Algorithms for GRB detection

AHEAD2020

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Summary and goals

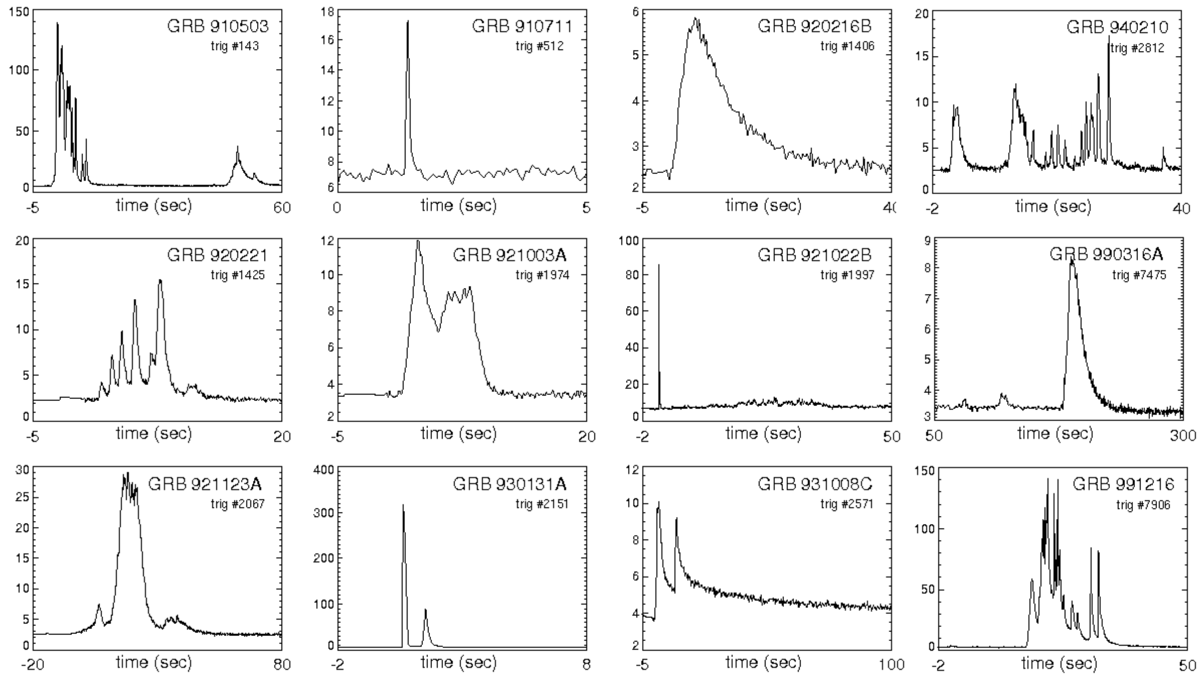
Goal: to design a better algorithm for GRB detection.

Context: HERMES missions, nanosatellite constellations.

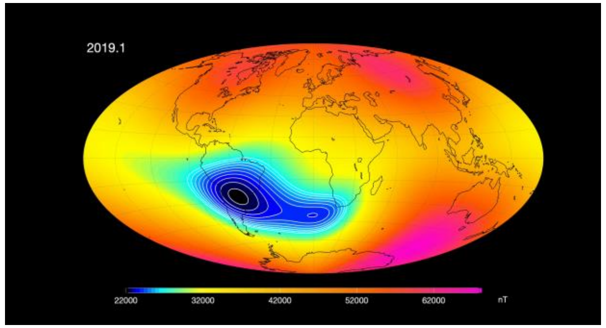
Rough summary:

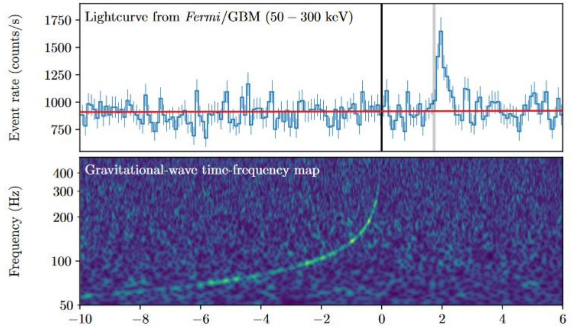
1. How GRBs are conventionally detected.
2. Changepoint detection techniques and FOCuS.
3. A few results.

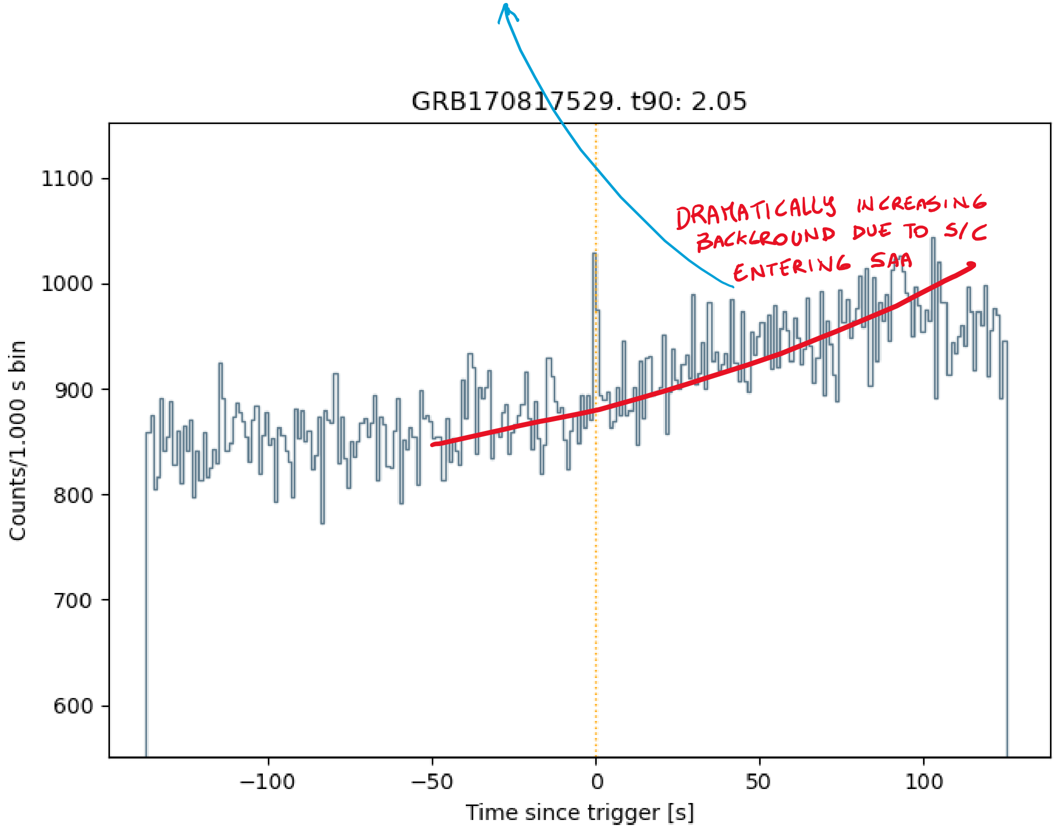
How a GRB looks like?



Histograms of photons counts for extremely bright GRBs detected by BATSE aboard NASA Compton. There is a whole zoo of shapes and durations. All of them do appear as a temporary change in rate over a poissonian background.







GRB170817529 is a short bursts and a very important one. It was the first burst observed with its gravitational counterpart. The background changes dramatically after detection.

How GRBs are detected

Same recipe over the last 50 years:

1. energetic photons are counted (binned) in time.
2. background photons count-rate is estimated somehow.
3. count observation significance is estimated over multiple, predefined time-scales (and energy bands/detectors).
4. a trigger is issued whenever a significance value exceeds a threshold.

pg. 667). Both the size and locations of the intervals over which the signal is averaged affect the result, and therefore one must consider many different values of the corresponding parameters. The idea is to minimize the chances of missing a signal because, for example, its duration is poorly matched to the interval size chosen. If the background is determined dynamically, by

[2]: Studies in astronomical time series analysis. VI. Bayesian Blocks representations – Scargle, Jackson et al.
http://doi.org/10.1088/0004-637X/764/2/167

SHORT RATE TRIGGERS

Running many short time scales through a triggering code can require most of the CPU time. Fortunately, the background counting rate of BAT is not expected to change on short time scales (i.e., less than a few seconds). Thus, for the short time scales we will use simple traditional triggers where there is a single background period of fixed duration before the foreground period. This is the type of trigger that was used on all GRB experiments from Vela to BATSE.

The short trigger looks for statistically significant increases in the count rate on five time scales: 4, 8, 16, 32, and 64 msec. This is done for nine different regions of

[1]: The Trigger Algorithm for the Burst Alert Telescope on Swift, Fenimore et al.
https://doi.org/10.1063/1.1579409

Increasingly complex algorithms over time (horizontal growth).

BAT uses about 800 different criteria to detect GRBs, each defined by a large number of commandable parameters. Usually the critical parameter is the time scale of the sample being analyzed for a statistically significant increase. There are three triggering

Setting the Triggering Thresholds on Swift, McLean et al..
https://doi.org/10.1063/1.1810931

Abstract. The High Energy Transient Explorer uses a triggering algorithm for gamma-ray bursts that can achieve near the statistical limit by fitting to several background regions to remove trends. Dozens of trigger criteria run simultaneously covering time scales from 80 msec to 10.5 sec or longer. Each criteria is controlled by about 25 con-

HETE Triggering algorithm, Fenimore et al.
https://doi.org/10.1007/10853853_108

offset by half of the accumulation time. A total of 120 different triggers can be specified, each with a distinct threshold.

[2]: THE FERMI GAMMA-RAY BURST MONITOR, Meegan et al.
https://doi.org/10.1088/0004-637X/702/1/791

4.1. Triggers

A burst trigger occurs when the flight software detects an increase in the count rates of two or more NaI detectors above an adjustable threshold specified in units of the standard deviation of the background rate. The background rate is an average rate accumulated over the previous T seconds (nominally 17), excluding the most recent 4 s. Energy ranges are confined to combinations of the eight channels of the CTIME data. Trigger timescales may be defined as any multiple of 16 ms up to 8.192 s.

[2]: THE FERMI GAMMA-RAY BURST MONITOR, Meegan et al.
https://doi.org/10.1088/0004-637X/702/1/791

A new algorithm for GRB detection

The idea:

let's make an algorithm which does not test for *many* timescales.. Let's make an algorithm that tests over *all* timescales!

Trivial solution exists in exhustive search. Yet not feasible: it's SLOW!
We want a fast algorithm.

Is this possible? How?

1. **Equipping the algorithm of a memory state and of the math necessary to evaluate evidences of a burst.**
2. **Having the algorithm work only when evidences are actually there.**

We realized a prototype of this algorithm yet we missed the math..

We got in contact with statistician Paul Fearnhead, University of Lancaster: **FOCuS**

FOCuS - Functional Online CUSUM

- Developed by Kim Ward and Gaetano Romano under supervision of Paul Fearnhead and Idris Eckley of statistics department of University of Lancaster. Very recent, unpublished results.
- An improvement to CUSUM method which computes the CUSUM test statistic **for all possible transient intensities $\boldsymbol{\mu}$** – equivalent to looking for all possible durations (one can prove this).
- The idea is to solve in μ the CUSUM recursion:

$$\zeta_i(\mu) = \max\left(0, \zeta_{i-1,\mu} + x_i \log \mu - \lambda_i(\mu - 1)\right)$$

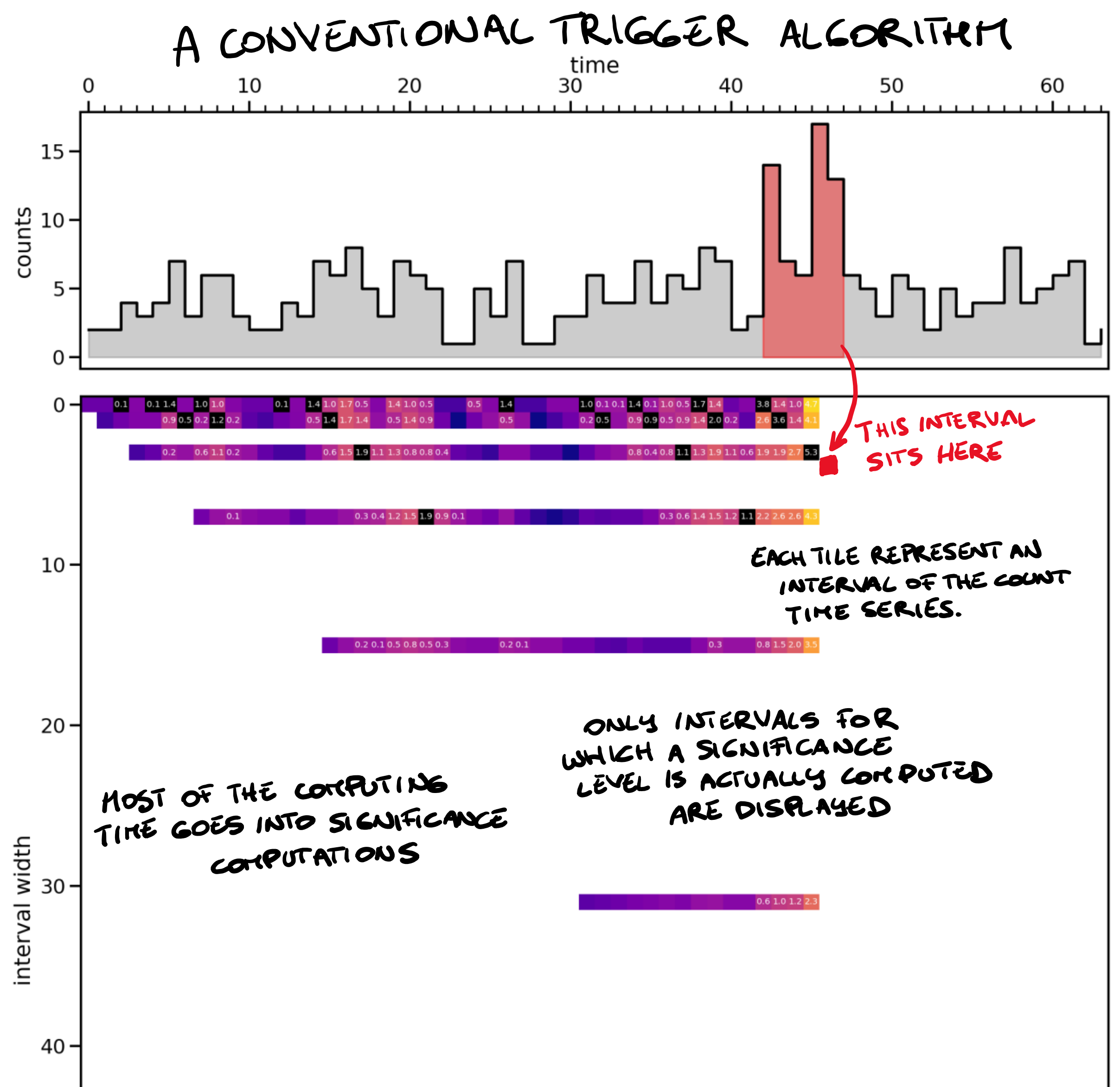
  The key fact making this possible: **solutions at a given time are piece-wise** functions (e.g. quadratics) which can be manipulated efficienty.

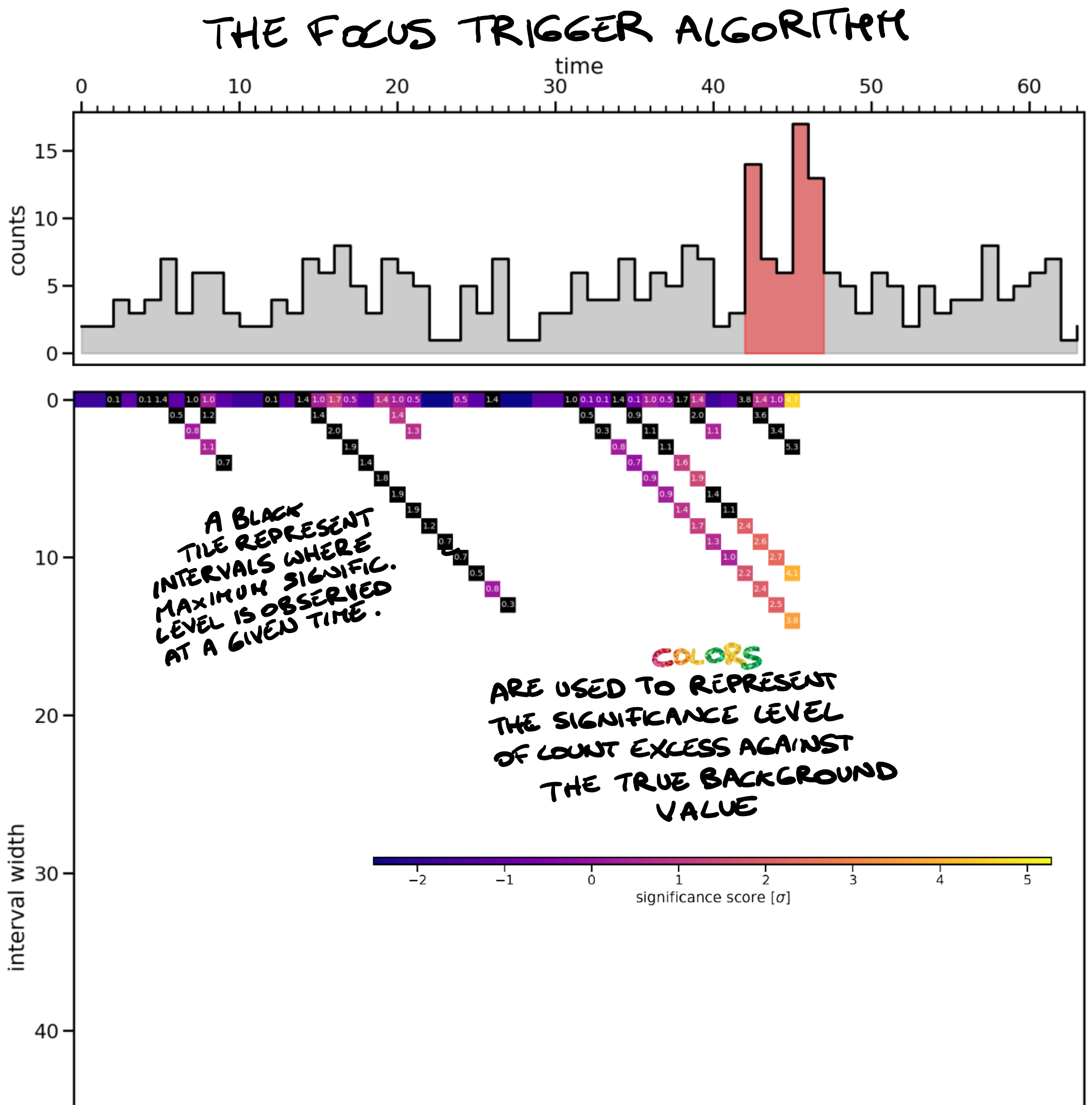
- These pieces are what you store in the memory state and represent changepoints.

A visual comparison

https://www.dropbox.com/s/kbes6o98b09sms0/BM_background_visualization_export.html?dl=0

https://www.dropbox.com/s/tsc8udpt3tzc5fu/focus_background_sworcw_export.html?dl=0





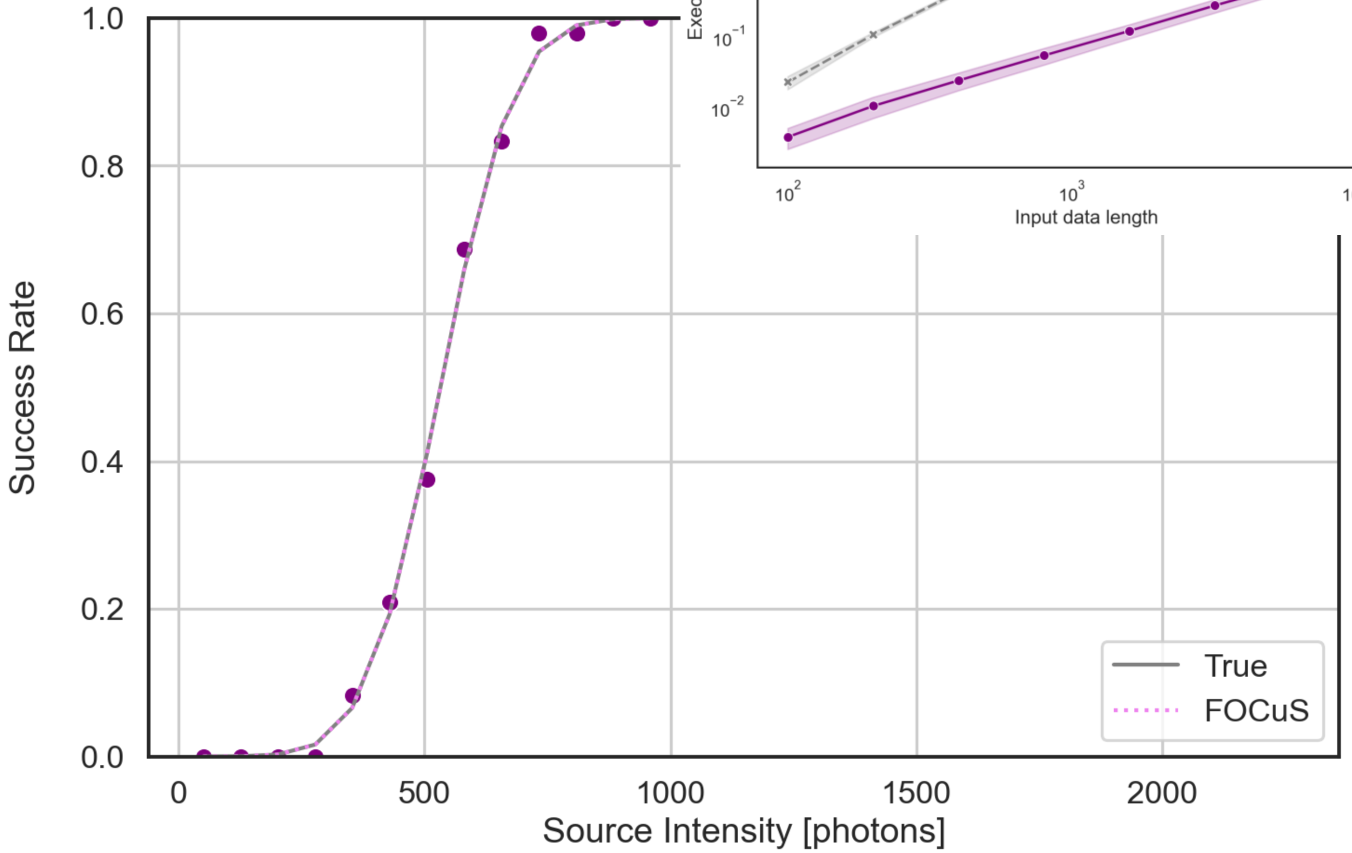
Some results: detection efficiency

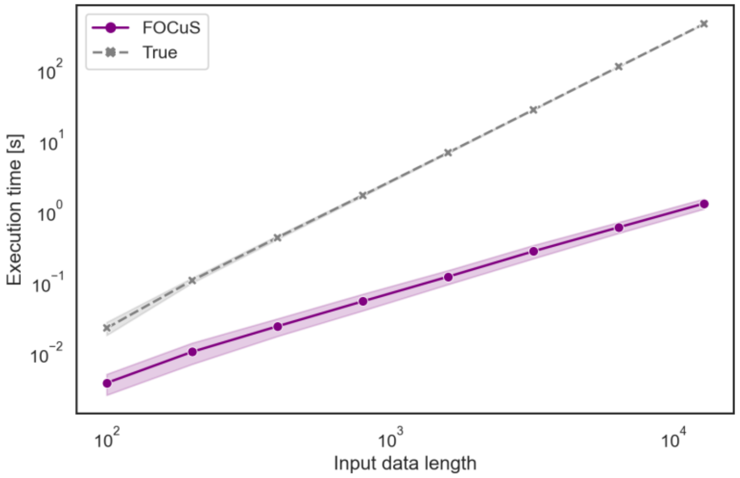
Note:

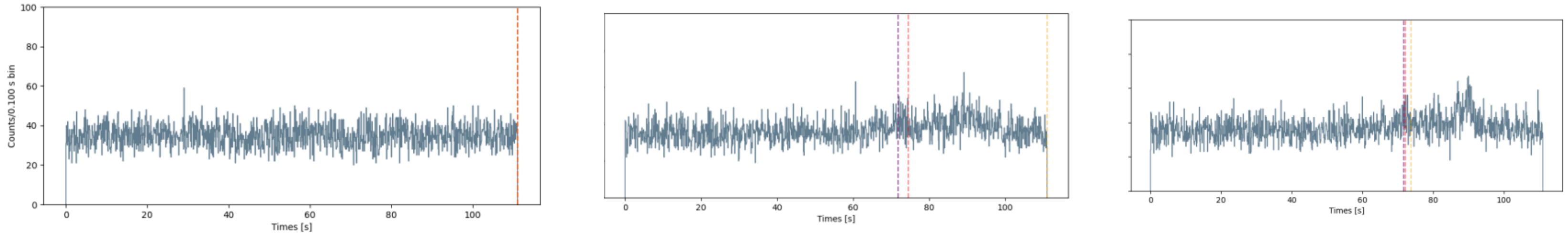
1. Testing against a benchmark trigger algorithm designed to simulate the operations of the algorithm serving Fermi-GBM.
2. Constant, poissonian background.
3. GRB time profile modelled after real observations of **long burst** GRB120707800.

Results:

1. Exact implementation of FOCuS operating with information on the true background rate had performances identical to those of an ideal, exhaustive search algorithm.







Assessing background

Whatever your detection algorithm, you will have to assess a background count-rate against which compare your observation.
In online applications the background level is guessed from the same data which are tested.
In many ways this is a problem of choosing a filter.

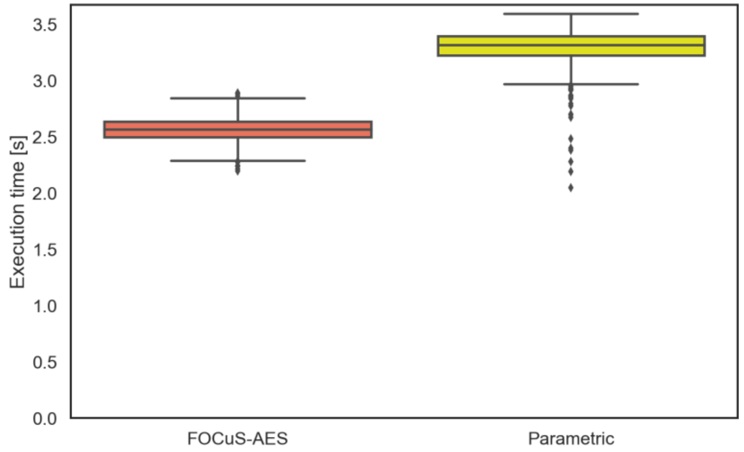
The conventional way – SMA:

$$M_{t,n} = M_{t-1} + \frac{x_t - x_{t-n+1}}{n}$$

Other MA approaches are investigation worthy – e.g., EMA:

$$S_t = \alpha x_t + (1 - \alpha) S_{t-1}$$

Some results: detection efficiency

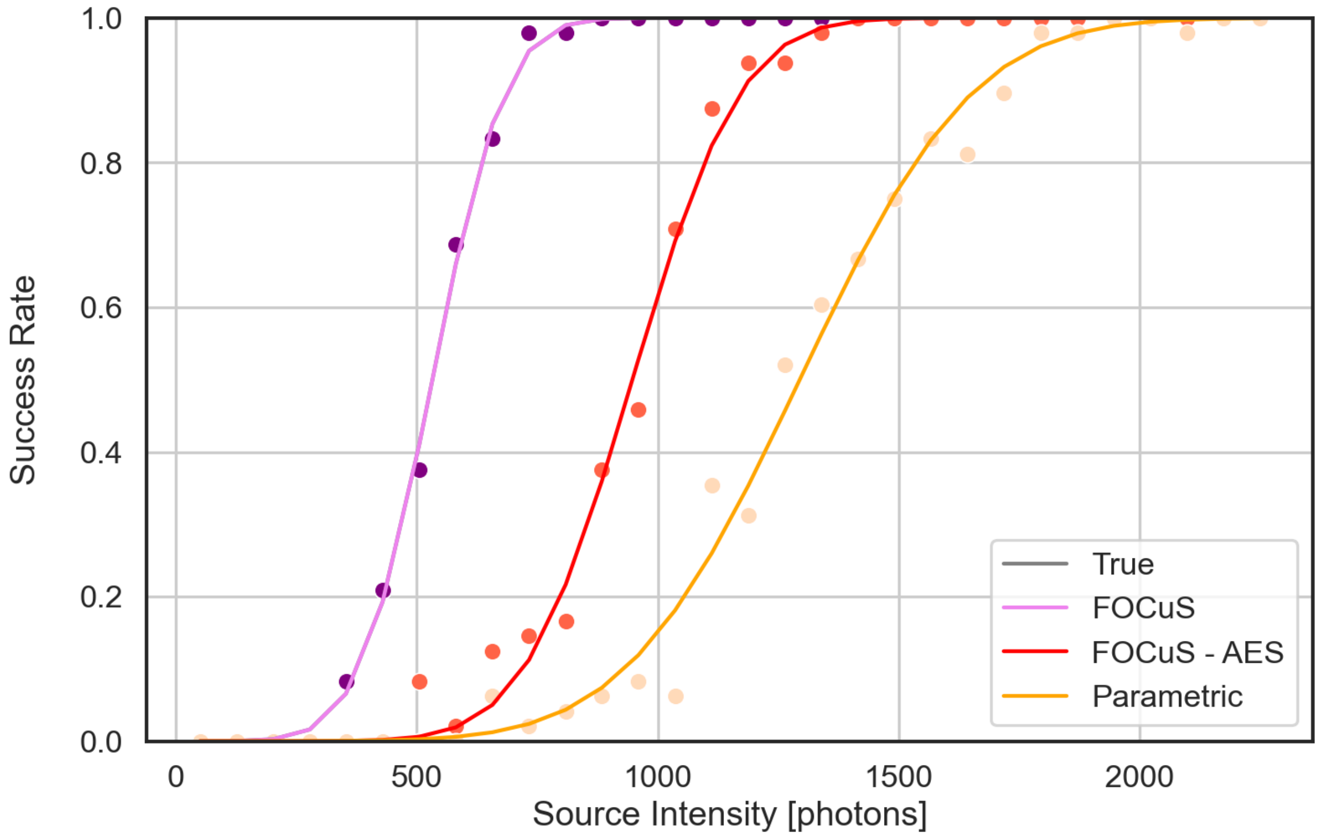


Note:

1. Testing against a benchmark trigger algorithm designed to simulate the operations of the algorithm serving Fermi-GBM.
2. Constant, poissonian background.
3. GRB time profile modelled after real observations of **long burst** GRB120707800.

Results:

1. Exact implementation of FOCuS operating with information on the true background rate had performances identical to those of an ideal algorithm.
2. Approximated implementations of FOCuS with automatic background assessment outeperformed the benchmark algorithm in all our tests.



That’s all

Sorry no biblio.

Thank you.

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