# SYSTEMATIC TIME-RESOLVED SPECTRAL ANALYSIS OF GAMMA-RAY BURSTS DETECTED BY FERMI-GBM

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*(on behalf of the Fermi-GBM Team)*

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Fermi Gamma-ray Space Telescope

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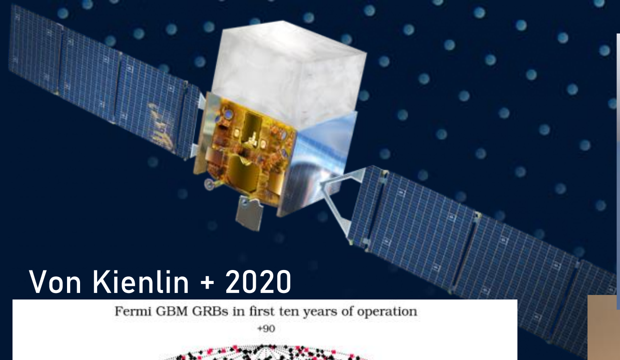
DIPARTIMENTO INTERATENEO DI FISICA

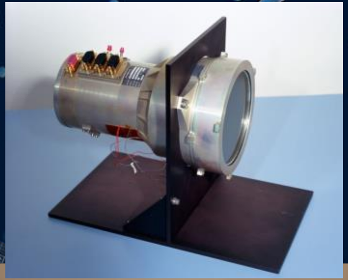
# INTRODUCTION

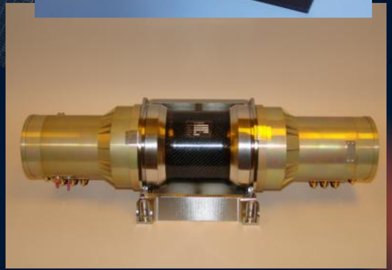
- During the last 16 years, the Fermi GBM has been the most prolific GRB detector ever, with more than 3800 observed GRBs to date.

- So far, only 1 time-resolved spectral catalog has been published (Yu et al. 2016), which covers the first 4 years of the mission (81 events).

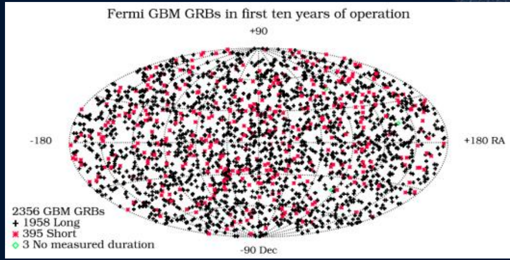
- Here we present a systematic time-resolved analysis of a subsample of bright GRBs.

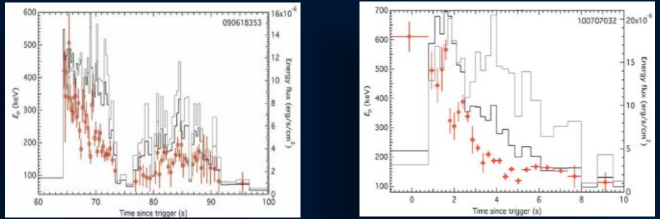




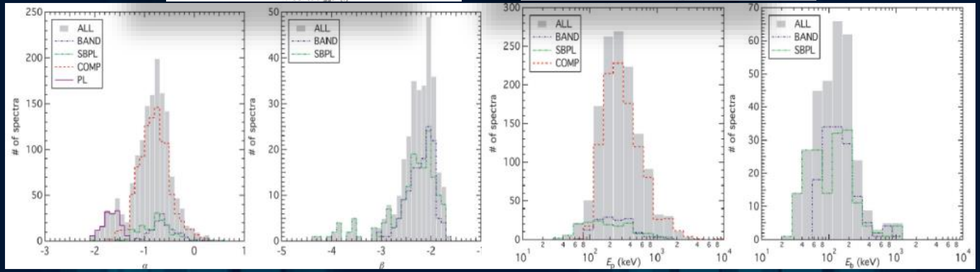


Von Kienlin + 2020




Yu + 2016



# NEW PIPELINE

## *Old analysis: 4-years time resolved spectral catalog (2016)*

- Software used for the analysis: RMFIT v4.3BA3
- Binning method: signal-to-noise ratio

## *Current analysis (2024)*

- Python-based data tools: GBM Data Tools (now superseded by the new Gamma-ray Data Tools[1,2] -> Adam Goldstein's talk on Thursday!)
- Binning method: Bayesian Blocks

1. https://astro-gdt.readthedocs.io/en/latest/index.html#gdt-core
2. https://astro-gdt.readthedocs.io/projects/astro-gdt-fermi/en/latest/index.html

1 2

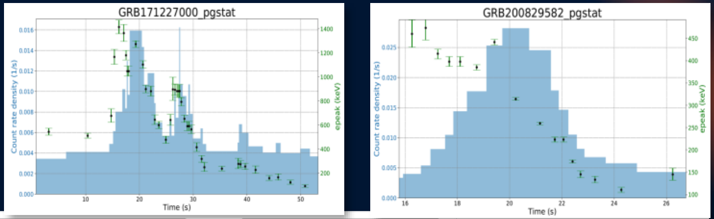
# BURST SELECTION CRITERIA

At least one of these criteria must be satisfied:

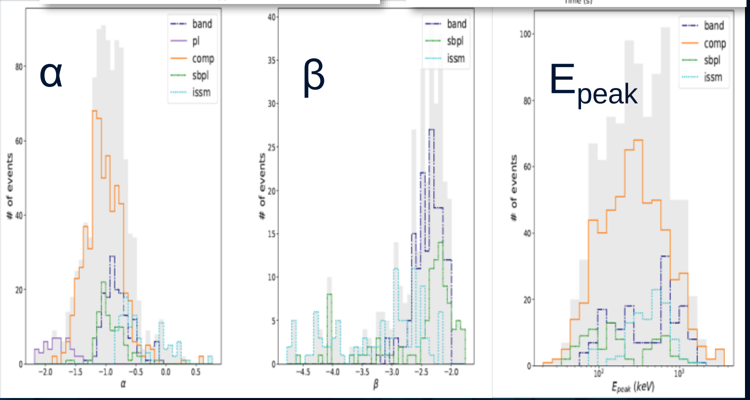
- Energy fluence $f > 5 \cdot 10^{-6}$ erg cm$^{-2}$
- Peak photon flux $F_p > 15$ photons cm$^{-2}$ s$^{-1}$ (in either 64 or 1024 ms binning timescales)

First test of the pipeline in 2023: **20 of the brightest GRBs from the entire mission lifetime**

| Model | N | Percentage (%) |
|---|---|---|
| BAND | 164 | 16.5 |
| PL | 50 | 5.0 |
| COMP | 575 | 57.8 |
| SBPL | 99 | 9.9 |
| ISSM | 107 | 10.8 |
| ALL | 995 | 100.0 |




Current test: all the bursts detected by GBM in the **first 2 years** of the mission (**495 total triggers** from July 11, 2008 to July 14, 2010).
Bright subsample consists of **195 events** (14 short).



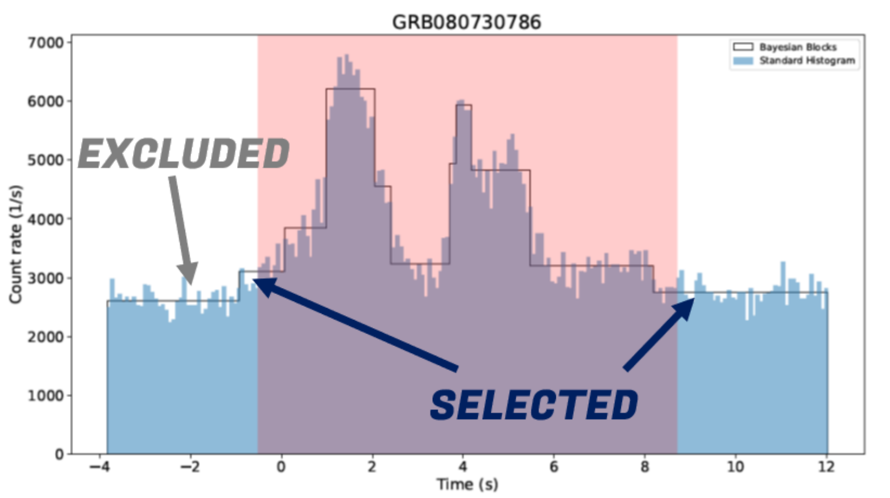
# BAYESIAN BLOCKS

The Bayesian Blocks algorithm* has been applied on each event using only the TTE file from the brightest NaI detector (energy range 8 – 900 keV).

Algorithm applied to a smaller time interval (to reduce computation time):

- Source interval ± 20% (long GRBs)
- Source interval ± 2 s (short GRBs)

Only GRBs with 5 or more bins covering the source range are selected for the spectral analysis -> 1770 intervals from 140 events (5 short).




*Parts of codes from 3ML framework
https://github.com/threeML/threeML

## Detectors and energy channels

- Detector masks from the spectral catalog (max 3 NaI and 1 BGO)
- NaI energy range: 8 – 900 keV
- BGO energy range: 250 keV – 40 MeV

## Background fitting

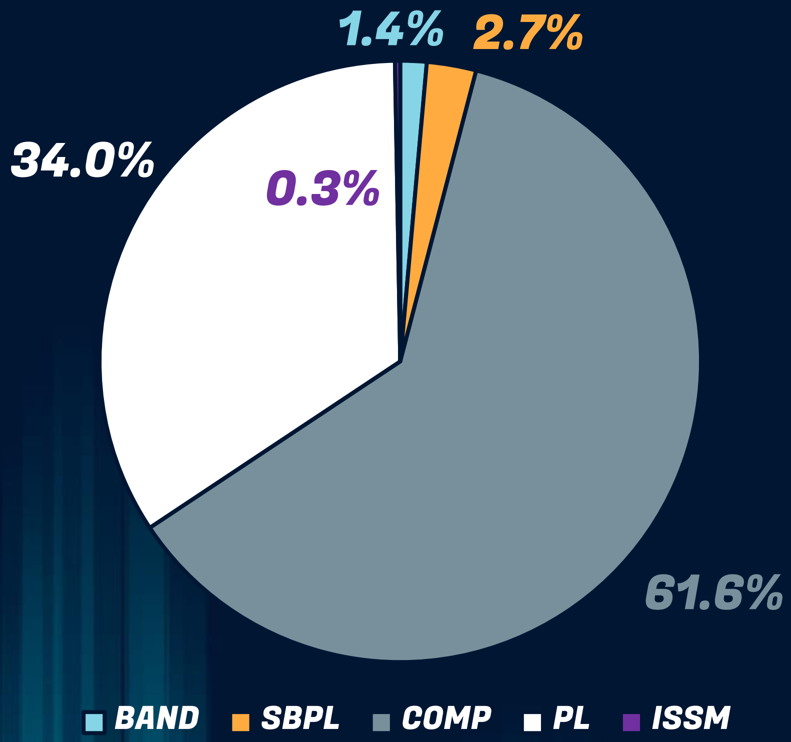
Order 2 polynomial fitted in the background intervals taken from lookup files

## Fitting models

All bins fitted in the source intervals with 5 models:

- Power-Law (PL)
- Cutoff Power-Law (COMP)
- Band function (BAND)
- Smoothly-Broken Power-Law (SBPL)
- Internal Shock Synchrotron Model (ISSM)

# BEST FIT FRACTIONS

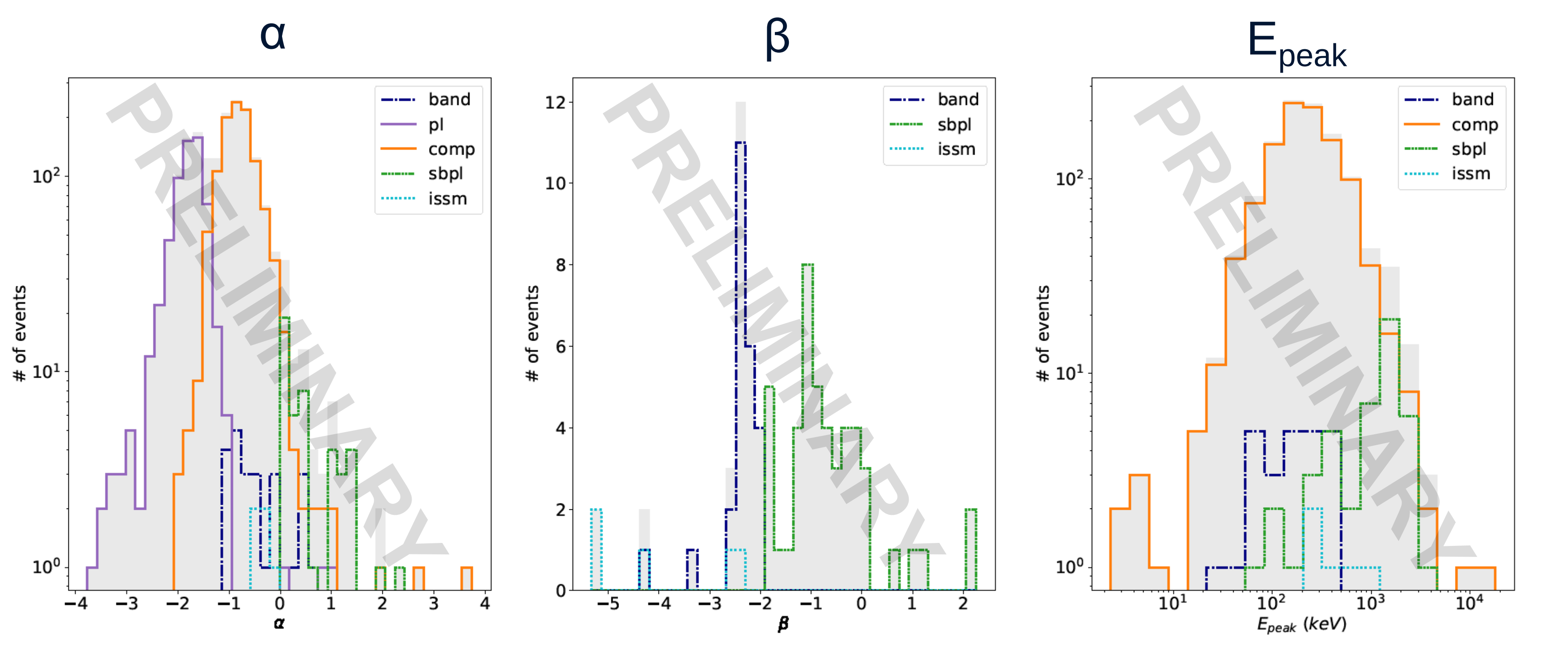



Comparison of PGSTAT statistics, subtracting $\Delta_{CRIT}$=11.83 for COMP and $\Delta_{CRIT}$= 20.41 for PL (models with less parameters preferred if PGSTATs are similar)

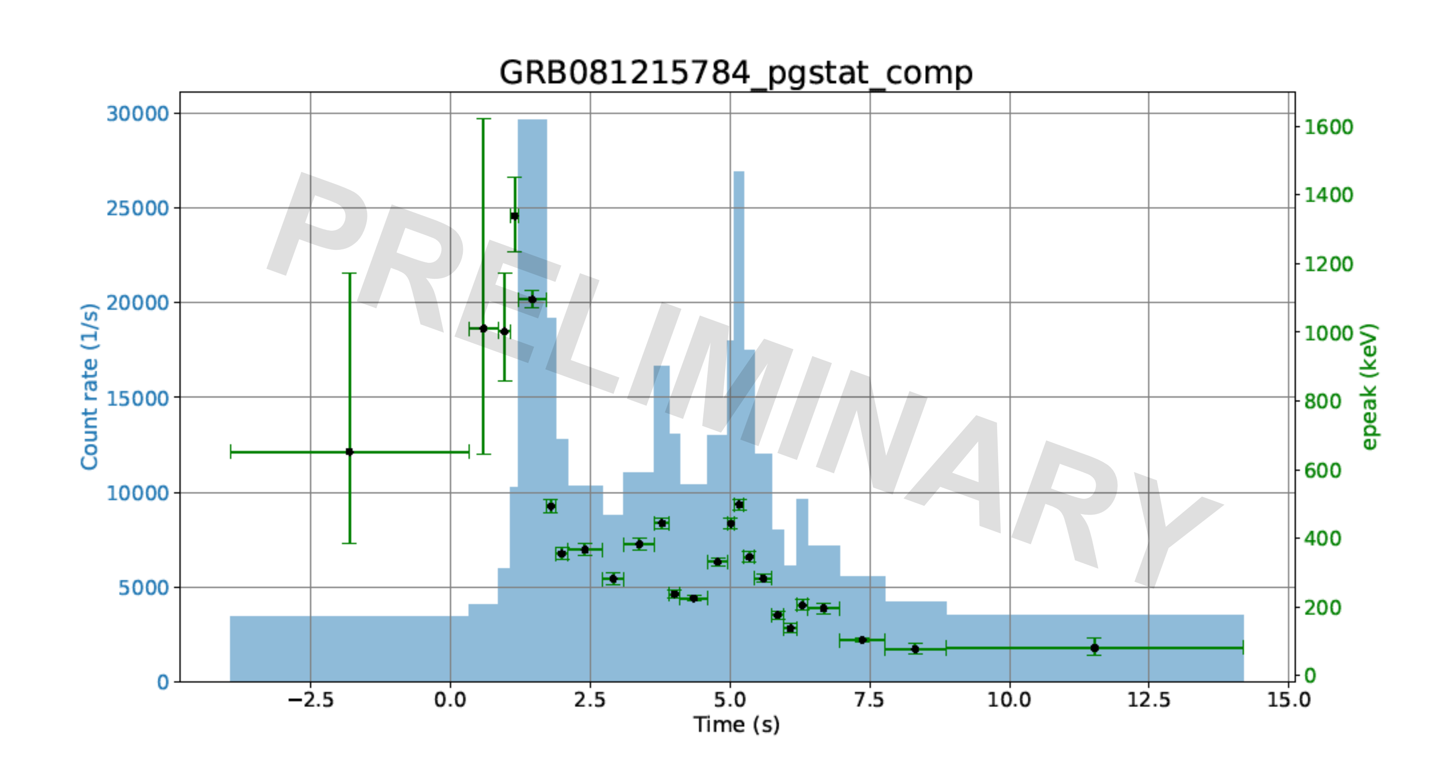
$\Delta_{CRIT}$ values are taken from the 10 yr spectral catalog [Poolakkil et al. 2021].

| MODEL | N | Percentage |
|---|---|---|
| BAND | 25 | 1.4% |
| SBPL | 47 | 2.7% |
| COMP | 1091 | 61.6% |
| PL | 603 | 34.0% |
| ISSM | 5 | 0.3% |

# PARAMETER DISTRIBUTIONS



# EPEAK EVOLUTION (COMP)



# SUMMARY

- Automation of the time-resolved analysis pipeline through python based API
- Bayesian Blocks algorithm for meaningful binning
- Test of the pipeline on a broader GRB sample with looser cuts
- Time reduction: BB + analysis of 1770 bins in less than a week!

## *Future plans*

- Costraints on parameter errors
- Cross-check of selected bins
- BEST model selection criteria
- Extention of the sample to the entire mission period

# THANKS FOR
# YOUR ATTENTION

# BACKUP

# BURST SELECTION CRITERIA – YU ET AL. 2016

At least one of these criteria must be satisfied:

- Energy fluence $f > 4 \cdot 10^{-5}$ erg cm$^{-2}$
- Peak photon flux $F_p > 20$ photons cm$^{-2}$ s$^{-1}$ (in either 64 or 1024 ms binning timescales)

***A total of 81 events have been selected (1 short)***

# FITTING MODELS

**PL**

$$F_{pl}(E) = A\left(\frac{E}{E_{piv}}\right)^{\alpha}$$

**COMP**

$$F_{comp}(E) = A\left(\frac{E}{E_{piv}}\right)^{\alpha} \exp\left[-(2+\alpha)\frac{E}{E_{peak}}\right]$$

**BAND**

$$F_{Band}(E) = A\begin{cases}\left(\frac{E}{E_{piv}}\right)^{\alpha}\exp\left[-(2+\alpha)\frac{E}{E_{peak}}\right] & \text{if } E \leq \frac{(\alpha-\beta)E_{peak}}{2+\alpha} \\ \left[\frac{(\alpha-\beta)E_{peak}}{(2+\alpha)E_{piv}}\right]^{\alpha-\beta}\left(\frac{E}{E_{piv}}\right)^{\beta}\exp(\beta-\alpha) & \text{otherwise}\end{cases}$$

**SBPL**

$$F_{pl}(E) = A\left(\frac{E}{E_{piv}}\right)^{p} 10^{(b-b_{piv})}$$

$$b = m\Delta\ln\left(\frac{e^{a}-e^{-a}}{2}\right),\ b_{piv} = m\Delta\ln\left(\frac{e^{a_{piv}}-e^{-a_{piv}}}{2}\right),$$
$$a = \frac{\log(E/E_b)}{\Delta},\ a_{piv} = \frac{\log(E_{piv}/E_b)}{\Delta},$$
$$m = \frac{\beta-\alpha}{2},\ p = \frac{\beta+\alpha}{2}$$

# ISSM

ISSM, based on the Internal Shock Synchrotron Model [Daigne et al. 2011] and developed by [Yassine et al. 2020]:

$$F_{ISSM}(E) = \frac{A}{\left[1 - \frac{E_p}{E_r}\left(\frac{2+\beta}{2+\alpha}\right)\right]^{\beta-\alpha}} \left(\frac{E}{E_r}\right)^{\alpha} \left[\frac{E}{E_r} - \frac{E_p}{E_r}\left(\frac{2+\beta}{2+\alpha}\right)\right]^{\beta-\alpha}$$

4 free parameters:

- low-energy index α
- high-energy index β
- peak energy $E_{peak}$
- amplitude A

# BAYESIAN BLOCKS

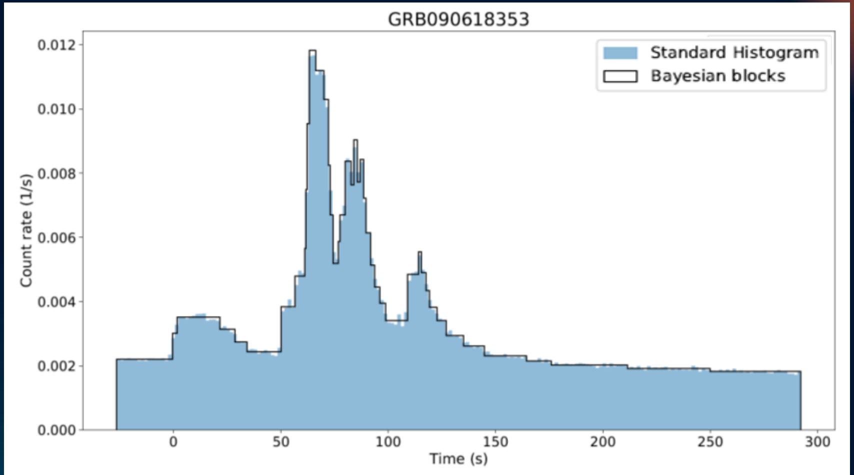
Dynamic histogramming method which optimizes a “fitness” function to determine an optimal binning for counting data.
In our case, the output of the algorithm is the most probable segmentation of the observation into time intervals during which the photon arrival rate is perceptibly constant.

Since the algorithm uses the Bayesian probability, a prior distribution has to be defined. An optimal choice for this case is:

$$prior = 4 - 73.53\ p_0\ N^{-0.478}$$

($p_0$ is the false positive probability, which has been set to $p_0 = 0.05$)

All the details about the Bayesian Blocks algorithm can be found in Scargle + 2013.



# BAYESIAN BLOCKS (2)

For series of times of discrete events, it is convenient to treat them as a continuum. In this case, the fitness function is easily obtained from the unbinned likelihood known as the Cash statistic:

$$\log L(\theta) = \sum_n \log M(t_n, \theta) - \int M(t, \theta) dt$$

My block model is constant with a single parameter M(t, λ) = λ, so for block k:

$$\log L^{(k)}(\lambda) = N^{(k)} \log \lambda - \lambda T^{(k)}$$

# PGSTAT

PGSTAT statistics comes from a Profile-Gaussian Likelihood, in which the signal is Poissonian (counts) and the background is assumed to have Gaussian uncertainties.

Example: the background spectrum may have been generated by some model based on correlations between the background counts and spacecraft orbital position.

$$PG = 2\sum_{i=1}^{N} t_s(m_i - f_i) - S_i \ln(t_s m_i + t_s f_i) + \frac{1}{2\sigma_i^2}(B_i - t_b f_i)^2 - S_i(1 - \ln S_i)$$

where:

$$f_i = \frac{-(t_s\sigma_i^2 - t_b B_i + t_b^2 m_i) \pm d_i}{2t_b^2}$$

$$d_i = \sqrt{[t_s\sigma_i^2 - t_b B_i + t_b^2 m_i]^2 - 4t_b^2[t_s\sigma_i^2 m_i - S_i\sigma_i^2 - t_b B_i m_i]}$$

https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/XSappendixStatistics.html