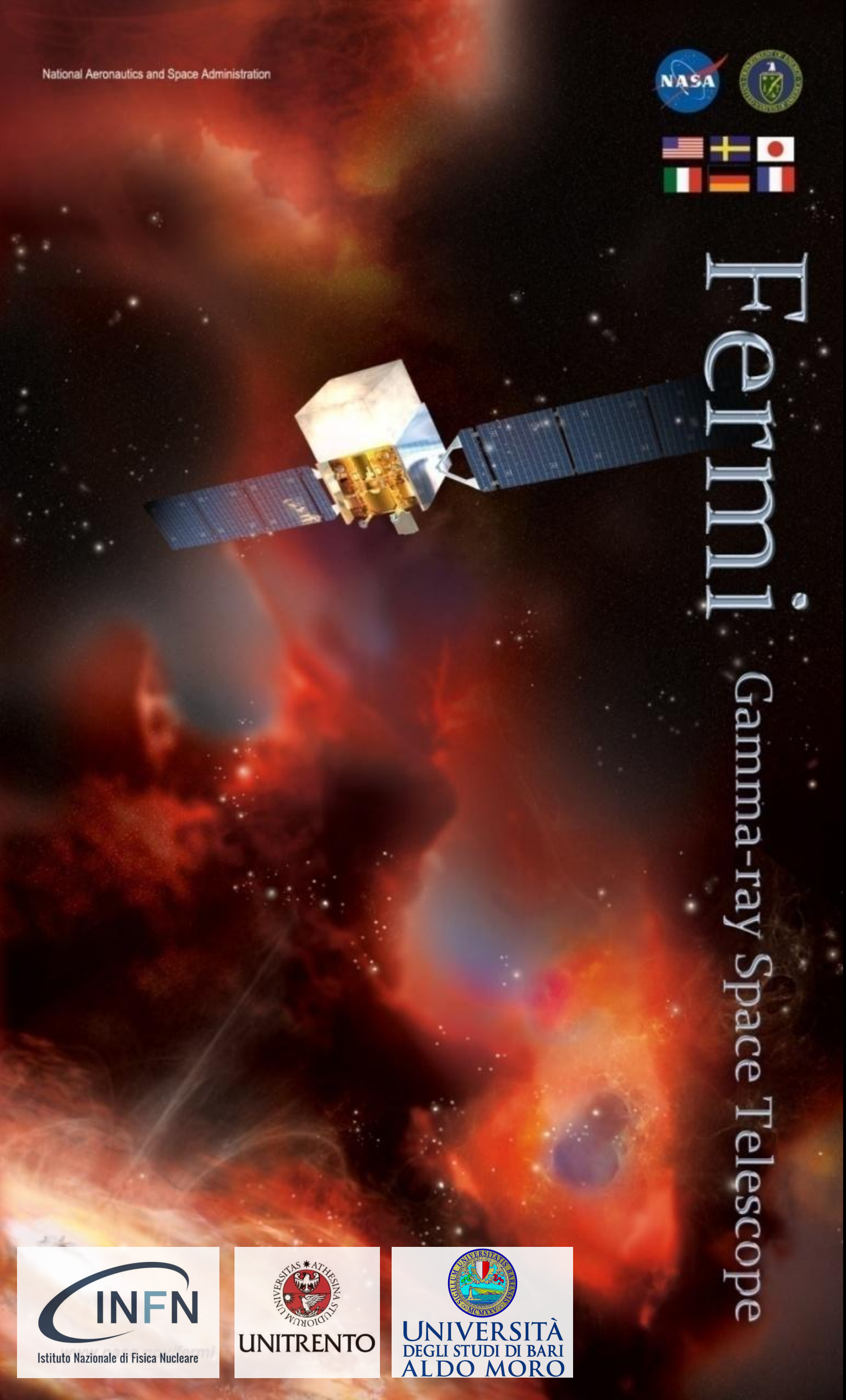

Analisi spettrale congiunta dei GRB

un approccio sistematico risolto nel tempo

Aldana Holzmann Airasca[1, 2];
Elisabetta Bissaldi [2, 3]; Leonardo Di Venere [2, 4];
Francesco Longo [5,6] per le collaborazioni *Fermi-LAT* e *Fermi-GBM*

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[4] University of Bari, [5] University of Trieste, [6] INFN Trieste

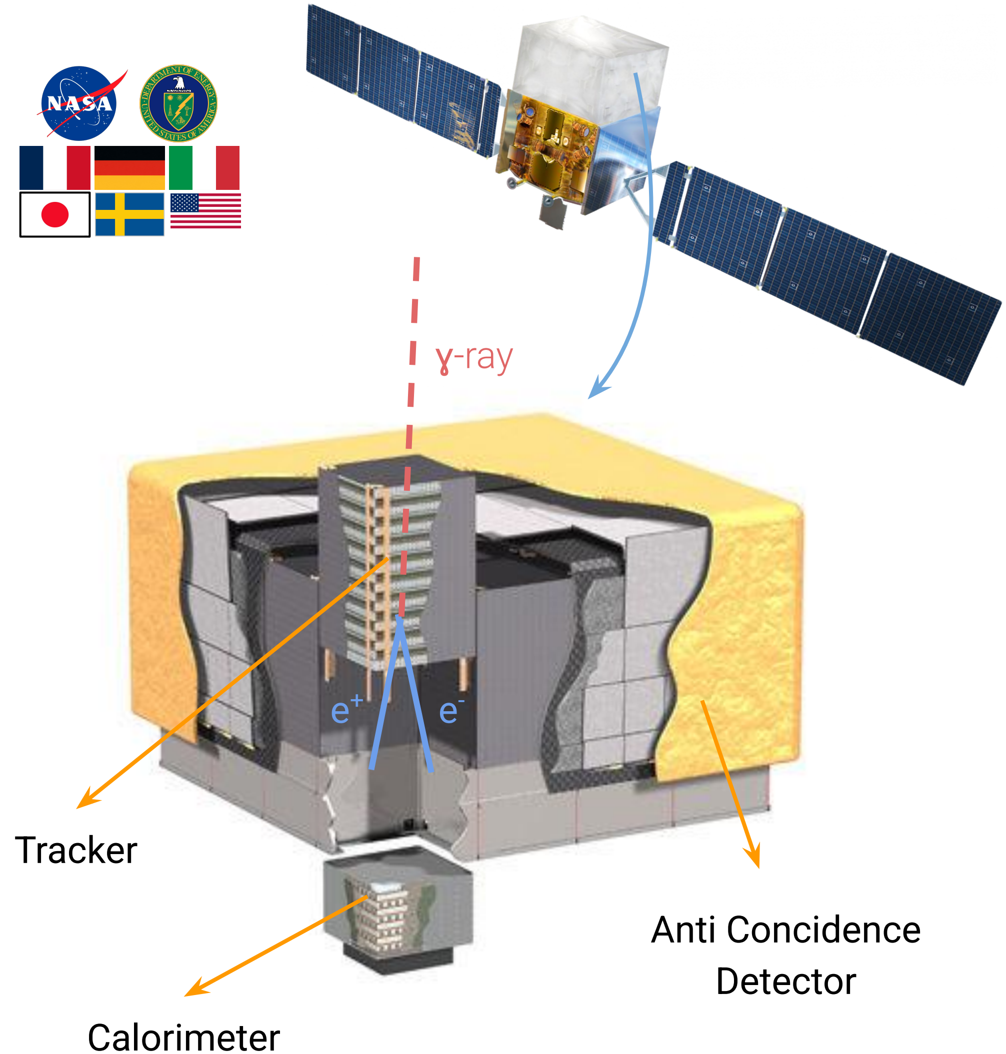
The Fermi mission: Large Area Telescope

The Fermi is an international space mission launched in June 2008. Orbits at ~500 km, with an incl. of 25.6° wrt Earth's equator

The Fermi-LAT is a pair conversion telescope devoted to the study of the gamma-ray sky.

It covers the energy range between
~ 20 MeV - > 300 GeV

- **LLE range** (Atwood et al. 2009): **30 MeV - 1 GeV**
- **LAT standard range: 100 MeV - > 300 GeV**



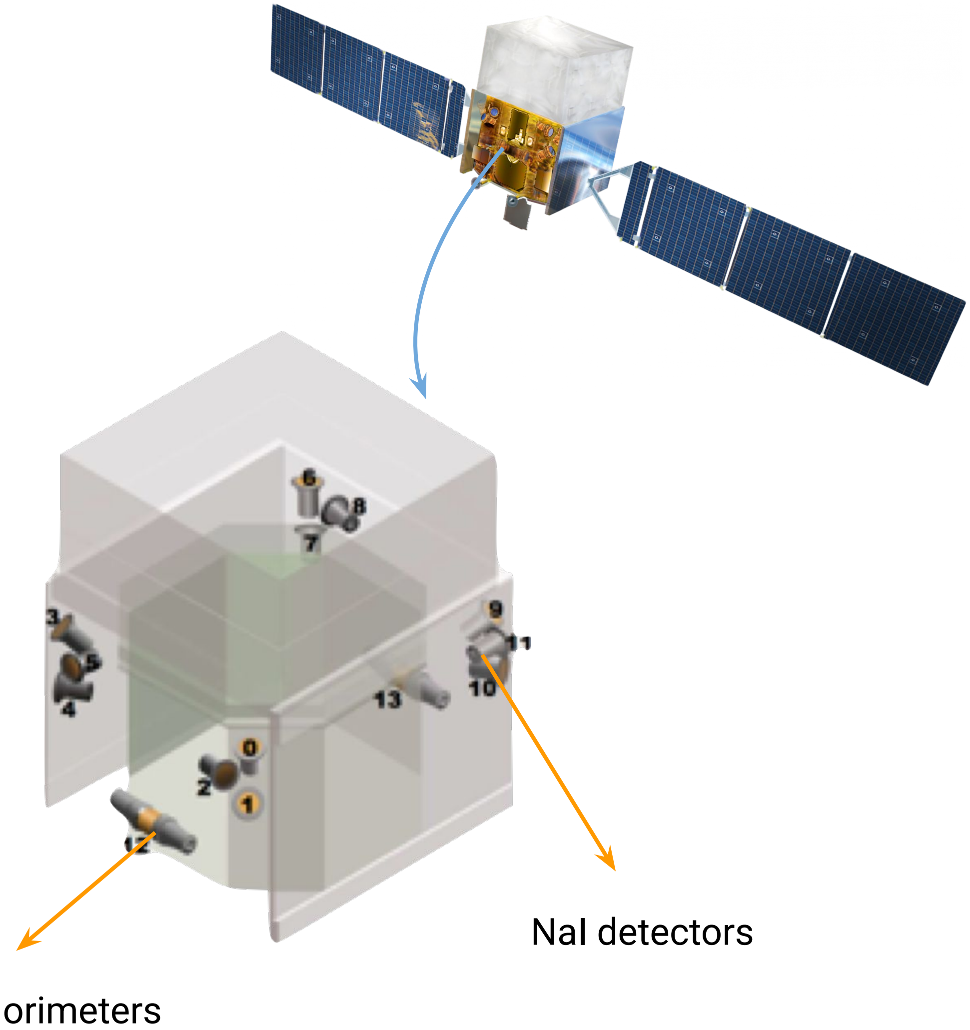
The Fermi mission: Gamma-ray Burst Monitor

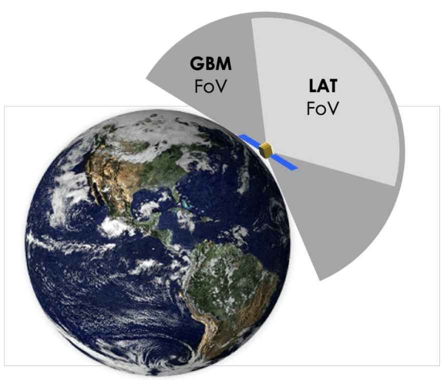
The Fermi-GBM is an instrument on board of the Fermi satellite, composed of:

- 12 NaI scintillator detectors and
- 2 BGO calorimeters.

It is mainly devoted to the study of Gamma-ray bursts, covering an energy range between

8 keV - 30 MeV





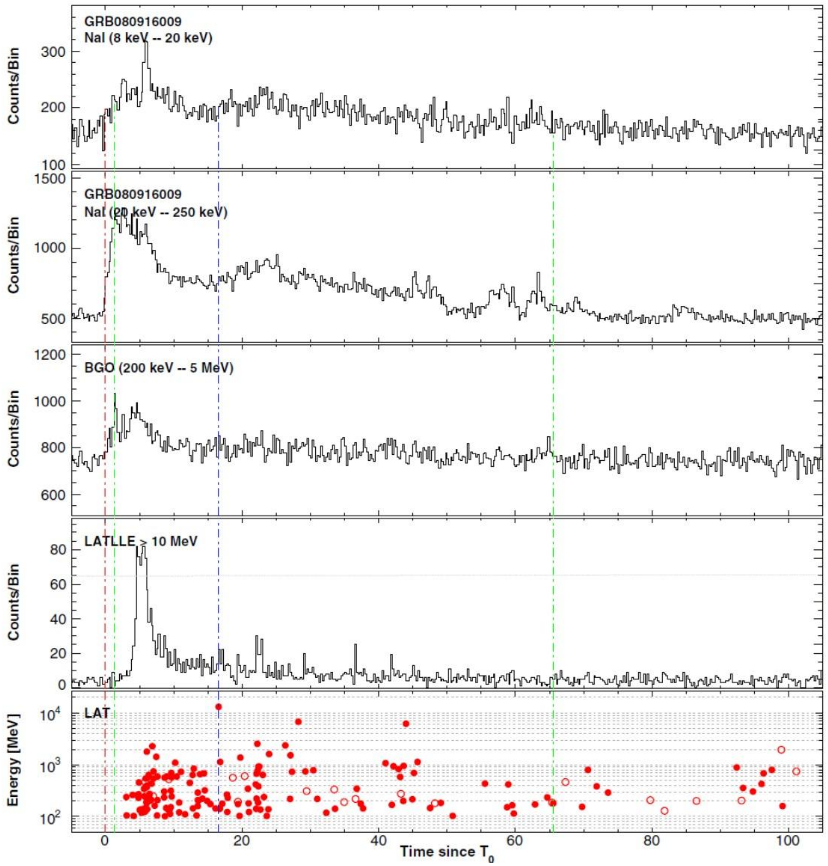
Gamma-ray Bursts (GRBs)

GRBs are extragalactic and extremely energetic transient emissions of electromagnetic radiation in the gamma-ray band.

They are considered to be the ***brightest and most energetic*** **objects in the universe**

There are two main types of GRBs:

- **Long GRBs (duration > 2 s) related to the death of massive stars.**
- **Short GRBs (duration < 2 s) due to the merge of neutron stars.**



Light curve of GRB 080916C (Ackermann et al. 2013)

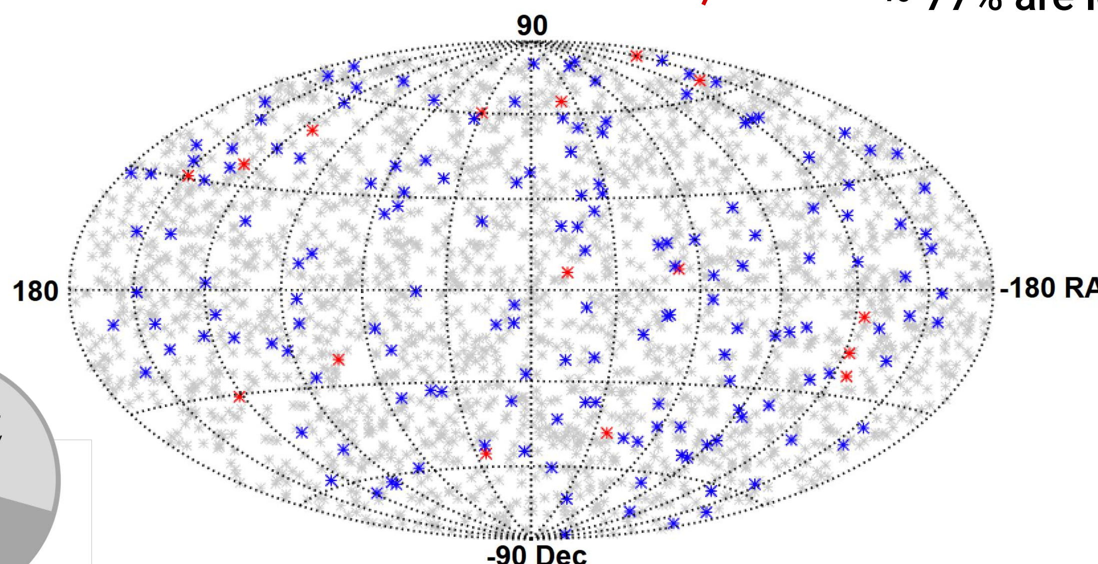
GRBs, some numbers

Yearly GBM observes ~ 250 GRBs while LAT ~15 bursts

To date:

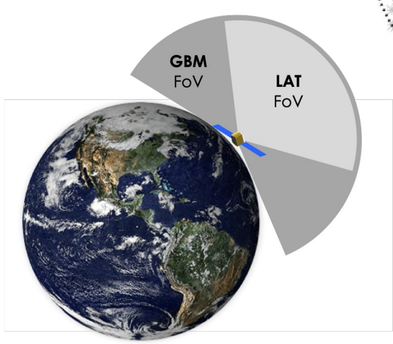
- **GBM-triggered GRBs are 4000**
- **LAT-detected only 267 events**

~ 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)

LAT GRBs:
- Long
- Short

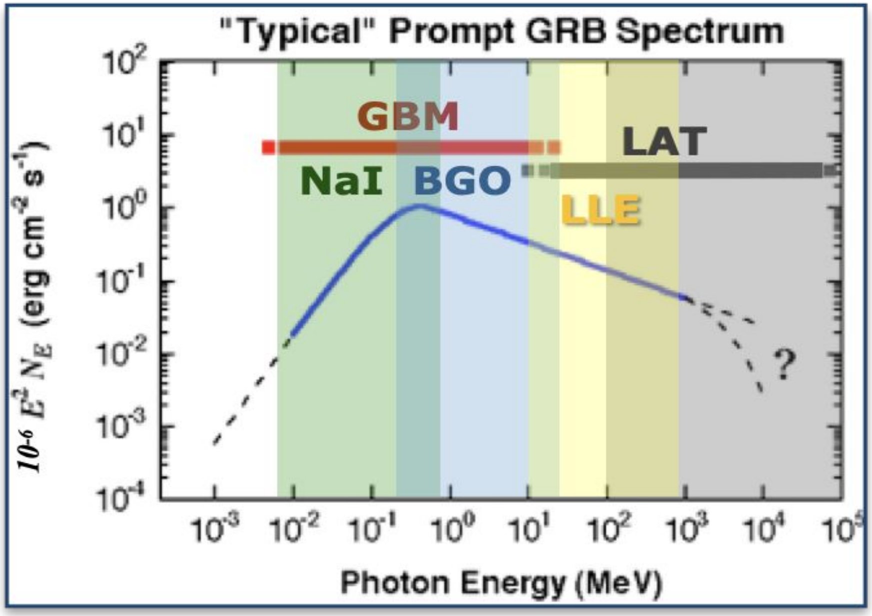


Spectral characteristics of GRBs

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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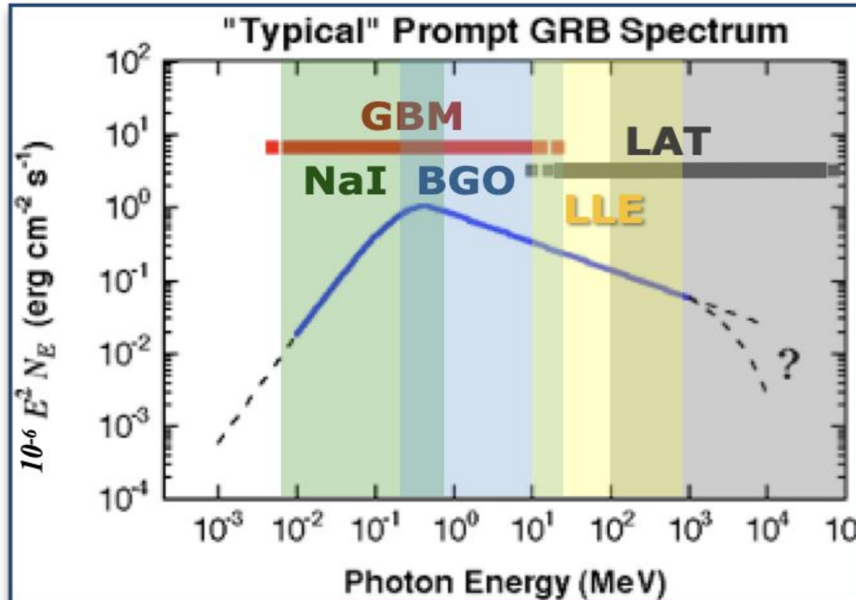

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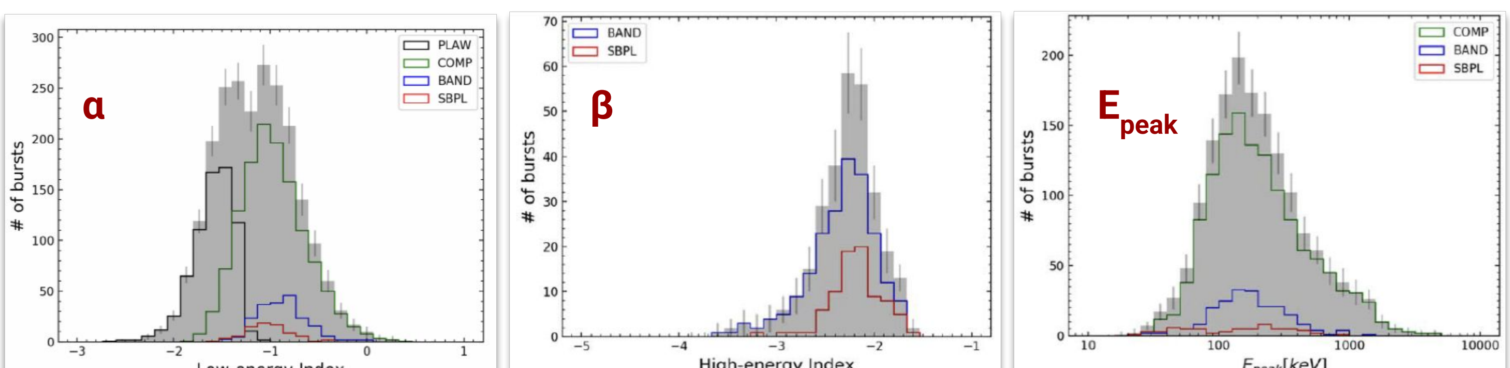
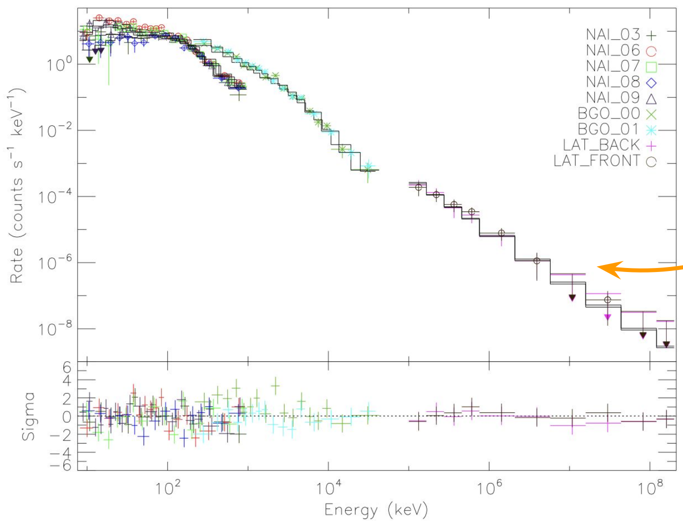


Distribution of spectral parameters (Poolakkil et al. 2021)

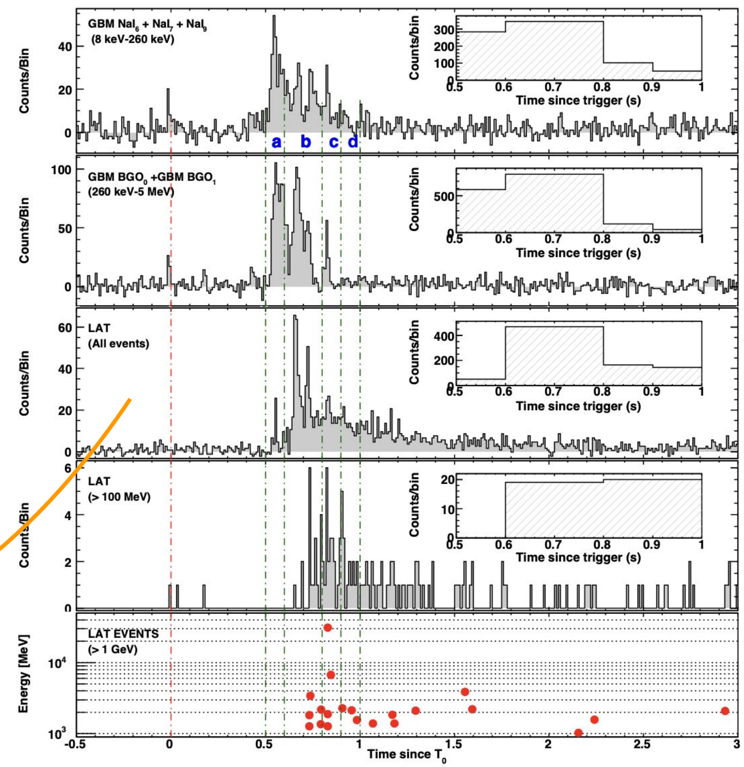
Individual exhaustive studies: short GRB 090510

Joint spectral analysis of data from GBM detectors and LAT was performed.

The burst was divided into smaller bins, and each bin was fitted with Band function and Band + extra components



Spectral analysis of bin a. the data is fitted with Band function



Light-curves at different energies from GRB 090510

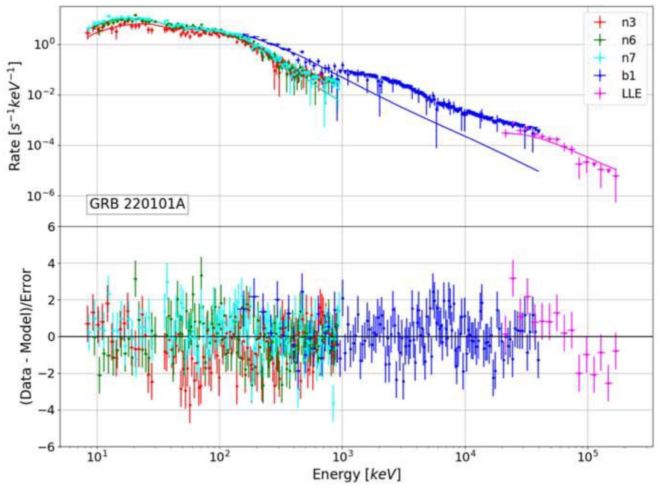
Akerman et al. 2010

Individual exhaustive studies: GRB 220101A

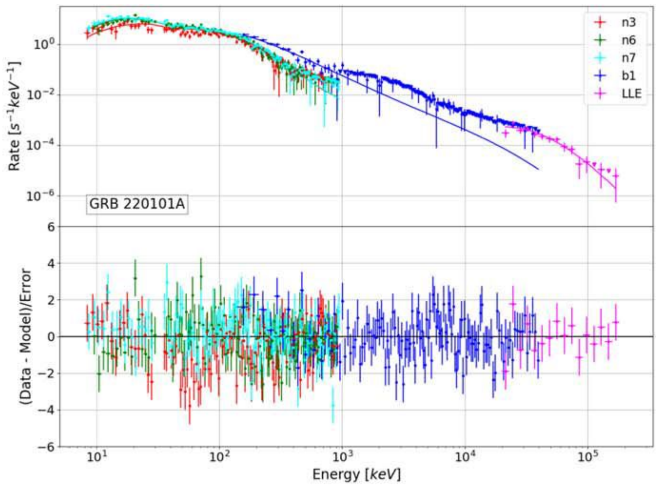
Joint spectral time-resolved and time-integrated analysis were performed.

Further models other than Band alone were tested, including Band + extra components and physically motivated models like ISSM (Yassine et al. 2020)

Band is not the best fitting function!



Spectral results. The data is fitted with Band with a High exponential cut-off function



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Scotton et al. 2023

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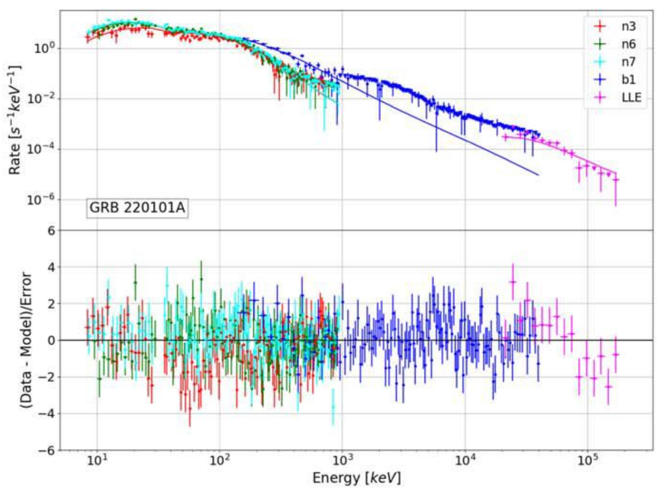

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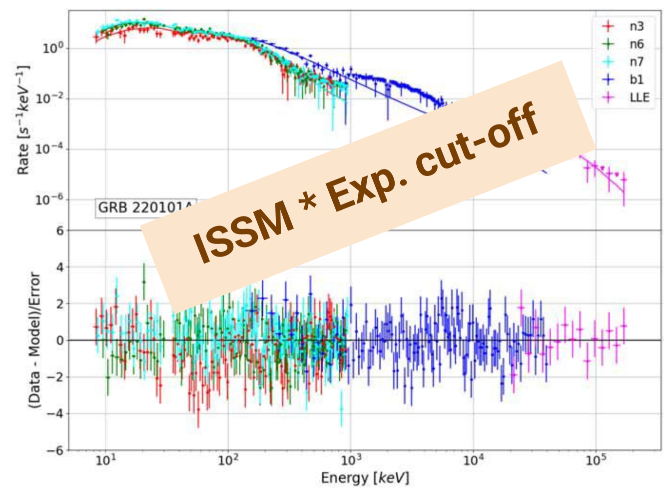

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Scotton et al. 2023

Overview of our project

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

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.

194 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.

Systematic analysis

For each one of the 194 events, we chose the time intervals for the analysis as:

- T_{90} ± 20% (for long GRBs)
- T_{90} ± 1 s (for short GRBs)

Time-integrated pipeline

12 spectral models are tested on each GRB

Time-resolved pipeline

The bins are created with the Bayesian Block method using the brightest NaI detector
Only bins with σ > 5 are considered

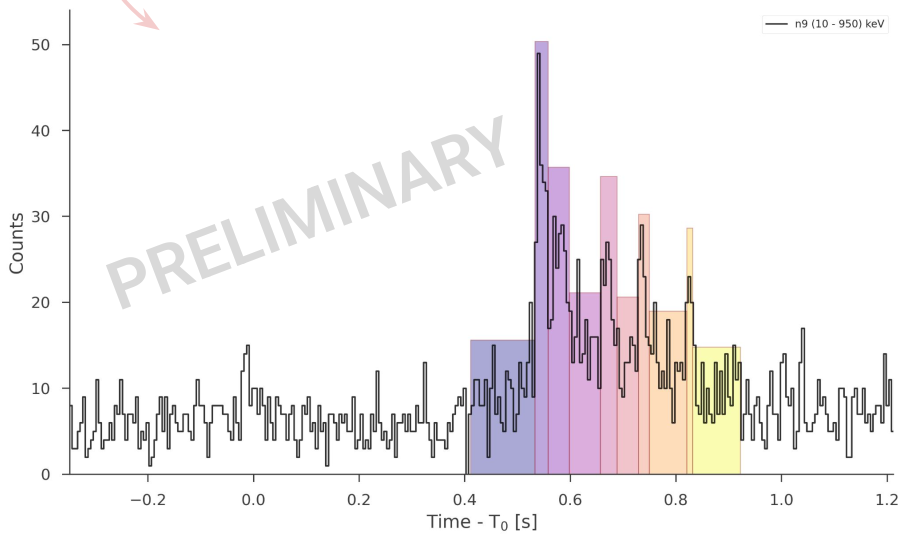
7 spectral models are tested on each bin

"Best fitting models" are defined using Bayesian information criteria (BIC) statistical parameters (needs refinement)

Example time-resolved 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 fitting functions
0.41 - 0.53 s	Compt.
0.53 - 0.56 s	Compt., Band, SBPL
0.56 - 0.60 s	Compt., SBPL
0.60 - 0.66 s	Compt., Band+BB, SBPL+BB, ISSM
0.66 - 0.69 s	Band, SBPL, ISSM
0.69 - 0.73 s	Band, SBPL, ISSM
0.73 - 0.75 s	Band, SBPL, SBPL+BB
0.75 - 0.82 s	Band+BB, SBPL+BB, ISSM+BB
0.82 - 0.83 s	SBPL
0.83 - 0.92 s	Pwl, Band, SBPL

Preliminary results on time-resolved analysis

The analysed sample (so far) contains 30 GRBs chosen among the refined list of events

With a total amount of 546 bins

The final determination of the best fitting model has not yet been done

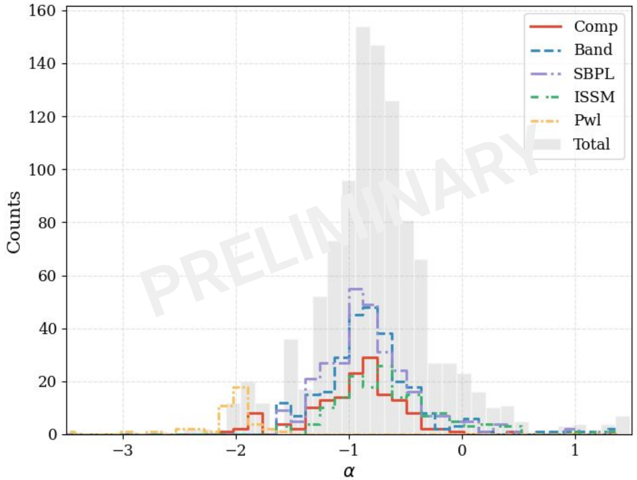
	Count	Percentage
SBPL	298	28 %
Band	274	26 %
ISSM	162	15 %
Comp	149	14 %
Band+BB	74	7 %
Pwl	50	4 %
SBPL+BB	41	3 %

Percentage of times each model fitted the bin data *reasonably*

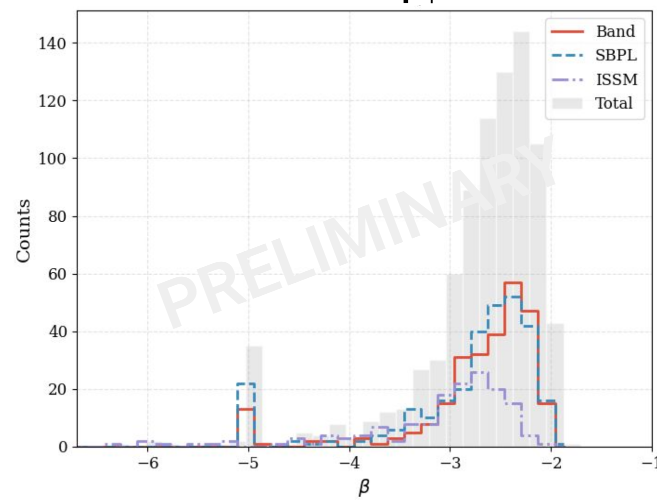
PRELIMINARY

Test results on the pipeline of time-resolved analysis

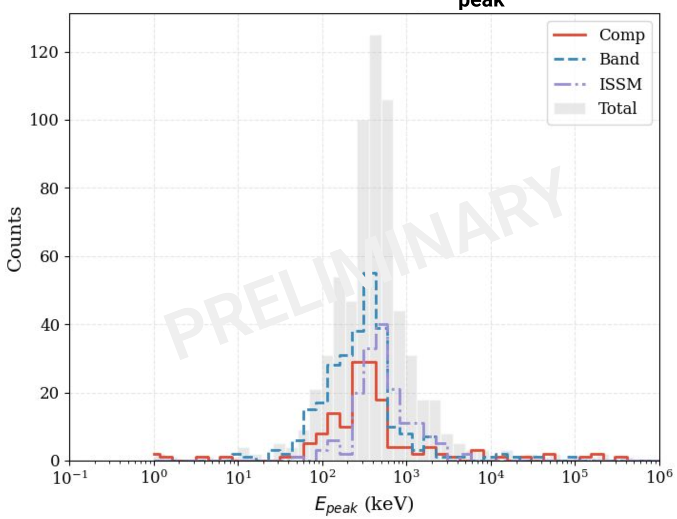
Distribution of the **α** parameter



Distribution of the **β** parameter



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



Preliminary results agree with literature values (Poolakkil et al. 2021)

Data Set	Low-energy Index	High-energy Index	E_{peak} (keV)
This Catalog BEST	$-1.08^{+0.45}_{-0.44}$	$-2.20^{+0.26}_{-0.29}$	180^{+307}_{-88}
Gruber et al. (2014)	$-1.08^{+0.43}_{-0.44}$	$-2.14^{+0.27}_{-0.37}$	196^{+336}_{-100}
Goldstein et al. (2012)	$-1.05^{+0.44}_{-0.45}$	$-2.25^{+0.34}_{-0.73}$	205^{+359}_{-121}
Kaneko et al. (2006)	$-1.14^{+0.20}_{-0.22}$	$-2.33^{+0.24}_{-0.26}$	251^{+122}_{-68}

Conclusions and future perspectives

- **We have two systematic pipelines one for time-resolved and one for time-integrated.**
- **Time-resolved on 30 events, very preliminary results and distribution of parameters appear to be reasonable**
- **Refine the selection of the best fit model for both types of analysis.**

- **Identify and study bursts that show an extra spectral component.**
- **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, take a look at the poster #102!).
- **Analyse 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.**

Conclusions and future perspectives

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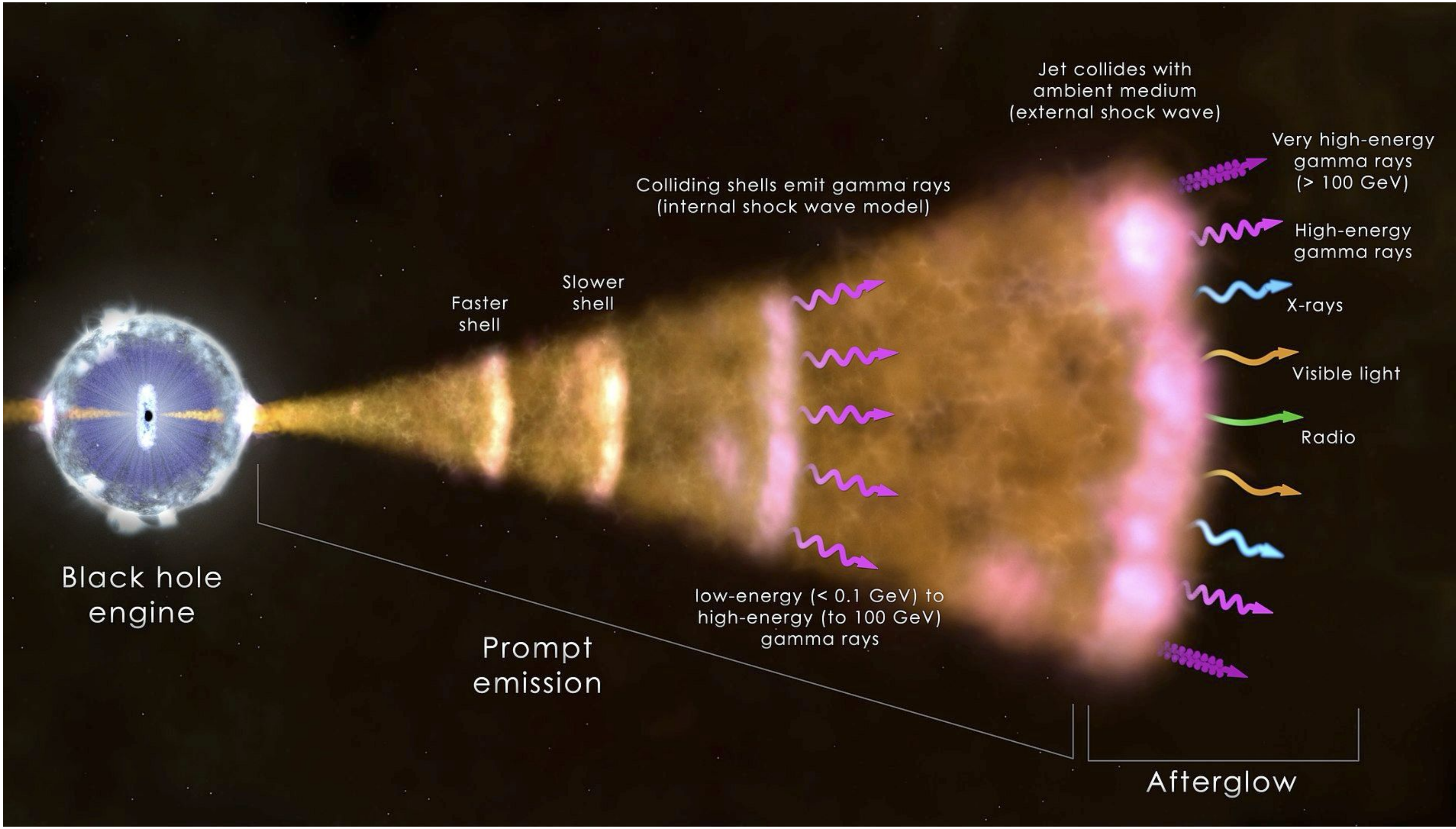
Thank you!

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}).

194 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

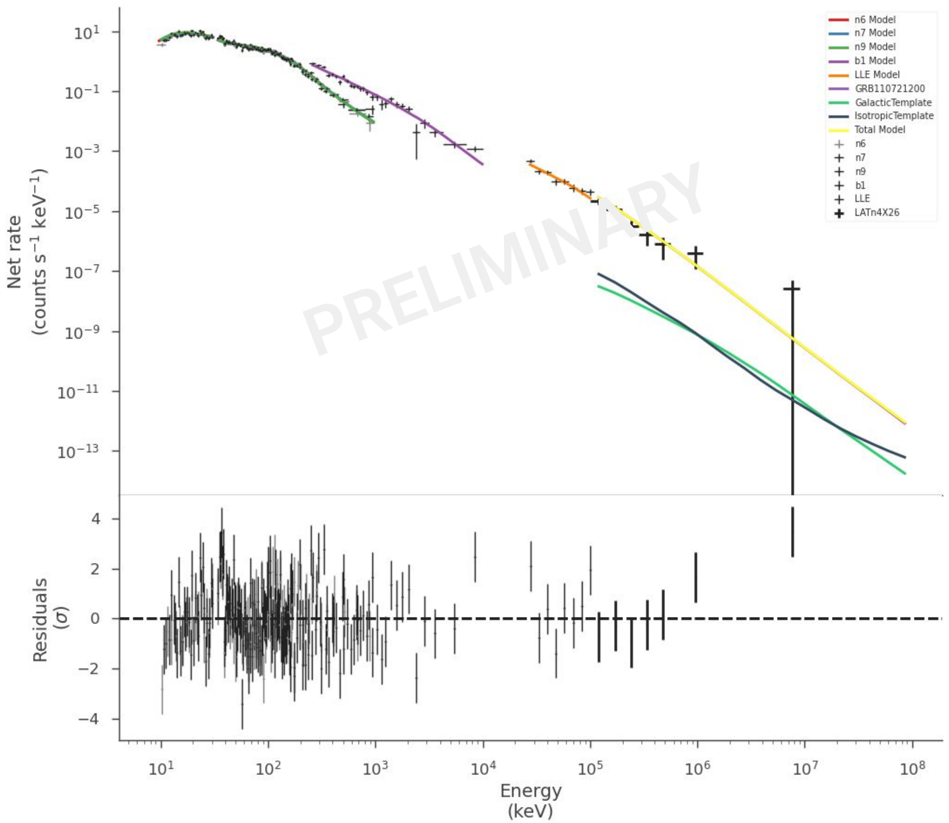
Joint time-integrated spectral analysis: GRB 110721A

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 results on time-integrated analysis

The analysed sample *(so far)* contains **52 GRBs** chosen among the refined list of events

The final determination of the best fitting model has not yet been done

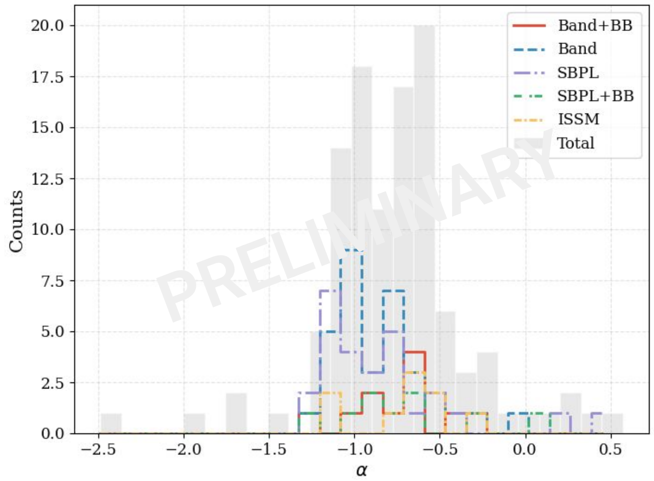
	Count	Percentage
Band	33	30.84
SBPL	27	25.23
Band+BB	11	10.28
Band+Pwl	9	8.41
ISSM	9	8.41
SBPL+BB	8	7.48
Band+E	5	4.67
Comp+Comp	2	1.87
Pwl	2	1.87
Comp+Pwl	1	0.93

Percentage of times each model fitted the burst *reasonably*

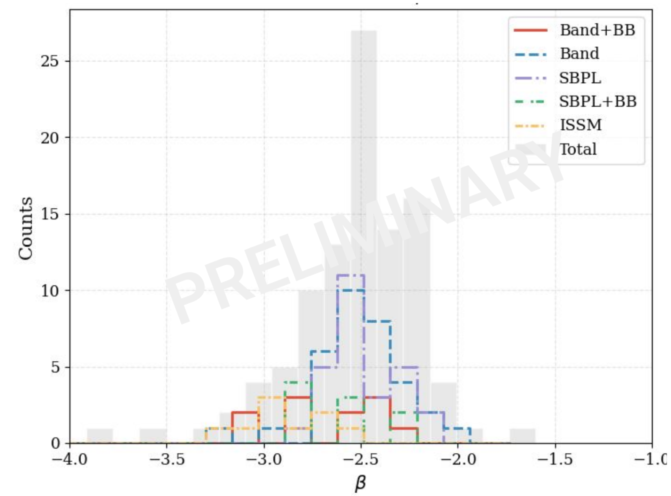
PRELIMINARY

Test results on the pipeline of time-integrated analysis

Distribution of the **α** parameter



Distribution of the **β** parameter



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