Implications of Joint Spectral Analysis from Fermi (GBM, LAT, and LLE) on Phenomenological GRBs Correlations

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CAPP

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Fermi

Gamma-ray Space Telescope

Outline

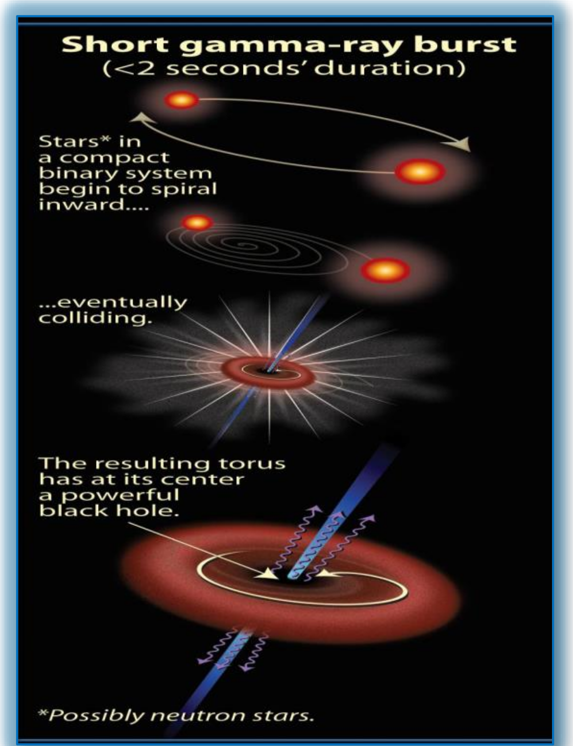
- Brief Introduction : GRBs
- Joint Spectral Analysis
- Fermi GRBs data
- Phenomenological Relations
- Preliminary results

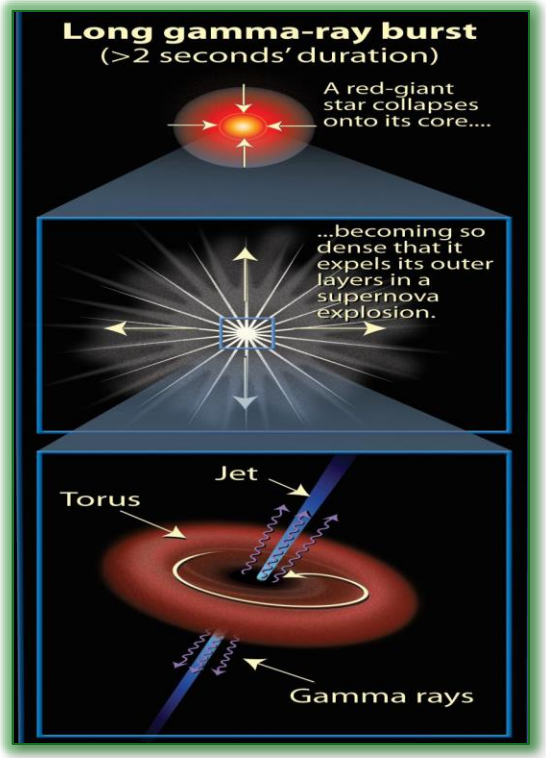
Brief Introduction

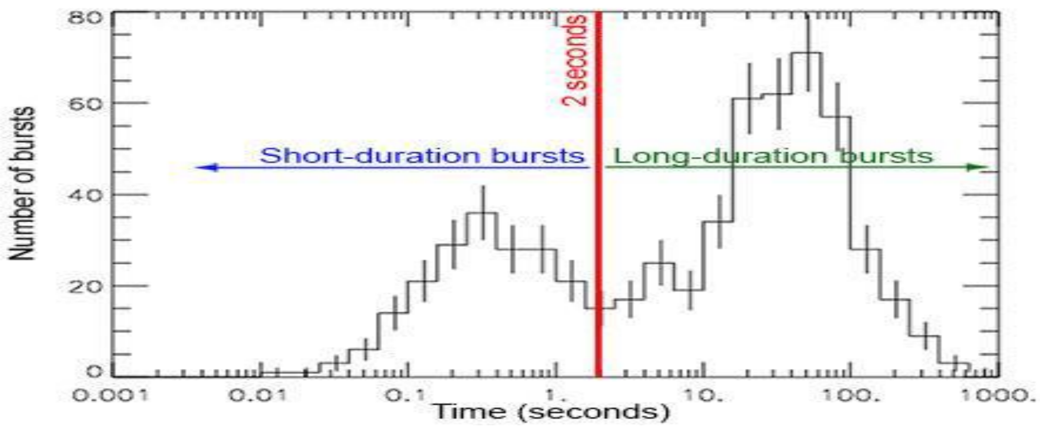
- ❑ A Gamma-Ray Burst (GRB) is the most energetic explosion yet discovered. Most of the energy is emitted in the keV to GeV range.

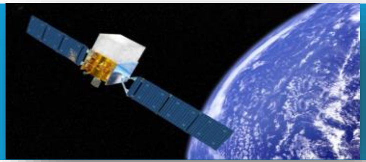
- ❑ GRBs have been detected at a high redshift up to **z = 9.2.**

- ❑ High-quality of GRBs data from different satellite instruments are now available (e.g., Fermi, Konus-Wind, INTEGRAL, SWIFT, and other) followed by ground-based optical telescope and gamma-ray telescopes such as H.E.S.S and MAGIC.









Fermi
GBM – LAT

Joint Spectral Analysis

Motivations

From joint spectral analysis we aim to minimize errors in the **spectral indices** and energy peak (**Ep**).

These parameters are then employed to explore **two phenomenological correlations.**

- **Amati relation**, relation between the intrinsic peak energy ($E_{i,peak}$) with the total isotropic energy (E_{iso}) over the burst's duration (T_{90}).
- **Yonetoku relation**, which relates ($E_{i,peak}$) to the peak isotropic luminosity (L_{iso}).

GRBs have the potential to be used as cosmological "standard candles," as proposed through several correlations, like Type Ia supernovae (SN Ia), which are widely used in cosmology for distance measurements.

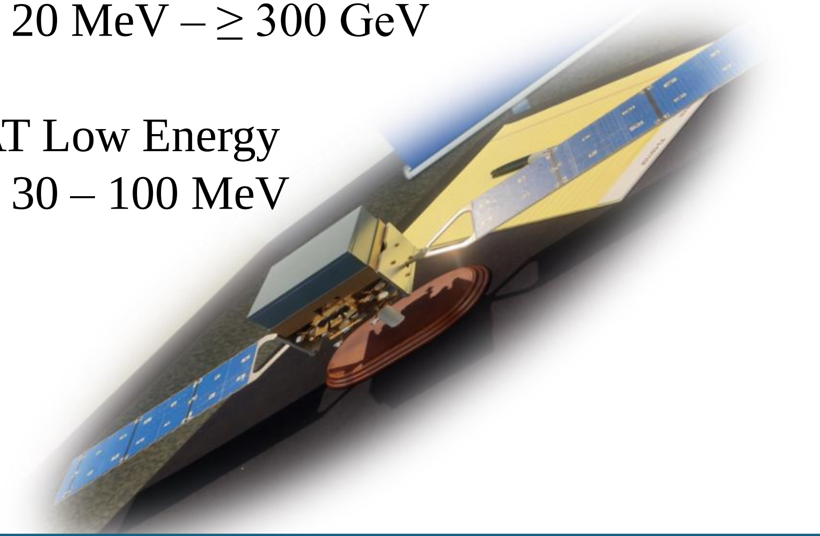
Joint Spectral Analysis - Data

Fermi Data: GBM-LAT-LLE

GBM: Gamma-ray Burst Monitor
8 KeV – 40 MeV
NaI detectors, the energy range from (K-edge 10 – 30 keV) to (40 – 900 keV), and for BGO detectors, it is 250 – 30000 keV.

LAT: Large Area Telescope
20 MeV – ≥ 300 GeV

LLE: LAT Low Energy
30 – 100 MeV



- **ThreeML***

The Multi-Mission Maximum Likelihood framework (3ML), allows multi-instruments likelihood analysis of astronomical data.

- **3ML** - Publicly available and supports for the Bayesian analysis approaches.
- Extending data from previous studies:

  - E.g., Dirirsa, F.F, Razzaque, S. , and Piron, F. 2018, 2019.

  - Use 26 GRBs Fermi(GBM-LAT) 2008 – 2017.

  + GRBs Fermi(GBM-LAT-LLE) 2018 – to 2023 in total **42 GRBs.**

- Download and selection of data: Two-time interval (T_{90}, peak)
- Fitting the background and conducting unbinned likelihood analysis for both LAT and LLE data, all done by 3ML.

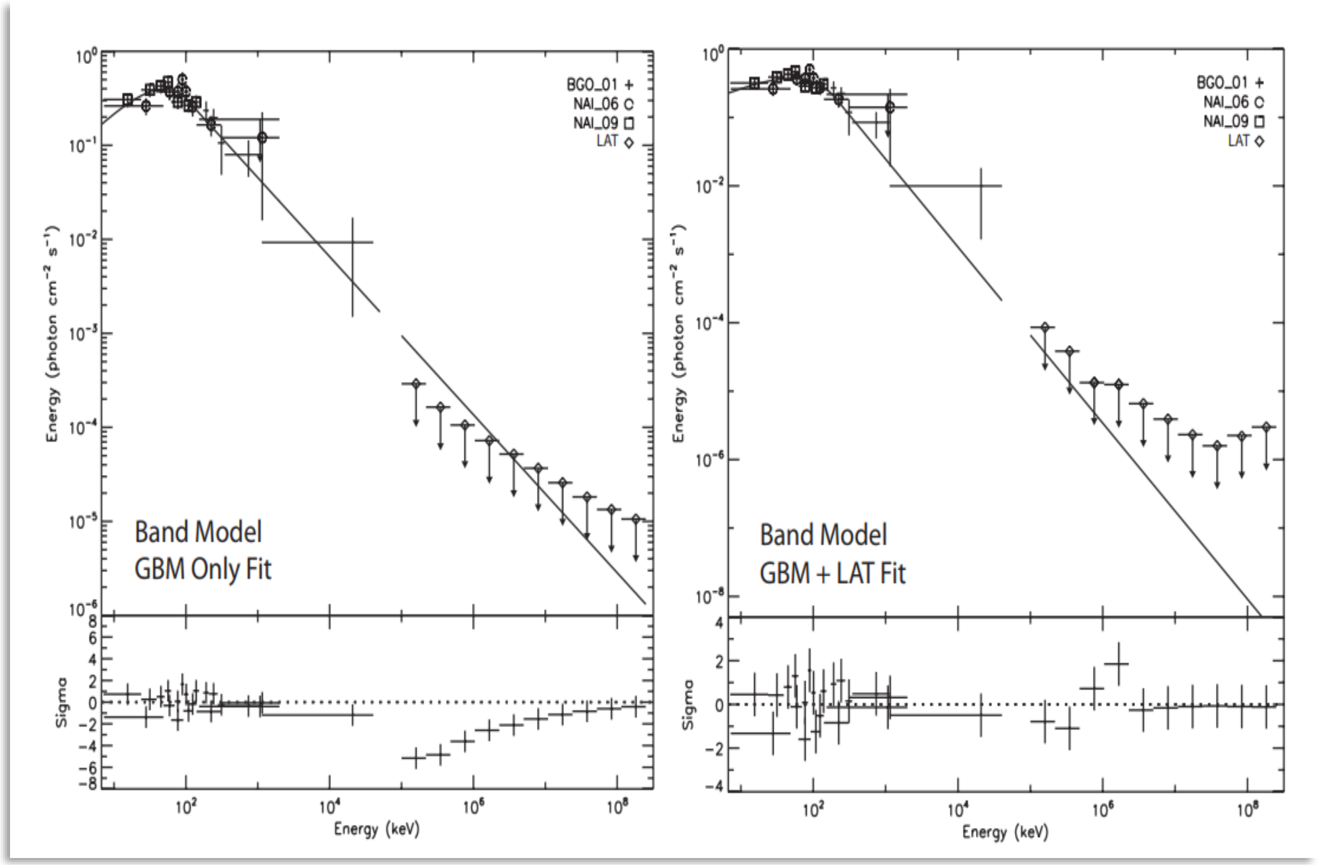
* https://threeml.readthedocs.io/en/stable/index.html

Joint Spectral Analysis – Spectral Models

- **Band Model:** *Band D et al ,. 1993*, with indices α, β, and spectral peak energy E_p in keV.

Fit Improvement

$$N_{Band}(E) = A_{Band} \begin{cases} \left(\frac{E}{100\ keV}\right)^{\alpha} exp\left[-\frac{E(2+\alpha)}{E_p}\right] & if\ E \le E_b \\ \left(\frac{E}{100\ keV}\right)^{\beta} exp(\beta-\alpha)\left[-\frac{E_p}{100\ keV}\ \frac{\alpha-\beta}{2+\alpha}\right]^{\alpha-\beta} & if\ E > E_b, \end{cases}$$



- **Comptonized Model:** *Steiner J. F. et al., 2009*
  With the photon index γ, and the peak energy E_p.

$$N_{Comp} = A_{Comp}\left(\frac{E}{100\ keV}\right)^{\gamma} \exp\left[-(2+\gamma)\frac{E}{E_p}\right]$$

Ackermann, Markus, et al,.2012.

Joint Spectral Analysis – Spectral Models

- **Internal Shoch Synchrotron Model (ISSM):**
  Yassine et al,. 2020, with indices α, β, and spectral peak energy E_p in keV. The four parameters of the ISSM—flux normalization, SED peak energy, and asymptotic slopes are like those of the Band function.

$$\frac{dN_{ISSM}}{dE}(E) = \frac{A_{ISSM}}{\left[1-\frac{E_p}{E_r}\left(\frac{2+\beta}{2+\alpha}\right)\right]^{\beta-\alpha}} \times \left(\frac{E}{E_r}\right)^{\alpha}\left[\frac{E}{E_r} - \frac{E_p}{E_r}\left(\frac{2+\beta}{2+\alpha}\right)\right]^{\beta-\alpha}$$

$$\frac{dN_{\mathtt{ISSM}}}{dE}(E_r) = A_{\mathtt{ISSM}}.$$

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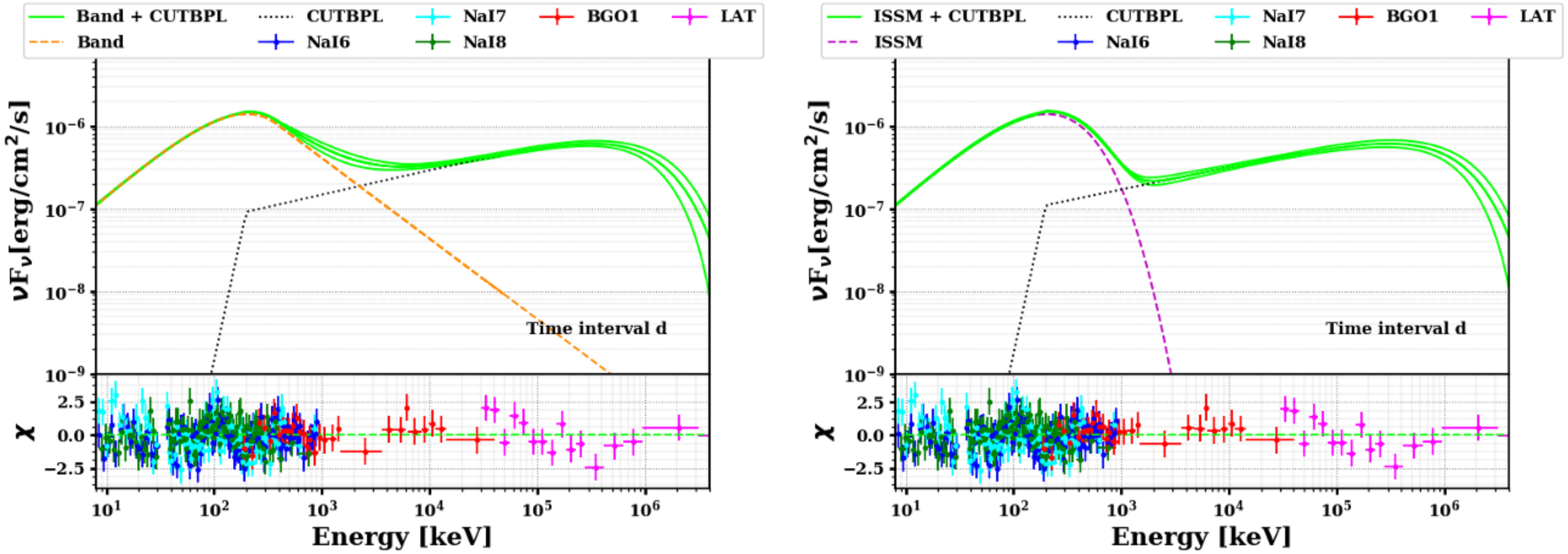


+ *Yassine 2020*

CUTBPL :
Broken Powerlaw with exponential cutoff

Joint Spectral Analysis – Spectral Models

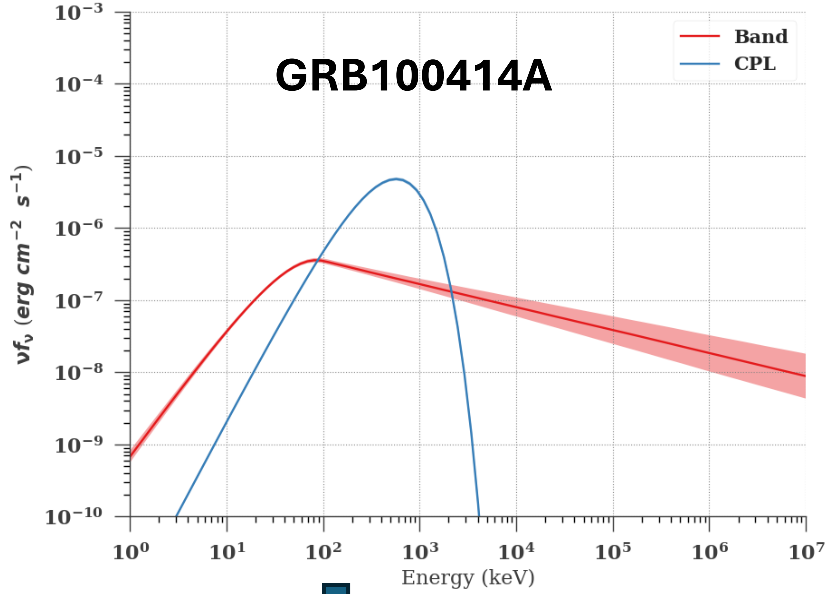
- **Best fit selection:**

Bayesian information criterion – **BIC** *Kass, Raftery et al, 1995.*

Model with the lower BIC value is preferred.

To assess improvements, we calculate **Δ BIC:**

Δ BIC ≥ 6 indicates a significant improvement in the model *Chand et al, 2018*.

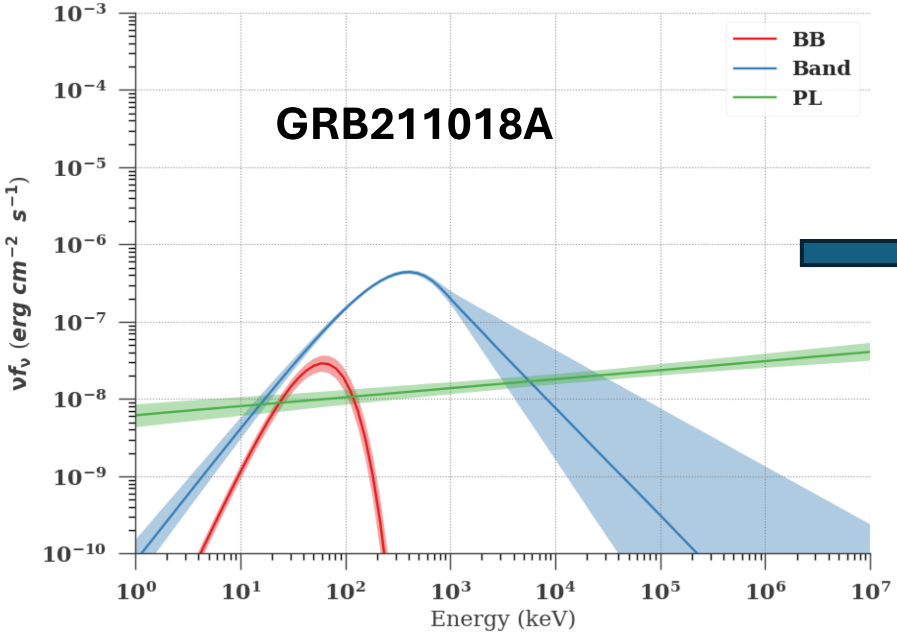


$$\Delta\, BIC = BIC_{Band+CPL} - BIC_{Band}$$

⋮

⋮

⋮



$$\Delta\, BIC = BIC_{Band+BB} - BIC_{Band+BB+PL}$$

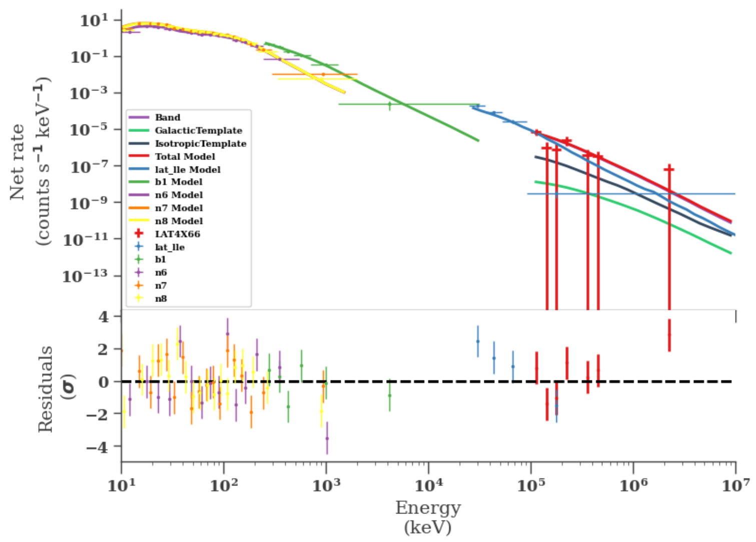
⋮

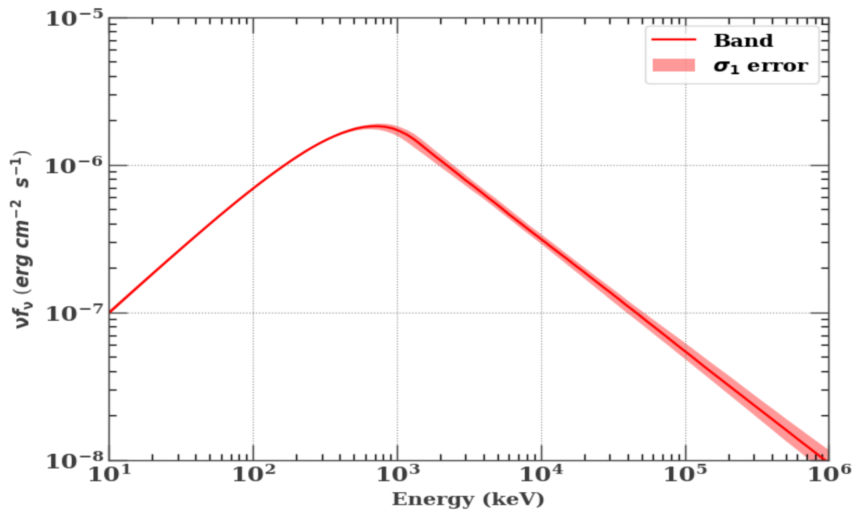
⋮

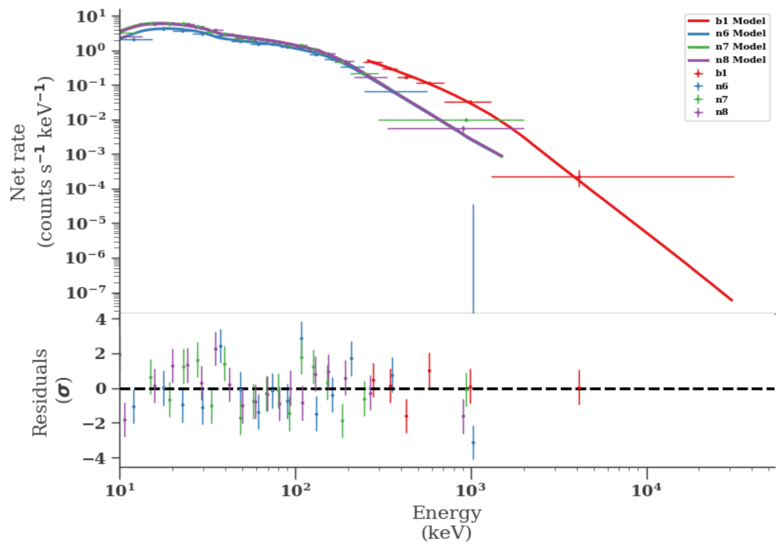
⋮

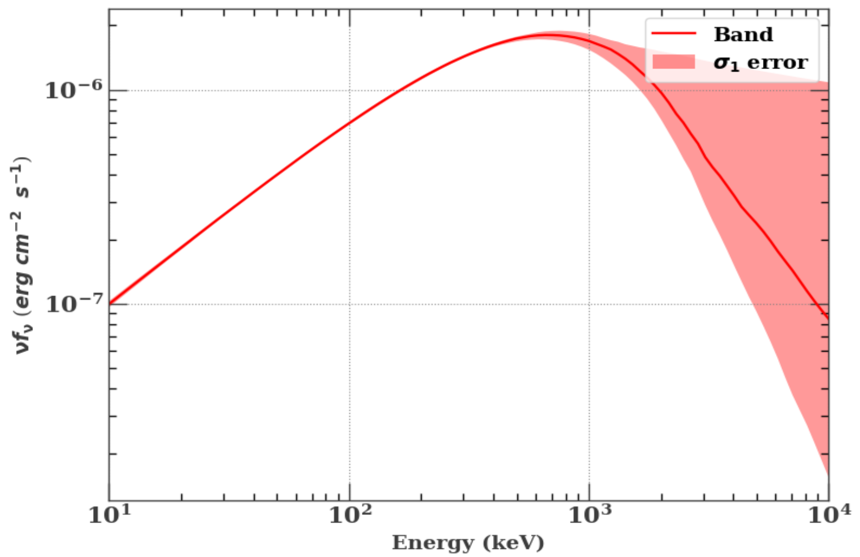
Preliminary results – Time integrated

GRBs Names	Instruments	Redshift	T_{90}	Model	α_1, γ	β	$E_p\ keV$	α_2	$kT\ keV$	Flux ($erg\ cm^{-2}\ s^{-1}$)	Total flux	$-\log(\mathcal{L})$	BIC	Δ BIC
GRB 090328	GBM+LAT+LLE	0.736	4.352 – 66.049	Band	-1.112±0.020	-2.77 ± 0.04	710_{70}^{-60}	-	-	$5.79_{0.23}^{-0.24} \times 10^{-6}$	$5.79_{0.23}^{-0.24} \times 10^{-6}$	4254	8572	-
GRB 090328	GBM			Band	-1.103±0.018	-4.0 ±2.3	680 ± 50	-	-	$5.1_{0.8}^{-0.5} \times 10^{-6}$	$5.1_{0.8}^{-0.5} \times 10^{-6}$	4060	8171	-



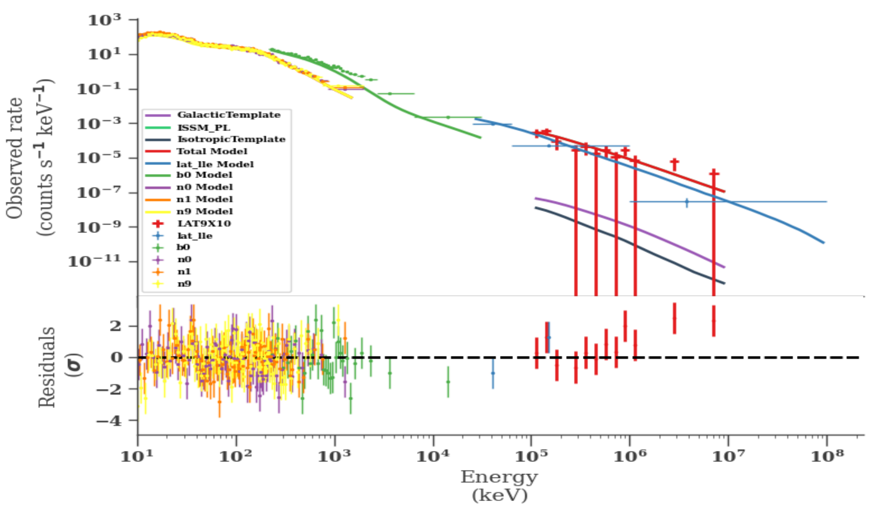


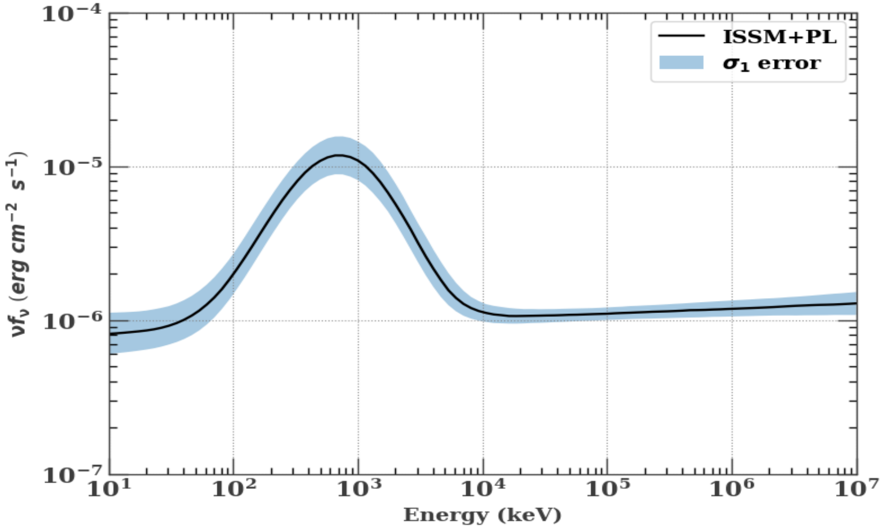


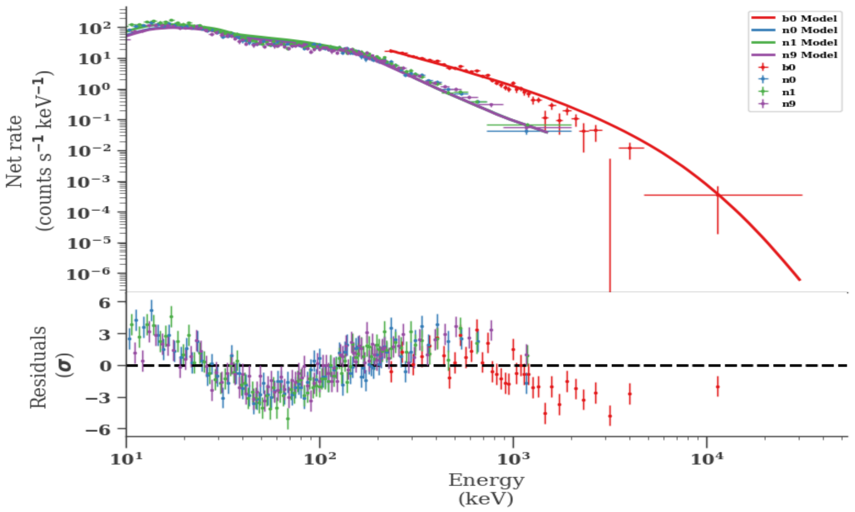


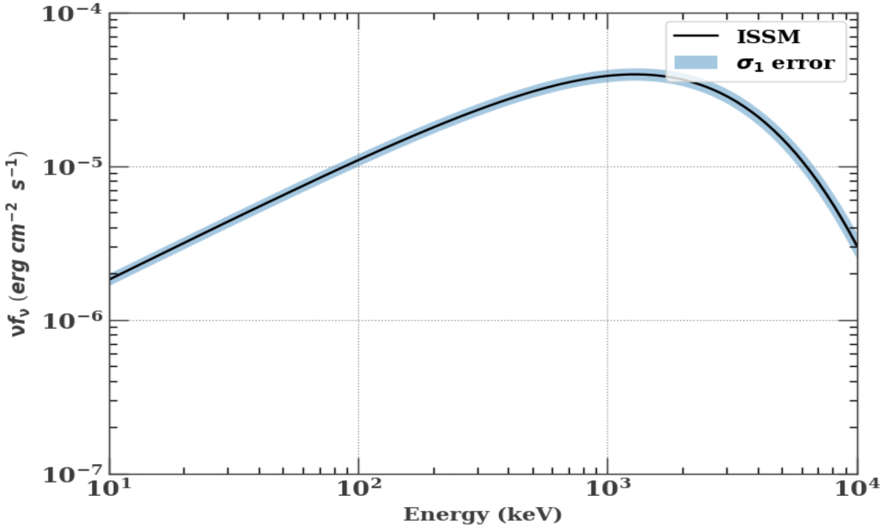
Preliminary results – Peak flux

GRBs Names	Instruments	Redshift	T_{90}	Model	α_1, γ	β	$E_p\,keV$	α_2	$kT\,keV$	Total flux	$-\log(\mathcal{L})$	BIC	ΔBIC
GRB 090902B	GBM+LAT+LLE	1.822	9.216-10.24	ISSM+PL	0.8 ± 0.5	-5.6 ± 0.8	690 ± 40	-1.93 ± 0.09	-	$3.0^{-0.8}1.1 \times 10^{-5}$	3431	1144	10
GRB 090902B	GBM	1.822	9.216-10.24	ISSM	-1.195 ± 0.010	-10.0 ± 0.0011	130 ± 6	-	-	$1.15^{-0.10}_{0.11} \times 10^{-4}$	4116	-	









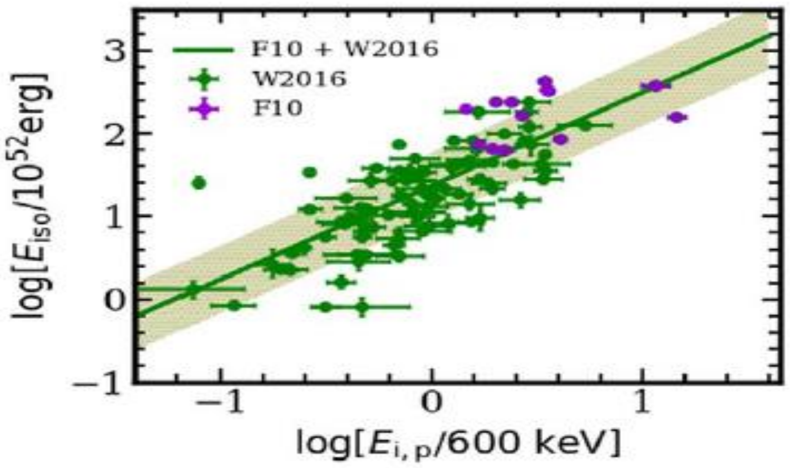
Phenomenological Relations

- **Amati (2002):**

$$\frac{E_{iso}}{10^{52}\,erg} = 10^{k}\left(\frac{E_{i,peak}}{E_{o}\,keV}\right)^{m} \qquad \rightarrow (\text{LGRBs - } \; T^{*}_{90} > \; 2\;s\,)$$

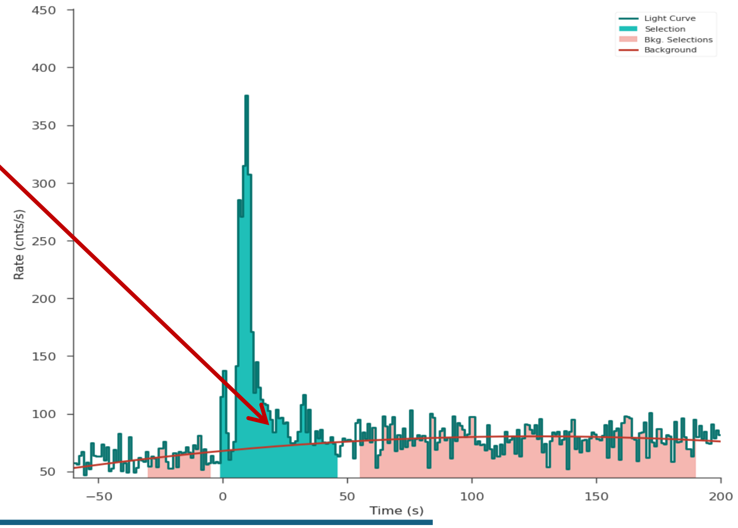
$$E_{iso} = \frac{4\pi d_L^2}{1+z}\, S_{bolo}$$

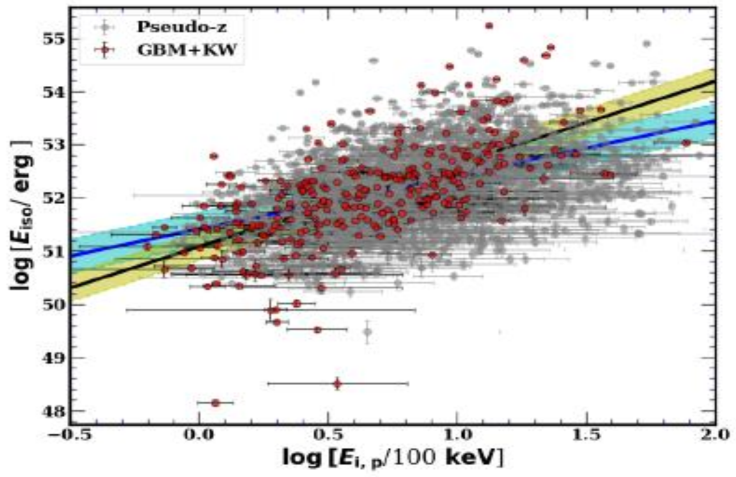
$$E_{i,peak} = E_p(1+z)$$



+ *Dirirsa, F.F 2018, 2019*

Light curve - GRB 130427A
Fermi - LLE





+ *Aldowma, T, 2024*

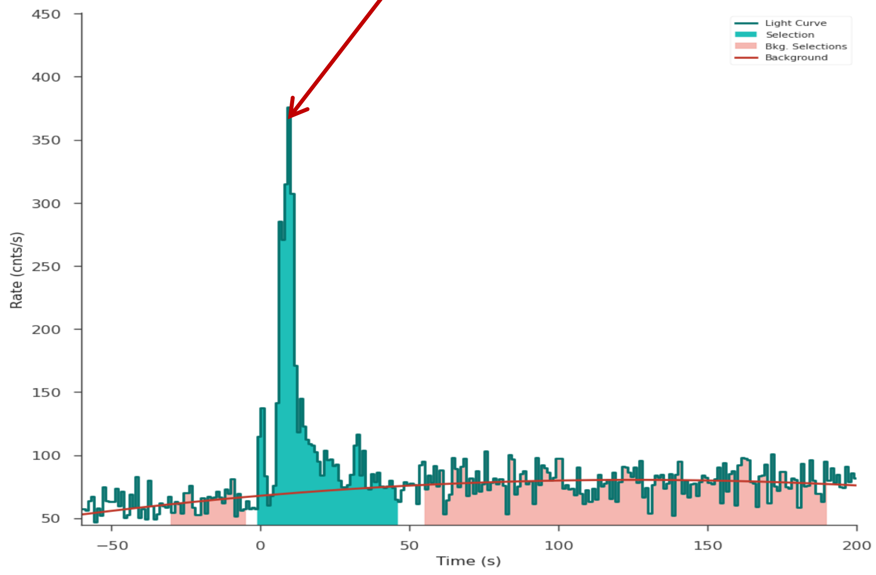
∗ T_{90} : the time to detect 90% of GRBs fluence.

Phenomenological Relations

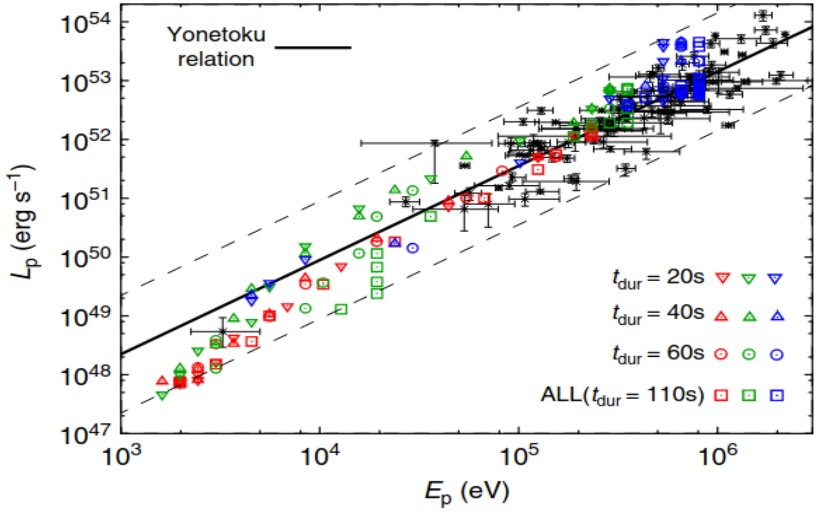
- **Yonetoku (2007):**

$$\frac{L_{iso}}{10^{51}} = 10^{k} \left(\frac{E_{i,peak}}{E_o\ keV}\right)^{m} \quad \rightarrow \text{(SGRBs - LGRBs)}$$

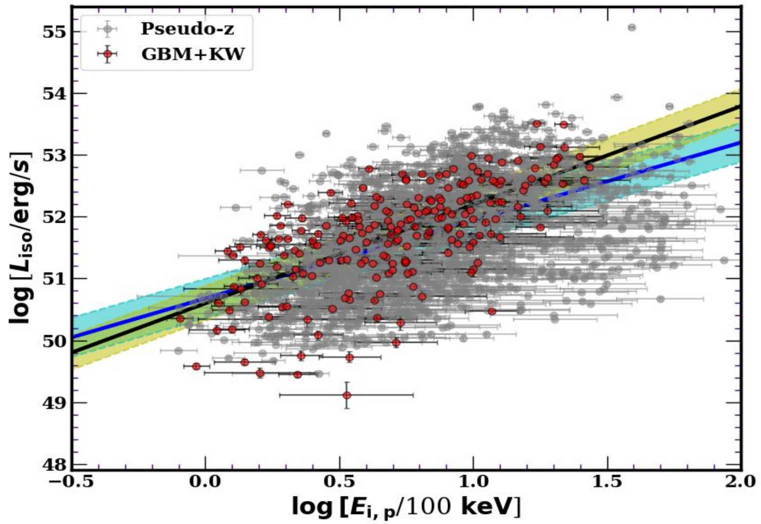
$$L_{iso} = 4\pi d_L^2\, P_{bolo}$$



Light curve - GRB 130427A
Fermi - LLE

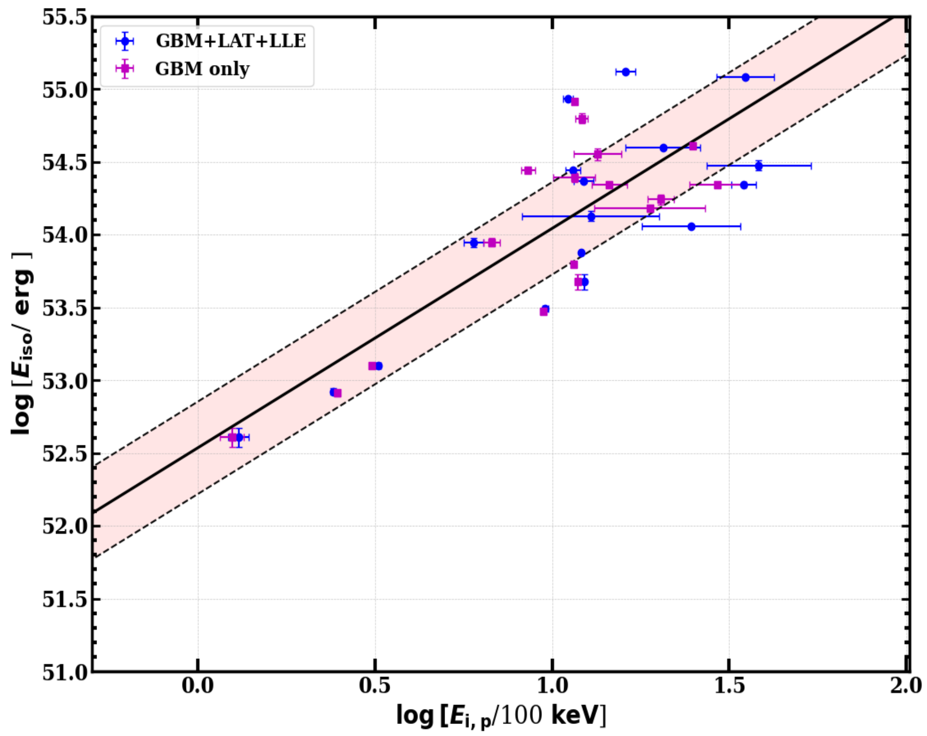


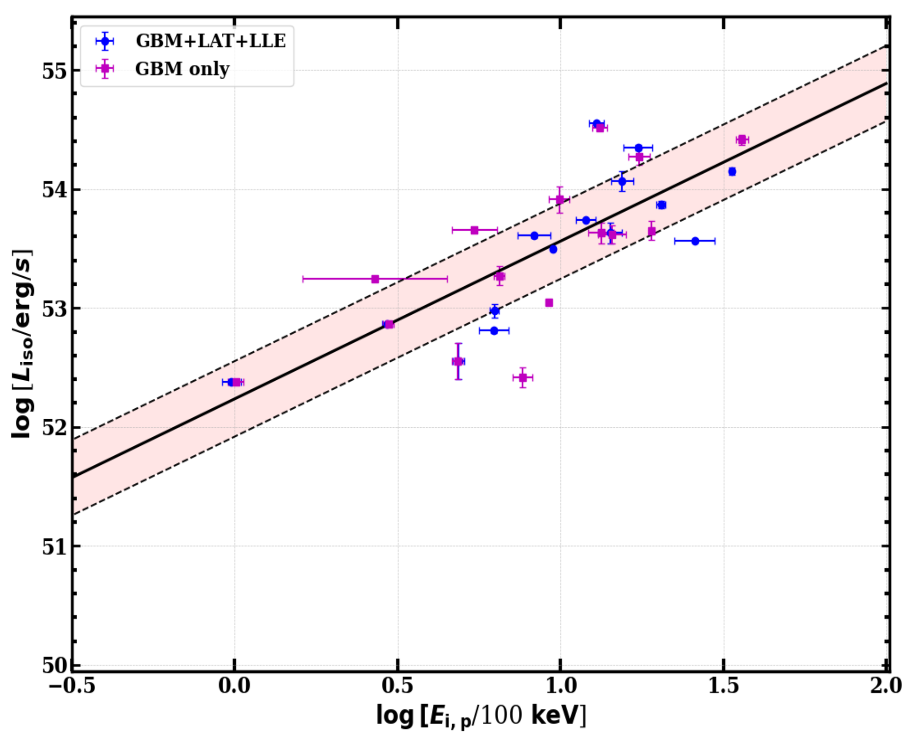
+ Ito, Hirotaka 2019



+ Aldowma, T. 2024

Preliminary results:





Linear fits for both the Amati and Yonetoku correlations for the joint fit (GBM-LAT-LLE) as well as for the GBM-only fit.

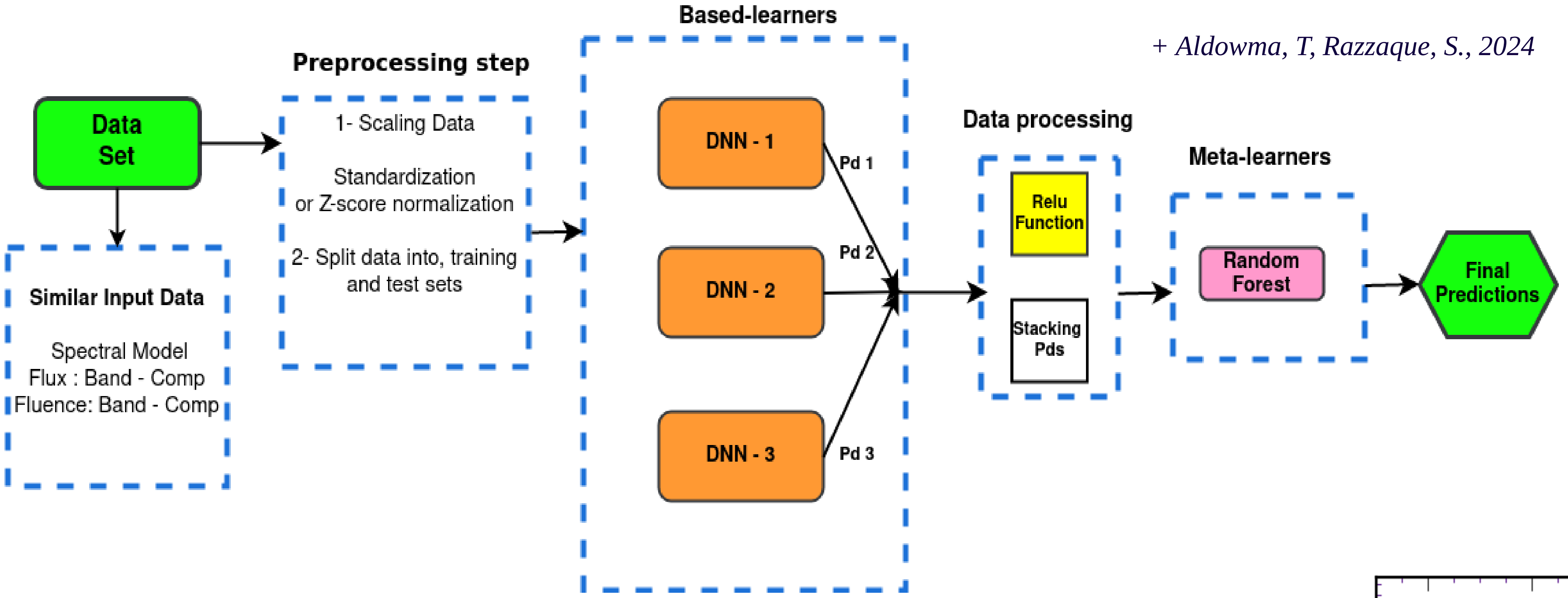
Summary

- ❖ We performed joint spectral fits on Fermi GRB data (GBM-LAT-LLE) and compared them with GBM-only fits to assess improvements in the analysis.
- ❖ From Δ BIC we identified the best-fit models.
- ❖ Using these optimal parameters, we explored the Amati and Yonetoku correlations to determine their potential in cosmological model.
- ❖ Our aim is to investigate which of these correlations can be reliably used to prob GRBs as cosmological standard candles.

Thank you

Backup - Machine Learning : Ensemble Model

+ *Aldowma, T, Razzaque, S., 2024*



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