A FUNDAMENTAL PLANE FOR LONG GAMMA-RAY BURSTS WITH X-RAY PLATEAUS

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ABSTRACT

A class of long gamma-ray bursts (GRBs) presenting light curves with an extended plateau phase in their X-ray afterglows obeys a correlation between the rest-frame end-time of the plateau, $T_a$, and its corresponding X-ray luminosity, $L_a$ (Dainotti et al.). In this work we perform an analysis of a total sample of 176 Swift GRBs with known redshifts, exhibiting afterglow plateaus. By adding a third parameter that is the peak luminosity in the prompt emission, $L_{\text{peak}}$, we discover the existence of a new three-parameter correlation. The scatter of data about this plane becomes smaller when a class-specific GRB sample is defined. This sample of 122 GRBs is selected from the total sample by excluding GRBs with associated supernovae (SNe), X-ray flashes and short GRBs with extended emission. With this sample the three-parameter correlation identifies a GRB “fundamental plane.” Moreover, we further limit our analysis to GRBs with light curves with good data coverage and almost flat plateaus, 40 GRBs forming our “gold sample.” The intrinsic scatter, $\sigma_{\text{int}} = 0.27 \pm 0.04$, for the three-parameter correlation for this last sub-class is more than two times smaller than the value for the $L_a - T_a$ one, making this the tightest three-parameter correlation that involves the afterglow plateau phase. Finally, we also show that a slightly less tight correlation is present between $L_{\text{peak}}$ and a proxy for the total energy emitted during the plateau phase, $L_a T_a$, confirming the existence of an energy scaling between the prompt and afterglow phases.

Key words: cosmological parameters – gamma-ray burst: general – methods: data analysis – radiation mechanisms: non-thermal

1. INTRODUCTION

Gamma-ray bursts (GRBs), very energetic events with typical isotropic prompt emission energies, $E_{\text{iso}}$ (erg), in the $10^{53}$ erg range, and they have been detected out to redshifts, $z$, of $\sim 10$ (Cucchiara et al. 2011). This last feature raises the tantalizing possibility of extending direct cosmological studies far beyond the redshift range covered by supernovae (SNe). However, GRBs are not standard candles in any trivial way. Indeed, the number of sub-classes into which they are grouped has grown. GRBs are classified depending on their duration into short ($T_\text{90} \lesssim 2\ s$) and long ($T_\text{90} \gtrsim 2\ s$) (Kouveliotou et al. 1993). Later, a class of GRBs with mixed properties, such as short GRBs with extended emission (ShortEE), was discovered (Norris & Bonnell 2006). Long GRBs, depending on their fluence (erg cm$^{-2}$), can be divided into normal GRBs or X-ray Flashes (XRFs); the latter are empirically defined as GRBs with a greater fluence in the X-ray band ($2-30\ \text{keV}$) than in the X-ray band ($30-400\ \text{keV}$). In addition, several GRBs also present associated SNe; hereafter they are referred to as GRB–SNe. Regarding light curve morphology, a complex trend in the afterglow has been observed with the Swift Satellite (Gehrels et al. 2004; O’ Brien et al. 2006), showing a flat part, the plateau, soon after the steep decay of the prompt emission. Along with these categories several physical mechanisms for producing GRBs have also been proposed. For example, the plateau emission has mainly been ascribed to millisecond newborn spinning neutron stars, (e.g., Zhang & Mészáros 2001; Troja et al. 2007; Dall’Osso et al. 2011; Rowlinson et al. 2013, 2014; Rea et al. 2015) or to accretion onto a black hole (Cannizzo & Gehrels 2009; Cannizzo et al. 2011). One promising field has been the search for correlations between relevant GRB parameters, (e.g., Amati et al. 2009; Yonetoku et al. 2004; Ghirlanda et al. 2004; Qi et al. 2009; Willingale et al. 2010; Oates et al. 2012) to attempt to use them as cosmological indicators and to gain insights into their nature.

The correlations discovered thus far suffer from having large scatters (Collazzi & Schaefer 2008), beyond observational uncertainties, highlighting that the events studied probably come from different classes of systems or perhaps from the same class of objects, but we do not yet observe a sufficiently large number of parameters to characterize the scatter. As the number of GRB categories has grown over the years, many with observed X-ray afterglows and measured redshifts, the possibility of isolating single classes has appeared. This allows this correlation is intrinsic, and not an artifact of selection effects or due to instrumental threshold truncation, as is also the case for the $L_{\text{peak}} - L_a$ correlation...
where $L_{\text{peak}}$ is the peak luminosity in the prompt emission.

In this letter we show how a careful discrimination of plateau phase GRBs can be performed to isolate, using X-ray afterglow light curve morphology, a sub-class of events that define a very tight plane in a three-dimensional space of \( \log L_a, \log T_a, \log L_{\text{peak}} \). A three-parameter correlation emerges with an intrinsic scatter, \( \sigma_{\text{int}} \), of 24\% less than the \( L_a - T_a - L_{\text{peak}} \) correlation for the sample of 122 long GRBs. When we choose a sub-sample of high-quality data (40 GRBs, hereafter the gold sample), a further 38\% reduction in \( \sigma_{\text{int}} \) appears. We also show through bootstrapping that the reduction in scatter is not an artifact of observational biases. Actually, Dainotti et al. (2010, 2011a) have already demonstrated through a careful data analysis and Monte Carlo simulations that to reduce the scatter of this correlation, an appropriate selection criterion related to observational GRB properties is more important than simply increasing sample size. The \( \sigma_{\text{int}} \) of the \( L_a - T_a - L_{\text{peak}} \) correlation for the gold sample is 54\% smaller than the scatter of the \( L_a - T_a \) correlation for the sample of 122 long GRBs. A slightly more scattered \( L_{\text{peak}} - (L_aT_a) \) correlation is also present, which, together with an almost constant total energy within the plateau phase for the gold sample, is indicative of a strong energy coupling between prompt emission and X-ray afterglow phase. In Sections 2 and 3 we describe the Swift data sample used and the three-parameter correlation, respectively. In Section 4 we present the \( (L_aT_a, L_{\text{peak}}) \) correlation as the tightest correlation currently available that involves the afterglow phase, and also present our concluding remarks.

2. SAMPLE SELECTION

We analyzed 176 GRB X-ray plateau afterglows detected by Swift from 2005 January up to 2014 July, with known redshifts, spectroscopic or photometric, available in Xiao & Schaefer (2009), on the Greiner webpage\(^7\) and in the Circulars Notice, excluding redshifts for which there is only a lower or an upper limit. The redshift range of our sample is (0.033, 9.4). We include all GRBs for which the Burst Alert Telescope+ X-Ray Telescope (XRT) light curves can be fitted by the Willingale et al. (2007) phenomenological model (hereafter W07). The W07 functional form for \( f(t) \) is:

\[
  f(t) = \begin{cases} 
  F_i \exp\left(\alpha_i \left(1 - \frac{t}{T_i}\right)\right) \exp\left(-\frac{L_i}{t}\right) & \text{for } t < T_i \\
  F_i \left(\frac{t}{T_i}\right)^{-\alpha_i} \exp\left(-\frac{L_i}{t}\right) & \text{for } t \geq T_i
  \end{cases}
\]

for both the prompt (index “\( i = p \)”) \( \gamma \)-ray and initial X-ray decay and for the afterglow (”\( i = a \)”), modeled so that the complete light curve \( f_{\text{tot}}(t) = f_p(t) + f_a(t) \) contains two sets of four free parameters \((T_i, F_i, \alpha_i, \beta_i)\). The transition from the exponential to the power law (PL) occurs at the point \((T_i, F_i e^{-\beta_i/T_i})\) where the two functional forms have the same value. The parameter \( \alpha_i \) is the temporal PL decay index and the time \( t_i \) is the initial rise timescale. We exclude the cases when the fitting procedure fails or when the determination of 1\(\sigma \) confidence intervals does not fulfill the Avni (1976) \( \chi^2 \) prescriptions; see the xspec manual.\(^8\) We compute the source rest-frame isotropic luminosity \( L_a \) in units of erg s\(^{-1}\) in the Swift XRT bandpass, \((E_{\text{min}}, E_{\text{max}}) = (0.3, 10)\) keV, as follows:

\[
  L_a = 4\pi D_L^2(z) F_X(E_{\text{min}}, E_{\text{max}}, T_b) \cdot K,
\]

where \( D_L(z) \) is the luminosity distance for the redshift \( z \), assuming a flat ΛCDM cosmological model with \( \Omega_M = 0.3 \) and \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( F_X \) is the measured X-ray energy flux in (erg cm\(^{-2}\) s\(^{-1}\)), and \( K \) is the K-correction for cosmic expansion (1 + \( z \))^\(\alpha-1\). The light curves are taken from the Swift webpage repository, http://www.swift.ac.uk/burst_analyser/., and we followed Evans et al. (2009) for the evaluation of the spectral parameters. As shown in Dainotti et al. (2010), requiring an observationally homogeneous sample in terms of \( T_90 \) and spectral lag properties implies removing short GRBs (\( T_90 \approx 2 \text{ s} \)) and ShortEE from the analysis. We remove the GRBs cataloged as ShortEE in Norris & Bonnell (2006), Levan et al. (2007), and Norris et al. (2010). For the removal of the remaining ShortEE GRBs we follow the definition of Norris et al. (2010), who identify ShortEE events as those presenting short spikes followed, within 10 s, by a drop in the intensity emission by a factor of 10\(^2\) to 10\(^3\), but with almost negligible spectral lag. Additionally, since there are long GRBs for which no SNe has not been detected, such as, for example, the nearby \( z = 0.09 \) SNe-less GRB 060505, the existence of a new group of long GRBs without SNe has been suggested, thus highlighting the possibility of two types of long GRBs, with and without SNe. Therefore, in the interest of selecting an observational homogeneous class of objects, we consider only the long GRBs with no associated SNe. Under these specific criteria, all the GRB–SNe that follow the Hjorth & Bloom (2011) classification are removed. Similarly, to keep the sample homogeneous regarding the ratio between \( \gamma \) and X-ray fluence, we removed all XRFs. The selection criteria are applied in the observer frame. Figure 1 shows the light curve for GRB 061121 with the best-fit model light curve superimposed. The plateau phase is clearly seen between 2.6 and 3.8 in \( \log(T) \) in units of seconds (s).

In all that follows, \( L_{\text{peak}}(\text{erg s}^{-1}) \) is defined as the prompt emission peak flux over a 1 s interval. Following Schaefer (2007) we compute \( L_{\text{peak}} \) as follows:

\[
  L_{\text{peak}} = 4\pi D_L^2(z) F_{\text{peak}}(E_{\text{min}}, E_{\text{max}}, T_b) \cdot K,
\]

where \( F_{\text{peak}} \) is the measured gamma-ray energy flux over a 1 s interval (erg cm\(^{-2}\) s\(^{-1}\)). To make the sample for this analysis more homogeneous regarding the spectral features, we consider only the GRBs for which the spectrum computed at 1 s has a smaller \( \chi^2 \) for a single PL fit than for a cutoff power law (CPL). Specifically, following Sakamoto et al. (2011), when the \( \chi^2_{\text{CPL}} - \chi^2_{\text{PL}} < 6 \), the PL fit is preferred. We additionally discard 6 GRBs that were better fit with a blackbody model than with a PL. This full set of criteria reduces the sample to 122 long GRBs. Finally, we construct a sub-sample by including strict data quality and morphology criteria: at least five points should be at the beginning of the plateau and the steep plateaus (the angle of the plateau greater than 41\(^\circ\)), which

\(^7\) http://www.mpe.mpg.de/~jcj/grbgen.html

\(^8\) http://heasarc.nasa.gov/xanadu/xspec/manual/XspecSpectralFitting.html
constitute 11% of the total sample and are the high angle tail of the distribution, are removed. The first of the above selection criteria guarantees that the light curves clearly present the transition from the steep decay after the prompt to the plateau. The number of points required for the W07 fit should be at least four, since there are four free parameters in the model, one of which should be after the end of the plateau. Thus, the requirement of six points in total (five at the start and at least one after the plateau) ensures a minimum number of points to have both a clear transition to the plateau phase (in fact, in some cases three points do not offer a wide enough time range to determine the start of the plateau) and simultaneously to constrain the plateau. This data quality cut defines the gold sample, which includes 40 GRBs. We have also checked through the T-test that this gold sample is not statistically different from the distribution of \( (L_{\text{a}}, T_{\text{a}}, T_{\text{peak}}, z) \) of the full sample, thus showing that the choice of this sample does not introduce any biases, such as the Malmquist or Eddington ones, against high luminosity and/or high redshift GRBs. Specifically, \( L_{\text{a}}, T_{\text{a}}, T_{\text{peak}}, \) and \( z \) of the gold sample present similar Gaussian distributions, but with smaller tails than the total sample (see Dainotti et al. 2015a); thus there is no shift of the distribution toward high luminosities, larger times, or high redshift. So the selection cut naturally removes the majority of the high error outliers of the variables involved, thus reducing the scatter of the correlation for the gold sample.

3. THE \( (L_{\text{a}}, T_{\text{a}}, L_{\text{peak}}) \) PARAMETER SPACE

The left panel of Figure 2 shows 176 GRBs in the \( (L_{\text{a}}, T_{\text{a}}, L_{\text{peak}}) \) parameter space, where distinct sub-classes of GRBs show greater spread about the plane than the gold sample. The right panel in Figure 2 shows the fundamental plane in projection for the 122 long GRBs; the reduction in the intrinsic scatter is clear.

To explore if the two-dimensional \( L_{\text{a}} - T_{\text{a}} \) correlation is the projection of a tighter \( (L_{\text{a}} - T_{\text{a}} - L_{\text{peak}}) \) plane, we plot the 122 long GRBs, in a \( (L_{\text{a}}, T_{\text{a}}) \) plane, binned according to their \( L_{\text{peak}} \) values into three equally populated ranges: \( 49.9 \leq \log L_{\text{peak}} \leq 51.4 \), \( 51.4 \leq \log L_{\text{peak}} \leq 51.8 \) and \( 51.8 \leq \log L_{\text{peak}} \leq 53.0 \) as red circles, blue squares, and black triangles, respectively, in the left panel of Figure 3. For reference, the curves show the best-fit lines of fixed slope equal to one and free intercept calculated for each \( L_{\text{peak}} \) bin. We see a clear monotonic trend, in that the intercept of the lines is determined by the \( L_{\text{peak}} \) bin of the sub-sample, all of which show a significantly smaller dispersion than the 122 GRB sample. The above is indicative of an underlying plane in the \( (L_{\text{a}}, T_{\text{a}}, L_{\text{peak}}) \) parameter space, the \( L_{\text{a}} - T_{\text{a}} \) correlation being just a projection of it. Introducing a third (prompt emission) parameter, \( L_{\text{peak}} \), reduces the \( L_{\text{a}} - T_{\text{a}} \) correlation scatter, in part associated with the prompt luminosity.

Parametrizing this plane using the angles \( \theta \) and \( \phi \) of its unit normal vector gives:

\[
\log L_{\text{a}} = C_{\alpha} - \cos(\phi)\tan(\theta)\log T_{\text{a}} - \sin(\phi)\tan(\theta)\log L_{\text{peak}},
\]

where \( C_{\alpha} = C(\theta, \phi, \sigma_{\text{int}}) + z_{\alpha} \) is the normalization of the plane correlated with the other variables, \( \theta, \phi, \) and \( \sigma_{\text{int}} \); while \( z_{\alpha} \) is the uncorrelated fitting parameter related to the normalization and \( C \) is the covariance function. This normalization of the plane allows the resulting parameter set, \( \theta, \phi, \sigma_{\text{int}}, \) and \( z_{\alpha} \), to be uncorrelated and provides explicit error propagation. Accounting for all the error propagation we fit an optimal plane for the gold sample distribution given by:

\[
\log L_{\alpha} = (15.75 \pm 5.3) - (0.77 \pm 0.1)\log T_{\alpha} + (0.67 \pm 0.1)\log L_{\text{peak}},
\]

where \( C_{\alpha} = (15.75 \pm 5.3), \cos(\phi)\tan(\theta) = -(0.77 \pm 0.1), \) and \( \sin(\phi)\tan(\theta) = (0.67 \pm 0.1) \pm 0.1. \) All the fits presented in the paper are performed using the D’Agostini method (D’Agostini 2005) with 1σ uncertainties on the coefficients given; \( \sigma_{\text{int}} = 0.27 \pm 0.04 \) is reduced by 36% when compared to the \( (L_{\text{a}} - T_{\text{a}}) \) correlation for the gold sample. The adjusted \( R_{\text{adj}}^2 \) for the gold sample is 0.80. \( R_{\text{adj}}^2 \) gives a modified version of the coefficient of determination, \( R^2 \), adjusting for the number of parameters in the model. \( R^2 = 0.81, \) the Pearson correlation coefficient, \( r, \) is 0.90 with a probability of \( P = 4.41 \times 10^{-15} \) for the same sample occurring by chance. The normalization of the plane, \( C(\sigma_{\text{int}}, \theta, \phi) \), is given by:

\[
C = 18.30 - 59.90\theta^2 - 0.29\sigma_{\text{int}}
+ 0.27\sigma_{\text{int}}^2 - 4.11\phi - 0.06\sigma_{\text{int}}\phi + 14.97\phi^2
+ \theta(92.07 - 0.09\sigma_{\text{int}} + 84.85\phi).
\]

For the 122 GRBs, results are:

\[
\log L_{\alpha} = (15.69 \pm 3.8) + (0.67 \pm 0.07)\log L_{\text{peak}} - (0.80 \pm 0.07)\log T_{\alpha},
\]

with \( \sigma_{\text{int}} = 0.44 \pm 0.03. \) Thus, the reduction in \( \sigma_{\text{int}} \) from the three-dimensional (3D) correlation for the sample of 122 GRBs to the 3D correlation for the gold sample is again 36%. The \( R_{\text{adj}}^2 \) for this distribution is 0.56, \( R^2 = 0.57, \) and \( r = 0.93 \) with \( P \leq 2.2 \times 10^{-16}. \) Finally, \( \sigma_{\text{int}} \) of the 3D correlation for the gold sample is 54% smaller than the one in the two-dimensional (2D) correlation for the 122 GRB sample.
The plane can be visualized edge-on in an infinite number of projections, according to how the projection angle is rotated. We choose a projection where the plane is seen edge-on and one of the axes contains only one of the three relevant parameters; see the right panel of Figure 3, which shows the plane for the gold sample. By comparing it with Figure 2, and noting the change in scales, it is obvious that $s_{\text{int}}$ has been substantially reduced, although a few outliers remain, keeping the scatter larger than the measurement errors.

To analyze the distributions of GRBs about the plane, we compute their geometric distance to it for the 122 GRBs and the gold sample; see Figure 4. The latter sample is less scattered about the plane than the first. This result is not due to the reduced sample size, as checked by $10^4$ Monte Carlo simulations using the bootstrapping of 40 GRBs from the total sample. The probability of obtaining such a random sample with an intrinsic scatter of $s_{\text{int}} \leq 0.27$ is 0.3%. Although we have considered all known biases, it cannot be ruled out completely that part of the reduction in scatter might be attributed to some unknown bias.

4. DISCUSSION AND COMPARISON WITH OTHER EXTENDED $L_{\alpha} - T_{\alpha}$ CORRELATIONS

To derive insights into the physical nature of the link between the prompt and afterglow parameters evident in the plane obtained, we explore the relation between a proxy of the plateau energy, $L_{\alpha} T_{\alpha}$, and $L_{\text{peak}}$. In Figure 5 we show that $(L_{\alpha} T_{\alpha}) \propto L_{\text{peak}}^{-0.59}$ with $r = 0.60$ and $P = 1.9 \times 10^{-13}$ for the gold sample, while $r = 0.70$ and $P = 4.2 \times 10^{-7}$ for the 122

![Figure 2](image-url)  
**Figure 2.** The left panel shows 176 GRBs in the $(L_{\alpha}, T_{\alpha}, L_{\text{peak}})$ space, with the fitted plane including GRB–SNe (white cones), X-ray flashes (blue spheres), short EE (red cuboid), and long GRBs (black circles). The right panel shows a much tighter plane that results from including only the 122 long GRB sample. The gray and black circles are GRBs that lie below and above the plane, respectively.

![Figure 3](image-url)  
**Figure 3.** Left panel: the $(L_{\alpha}, T_{\alpha})$ plane with error bars, binned into three equally populated $L_{\text{peak}}$ ranges: $49.9 \leq \log L_{\text{peak}} \leq 51.4$ (red circles), $51.4 \leq \log L_{\text{peak}} \leq 51.8$ (blue squares), and $51.8 \leq \log L_{\text{peak}} \leq 53.0$ (black triangles). The right panel shows the edge-on projection along the intrinsic plane for the $(L_{\alpha}, T_{\alpha}, L_{\text{peak}})$ correlation for the gold sample.
GRBs. This result demonstrates that the prompt kinetic power is strongly correlated with the plateau energy, for the well-defined plateau exhibiting GRBs. The best-fit slope with $s_{\text{int}} = 0.29$ is

$$\log(L_a T_a) = 20.63 + 0.59 \log(L_{\text{peak}}).$$

(8)

This correlation is different from the one presented in Bernardini et al. (2012), where $L_a T_a$ and two additional parameters, $E_{\text{peak}}$ and $E_{\text{iso}}$, are explored, yielding $s_{\text{int}} = (0.31 \pm 0.03)$. Another plane $(L_{\text{peak}} - E_{\text{iso}} - E_{\text{peak}})$ has been defined, but only among prompt emission parameters (Tsutsui et al. 2009). We compare the $L_{\text{peak}} - L_{\text{iso}} - L_{\text{peak}}$ correlation with other three-parameter correlations, which are extensions of the $L_a - T_a$ correlation. Xu & Huang (2012) obtained a tighter $(L_{\text{peak}} - T_a - E_{\text{iso}})$ correlation with $s_{\text{int}} = 0.43$, as compared to the $(L_a - T_a)$ one, which yielded $s_{\text{int}} = 0.85$ for their sample. The $s_{\text{int}}$ of our $(L_a, T_a, L_{\text{peak}})$ plane is 37% smaller than the $s_{\text{int}}$ of the $(L_a - T_a - E_{\text{iso}})$ plane.

In fact, Dainotti et al. (2011b, 2015b) showed that $L_{\text{iso}} - L_{\text{iso}}$, where $L_{\text{iso}} = E_{\text{iso}}/T_{90}$ correlates better than $L_{a} - E_{\text{iso}}$ and $L_a - L_{\text{peak}}$, correlates better than $L_a - L_{\text{iso}}$, respectively. Thus, $L_{\text{peak}}$ is more tightly related to $L_a$ than any other prompt $L_{\text{iso}}$. This suggests that $L_{\text{peak}}$ and not $E_{\text{iso}}$ should be a third parameter in the search for a three-parameter correlation. Indeed, Dainotti et al. (2015b) have demonstrated through the EP method that the $L_{\text{peak}} - L_{\text{peak}}$ correlation is intrinsic and not due to any selection bias. Thus, from the intrinsic nature of the $L_{\text{peak}} - L_{\text{peak}}$ and the $L_{a} - T_a$ correlations, it follows that the $(L_{\text{peak}}, T_a, L_{\text{peak}})$ correlation is also intrinsic.

Another extension of the $L_{\text{peak}} - L_{\text{peak}}$ correlation ($T_{\text{iso}}, L_a, E_{\text{peak}}$) is presented in Izzo et al. (2015), where $\sigma_{\text{int}} = 0.34$. This scatter is larger by 21% than the $\sigma_{\text{int}} = 0.27$ for the $(L_{\text{peak}}, T_a, L_{\text{peak}})$ plane. Note that $L_{\text{peak}}$ is a more suitable variable than $E_{\text{peak}}$, as $L_{\text{peak}}$ is subject only to low-luminosity truncation and leads to the intrinsic $L_{\text{peak}} - L_{\text{peak}}$ correlation (Dainotti et al. 2015b). On the other hand, $E_{\text{peak}}$ can introduce biases due to threshold limits at both low and high energies (see Lloyd & Petrosian...
and its intrinsic distribution, which would possibly allow a bias-free \((T_{\text{int}}, L_{\text{iso}}, L_{\text{peak}})\) correlation, has not yet been determined.

To conclude, by isolating 40 long GRBs (without associated SNe and excluding also XRFs) with well-defined plateaus, we obtain a 3D correlation that is significantly tighter (54%) than the 2D correlation for the 122 long GRBs. This correlation can be a useful tool for reducing the uncertainties in inferred cosmological parameters in the high redshift range accessible only to GRBs. Additionally, it can further constrain GRB physical models that connect prompt and afterglow plateau properties. It is also worth investigating if the \((L_{\text{iso}} - T_{\text{iso}} - E_{\text{iso}})\) and \((L_{\text{iso}} - T_{\text{iso}} - L_{\text{peak}})\) correlations might both be the reflection of the same underlying physics (Shao & Dai 2007 and Wang et al. 2016).

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