The impact of selection biases on the $E_{\text{peak}} - L_{\text{iso}}$ correlation of Gamma Ray Bursts

G. Ghirlanda$^{1,*}$, G. Ghisellini$^1$, L. Nava$^2$, R. Salvaterra$^3$, G. Tagliaferri$^1$, S. Campana$^1$, S. Covino$^1$, P. D’Avanzo$^1$, D. Fugazza$^1$, A. Melandri$^1$, S. D. Vergani$^1$

$^1$INAF – Osservatorio Astronomico di Brera, via E. Bianchi 46, I-23807 Merate, Italy
$^2$APC Université Paris Diderot, 10 rue Alice Domon et Leonie Duquet, F-75205 Paris Cedex 13, France
$^3$INAF - IASF Milano, via E. Bassini 15, I-20133 Milano, Italy

ABSTRACT

We study the possible effects of selection biases on the $E_{\text{peak}} - L_{\text{iso}}$ correlation caused by the unavoidable presence of flux–limits in the existing samples of Gamma Ray Bursts (GRBs). We consider a well defined complete sample of Swift GRBs and perform Monte Carlo simulations of the GRB population under different assumptions for their luminosity functions. If we assume that there is no correlation between the peak energy $E_{\text{peak}}$ and the isotropic luminosity $L_{\text{iso}}$, we are unable to reproduce it as due to the flux limit threshold of the Swift complete sample. We can reject the null hypothesis that there is no intrinsic correlation between $E_{\text{peak}}$ and $L_{\text{iso}}$ at more than 2.7σ level of confidence. This result is robust against the assumptions of our simulations and it is confirmed if we consider, instead of Swift, the trigger threshold of the BATSE instrument. Therefore, there must be a physical relation between these two quantities. Our simulations seem to exclude, at a lower confidence level of 1.6σ, the possibility that the observed $E_{\text{peak}} - L_{\text{iso}}$ correlation among different bursts is caused by a boundary, i.e. such that for any given $E_{\text{peak}}$, we see only the largest $L_{\text{iso}}$, which has a flux above the threshold of the current instruments.

Key words: Gamma-ray: bursts — Radiation mechanisms: non thermal

1 INTRODUCTION

The isotropic luminosity $L_{\text{iso}}$ and the isotropic energy $E_{\text{iso}}$ of Gamma Ray Bursts (GRBs) are strongly correlated with their peak spectral energy $E_{\text{peak}}$ (i.e. the peak of the $\nu F_{\nu}$ spectrum). The spectral–energy correlations of GRBs gathered the interest of the scientific community for their possible implications on the physics of GRBs (Yamazaki, Ioka & Nakamura 2004; Eichler & Levinson 2005; Lamb, Donaghy & Graziani 2005; Levinson & Eichler 2005; Rees & Meszaros 2005; Toma, Yamazaki & Nakamura 2005; Barbiellini et al. 2006; Ryder et al. 2006; Thompson 2006; Giannios & Spruit 2007; Thompson, Meszaros & Rees 2007; Guida, Bernardini & Bianco 2008; Panaitescu 2009), but also raised an intense debate about the strong selection biases they might suffer of (Band & Preece 2005; Nakar & Piran 2005; Butler et al. 2007; Butler, Kocevski & Bloom 2009; Shahmoradi & Nemiroff 2011; Kocevski 2012; but see Ghirlanda, Ghisellini & Firmani 2005; Bosnjak et al. 2008; Ghirlanda et al. 2008; Nava et al. 2008; Amati, Frontera & Guidorzi 2009; Krimm et al. 2009).

Ghirlanda et al. (2012) studied the comoving frame properties of a small sample of GRBs for which the bulk Lorentz factor $\Gamma$ could be estimated. They found that $\Gamma$ is correlated with $L_{\text{iso}}$ and with $E_{\text{peak}}$. These newly found correlations offer an interpretation of the $E_{\text{peak}} - L_{\text{iso}}$ correlation as a sequence of $\Gamma$ factors, the most luminous GRBs have the largest $\Gamma$ and $E_{\text{peak}}$.

Since these correlations involve the rest frame prompt $\gamma$–ray emission properties ($E_{\text{peak}}$, $E_{\text{iso}}$ and $L_{\text{iso}}$) of GRBs with measured redshift $z$, it has been argued that they are strongly biased by (i) the instrumental detector–trigger threshold and/or by (ii) the redshift dependence of the involved observables (e.g. Butler et al. 2007).

Different studies (Ghirlanda et al. 2008; Nava et al. 2008) quantified the possible instrumental selection biases finding that, even if present, they cannot be responsible for the existence of the spectral–energy correlations. While the $E_{\text{peak}} - E_{\text{iso}}$ and $E_{\text{peak}} - L_{\text{iso}}$ correlations are defined considering the time–integrated spectra of GRBs, it has been shown (Firmani et al. 2009; Ghirlanda et al. 2010; 2011a; 2011b) that similar correlations hold within individual bursts. This is a strong argument in favour of the physical origin of the correlations since within a single burst the instrumental selection effects (e.g. the flux–limited threshold of any burst detector), or possible effects due to the dependence of $E_{\text{peak}}$, $E_{\text{iso}}$ and $L_{\text{iso}}$ on the redshift do not play a role.

Discovered with a dozen of GRBs with known redshifts (Yonetoku et al. 2004; Amati et al. 2002), the $E_{\text{peak}} - L_{\text{iso}}$ and the...
$E_{\text{peak}} - E_{\text{iso}}$ correlations have been updated in the last decade by an increasing number of bursts with measured $z$ (see e.g. Nava et al. 2011 for a recent update). Nevertheless, these samples are not complete in the sense that there is no well defined flux limited sample with the redshifts measured for all GRBs. This raised the suspect that the incompleteness in the redshift knowledge might bias such correlations.

Nava et al. 2012 (N12, hereafter) studied the $E_{\text{peak}} - E_{\text{iso}}$ and the $E_{\text{peak}} - L_{\text{iso}}$ correlations with a flux limited sample of GRBs detected by Swift which has also a high level of redshift determination. This complete Swift sample, presented in Salvaterra et al. 2012 (S12, hereafter), was selected starting from the 50% redshift complete sample of Jackobsson\cite{2008ApJ...680..509J} and considering the 58 bright Swift GRBs with a 1 s peak flux (integrated in the 15–150 keV energy band) $F \geq F_{\text{lim}} = 2.6 \text{ ph cm}^{-2} \text{s}^{-1}$. The redshift recovery rate of a such selected sample turns out to be 90%. Therefore, this flux–limited sample has also a high level of completeness in redshift. S12 study the luminosity function (LF) of GRBs throughout the Swift complete sample finding that evolution in luminosity or in density is required in order to account for the observations. Among other results, N12 find that the correlations defined with the complete Swift sample are statistically robust: the rank correlation coefficient is $\rho = 0.76(0.70)$ and chance probability $P = 7 \times 10^{-10}(1 \times 10^{-6})$ for the $E_{\text{peak}} - E_{\text{iso}}$ ($E_{\text{peak}} - L_{\text{iso}}$) correlation. Moreover, the correlation properties (i.e. slope and normalization) of the complete Swift sample are consistent with those defined with the incomplete larger sample of 136 bursts with known $z$ and spectral parameters (see N12).

Complete samples are at the base of any population studies. In this paper we study the impact of instrumental selection effects on the $E_{\text{peak}} - L_{\text{iso}}$ correlation using as a reference the complete Swift sample of GRBs described in S12 and analyzed (in terms of its $E_{\text{peak}} - L_{\text{iso}}$ correlation) in N12. In particular, since no clear consensus has been reached yet on the physical origin of these correlations we aim to answer to this specific question: might the $E_{\text{peak}} - L_{\text{iso}}$ correlation be produced by the threshold of a flux–limited sample of bursts?

To this aim we use a population synthesis code that generates a large sample of GRBs (following some prescriptions for its luminosity and redshift distribution – described in §2) and assuming that there is no correlation between $E_{\text{peak}}$ and $L_{\text{iso}}$. Throughout the paper we make use of the following nomenclature:

- "complete Swift sample": this is the sample defined in S12 of 58 GRBs detected by Swift–BAT with $F \geq F_{\text{lim}}$, of which 90% have measured redshifts. Forty–six out of 58 bursts (79%) have well constrained peak energy and $L_{\text{iso}}$ and their $E_{\text{peak}} - L_{\text{iso}}$ correlation is obtained in the complete sample of simulated bursts (§3) as only due to the cut in the flux. If we cannot find a statistically significant $E_{\text{peak}} - L_{\text{iso}}$ correlation in the simulated complete sample we then reject the null hypothesis that the real one is due to the flux–limit of the sample selection. In the latter case, we are left with two possibilities, that we also test in this work (§5), for the nature of the $E_{\text{peak}} - L_{\text{iso}}$ correlation: either it is an intrinsic correlation to GRBs (as also supported by the existence of a similar correlation within individual bursts – Ghirlanda et al. 2010, 2011, 2011a) with a symmetric scatter of data points around it, or it is caused by a boundary (as proposed by Nakar & Piran 2005), i.e. there is a considerable fraction of bursts with intermediate/large $E_{\text{peak}}$ and low luminosities (§5). We also verify with our code (§4) the recent claims on selection effects (Kocevski 2012) induced by the BATSE trigger threshold.

The main advantage of our population synthesis code is that it relies on a small number of assumptions (described in §2). We focus on testing the $E_{\text{peak}} - L_{\text{iso}}$ correlation because for any simulated GRB with given $z$, $L_{\text{iso}}$ and $E_{\text{peak}}$, its 15–150 keV peak flux is easily compared with the $F_{\text{lim}}$ of the Swift complete sample. The adoption of the complete Swift sample is also relevant, because the $E_{\text{peak}} - L_{\text{iso}}$ correlation defined with this sample is independent from biases induced by the measurement of the redshifts (N12).

Throughout the paper we assume a standard flat universe with $h = \Omega_{\Lambda} = 0.7$.

## 2 SIMULATION SETUP

We need to simulate a population of bursts with $z$ and $L_{\text{iso}}$ assuming a redshift density distribution and a luminosity function, respectively. To every simulated GRB we assign also a peak energy $E_{\text{peak}}$ and assume a typical spectral shape in order to compute its 15–150 keV flux and compare it with $F_{\text{lim}}$. The main steps of our population synthesis code are:

1. We simulate a population of GRBs distributed in redshift $z$ according to the GRB formation rate (GRBFR) $\psi(z)$ derived by Li 2008 (which extended to higher redshifts the results of Hopkins & Beacom 2008):

   \[
   \psi(z) = \frac{0.0157 + 0.118z}{1 + (z/3.23)^{23.66}}
   \]

   where $\psi(z)$ is in units of $M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}$. This is the same $\psi(z)$ adopted by S12 to derive the LF from the complete Swift sample. We simulate bursts with $z \leq 10$.

2. We assign peak luminosities to the simulated GRBs adopting the same luminosity function $\psi(L_{\text{iso}})$ used by S12 for studying the complete Swift sample:

   \[
   \psi(L_{\text{iso}}) \propto \frac{L_{\text{iso} \leq L_{\text{cut}}}}{L_{\text{cut}}^a} ; \quad L_{\text{iso}} \leq L_{\text{cut}}
   \]

   \[
   \psi(L_{\text{iso}}) \propto \frac{L_{\text{iso} > L_{\text{cut}}}}{L_{\text{cut}}^b} ; \quad L_{\text{iso}} > L_{\text{cut}}
   \]

   In S12 both the cases of a luminosity function evolving with redshift as $(1 + z)^{bL}$ or a density evolution of the GRB population as $(1 + z)^{bL}$ are considered. Therefore, we distinguish these two cases. Note that S12 assumed the $E_{\text{peak}} - L_{\text{iso}}$ correlation in constraining the LF free parameters $(a, b, L_{\text{cut}}, \delta_1, \delta_2)$. Since this is in contrast with the null hypothesis we aim to test (i.e. that there is no $E_{\text{peak}} - L_{\text{iso}}$ correlation), we cannot use the parameter values of the LF reported in S12. For consistency with our null hypothesis, we have recomputed the LF of the complete Swift sample with the same analytic method adopted in S12 but without assuming the $E_{\text{peak}} - L_{\text{iso}}$ correlation. The LF parameters $(a, b, L_{\text{cut}}, \delta_1, \delta_2)$ adopted in our simulation (see Tab. \textbf{1}) are consistent, within the errors, with those reported in S12.

1. http://www.rauvis.hi.is/~pja/GRBsample.html
(3) We assign to each simulated burst a peak energy $E_{\text{peak}}$. We consider that $E_{\text{peak}}$ is uncorrelated with $L_{\text{iso}}$. We adopt a log-normal $\xi(E_{\text{peak}})$ distribution centered at 337 keV (i.e. the average value for long GRBs with known $z$) with a dispersion of $\sigma \approx 0.6$ dex. Assuming such a large dispersion of $\xi(E_{\text{peak}})$ ensures that we simulate soft GRBs (i.e. X-ray flashes) with $E_{\text{peak}}$ of few tens of keV and hard bursts with $E_{\text{peak}}$ of tens of MeV.

(4) We derive the peak flux of each simulated burst in the 15–150 keV energy band of Swift–BAT:

$$F = \int_{15 \text{ keV}}^{150 \text{ keV}} N(E; \alpha, \beta, E_{\text{peak}}^{\text{obs}}, z) \, dE$$

where $N(E; \alpha, \beta, E_{\text{peak}}^{\text{obs}}, z)$ is the observer frame photon spectrum re-normalized through $L_{\text{iso}}$. We assume for the GRB spectra the Band function (Band et al. 1993) with fixed low and high energy spectral index, $\alpha = -1.0$ and $\beta = -2.25$ (as done in S12).

From the simulated sample of GRBs we extract a sub-sample of bursts with (a) $F \geq F_{\text{lim}} = 2.6$ ph cm$^{-2}$ s$^{-1}$ and (b) $E_{\text{peak}}^{\text{obs}}$ within 15 keV and 2 MeV. The GRBs used for the definition of the spectral–energy correlations have their $E_{\text{peak}}^{\text{obs}}$ measured. It is not mandatory that $E_{\text{peak}}^{\text{obs}}$ is measured through Swift data, since most of the Swift bursts in the complete sample have been observed by the Konus Wind satellite or other instruments (such as the GBM onboard Fermi). Still we require that $E_{\text{peak}}^{\text{obs}}$ is within the range of energy covered by the present instruments. The sub-sample selected as above is the "complete sample of simulated GRBs".

We then study the correlation between $E_{\text{peak}}$ and $L_{\text{iso}}$ of the complete sample of simulated bursts and compare it with the observed correlation defined by the complete Swift sample. We will also perform the same simulation by modifying assumption (3). In particular we will assume that $E_{\text{peak}}$ and $L_{\text{iso}}$ are correlated as found in real GRBs of the complete Swift sample (§5.1) or that the $E_{\text{peak}} - L_{\text{iso}}$ correlation is caused by a boundary in the corresponding plane (§5.2).

### 3 RESULTS

By studying the complete Swift sample of GRBs, N12 found that the $E_{\text{peak}} - L_{\text{iso}}$ correlation defined by the 46 GRBs in this sample with known $E_{\text{peak}}$ and $L_{\text{iso}}$ has the following properties:

- its rank correlation coefficient is $\rho = 0.7$ and its associated chance probability $P_\rho = 10^{-6}$, i.e. it is significant at more than 3$\sigma$;
- the fit of the correlation with a powerlaw $\log(L_{\text{iso}}) = m \log(E_{\text{peak}}) + q$ gives $m = 0.53 \pm 0.06$ (1$\sigma$) and $q = -25.3 \pm 3.2$ (1$\sigma$) for the correlation slope and normalization, respectively;
- the scatter of the 46 GRBs computed perpendicular around this best fit line has a dispersion of $\sigma_r \approx 0.29$ dex;
- the complete Swift sample has no outlier at more than 3$\sigma$, except for one burst at the limit of the 3$\sigma$ dispersion of the correlation.

The goal of our simulations, for a given set of input assumptions (i.e. $\psi(z)$, $\phi(L_{\text{iso}})$, $\xi(E_{\text{peak}})$, is (1) to produce a significant correlation in the $E_{\text{peak}} - L_{\text{iso}}$ plane and (2) to obtain a correlation which is consistent with that of the real GRB sample of comparison, i.e. the Swift complete sample. The simulation described in §2 is repeated 300 times with the same initial assumptions. For each repeated simulation the complete sample of simulated GRBs is analyzed deriving the parameters of its $E_{\text{peak}} - L_{\text{iso}}$ correlation. At the end of a cycle, i.e. after 300 repeated simulations, we derive:

- the percentage $P_\rho$ (Col. 6 in Tab. 1) of simulations showing a $E_{\text{peak}} - L_{\text{iso}}$ correlation of the complete sample of simulated GRBs significant at least at the 3$\sigma$ level. We consider a correlation significant if the chance probability of its rank correlation coefficient is $\lesssim 10^{-3}$.
- the percentage $P$ (Col. 7 in Tab. 1) of simulations significant at more than 3$\sigma$ with a slope $m$ and normalization $q$ consistent (within their 1$\sigma$ errors) with the slope and normalization of the correlation defined by the Swift complete sample and with a scatter $\sigma_r \lesssim 0.29$, i.e. that of the observed correlation;
- the average percentage of simulated bursts which are out-
Table 1. $P_\rho$ is the percentage of simulations giving a significant correlation (i.e. with chance probability $\leq 10^{-3}$). $P$ is the percentage of simulations giving a significant correlation with slope $m$ and normalization $q$ consistent, within their 1σ errors, with the correlation of the real Swift complete sample and with a scatter $\sigma_L < 0.29$ (i.e. that of the observed correlation of the Swift complete sample). $\%\text{Out} \uparrow$ ($\%\text{Out} \downarrow$) give the percentage of GRBs in the complete sample of simulated bursts which are outliers at more than 3σ of the $E_{\text{peak}} - L_{\text{iso}}$ correlation defined by the complete Swift sample. The arrows correspond to the outliers below (\downarrow) and above (\uparrow) the boundary of the 3σ scatter (dot–dashed blue lines in all the figures).

| φ(L) | a | $L_{\text{cut}}$ erg s\(^{-1}\) | b | $\delta$ | $P_\rho$ | $P$ | $\%\text{Out} \uparrow$ | $\%\text{Out} \downarrow$ |
|------|---|-----------------|---|---|---|---|---|---|
| Density | -1.37 | $3.8 \times 10^{52}$ | -2.37 | 1.22 | 7.3% | 0.7% | 0.7% | 2.0% |
| Luminosity | -1.4 | $10^{53}$ | -2.13 | 2.67 | 8.3% | 0.6% | 1.0% | 2.2% |
| $E_{\text{peak}} - L_{\text{iso}}$ boundary | -1.4 | $10^{51}$ | -2.13 | 2.67 | 100% | 66% | 0.07% | 0.2% |
| K12 (BATSE) | -1.22 | $10^{53}$ | -3.89 | 0.5% | 0.0% | 2.6% | 0.7% |
| K12 (Swift) | -1.22 | $10^{53}$ | -3.89 | 0.7% | 0.0% | 0.4% | 1.3% |

For a certain set of assumptions (ψ(z) and φ($L_{\text{iso}}$)) our term of comparison is the correlation observed in the Swift complete sample (N12). Therefore, the best match between the “simulated world” and the “reality” is when $P_\rho$ and $P$ are large and the percentage of outliers at more than 3σ is consistent with 0.3%.

In addition, we also check that the complete sample of simulated GRBs has a redshift distribution and a flux distribution consistent with those of the real complete Swift sample. Since we adopt the LF derived from the complete sample of S12, we should find a complete sample of simulated bursts with $\psi(\tilde{z})$ and $\phi(L_{\text{iso}})$ consistent with those of the real sample, and indeed this is the case.

Tab.1 lists the input assumptions (LF parameters) and the results of our simulations which are also shown in Fig. 1, 2, 3, 4. The contours are obtained by smoothing the distribution of 13800 data points, i.e. 46 simulated GRBs in 300 repeated simulations. The red contours, for instance, are obtained by smoothing the distribution of 13800 data points, i.e. 46 simulated GRBs in 300 repeated simulations.

4 NULL HYPOTHESIS: NO INTRINSIC $E_{\text{peak}} - L_{\text{iso}}$ CORRELATION

Under the null hypothesis that there is no intrinsic correlation between $E_{\text{peak}}$ and $L_{\text{iso}}$ we find that $\sim 92.7\%$ (91.7%) of the 300 repeated simulations do not produce a significant (at least at the 3σ level of confidence) $E_{\text{peak}} - L_{\text{iso}}$ correlation (Tab.1) in the case of density (luminosity) evolution. Moreover, if we also require that the correlation obtained with the simulated bursts is consistent (in terms of its slope, normalization and scatter) with that observed in the Swift complete sample, the percentage of simulations satisfying all our constraints drops to $P = 0.7%$ ($P = 0.3\%$ in the case of luminosity evolution). In other words, we can never reproduce the observed correlation through our simulations if we assume that $E_{\text{peak}}$ and $L_{\text{iso}}$ are uncorrelated. Therefore, we can reject the null hypothesis (i.e. that there is no correlation between $E_{\text{peak}}$ and $L_{\text{iso}}$) at the 2.7σ and 3σ confidence level in the case of density and luminosity evolution of the GRB population, respectively. These results are shown in Figs. 1, 2 where the solid contours represent the subsample of simulated bursts extracted with the same flux limit of the Swift complete sample (open blue circles in these figures) and the dashed contours represent the total population of simulated bursts. From these plots, it appears that the simulated bursts cannot reproduce the distribution of the real data points (blue open circles) in the $E_{\text{peak}} - L_{\text{iso}}$ plane.

The solid (red) contours of Fig. 1 show a very weak correlation (in the upper–left part of the plane). Indeed, the flux–limit induces a weak correlation in the $E_{\text{peak}} - L_{\text{iso}}$ plane by excluding part of the observables’ space (i.e. the upper–left part of the $E_{\text{peak}} - L_{\text{iso}}$ plane). However, a very weak correlation as that shown by the (red) solid lines in Fig. 1 has a very high significance if it is computed for all the 13800 data points resulting from the 300 repeated simulations. This is because the correlation significance would be dominated by the extremely large data sample. Instead, our goal is to compare samples of comparable sizes: the 46 GRBs of the complete sample versus the 46 GRBs of the simulated complete sample (the latter are produced in each of the 300 repeated simulations). For this reason, in analyzing our results, we have computed, for instance, the percentage of repeated simulations that generate a sample of 46 simulated GRBs which have a significant correlation in the $E_{\text{peak}} - L_{\text{iso}}$ plane. As we discuss in §3, although an apparent very weak correlation is produced by the flux–limit in Fig. 1 in the upper–left part of the plane, the overall distribution of the data points violates most of our constraints.

Under the null hypothesis of no correlation between $E_{\text{peak}}$ and $L_{\text{iso}}$, we have computed the average percentage of GRBs which are outliers at more than 3σ below (%Out ↓ in Tab.1) the observed $E_{\text{peak}} - L_{\text{iso}}$ correlation defined by the Swift complete sample. According to our simulations, Swift should have detected a percentage between 2.0–2.2% (see Tab.1) of GRBs with intermediate $E_{\text{peak}}$ and large $L_{\text{iso}}$ (e.g. $10^{52–54}$ erg s\(^{-1}\)). These bursts (1 event on average) should be below the 3σ limit of the $E_{\text{peak}} - L_{\text{iso}}$ correlation (dot–dashed line in Fig. 1) defined by the complete Swift sample. At present, there are no outliers in the bottom/right triangle of the $E_{\text{peak}} - L_{\text{iso}}$ plane, either in the complete Swift sample or more generally in the whole population of GRBs with measured $z$ and known $E_{\text{peak}}$ and $L_{\text{iso}}$ (e.g. see N12).

A similar argument applies to the simulated GRBs of the complete sample that have high $E_{\text{peak}}$ and low $L_{\text{iso}}$. The 0.7–1.0% of simulated bursts with $F > F_{\text{lim}}$ lie above the 3σ upper boundary of the $E_{\text{peak}} - L_{\text{iso}}$ correlation of the real burst sample. While there are no outliers in the complete Swift sample in this part of the plane, it has been discussed in the literature if a fraction of bursts with intermediate/large $E_{\text{peak}}$ and low $L_{\text{iso}}$ could already be present in the populations of GRBs detected by different satellites (e.g Nakar & Piran 2005; Band & Preece 2006). On the other hand, Nava et al. (2011) have shown that there are no outliers of the $E_{\text{peak}} - L_{\text{iso}}$
correlation at more than 3σ in the BATSE and Fermi population of GRBs.

Note also that a considerable fraction (∼20%) of the simulated GRBs with $F \geq F_{\text{lim}}$ have a peak energy $E_{\text{peak}}$, in the observer rest frame, larger than the upper Swift energy threshold of 350 keV but still lower than 2 MeV, which roughly corresponds to the limit of current instruments with the largest energy range that can measure $E_{\text{peak}}$ (e.g. Fermi and Konus).

Kocevsky 2012 (K12, hereafter) performed a population study finding that the $E_{\text{peak}} - L_{\text{iso}}$ correlation is induced by a combination of the redshift/luminosity function of GRBs with the detection limit of a given instrument (BATSE in his study). K12 attributes the existence of the $E_{\text{peak}} - L_{\text{iso}}$ correlation to the combination of the Malmquist bias (i.e. the detection of the most luminous GRBs at high $z$ preferentially), the flux limit of the detector, and its limited band-pass. According to this interpretation the most luminous GRBs at high $z$ with intermediate $E_{\text{peak}}$ goes undetected because their $E_{\text{peak}}^\text{obs} = E_{\text{peak}}/(1 + z)$ falls below the low energy threshold of the detector (i.e. 15 keV in the case of Swift–BAT). This argument is intuitively plausible: a detector sensitive in a given energy range should hardly detect bursts with $E_{\text{peak}}^\text{obs}$ outside this range. However, what matters for triggering a burst is its peak flux (integrated in the detector energy range) which depends on the spectral shape of the burst (e.g. $E_{\text{peak}}^\text{obs}$, $\alpha$, $\beta$) and the normalization of the spectrum. If this flux is larger than the detector flux limit, the burst will be detected no matter its $E_{\text{peak}}^\text{obs}$. Our simulations in the case of luminosity evolution, for instance, predict that ∼13% of the simulated GRBs with $F \geq F_{\text{lim}}$ have $E_{\text{peak}}^\text{obs} < 15$ keV (i.e. the lower threshold of the BAT energy band–pass). In other words, these bursts are bright enough to be detected by Swift, despite the fact that their $E_{\text{peak}}^\text{obs}$ is outside the BAT energy range. Therefore, the absence of GRBs in the lower/right plane of the $E_{\text{peak}} - L_{\text{iso}}$ correlation cannot be entirely attributed to this effect.

Our population synthesis code is simpler than that of K12 because we test the $E_{\text{peak}} - L_{\text{iso}}$ correlation through the complete Swift sample. In our case, by simulating $z$, $L_{\text{iso}}$ and $E_{\text{peak}}$ we can immediately compute the peak flux of a simulated GRB and compare it with the flux limit. The simulation of K12 concerns the $E_{\text{peak}} - E_{\text{iso}}$ correlation, which involves the time integrated spectral properties of GRBs, and requires several assumptions (e.g. on the profile structure and time evolution of the spectrum during a burst) in order to simulate a GRB light curve and verify if it can be detected by BATSE (in turn, this also requires K12 to model a typical background and the BATSE detector response matrix). The advantage of our simulation is that it uses the $F_{\text{lim}}$ of the complete sample of S12, which is a simple sharp cut in the 15–150 keV peak flux of the simulated GRB population.

K12 adopts a slightly different LF and performs the simulation for BATSE. We assumed his luminosity function and redshift density distribution $\phi(L_{\text{iso}})$ and $\xi(z)$ (originally derived from Butler et al. 2011). We have implemented in our code the BATSE detection algorithm as described in Band (2003). The results of this simulation are shown in Fig. 3 and reported in Tab. 1 (labelled K12). Under the null hypothesis of no correlation between $E_{\text{peak}}$ and $L_{\text{iso}}$, the majority (99.5%) of the repeated simulations show no significant $E_{\text{peak}} - L_{\text{iso}}$ correlation in the sample of bursts that should be detected by BATSE. The percentage of outliers that we find is 0.7% below the correlation and 2.3% above the correlation (see Fig. 3 and Tab. 1). We compare the results of the simulation assuming the BATSE trigger threshold with the complete Swift sample instead of using the larger (but highly incomplete) sample of all the bursts with measured $z$ and known spectral parameters. This is justified by the findings of N12 that show that the $E_{\text{peak}} - L_{\text{iso}}$ correlation defined by the complete Swift sample (46 events with $E_{\text{peak}}$ and $L_{\text{iso}}$ known) is quite similar to the correlation defined with the larger sample of 136 GRBs with measured $z$ and known spectral parameters ($E_{\text{peak}}$, $L_{\text{iso}}$). We have also tested the LF adopted by K12 but with the flux limit of Swift. We show in Fig. 3 (see also Tab. 1) the contours corresponding to the complete sample of simulated GRBs (dot–dashed contours). Also in this case we are not able to obtain a significant (at more than 3σ) $E_{\text{peak}} - L_{\text{iso}}$ correlation in 96% of the repeated simulations under the null hypothesis that there is no $E_{\text{peak}} - L_{\text{iso}}$ correlation.

5 $E_{\text{peak}} - L_{\text{iso}}$ CORRELATION OR BOUNDARY?

We have shown in §4 that if there is no correlation between $E_{\text{peak}}$ and $L_{\text{iso}}$ the apparent correlation between these two observables cannot be produced by the flux limit cut of the complete Swift sample or of the BATSE instrument. We still have two possibilities: (i) to assume the observed correlation and use it in simulating the GRB population; (ii) assume that the $E_{\text{peak}} - L_{\text{iso}}$ correlation is produced by a boundary in the corresponding plane.

For these reasons, it is worthwhile to test the possibility that there is a population of GRBs with a uniform distribution of $L_{\text{iso}}$ above the $E_{\text{peak}}$–$L_{\text{iso}}$ correlation. In this case their absence in the observed $E_{\text{peak}}$–$L_{\text{iso}}$ plane could be induced by the trigger threshold and/or by a bias related to the detection of the bursts with the smallest jet opening angles. Here we study the former possibility (i.e. absence due to the detector threshold).

5.1 Real correlation

We repeat the Monte Carlo simulation to obtain a population of GRBs assuming that $E_{\text{peak}}$ and $L_{\text{iso}}$ are intrinsically correlated. We assume that the correlation between $E_{\text{peak}}$ and $L_{\text{iso}}$ has the same properties as the correlation that we observe in the complete sample of Swift bursts (point (3) of §2). In particular we refer to the slope,
normalization and scatter found in N12. Then, from our simulated population of GRBs, we select those that satisfy the requirements on the peak flux and on $E_{\text{peak}}$ and we study the $E_{\text{peak}} - L_{\text{iso}}$ correlation in this sub-sample. In this sub-sample we expect, of course, to find a strong correlation, since we have assumed it in simulating the population of GRBs.

The main reason for performing this test is for self-consistency and also to verify whether the cuts introduced (flux limit and constraints on $E_{\text{peak}}$) in defining the complete sample of simulated GRBs do affect the characteristics of the correlation and lead us to find a correlation which is different from the correlation that we have assumed for the simulation. For example, if we simulate a sample satisfying a given correlation, we can expect that the introduction of a flux limit could reduce the scatter (and maybe also modify the slope) of the correlation that we find.

The results are shown in Fig. 4 and reported in Tab. 1. We find a good agreement between the complete Swift sample of simulated bursts (solid contours in Fig. 4) and the complete Swift sample of real bursts (open points in Fig. 4). All the repeated simulations (we have assumed the LF with luminosity evolution but the results do not depend on this choice) produce a significant correlation in the $E_{\text{peak}} - L_{\text{iso}}$ plane (see Tab. 1) and in 66% of the simulations such a significant correlation is consistent in slope, normalization and scatter with that defined by the Swift complete sample.

5.2 Boundary

We can also test the possibility that the $E_{\text{peak}} - L_{\text{iso}}$ correlation is caused by a boundary. To this aim, we perform the simulation by assuming that bursts follow the boundary represented by the log($E_{\text{peak}}$) = $m$ log($L_{\text{iso}}$) + $q$ (with $q$ and $m$ being the normalization and slope of the $E_{\text{peak}} - L_{\text{iso}}$ correlation found by N12 for the complete Swift sample). For each simulated value of $L_{\text{iso}}$, we assign a peak energy $E_{\text{peak}}$ according to a probability distribution:

$$\phi(E_{\text{peak}}) = A e^{-\frac{(E_{\text{peak}} - E_{\text{peak,c}})^2}{2 \sigma_{\text{peak}}^2}}; \quad \text{if } E_{\text{peak}} \leq E_{\text{peak,c}}$$

$$= A; \quad \text{if } E_{\text{peak}} > E_{\text{peak,c}}$$

where log($E_{\text{peak,c}}$) = $m$ log($L_{\text{iso,c}}$) + $q$. This distribution introduces a sharp decrease of the simulated bursts below the observed $E_{\text{peak}} - L_{\text{iso}}$ correlation, which then forms a boundary in the $E_{\text{peak}} - L_{\text{iso}}$ plane with a uniform distribution of GRBs above it. We report the results in Tab. 1 and show them in Fig. 5. Under this hypothesis, we find that a considerably large fraction (87%) of the repeated simulations produces a strong $E_{\text{peak}} - L_{\text{iso}}$ correlation but only 12% of the correlations seem consistent with the correlation of the Swift complete sample. 1.4% of outliers at more than $3\sigma$ above the correlation are found. By contrast, in the samples of bursts without measured redshifts of BATSE and Fermi, Nava et al. (2011) have shown that there are no outliers at more than $3\sigma$ of the $E_{\text{peak}} - L_{\text{iso}}$ correlation.

6 CONCLUSIONS

We performed Monte Carlo simulations of GRBs with a given redshift distribution and luminosity function (as described in Eq. 1 and Eq. 2 respectively). We have made the null hypothesis that there is no intrinsic correlation between the luminosity $L_{\text{iso}}$ and the peak energy $E_{\text{peak}}$ of the simulated bursts. We have considered the GRBs that have a peak flux $\geq F_{\text{lim}} = 2.6$ ph cm$^{-2}$ s$^{-1}$ which is the same flux limit of the complete Swift sample studied in S12 and N12 and we also required that $E_{\text{peak}}$ of the detected bursts can be measured by current instruments, i.e. that it lies in the 15 keV–2 MeV energy range. These are the simulated bursts that would be detected by Swift. The use of a flux–limited sample of Swift bursts as that defined in S12 has the advantage that it avoids several complexities related to the Swift trigger method (e.g. dependence from the time evolution of the signal and significance with respect to a time–variable background or dependence from off–axis detector response). In particular the flux–limit of the S12 sample is sufficiently high that the selected sample should be free from these trigger–related issues.

If we make the hypothesis that there is no correlation between $E_{\text{peak}}$ and $L_{\text{iso}}$, only in 7.3% of the repeated simulations (e.g. for the case of a GRB population evolving in density with redshift, as found in S12) we find a statistically robust (i.e. chance probability
of the rank correlation coefficient \( \leq 10^{-2} \) \( E_{\text{peak}} - L_{\text{iso}} \) correlation. If we also require that our simulations produce a correlation similar (in slope, normalization and scatter) to that observed among real GRBs of the complete Swift sample, the percentage reduces to 0.7%. Therefore, we reject the null hypothesis that there is not an intrinsic correlation at the 2.7σ level of confidence (3.0σ for the case of luminosity evolution). These results suggest that a correlation between \( L_{\text{iso}} \) and \( E_{\text{peak}} \) should exist. Since for Swift we have considered a bright cut on the peak flux (to match that adopted in the definition of the complete sample of S12), our results are obtained for the most conservative case. Similar results, i.e. the impossibility to produce a strong \( E_{\text{peak}} - L_{\text{iso}} \) correlation as due to the trigger threshold, are also obtained for BATSE.

An alternative possibility is that there is a boundary in the \( E_{\text{peak}} - L_{\text{iso}} \) plane (Nakar & Piran 2005). If we assume that this boundary is coincident with the observed \( E_{\text{peak}} - L_{\text{iso}} \) correlation, the scatter of the data points around it is not symmetric but there is a larger fraction of bursts with intermediate \( E_{\text{peak}} \) and low luminosities. The trigger threshold here could play a role in hiding the events with extremely low luminosity. Our simulations, assuming the existence of the \( E_{\text{peak}} - L_{\text{iso}} \) correlation as a boundary, suggest that while a considerable percentage (87%) of simulations produce a correlation between \( L_{\text{iso}} \) and \( L_{\text{peak}} \), only 10% of the simulations also produce a correlation with slope, normalization and scatter consistent with that of the real GRB sample. This result excludes at the 1.6σ confidence level the boundary case, as we have modeled it here. In particular, we assumed that the distribution of bursts above the boundary is uniform. It could still be possible, however, that a boundary with an asymmetric scatter below and above it exists due to some other property of GRBs (e.g. their jet opening angle). This possibility requires more elaborated simulations that are outside the scope of this paper. In conclusion, our simulations show that there is a correlation between \( E_{\text{peak}} \) and \( L_{\text{iso}} \), and this cannot be due to a selection bias caused by a flux-limited sample.

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REFERENCES

Amati, L., Frontera, F., Tavani, M. et al. 2002, A&A, 390, 81
Amati, L., Frontera, F., & Guidorzi, C. 2009, A&A, 508, 173
Band, D. L., & Preece, R. 2005, ApJ, 627, 319
Barbiellini, G., Longo, F., Omodei, N. et al. 2006, NCimB, 121, 1363
Bosnjak, Z., Celotti, A., Longo, F., Barbiellini, G. 2008, MNRAS, 384, 599
Butler, N. R., Kocevski, D., Bloom, J. S., & Curtis, J. L. 2007, ApJ, 671, 656
Butler, N. R., Kocevski, D., & Bloom, J. S. 2009, ApJ, 694, 76
Eichler, D., & Levinson, A. 2005, ApJ, 635, 1182
Firmani, C., Cabrera, J. I., Avila-Reese, V. 2009, MNRAS, 393, 1209
Ghirlanda, G., Ghisellini, G., Lazzati, D. 2004, ApJ, 616, 331
Ghirlanda, G., Ghisellini, G., Firmani, C. 2005, MNRAS, 361, L10
Ghirlanda, G., Nava, L., Ghisellini, G., Firmani, C., Cabrera, J. I., 2008, MNRAS, 387, 319
Ghirlanda, G., Nava, L.; Ghisellini G., 2010, A&A, 511, 43
Ghirlanda, G., Ghisellini G., Nava, L., 2011a, MNRAS, 418, L109
Ghirlanda, G., Ghisellini G., Nava, L., 2011b, MNRAS, 410, L97

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Ghirlanda, G., Nava, L., Ghisellini G., et al., 2012, MNRAS, 420, 483
Giannios, D., & Spruit, H. C. 2007, A&A, 469, 1
Guida, R., Bernardini, M. G., & Bianco, L. 2008, A&A, 487, L37
Kocevski, D., 2012, ApJ subm., arXiv:1110.6173
Krimm, H. A., Yamaoka, K., Sugita, S., et al. 2009, ApJ, 704, 1405
Lamb, D. Q., Donaghy, T. Q., & Graziani, C. 2005, ApJ, 620, 355
Lewinwson, A., & Eichler, D. 2005, ApJ, 629, L13
Nakar, E, & Piran, T. 2005, MNRAS, 360, L73
Nava, L., Ghirlanda, G., Ghisellini, G, Firmani, C. 2008, MNRAS, 391, 639
Nava, L., Ghirlanda, G., Ghisellini, G. et al., 2011, MNRAS, 415, 3153
Nava, L., Salvaterra, R., Ghirlanda, G., et al., 2012 (N12), MNRAS in press, arXiv:1112.4470
Panaitescu, A. 2009, MNRAS, 393, 1010
Rees, M., & Meszaros, P. 2005, ApJ, 628, 847
Ryde, F., Bjornsson, C., Kaneko, Y. et al. 2006, ApJ, 652, 1400
Salvaterra, R., Campana, S., Vergani, S. D., et al. 2012, ApJ in press, arXiv:1112.1700
Shahmoradi, A., & Nemiroff, R. J. 2011, MNRAS, 407, 2075
Toma, K., Yamazaki, R., & Nakamura, T. 2005, ApJ, 655, 481
Thompson, C. 2006, ApJ, 651, 333
Yamazaki, R., Ioka, K., & Nakamura, T. 2004, ApJ, 606, L33
Yonetoku, D., Murakami, T., Nakamura, T. et al. 2004, ApJ, 609, 935