Probing Gamma-ray Burst as Possible Cosmological Standard Candles through Machine Learning Models

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Abstract

Gamma-ray bursts (GRBs) represent the most powerful explosions detected across electromagnetic wavebands, originating from the deaths of massive stars (Long-duration) or the merger of two neutron stars (Short-duration). Underlining their significance as cosmic probes similar to supernovae type Ia. Extensive efforts have been devoted to using GRBs as cosmological standard candles, leading to the discovery of several empirical relations. In this study, we leverage GRB data from the Fermi-GBM and Kouns-Wind catalogs to estimate pseudo-redshifts for a number of GRBs. This estimation is accomplished by applying Machine Learning techniques, specifically deep neural networks in stacking with the Random Forest algorithm, forming an ensemble model. Subsequently, we conduct a joint spectral analysis using data from Fermi (GBM and LAT) and Swift (BAT and XRT) to attain the most optimal fit, using the ThreeML software. Using the best-fit spectral parameters alongside the pseudo-redshift data, we investigate the Amati relation, a correlation between the intrinsic peak energy ($E_{i,\,peak}$) of the spectrum, and isotropic energy (E_{iso}) over the burst duration (T_{90}). Furthermore, we also revisit the Yonetuko relation, which correlates between Ei, peak, and the peak isotropic luminosity (L_{iso}). These analyses aim to deepen our understanding of GRB characteristics and their potential as cosmological standard candles.

Background

Motivation 1

From pseudo-redshift GRB samples using the best-fit ensemble models ("Compton flux" and "Band fluence and flux"), we explored the Amati and Yonetoku correlations. We included only these correlations in our study due to the availability of relevant data in the Fermi-GBM and Konus-Wind catalogues, which lack the necessary information for other relations like the Ghirlanda and spectral-lag luminosity relations.

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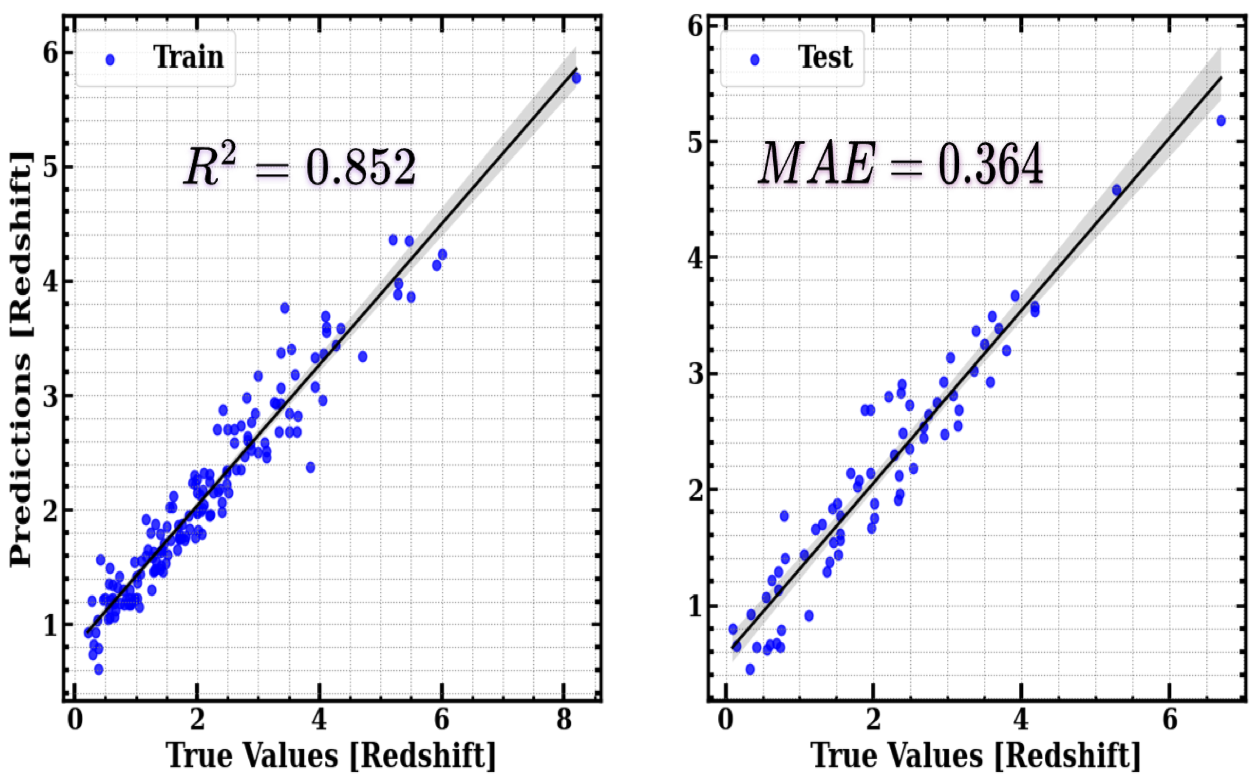
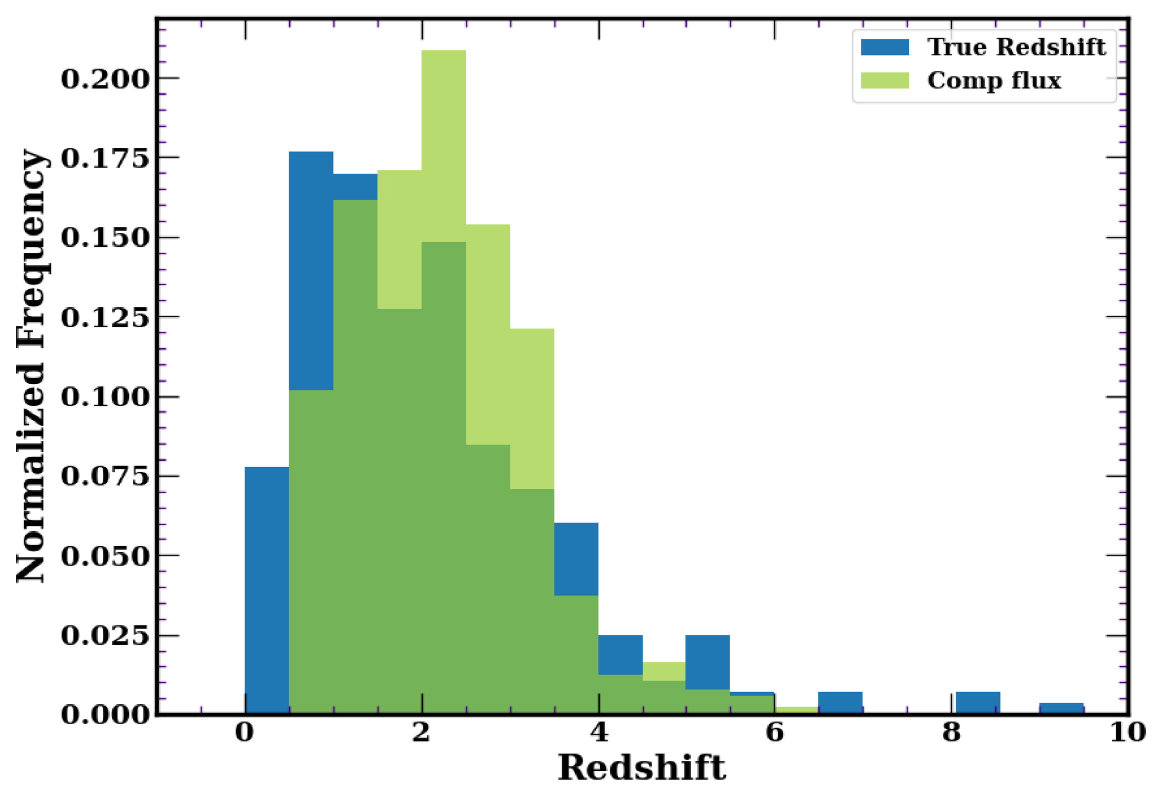
Motivation 2

From joint spectral analysis we aim to minimize errors in the spectral indices and energy peak (Ep), and then revisit both the Amati and Yonetoku relations to see if they enhance the fit from the joint spectral analysis.

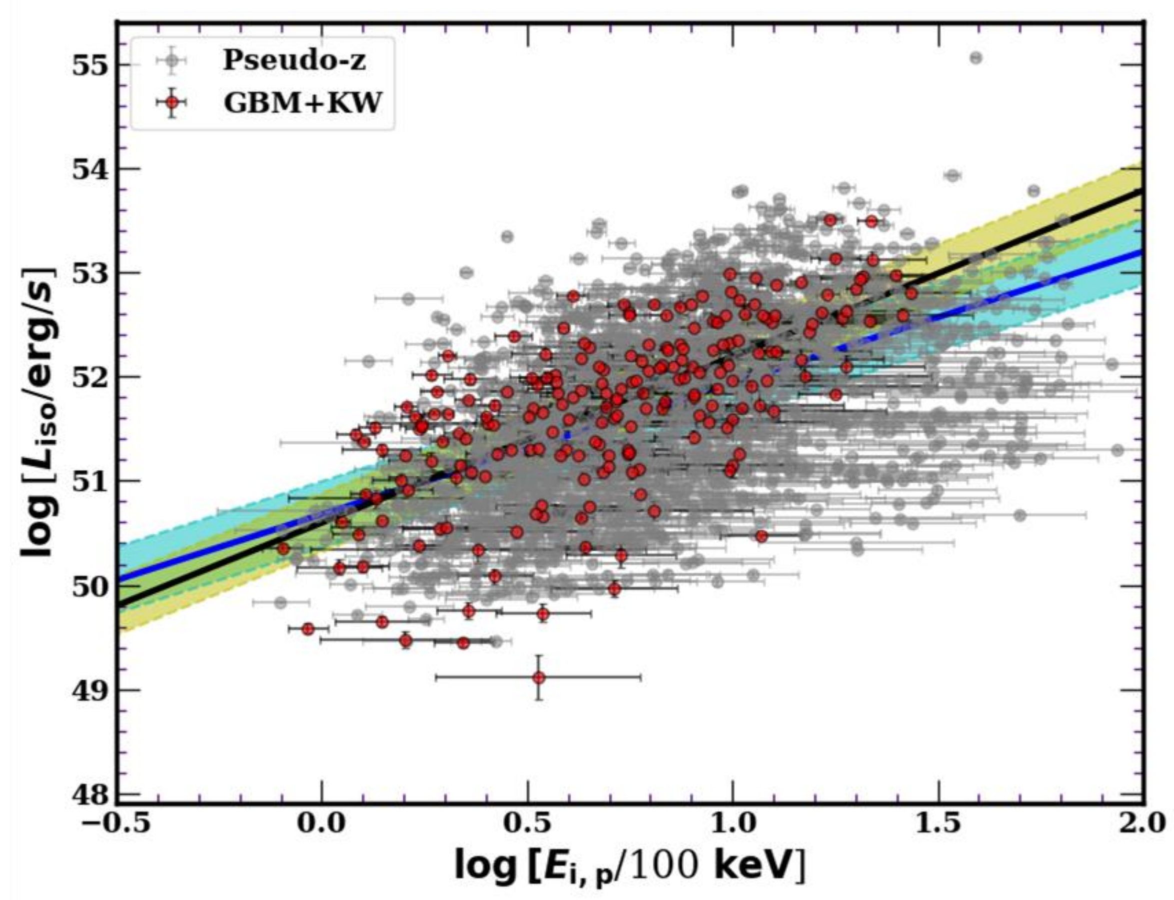
Machine Learning : Ensemble Model



★ Predicted redshift from the ensemble models (DNNs + Random Forest) vs. true redshift for train and test samples from the combined KW-GBM data with known redshift.



★ Normalized histograms comparing GRB samples with "True-Redshift" and pseudo-redshift obtained with different it ensemble models, with **p-value = 0.819**



★ The Yonetoku relation fits the GRB samples with true redshift (red-filled circles) and pseudo-redshift (gray-filled circles).

Joint Spectral Analysis

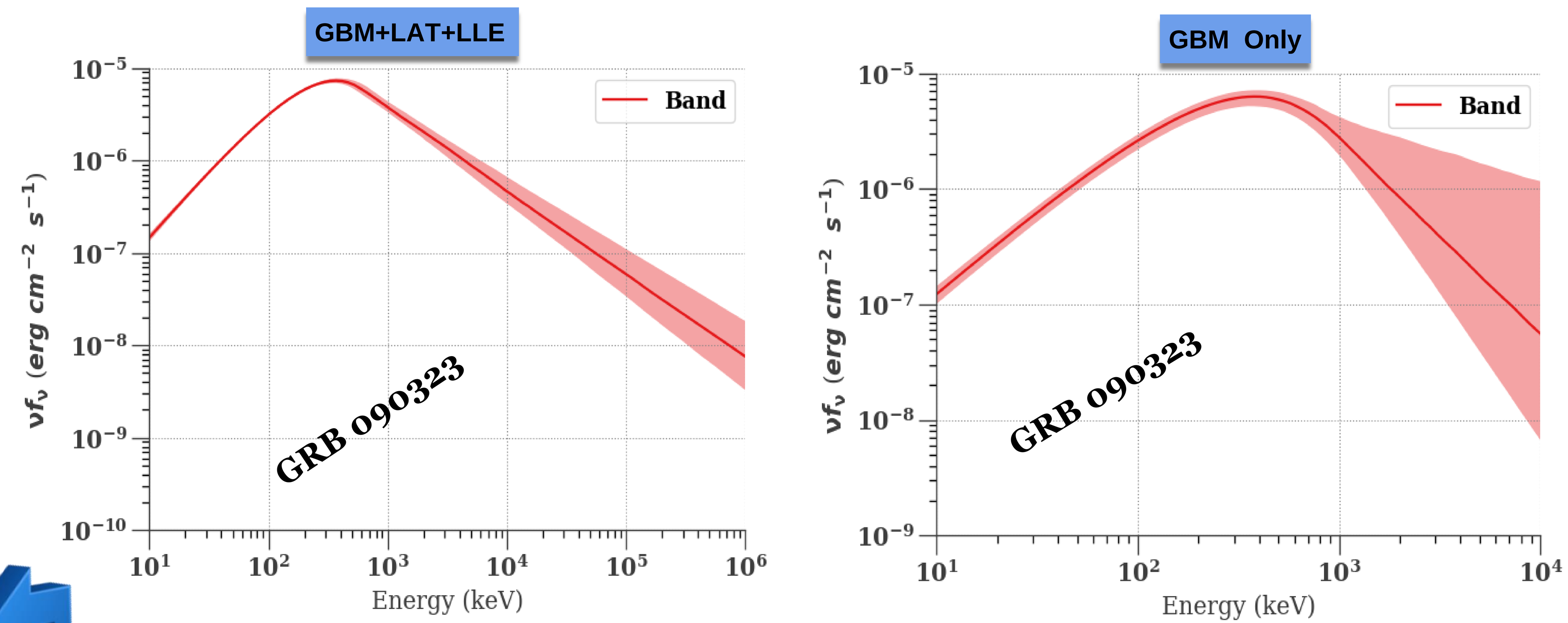
Using 3ML, we performed a joint spectral fit combining Fermi (**GBM-LAT-LLE**) data and GBM data alone for two distinct time intervals: time-integrated and peak. The analysis spans data collected from 2008 to 2022, focusing only on cases with LLE data for the joint fit. We then compared the results of the joint fit with those from the GBM-only fit.

$$E_{iso} = 10^k \left(\frac{E_{i,peak}}{E_0 keV}\right)^m$$

$$L_{iso} = 10^k \left(\frac{E_{i,p}}{E_0 keV}\right)^m$$

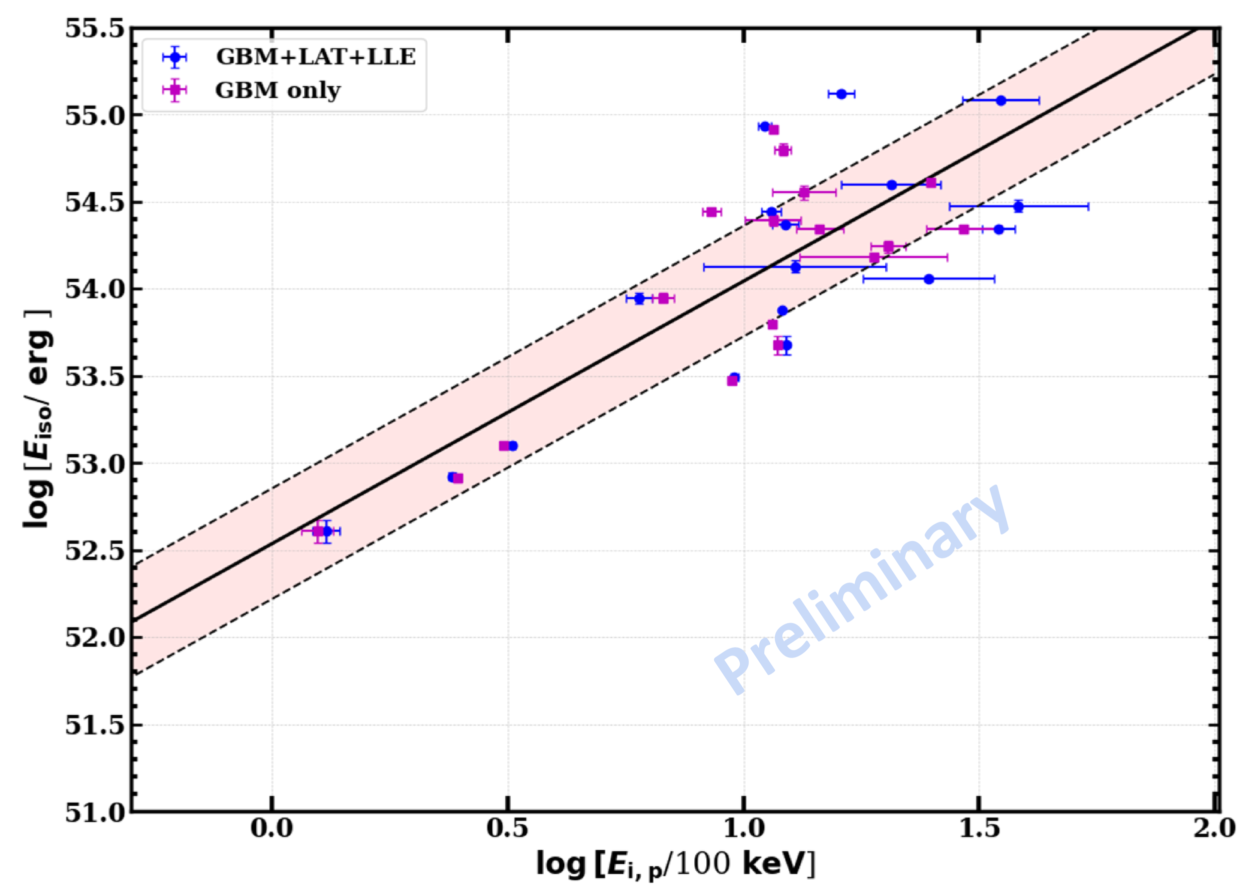
GRBs List

- GRB 080916C
- GRB 090323
- GRB 090328
- GRB 090424
- GRB 090902B
- GRB 090926A
- GRB 110721A
- GRB 130427A
- GRB 131108A
- GRB 131231A
- GRB 141028A
- GRB 150314A
- GRB 170214A
- GRB 170405A
- GRB 190114C
- GRB 220101A

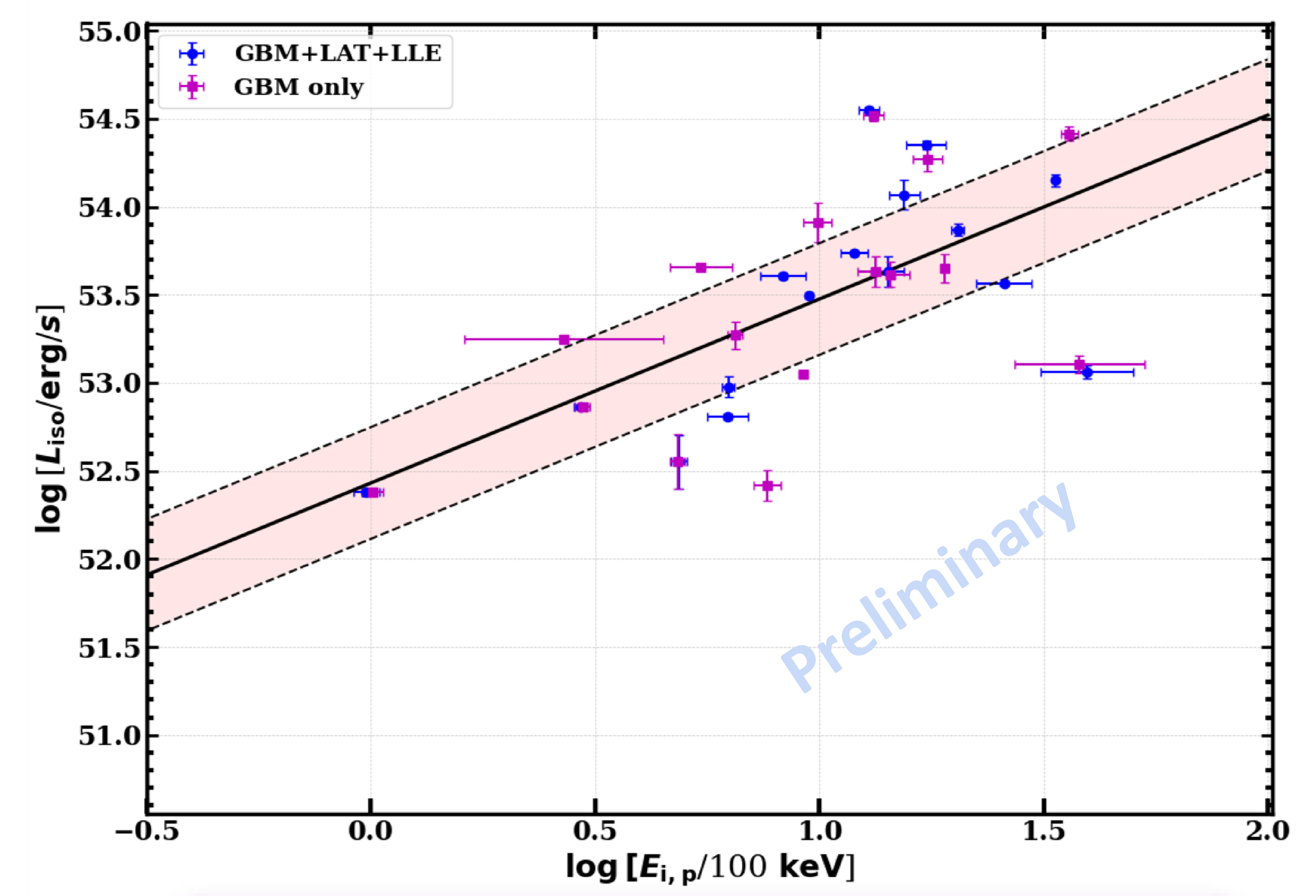


We focus on two-time intervals, specifically T_{90} (the duration of the burst) and peak flux, to evaluate how these factors may enhance fit quality and provide better constraints on critical parameters such as *Epeak* and spectral indices. The spectral analysis cover GRB data from 2008 to 2022, aiming to build upon previous research and achieve a deeper understanding.

- For example, Dirirsa, F.F., Razzaque, S., and Piron, F. 2018, 2019.



★ The Amati relation fits from Fermi GRB samples with redshift GBM only (blue-filled circle) and joint data (purple-filled circle).



★ The Yonetoku relation fits Fermi GRB samples with redshift GBM only (blue-filled circle) and joint data (purple-filled circle).

Summary

Our machine learning models show that the DNN models with Random forest can obtain a good estimation depend on the MAE and . Numerous efforts have been made to use GRBs as cosmological standard candles through various correlations. Spectral parameters from different fits and instruments have been analysed for many GRBs, particularly "Bright" GRBs. Most correlations rely on luminosity distance, which depends on redshift. With many pseudo-redshifts, we can constrain GRBs using the Yonetoku correlation as determined by the machine learning best-fit model. Joint spectral analysis allows us to revisit both the Amati and Yonetoku correlations.

References

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