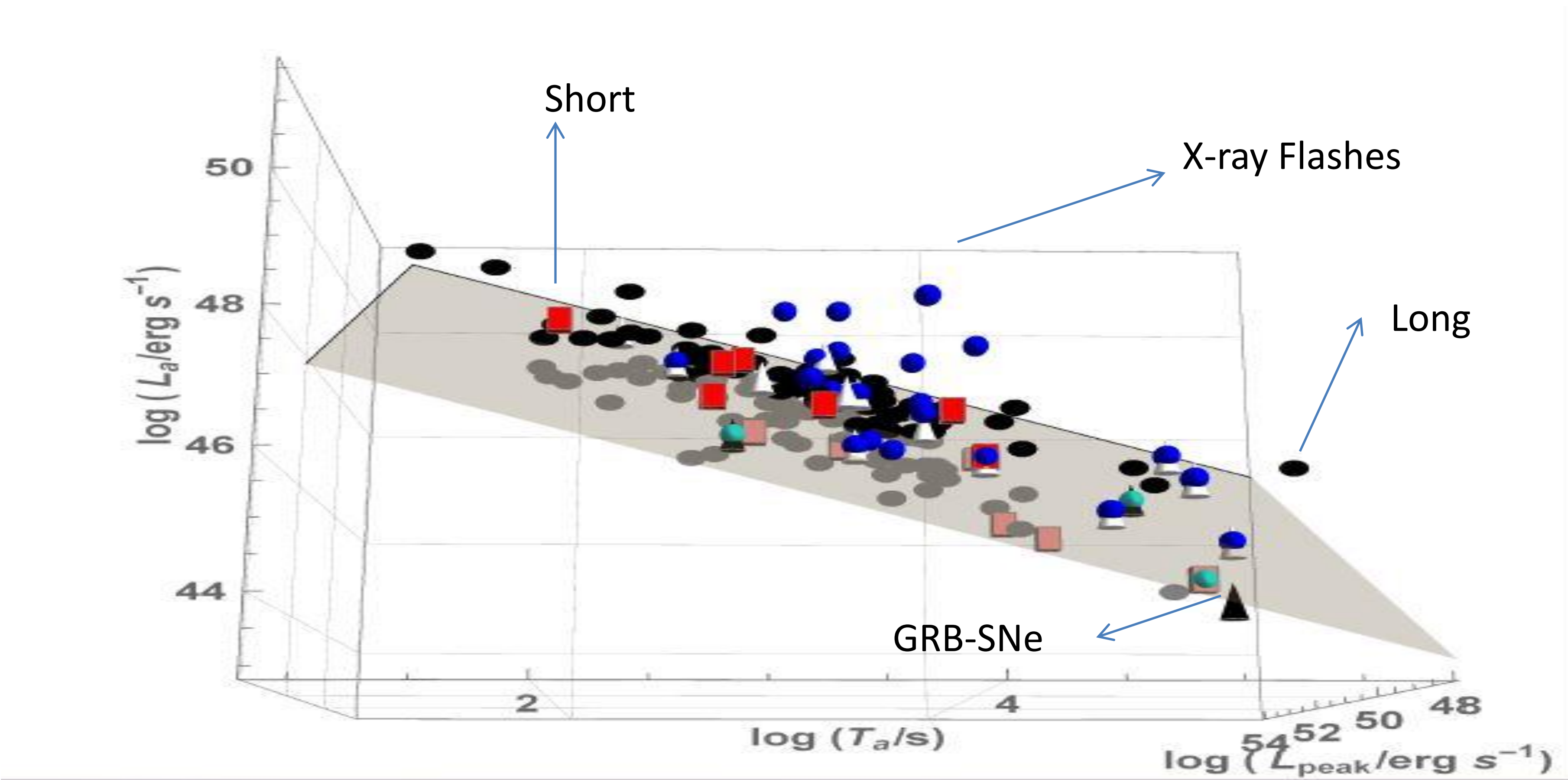


THUS, AN EXTENSION OF THE LA-TA CORRELATION GIVEN THE INTRINSIC NATURE OF LX-TA AND LPEAK-LA

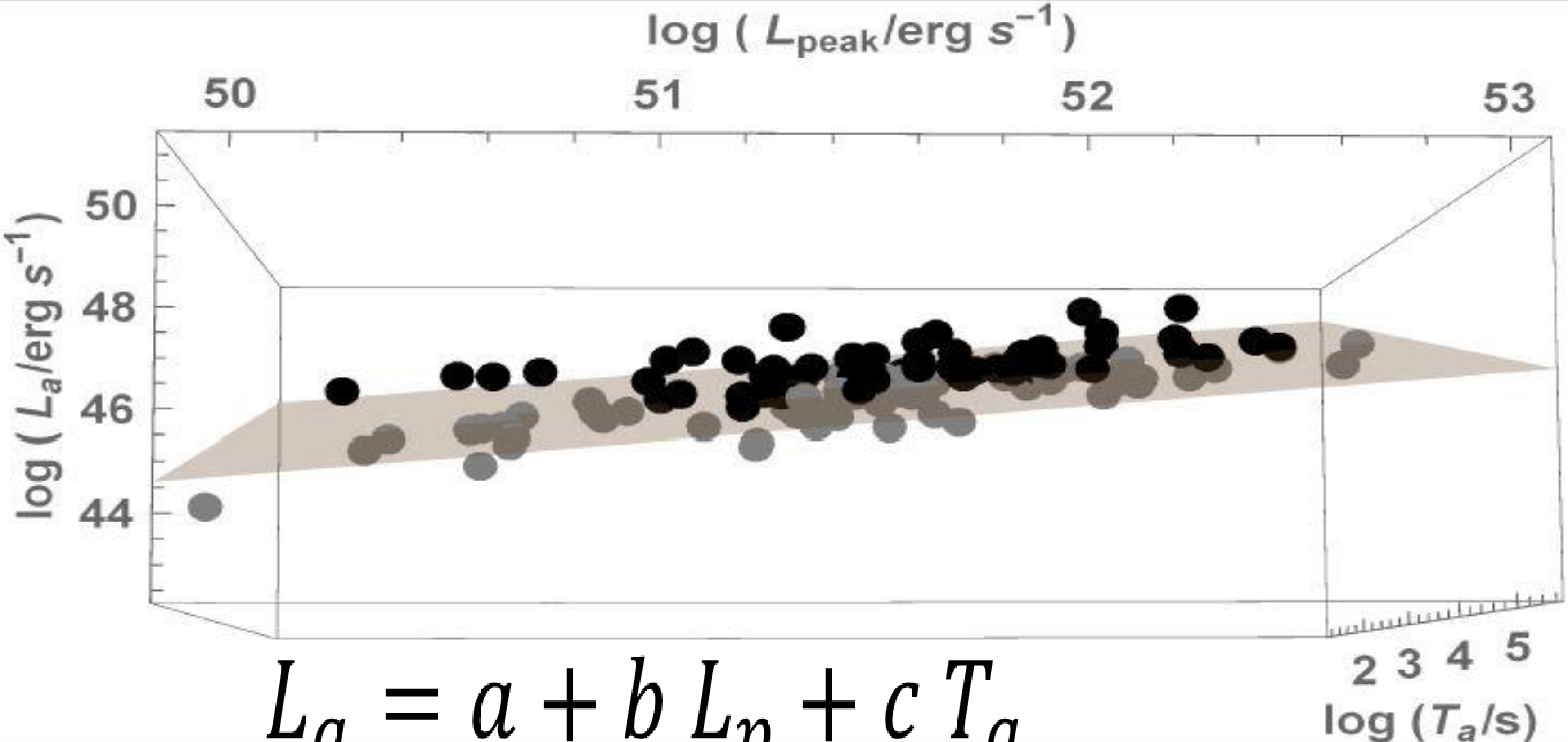
ApJL 2016, **ApJL**, 825L, 20

Press release by NASA:
https://swift.gsfc.nasa.gov/news/2016/grbs_std_candles.html
Mention in Scientific American , Stanford , INAF Blogs and many online newspapers took the news.

- also the 3D Lpeak-Lx-Ta correlation is intrinsic and it reduces the scatter



Only purely LGRBs 122 without GRB-SNe, Short and XRFs



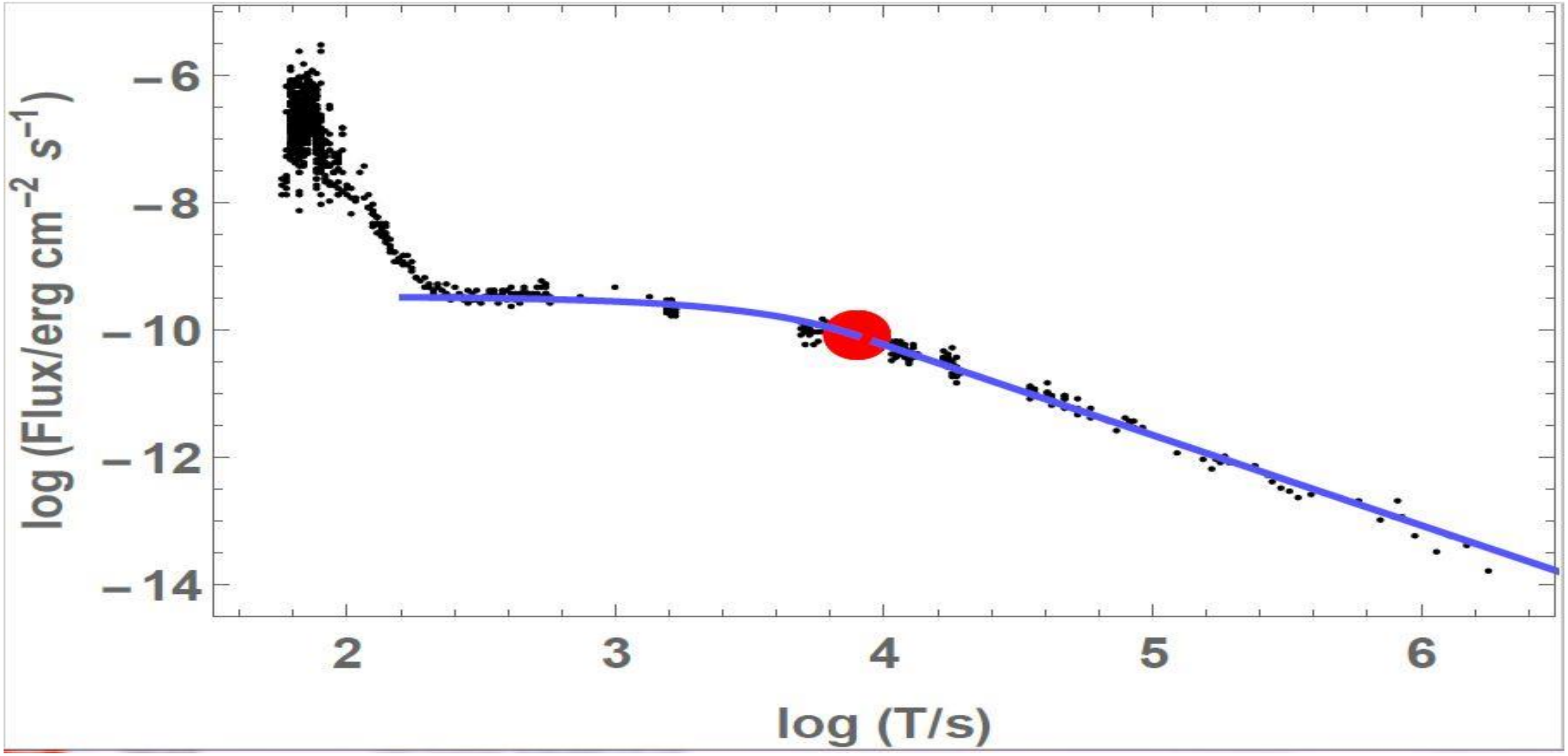
$$L_a = a + b\,L_p + c\,T_a$$

Log *La* = (15.69 3.8) + (0.67 0.07) log *Lpeak +* (0.80 0.07) log *Ta*

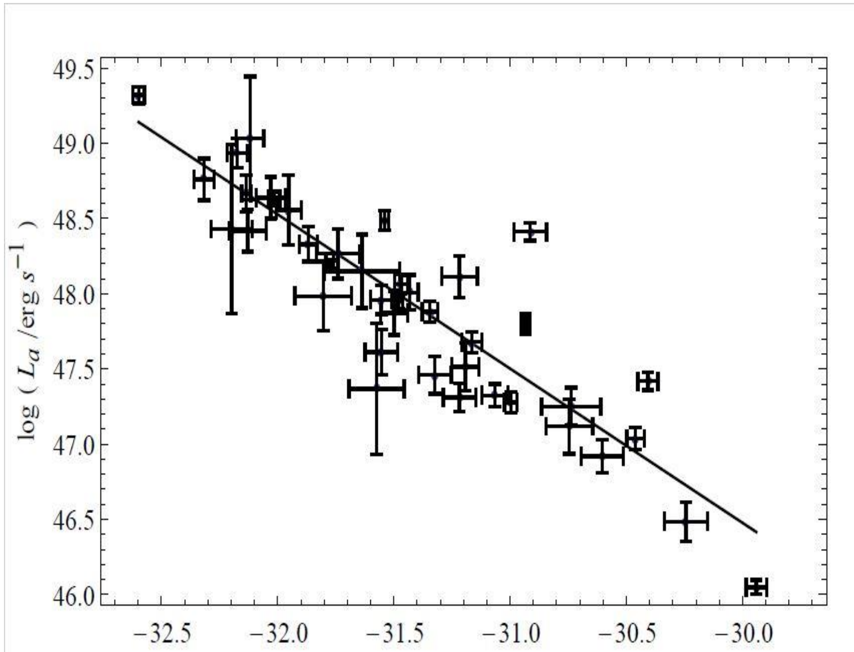
distinct sub-classes of GRBs (previous slide) show greater spread about the plane than the LGRBs. *σint* = 0.44 ± 0.03, 24% less than the *La- Ta* correlation for the sample of 122 LGRBs.

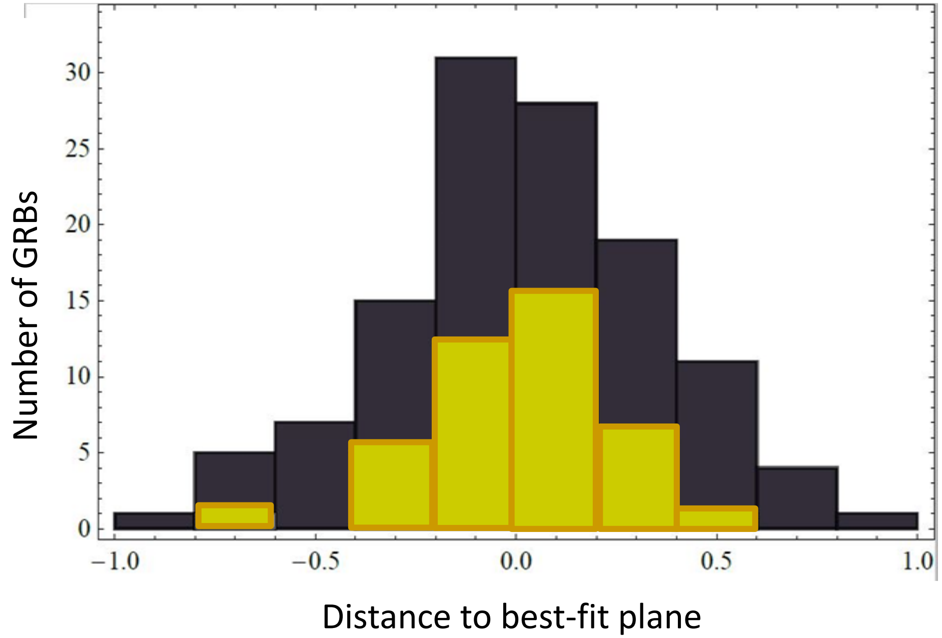
However, we aim at a further reduction in σint in order to use this correlation to further constrain cosmological parameters

- The gold sample : Flat plateau (< 41 degrees)
- Minimum 5 points at the beginning of the plateau



The 3D correlation for the gold sample 40 GRBs





(15.75 ± 5.3) + (0.77 ± 0.1) log *Ta* + (0.67 ± 0.1) log *Lpeak*

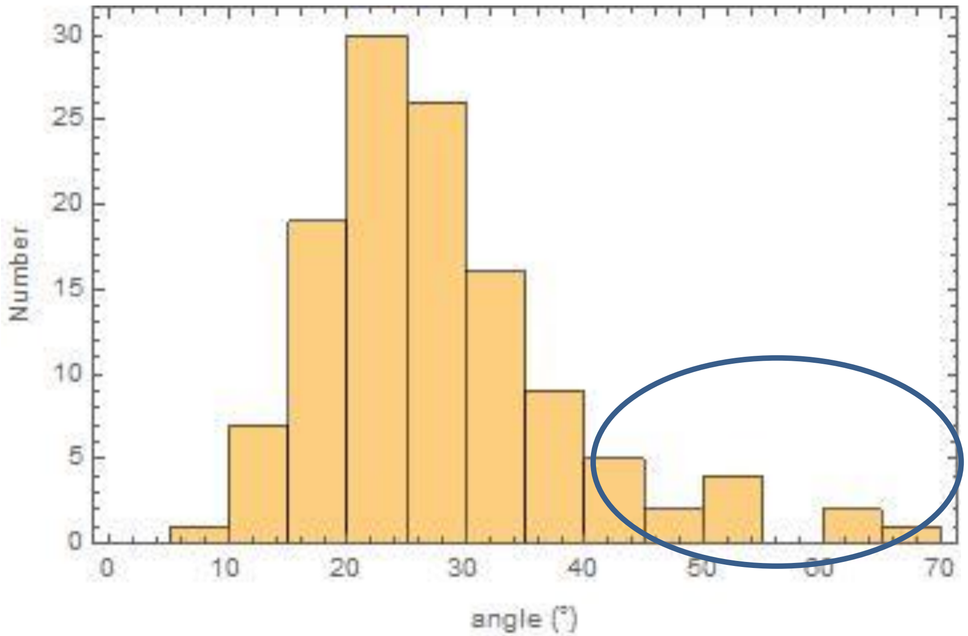
R=0.93 with P =2.2*10^(-16) σint=0.27

We note that the closest GRBs to the plane belong to the gold sample. This is not an effect of selection of the sample.

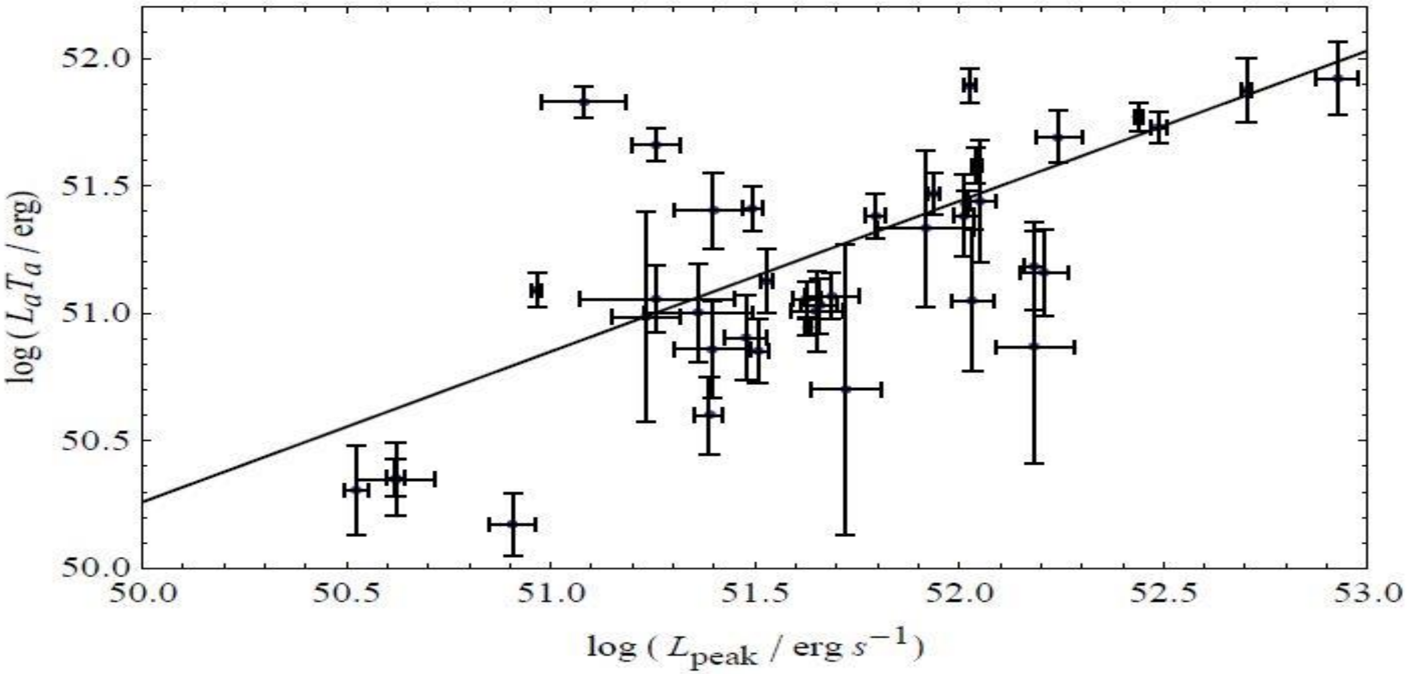
Monte Carlo simulations showed that the Probability of obtaining such a sigma with Random 40 GRBs drawn from 122 is 0.3%, so definitely not a selection of the sample!

Selection effects

- Regarding the angle cut we show that there is a tail of the distribution above 41° and we remove it, this tail constitutes only the 11% of the total distribution



The 3D correlation as the 2D Lpeak vs La*Ta



The prompt kinetic power is strongly correlated with the plateau energy, for the GRBs with well-defined plateaus.

The best fit slope with σint=0.29 is: log(La*Ta) = 20.63 + 0.59 log (Lpeak)

This fit as well as the other presented are done using the D'Agostini method

Comparison with other 3D correlations

- Bernardini et al. (2012) Epeak-Eiso-La*Ta with σint=(0.31 ± 0.03).
- Tsutsui et al. 2009 another fundamental plane Lpeak-Eiso-Epeak but only amongst prompt emission parameters.
- Xu & Huang (2011) a significantly tighter (La-Ta-Eiso) correlation with σint =0.43, as compared to the (La-Ta) one which yields σint=0.85, for their particular chosen sample.
- Their gold sample is flat plateau, no flares in the plateau and no flares before plateau.
- σint of (La,Ta,Lpeak) plane is smaller by 37% of (La-Ta-Eiso) .

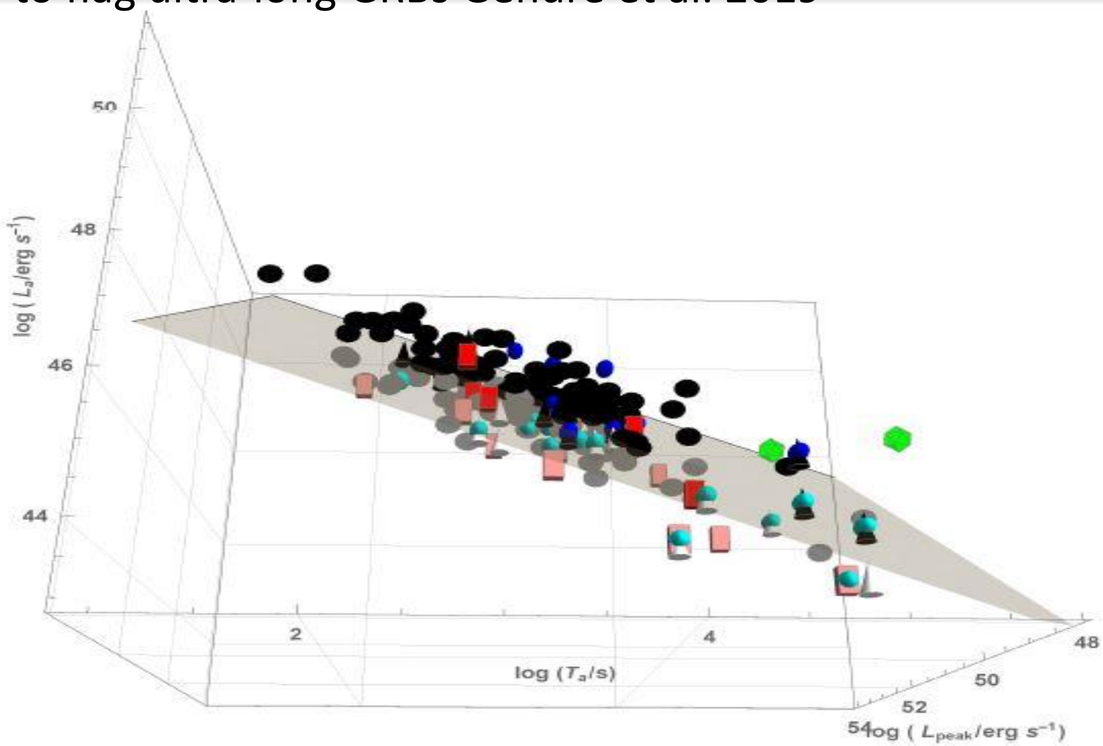
- We conclude that the (La,Ta,Lpeak) is an improvement on the La-Ta correlation as well as on the (La, Ta, Eiso and Epeak-Eiso-La*Ta) correlation.

Adding the ultra-long GRBs to the fundamental plane.

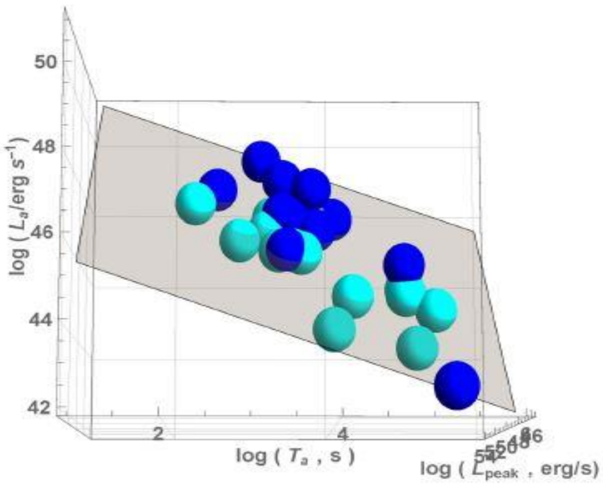
Ultra-long GRBs=remarkably unusual X-ray and optical light curves, very different from classical GRBs, with long-lasting, highly variable X-ray emission.

Progenitors types:

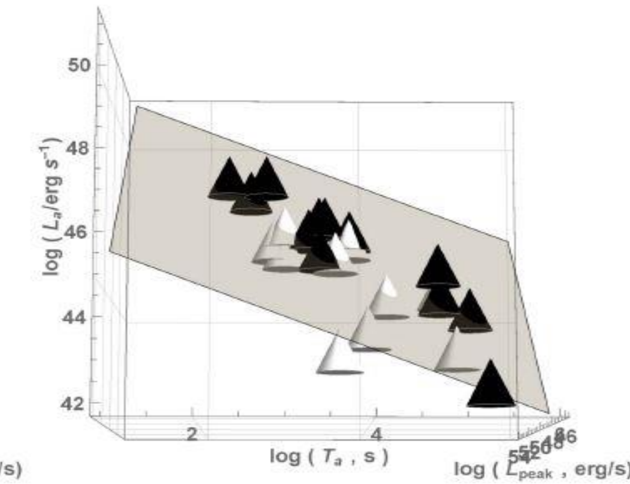
- engine-driven explosions of stars of much larger radii than those of the common GRB progenitors
- the tidal disruption of stars by supermassive BH (Levan et al. 2014)
- a low-metallicity blue supergiant progenitor (Piro et al. 2014).
- How to flag ultra-long GRBs Gendre et al. 2019



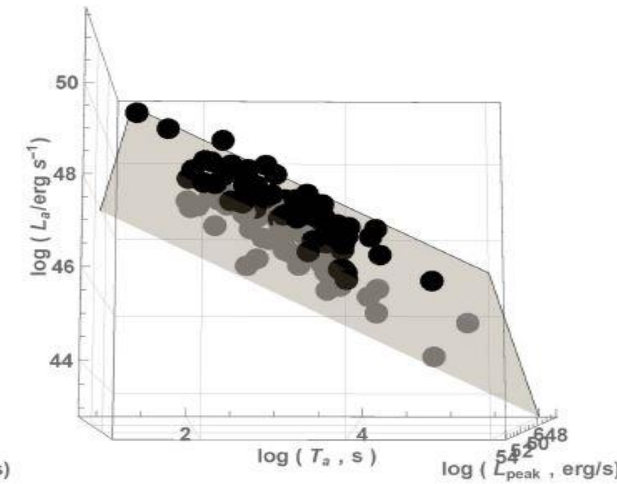
Planes with a smaller decreasing scatter



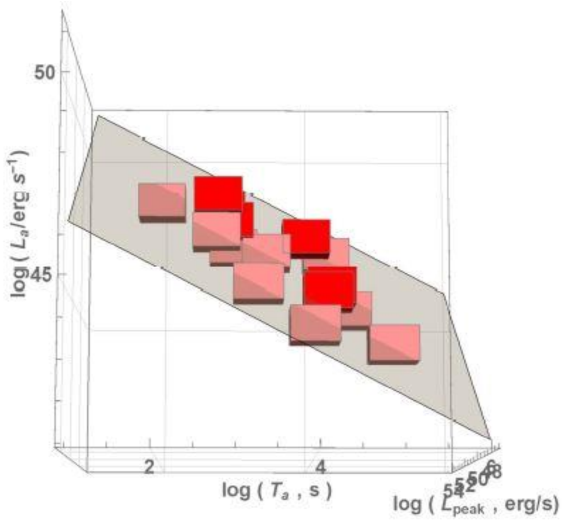
X-ray flashes (blue spheres)



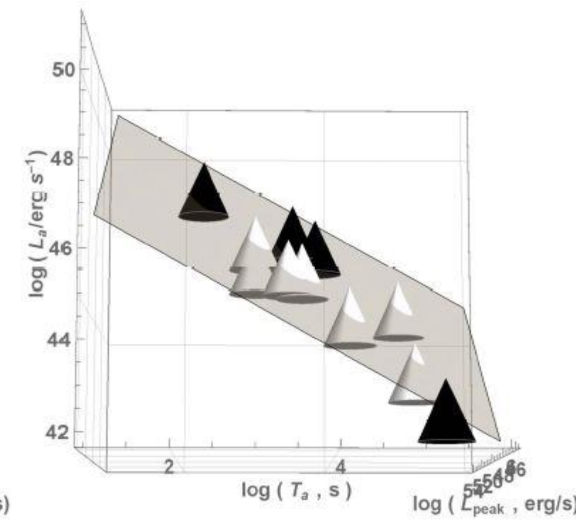
GRB-SNe (black and white cones)



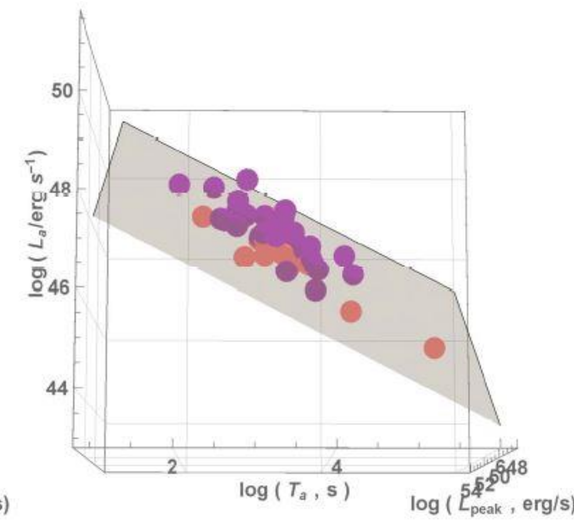
LGRBs (black and grey points)



SEE(red and pink squares)

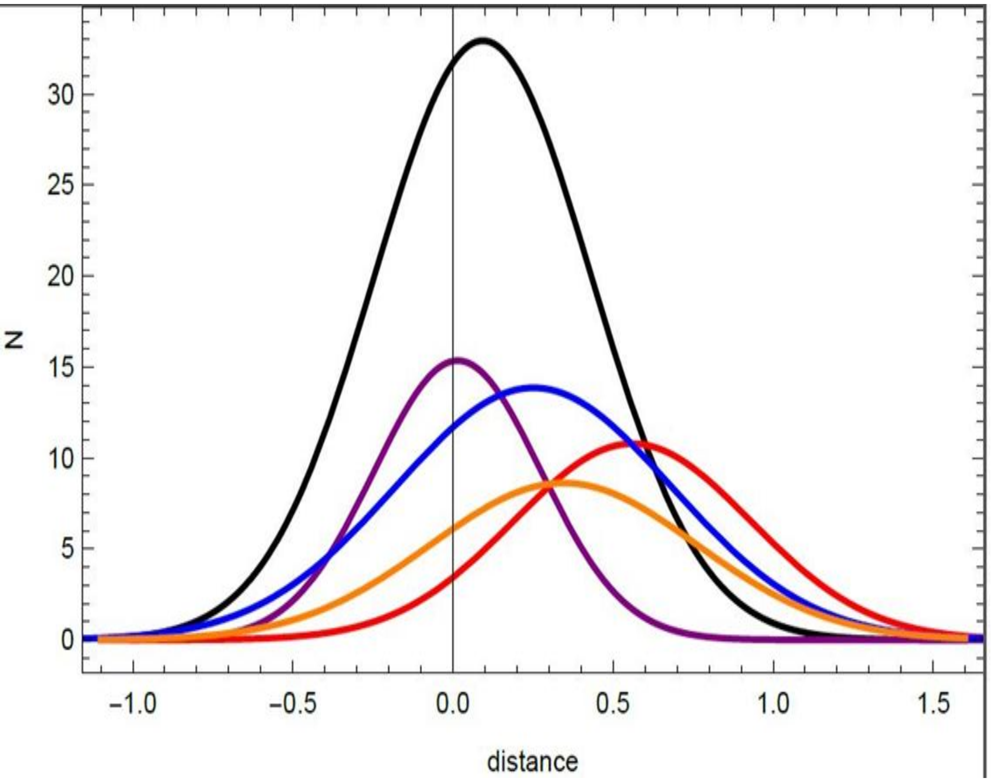


GRB-SNe spectroscopically associated



LGRBs gold sample

184 GRBs



(Dainotti et al. 2017, ApJ, 848,88): the gold sample has the smallest scatter.

Press release by INAF, by Nature-Index, a research highlight at Stanford by Nature index, and by Le Scienze (the Italian version of Scientific American): http://www.inaf.it/en/inaf-news/gold-grb#null

Interviewed by the national daily news
Italian Television.

https://www.facebook.com/Marie.Curie.Actions/photos/a.443662259040646/2766583496748499/?type=3&theater
Marie Curie Fellow of the week (5-12 of May 2019)

Using Fermi-GBM data and Ta as dependent variable

Table 4

Table of Best-fit Values for Relation Plane Parameters Using the Gold Sample Where the Dependent Variable T_a Is Either Normalized or Standardized

Category	C_o'	a'	b'	$\sigma_{\rm int}$	Δ_σ
Gold normalized	21.91 ± 6.58	-0.74 ± 0.10	0.29 ± 0.09	0.30 ± 0.04	6%
Gold standardized	21.08 ± 6.67	-0.75 ± 0.11	0.29 ± 0.09	0.30 ± 0.04	6%

Note. We note that there is not a significant change in the scatter, $\sigma_{\rm int}$, from that of the gold sample in Table 3, showing that the fitting method used is not sensitive to scale differences.

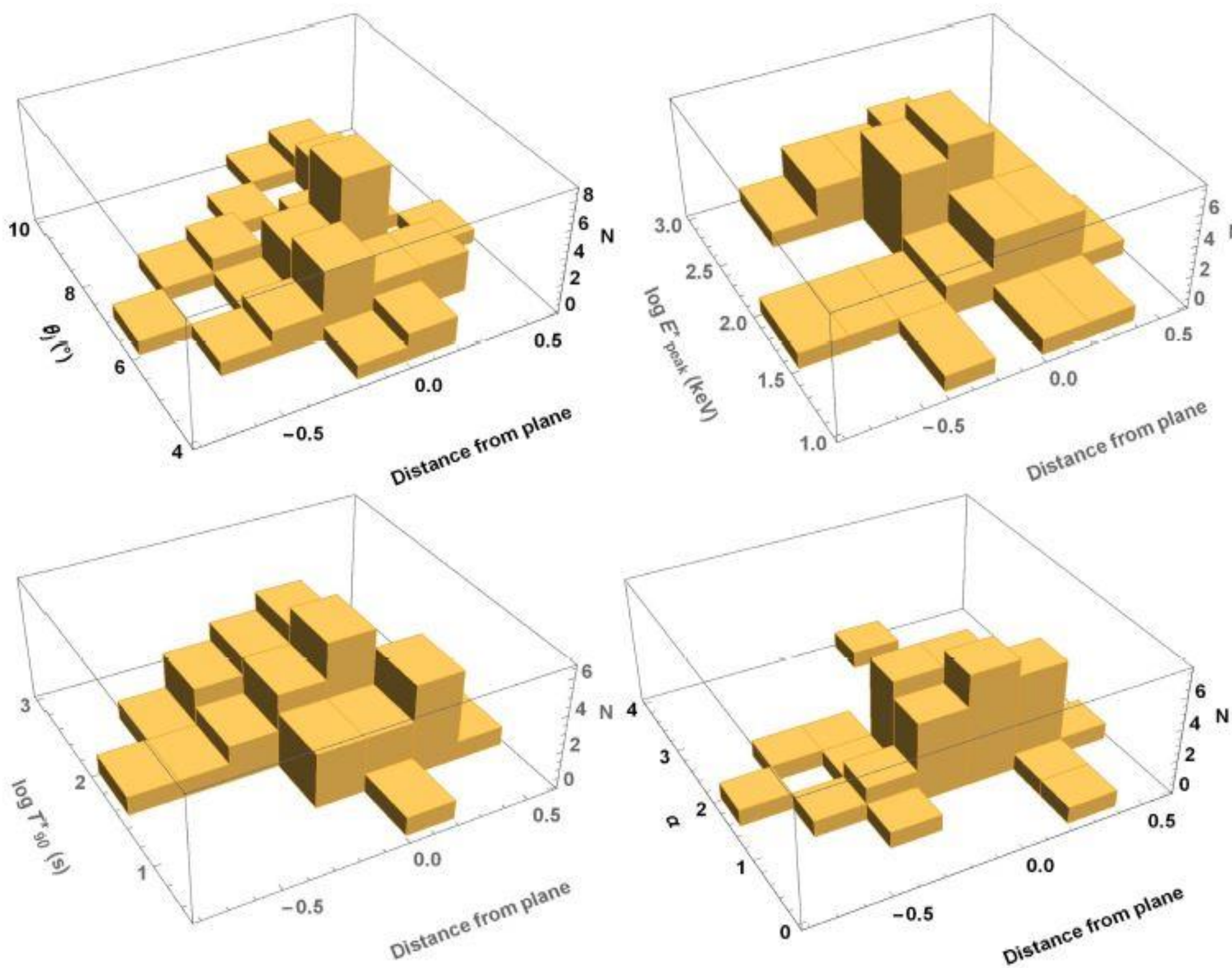
Table 5

Table of Best-fit Values for Relation Plane Parameters in Order of Increasing Scatter, $\sigma_{\rm int}$

Category	C_o	a	b	$\sigma_{\rm int}$	N
Long (*Fermi*)	21.34 ± 5.96	-0.89 ± 0.07	0.58 ± 0.10	0.43 ± 0.07	34
Long (*Swift*)	17.22 ± 7.50	-0.88 ± 0.09	0.65 ± 0.13	0.48 ± 0.07	34

Note. These values are computed assuming 1024 ms.

The dependence of the fundamental plane from prompt parameters



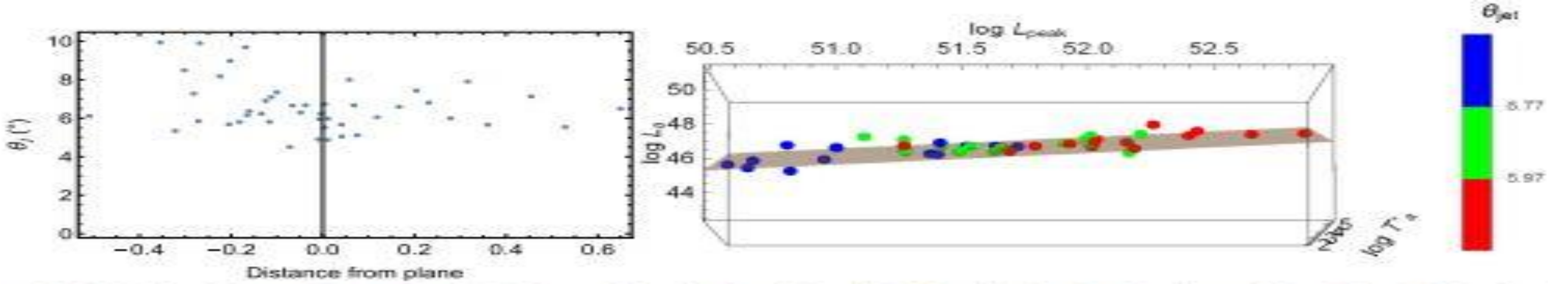


Figure 5. Left: 2D plot of θ_{jet} over distance from the fundamental plane for the gold sample. Right: color bar plot of fundamental plane with a color bar depending on θ_{jet}.

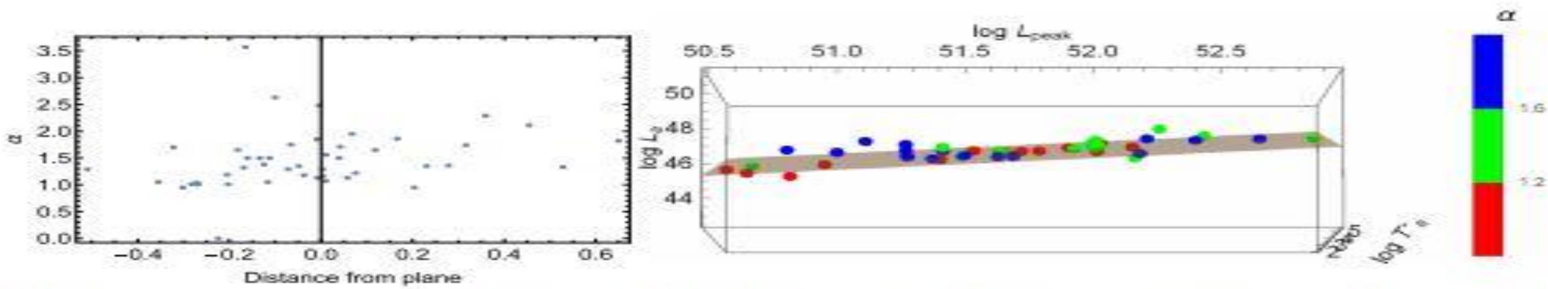
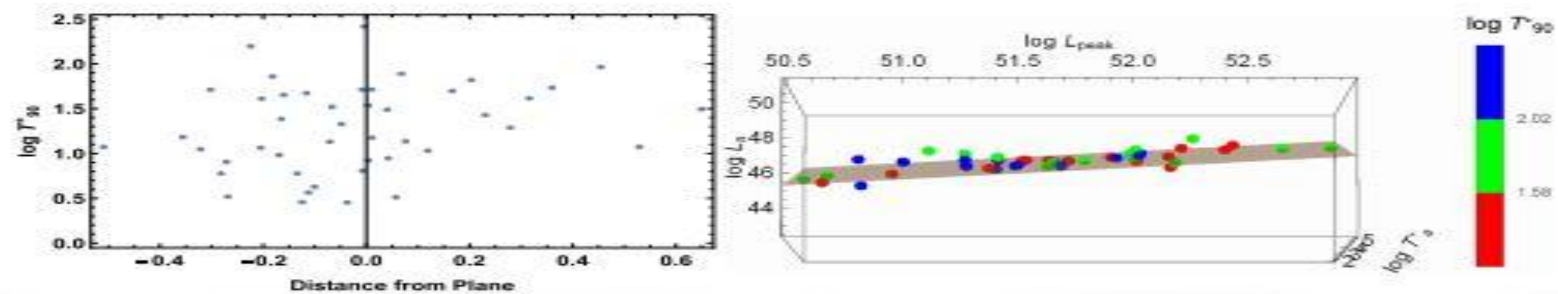
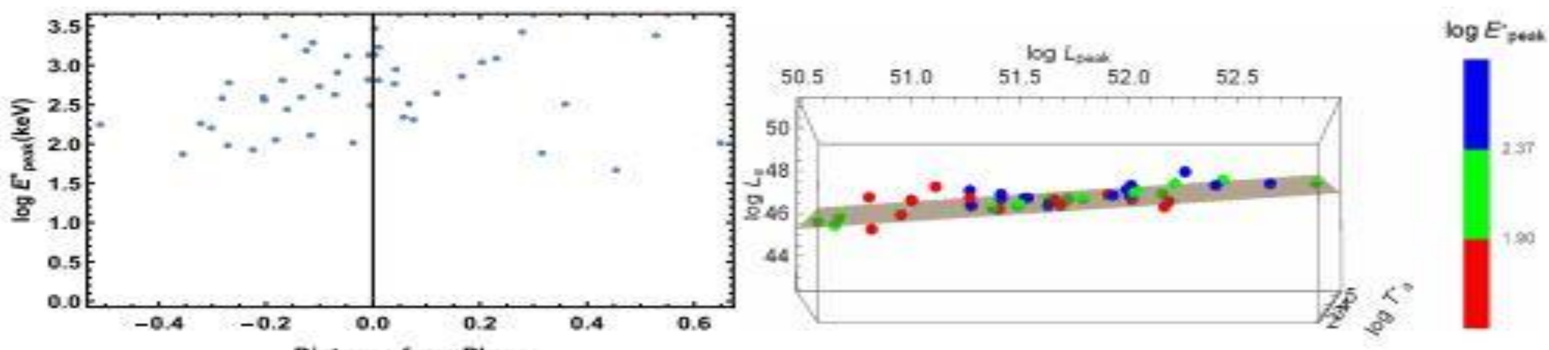


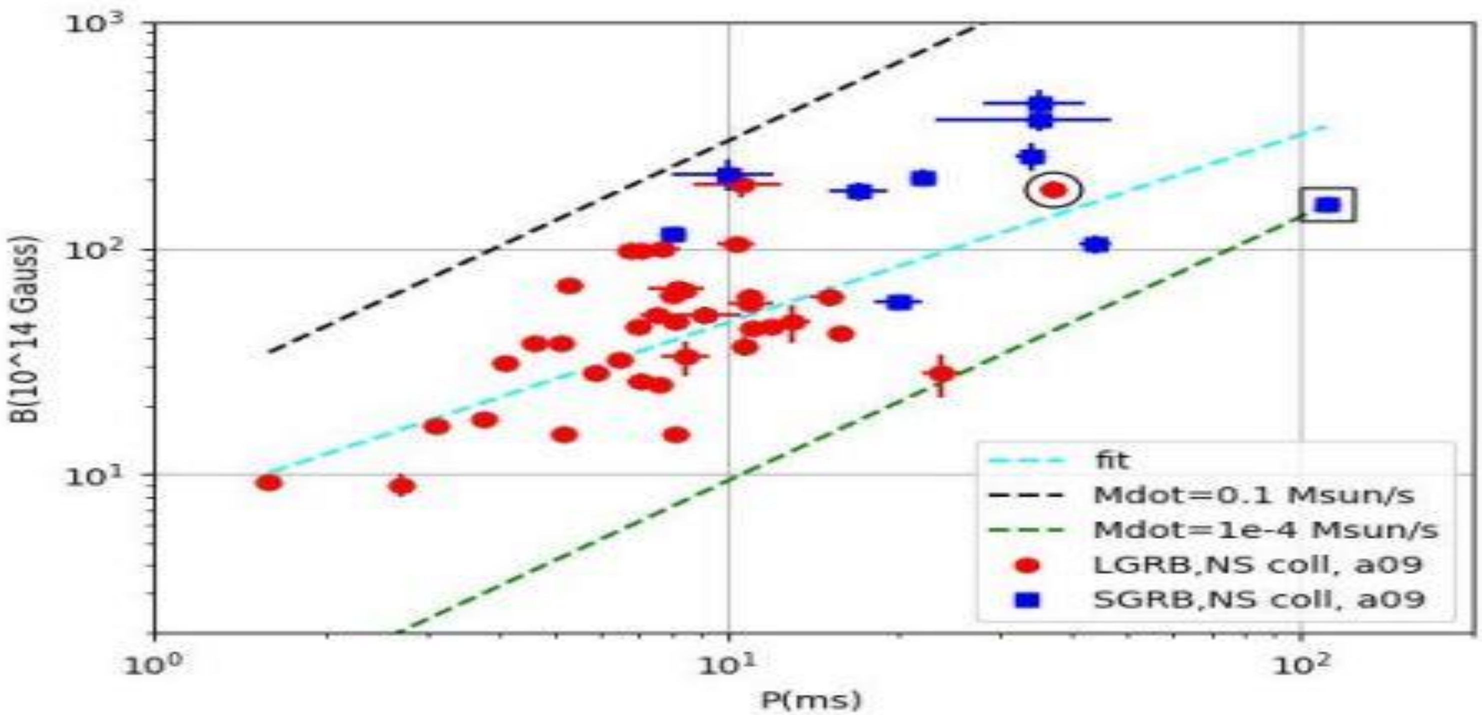
Figure 6. Left: 2D plot of α over distance from the fundamental plane for the gold sample. Right: color bar plot of fundamental plane with a color bar depending on α.





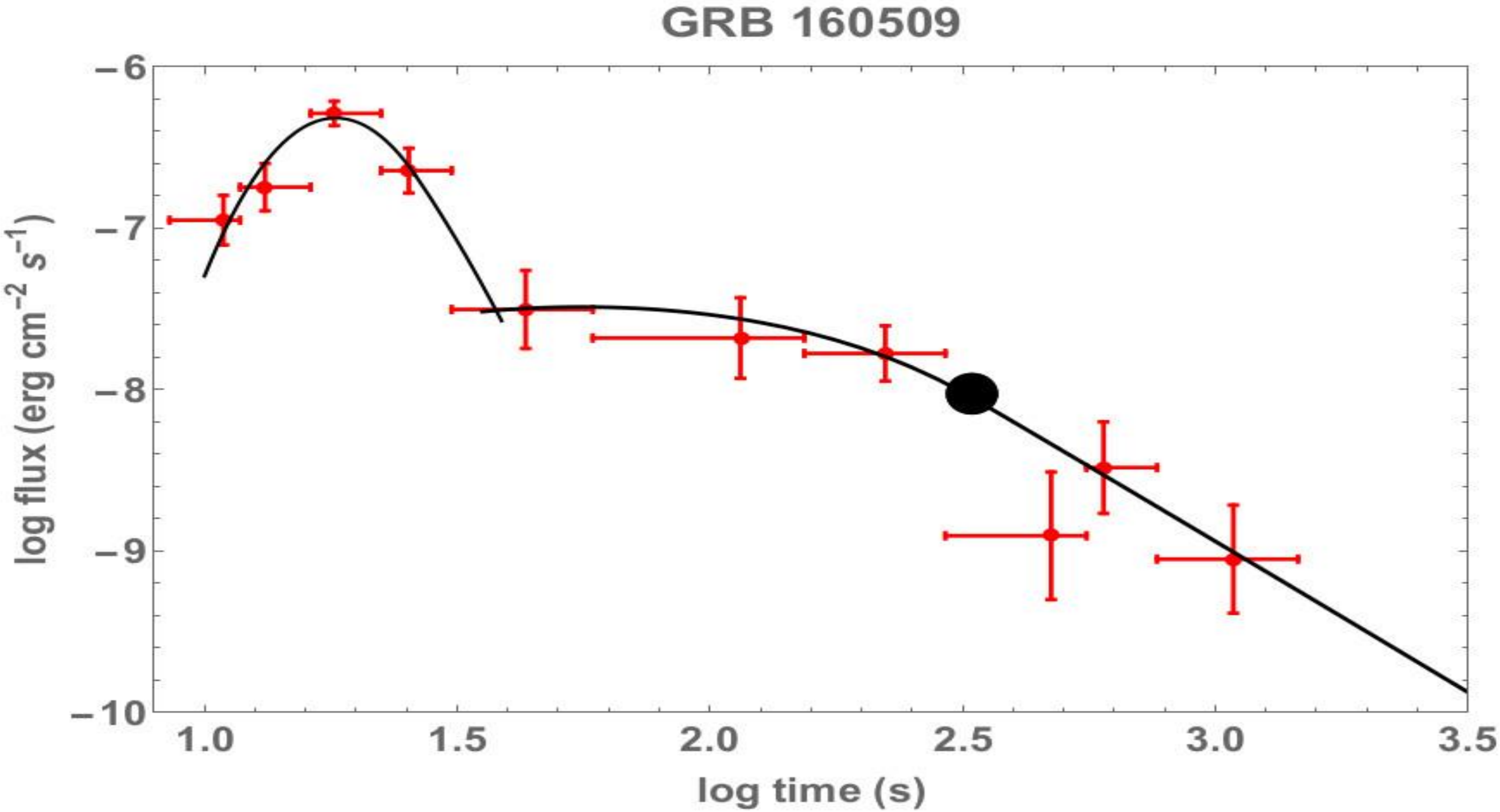
2 different categories within the magnetar scenario

Stratta, Dainotti et al. 2018, ApJ, 869, 155

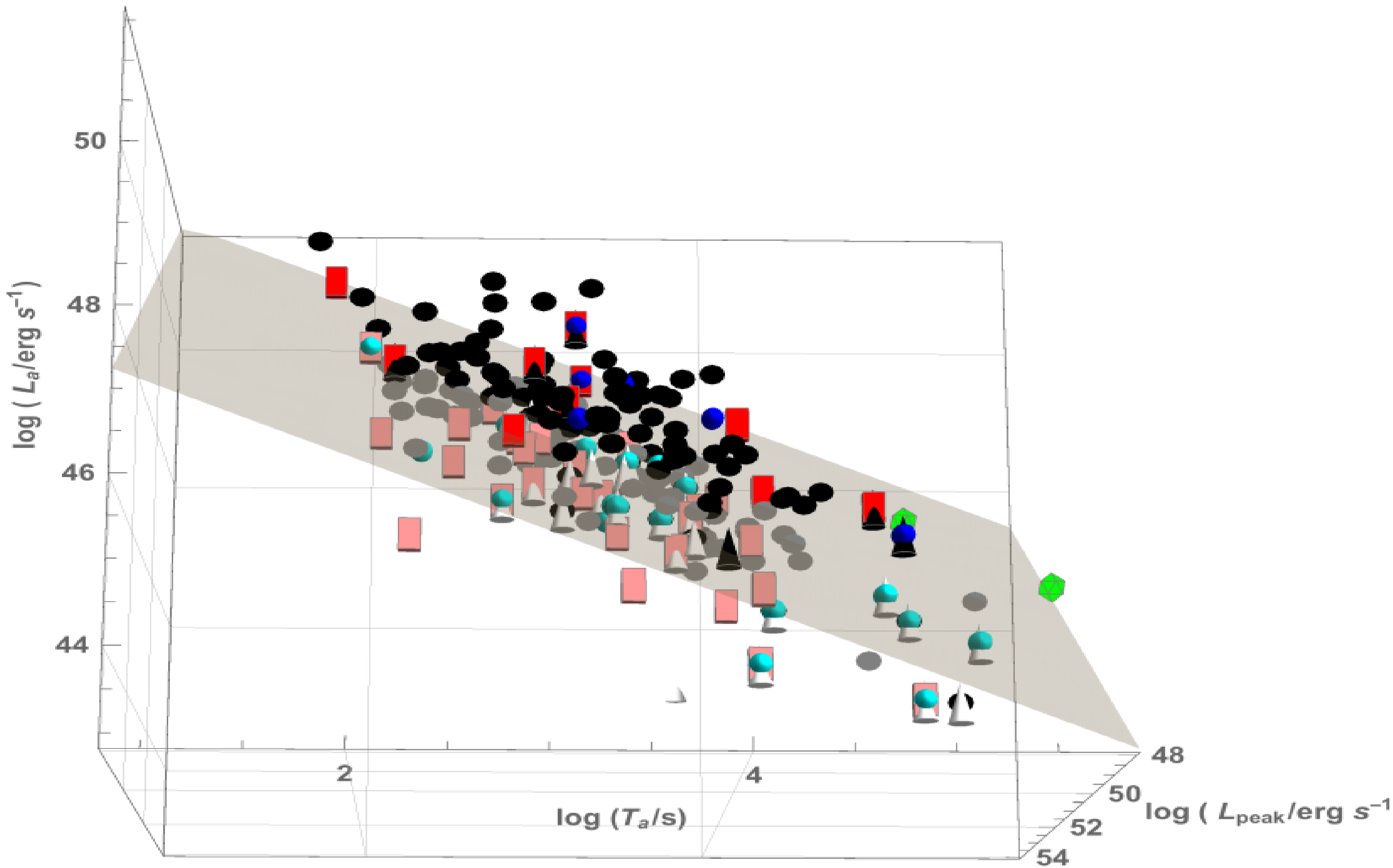


The spin-down luminosity of the magnetar is entirely beamed within the jet opening angle (data points) for a braking index n=2.1 (α = 0.9). The long GRBs are marked as red circles while the SEEs are blue squares. Dashed lines indicate the expected B −P relations from accreting NS for an accretion rate of 0.1M/s (black) and 10−4M/s (green) and the best-fit relation (cyan). The two framed data points indicates the long GRB 070208 (circle) and the peculiar GRB 060614A (square).

Indication of the plateau in the LAT data? See Second GRB LAT Catalog (Ajello et al. 2019, ApJ, 878, 52)



Update of the 3D relation with 2 years of more measurements 232 GRBs (only firm redshift taken from Greiner web page)



Conclusions and future prospects

- The 3D correlation so far it is the tightest among prompt-afterglow correlations
- It is confirmed for GRBs observed by GBM.
- The gold sample is a step forward for the hunt on the standard candles
- It is robust on the 3D formulation, no dependence on other prompt parameters
- The theoretical interpretation (magnetar, BH or Photospheric emission model) will lead to a more robust theoretical ground of a sample that can become standard candle
- Verify if LAT GRBs follow the 3D correlation
- Application of the 3D plane to obtain cosmology

Gamma-ray Burst Correlations

Current status and open questions

1. Details of GRB correlations
2. Selection bias
3. Distance estimators
4. Cosmological tools
5. Model discriminators

published in IOP Physics Expanding series ebook collection in August