Slope evolution of GRB correlations and cosmology

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ABSTRACT
Gamma-ray bursts (GRBs) observed up to redshifts $z > 9.4$ can be used as possible probes to test cosmological models. Here we show how changes of the slope of the luminosity $L_{\text{iso}}^{*}$–break time $T_{\text{b}}^{*}$ correlation in GRB afterglows, hereafter the LT correlation, affect the determination of 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 $5\sigma$ factor, we find an overestimated value of the matter density parameter, $\Omega_{M}$, compared to the value obtained with Type Ia supernovae, while the Hubble constant, $H_0$, best-fitting value is still compatible in $1\sigma$ compared to other probes. We show that this compatibility of $H_0$ is due to the large intrinsic scatter associated with the simulated sample. Instead, if we consider a subsample of high-luminosity GRBs ($\text{High } L$), we find that the evaluation of both $H_0$ and $\Omega_{M}$ is not more compatible in $1\sigma$ and $\Omega_{M}$ is underestimated by 13 per cent. However, the $\text{High } L$ sample choice reduces dramatically the intrinsic scatter of the correlation, thus possibly identifying this sample as the standard canonical ‘GRBs’ confirming previous results presented by Dainotti et al. Here, we consider the LT correlation as an example, but this reasoning can also be extended for all other GRB correlations. In the literature so far, GRB correlations are not corrected for redshift evolution and selection biases; therefore, we are not aware of their intrinsic slopes and consequently how far the use of the observed correlations can influence the derived ‘best’ cosmological settings. Therefore, we conclude that any approach that involves cosmology should take into consideration only intrinsic correlations and not the observed ones.

Key words: cosmological parameters.

1 INTRODUCTION
The high fluence values (from $10^{-7}$ to $10^{-4}$ erg cm$^{-2}$) and the huge isotropic energy, $E_{\text{iso}}$, emitted ($\approx 10^{48}$–$10^{53}$ erg) in the prompt emission phase make gamma-ray bursts (GRBs) the most violent and energetic astrophysical phenomena. These features allow one to detect them up to very high redshift, thus offering the intriguing possibility of using them as standard candles to trace the Hubble diagram deep into the matter-dominated era. To this end, one has to rely on scaling relations between an observable redshift-independent quantity and a distance-dependent one so that the measurement of the former allows the determination of the distance. Many empirical motivated correlations are presently available to carry out this programme (Fenimore & Ramirez-Ruiz 2000; Norris, Marani & Bonnell 2000; Ghirlanda, Ghisellini & Lazzati 2004; Liang & Zhang 2005; Amati et al. 2008), thus fuelling the hope to turn GRBs into standardizable distance indicators as Type Ia supernovae (hereafter SNeIa). However, the above correlations have $E_{\text{iso}}$ as one variable, and because of that they suffer double truncation due to the detection selection threshold (Lloyd & Petrosian 1999). Notwithstanding this problem, these correlations have been used to constrain cosmological models. Combining the estimates from different correlations, Schaefer (2007) first derived the GRB Hubble diagram (hereafter HD) for 69 objects, while Cardone et al. (2009, 2010) used a different calibration method and add the luminosity–time correlation (Dainotti, Cardone & Capozziello 2008; Dainotti et al. 2010, 2011b) to update the GRB HD. A more recent compilation of GRBs with measured values of different correlation-related quantities has been presented in Xiao & Schaefer (2009) and used in Cardone, Perillo & Capozziello (2011) to investigate the impact of systematics on the GRB HD.

Notwithstanding these remarkable first attempts, whether GRBs can indeed be considered standardizable distance indicators is a

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for a subsample of 66 long-duration GRBs analysed in Dainotti et al. (2010). The probability of the correlation of the (101 long GRBs) occurring by chance within an uncorrelated sample is $P \approx 10^{-18}$ (Bevington & Robinson 2003).

To determine the intrinsic slope of the correlation, it is necessary to evaluate whether the variables $L_X$ and $T_a^*$ are correlated with redshift or are statistically independent of it. For example, the correlation between $L_X$ and the redshift, $z$, is what we call luminosity evolution, and independence of these variables would imply an absence of such evolution. The EP method prescribed how to remove the correlation by defining new and independent variables.

Dainotti et al. (2013) determined the correlation functions, $g(z)$ and $f(z)$, when determining the evolution of $L_X$ and $T_a^*$ so that de-evolved variables $L_X' \equiv L_X/g(z)$ and $T_a' \equiv T_a^*/f(z)$ are not correlated with $z$. The evolutionary function are parametrized by simple correlation functions

$$g(z) = (1 + z)^{k_x} , \quad f(z) = (1 + z)^{k_a}$$

so that $L_X' = L_X/g(z)$ refers to the local ($z = 0$) luminosities. Dainotti et al. (2013) found that there is no discernable luminosity evolution, $k_x = -0.05^{+0.35}_{-0.55}$, but there is an evolution in $T_a^*$, $k_{T_a} = -0.85^{+0.30}_{-0.36}$ especially at high redshift. Moreover, applying again the EP method to the de-evolved observables, they found that the correlation between $L_X'$ and $T_a'$ is $a = -1.07^{+0.09}_{-0.14}$. Therefore, we note a steepening in the slope parameters in the real data when we consider a previous analysis (Dainotti et al. 2010), and in Dainotti et al. (2013) we attribute this steepening to selection effects and redshift evolution of the observables. Therefore, the aim of the paper is to show how much a departure from $5\sigma$ above and below the central value of the intrinsic slope can affect the cosmological results. There is a wide discussion about the reliability of the GRB as possible cosmological probes due to the wide scatter of GRB correlations and due to the fact that all the GRB correlations may be affected by redshift evolution of their parameters and selection effects. Therefore, it is important to put a limit on how far we can depart from an intrinsic distribution of observables before changing dramatically the estimate of cosmological models. Another question we address is how much difference exists between results obtained from a subsample of high-luminosity GRBs and the ones of the overall sample. We discuss here a simulated data set of 101 GRBs with an imposed correlation slope, $a = -1.52$, assuming the fiducial Delta cold dark matter ($\Lambda$CDM) flat cosmological model with $\Omega_M = 0.291$ and $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, see Fig. 1. We built this set associating with each real data of the distribution

![Figure 1](https://academic.oup.com/mnras/article-abstract/436/1/82/970802/163232)

**Figure 1.** Best-fitting curves for the $L_X-T_a^*$ correlation superimposed on the data in our full Bayesian approach, as it results for the FlatCPL model and GRB + SNeIa + $H(z) + H_0$ data sets.
a simulated \( L_X \) with the slope \(-1.52 \) obtained performing a Monte Carlo simulation with the real distributions. More precisely, the simulated luminosities are determined by applying an LT correlation with \( \log L_X \approx -1.52 \log T_\nu^* \), where \(-1.52 \) is the imposed a slope of the LT correlation and we choose \( \sigma_{\text{int}} = 0.93 \) as the intrinsic scatter, much wider than the scatter obtained from the real observed data sample, \( \sigma_{\text{int}} = 0.66 \). The aim of increasing the scatter is to see how much with a wider dispersion the best-fitting parameters of the cosmology change and how much this scatter can be reduced if we consider the high-luminosity subsample. From this total sample of GRBs, we selected a subsample, called \( \text{High} \) \( L \) samples, with the condition that \( L_X \geq 48.7 \) and the other sample will be called \( \text{Full} \).

The reason for this choice is that we have demonstrated in Dainotti et al. (2013) that the luminosity function corrected by the redshift evolution and selection effects is equal to the observed luminosity function for luminosities \( L_X \geq 48 \). Here we could have chosen a sample with this exact feature, but in such a case we would have had a smaller (than 5\( \sigma \)) difference from the intrinsic slope. We keep a symmetry of a 5\( \sigma \) scatter above (the \( \text{Full} \) sample) and below (the \( \text{High} \) \( L \) sample) the intrinsic slope.

### 3 Cosmology and the Circularity Problem

In the previous approach (Dainotti et al. 2008, 2010, 2011b), some of us estimated the parameters \( (a, b) \) and the intrinsic scatter \( \sigma_{\text{int}} \) assuming the fiducial \( \Lambda \)CDM flat cosmological model with \( \Omega_M = 0.291 \) and \( H_0 = 71 \) km s\(^{-1}\) Mpc\(^{-1}\). We adopt the same cosmological model for simulating the data. When these parameters, \( a \) and \( b \), are fixed by a given cosmology, we face the so-called circularity problem. In order to determine the GRB luminosity \( L_X^* \), we need to set a cosmological model, namely the determination of the calibration parameters \( (a, b, \sigma_{\text{int}}) \) can be different depending on which cosmology is adopted. Although several methods have been proposed to avoid this problem (Kodama et al. 2008; Liang et al. 2008; Cardone, Capozziello & Dainotti 2009; Wei & Zhang 2009; Capozziello & Izzo 2010; Demianski, Pedipalumbo & Rubano 2001; Demianski et al. 2012), it is highly desirable according to the Pettorjus et al. (2009) approach to correctly take care of it in its full generality fitting together both the calibration parameters \( (a, b, \sigma_{\text{int}}) \) and the cosmological parameters each time for a given model.

Following Diaferio, Ostorero & Cardone (2011), we therefore constrain the \( p_{\text{GRB}} = (a, b, \sigma_{\text{int}}) \) calibration quantities and the set of cosmological parameters \( p_c \) by considering the likelihood function: \(^1\)

\[
\mathcal{L}_{\text{GRB}} = \frac{1}{(2\pi)^{N_{\text{GRB}}/2} p_{\text{GRB}}^{1/2}} \exp \left[ -\frac{1}{2} \chi^2_{\text{GRB}}(p_{\text{GRB}}; p_c) \right],
\]

where

\[
\chi^2_{\text{GRB}} = \sum_{i=1}^{N_{\text{GRB}}} \log L_X^*(p_c, p_{\text{GRB}'}) - a \log(T_{\nu}^* + b) - a^2(a_i^*)^2 + (a_i^*)^2 + \sigma_{\text{int}}^2
\]

and

\[
\Gamma_{\text{GRB}}(p_{\text{GRB}}) = \prod_{i=1}^{N_{\text{GRB}}} \left( a_i^2 + (a_i^*)^2 + \sigma_{\text{int}}^2 \right)
\]

\(^1\) Note that we have here not expanded \( \log L_X^* \) in terms of the measured quantities \( p_{\text{obs}} \), so that our likelihood function looks different from the one in Diaferio et al. (2011). The two expressions are actually consistent with each other should we use the relation among \( L_X^* \) and \( p_{\text{obs}} \).

with \( p_{\text{obs}} = (F_j, T_{\nu}^*, \beta^*) \) the set of simulated quantities needed to estimate \( \log L_X^* \) for the \( i \)-th GRB given the cosmological parameters \( p_c, \sigma_{\beta}^i, \sigma_{T_{\nu}^*}^i \) and the error on \( T_{\nu}^* \), \( \sigma_{T_{\nu}^*}^i \). The one on \( \log L_X^* \) obtained by propagating the measurement uncertainties on \( p_{\text{obs}} \) and the sum is over \( N_{\text{GRB}} \) objects in the sample.

Equations (2)–(4) are the same as some of us have adopted in previous papers (Dainotti et al. 2008, 2010, 2011b) motivated by a Bayesian approach (D’Agostini 2005; Kelly 2007) to the calibration problem with the only difference that the best-fitting zero point \( b \) is not analytically expressed as a function of \( (a, \sigma_{\text{int}}) \), but it is free and added to the list of quantities to be determined, which thus sums up to \( N_c + 3 \). In order to strengthen the constraints in such a large dimensional space, we add two further data sets, the Union2.1 SNeIa sample containing 580 objects over the redshift range \( 0.015 \leq z \leq 1.414 \) (Suzuki et al. 2012) and the \( H(z) \) over the redshift range \( 0.1 \leq z \leq 1.75 \) (Stern et al. 2010). The combined likelihood for GRBs, SNeIa and \( H(z) \) data simply reads \( \mathcal{L} = \mathcal{L}_{\text{GRB}} \times \mathcal{L}_{\text{SNeIa}} \times \mathcal{L}_H \times \mathcal{L}_{\text{SNeIa}} \), where the last term \( \mathcal{L}_0 \) with \( (h_{\text{obs}}, \sigma_{b}) = (0.738, 0.024) \) has been introduced to take care of the recent measurements of the present day Hubble constant by the Supernova HO for the Equation of State (Riess et al. 2009) collaboration.

For an assumed cosmological model characterized by a given set of \( p_c \) parameters to be determined, the best-fitting calibration quantities \( (a, b, \sigma_{\text{int}}) \) will be the ones which maximize the full likelihood function \( \mathcal{L}(p_{\text{GRB}}; p_c) \). In order to efficiently sample the \( (N_c + 3) \)-dimensional parameter space, we use a Markov chain Monte Carlo method running three parallel chains and using the Gelman & Rubin (1992) test to check convergence. The histograms of the parameters from the merged chain after burn in cut and thinning are then used to infer median values and confidence ranges.

### 4 RESULTS

In order to evaluate the likelihood function and hence constrain the cosmological parameters, we first have to choose a cosmological model. To this end, we will assume a two-component universe filled by dust matter and dark energy (DE) with the equation of state (EoS) given by the CPL (Chevallier & Polarski 2001; Linder 2003) ansatz \( w(z) = w_0 + w_{\text{a}}z/(1 + z) \). The dimensionless Hubble parameter \( E(z) = H(z)/H_0 \) then reads

\[
E^2(z) = (1 - \Omega_M - \Omega_X)(1 + z)^2 + \Omega_M(1 + z)^3 + \Omega_X(1 + 3z^2 + w_{\text{a}}) \exp \left( \frac{-3w_{\text{a}}z}{1 + z} \right)
\]

with \( \Omega_M, \Omega_X \) the present-day matter and DE density parameters. Since we are mainly interested in showing how the constraints on cosmological parameters change with a different correlation slope rather than constraining the cosmological parameters \( \Omega_M, \Omega_X, w_0, w_{\text{a}}, h \) themselves, we will consider only two particular cases. For the first model (referred to as OLCDM), we assume that DE is described by a cosmological constant term, thus setting \( (w_0, w_{\text{a}}) = (-1, 0) \), but leave open the possibility that the Universe is not spatially flat. As a second case (dubbed in the following FCPL), we force the model to be flat (hence \( \Omega_X = 1 - \Omega_M \)), but allow for a varying DE EoS and let the fit determine \( w_0, w_{\text{a}} \).

Since both the correlation coefficient and a rough visual examination have shown that the GRBs in the \( \text{Full} \) and \( \text{High} \) \( L \) samples follow different \( L_X - T_{\nu}^* \) correlations, i.e. the values of \( (a, b, \sigma_{\text{int}}) \) for the two sets are not equal, we will discuss the results of the likelihood analysis for two distinct cases depending on which GRB sample is used to compute \( \mathcal{L}_{\text{GRB}} \). Finally, we will also check whether the inclusion

\[\text{...}\]
of non-GRB data biases in some unpredictable way the calibration of the $L_X-T_a$ correlation by fitting the cosmological models to a modified likelihood function defined as $\mathcal{L}_{\text{mod}} = \mathcal{L}_{\text{GRB}} \times \mathcal{L}_0 \times \mathcal{L}_M$, where the term $\mathcal{L}_0$ with $(\omega_M, \sigma_M) = (0.1356, 0.034)$ represents a constraint on the physical matter density $\omega_M = \Omega_M h^2$ from the Wilkinson Microwave Anisotropy Probe 7 (WMAP7; Komatsu et al. 2011) Cosmic Microwave Background Radiation (CMBR) analysis. Note that we include this term in order to alleviate the degeneracy among the calibration and the cosmological parameters. When fitting to GRBs + SNeIa + $H(z)$, we do not include the $\mathcal{L}_M$ since the SNeIa + $H(z)$ data play the role of constraining the background expansion, thus leaving to GRB data the task to calibrate the $L_X-T_a$ correlation.

4.1 Full sample

Table 1 summarizes the results of the likelihood analysis using the Full GRB sample both with and without the SNeIa and $H(z)$ data for the two cosmological models considered.

| Id   | $\omega_M$ | $\sigma_M$ | $\omega_0$ | $\sigma_0$ | $\omega_k$ | $\sigma_k$ |
|------|------------|------------|------------|------------|------------|------------|
| 0.241 | 0.264      | 0.255      | 0.203      | 0.325      | 0.166      | 0.395      |
| 0.91  | 0.932      | 1.065      | 0.529      | 1.18       | 0.256      | 1.2        |
| 0.73  | 0.731      | 0.732      | 0.706      | 0.756      | 0.683      | 0.778      |
| $a$   | $-1.52$    | $-1.61$    | $-1.613$   | $-1.76,-1.478$ | $-1.88,-1.133$ | $-1.66,-1.58,-1.545$ |
| $b$   | 52.94      | 53.27      | 53.24      | (52.76, 53.81) | (52.23, 54.24) | 53.43      | 53.13      | 53.05      | (52.66, 53.78) | (52.29, 54.38) |
| $\sigma_{int}$ | 0.93 | 0.95 | 0.96 | (0.88, 1.045) | (0.82, 1.15) | 0.90 | 0.97 | 0.97 | (0.89, 1.044) | (0.83, 1.12) |
| $\Omega_M$ | 0.241  | 0.264 | 0.255 | (0.203, 0.325) | (0.166, 0.395) | 0.348 & 0.326 & 0.327 & (0.284, 0.367) & (0.22, 0.40) |
| $\Omega_X$ | 0.91  | 0.932 | 1.065 | (0.529, 1.18) & (0.256, 1.2) | 0.912 & 0.831 & 0.852 & (0.703, 0.926) & (0.64, 0.967) |
| $h$   | 0.73       | 0.731      | 0.732      | (0.706, 0.756) | (0.683, 0.778) | 0.736 & 0.731 & 0.733 & (0.712, 0.746) & (0.69, 0.763) |

Figure 2. Left-hand panel: regions of confidence for the marginalized likelihood function $\mathcal{L}(\sigma, \omega)$, obtained marginalizing over $b$ and the cosmological parameters using the total simulated sample. The bright brown regions indicate the $\sigma$ (full zone) and $2\sigma$ (bright grey) regions of confidence, respectively. On the axes are plotted the box-and-whisker diagrams relatively to the $a$ and $\sigma_{int}$ parameters: the bottom and top of the diagrams show the 25th and 75th percentiles (the lower and upper quartiles, respectively), and the band near the middle of the box shows the 50th percentile (the median). Right-hand panel: regions of confidence for the marginalized likelihood function $\mathcal{L}(\Omega_M, h)$.

First, we consider the OLCMD model which we have parametrized in terms of the present-day values of the matter and DE density parameters and the Hubble constant. While $h$ is well in agreement with the estimates from both the local distance estimators (Riess et al. 2009) and the CMBR-based data (Komatsu et al. 2011), the median values for both $(\Omega_M, \Omega_X)$ are larger if compared to a fiducial $\Omega_M \sim 0.27$ obtained in previous works (see, e.g., Davis et al. 2007; Amanullah et al. 2010). Therefore, using a different intrinsic slope will bring a difference of 13 per cent on the best estimate of the $\Omega_M$ parameter, see Fig. 2. The constraints on the curvature parameter turn out to be

$\Omega_k h^2 = -0.52$, $\langle \Omega_k \rangle = -0.24$, $\tilde{\Omega}_k = -0.37$,

68 per cent CL = $(-0.49, 0.15)$, 95 per cent CL = $(-0.59, 0.45)$

for the fit to GRB + $\omega_M + H_0$ and

$\langle \omega_k \rangle h^2 = -0.305$, $\langle \tilde{\Omega}_k \rangle = -0.177$, $\tilde{\Omega}_k = -0.22$, $xx$

68 per cent CL = $(-0.33, 0.0335)$, 95 per cent CL = $(-0.39, 0.11)$.
when fitting the GRB + SNeIa + $H(z) + H_0$ data set. Here we even have median values pointing towards non-flat models for both fits; a spatially flat universe is in agreement with, e.g., the WMAP7 only within 95 per cent, giving $\Omega_M = -0.080^{+0.071}_{-0.090}$. This discrepancy can be outlined not only from the fact that in this case we are unable to strongly discriminate among flat and non-flat models, but also from the fact that this is still not possible when SNeIa data are added to the fit.

Forcing the model to be spatially flat but modelling the DE EoS with the CPL ansatz leads to the constraints for the FCPL model listed in the second half of Table 1. There is a striking difference among the results for the GRB + $\omega_m + H_0$ and the GRB + SNeIa + $H(z) + H_0$ data sets. First, we note that the matter density parameter $\Omega_M$ is larger when GRBs and SNeIa are fitted together.

As already stressed, the constraints on $(w_a, w_c)$ are radically different for the GRB + $\omega_m + H_0$ and the GRB + SNeIa + $H(z) + H_0$ fits.

### 4.2 High L sample

Let us now consider the fits using only the 18 GRBs in the High L sample, namely a sample of GRBs with luminosity larger than the threshold value ($\log L_X^2 \, h_0 = 48.7$). Actually, the value of $\log L_X^2$ depends on the cosmological model adopted to estimate the GRB distance so that, in principle, whether a GRB enters or not the High L sample is a function of the unknown underlying cosmological parameters. As is clear, maximizing $L$ is the same as minimizing the sum of the single $\chi^2$ terms. Let us suppose that there are two sets of cosmological parameters $p_0$, which give comparable values of $X_{\text{SNeIa}} + X_H$ so that the preferred one will be that with the lowest $\chi^2_{\text{GRB}}$. This happens for a subsample by imposing the cut $\log L_X^2_{\text{fid}} \geq 48.7$ with $\log L_X^2_{\text{fid}, \text{int}}$ the value estimated for a fiducial flat $\Lambda$CDM model with $(\Omega_M, h) = (0.266, 0.710)$. Although such a choice is somewhat arbitrary, we have checked a posteriori that the results (summarized in Table 2) do not change if we change the fiducial model used for the selection of High L GRBs.

As for the fits to the Full sample, we again find that the constraints on the calibration parameters only weakly depend on either the cosmological model or the data set used [with or without SNeIa and $H(z)$ data]. Indeed, although the best-fitting and median values change, the 68 per cent CL is in full agreement. We also note that adding the SNeIa and $H(z)$ data does not significantly improve the constraints on the calibration parameters.

Table 2. Same as Table 1 but using the High L GRB sample.

| Id | $x_{\text{fid}}$ | $(\chi)$ | 68 per cent CL | 95 per cent CL | $x_{\text{fid}}$ | $(\chi)$ | 68 per cent CL | 95 per cent CL |
|----|-----------------|----------|-----------------|-----------------|-----------------|----------|-----------------|-----------------|
| $\Omega_M$ | 0.332 | 0.311 | 0.309 | (0.248, 0.374) | (0.187, 0.438) | 0.39 | 0.3455 | 0.356 | (0.284, 0.401) |
| $\Omega_X$ | 0.912 | 0.576 | 0.532 | (0.151, 1.042) | (0.106, 1.241) | 0.824 | 0.774 | 0.787 | (0.687, 0.860) |
| $h$ | 0.743 | 0.738 | 0.738 | (0.714, 0.762) | (0.692, 0.786) | 0.731 | 0.738 | 0.738 | (0.721, 0.759) |
| $a$ | -0.46 | -0.40 | -0.37 | (-0.61, -0.20) | (-0.82, -0.06) | -0.37 | -0.32 | -0.28 | (-0.51, -0.18) |
| $b$ | 50.58 | 50.47 | 50.41 | (49.89, 51.09) | (49.48, 51.72) | 50.30 | 50.21 | 50.14 | (49.78, 50.68) |
| $\sigma_{\text{int}}$ | 0.33 | 0.38 | 0.37 | (0.31, 0.45) | (0.26, 0.55) | 0.35 | 0.38 | 0.37 | (0.29, 0.46) |
| $\Omega_M$ | 0.235 | 0.235 | 0.235 | (0.171, 0.297) | (0.119, 0.359) | 0.294 | 0.310 | 0.313 | (0.256, 0.368) |
| $w_0$ | -0.71 | -0.86 | -0.78 | (-1.21, -0.56) | (-1.46, -0.47) | -0.97 | -1.02 | -1.03 | (-1.18, -0.78) |
| $w_a$ | 0.73 | -0.01 | -0.12 | (-0.45, 0.56) | (-1.22, 1.38) | -0.62 | -0.78 | -0.79 | (-1.03, -0.54) |
| $h$ | 0.732 | 0.738 | 0.738 | (0.714, 0.762) | (0.690, 0.786) | 0.737 | 0.728 | 0.730 | (0.710, 0.747) |
| $a$ | -0.53 | -0.37 | -0.37 | (-0.59, -0.15) | (-0.80, -0.03) | -0.67 | -0.67 | -0.64 | (-0.85, -0.54) |
| $b$ | 50.67 | 50.37 | 50.37 | (49.73, 50.98) | (49.38, 51.59) | 51.30 | 51.25 | 51.17 | (50.86, 51.83) |
| $\sigma_{\text{int}}$ | 0.32 | 0.38 | 0.37 | (0.31, 0.45) | (0.26, 0.57) | 0.38 | 0.36 | 0.34 | (0.30, 0.43) |

Comparing the calibrations parameters $(a, b, \sigma_{\text{int}})$ for the Full and High L samples shows one of the most important outcomes of the present analysis. The $L_X^2 - T_a^*$ relation traced by the high-luminosity GRBs is much more shallow (the median $|a|$ being smaller) and tight (with $\sigma_{\text{int}}$ decreasing from $\sim1$ to $\sim0.4$) than the corresponding one for the Full sample, see Fig. 3. A possible reduction of the intrinsic scatter for samples made out of large-luminosity GRBs only was already pointed out in Dainotti et al. (2011b). Here, some of us have shown that the selection on $\log L_X^2$ helps reducing the scatter without biasing in any other way the sample from the point of view of the other GRB properties (such as the time duration $T_a^*$ and the slope $\beta_a$ of the GRB energy spectrum). In that paper, we have, however, not explored further the dependence of the slope $a$ on the threshold luminosity, but only on the error energy parameter $\sigma(E)^2 = \sigma_{E_a}^2 + \sigma_{E_a}^2$. The more the sample is dominated by low-$\sigma(E)$ GRBs, the shallower and tighter is the $L_X^2 - T_a^*$ relation. Since low-$\sigma(E)$ GRBs have typically large luminosity, the effect found in Dainotti et al. (2011b) goes in the same direction. This happens also with simulated data.

We note that the Full sample results have a closer value of the flat cosmological model predicted by the SNeIa sample, while the High L sample differs by 5 per cent in the value of $H_0$ computed in Petersen, Holst & Esben (2010), and the scatter in $\Omega_M$ is underestimated by 13 per cent, see Fig. 4. Therefore, we conclude that we
In the real sample, we have only 11 IC GRBs as well as in the simulated parameters: the bottom and top of the diagrams show the 25th and 75th percentiles (the lower and upper quartiles, respectively), and the band near the middle of the box shows the 50th percentile (the median).

Right-hand panel: regions of confidence for the marginalized likelihood function \( \mathcal{L}(\Omega_{\text{M}}, h) \).

need to follow one of these two approaches: either we use a high-luminosity sample with the condition that \( \log L^*_{\text{X, int}} \geq 48 \), namely we have to choose the sample using as a fiducial cut exactly the luminosity for which the raw luminosity function coincides with the luminosity function corrected by the EP method (Dainotti et al. 2013) or we should include in the evaluation of the cosmological parameters the luminosity and time evolution in the procedure described in Section 3.

5 CONCLUSIONS

The need to push the determination of the HD deep into the matter-dominated era has been the main driver for trying to make GRBs standardizable candles so that they can probe cosmic expansion up to \( z \sim 9.4 \). The LT correlation we have discussed here stands out as one of the strategies implemented to achieve this goal emerging as the only one based on the X-ray afterglow quantities. Moving along the road explored in our previous works, we here show an appropriate analysis that one should do with GRB correlations considering their intrinsic slope and we show here how much changing the correlation slope we obtain departure from a standard cosmology. The test with simulated data has also allowed us to jointly fit both the calibration and cosmological parameters, in order to fully take care of the circularity problem. To this end, we have added also SNeIa and \( H(z) \) data to break the degeneracy among calibration and cosmology also checking whether the combination with non-GRB data biases the estimate of the \((a, b, \sigma_{\text{int}})\) quantities.

The results of cosmology change using the high-luminosity or full sample; this means that the change of the correlation slope from the intrinsic one biases the cosmological results. Here, we consider a simulated case, but the redshift evolution as is explained in Dainotti et al. (2013) should be taken into account, in order to maximize the possibility to use correlations as cosmological tools. Moreover, in this approach the simulated data resemble a mixed sample of long and IC GRBs (Norris et al. 2010). Therefore, here we put another caveat on the use of whole sample of GRBs used for cosmological studies, namely being uncertain of the physical mechanism behind the LT correlation, one cannot exclude the possibility that this unknown engine does not work in the same way for long and IC GRBs so that jointly fitting both classes biases the slope determination.

Should this be the case, one would likely find a larger intrinsic scatter which is what we indeed obtain. Unfortunately, the number of IC GRBs in our sample is too small\(^2\) to efficiently carry out the fitting analysis we have used here. Therefore, the validation of such a hypothesis has to be postponed until a still larger data set of IC GRBs is at our disposal.

The existence of this sample suggests that the physical mechanism underlying the LT correlation is luminosity dependent, because above a certain luminosity value the raw luminosity function coincides with the luminosity function corrected by selection biases and redshift evolution.

In conclusion, we can claim that the present analysis opens a new perspective in the use of GRB correlations as cosmological tools, namely this research posed a strong caveat against the use of the observed GRB correlations not corrected by redshift evolution and selection biases.

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\(^2\) In the real sample, we have only 11 IC GRBs as well as in the simulated sample.
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