GRB CORRELATIONS AND THEIR COSMOLOGICAL APPLICATIONS

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WHY GRBS AS POSSIBLE COSMOLOGICAL TOOLS?

They are good candidates as cosmological tools

Because

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

Much more distant than SN Ia (z=1.7) and quasars (z=6)

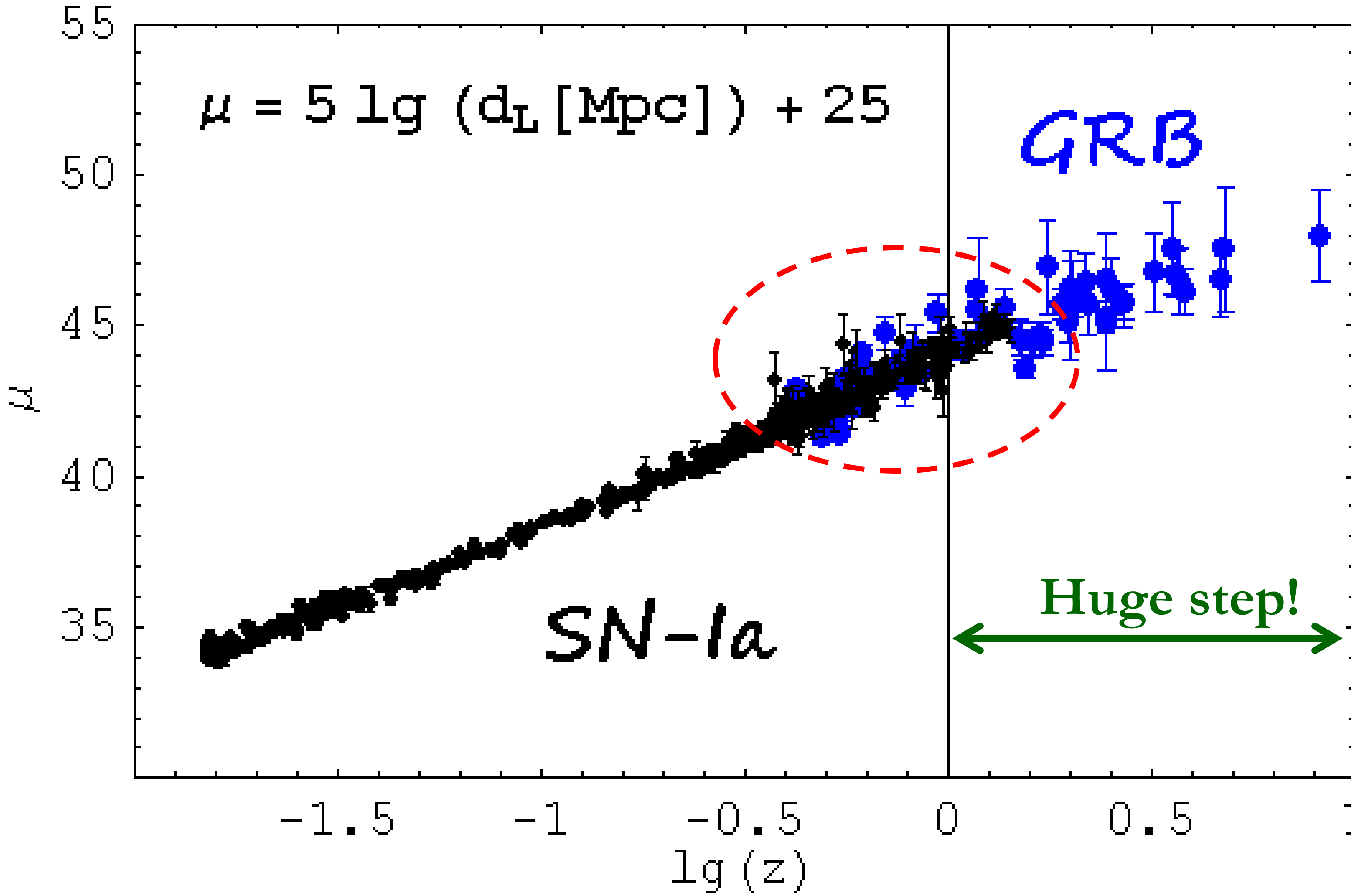
Free from dust extinction

The most powerful events, up to 10^{54} erg/s

BUT

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

SN-IA & GRBS, DISTANCE LADDER



Step to prepare the sample of SNe Ia to use them for cosmology

Directly extract a distance estimate
from light-curves=> need a training set of SNe for which we know a priori the distance

1) Apply k-corrections : transform photometric measurements to standard rest-frame bands

2) Fit corrected light curves to a set of Templates, consider the (B-V) color excess as a measurement of host galaxy extinction

THE FUNCTION USED TO CONSTRAIN COSMOLOGICAL PARAMETERS

for each SN, three parameters are derived :

- **apparent magnitude (mb), stretch (s), and a color (c) (We saw in these days in the talk of Maeda-san and Tanaka-san the Philipp relation (bivariate distribution of mb and strech))**
- **the distance estimate is a linear combination of those parameters:**

- $m_{B}^{mod} = 5\log D_{\mathbf{L}}(z, w, \Omega_M, \Omega_\lambda) - \alpha(s-1) + \beta c + M_B$

  m_B are the maximum-light SN restframe *B*-band apparent magnitudes and m_B^{mod} are the model *B*-band magnitudes for each SN
- w is the equation-of-state parameter of dark energy
- Ω_M fractional energy densities of matter
- Ω_λ fractional energy density of dark energy
- α and β parameterize the *s* and *C*–luminosity relationships

- coefficients α and β are fitted at the same time as cosmology

Notwithstanding the variety of GRB's different peculiarities, some common features may be identified looking at their light curves.

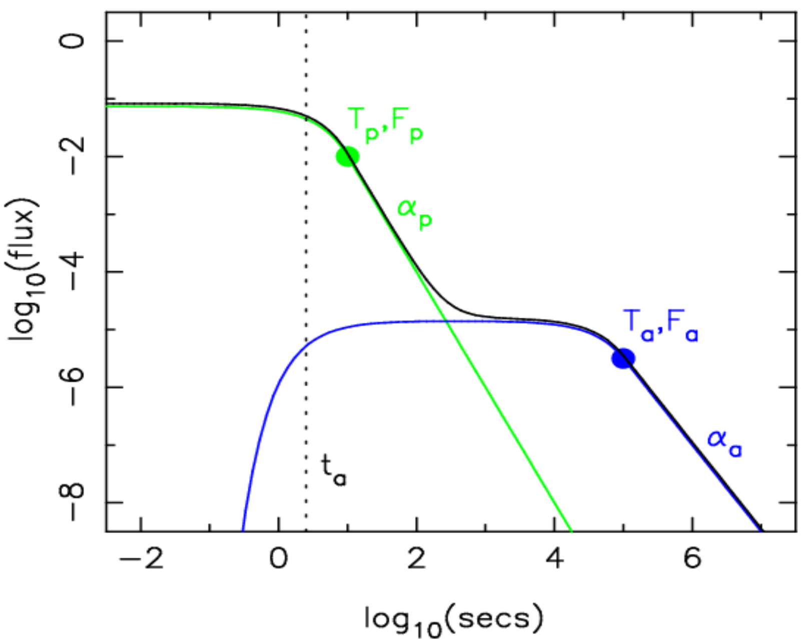
A breakthrough :

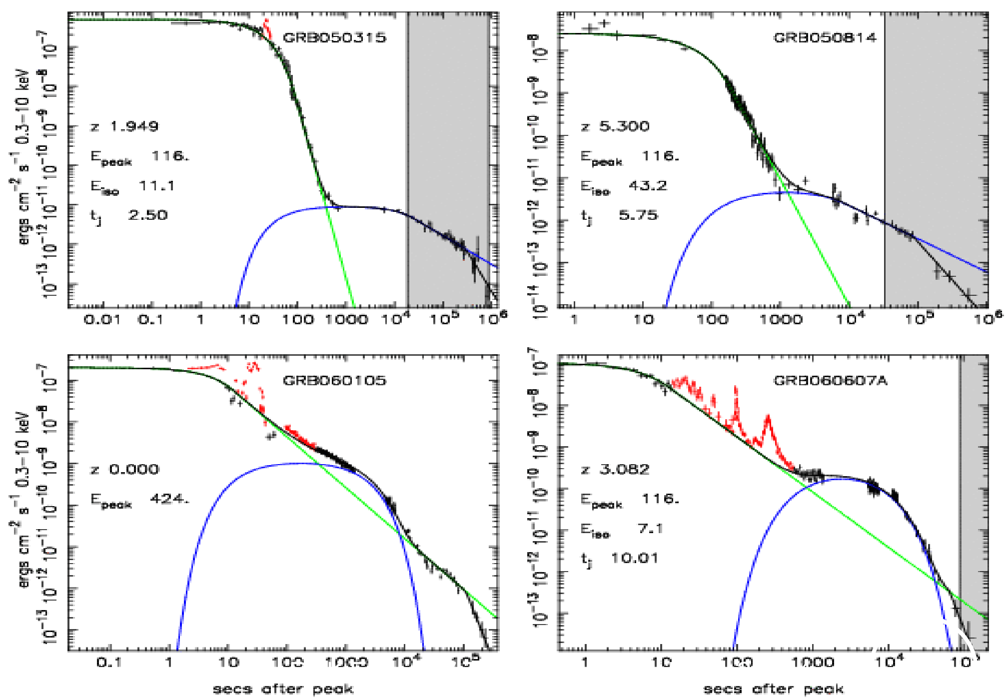
- a more complex behavior of the light curves, different from the broken power-law assumed in the past (Obrien et al. 2006,Sakamoto et al. 2007). A plateau phase has been discovered.

Phenomenological model with SWIFT lightcurves

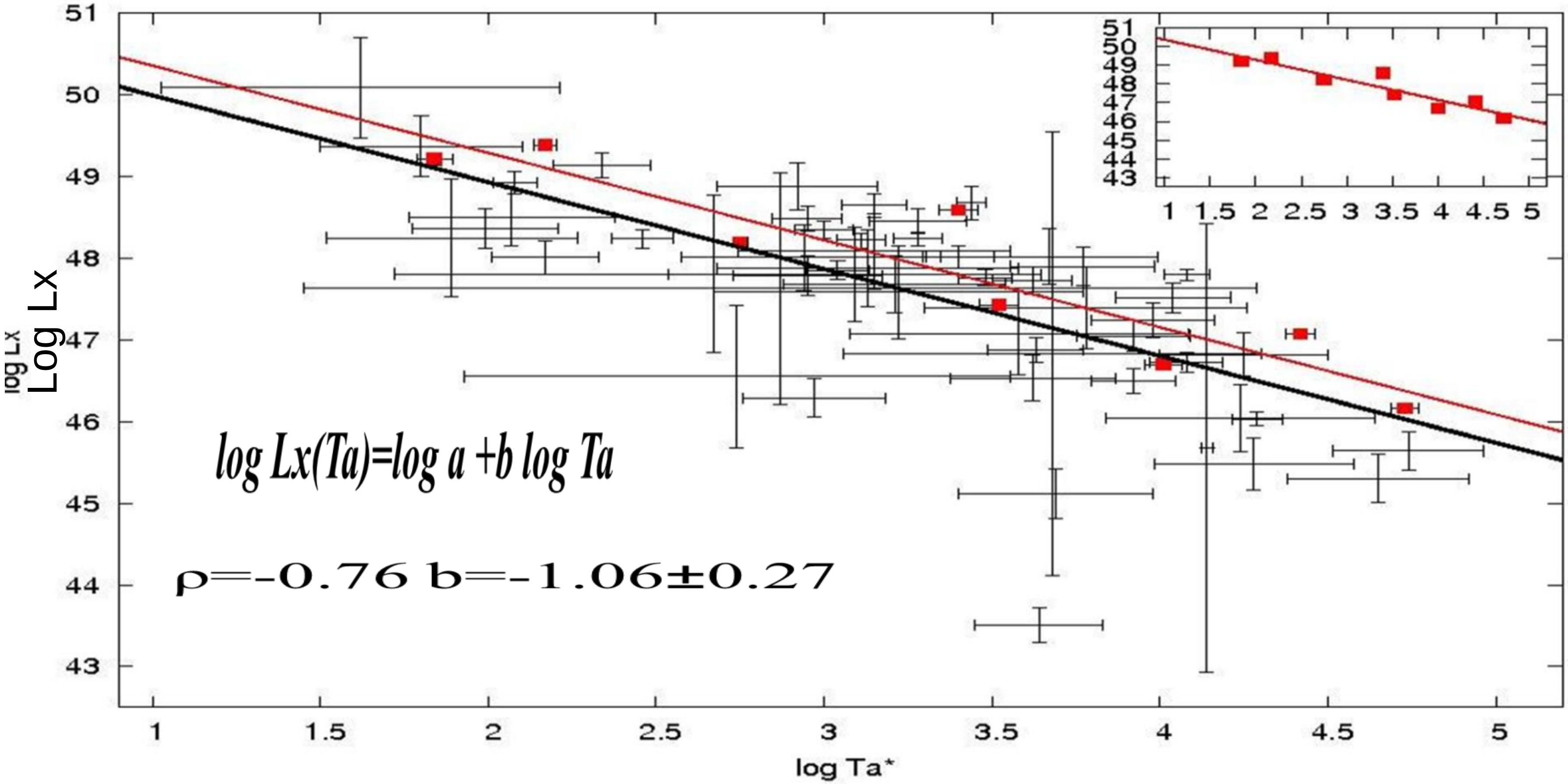
A significant step forward in determining common features in the afterglow

- X-ray afterglow light curves of the full sample of Swift GRBs shows that they may be fitted by the same analytical expression (Willingale et al. 2007)





Dainotti et al. correlation $L_X - T^*_a$

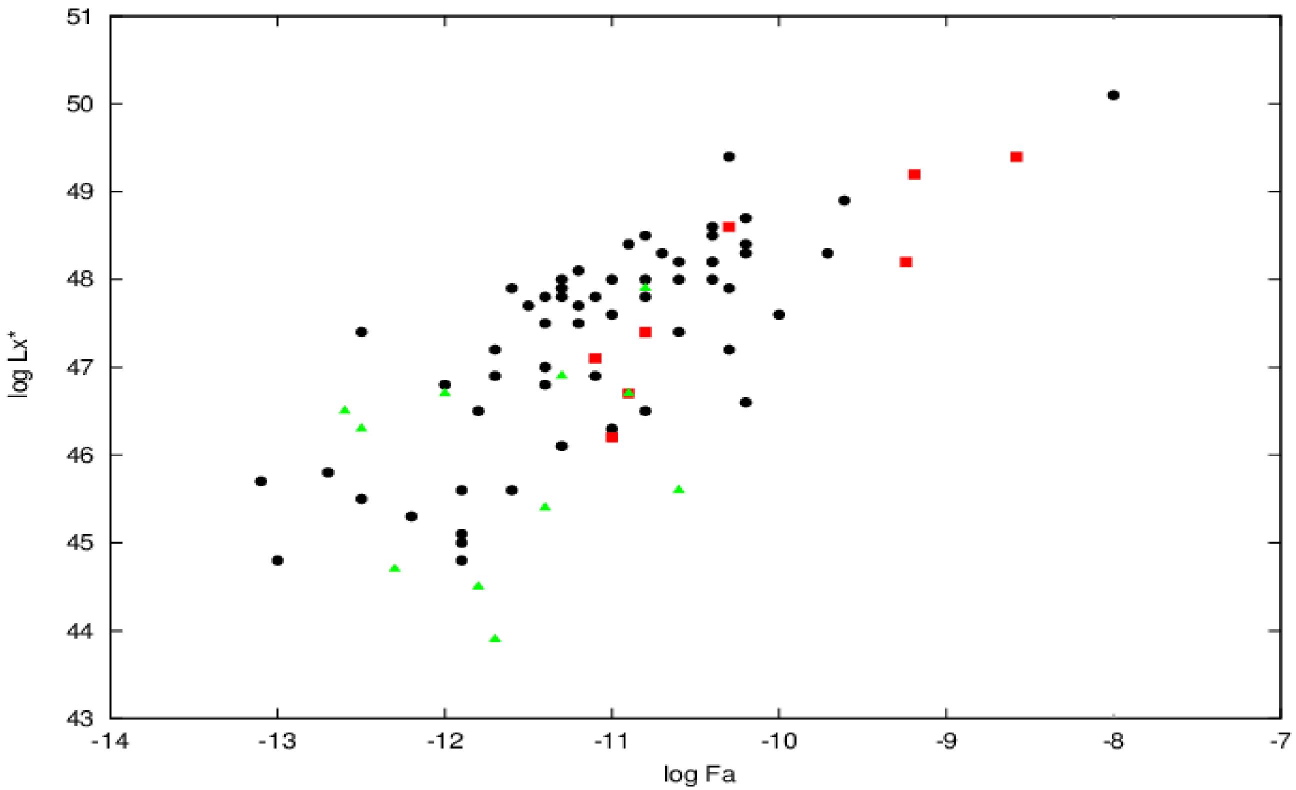


Firstly discovered in 2008 by Dainotti, Cardone, & Capozziello MNRAS, 391, L 79D (2008)

Later updated by Dainotti, Willingale, Cardone, Capozziello & Ostrowski ApJL, 722, L 215 (2010)

Lx(T*a) vs T*a distribution for the sample of 62 long afterglows

IS THE TIGHT CORRELATION DUE TO BIAS SELECTION EFFECTS?



If we had had a selection effect we would have observed the red points
only for the higher value of fluxes.

The green triangles are XRFs, red points are the low error bar GRBs

PROMPT – AFTERGLOW CORRELATIONS

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

A search for possible physical relations between the afterglow characteristic luminosity $L^*_a \equiv L_x(T_a)$

and

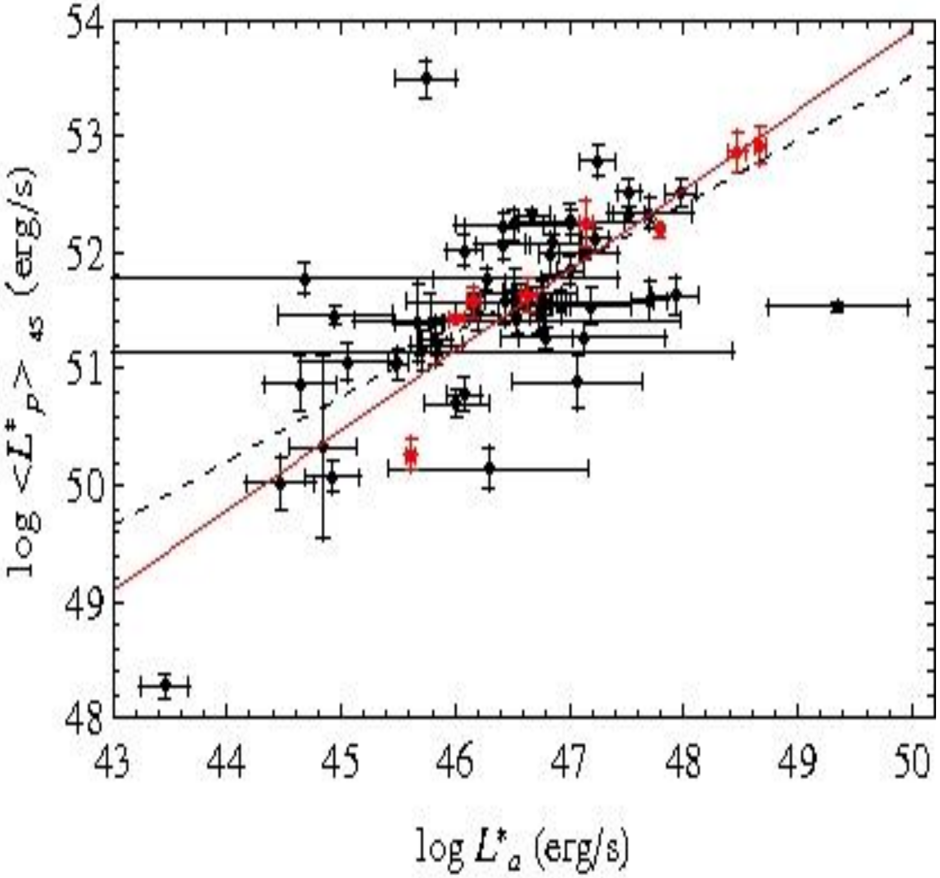
the prompt emission quantities:

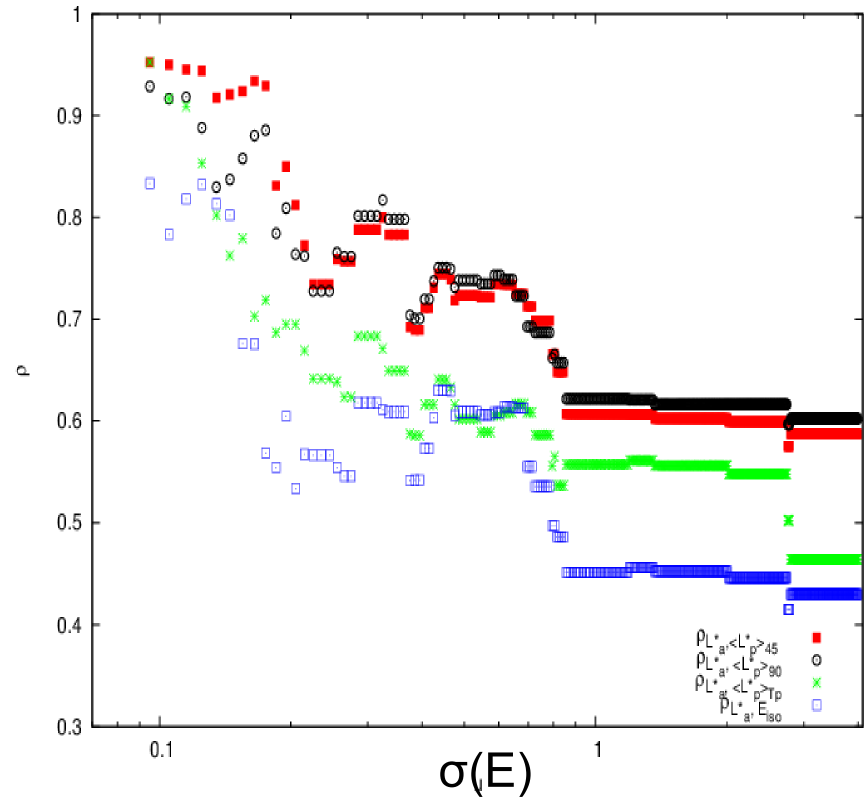
1.) the mean luminosity derived as $\langle L^*_p \rangle_{45} = E_{iso}/T^*_{45}$

2.) $\langle L^*_p \rangle_{90} = E_{iso}/T^*_{90}$

3.) $\langle L^*_p \rangle_{T_p} = E_{iso}/T^*_p$

4.) the isotropic energy E_{iso}





Correlation coefficients ρ for for the long GRB subsamples with the varying error parameter σ(E)

L*a vs. <L*p>45 for 62 long GRBs (the **σ(E)** ≤ 4 subsample).

$$\sigma(E) = (\sigma_{Lx}^2 + \sigma_{Ta}^2)^{1/2}$$

(L*A, <L*P>45) - RED
(L*A, <L*P>90) - BLACK
(L*A, <L*P>TP) - GREEN
(L*A, EISO) - BLUE

Conclusion I

GRBs with well fitted afterglow light curves

obey tight physical scalings, both in their afterglow properties and in the prompt-afterglow relations.

We propose these GRBs as good candidates for

the standard Gamma Ray Burst

to be used both

- in constructing the GRB physical models and

- **in cosmological applications**
- **(Cardone, V.F., Capozziello, S. and Dainotti, M.G 2009, MNRAS, 400, 775C**
- **Cardone, V.F., Dainotti, M.G., Capozziello, S., and Willingale, R. 2010, MNRAS, 408, 1181C)**

LET'S GO ONE STEP BACK

BEFORE

proceeding with any further application to cosmology

or using the luminosity-time correlation as discriminant among theoretical models for the plateau emission

We need to answer the following question:

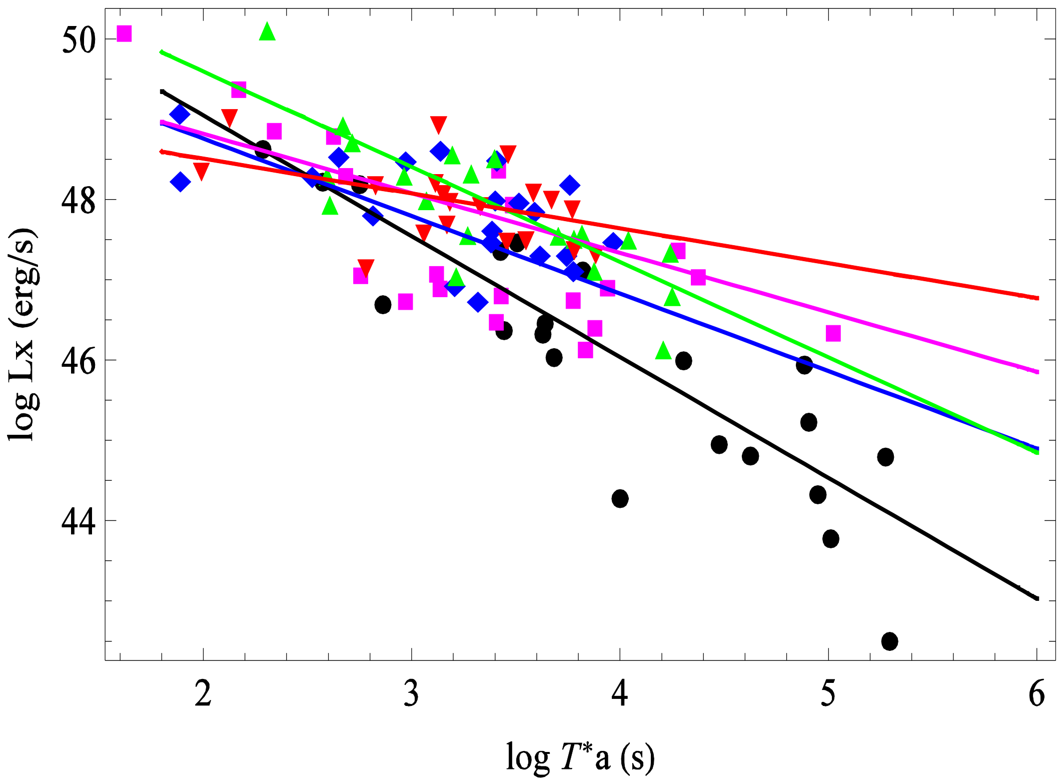
Is what we observe a truly representation of the events or there might be selection effect or biases?

Is the LT correlation intrinsic to GRBs, or is it only an apparent one, induced by observational limitations and by redshift induced correlations?

THEREFORE,

at first one should determine the true correlations among the variables

DIVISION IN REDSHIFT BINS FOR THE UPDATED SAMPLE OF 100 GRBS (WITH FIRM REDSHIFT AND PLATEAU EMISSION)



The same distribution divided in 5 equipopulated redshift bins shown by different colours:

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 $z \geq 3.45$.

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

ρ=-0.73 for all the distribution

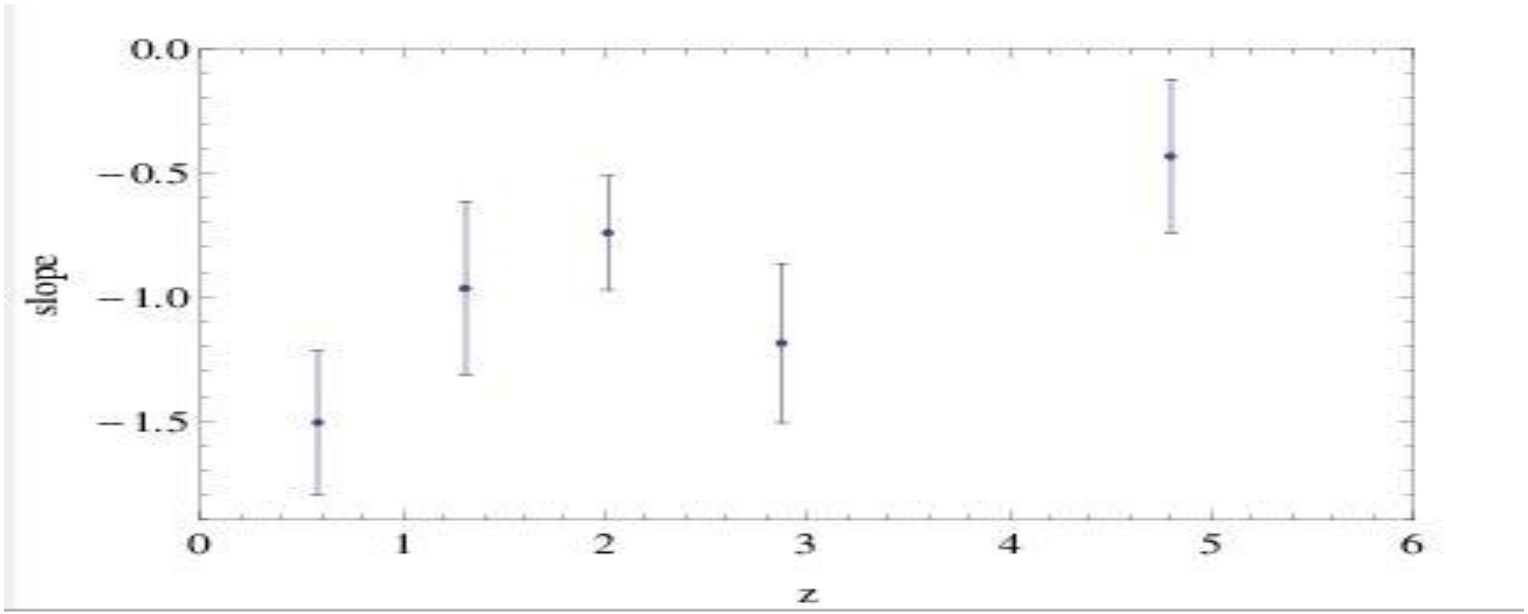
b= -1.27 ± 0.15 1σ compatible with the previous fit

THE SLOPE EVOLUTION

From a visual inspection it is hard to evaluate if there is a redshift induced correlation. Therefore, we have applied the test of Dainotti et al. 2011, ApJ, 730, 135D to check that the slope of every redshift bin is consistent with every other.

BUT It is not enough to answer definitely the question.

The slope of each redshift bin are compatible in 2 sigma from the first to the last, while in 1 sigma the contiguous ones.



THEREFORE, FOR A MORE RIGOROUS UNDERSTANDING WE APPLY:

The **Efron & Petrosian method (EP)** (ApJ, 399, 345,1992)

to obtain unbiased correlations, distributions, and evolution with redshift from a data set truncated due to observational biases.

corrects for instrumental threshold selection effect and redshift induced correlation

has been already successfully applied to GRBs (Lloyd,N., & Petrosian, V. ApJ, 1999)

The technique we applied

Investigates whether the variables of the distributions, L^*_X and T^*_a are correlated with redshift or are statistically independent.

do we have luminosity vs. redshift evolution? $g(z)$

do we have plateau duration vs. redshift evolution? $f(z)$

If yes

how to accomodate the evolution results in the analysis?

→ **By defining new independent variables!**

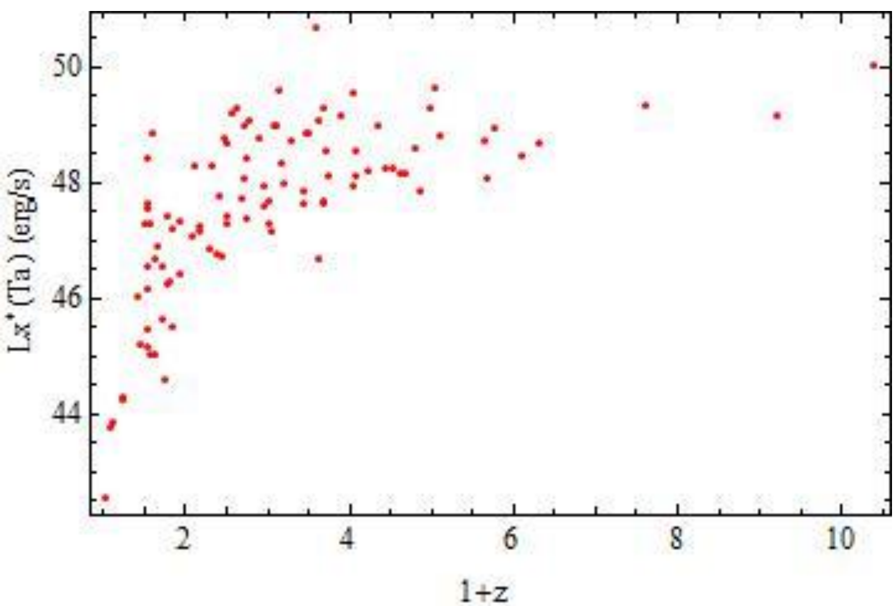
HOW TO COMPUTE G(Z) AND F(Z)?

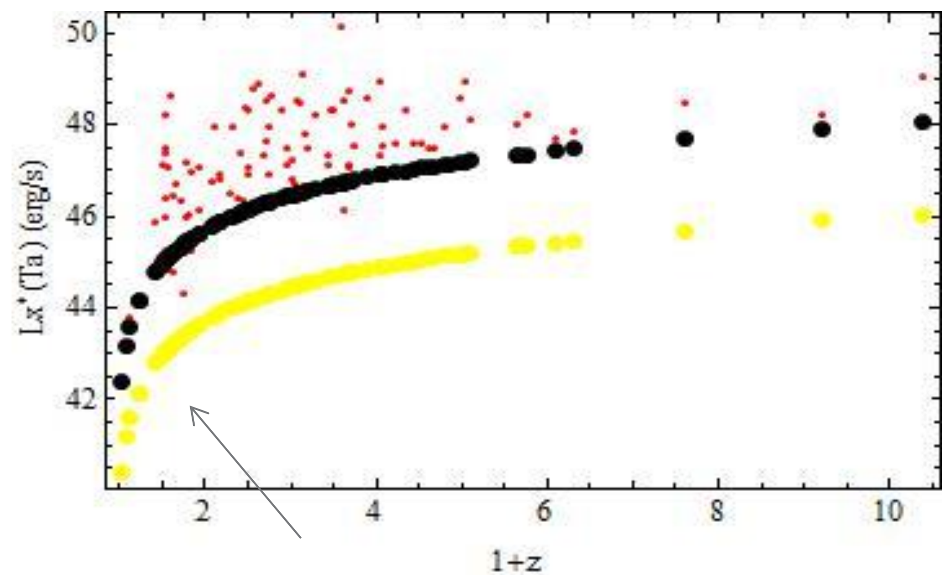
The EP method deals with

data subsets that can be constructed to be independent of the truncation limit suffered by the entire sample.

This is done by creating 'associated sets', which include all objects that could have been observed given a certain limiting luminosity.

We have to determine the limiting luminosity for the sample





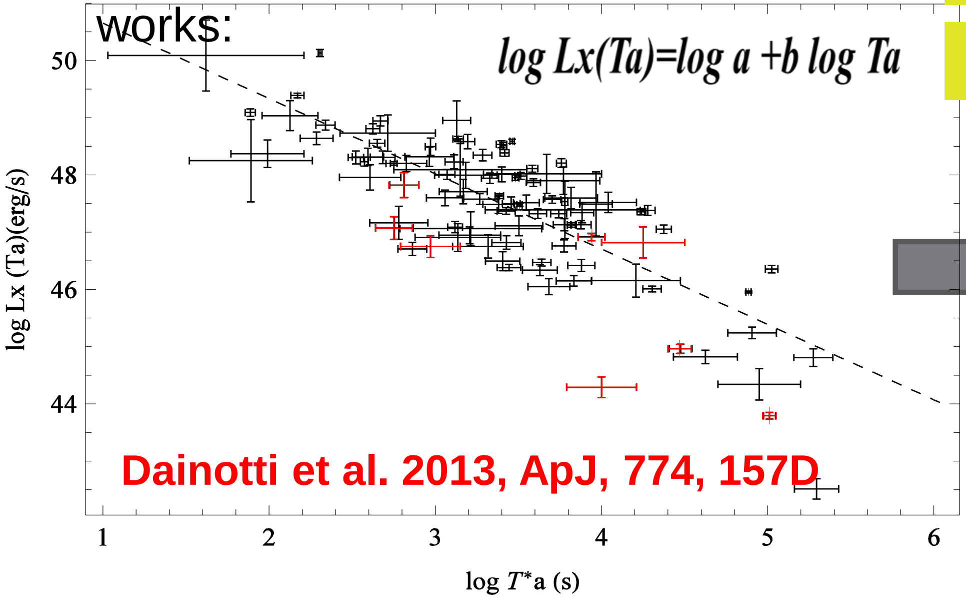
The more appropriate Flux limit is the black dotted line Flux= $1.4 * 10^{-12}$ erg/(cm^2*s)

LUMINOSITY-TIME CORRELATION IN X-RAY AFTERGLOWS

This is the last update of previous works:

Dainotti, et al. MNRAS, 391, L 79D (2008)

Dainotti et al. ApJL, 722, L 215 (2010)

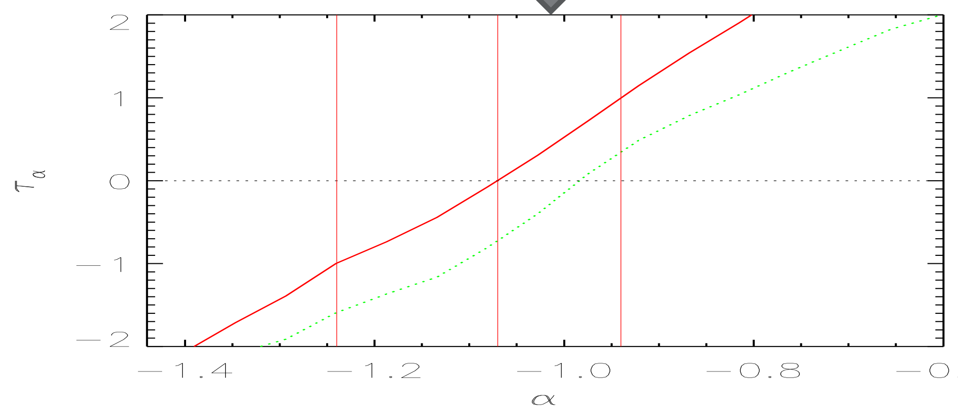


The observed correlation slope vs the intrinsic one

-1.07 ± 0.14

The observed slope $b=-1.27 \pm 0.15$

After correction of luminosity and time evolution , and luminosity detection bias through the Efron & Petrosian (1999) technique one obtains the intrinsic correlation



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

CONCLUSIONS - PART II

The correlation La-Ta exists !!!

It can be useful as model discriminator among several models that predict the Lx-Ta anti-correlation:

energy injetion model from a spinning-down magnetar at the center of the fireball *Dall' Osso et al. (2010), Xu & Huang (2011), Rowlinson & Obrien (2011)*

Accretion model onto the central engine as the long term powerhouse for the X-ray flux *Cannizzo & Gerhels (2009), Cannizzo et al. 2010*

Prior emission model for the X-ray plateau *Yamazaki (2009)*

DOES THE LX-TA CORRELATION EXIST FOR LAT GRBS?

First step: we can determine the existence of the plateaus ?

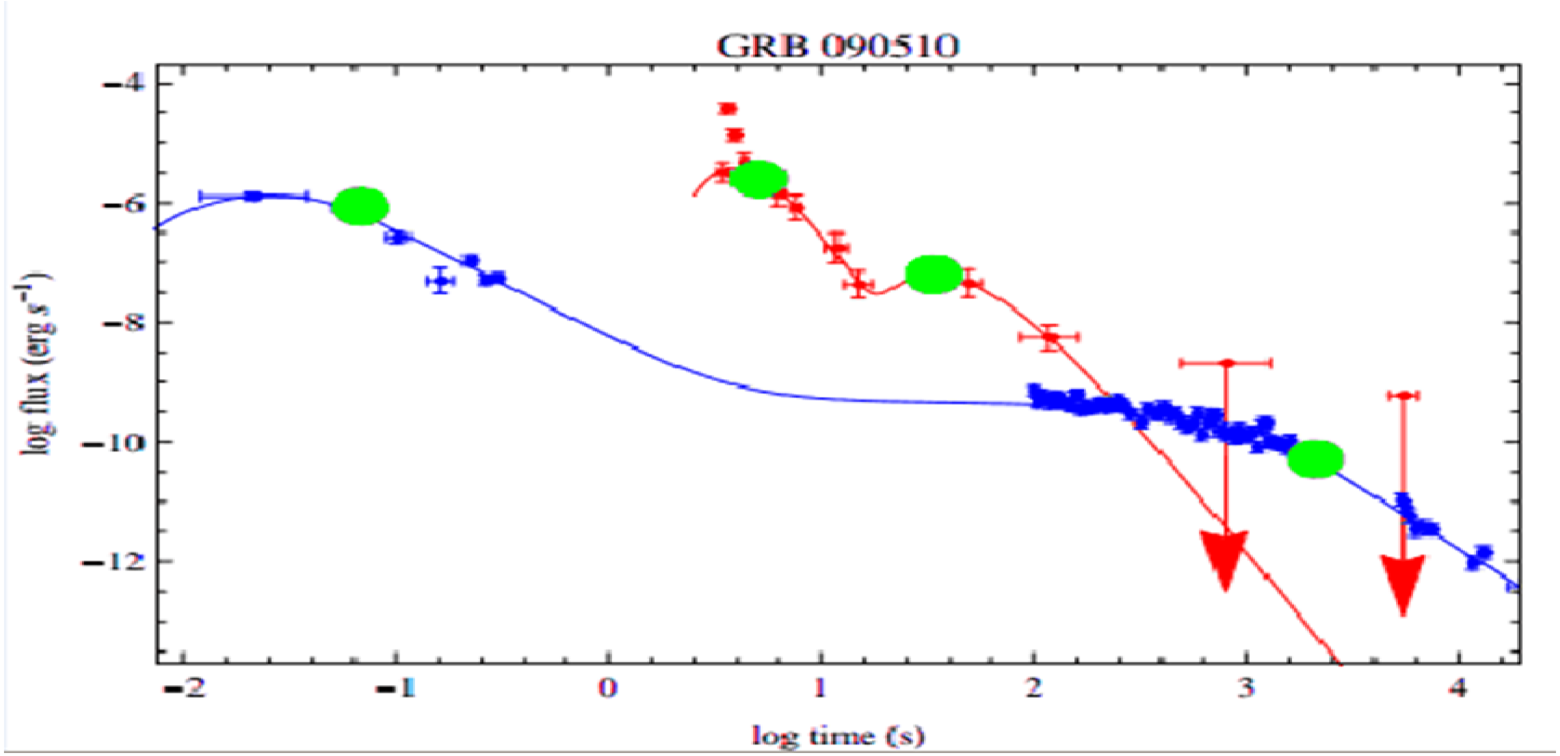
If exists does it depend to a forward shock emission?

From a sample of 35 GRBs (Ackerman et al. 2013, the First Fermi-LAT GRB catalog) we can safely select only 4 GRBs with firm redshift if we consider the fits without upper limits only.

What is the most appropriate method to deal with X-ray and LAT data together?

We show simultaneously the X-ray and LAT light curves.

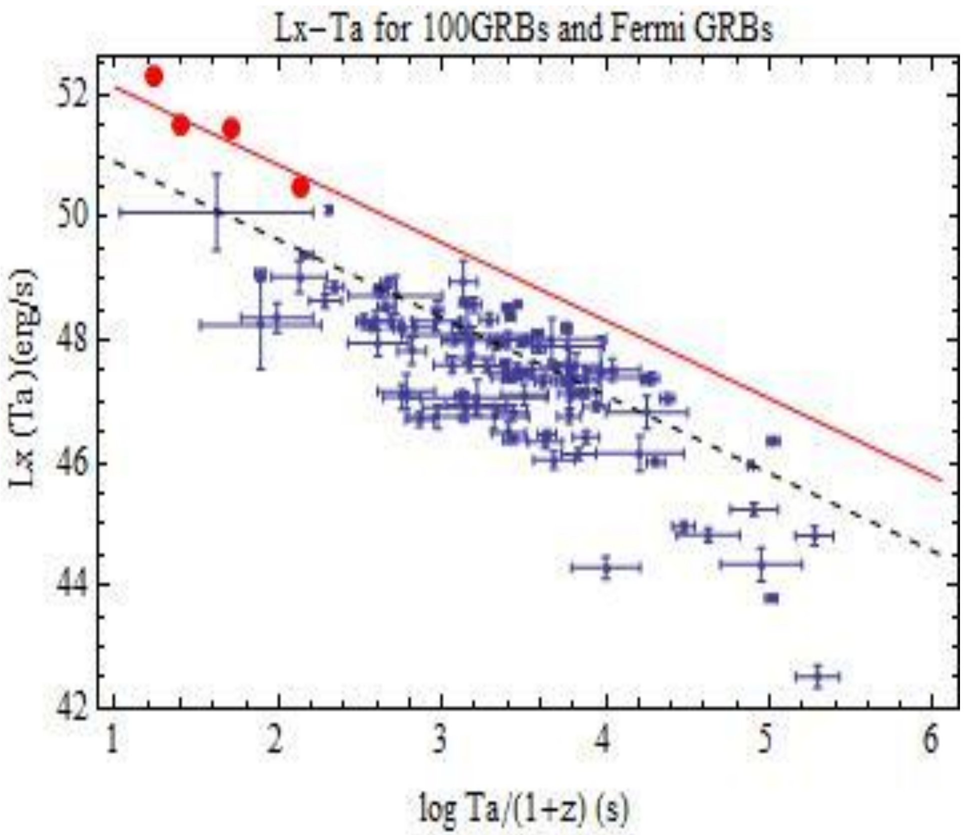
GRB 090510 SHORT HARD - A SPECTROSCOPIC REDSHIFT Z=0.903±0.003 (RAU ET AL. 2009)



The only case with an overlap between LAT data and XRT at 100 s.

Fit: Fp=-3.5,alp=6.34,Tp=0.66,tp=0, Fa=-5.34, ala=4.35, Ta=1.51,ta=20
reduced χ^2 power law: $\chi^2 = 0.09$ P=0.02, reduced χ^2 plateau: =0.61 P=0.99

CONCLUSION: LUMINOSITY-TIME RELATIONS FOR HIGH ENERGY GRBS



Even as the paucity of the data restrains us from drawing any definite conclusion we note similar fitted slopes for L-T correlation,
but with different normalizations.

L-T correlation seems not to depend on particular energy range:

a physical scaling for GRB afterglows both in X-rays and in γ-rays.

Normalizations: **log a=52.17 in X-rays and 53.40 in γ-rays**

Dainotti et al. 2011a The Astrophysical Journal, 730:135 (10pp), 2011

PART III GRB AS A DISTANCE ESTIMATOR

Distance modulus: $$\mu = 25 + 5 \log D_L(z)$$

$\Phi(E) \propto E^{-\gamma_a} \propto E^{-(\beta_a+1)}$, where (β_a, γ_a) are the spectral and photon indices, respectively.

$$L_X^* = \frac{4\pi D_L^2(z) F_X}{(1+z)^{1-\beta_a}}, \quad (6)$$

where $F_X = F_a \exp(-T_p/T_a)$ is the observed flux at the time T_a.

$$\begin{aligned}\mu_{\rm obs}(z) &= 25 + \frac{5}{2}\log\left[\frac{L_X^*(T_a)}{4\pi f_a(T_a, T_p, F_a T_a)(1+z)^{(-1+\beta_a)}}\right] \\ &= 25 + \frac{5}{2}\left\{a \log\left[\frac{T_a}{1+z}\right] + b\right\} \\ &\quad - \frac{5}{2}\log\left[4\pi f_a(T_a, T_p, F_a T_a)(1+z)^{(-1+\beta_a)}\right], \quad (15)\end{aligned}$$

UPDATING THE GRB HUBBLE DIAGRAM
WITH THE DAINOTTI ET AL. CORRELATION

Allows to increase both the GRBs sample (83 GRBs vs 69) in Schaefer et al. 2006

reduce the uncertainty on the distance moduli μ*(z) of the 14%* **Cardone, V.F., Capozziello, S. and Dainotti, M.G 2009, MNRAS, 400, 775C**

The use of the HD with the only Dainotti et al. correlation alone or in combination with other data shows that the use of GRBs leads to constraints in agreement with previous results in literature.

A larger sample of high-luminosity GRBs can provide a valuable information in the search for the correct cosmological model (Cardone, V.F., Dainotti, M.G et al. 2010, MNRAS, 408, 1181)

HOW SELECTION EFFECTS CAN INFLUENCE CORRELATION AND COSMOLOGY AND WHAT IS THE CIRCULARITY PROBLEM?

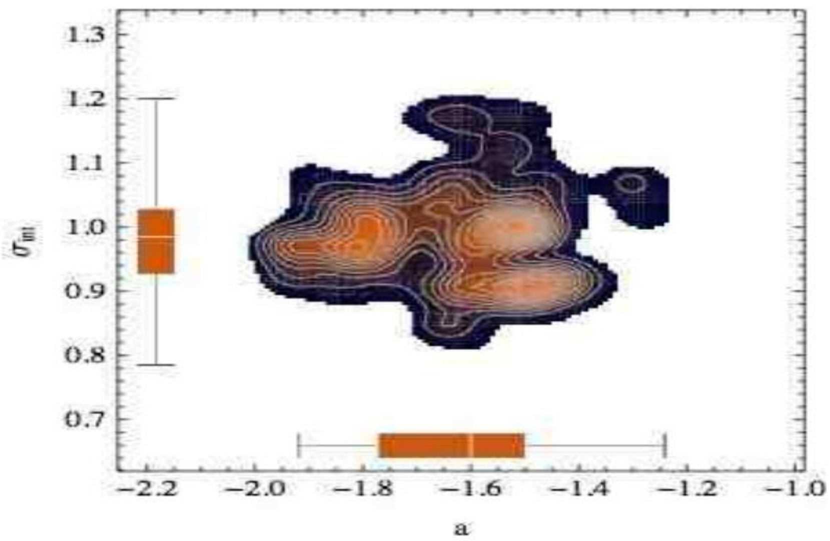
In Dainotti et al. 2013b MNRAS, 436, 82D we show how the change of the slope of the correlation can affect the cosmological parameters.

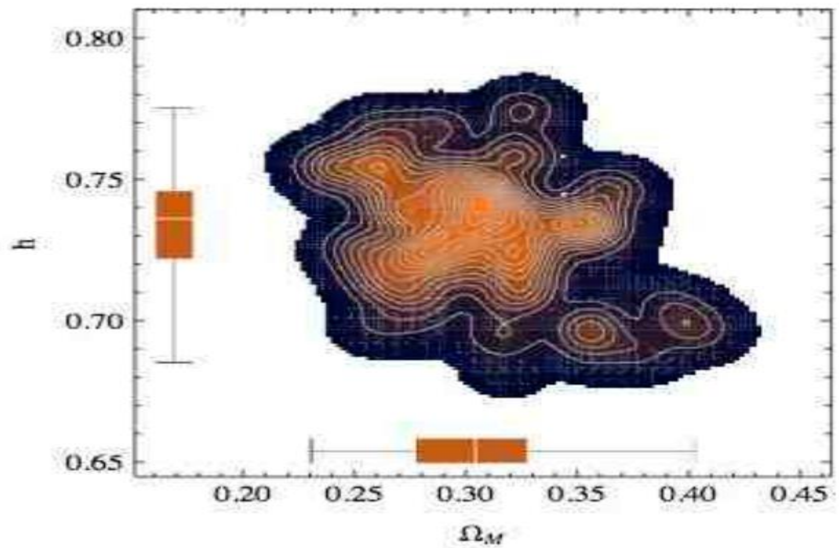
With a simulated data set of 101 GRBs with a central value of the correlation slope that differs on the intrinsic one by a 5σ factor.

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

FULL SAMPLE : GRB+SNE +H(Z)

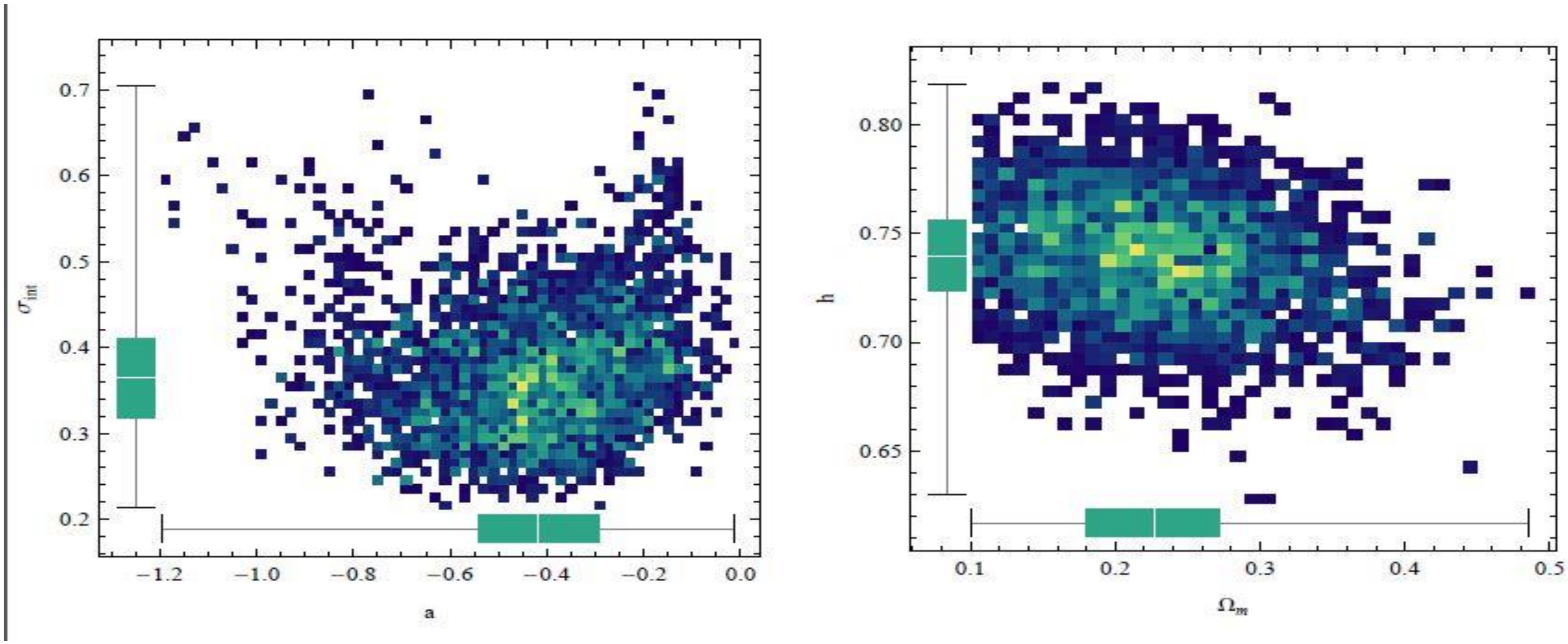




Parameters for non flat/flat models are not distinguishable: Overestimated of the 13% in Ω_M, compared to the Ia SNe (Ω_M , σ_M) = (0.27, 0.034), while the H_0, best-fitting value is compatible in 1σ compared to other probes.

We show that this compatibility of H_0 is due to the large intrinsic scatter associated with the simulated sample.

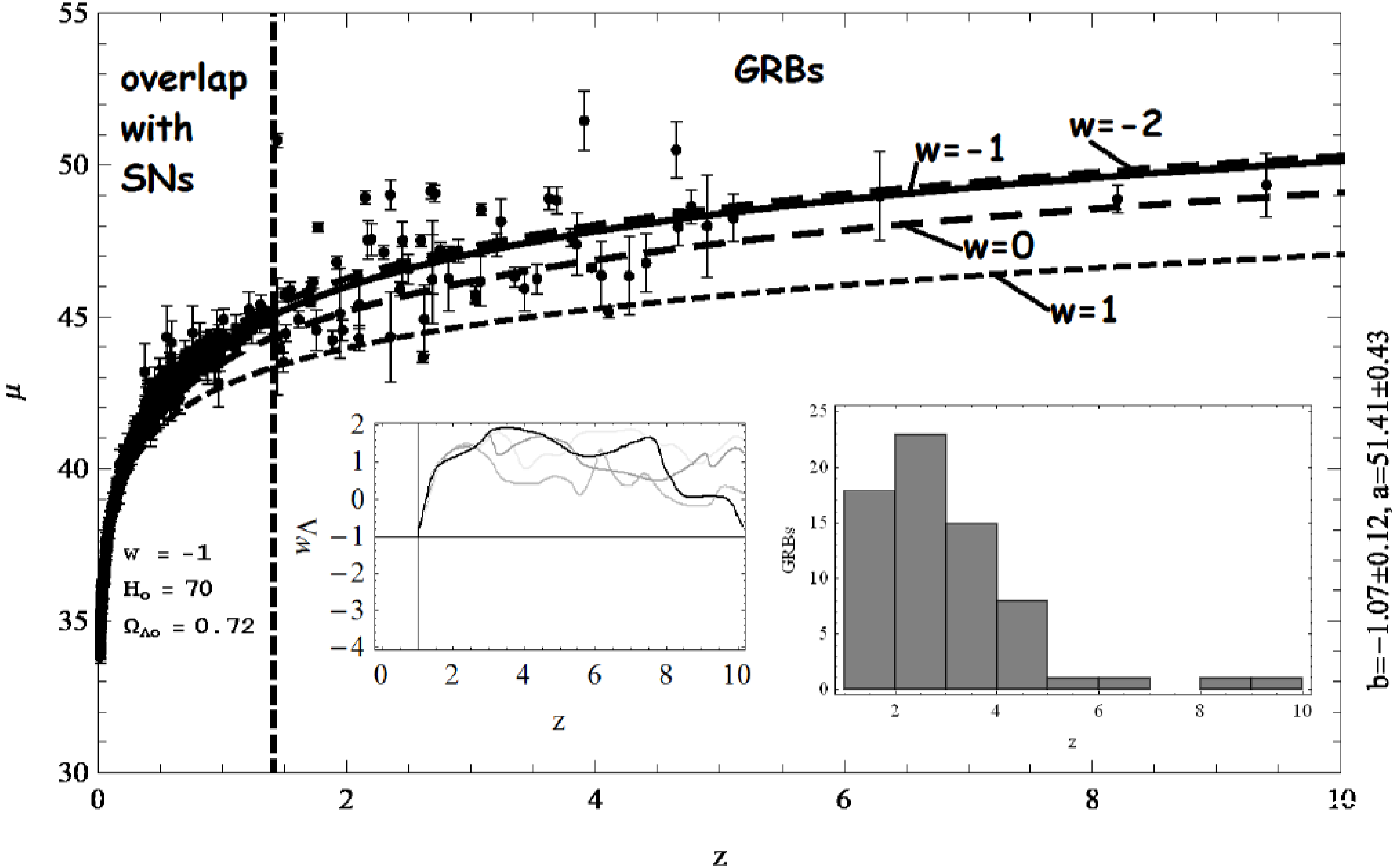
HIGH LUMINOUS SAMPLE: GRBS ONLY



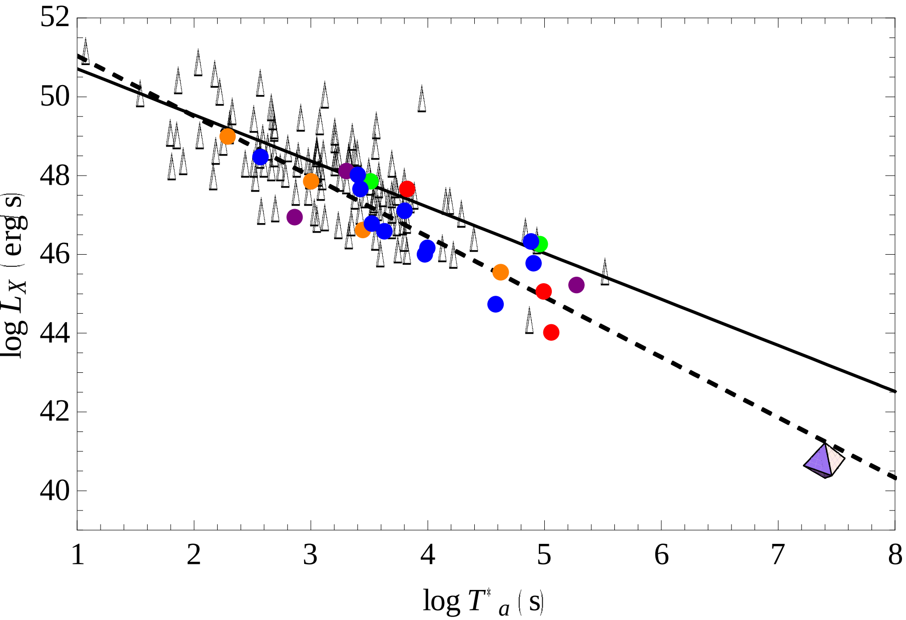
Threshold value $(\log L_{*X})_{th} = 48.7$, we are far well enough to the point in which the corrected luminosity function departs from the observed value $L_X=47$.
HighL sample differs of 5% in the value of H_0 computed in Peterson et al. 2010, while the scatter in Ω_M is underestimated by the 13%.

DISTANCE LADDER: FROM SNE TO GRBS

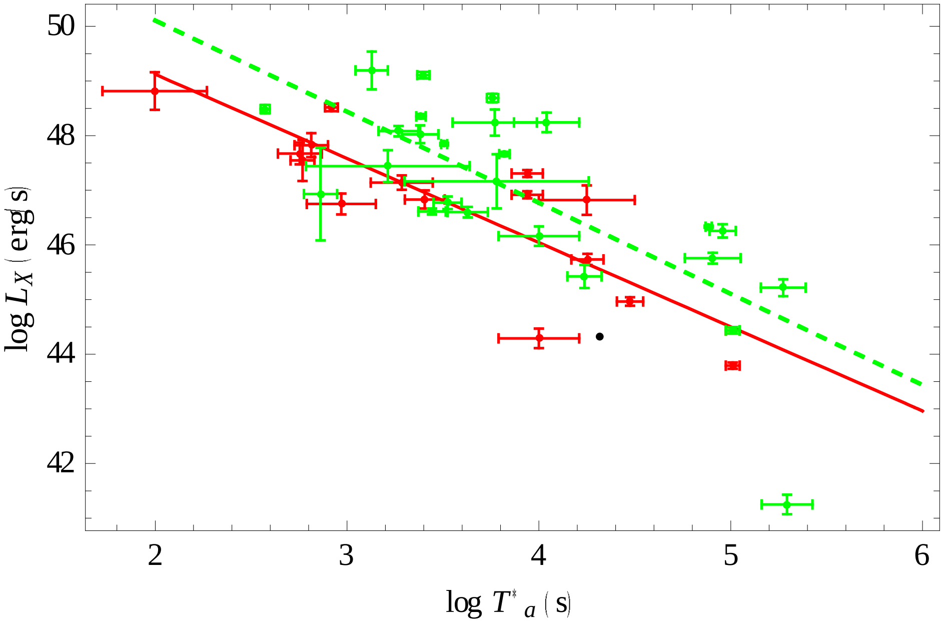
Postnikov, Dainotti et al. 2014,APJ, 783, 126P.



Looking for a more homogeneous sample for a "Standard GRB set" both for cosmology and for a more precise redshift estimator

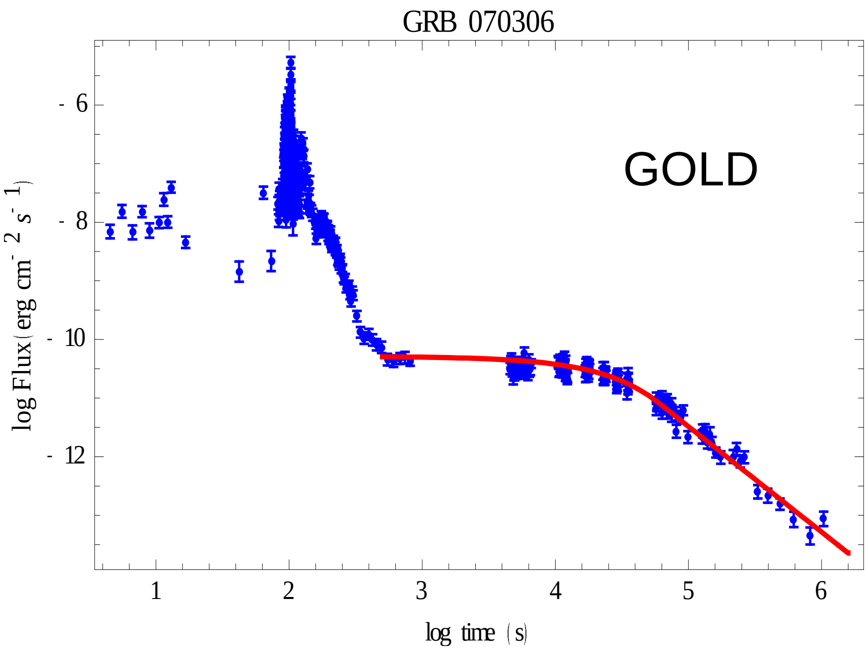


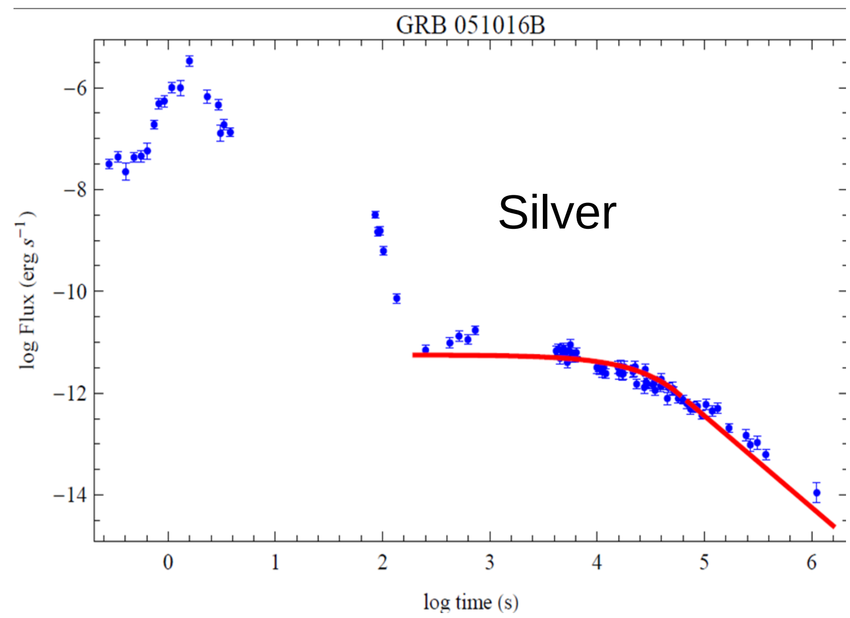
LONG SAMPLE AND GRB-SNE ASSOCIATED SAMPLE.

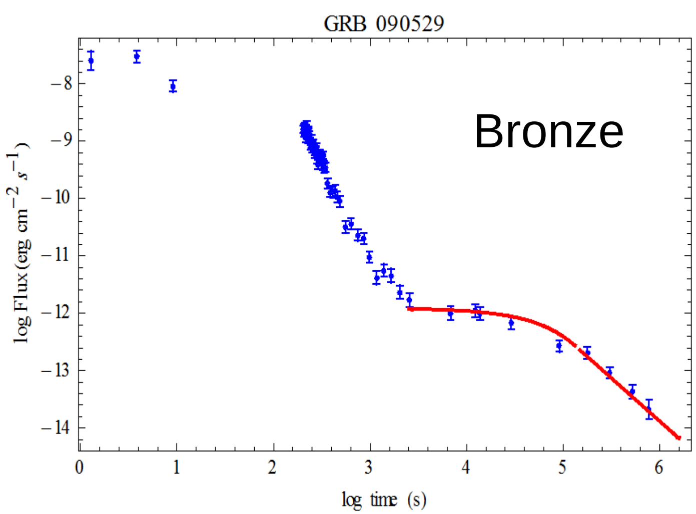


XRF and Short GRBs

CLASSIFICATION ACCORDING TO THE LIGHTCURVES







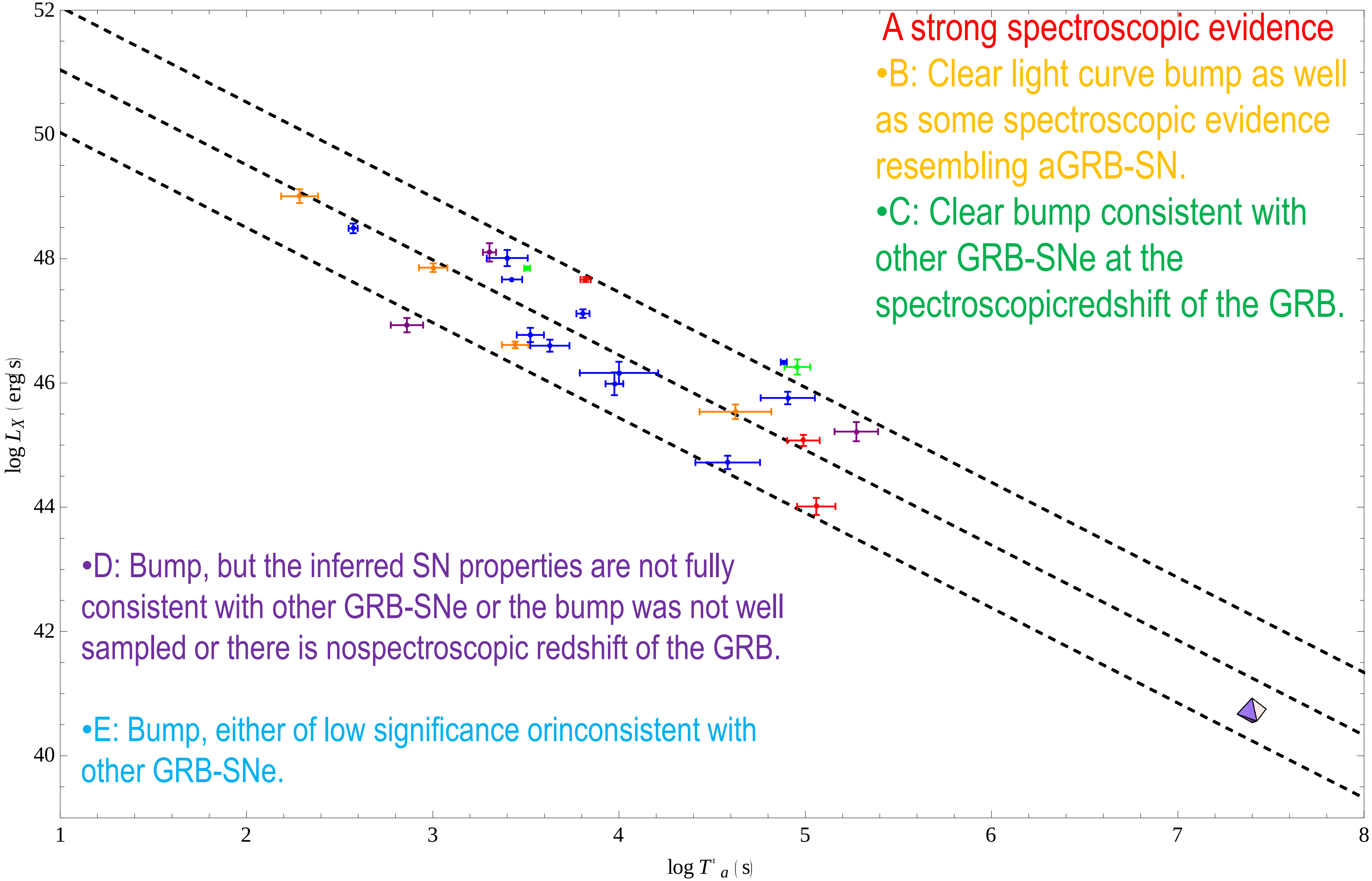
- Gold sample has a very well defined plateau.
- Silver sample has less coverage of data some lack of points or the plateau is not very flat.
- Bronze sample has few points in the plateau.
- The values of the reduced χ^2 is closer to 1 for gold and less for silver and bronze respectively

LOOKING FOR A MORE HOMOGENOUS PHYSICAL SUBSAMPLE

We divide GRBs-SNe in the following categories:

- **A: Strong spectroscopic evidence.**
- **B: Clear light curve bump as well as some spectroscopic evidence resembling a GRB-SN.**
- **C: Clear bump consistent with other GRB-SNe at the spectroscopic redshift of the GRB.**
- **D: Bump, but the inferred SN properties are not fully consistent with other GRB-SNe or the bump was not well sampled or there is no spectroscopic redshift of the GRB.**
- **E: Bump, either of low significance or inconsistent with other GRB-SNe.**

The two dotted lines are the representation of 1 σ error around the best fitted slope. All the data points are within 1 σ. A+B category show ρ= -0.96 with P=1.4*10^3



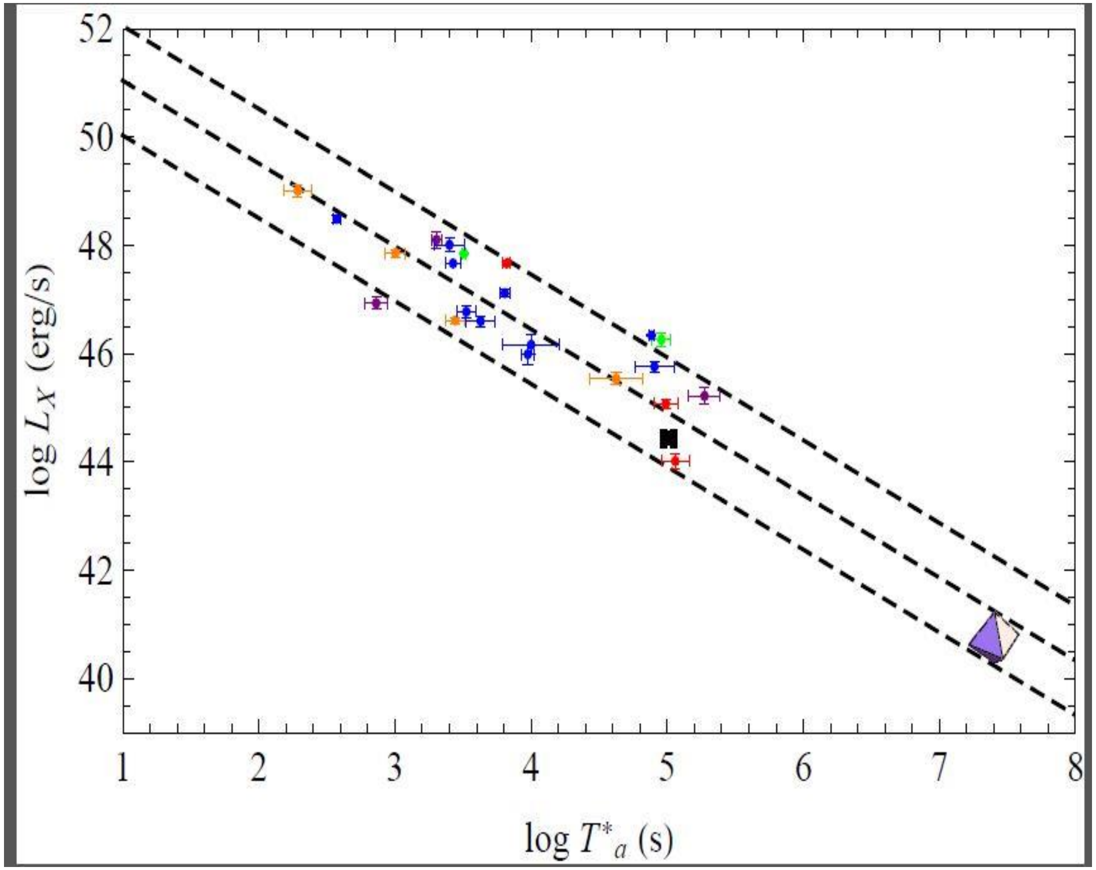
COMPARISON WITH CORRELATION COEFFICIENTS AND SLOPES

Table 1: GRB division in subsamples, the number of GRB in each category, N, the slope of the correlation, a, the normalization, b, the Spearman correlation coefficient, ρ, the Kendall τ statistics and the Probability, P, that an uncorrelared distribution can be drawn by chance. The first 4 categories are based on literature classification, while the last three categories are based on morphology of the lightcurves as described earlier.

GRB category	N of GRBs	a	b	ρ	τ	P
GRB-SNe	23	-1.45 ±0.26	51.54 ±1.02	-0.92	-0.74	$5.62 * 10^{-10}$
GRB-SNe (A+B category)	9	-1.89 ±0.37	53.84 ±1.69	-0.96	-0.78	$1.4 * 10^{-3}$
Short	17	-1.37 ±0.53	51.24 ±1.99	-0.87	-0.70	$1.57 * 10^{-6}$
Long	122	-1.22 ±0.14	52.10 ±0.45	-0.70	-0.52	$3.79 * 10^{-21}$
XRF	25	-1.66 ±0.42	53.44 ±1.63	-0.72	-0.54	$1.64 * 10^{-6}$

There is overlapping within 2 σ between GRB-SNe and long in the slope of the correlation, therefore from this fact we can't draw conclusion about similarities or differences (Payne 2003)
The bidimensional KS=1.4 10^(-6) for the two Lx,Ta distributions thus demonstrating that the GRB-SNe is not drawn by the same distribution.

WHERE IS 060614 (SURELY NOT ASSOCIATED WITH SNE) IN THE LX-TA CORRELATION?

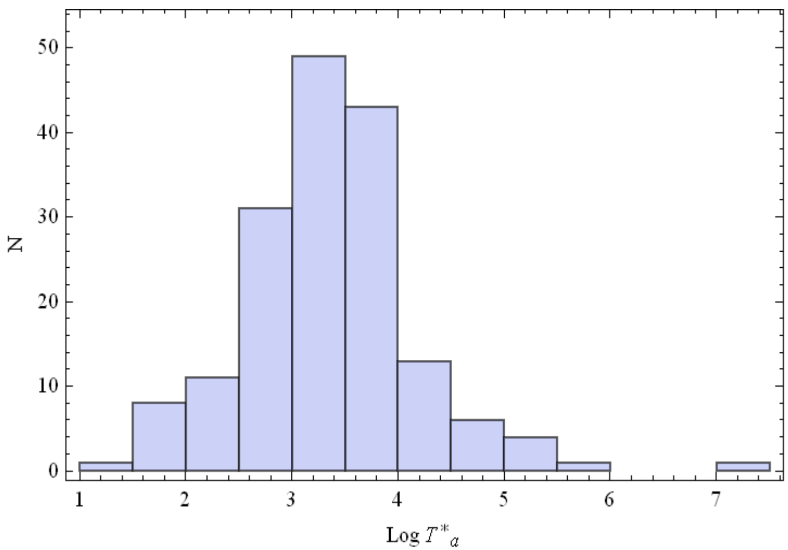


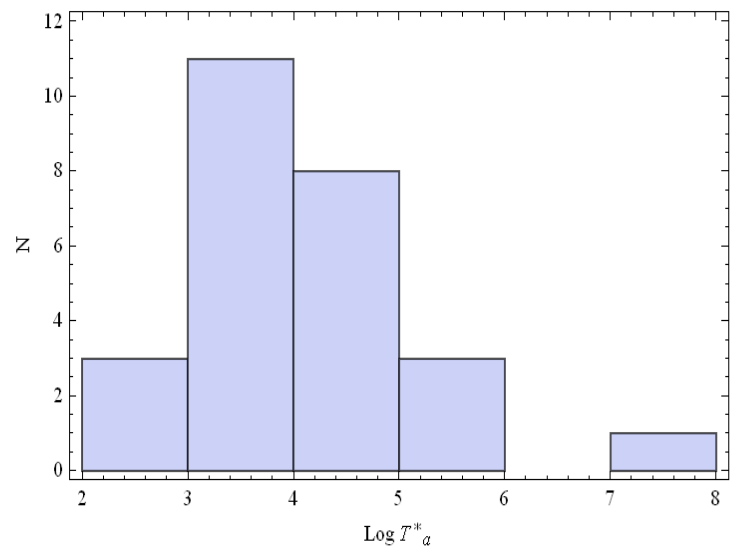
if we regard SN 1998bw and 2006aj as two extremes defining the GRB-SNe, these three GRBs (B category) are still somewhere between A category. 081007/2008hw could be an outlier in the (naively-developed through a small sample) relation between peak magnitude and light curve speed (faster, the fainter), but one might need to do own fit to the data to see it is statistically justified.

GRB 060614 is within 1 σ thus the higher correlation coefficient seems not to be driven by Sne association

POSSIBLE EXPLANATION OF WHY THE CORRELATION IS STEEPER (SUGGESTION BY MAEDA-SAN)

- the distribution of duration (or luminosity) in each sample, the distributions are consistent with being the same?
- If we fit with a Gaussian distribution μ_{long}= 3.24, σ_{long}=0.71, while for GRB-SNe $\mu_{GRB\text{-}SNe}$= 4.07, $\sigma_{GRB\text{-}SNe}$=1.02





However, we are not sure that the Gaussian distribution is the best representation for these data

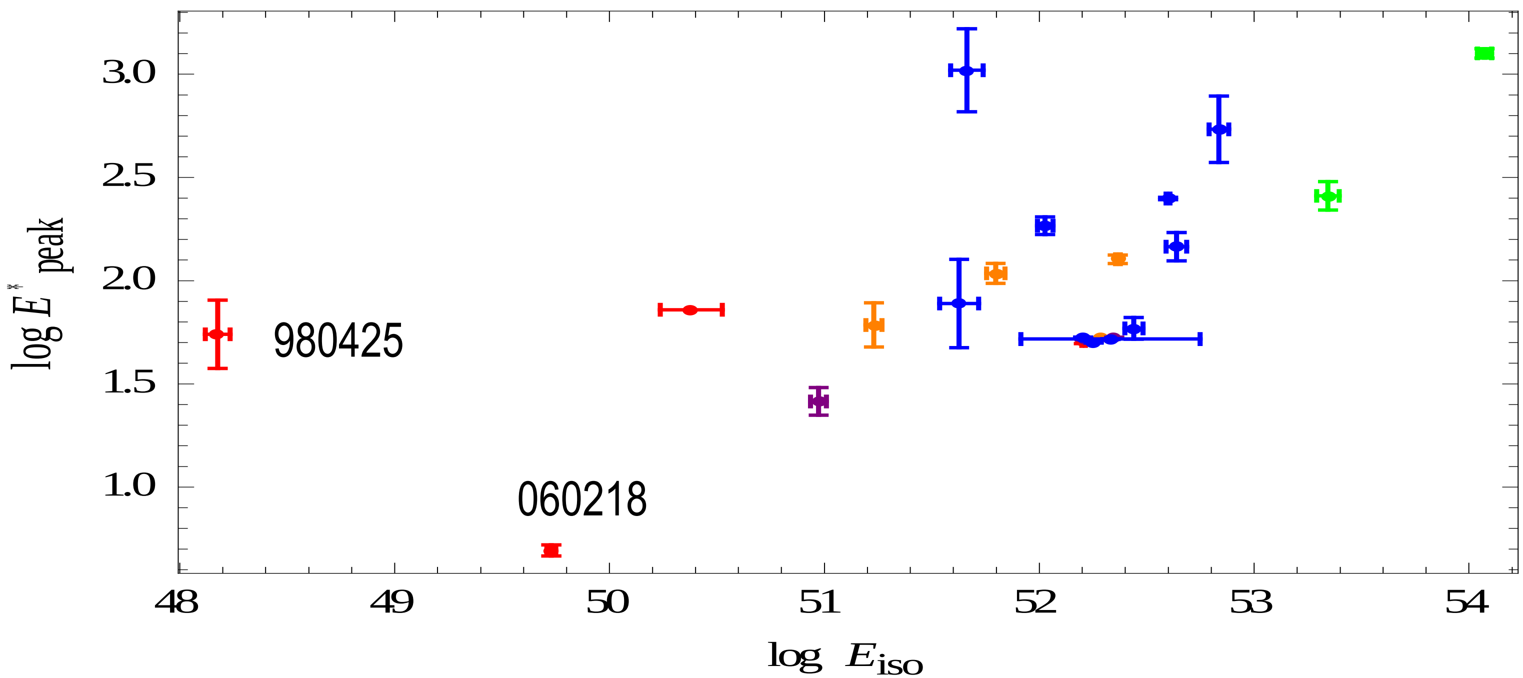
CORRELATION COEFFICIENT OF **LOG E_{ISO} - LOG E^*_{PEAK}**

The Spearman Correlation Coefficient ρ for Epeak vs Eiso in the GRB-SNe sample is ρ=0.45, while for the Epeak Eiso correlation for the total sample ρ=0.95. The difference in percentage is of 52.63 %

The slope for the TOTAL SAMPLE correlation is logEpeak=0.5*(LogEiso)+2*10^52,

while for GRB SNe associated LogEpeak=0.99*(LogEiso)+2*10^52

The Lx - Ta Sample for GRBs associated with SNe ρ =-0.92



CONCLUSIONS III AND FUTURE PERSPECTIVES:

This new subsample of GRBs could be as a test for cosmology together with type Ia SNe, because it is at small redshift range.

Investigation on why the GRB-Sne correlation is much tigher than the long normal Sne is still ongoing

We extended study of DE EoS up to redshift 9 using tight observational correlation in subclass of GRBs.

Resulting EoS band is consistent with cosmological constant (-1) and show small tendency for variations, although leaving it open for more data to come.

Current GRB events number and their luminosity distance estimation errors are consistent with what predicted by extrapolation from SNeIa and BAO. More (100 per Δz=1) and better quality (error/10) GRB data needed to narrow DE EoS at higher redshifts (Dainotti et al. 2011 suggests it is within reach).

Future work is to repeat the method changing the a and b parameters of the correlation together with the cosmological setting in order to have available all the GRB numbers