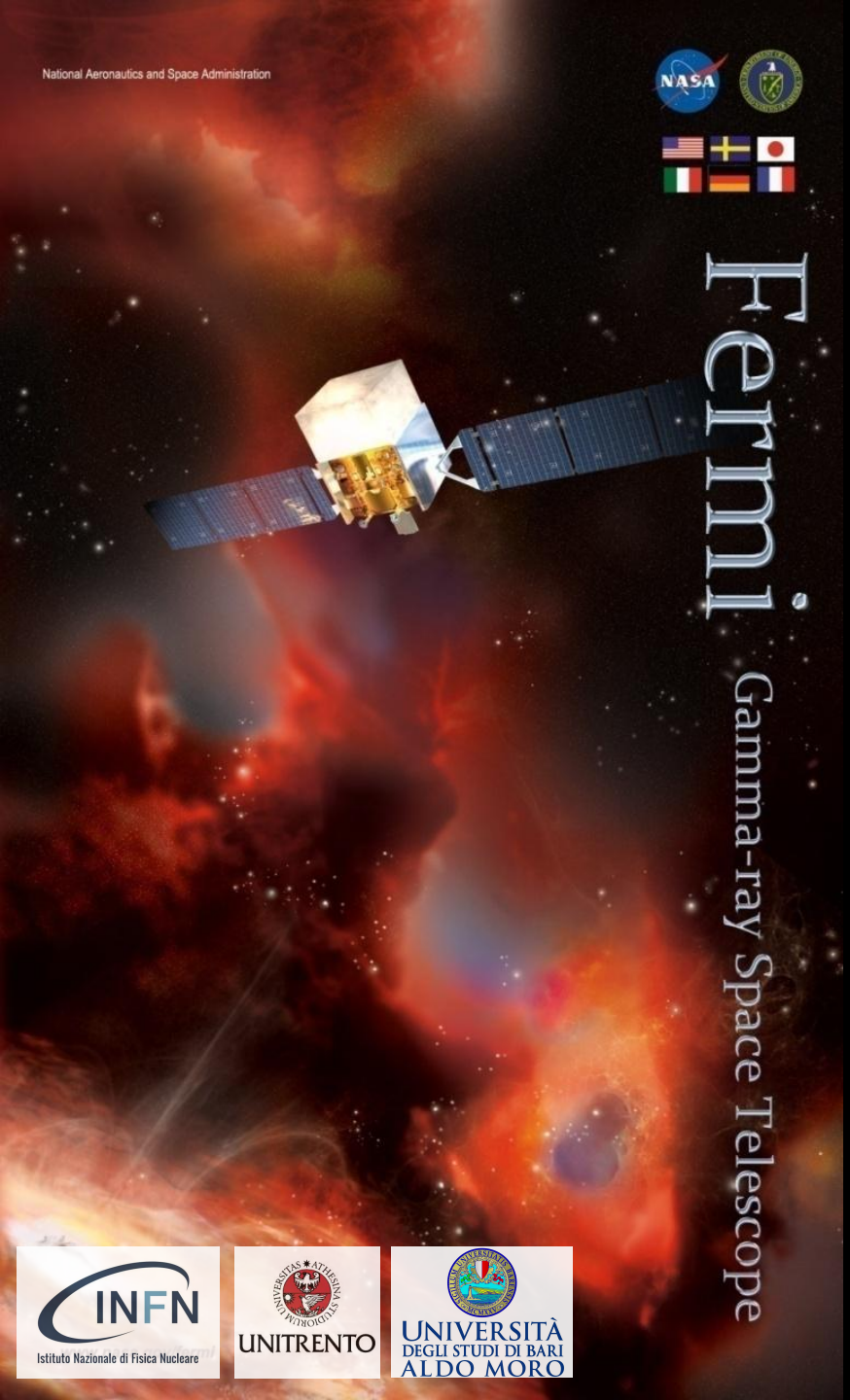


A time-resolved, systematic approach to GRB physics

Aldana Holzmann Airasca[1, 2];
Elisabetta Bissaldi [2, 3]; Leonardo Di Venere [2, 4];
Francesco Longo [5,6]
on behalf of the *Fermi-LAT* and *Fermi-GBM*

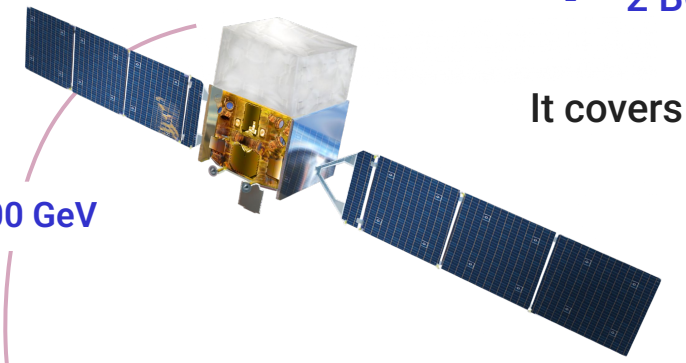
[1] University of Trento, [2] INFN Bari, [3] Politecnico di Bari,
[4] University of Bari, [5] University of Trieste, [6] INFN Trieste

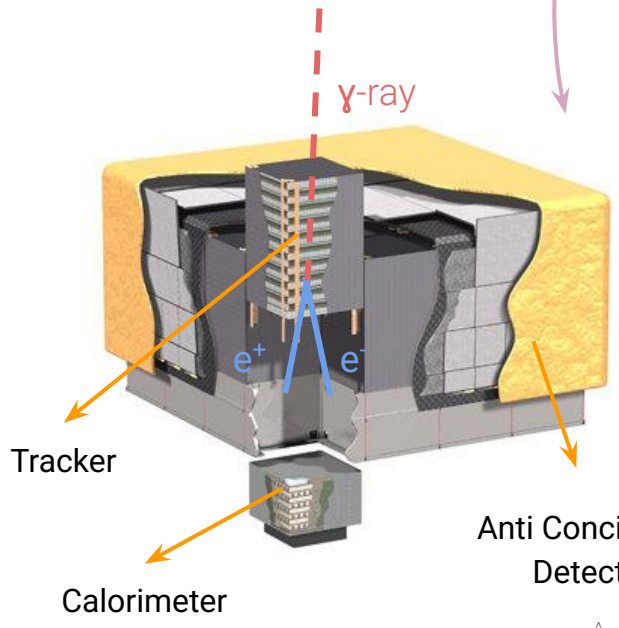
The Fermi mission: LAT and GBM

The Fermi-LAT is a pair conversion telescope covering an energy range between

~ 20 MeV - > 300 GeV

- LLE range: **30 MeV - 1 GeV**
- LAT standard range: **100 MeV - > 300 GeV**



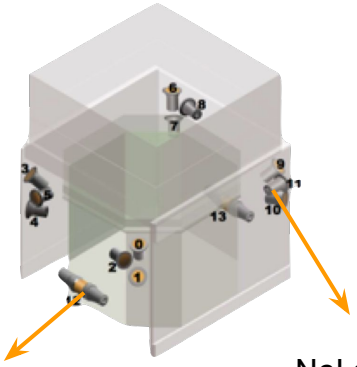


The Fermi-GBM is composed of:

- **12 NaI scintillator detectors and**
- **2 BGO calorimeters.**

It covers an energy range between

8 keV - 30 MeV



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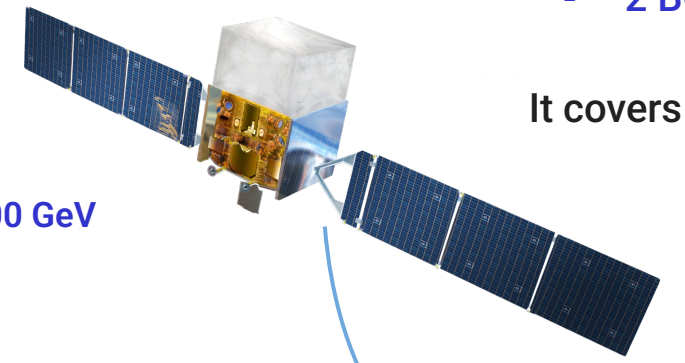

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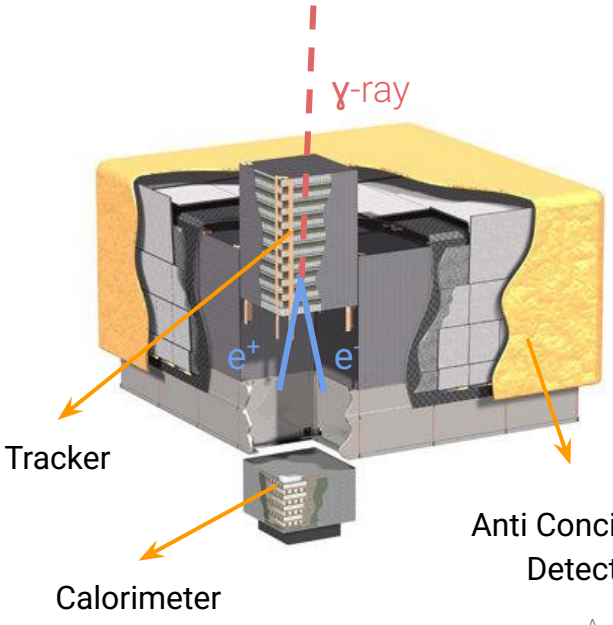
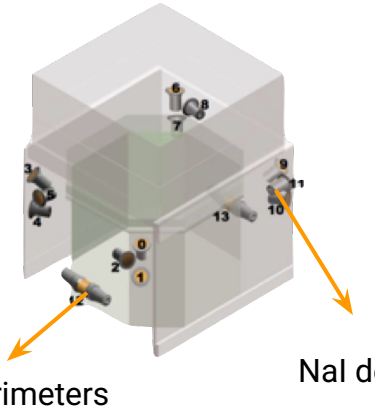


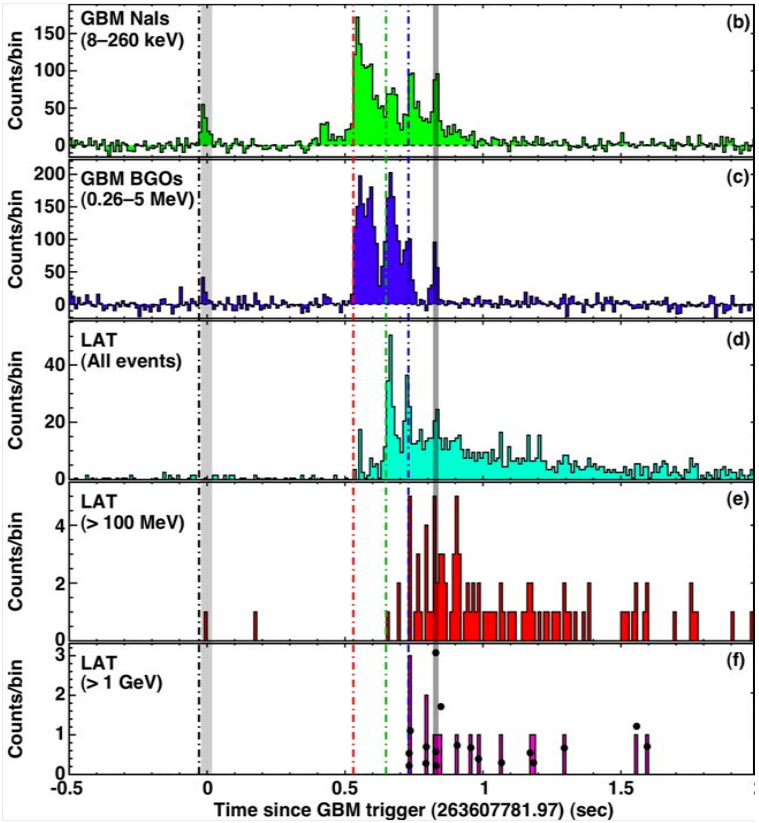


Gamma-ray Bursts (GRBs)

GRBs are the most energetic and luminous explosions observed in the universe, with its main emission in the gamma-rays band.

These bursts have two main phases:

- The prompt emission, a short flash of high-energy photons lasting from milliseconds to minutes.
- The afterglow, a longer-lasting multiwavelength emission.



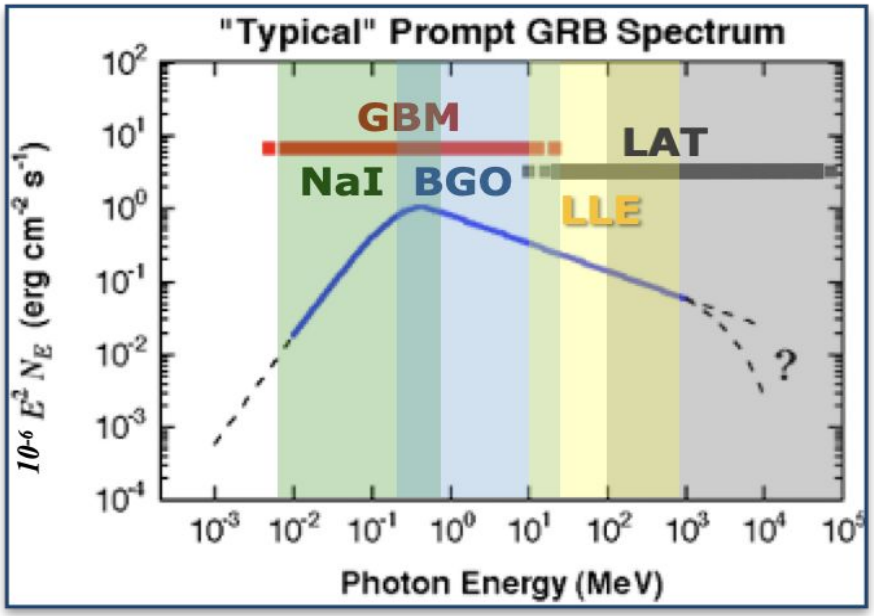
Light curve of GRB 090510 (Ackermann et al. 2010)

Spectral characteristics of GRBs

GRB continuum spectrum is non-thermal, with most of the luminosity emitted in the energy range ~100 keV to ~1 MeV

The spectrum is “typically” well fitted with phenomenological *Band* (1993) function:

$$K \times \begin{cases} \left(\frac{E}{E_{\rm piv}}\right)^{\alpha} \exp\left[-\frac{E(2+\alpha)}{E_{\rm peak}}\right] & \text{if } E \leq E_{\rm break} \\ \left(\frac{E}{E_{\rm piv}}\right)^{\beta} \exp(\beta-\alpha)\left[\frac{E_{\rm peak}(\alpha+\beta)}{E_{\rm piv}(2+\alpha)}\right]^{\alpha-\beta} & \text{otherwise} \end{cases}$$



(Fermi LAT collaboration 2008)

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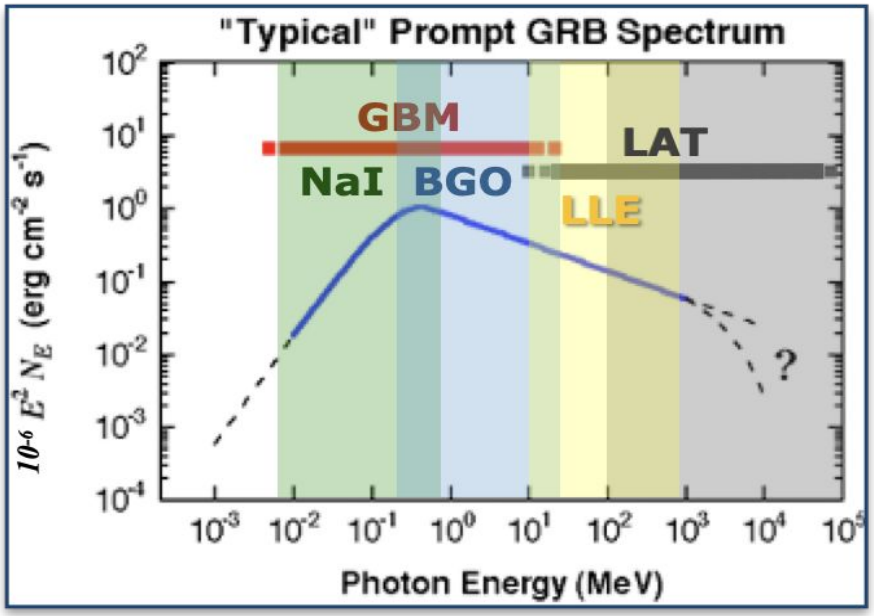
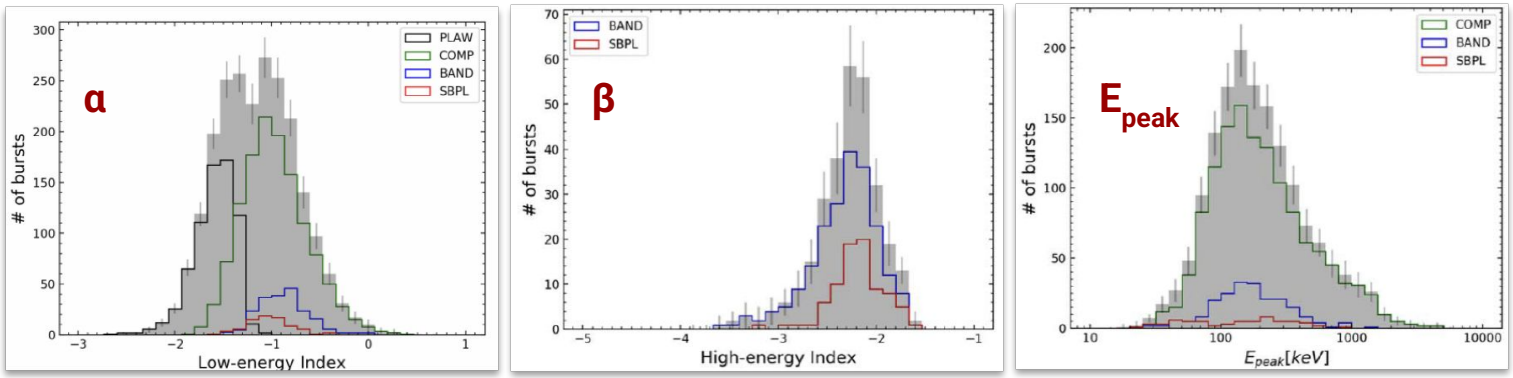


(Fermi LAT collaboration 2008)



Distribution of spectral parameters (Poolakkil et al. 2021)

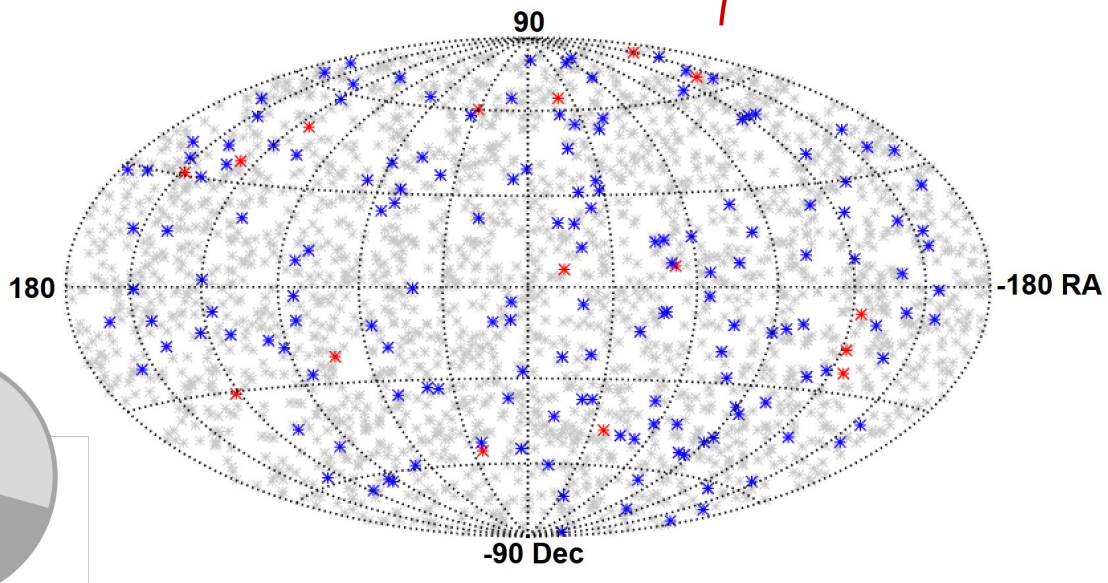
Fermi GRBs, some numbers

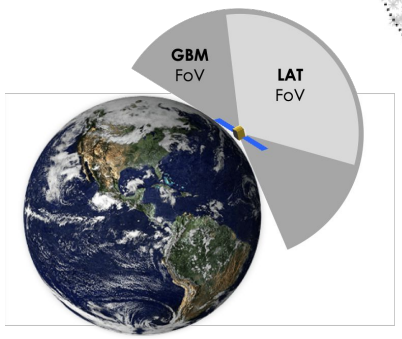
Yearly GBM observes ~ 250 GRBs while LAT ~15 bursts

To date:

- **GBM-triggered GRBs are 4000**
- **LAT-detected only 267 events**

~ 23% of them are short and
~ 77% are long





Sky distribution of GBM-triggered and LAT-triggered GRBs, from 07-2008 to 07-2018 (Ajello et al. 2019)

Past population studies

Population studies can help to identify common properties, since there are no two identical GRBs!

Past systematic studies:

- **1 joint LAT-GBM time-integrated spectral catalog** (Ackerman et al. 2013)
- **1 LAT only GRB catalog** (Ajello et al. 2019)
- **5 GBM only catalogs were published:**
  - **4 GBM GRB spectral catalogs, last one in 2018** (Poolakkil et al. 2021)
  - **1 GBM GRB time-resolved catalog** (Xu et al. 2016)

~ 40 papers dedicated to individual GRBs

Joint systematic time-integrated and time-resolved analysis of the 16 years of mission is yet to be done

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Joint systematic time-integrated and time-resolved analysis of the 16 years of mission is ~~yet to be done~~ work in progress

Sample selection and analysis

The sample selection was performed considering the first 16 years of data (from August 2008 to September 2024). The total sample has 257 bursts.

A refined list of events is used for the systematic analysis:

- The selection was considering that the arrival of the first LAT photon should fall inside the main emission measured by GBM (T_{90}).

167 bursts meet the criteria

Analysis tools and details

The analysis was performed entirely using the 3ML package (Vianello et al. 2015), with a pipeline built based on the tutorials available online.

Common high-level interface which allows maximum likelihood and Bayesian analysis using data from multiple missions in an unified way.

3ML

Multi-Mission Maximum Likelihood Framework

Workflow of the systematic analysis

For each event we chose the time intervals for the analysis as:

- T_{90} $^{+50\%}_{-20\%}$ **for long GRBs**
- $T_{90} \pm 1$ s **for short GRBs**

The bins are created with the Bayesian Block method using the brightest NaI detector

Only bins with a S/N ratio > 5σ are considered

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The bins are created with the Bayesian Block method using the brightest NaI detector

Only bins with a S/N ratio > 5σ are considered

8 spectral models are tested on each bin

All models with relative errors < 50% are consider GOOD models

The BEST model is chosen based on the BIC criteria (Chand et al, 2018.) **wrt the Comptonized model:**

$$\Delta\mathrm{BIC} = \mathrm{BIC}_{\mathrm{Comp.}} - \mathrm{BIC}_{\mathrm{Model\ X}} < 6$$

Band model

$$K \times \begin{cases} \left(\frac{E}{E_{\mathrm{piv}}}\right)^{\alpha} \exp\left[-\frac{E(2+\alpha)}{E_{\mathrm{peak}}}\right] & \text{if } E \leq E_{\mathrm{break}} \\ \left(\frac{E}{E_{\mathrm{piv}}}\right)^{\beta} \exp(\beta-\alpha)\left[\frac{E_{\mathrm{peak}}(\alpha+\beta)}{E_{\mathrm{piv}}(2+\alpha)}\right]^{\alpha-\beta} & \text{otherwise} \end{cases}$$

SBPL model

$$K\left(\frac{E}{E_{\mathrm{break}}}\right)^{\alpha}\left[1+\frac{E}{E_{\mathrm{break}}}^{\frac{1}{\Delta}}\right]^{(\beta-\alpha)\Delta}$$

ISSM model

$$K\left[1-\frac{E_{\mathrm{peak}}}{E_{\mathrm{ref}}}\left(\frac{2+\beta}{2+\alpha}\right)\right]^{\alpha-\beta}\left(\frac{E}{E_{\mathrm{ref}}}\right)^{\alpha}\left[\frac{E}{E_{\mathrm{ref}}}-\frac{E_{\mathrm{peak}}}{E_{\mathrm{ref}}}\frac{(2+\beta)}{(2+\alpha)}\right]^{\beta-\alpha}$$

Comptonized model

$$K\left(\frac{E}{E_{\mathrm{ref}}}\right)^{\alpha}\exp-\frac{(\alpha+2)E}{E_{\mathrm{peak}}}$$

Power-law model

$$K\frac{E}{E_{\mathrm{piv}}}^{\alpha}$$

+

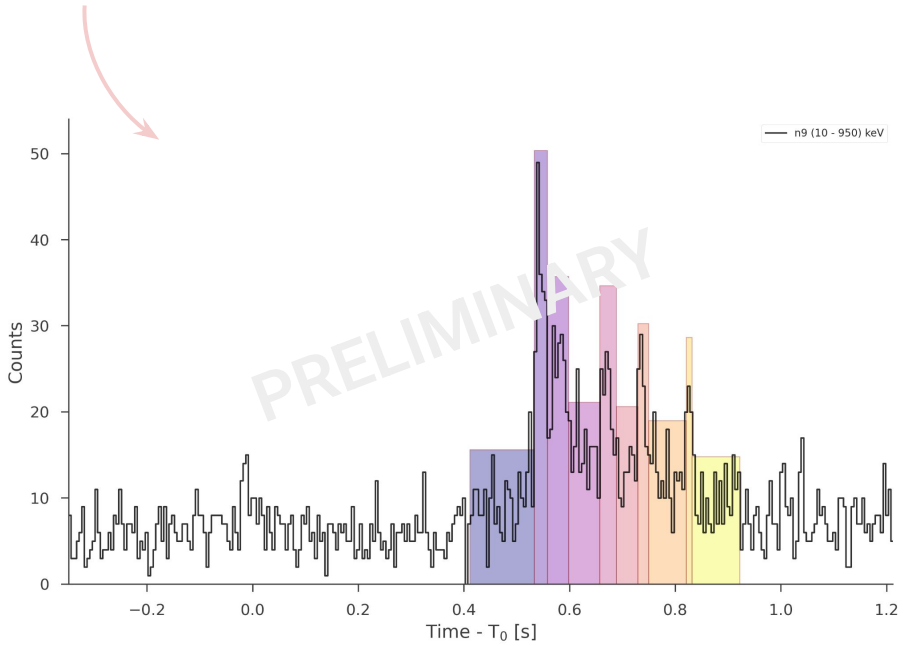
Black body

$$K\frac{E^2}{\exp(\frac{E}{\mathrm{kT}})-1}$$

Example of the analysis: GRB 090510

Total time interval used: T_0 - 1.05 s - T_0 + 1.91 s

Divided into 10 bins



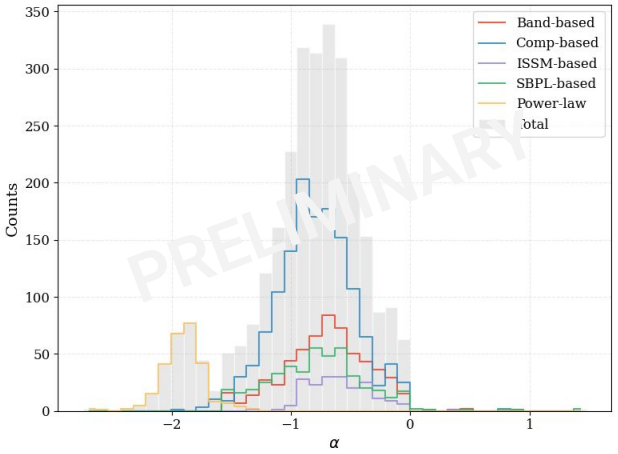
Light-curve of detector NaI 9 of GRB 090510. Obtained bins are shown in colors.

Time interval	Best func.
0.41 - 0.53 s	Compt.
0.53 - 0.56 s	Compt.
0.56 - 0.60 s	Compt.
0.60 - 0.66 s	Compt.
0.66 - 0.69 s	Band
0.69 - 0.73 s	Band
0.73 - 0.75 s	Band
0.75 - 0.82 s	Band+BB
0.82 - 0.83 s	SBPL
0.83 - 0.92 s	Pwl

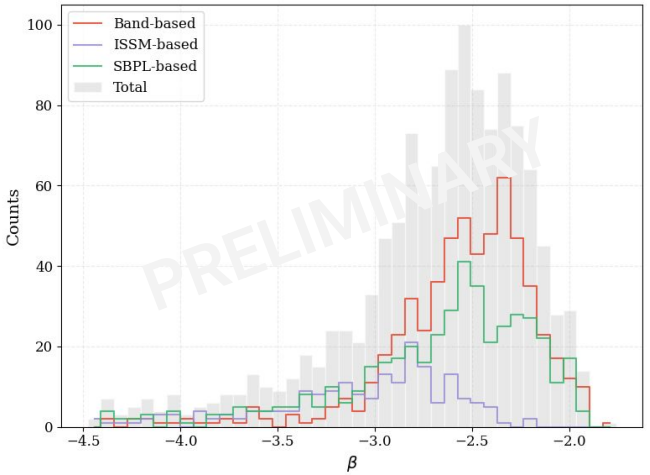
Preliminary distributions BEST sample

The total amount of analysed bins is 2971

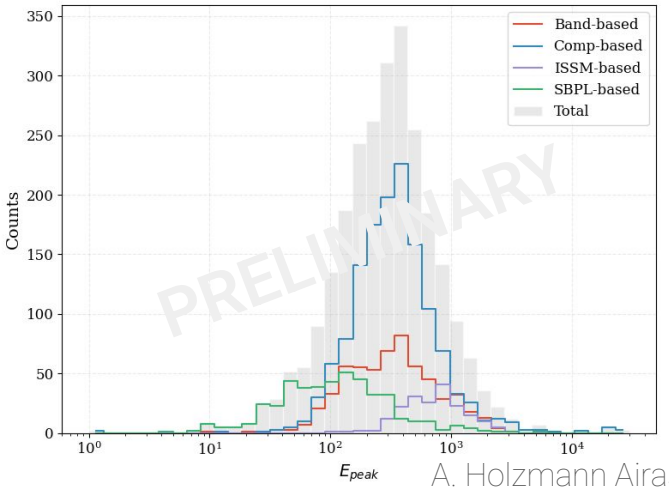
Distribution of the **α** index



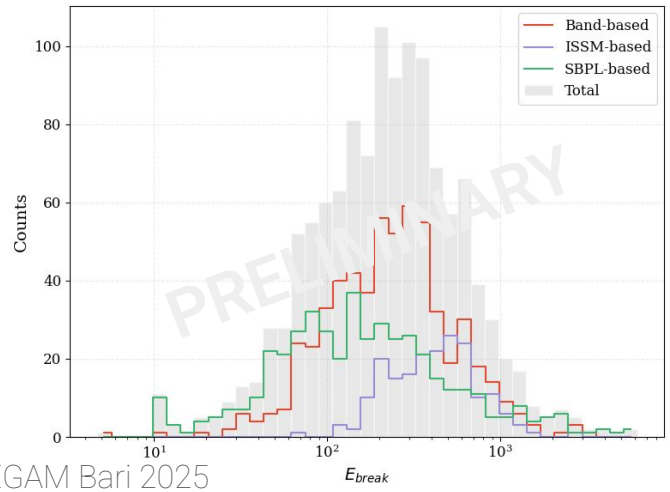
Distribution of the **β** index



Distribution of the $\mathbf{E_{peak}}$



Distribution of the $\mathbf{E_{break}}$



Some preliminary general results

PRELIMINARY

Data set	Low-energy index	High-enegy index	E_{peak} [keV]	E_{break} [keV]
Systematic analysis GOOD	$-0.86^{+0.38}_{-0.81}$	$-2.77^{+0.37}_{-0.59}$	290^{+400}_{-190}	240^{+300}_{-150}
Systematic analysis BEST	$-0.79^{+0.35}_{-0.47}$	$-2.58^{+0.33}_{-0.52}$	300^{+410}_{-190}	280^{+350}_{-150}

	Data Set	Low-energy Index	High-energy Index	$E_{\rm peak}$ (keV)	$E_{\rm break}$ (keV)
				Fluence Spectra	
GBM 10 years cat.	Poolakkil et al. 2021	$-1.08^{+0.45}_{-0.44}$	$-2.20^{+0.26}_{-0.29}$	180^{+307}_{-88}	107^{+88}_{-49}
GBM 4 years cat.	Gruber et al. (2014)	$-1.08^{+0.43}_{-0.44}$	$-2.14^{+0.27}_{-0.37}$	196^{+336}_{-100}	103^{+129}_{-63}
GBM 2 years cat.	Goldstein et al. (2012)	$-1.05^{+0.44}_{-0.45}$	$-2.25^{+0.34}_{-0.73}$	205^{+359}_{-121}	123^{+240}_{-80}
BATSE cat.	Kaneko et al. (2006)	$-1.14^{+0.20}_{-0.22}$	$-2.33^{+0.24}_{-0.26}$	251^{+122}_{-68}	204^{+76}_{-56}

Results of the distribution of spectral parameters (Poolakkil et al. 2021)

Conclusions and future perspectives

- **We have two systematic pipelines one for time-resolved and one for time-integrated.**
- **Time-resolved on 167 events, preliminary results and distribution of parameters appear to be reasonable**

To-do list:

- **Identify and study bursts that show an extra spectral components.**
- **Analyse how the results of the GBM only time-resolved analysis changes when adding LAT data** (work in progress in collaboration with D. Depalo and E. Bissaldi).
- **In depth study of the spectral evolution of the parameters, with particular interest in seeing if the firsts bins of the long GRBs are similar to the short events.**

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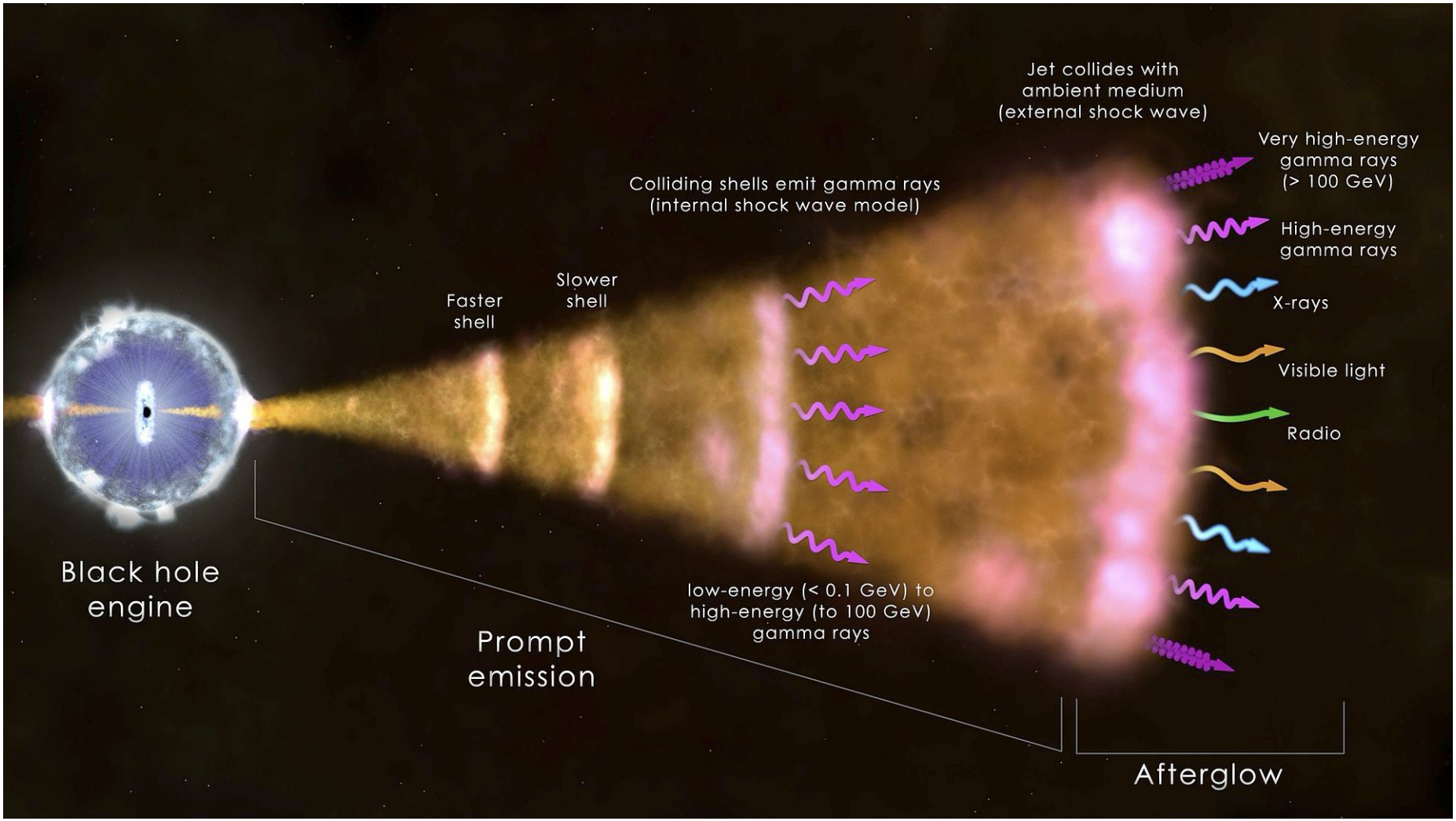
Thank you!

Backup slides

Fireball model



Sample selection more details

The sample selection was performed considering the **first 16 years of data** (from August 2008 to September 2024).

The total sample size is **257 bursts**:

- 14 don't have a GBM file and/or where not *seen* by BGO detectors
- ~ 78 have more than 5 σ significance in LLE

A refined list of events is used for the systematic analysis:

- The selection was considering that the arrival of the first LAT photon should fall inside the T_{90} as measured by GBM.
- The surviving events were sorted into decreasing order of the TS value in the GBM time-window (T_{90}).

167 bursts meet the criteria

Analysis details

- The analysis was performed entirely using the **3ML package**, with a pipeline built based on the tutorials available online.
- **GBM** and **LLE** data (*TTE, CSPEC and .rsp files*) is downloaded from the online database, using basic information regarding the T_{90} and background from the online catalog.
- **LAT** data is downloaded from the HEARSAC archive and the *CSPEC, .rsp, eventfile* and *ft2file* are created using the *FermiTools*.
- After performing the interval selection for the analysis, *DispersionSpectrumLike* (for GBM and LLE) and *FermiLATLike* (for LAT) plugins are created.
  - For GBM the energy selection goes from 10-30 keV - 35-1000 keV for NaI detectors and 0.25-10 MeV for BGO,
  - For LLE goes from 30-100 MeV,
  - And for LAT > 100 MeV
- The spectral fit is performed using different models

Models used for spectral fitting

Band model

$$K \times \begin{cases} \left(\frac{E}{E_{\rm piv}}\right)^{\alpha} \exp\left[-\frac{E(2+\alpha)}{E_{\rm peak}}\right] & \text{if } E \leq E_{\rm break} \\ \left(\frac{E}{E_{\rm piv}}\right)^{\beta} \exp(\beta-\alpha)\left[\frac{E_{\rm peak}(\alpha+\beta)}{E_{\rm piv}(2+\alpha)}\right]^{\alpha-\beta} & \text{otherwise} \end{cases}$$

SBPL model

$$K\left(\frac{E}{E_{\rm break}}\right)^{\alpha}\left[1+\frac{E}{E_{\rm break}}^{\frac{1}{\Delta}}\right]^{(\beta-\alpha)\Delta}$$

ISSM model

$$K\left[1-\frac{E_{\rm peak}}{E_{\rm ref}}\left(\frac{2+\beta}{2+\alpha}\right)\right]^{\alpha-\beta}\left(\frac{E}{E_{\rm ref}}\right)^{\alpha}\left[\frac{E}{E_{\rm ref}}-\frac{E_{\rm peak}}{E_{\rm ref}}\frac{(2+\beta)}{(2+\alpha)}\right]^{\beta-\alpha}$$

Comptonized model

$$K\left(\frac{E}{E_{\rm ref}}\right)^{\alpha}\exp-\frac{(\alpha+2)E}{E_{\rm peak}}$$

Power-law model

$$K\frac{E}{E_{\rm piv}}^{\alpha}$$

Exp. cut

$$K\exp\frac{-E}{E_{\rm cut}}$$

Black body

$$K\frac{E^2}{\exp(\frac{E}{\rm kT})-1}$$

- Band
- Band + BB
- SBPL
- SBPL + BB
- ISSM
- Pwl
- Comp
- Band + Pwl
- Band * Exp.
- ISSM * Exp.
- Comp. + Comp.
- Comp. + Pwl

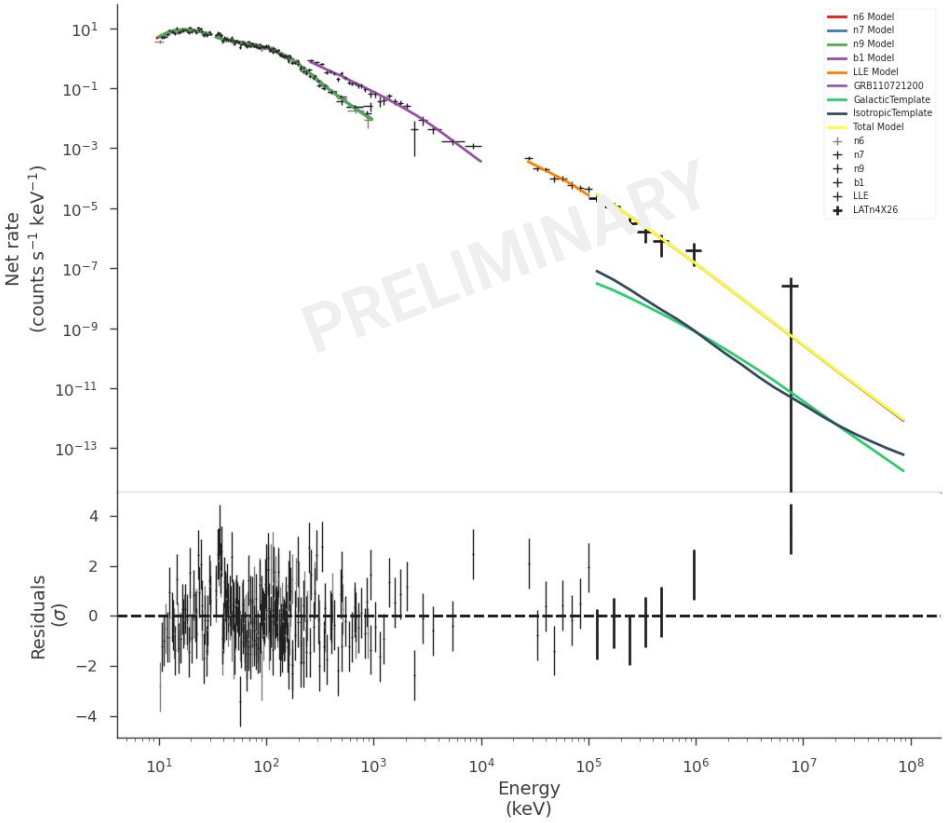
Joint time-integrated spectral analysis: GRB 110721A

Time interval used:

T_0 - 4.36 s - T_0 + 26.19 s

Best models: **Band + BB** and **SBPL + BB**

Parameter	Value	
α	-1.236	± 0.017
β	-2.717	± 0.061
E_{peak} [keV]	2300	± 290
kT [keV]	32.3	± 2.3
Norm (10^{-3})	11.29	± 0.65



Time-integrated spectral analysis results of GRB 110721A fitted with Band+BB function

Preliminary general time-resolved results

The total amount of analysed bins is 2971

GOOD sample

Model	Count	Percentage
Pwl	2849	25.40
Comp	2272	20.25
SBPL	1998	17.81
Band	1606	14.32
ISSM	827	7.37
SBPL+BB	734	6.54
Band+BB	628	5.60
ISSM+BB	304	2.71

Percentage of times a function fitted the bin data *reasonably*

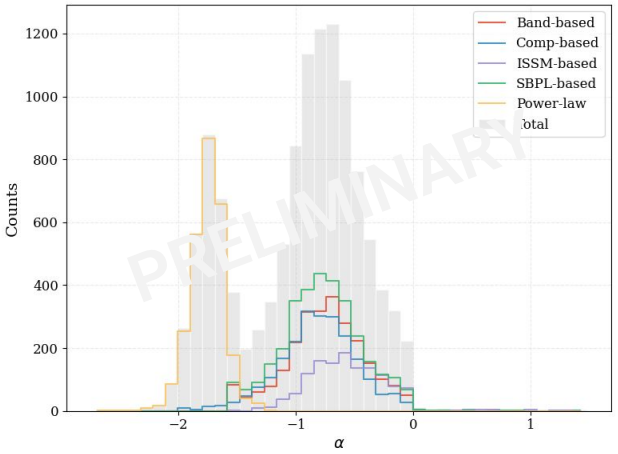
BEST sample

Model	Count	Percentage
Comp	1591	54.49
Pwl	491	16.82
Band	419	14.35
SBPL	269	9.21
ISSM	99	3.39
Band+BB	24	0.82
SBPL+BB	16	0.55
ISSM+BB	11	0.38

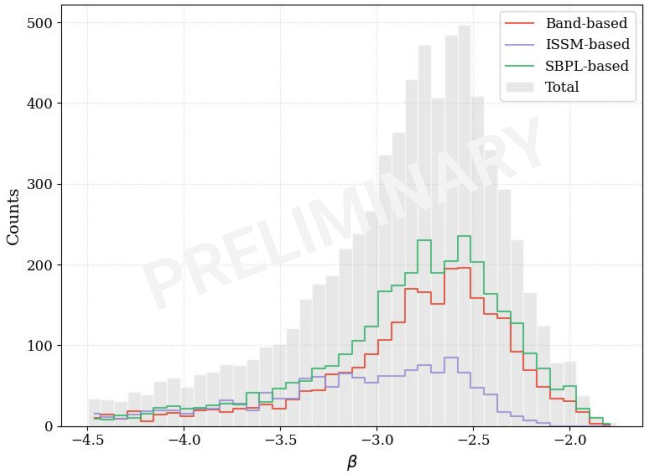
Percentage of best fitting sample for each bin

Preliminary distributions GOOD sample

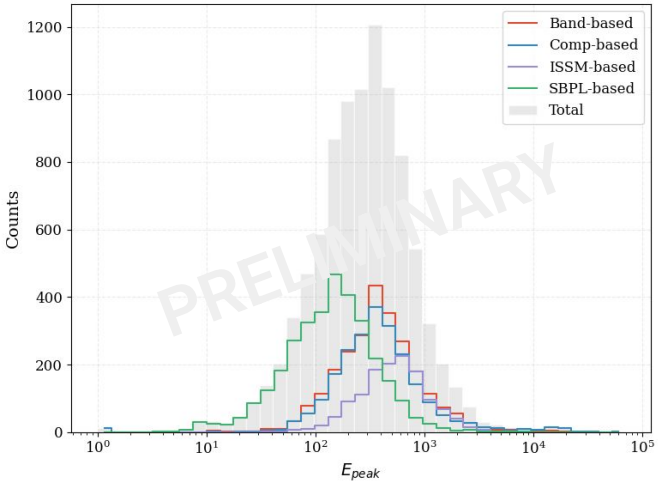
Distribution of the **α** index



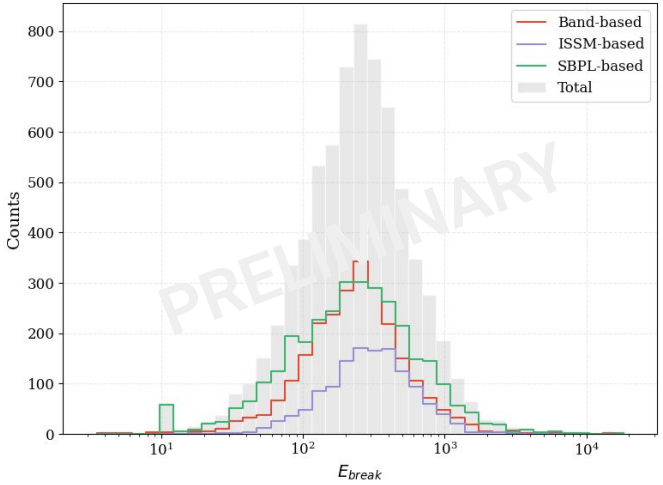
Distribution of the **β** index



Distribution of the $\mathbf{E_{peak}}$



Distribution of the $\mathbf{E_{break}}$



Preliminary results on time-integrated analysis

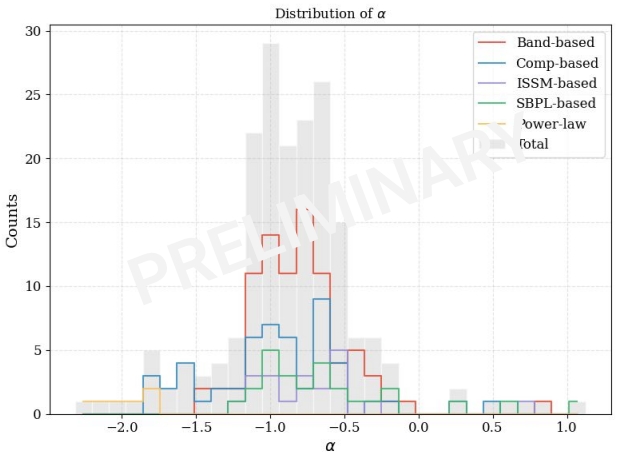
BEST sample

Model	Count	Percentage
Band	68	36.17
Comp	34	18.09
ISSM	20	10.64
Comp+Comp	13	6.91
SBPL	12	6.38
SBPL+BB	10	5.32
Band+BB	7	3.72
Pwl	6	3.19
Band+Pwl	5	2.66
SBPL*E	4	2.13
Comp+Pwl	4	2.13
Band*E	4	2.13
ISSM+BB	1	0.53

Percentage of best fitting sample for each burst

Test results on the pipeline of time-integrated analysis

Distribution of the **α** index



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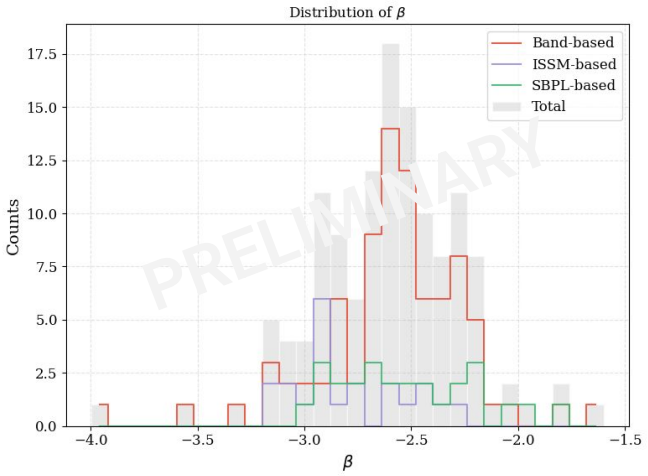
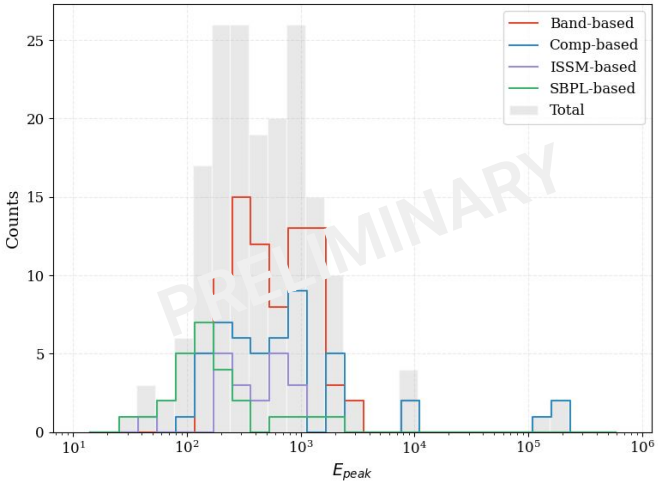
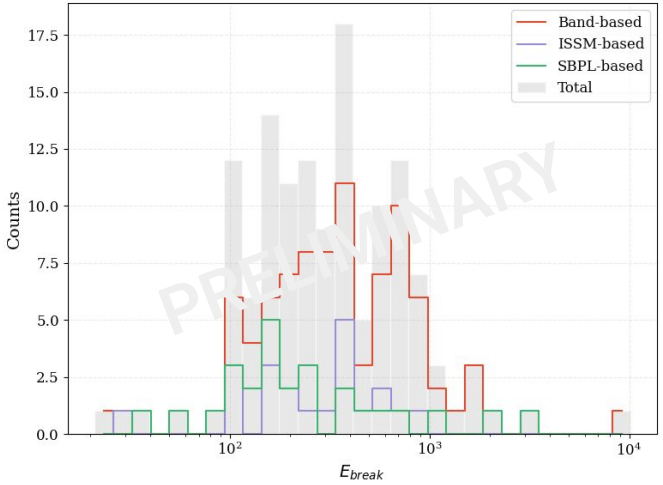


Distribution of the $\mathbf{E_{peak}}$

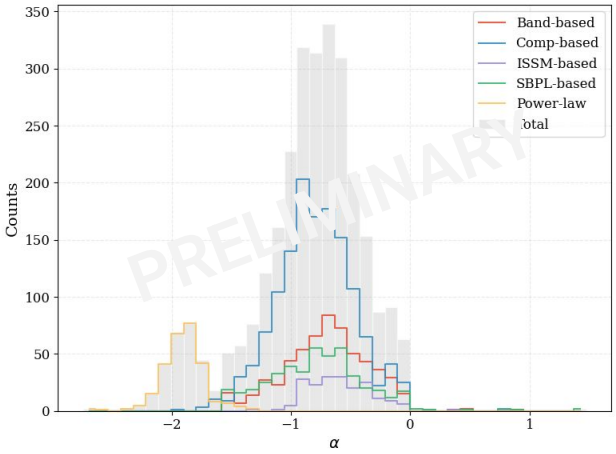


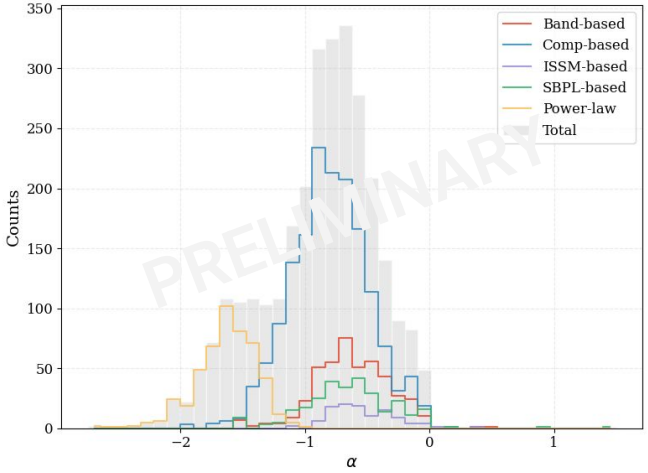
Distribution of the $\mathbf{E_{break}}$



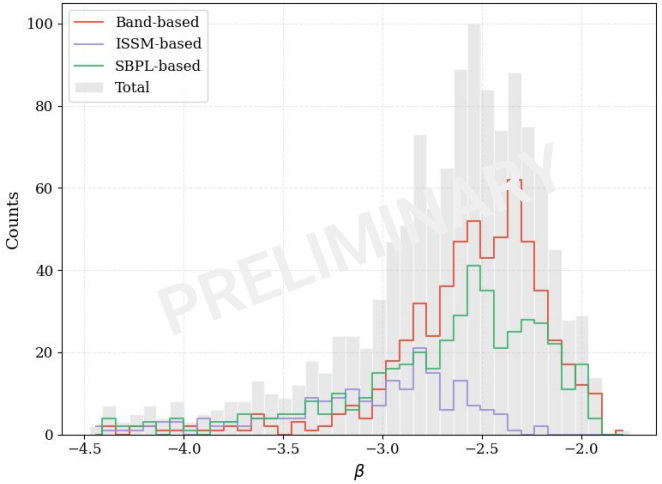
Preliminary comparisons with GBM only analysis

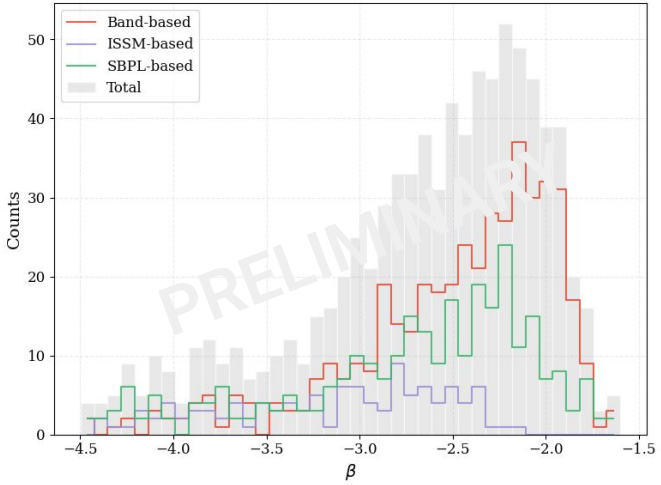
Distribution of the **α** index





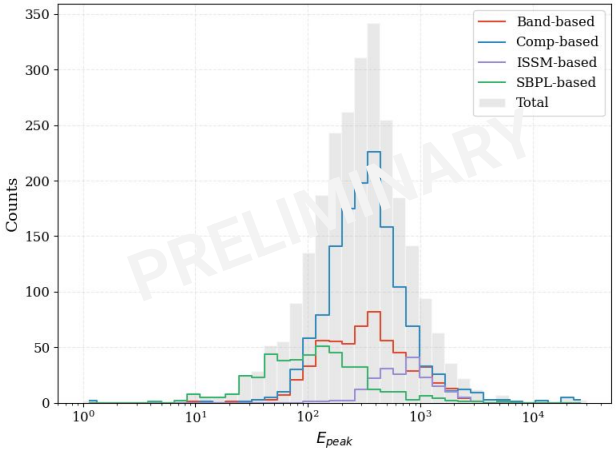
Distribution of the **β** index

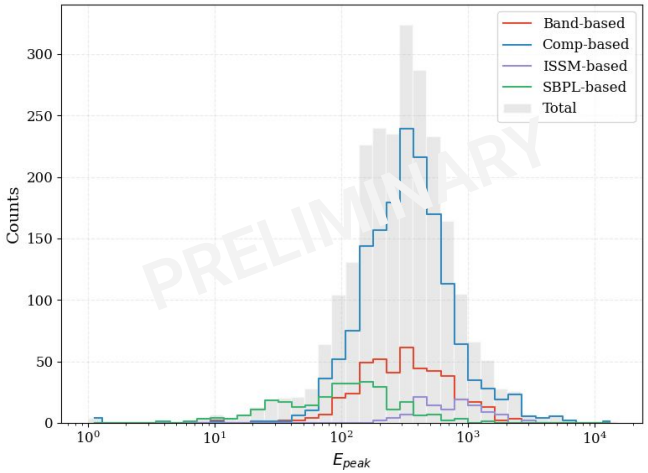




Preliminary distributions BEST sample

Distribution of the $\mathbf{E_{peak}}$





Distribution of the $\mathbf{E_{break}}$