A fundamental plane for GRB afterglows and perspective for the Theseus mission

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It is the time of the transient astronomy and to use GRBs as cosmological tools

why GRBs as possible cosmological tools?

Because

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

Theseus will observe between 10 and 25 GRBs at z > 8 and several at z > 10 over a three year mission.

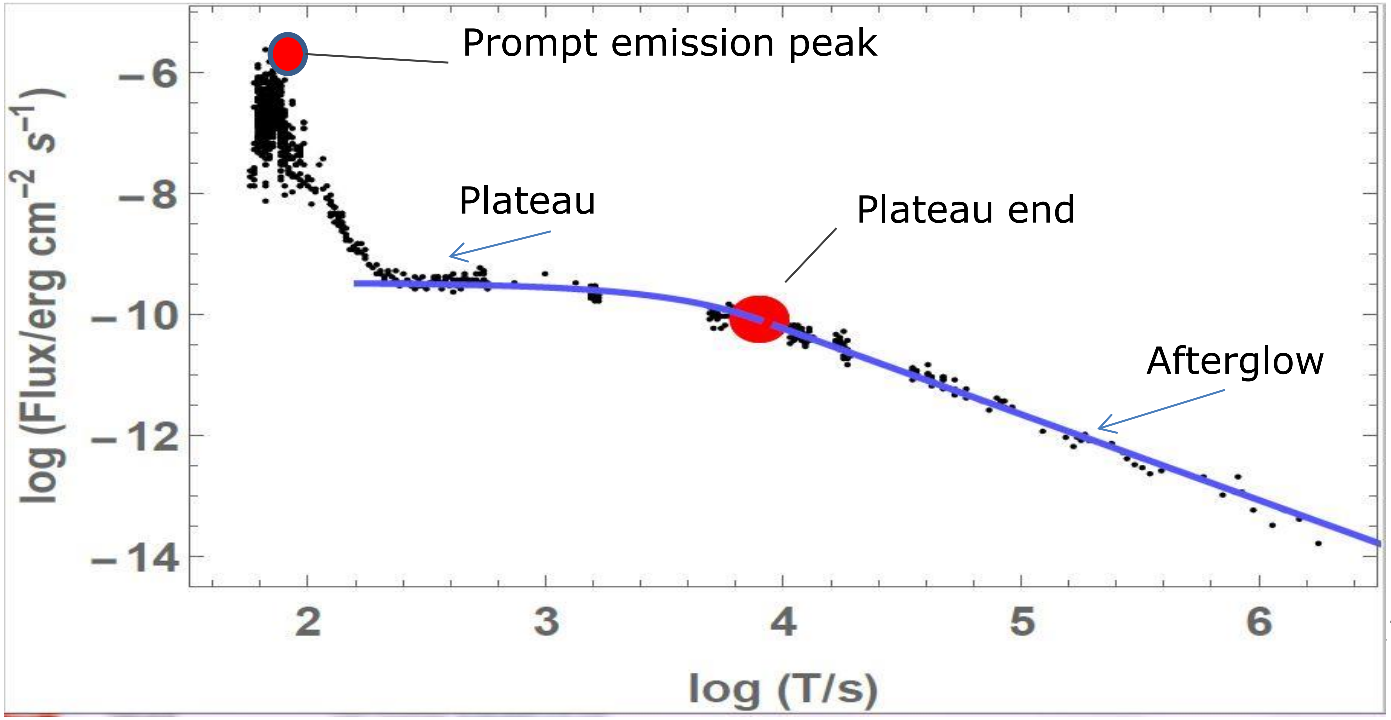
Much more distant than SN Ia (z=1.914) and quasars (z=6)

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.

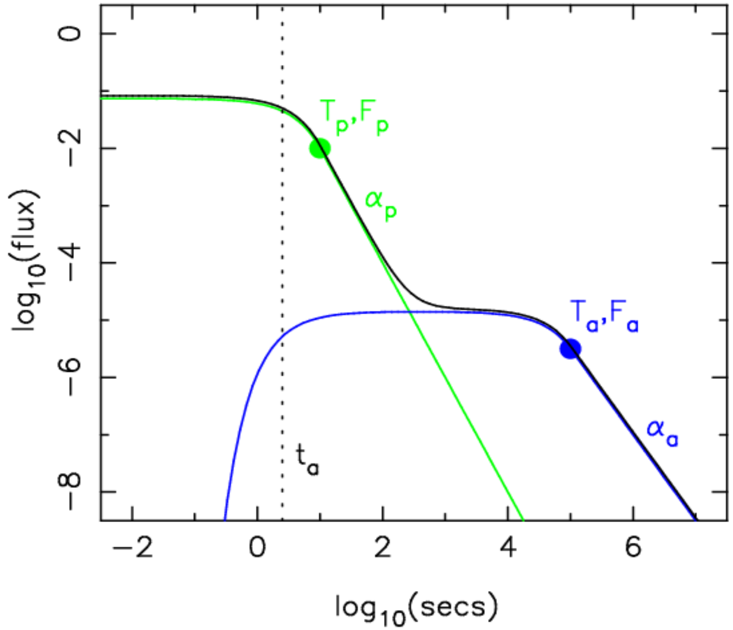
Important features of a well-sampled GRB light curve observed by Burst Alert Telescope+ X-Ray Telescope +Swift (2004-ongoing)



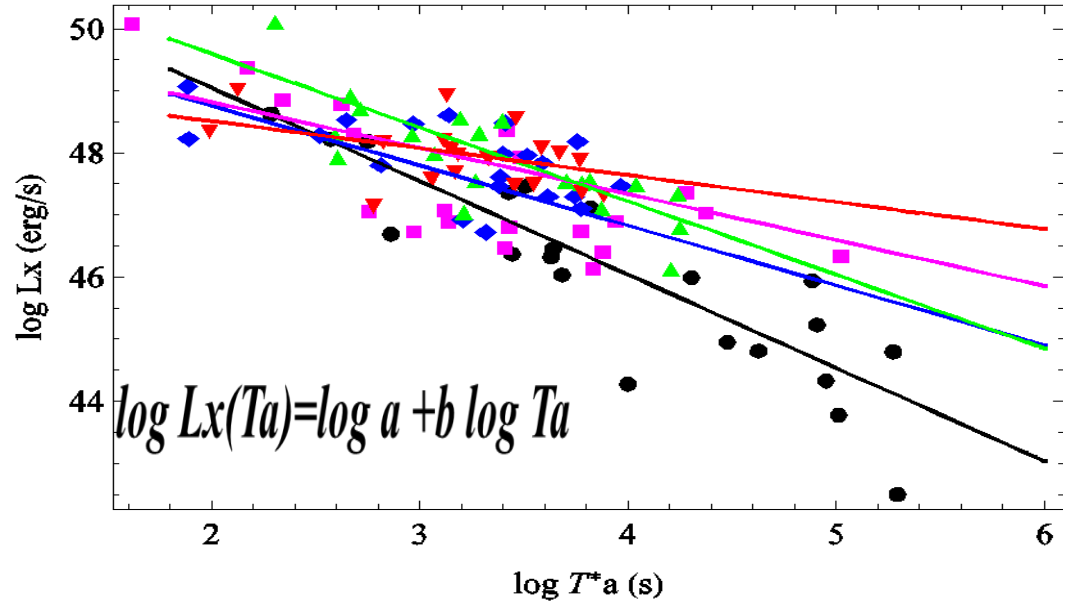
For 20 years, we’ve been trying to figure out how to use GRBs as standard candles, but the light curves vary widely -- “If you've seen one GRB, you've seen one GRB” -- confounding efforts to isolate common properties.

A possible reliable candidate is the $L_X - T^*_a$

Willingale et al. 2007, ApJ, 662, 2, 1093



Dainotti et al. 2013, ApJ, 774, 157D



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

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)

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

The magnetar central engine model may also explains this correlation

- The spinning down millisecond magnetar analytically reproduces the LT intrinsic correlation

$$L_{0,49} \sim (B_{p,15}^2 P_{0,-3}^{-4} R_6^6)$$

$$T_{em,3} = 2.05\,(I_{45} B_{p,15}^{-2} P_{0,-3}^2 R_6^{-6}),$$

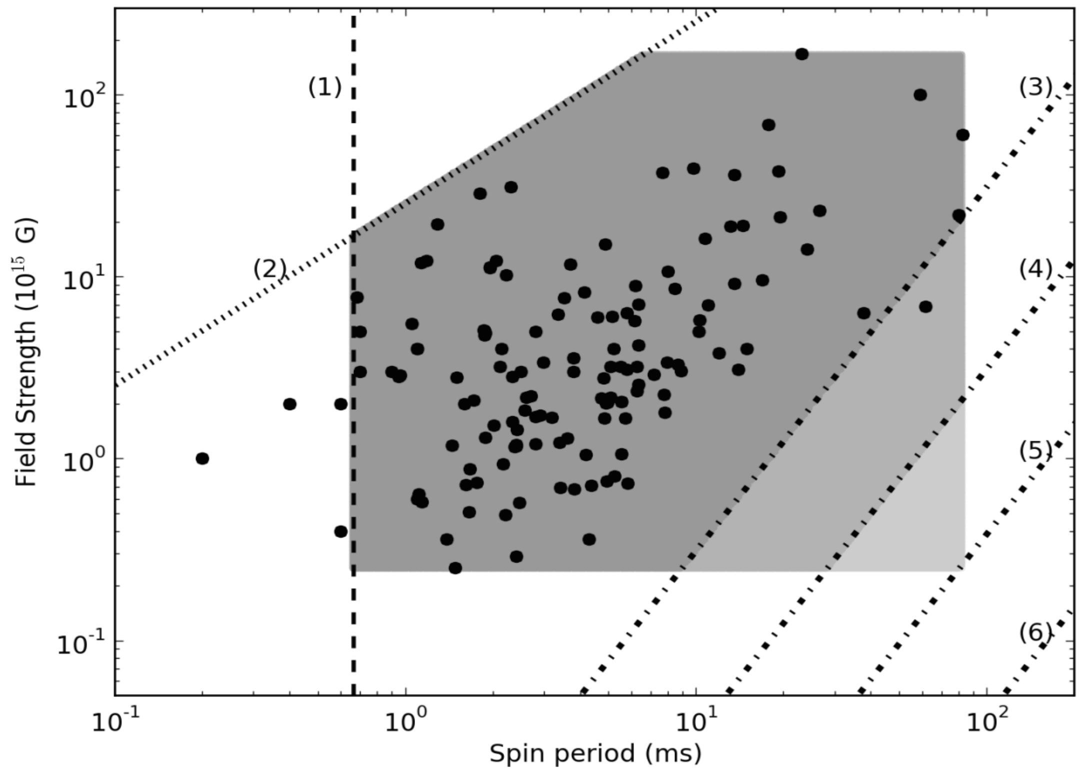
Substituing Radius in the L0,49

$$\log(L_0) \sim \log(10^{52} I_{45}^{-1} P_{0,-3}^{-2}) - \log(T_{em})$$

acorr=log(ϵ)−log(1−cosθ)+a

ϵ is the efficiency which describes the proportion of the spin-down luminosity of the magnetar that has been transferred to observable radiation

- **Rowlinson, Gompertz, Dainotti, et al. 2014, MNRAS, 443,1779**



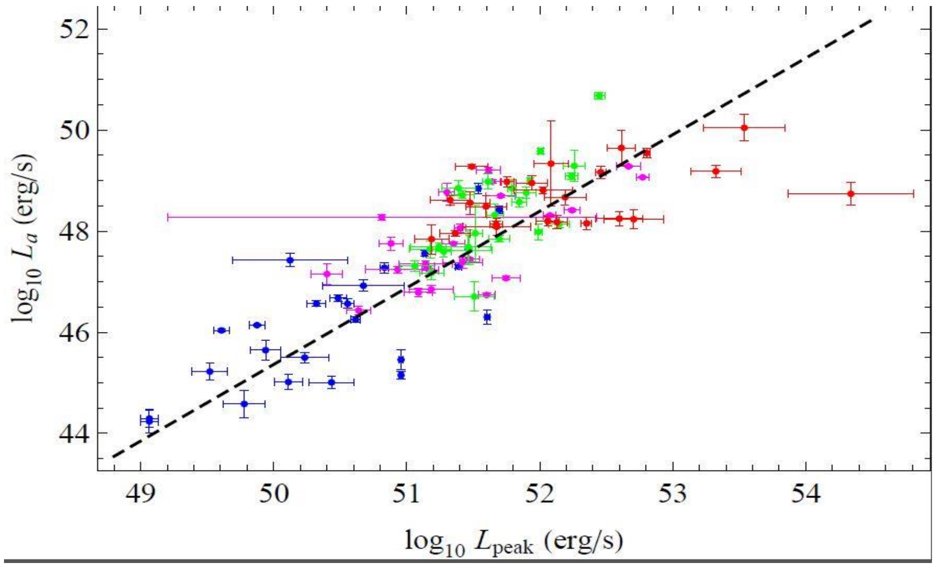
Black points: Fitted magnetar parameters from GRB X-ray lightcurves (Lyons et al. 2010; Dall'Osso et al. 2011; Gompertz et al. 2013; Rowlinson et al. 2013; de Ugarte Postigo et al. 2013; Yi et al. 2014; Lu & Zhang 2014)

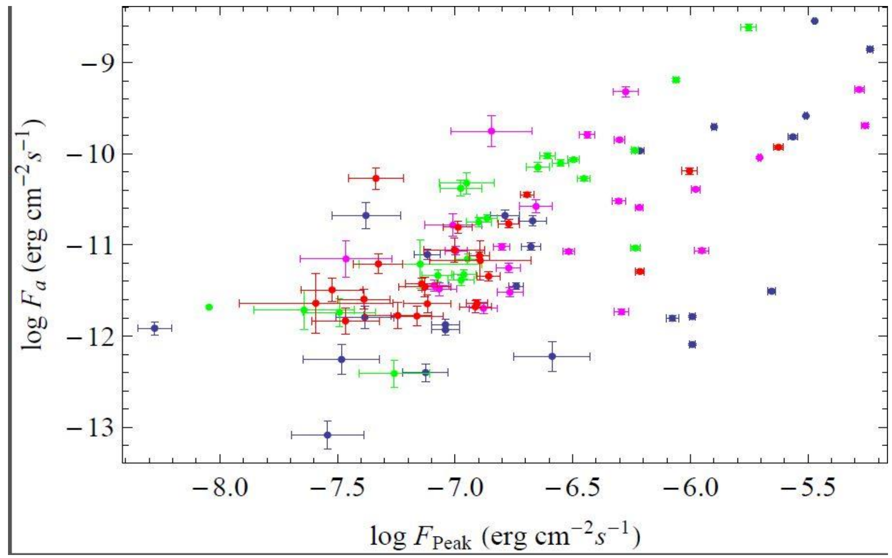
$B_{max} \sim 2 \times 10^{17}$ G and $B_{min} \sim 3 \times 10^{14}$ G

Also prompt-afterglow correlations are intrinsic !!!

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

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

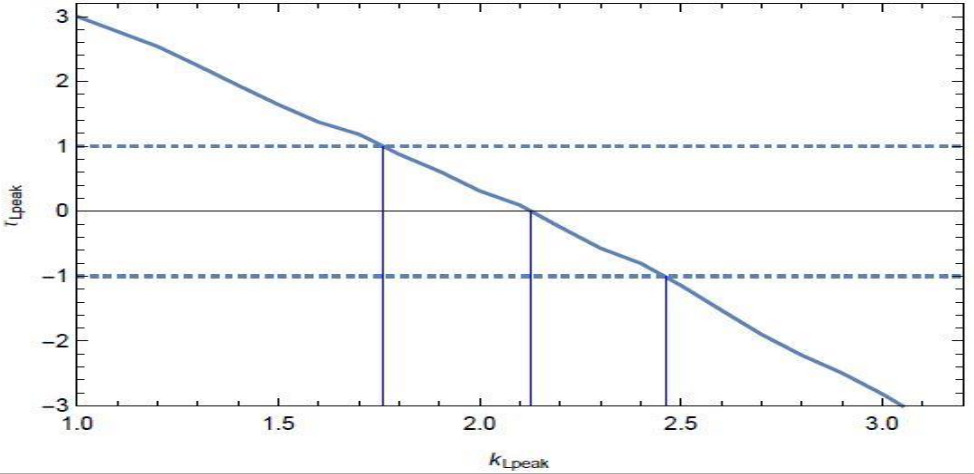




A = −14.67 ± 3.46 and B=1.21+0.14−0.13

logLa=A+BlogLpeak

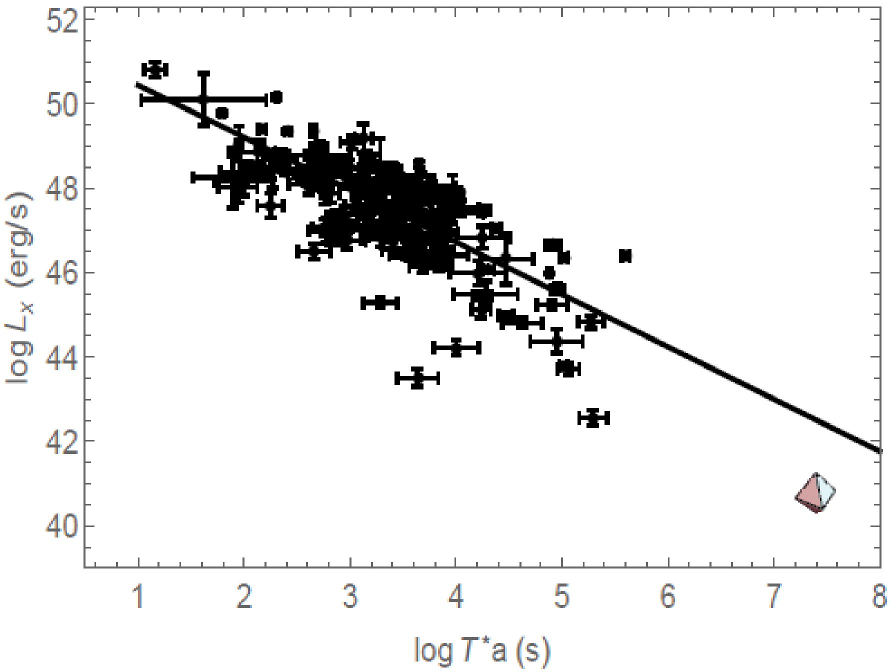
there is a strong evolution in the prompt, 2.13+(0.33,−0.37) consistent with other results, Petrosian et al. 2015, Yonetoku et al. 2005, found a steeper evolution 2.60+/0.15 but still compatible with 1 sigma with this one.

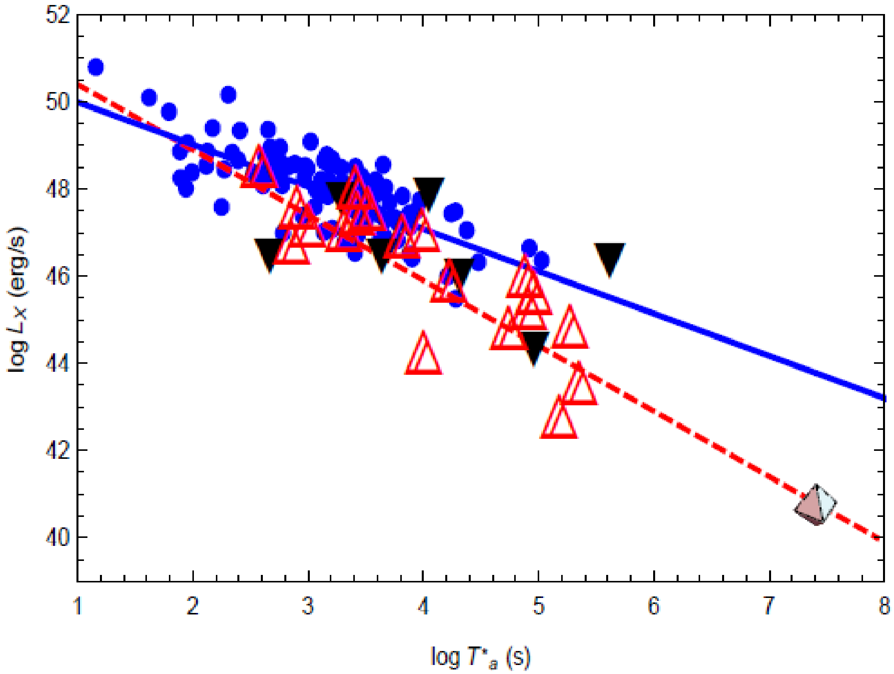


How selection effects can influence correlation and cosmology and what is the circularity problem?

- In Dainotti et al. 2013b MNRAS, 436, 82D it is shown how the change of the slope of the correlation can affect the cosmological parameters with a simulated data set of 101 GRBs with a central value of the correlation slope that differs on the intrinsic one by a 5σ factor (there is an overestimation and underestimation of 10% of the H0 and Ωm).
- The circularity problem derive from the fact that the parameters a and b depend on a given cosmology.
- A way to overcome this problem is to change contemporaneously the fit parameters and the cosmology
- Postnikov, Dainotti, Hernadez & Capozziello 2014, ApJ, 783, 126P we use SNe Ia to put a prior on Ho instead.

Looking for a more homogeneous sample for a "Standard GRB set for cosmology" (Dainotti et al. 2017 A&A, 600A,98D)





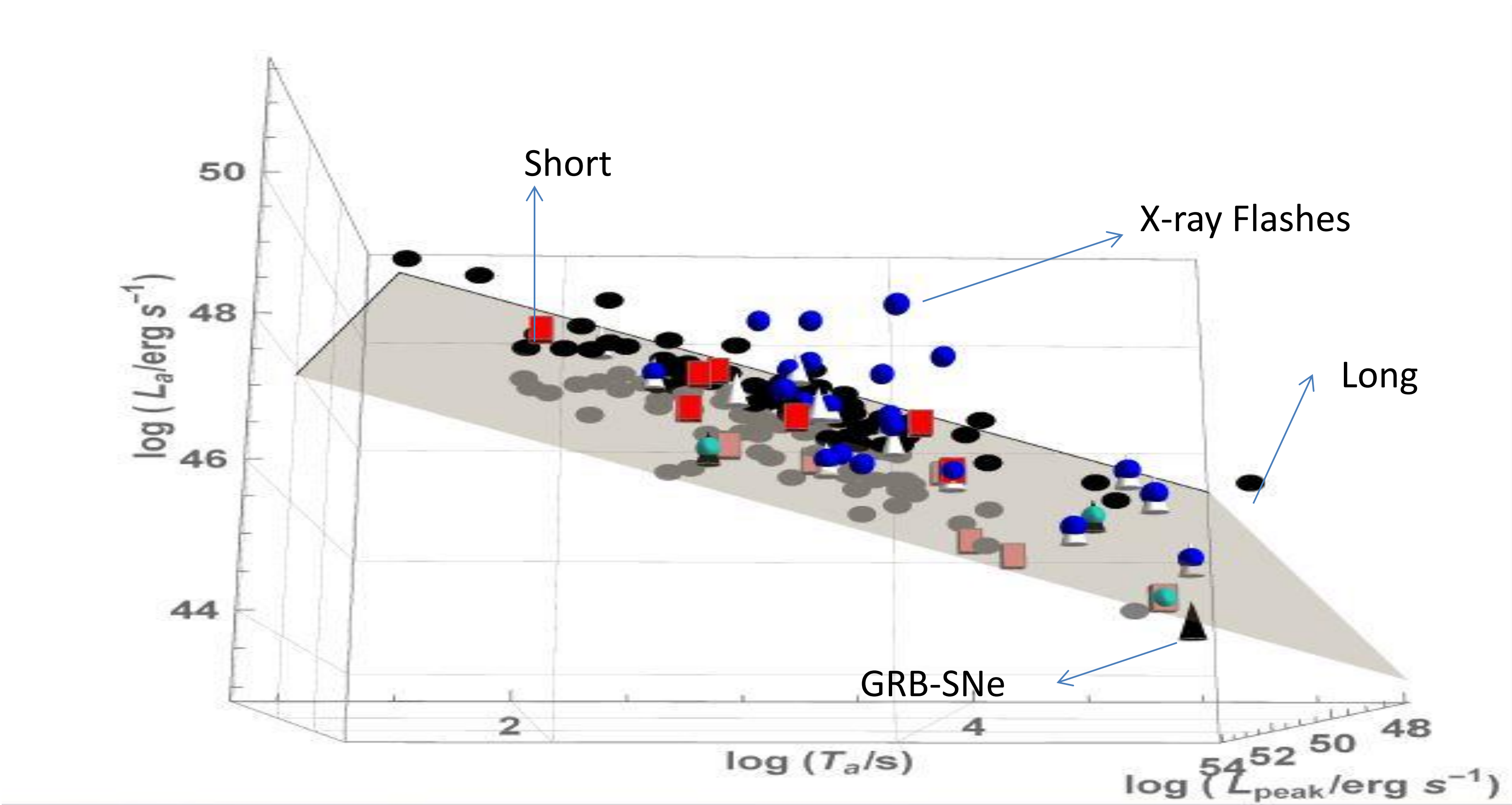
Long Sample (blue points) for which the SNe is not seen

and GRB-SNe associated (Red triangles)

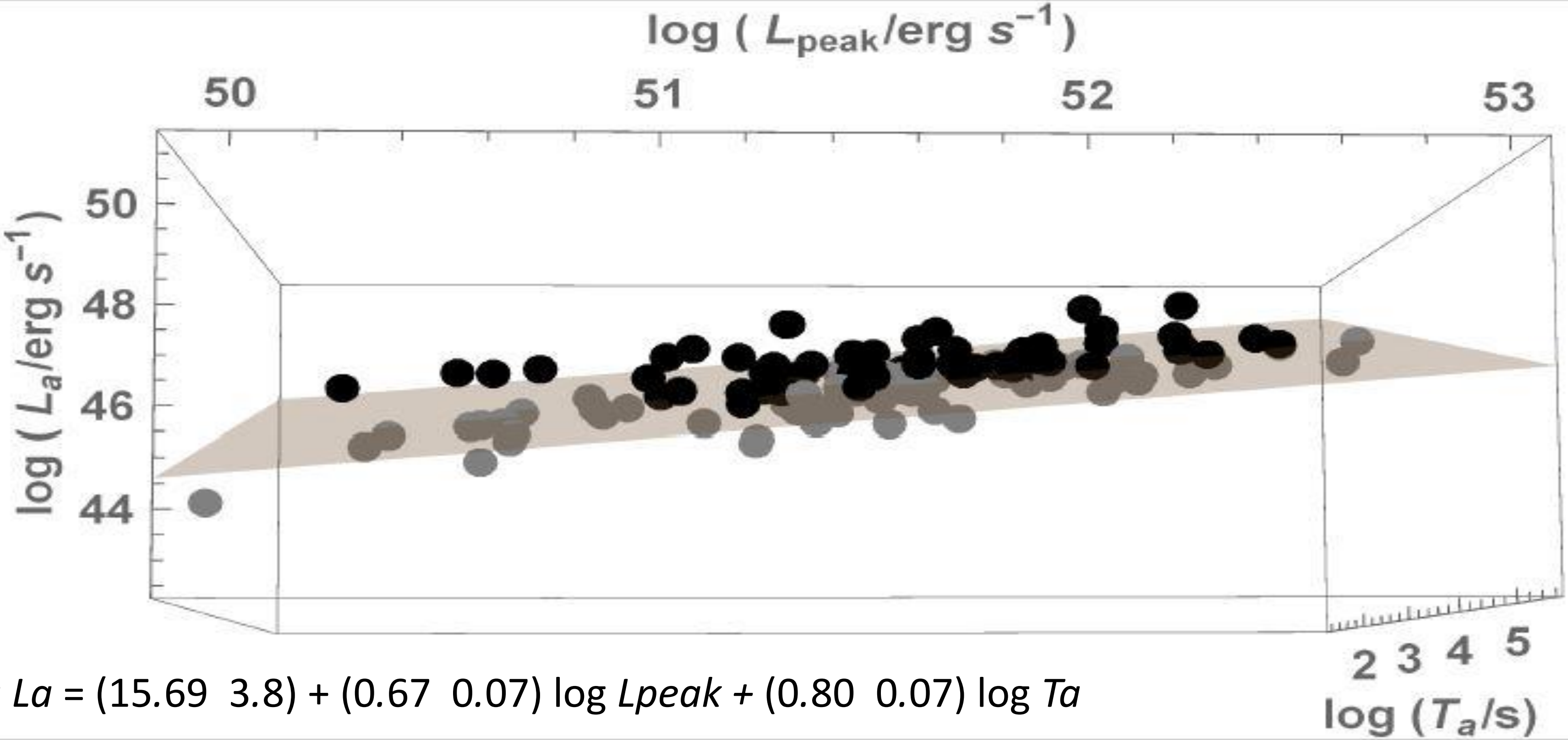
THUS, AN EXTENSION OF THE LA-TA CORRELATION GIVEN THE INTRINSIC NATURE OF LX-TA AND LPEAK-LA

ApJL 2016, 825L, 20, chosen by American Astronomical Society as a NASA press release see https://swift.gsfc.nasa.gov/news/2016/grbs_std_candles.html

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



Only purely long GRBs 122 without GRB-Sne, Short and XRFs



$\log La = (15.69\ \ 3.8) + (0.67\ \ 0.07) \log Lpeak + (0.80\ \ 0.07) \log Ta$

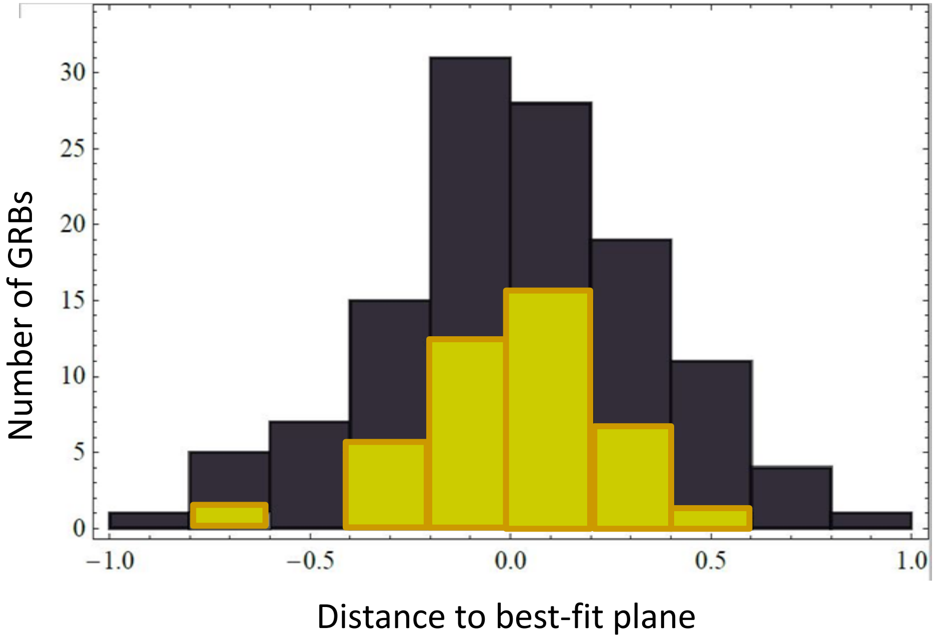
we see that distinct sub-classes of GRBs (previous slide) show greater spread about the plane than the long sample. A three parameter correlation emerges with a scatter $\sigma_{int} = 0.44 \pm 0.03$, which is 24% less than the *La- Ta* correlation for the sample of 122 long GRBs.

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

R=0.93 with P =2.2*10^(-16) σint=0.27

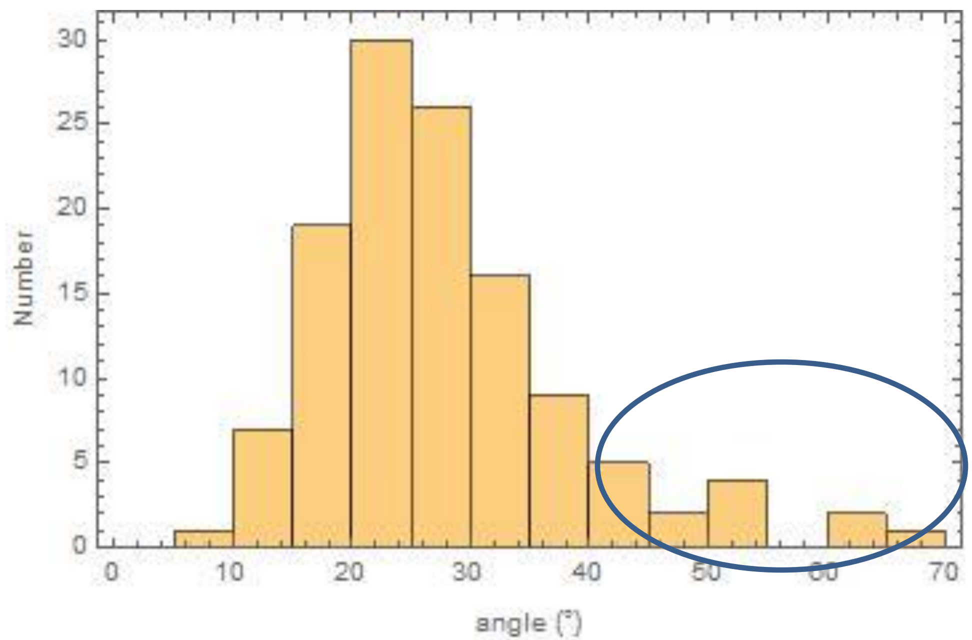


The closest GRBs to the plane belong to the gold sample.
This is not an effect of selection of the sample.

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

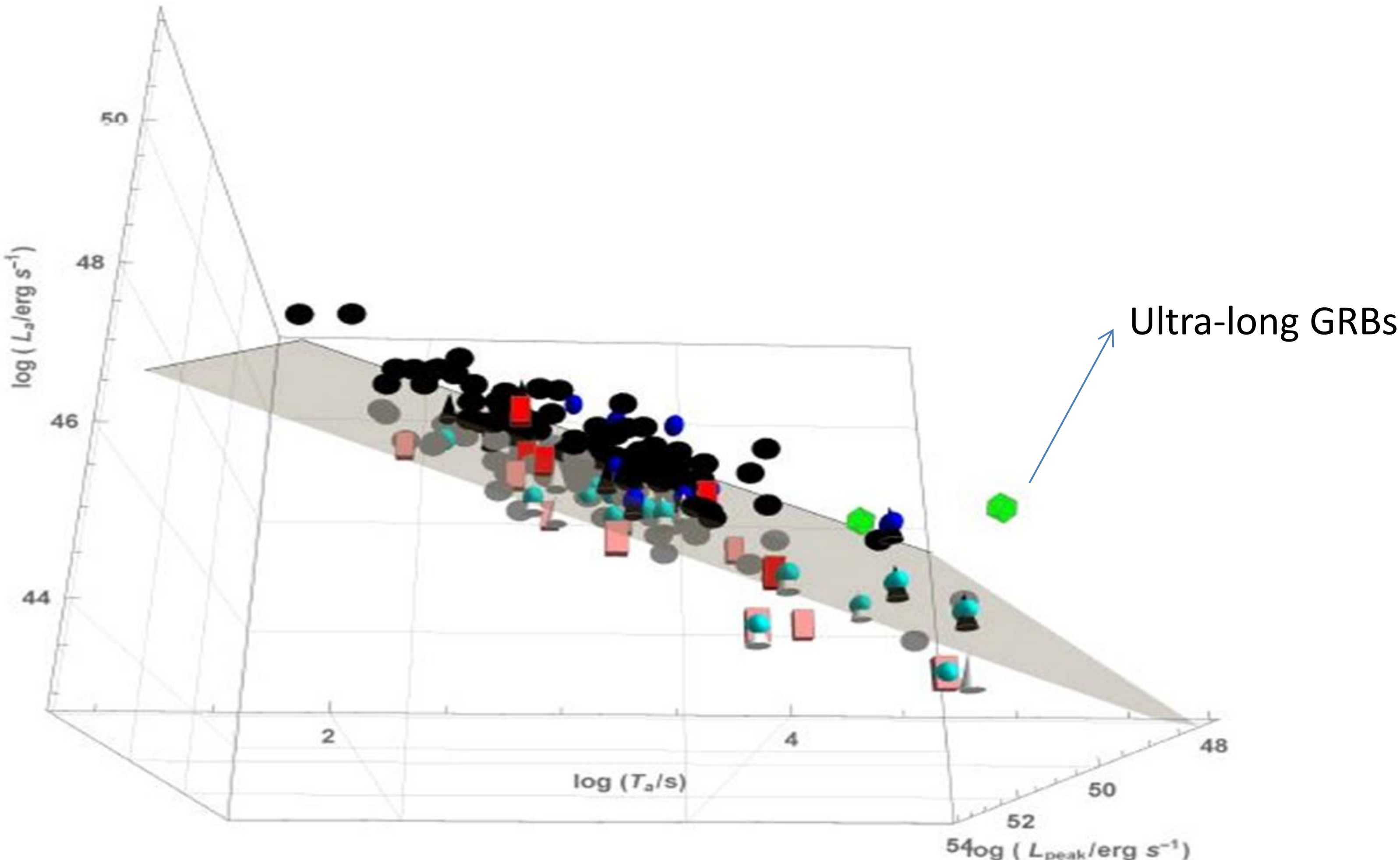
- Regarding the angle cut we show that there is a tail of the distribution above 41° and we remove it, this tail constitutes only the 11% of the total distribution



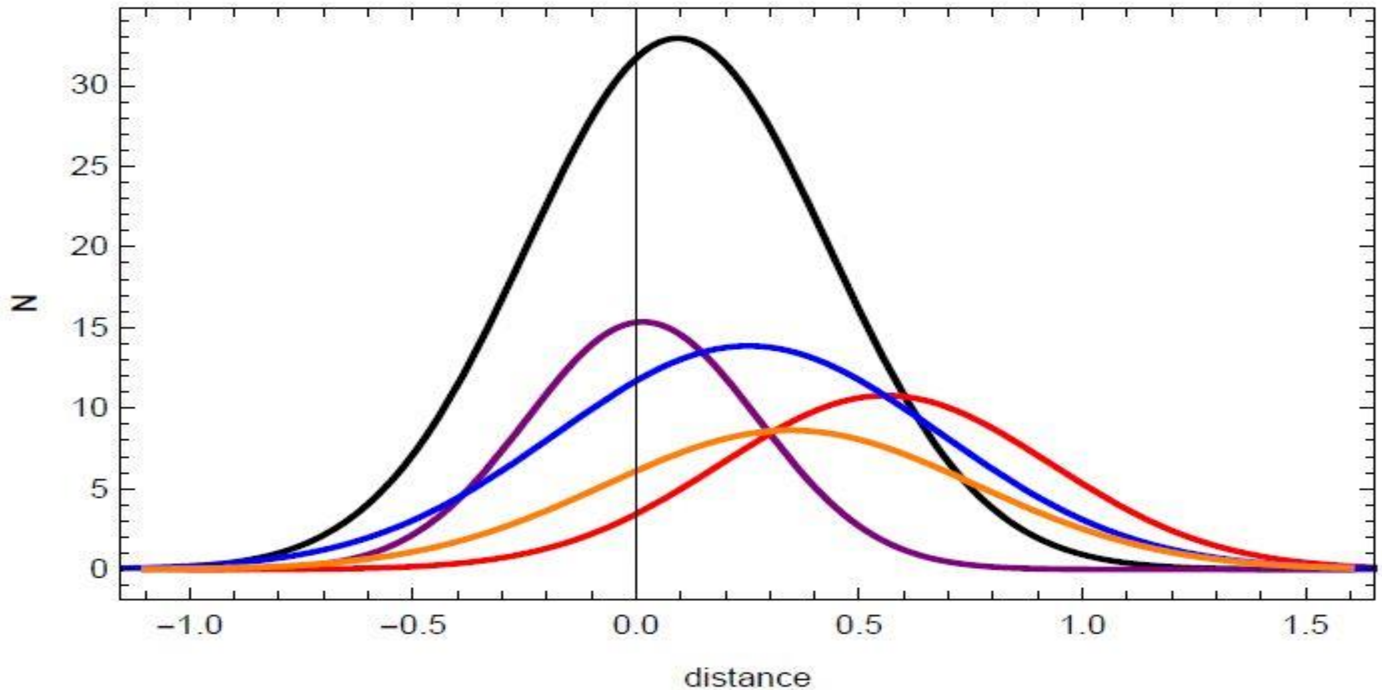
Updating the sample (183 GRBs in the all sample): The fundamental plane with the ultra-long GRBs

(Dainotti et al. 2016, ApJ, http://adsabs.harvard.edu/abs/2017arXiv170404908D):

the gold sample has still the smallest scatter

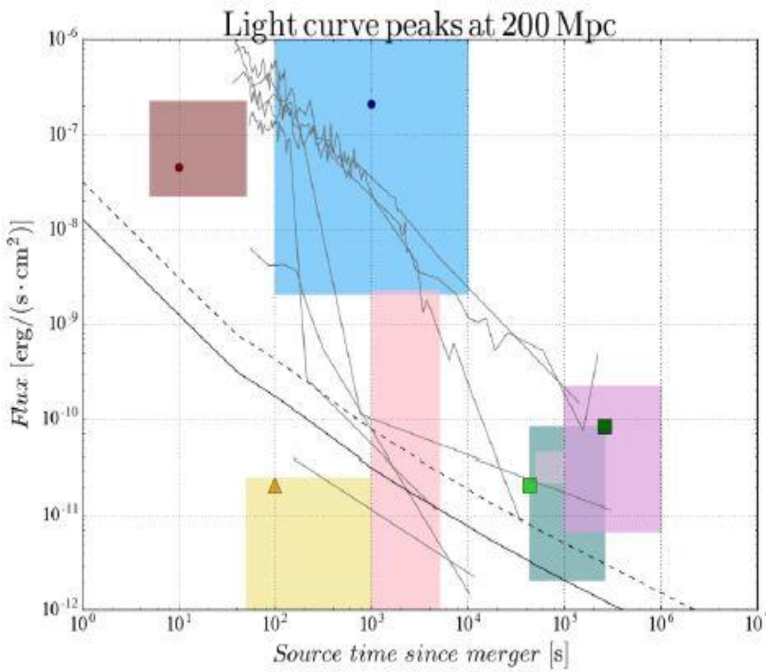


The short GRBs with EE pinpoints a statistical different plane from the gold sample



A plot showing Gaussian fits of the distributions of the distances from the fundamental plane for GRBs of each category, including GRB-SNe (orange), XRF (blue), SEE (red), gold sample GRBs (purple), long GRBs (black). The perpendicular line shows the reference of the gold sample compared to the other categories.
Chance probability that this difference is drawn by chance is 10^-5.

Perspective with Theseus of observing the plateaus



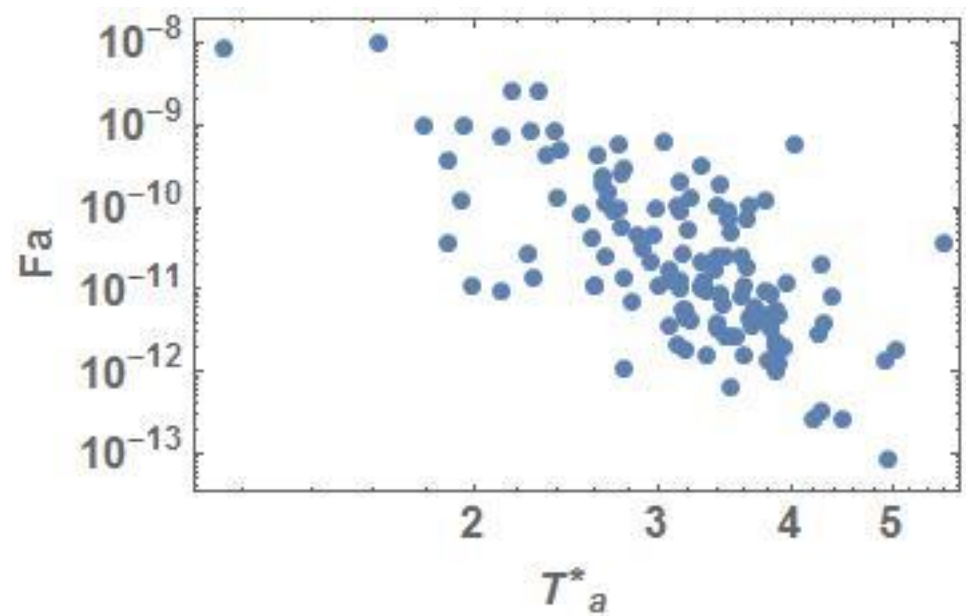


Fig. 10 Expected X-ray fluxes from different modelling of X-ray emission from NS-NS merger systems, that are among the most probable GW sources that will be detected in the following years by the second- and third- generation GW detectors. Grey solid lines show a typical GRB X-ray afterglow observed with Swift/XRT. Dots show the expected flux using fiducial parameters for each model. The black and dashed line show the THESEUS/SXI sensitivity as a function of the exposure time (credit: S. Vinciguerra)

Conclusions and Future perspectives:

- The 3D correlation for the gold sample has an intrinsic scatter 54% smaller than the long GRB for the Lx-Ta correlation.

- The new subsample of GRBs gold could be as a test for cosmology together with type Ia SNe. With Theseus with 1 year of observation we can double or triplicate the sample in terms of redshift.

- With a smaller scatter around σ_{int}=20% we expect to have a more powerful distance estimator and with this correlation with a 10% scatter less we expect more constraining results for cosmology.

- The fundamental plane is independent on other prompt parameters, T_{90}, θ_{jet}, E_{peak}. Thus the plane is stable with the parameters defined.
- The correlation also holds for high energy GBM bursts.

- Future work: is to repeat the method in Dainotti et al. (2013b) changing the a and b parameters of the correlation together with the cosmological setting and to change also the evolutions of both the variables luminosity and time and Lpeak.
- To investigate further the parametric, non parametric models and machine learning to obtain the redshift estimator.