UNIVERSITÀ DI TRENTO

HERMES Scientific Pathfinder

UNIVERSITÀ DEGLI STUDI DI PALERMO

INAF ISTITUTO NAZIONALE DI ASTROFISICA OSSERVATORIO ASTRONOMICO DI TRIESTE

PhD SST Space Science and Technology

DEPARTMENT OF

PHYSYCS

Temporal analysis of light-curves from transient sources

Detectors TOAs lists auto-calibration and evaluation of experimental delays

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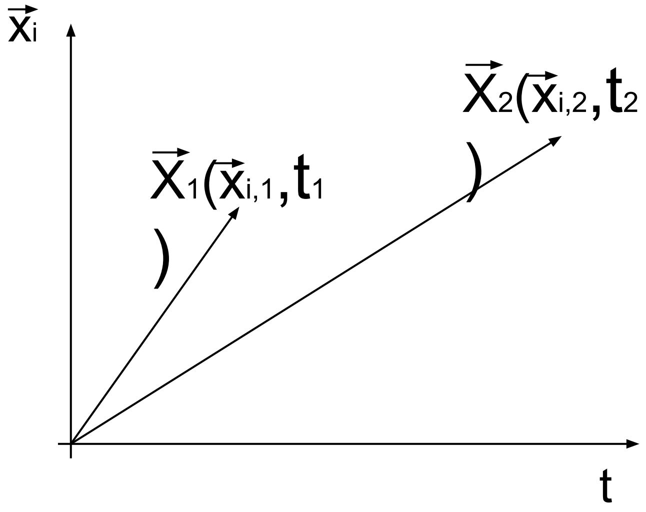
How to build a light curve

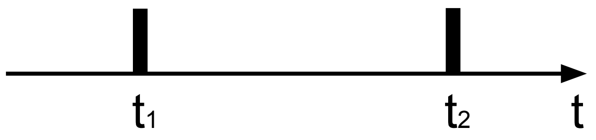
Th: A counter is a device that triggers when a generic event interacts with the material of the instrument, corresponding to the collapse of the wave function of the electromagnetic signal. We do not possess any absolute information about the rate of the observed signal.



- To deduce the experimental rate from counts is not a straightforward operation. The concept of instantaneous rate is analogous to deriving instantaneous velocity.

$$r(t) = \frac{1}{t_2 - t_1}$$

- The instantaneous rate is the inverse of the time difference between two consecutive events.
- It is necessary to have information about at least two arrival times.



$$P(\mu, k = 1) = r\,\Delta t\, e^{-r\Delta t}$$

- Similarly, many counts allows for deducing the average rate over the time Δt.
- With some probability, every possible rate value could have resulted in the counting of the event following the previous one considered as the reference event.

$$P(\mu, k) = \frac{\mu^k e^{-\mu}}{k!}$$

Poisson treatment of rate confidence levels

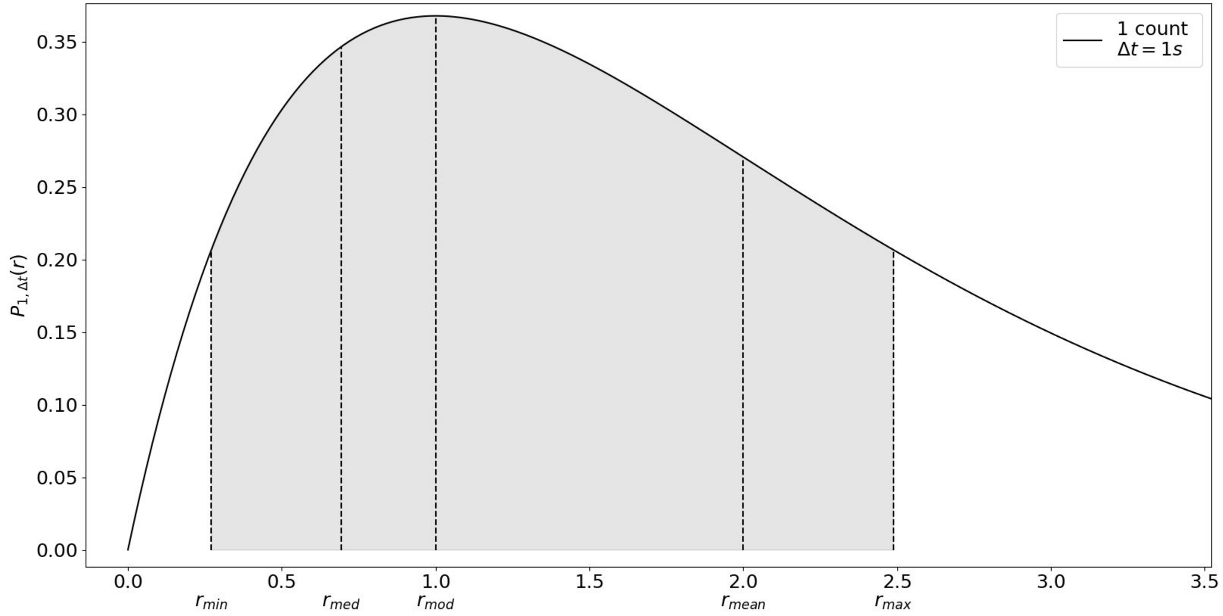
Leone et al., 2024a

$$P(\mu, k) = \frac{\mu^k e^{-\mu}}{k!}\ ,\ P(\mu, k=1) = r\,\Delta t\, e^{-r\Delta t}$$

$$\int_{r_{min}}^{r_{max}} P_{n,\Delta t}(r)\, dr = CL$$

$$P_{1,\Delta t}(r_{min}) = P_{1,\Delta t}(r_{max})$$

$$Mode = \frac{1}{\Delta t}$$

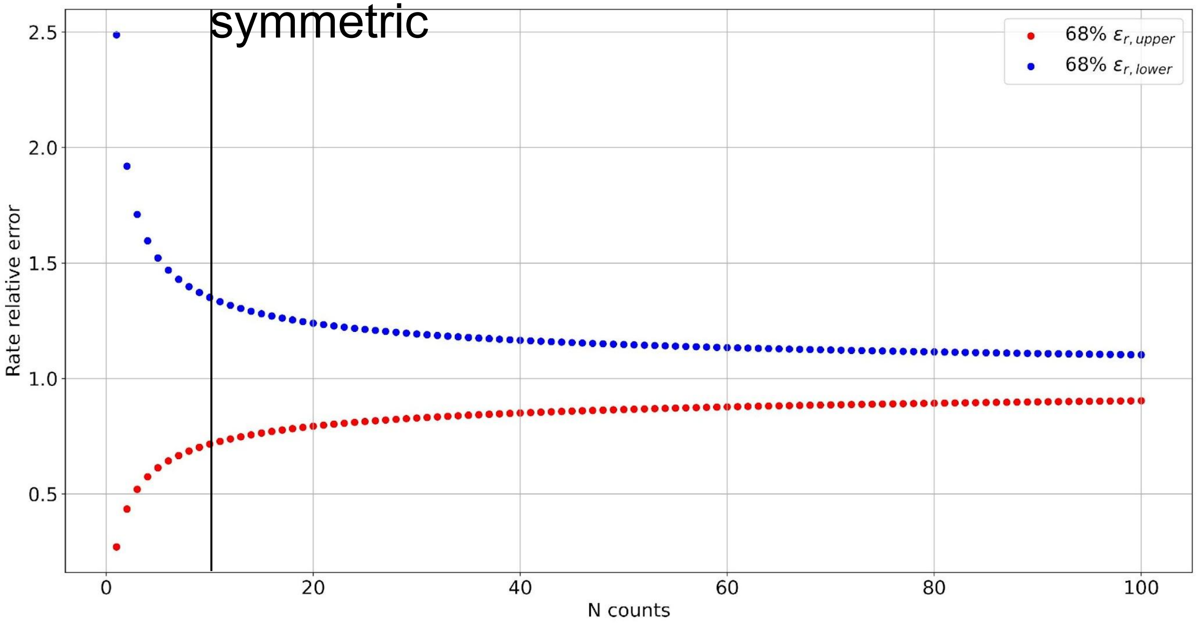


Poisson probability for a single event detection

Poisson treatment of rate confidence levels

Leone et al., 2024a

N>10: confidence level is symmetric



68% confidence level. Relative error in the rate as a function of the number of counted events.

Constant bin size light curves

- N=0 -> Rate = 0 c/s, but the confidence level represents only an upper limit value.
- Confidence levels for N<10 are not symmetric.
- N>10 $\varepsilon_r = \frac{1}{\sqrt{N}}$

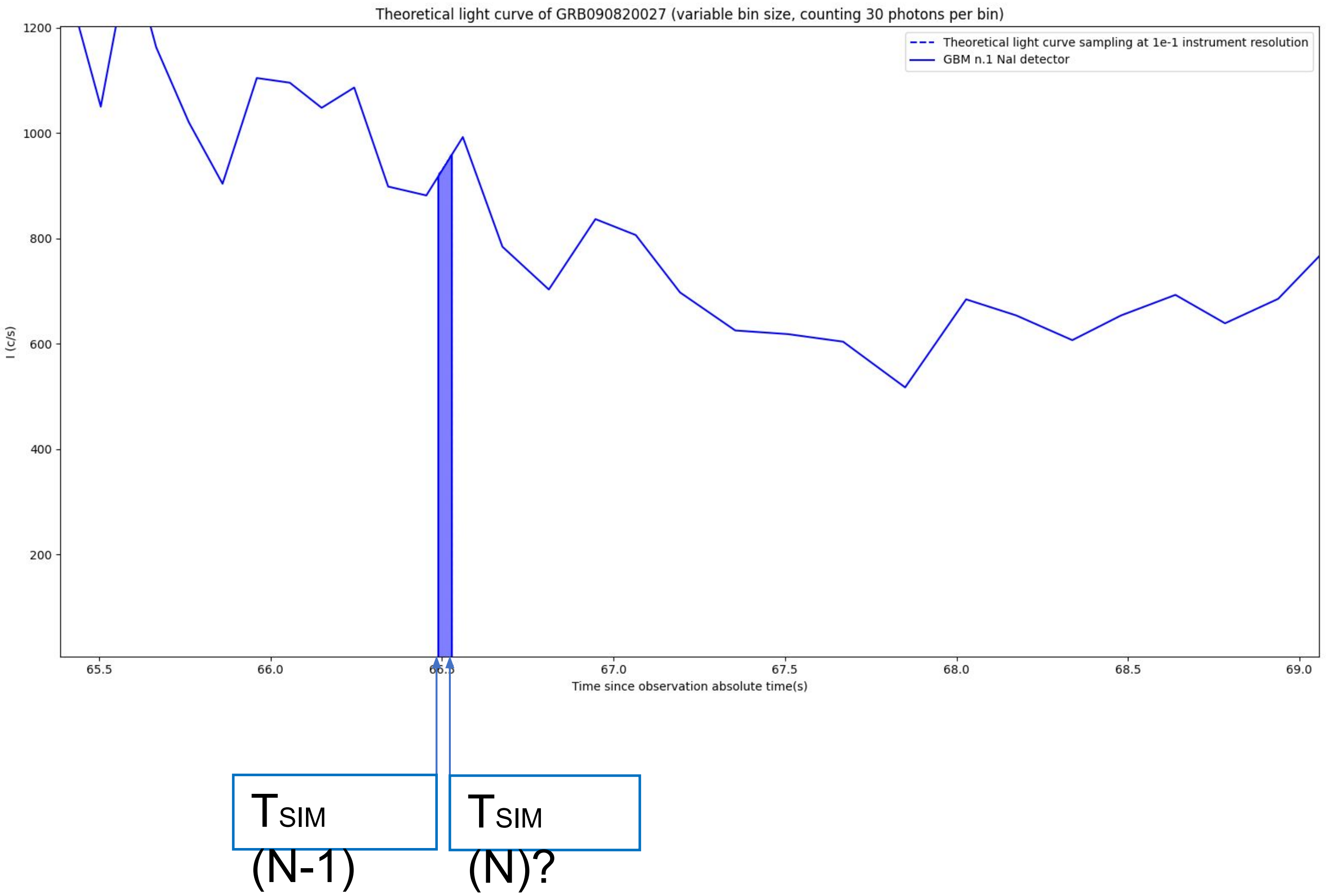
A variable bin size (with N>10) resolves all the described issues, ensuring a consistent light curve associated with uniform statistics.

A method to simulate a time variable rate

Leone et al., 2024a

- We want to avoid the huge waste of memory and significally reduce calculation time.
- Generalization of the inversion method for simulating time-varying processes

$$\int_{T_{SIM}(N-1)}^{T_{SIM}(N)} \lambda(t')\, dt' = -log[1 - RND(0,1)]$$



- By inverting this formula, you can solve a second order equation to extimate the following simulated TOA.

  - RND(0,1) return real values with a flat distribution
  - The integral has a simple trapezoidal solution (B+b) h / 2

A method to simulate a time variable rate

Leone et al., 2024a

$$\int_{T_{SIM}(N-1)}^{T_{SIM}(N)} \lambda(t')\,dt' = -log[1 - RND(0,1)]$$

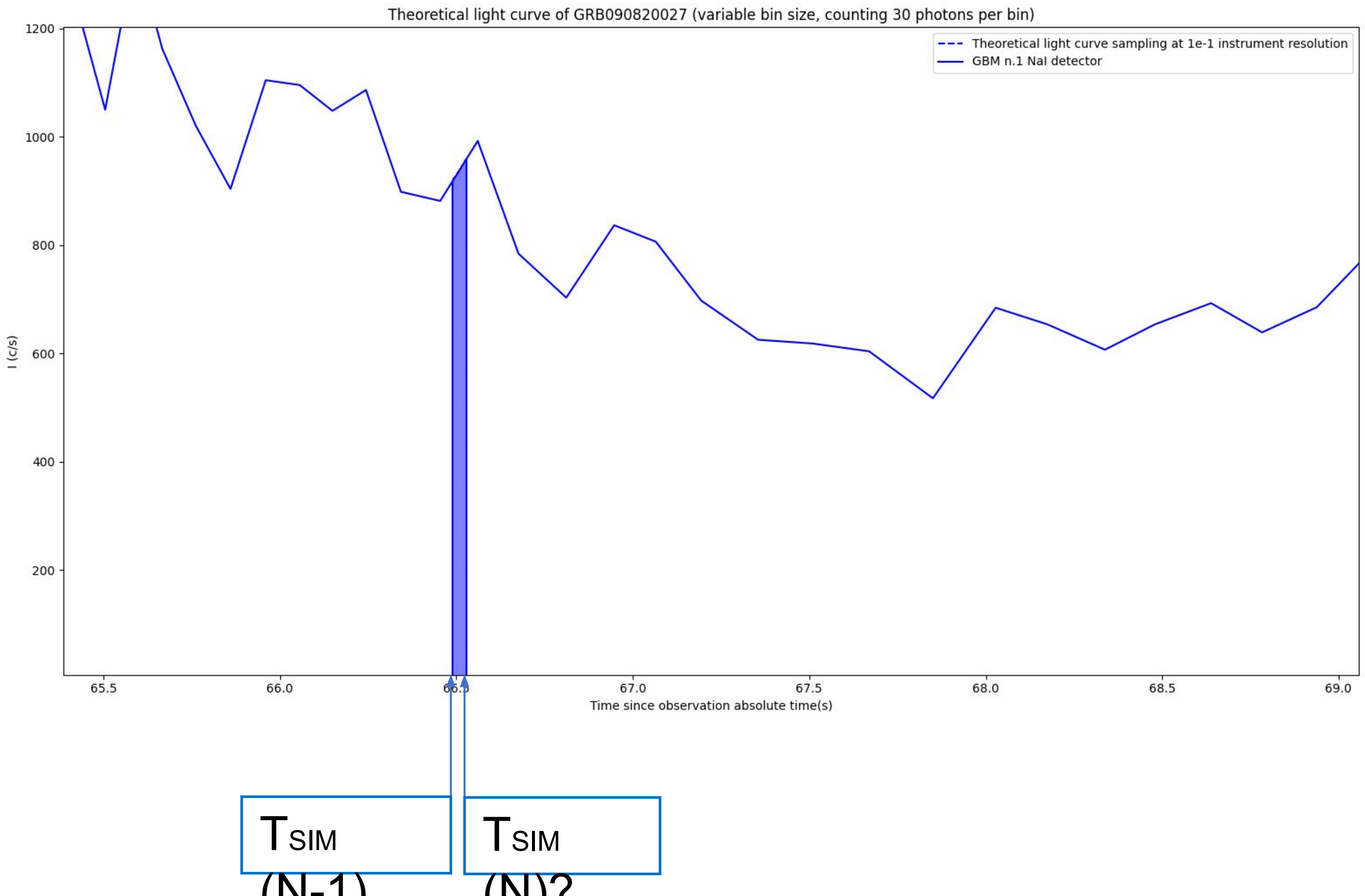
$$mx^2 + x(\lambda(\bar{t}) + \lambda_1 - mt_1 - m\bar{t}) - \bar{t}\lambda\bar{t} - \bar{t}\lambda_1 + mt_1\bar{t} - 2ZETA = 0$$

$$ZETA \equiv -ln\{1 - RND(0,1)\}$$

$$B = \lambda(\bar{t}) + \lambda_1 - mt_1 - m\bar{t}$$

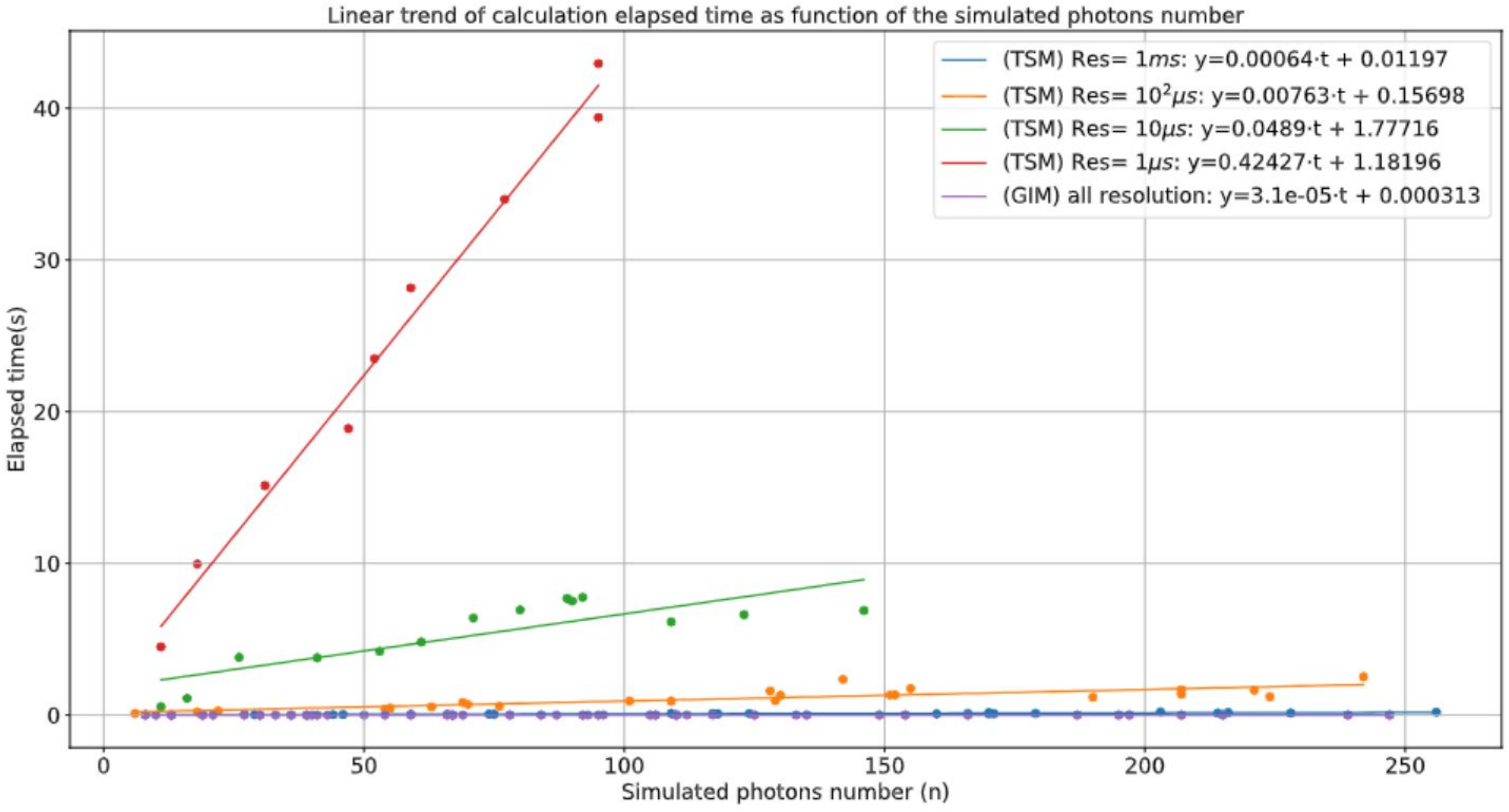
$$C = -\bar{t}\lambda\bar{t} - \bar{t}\lambda_1 + mt_1\bar{t} - 2ZETA$$

$$x = \frac{-B + \sqrt{B^2 - 4mC}}{2m}$$



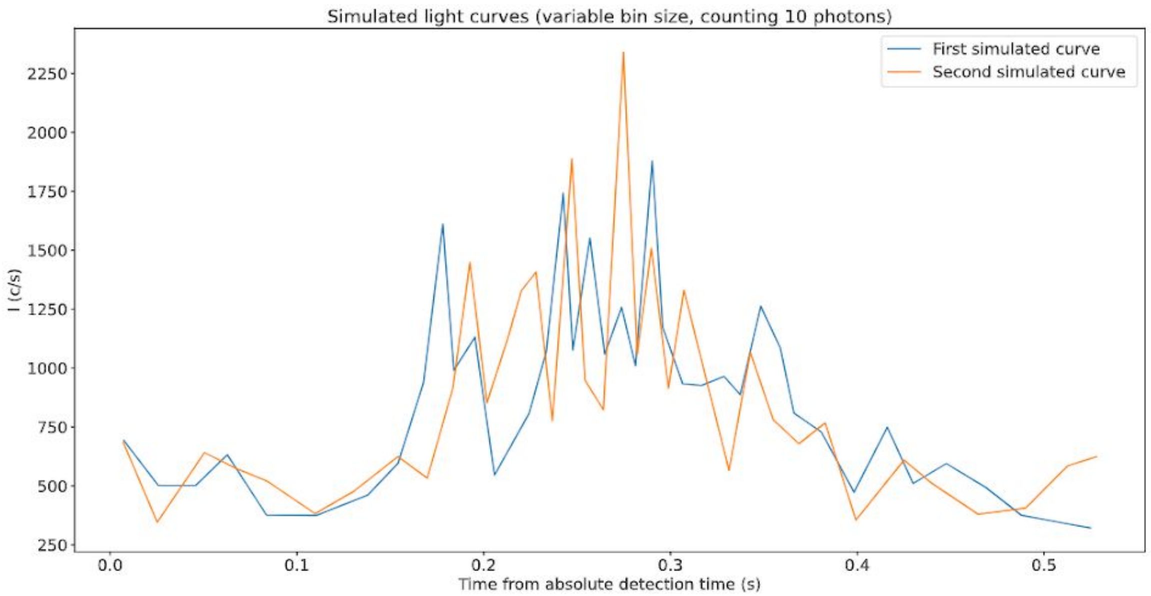
Generilized Inversion Method (GIM) vs Traditional Simulation Methods (TSI

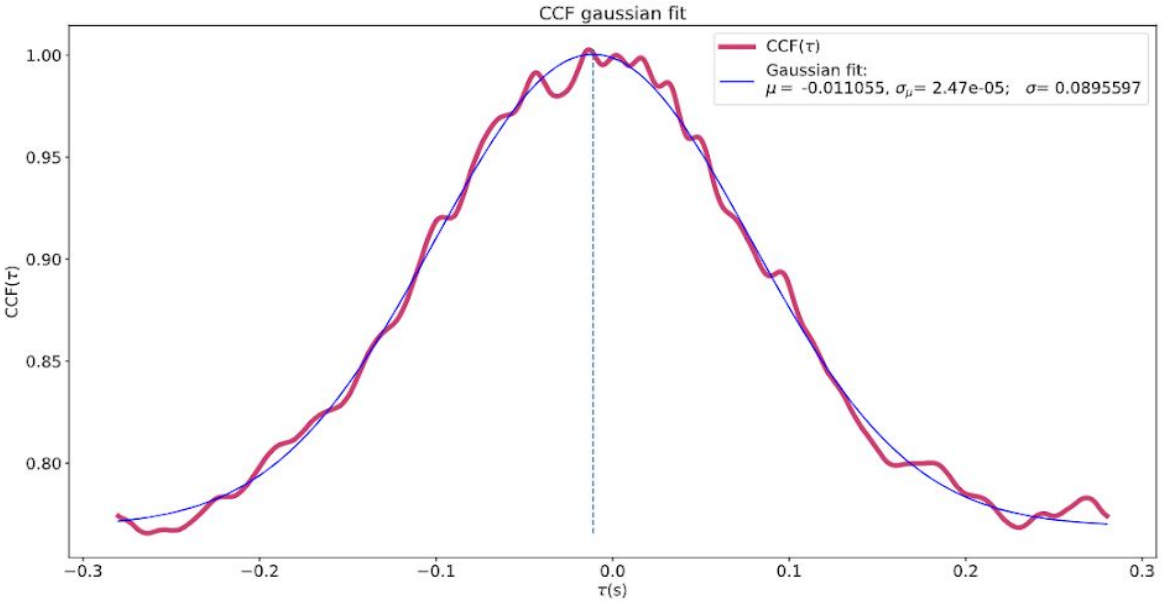
Leone et al., 2024a



Leone et al., 2024a

How to estimate experimental delay



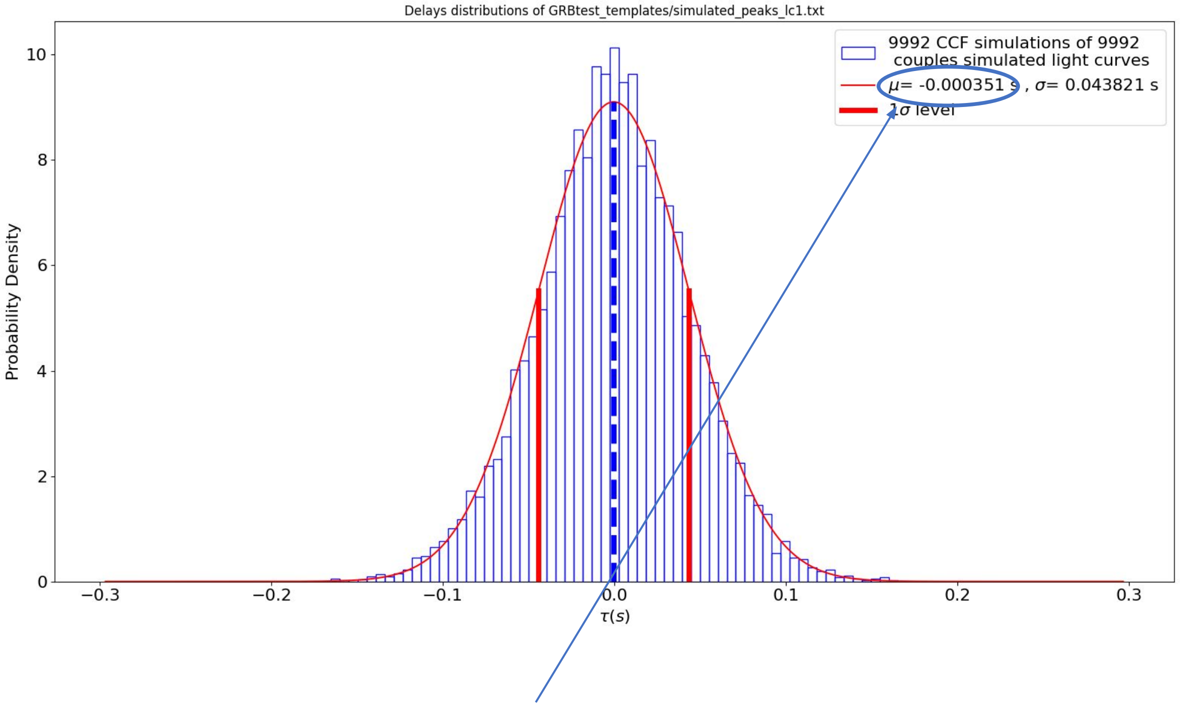


$$CCF(\tau) = \int_{-\infty}^{+\infty} x^*(\tau) \cdot y(t+\tau) d\tau$$

- Cross-correlation is a mathematical operation performed between two continuous theoretical signals.
- The "one-shot" cross-correlation function (CCF) can be considered as the theoretical delay only if we have knowledge of the true signals associated with the source.
- The experimental observations provided by the detectors are subject to Poissonian statistics, resulting from the quantum measurement process of the signal.
- In this case the ‘one shot’ CCF between two detectors light curve is just a particular possonian realization of the true delay.

Experimental delay = 'Statistical delay'

$$CCF(\tau) = \int_{-\infty}^{+\infty} x^*(\tau) \cdot y(t+\tau) d\tau$$



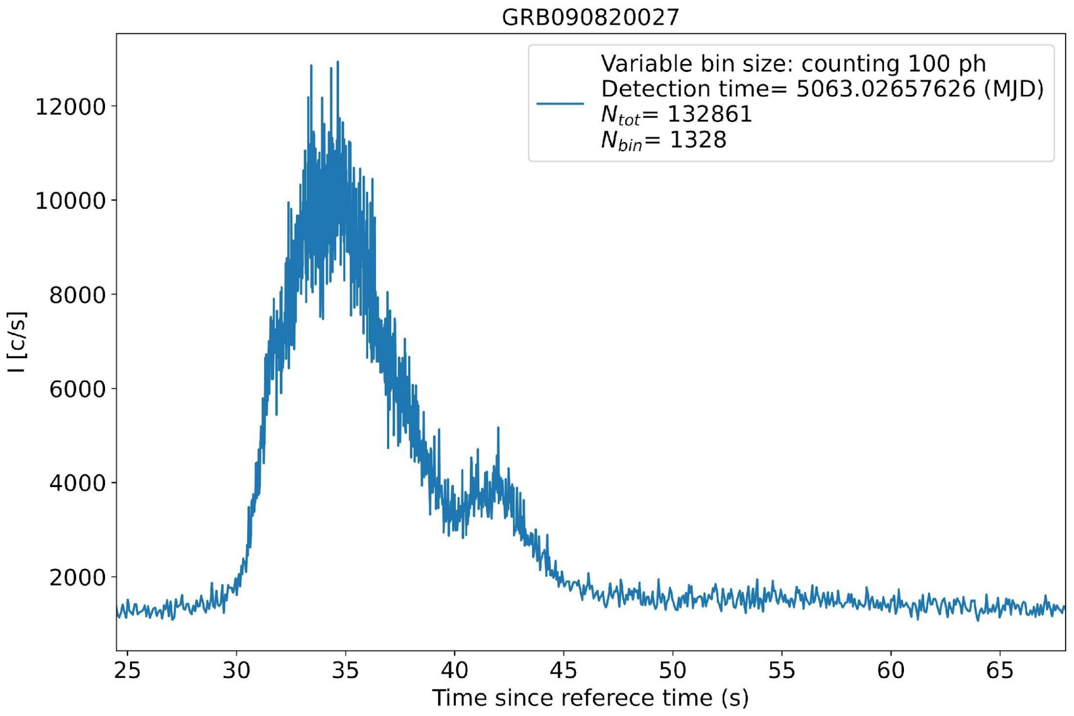
- The closest experimental delay to the true theoretical delay is the average of multiple experiments, and the associated error is the standard deviation of the distribution.

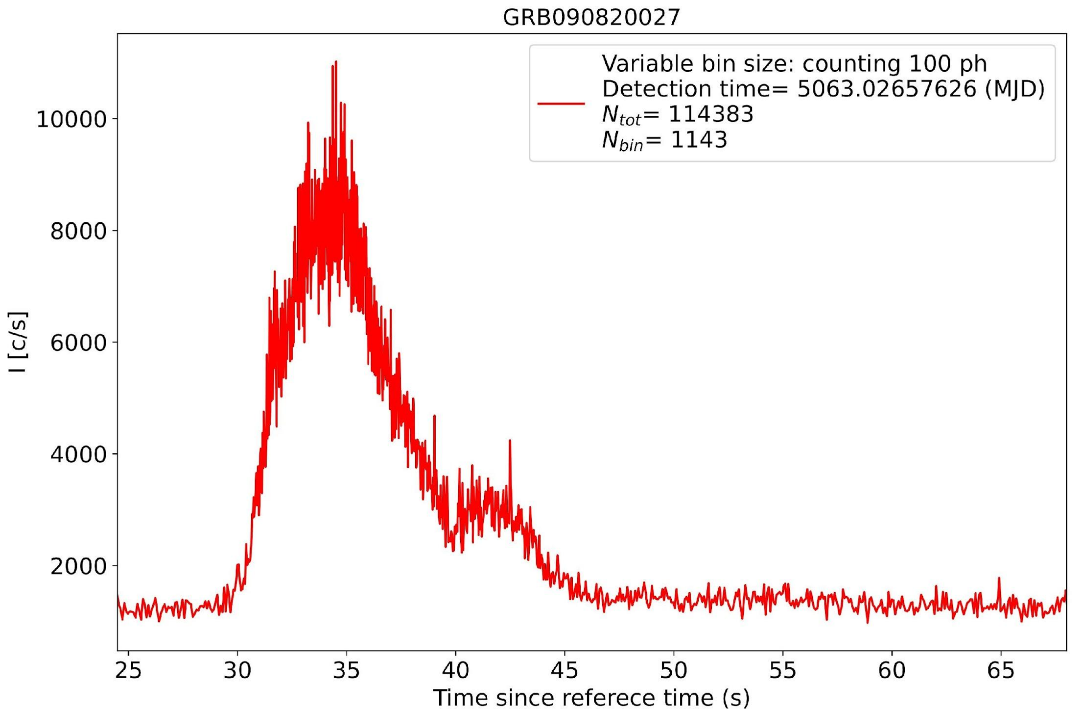
- Cross-correlation is a mathematical operation performed between two continuous theoretical signals.
- The "one-shot" cross-correlation function (CCF) can be considered as the theoretical delay only if we have knowledge of the true signals associated with the source.
- The experimental observations provided by the detectors are subject to Poissonian statistics, resulting from the quantum measurement process of the signal.
- In this case the 'one shot' CCF between two detectors light curve is just a particular possonian realization of the true delay.

THE QUANTUM FINGERPRINT

Leone et al., 2024b

Each detector observation corresponds to a specific Poissonian realization of the electromagnetic signal interacting with the detector material. Each realization is linked to a distinct Poissonian footprint, referred to as the "**quantum fingerprint**".





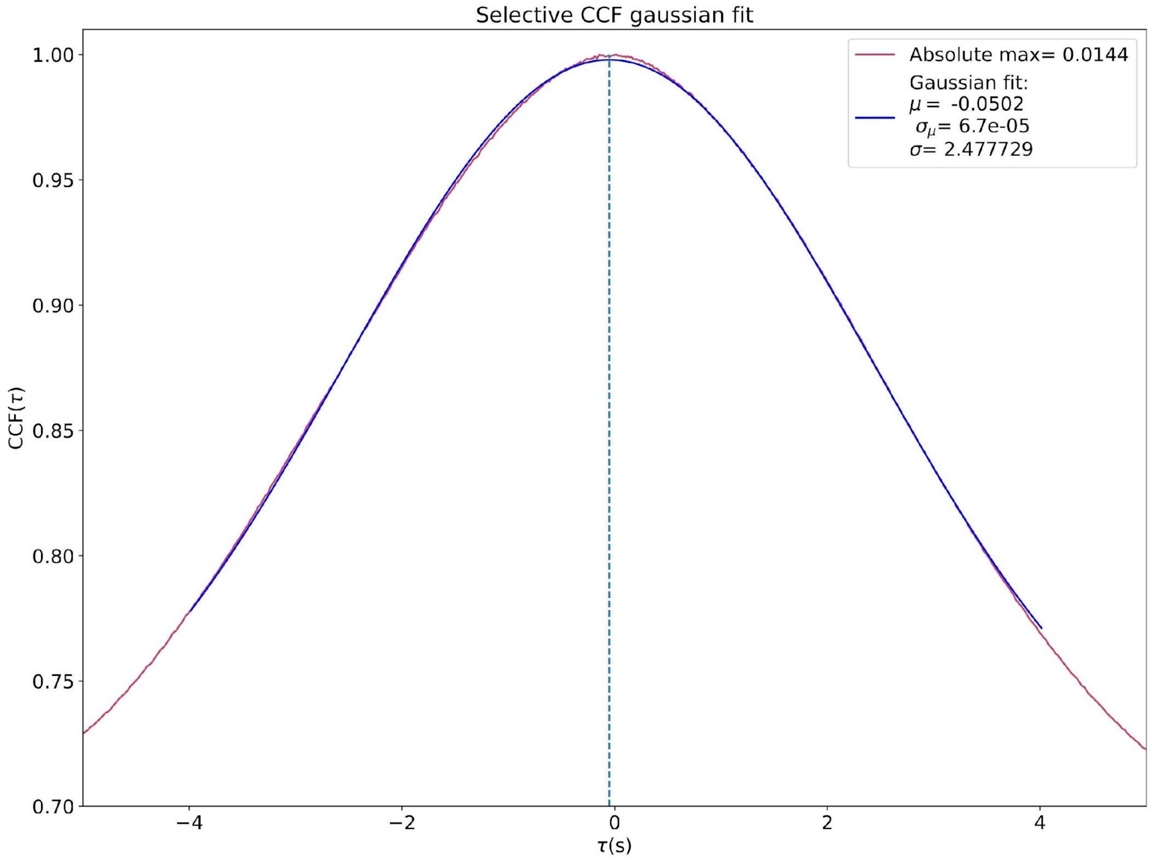
Fermi/GBM detectors observing GRB090820027

THE QUANTUM FINGERPRINT

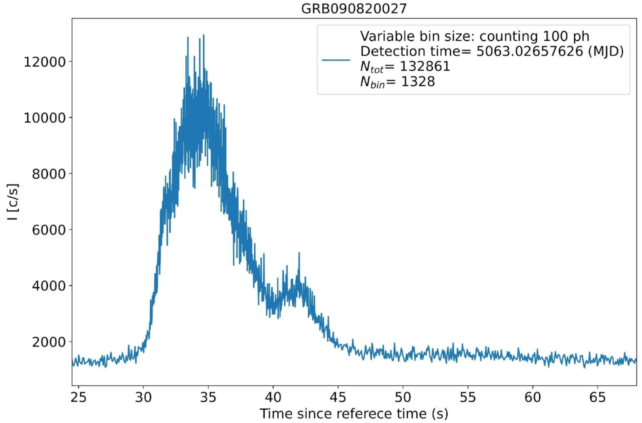
Leone et al., 2024b

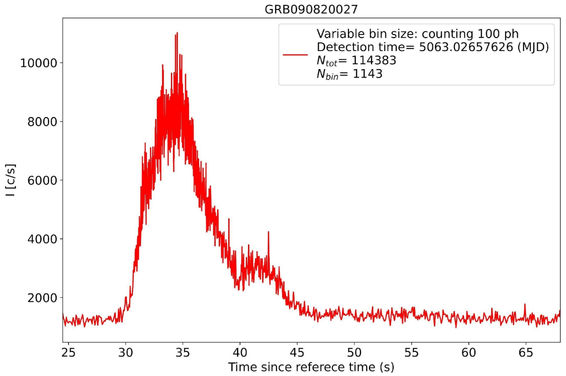
A significative delay between GRB light curves of two identical detectors observing the same source? **No!**
(equally spatially located, same energy band, 2 identical NaI detectors)

If we had 100 GBM detectors at our disposal, the distribution of delays would be centered around zero delay.



The standard deviation of the distribution informs us about the extent to which individual delays fluctuate around zero.



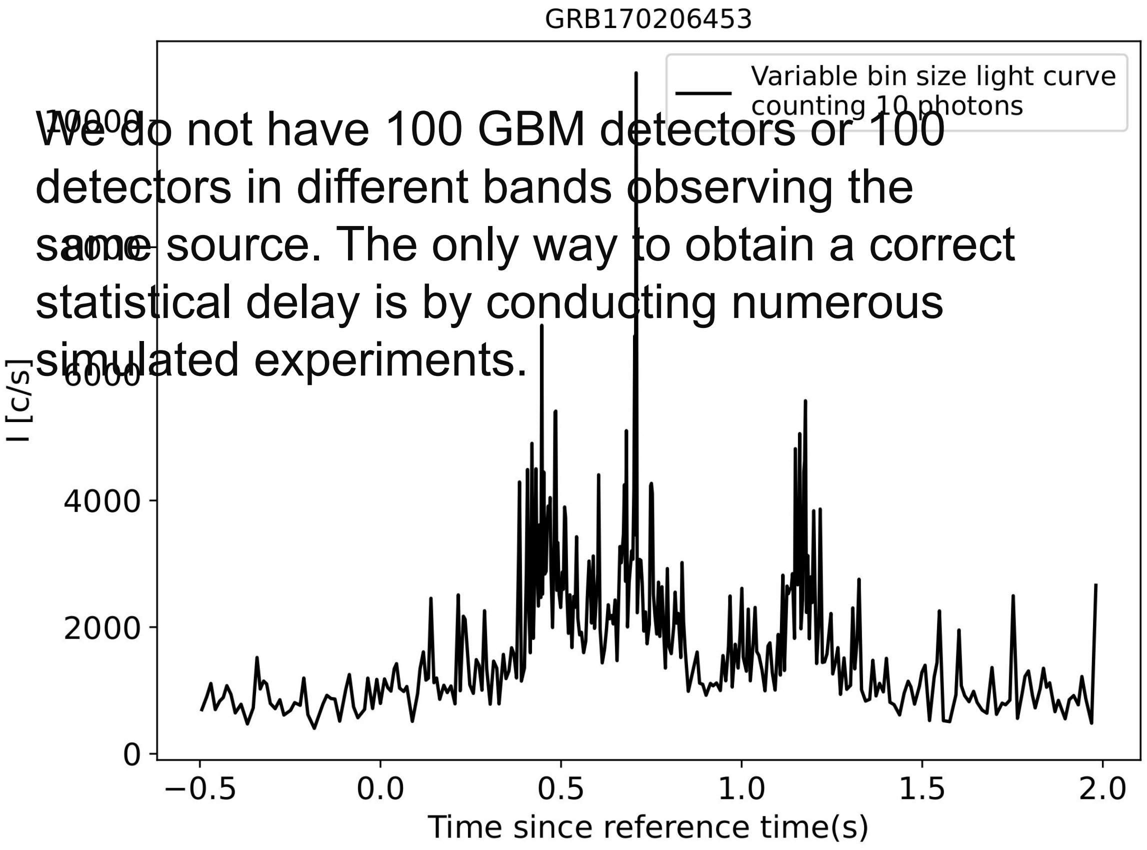


«Quantum mechanics at work»

THE QUANTUM FINGERPRINT

Leone et al., 2024b

How to manage with light curves simulation

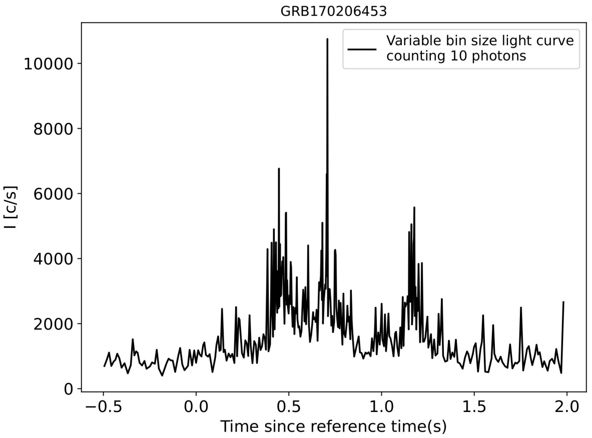


We do not have 100 GBM detectors or 100 detectors in different bands observing the same source. The only way to obtain a correct statistical delay is by conducting numerous simulated experiments.

THE QUANTUM FINGERPRINT

Leone et al., 2024b

How to manage with light curves simulation

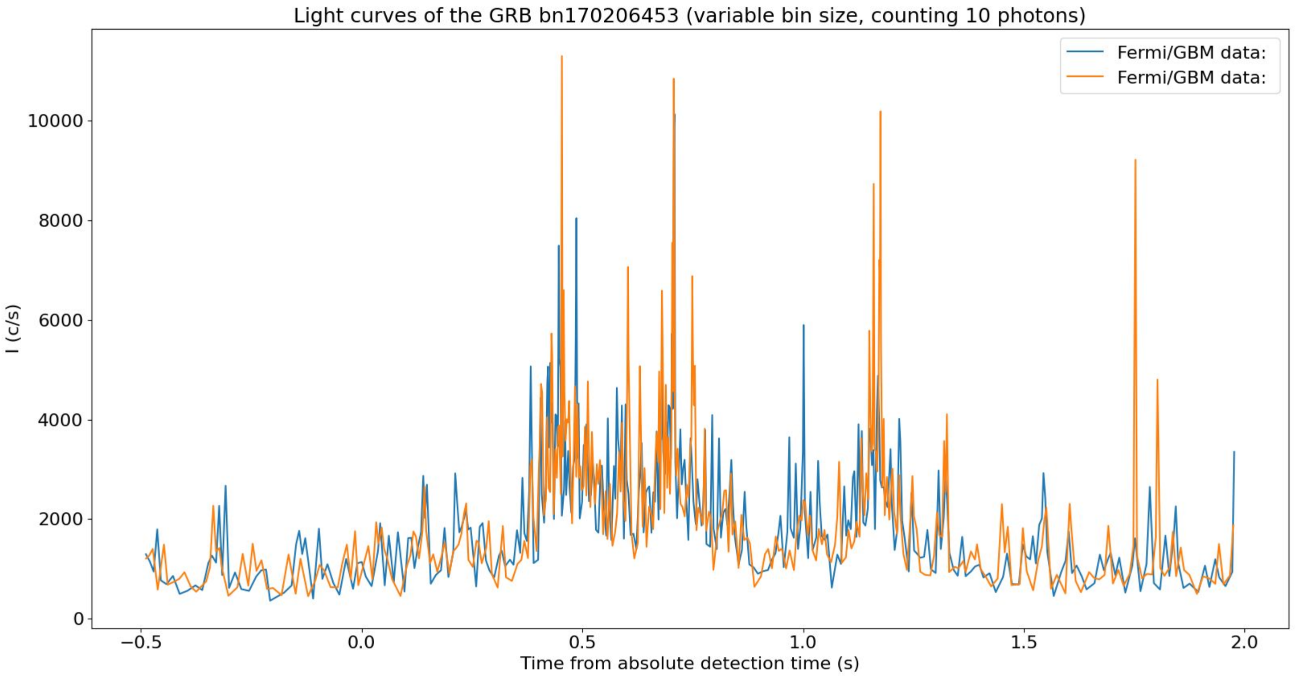


Starting experimental observation

Single
Pool
Method

CCF between light curves simulated
from the same poiss. realization

A significative narrow peak appears



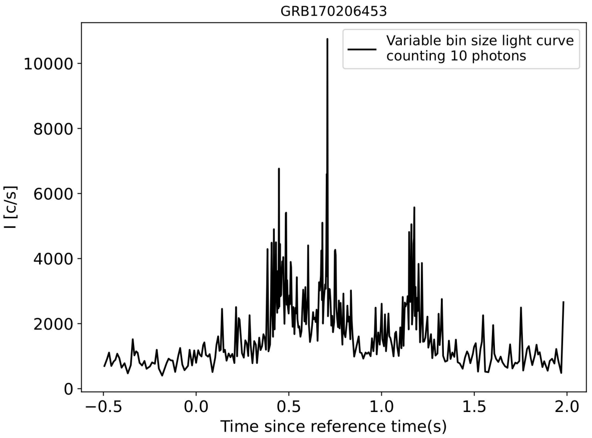
Both two simulated light curves have the same quantum fingerprint

Two light curves are simulated from the same Poisson Realization: they are associated with the same quantum fingerprint related to that experimental observation.

THE QUANTUM FINGERPRINT

Leone et al., 2024b

How to manage with light curves simulation



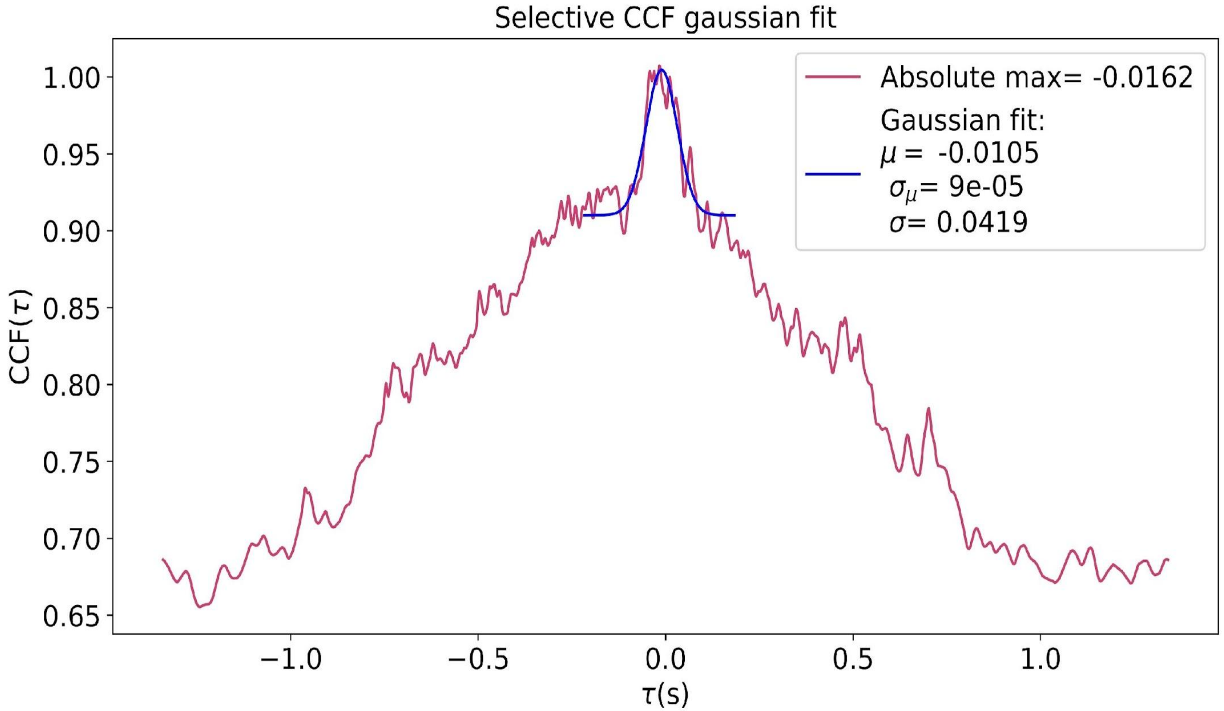
Starting experimental observation

Double Pool Method

CCF between light curves obtained by randomly splitting in 2 the starting TOAs list

Light curves obtained by the two sub-TOAs lis

The narrow peak disappears



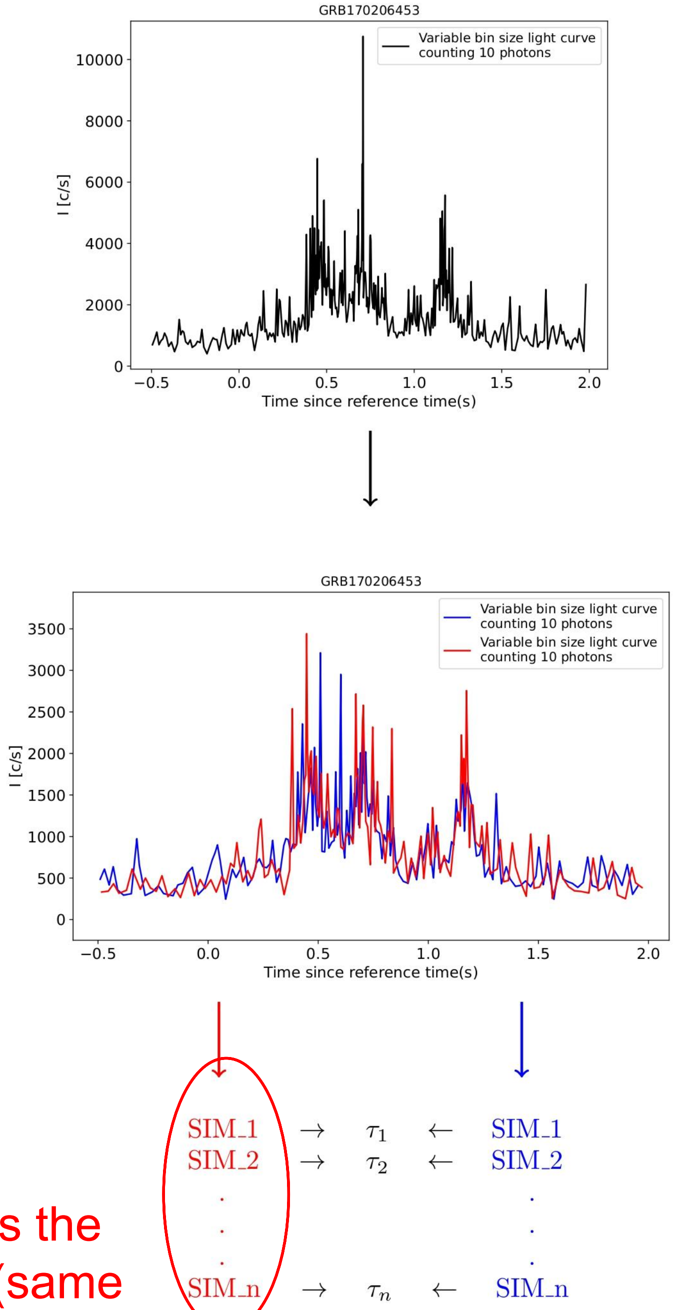
The two simulated light curves have different quantum fingerprints

The observed experimental TOAs list is randomly divided in two sub-TOAs lists. The only way to delete the quantum fingerprint effect is by halving the starting TOAs list.

DETECTOR AUTO-CALIBRATION

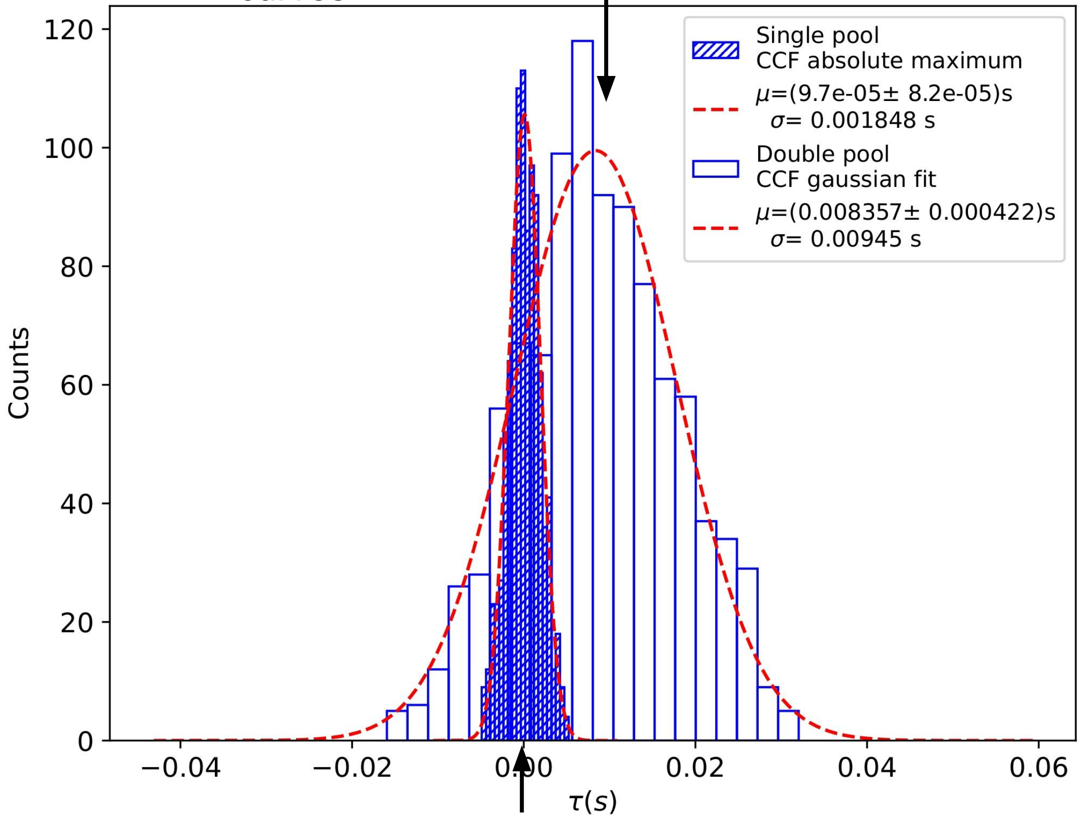
DOUBLE POOL METHOD

CCFs are performed between light curves simulated from two different poissonian realization (different quantum fingerprints – no CCF peak)



Single pool method: cross-correlating light curves obtained by simulating always the same poissonian realization (same quantum fingerprint)

Double pool method provides a distribution that reflect the real statistic of the observed GRB. The distribution is centered around the intrinsic delay between the two randomly half splitted curves

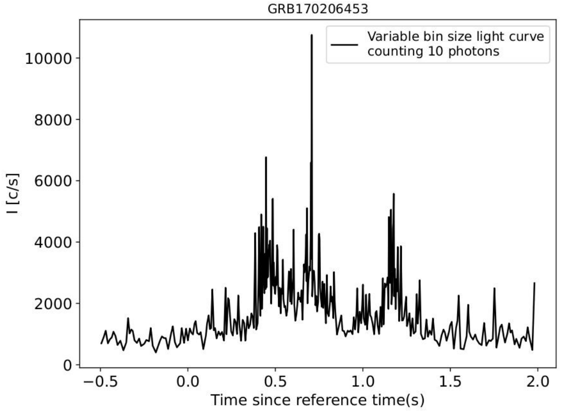


Single pool method results in a false narrowed distribution around zero

DETECTOR AUTO-CALIBRATION

MODIFIED
DOUBLE POOL
METHOD

1. Two lists of TOAs are obtained by randomly dividing the initial TOAs list
↓
Two light curve
↓
A delay is obtained by CCF



TOAs_1→ τ_1 ← TOAs_1

TOAs_2 . TOAs_2

.

.

1. Other two lists of TOAs are obtained by randomly dividing the initial TOAs list
↓
Two light curve
↓
A delay is obtained by CCF

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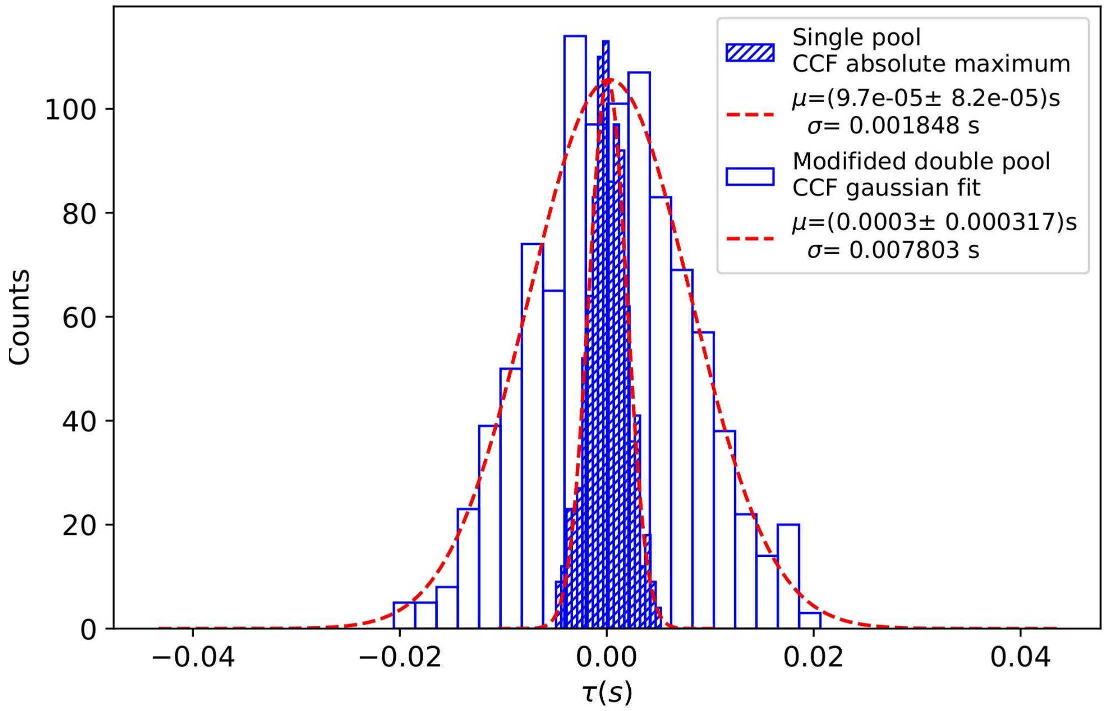
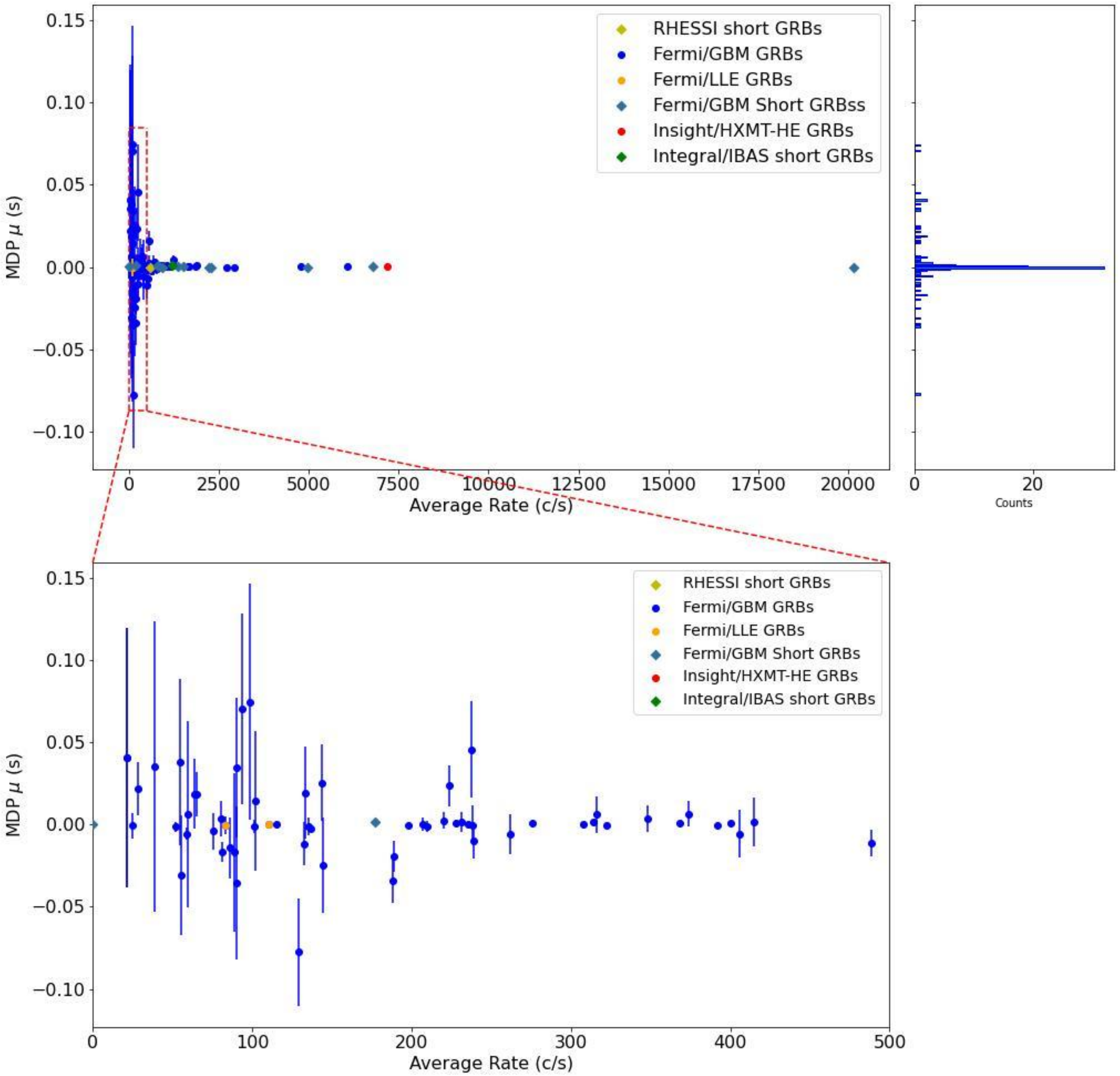


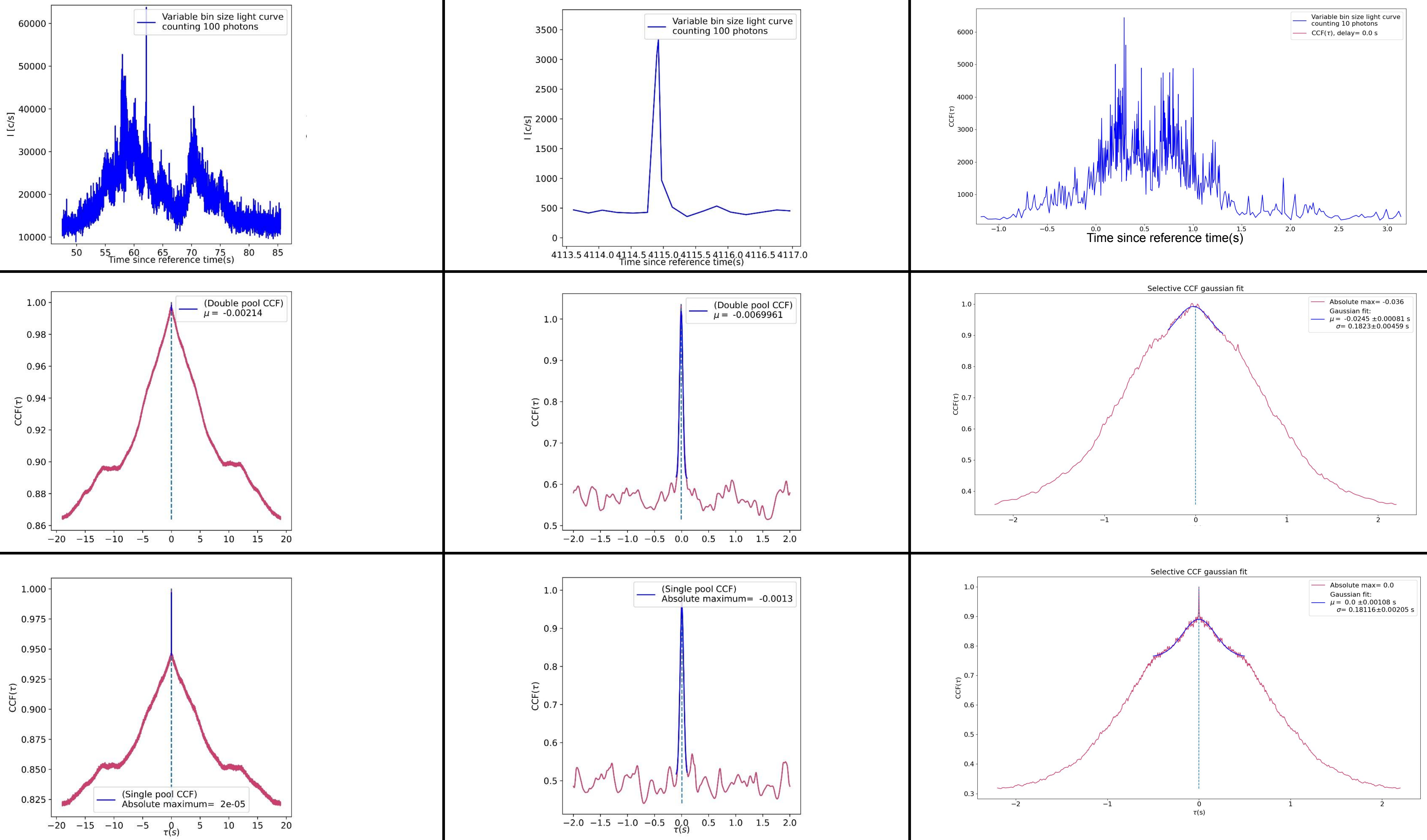
Auto-calibration intrinsic delays

Leone et al., 2024c

- Centroids of distribuions obtained by applying the MDP auto-calibration method to detectors data.
- 150 GRBs auto-calibration shows zero compatibility by considering the error on the mean (according to poissonian statistics).



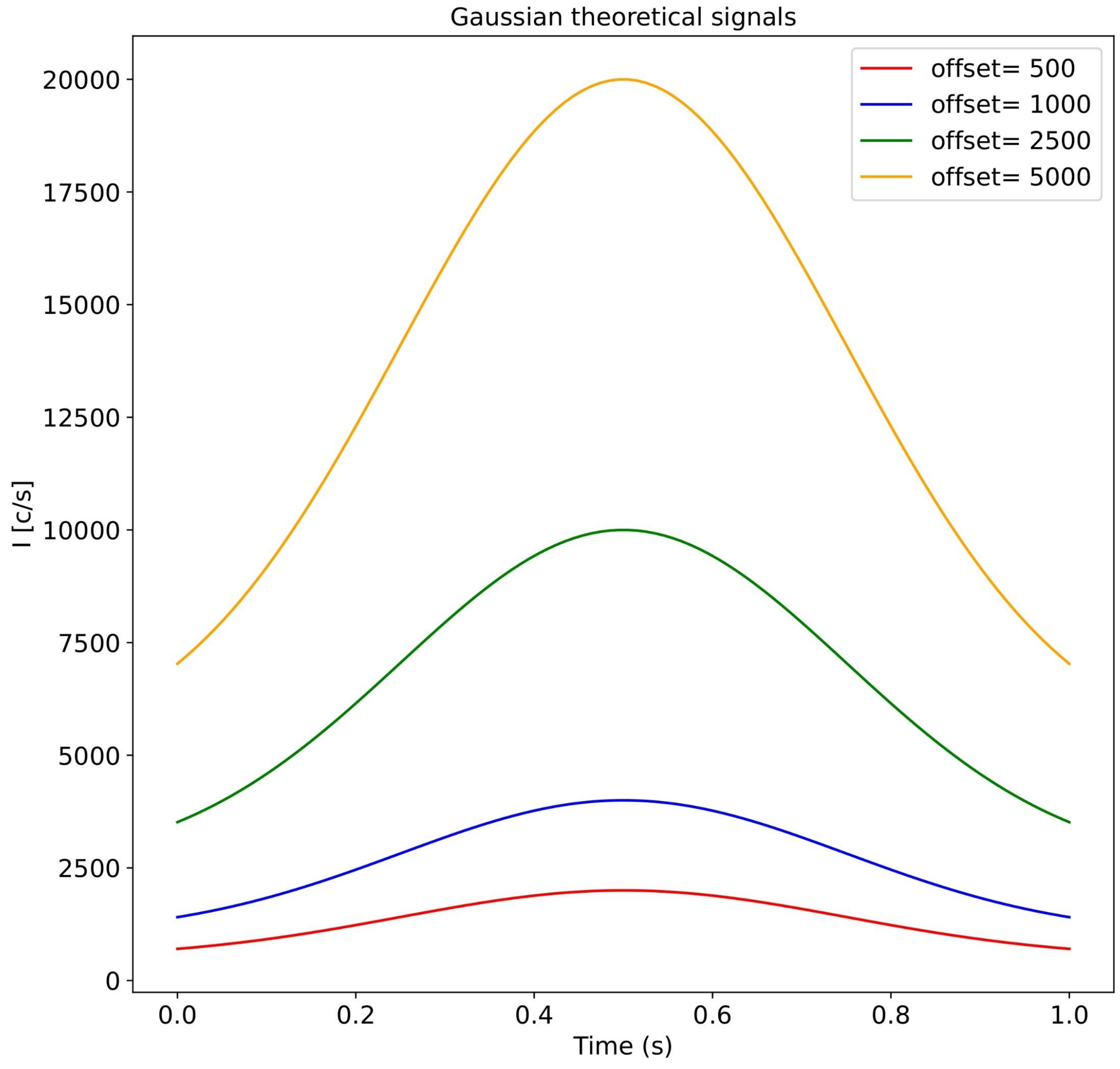
	Insight/HXMT-HE 1-600 (KeV)	Integral/IBAS 15-200 (KeV)	RHESSI 0.001 - 15 (MeV)

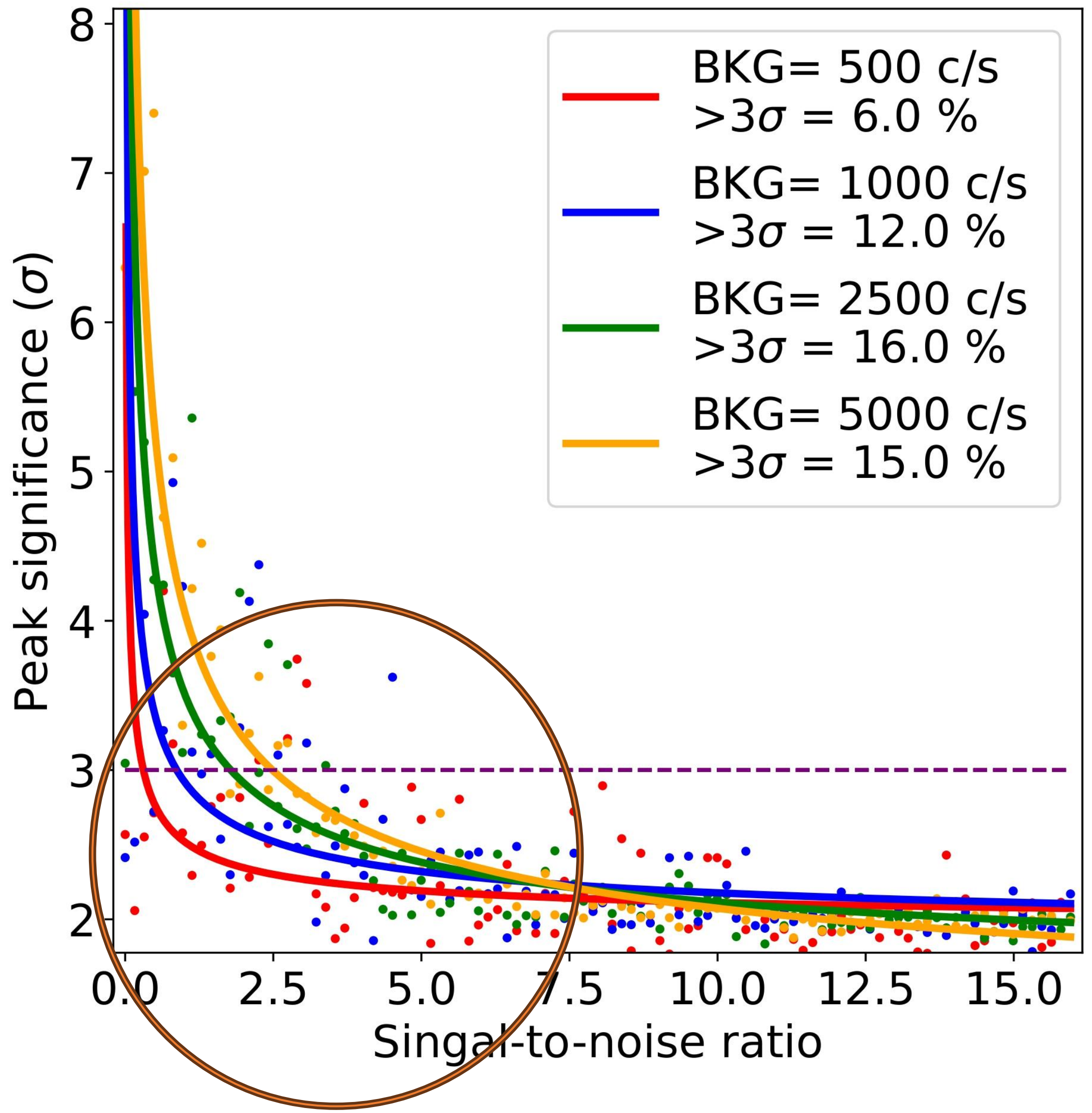


Modified Double Pool Method

Single Pool Method

The quantum fingerprint effect increases as the signal-to-noise-ratio decrease

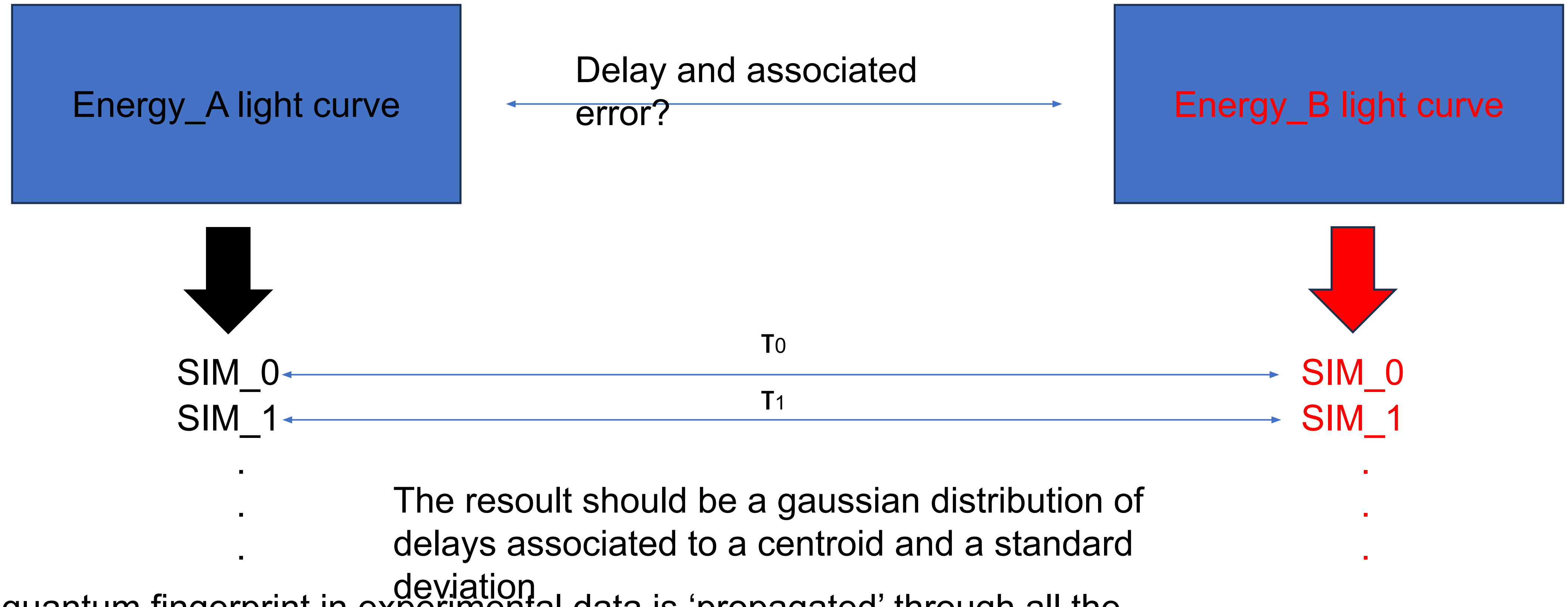




CCF techniques for multi-energy bands light curves

How to delete quantum fingerprint effect during delays and associated errors estimations

- When we obtain a TOAs list from a detector, we can build an experimental light curve as a specific poissonian realization of the observed electromagnetic signal. This is associated with a particular ‘quantum fingerprint’.



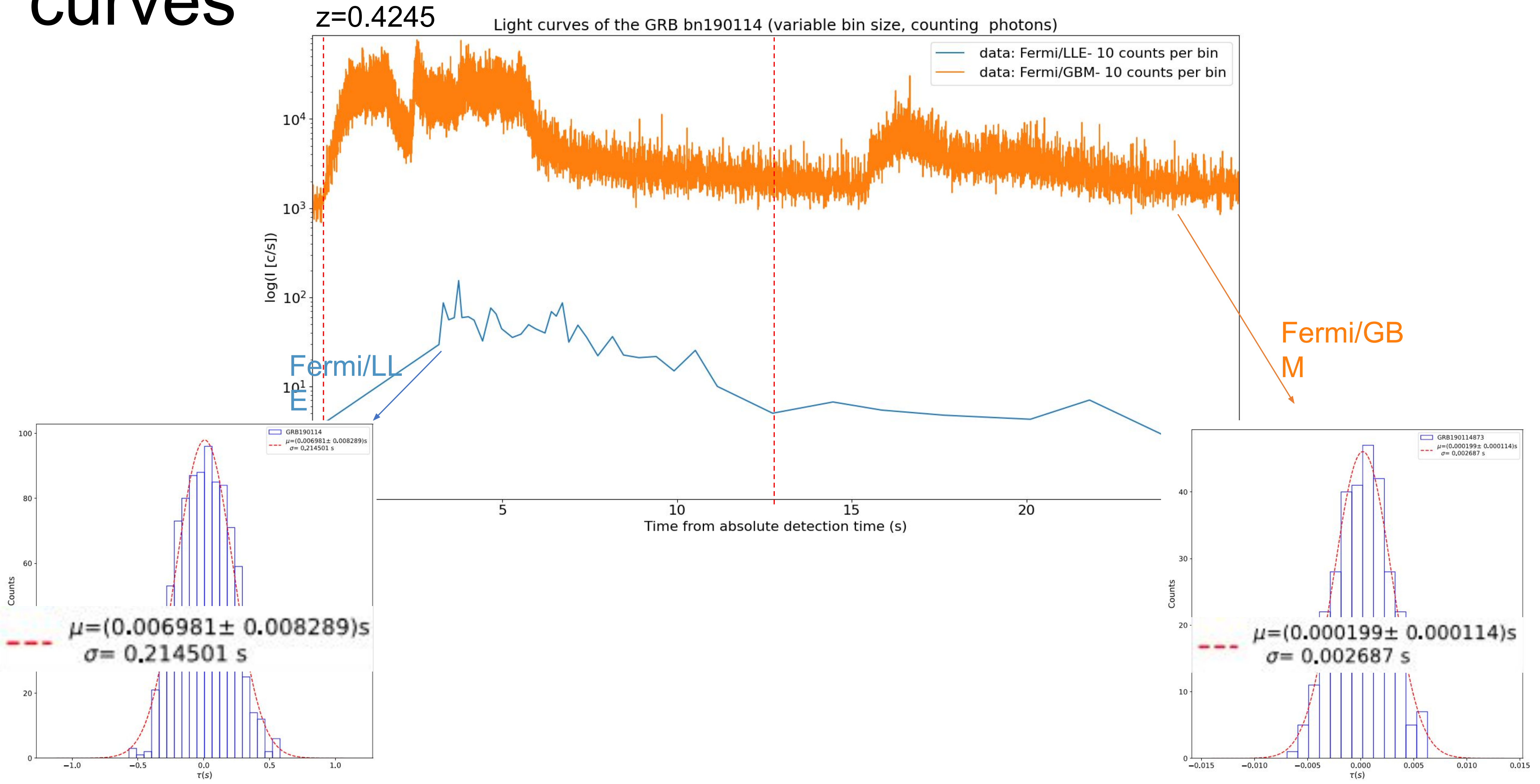
The quantum fingerprint in experimental data is ‘propagated’ through all the simulated light curves. The estimated delay and the associated errors are affected by the quantum fingerprint effect.

CCF techniques for multi-energy bands light curves

How to delete quantum fingerprint effect during delays and associated errors estimations

The only way to delete the QF effect is by using the modified double pool method on each light curve (LC): intrinsic temporal precision in each detector that limits the precision in delay estimation

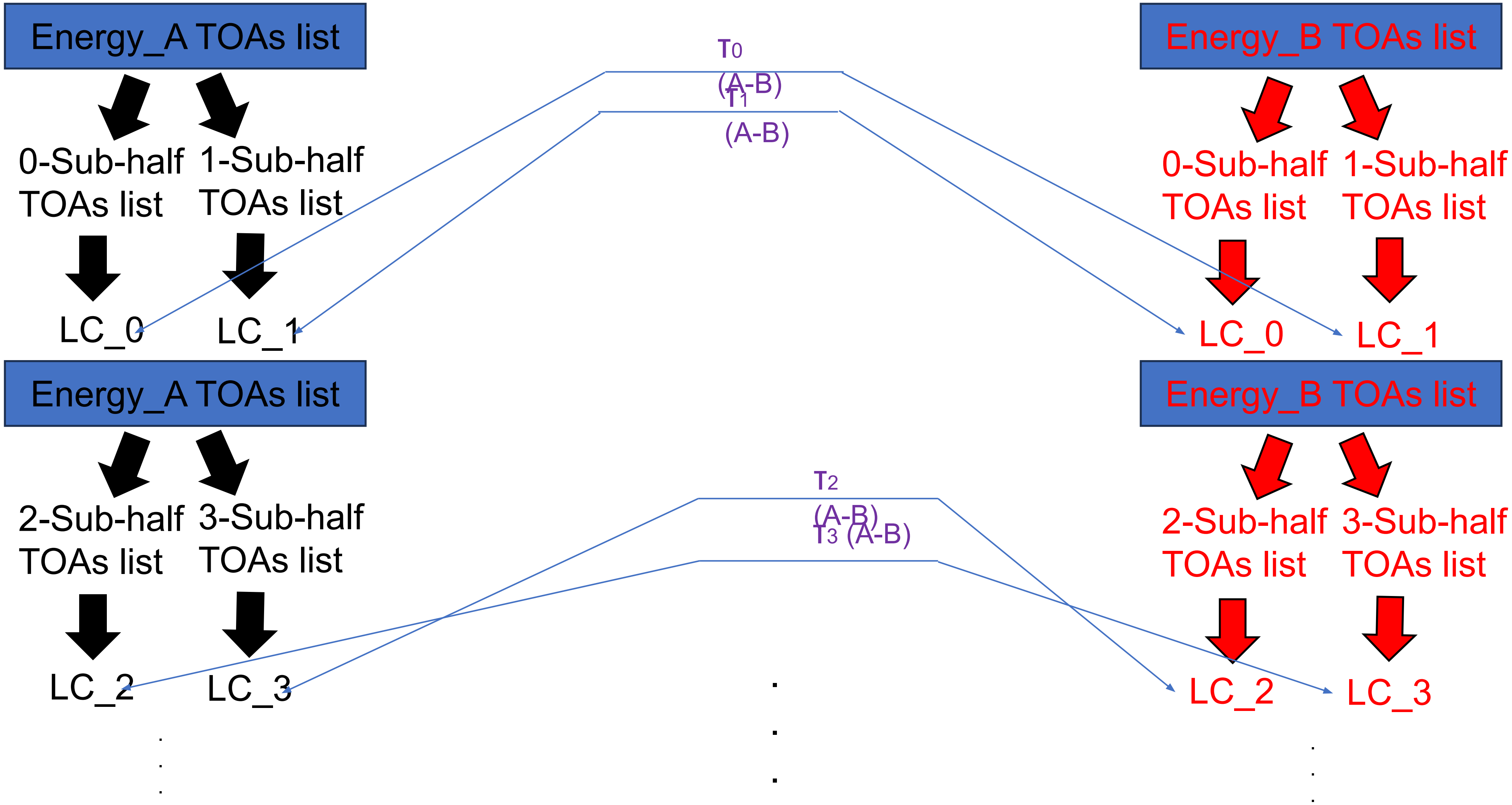
CCF techniques for multi-energy bands light curves



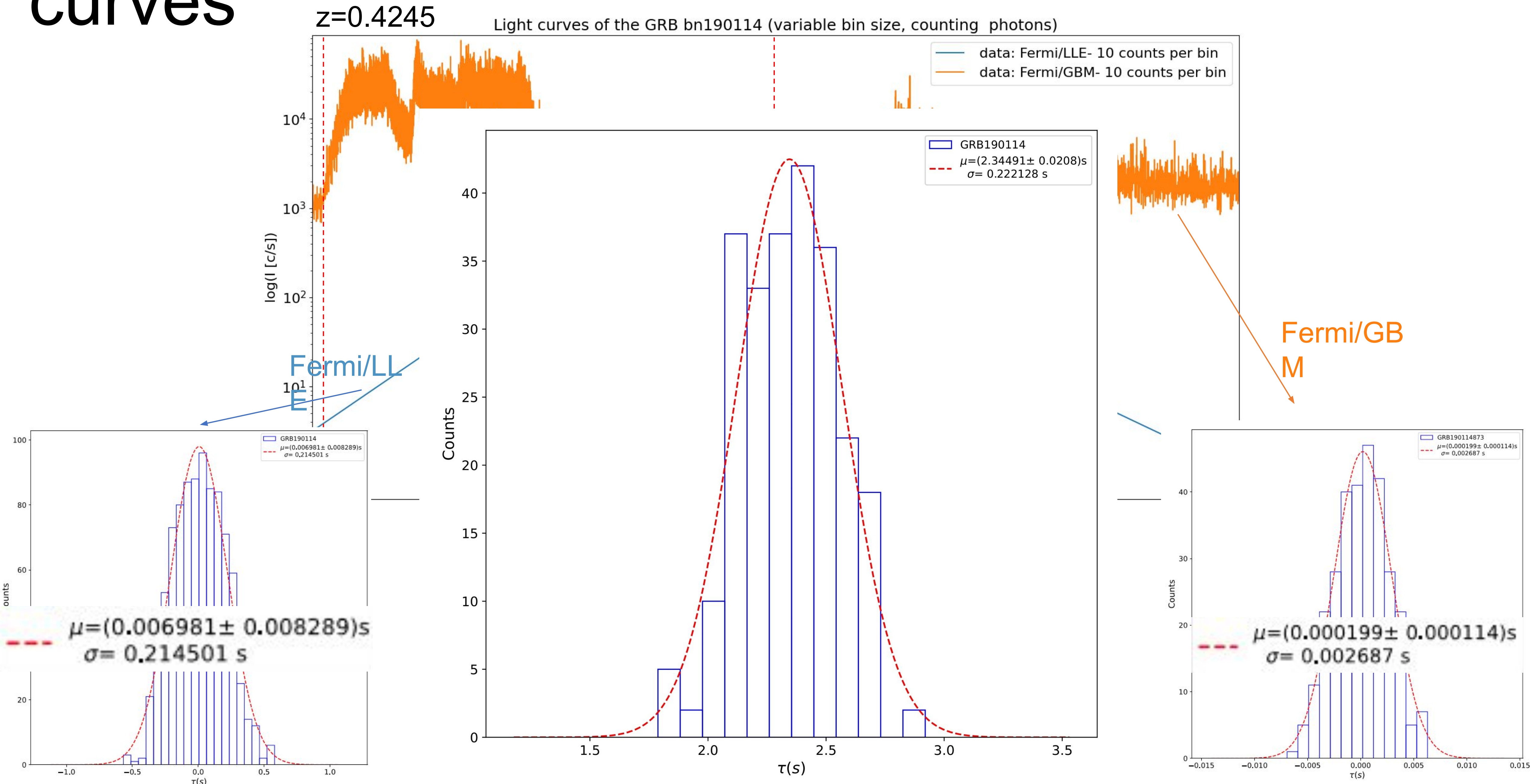
CCF techniques for multi-energy bands light curves

How to delete quantum fingerprint effect during delays and associated errors estimations

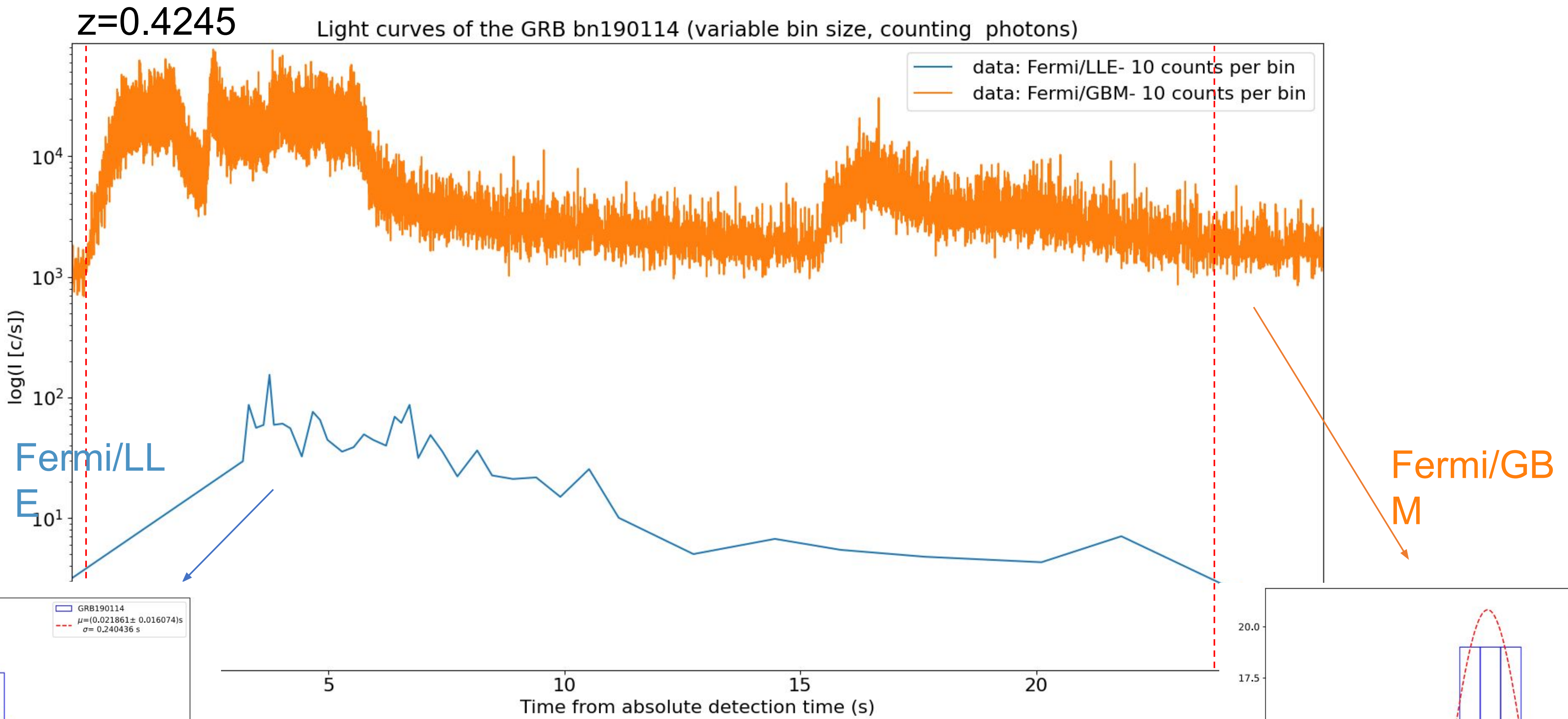
The only way to delete the QF effect is by using the modified double pool method on each light curve (LC): estimate of the delay between the two light curves and the associated error.

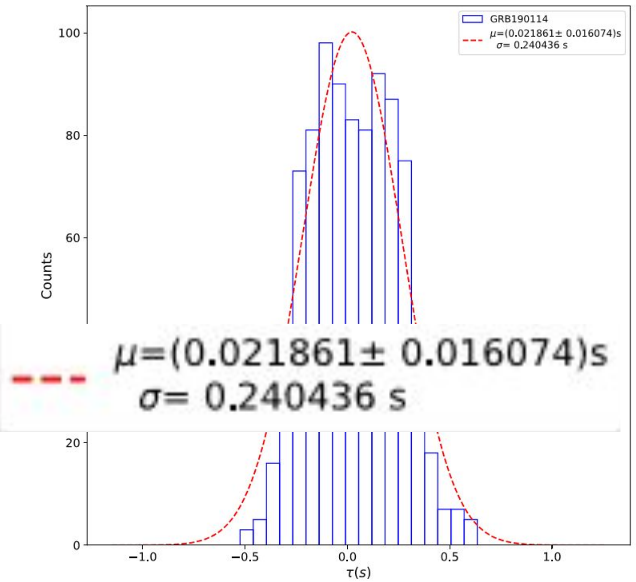


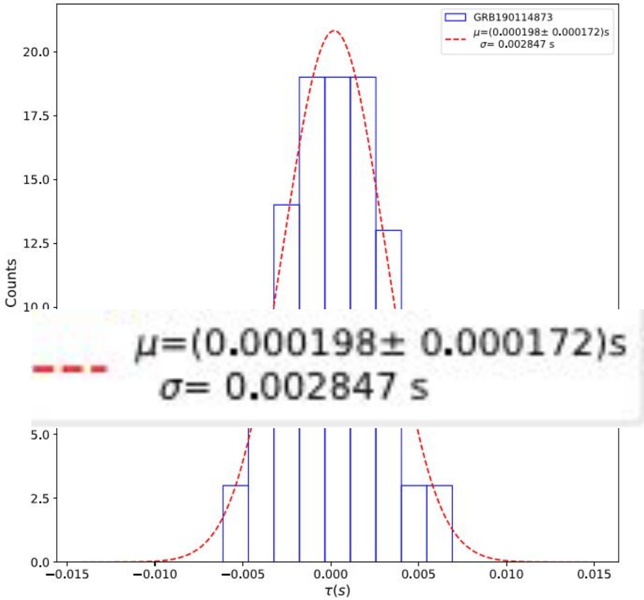
CCF techniques for multi-energy bands light curves



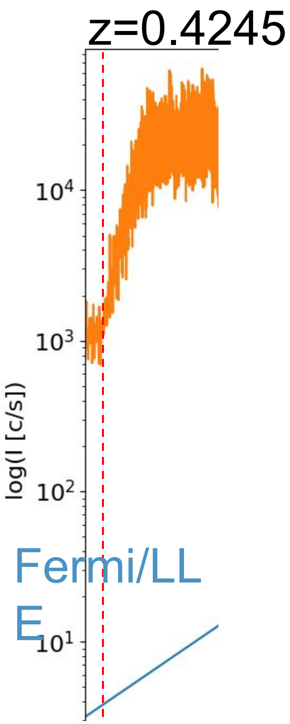
CCF techniques for multi-energy bands light curves

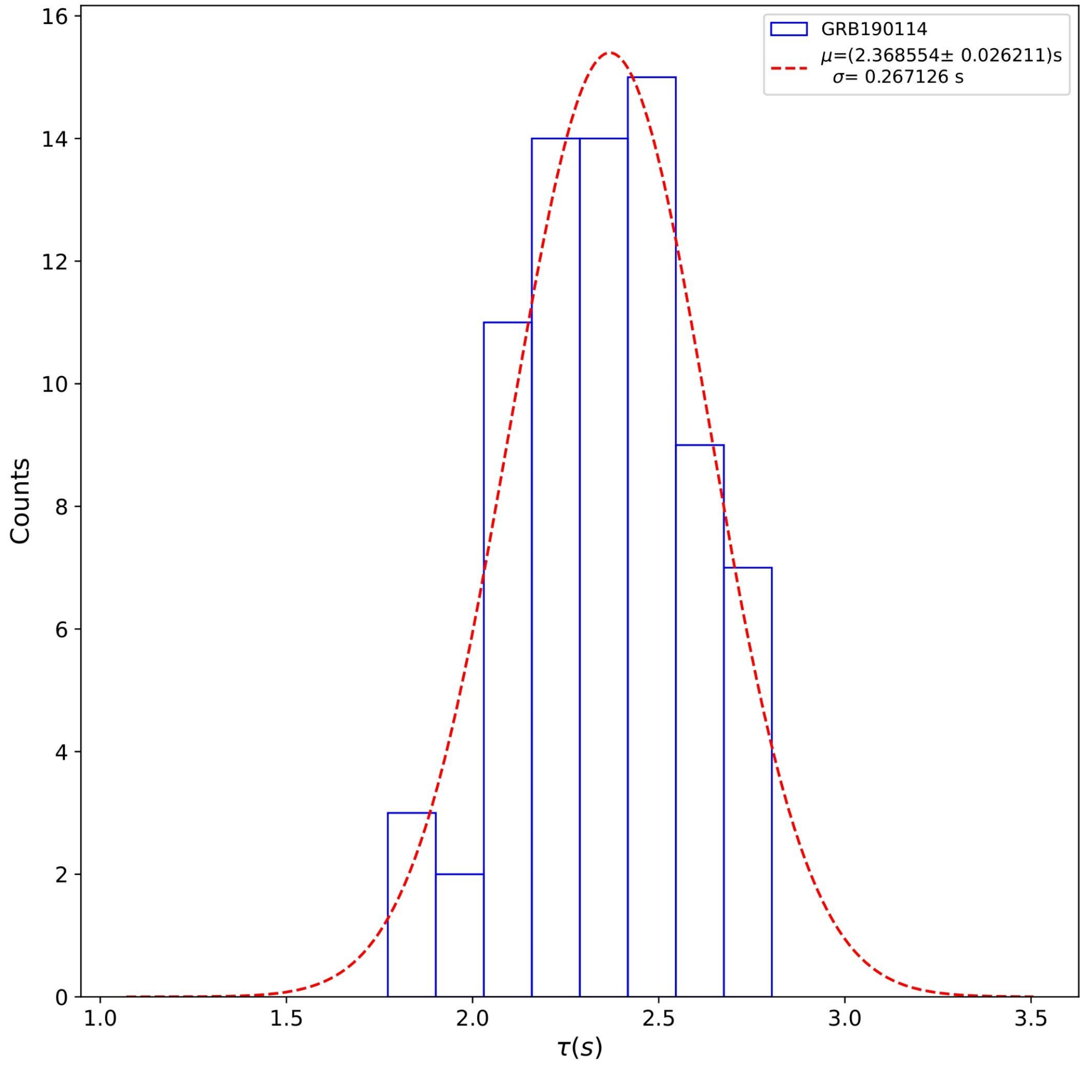


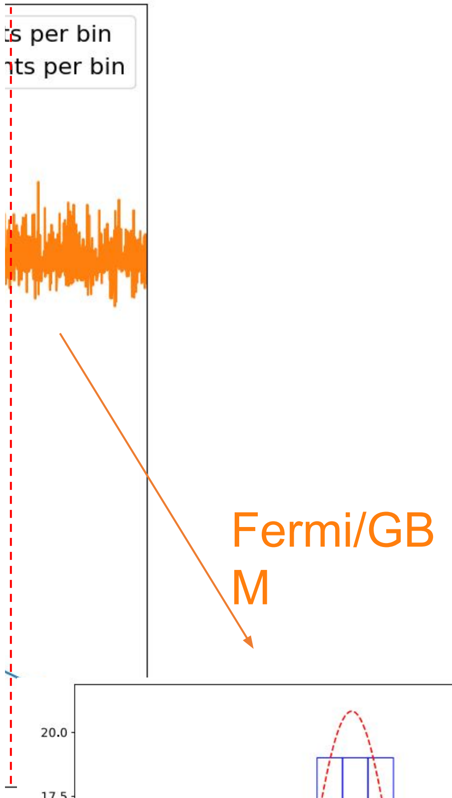


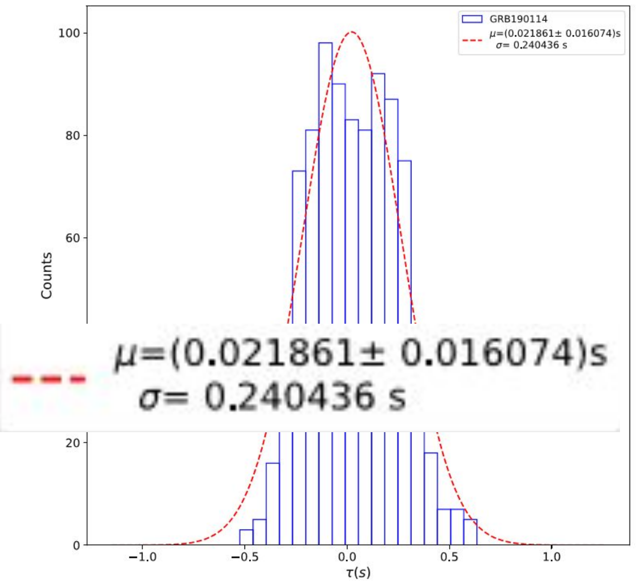


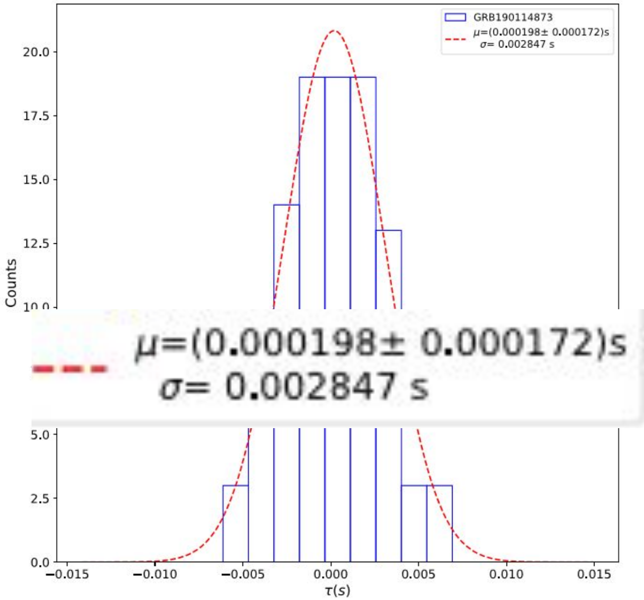
CCF techniques for multi-energy bands light curves



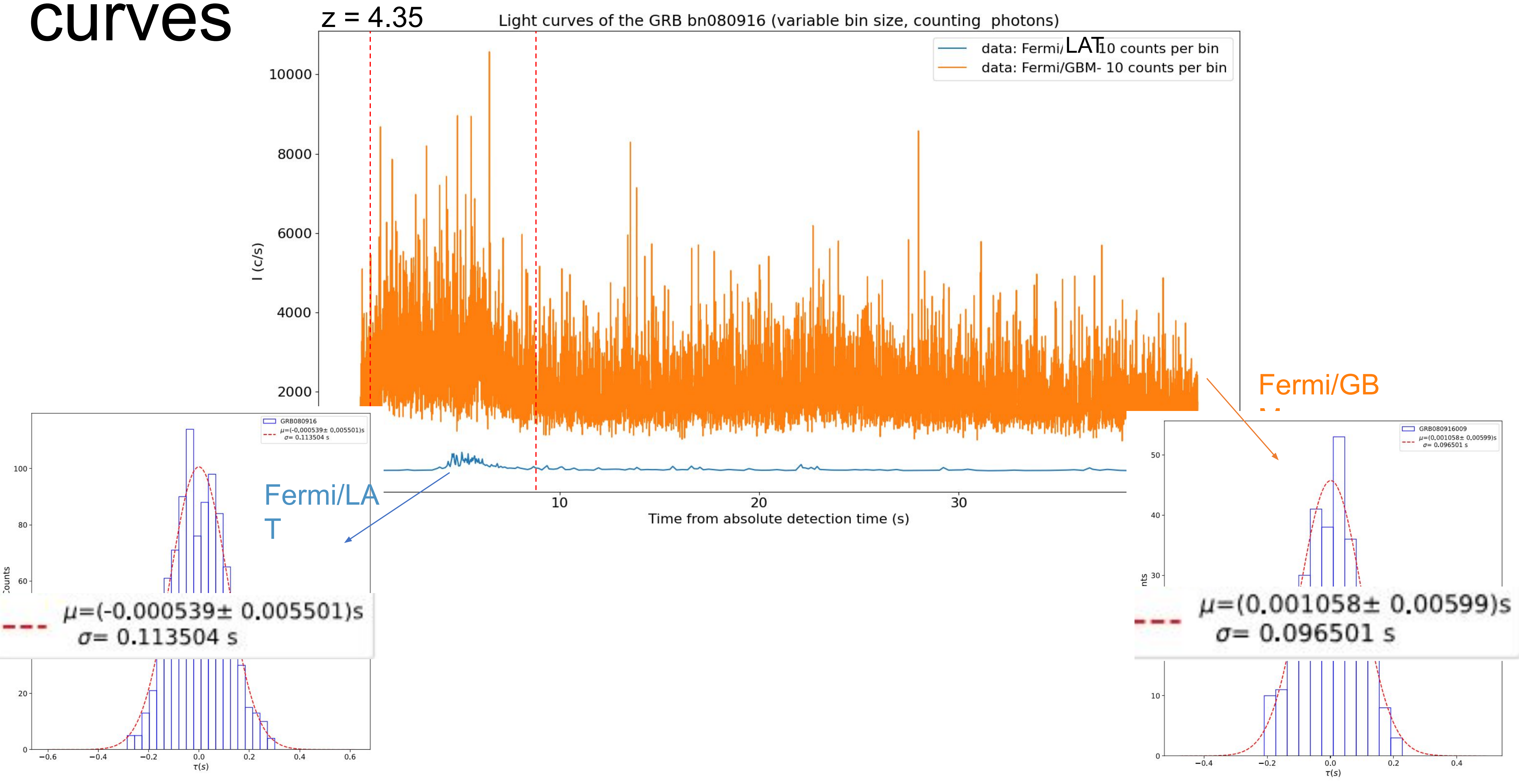




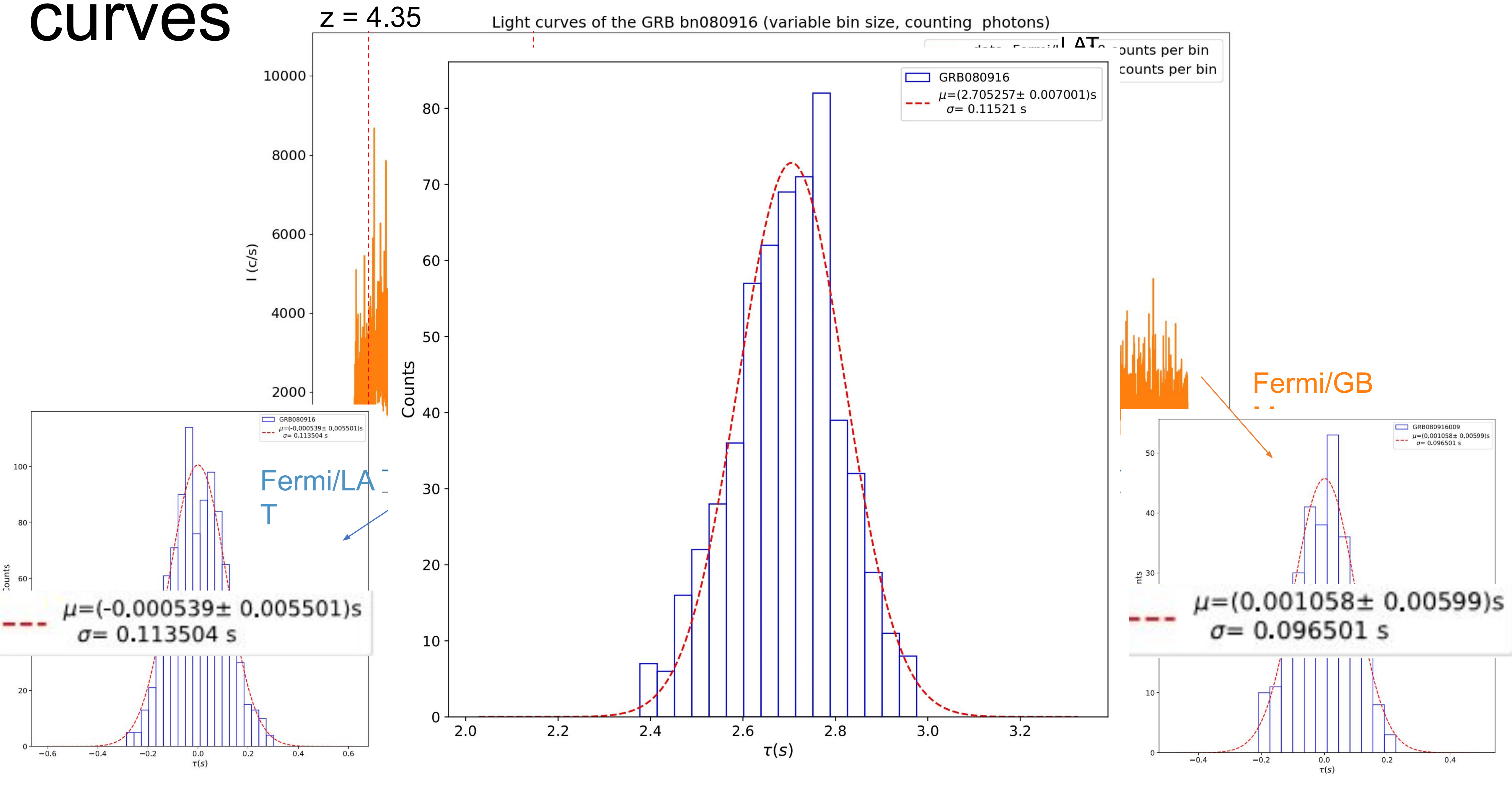




CCF techniques for multi-energy bands light curves

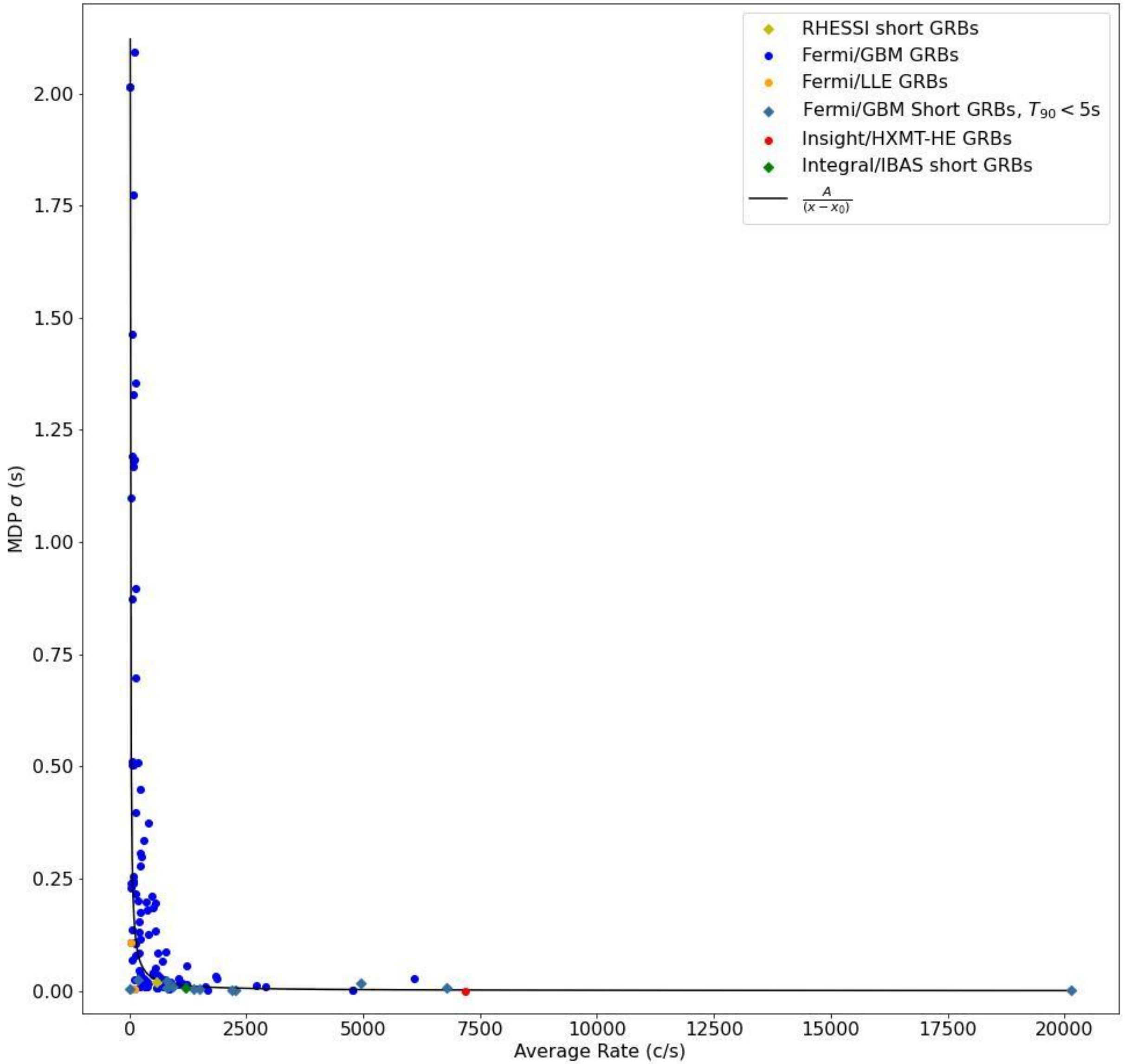


CCF techniques for multi-energy bands light curves



GRBs relations

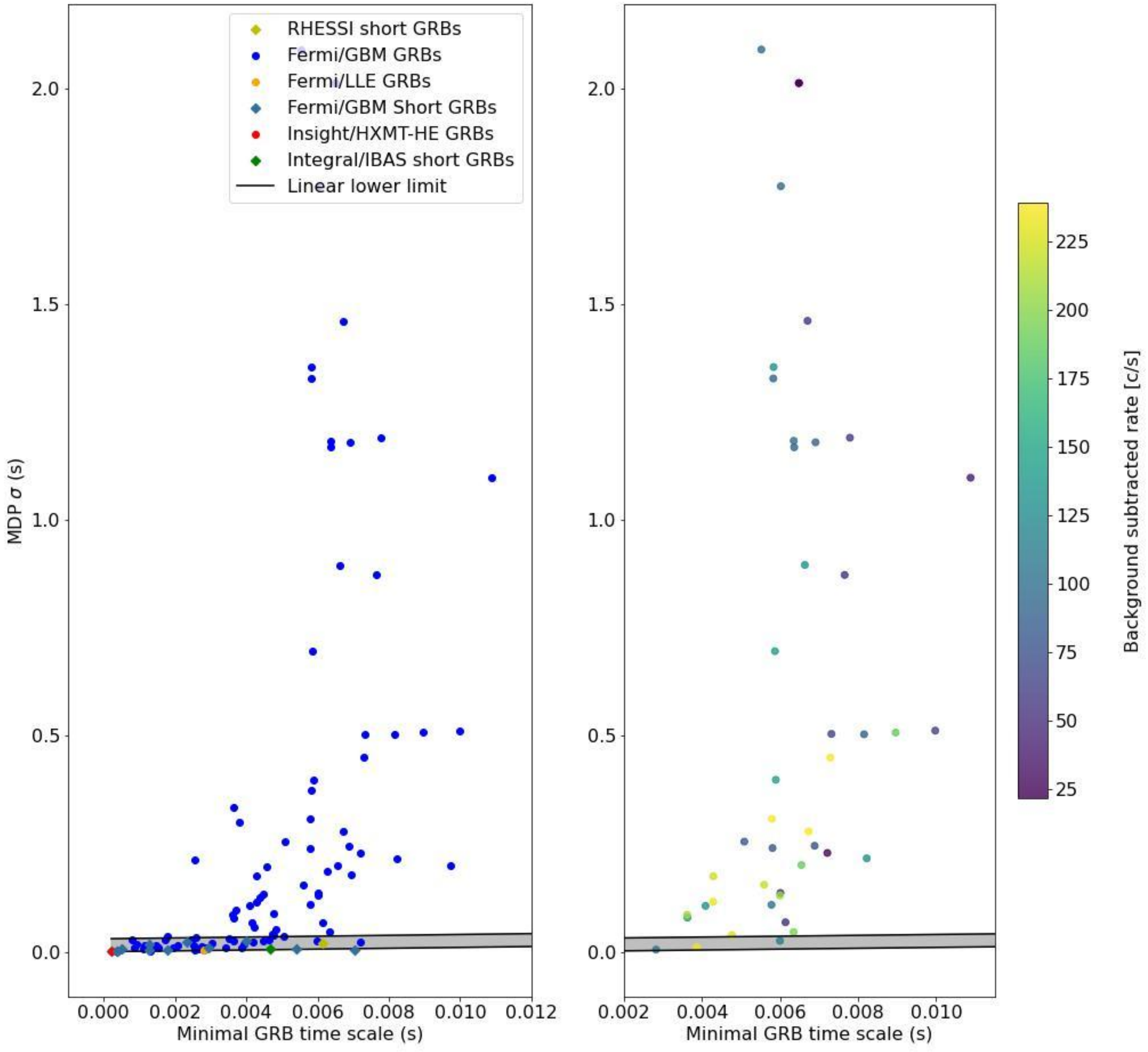
Leone et al., 2024c



- In the estimation of delays, the precision achievable through temporal analysis is limited by the average burst rate observed.
- That relation is independent on the considered energy band or the instrument

GRBs temporal analysis

Leone et al., 2024c



- The minimum time scale variation of the GRB is estimated as the minimum time required to achieve a rate change compared to both the preceding and succeeding values by at least 3 sigma.
- GRBs light curves are build by variable bin size (by counting 10 photons per bin)
- The precision of the GRB temporal analysis is also dependent on the minimal GRB time scale

Conclusion

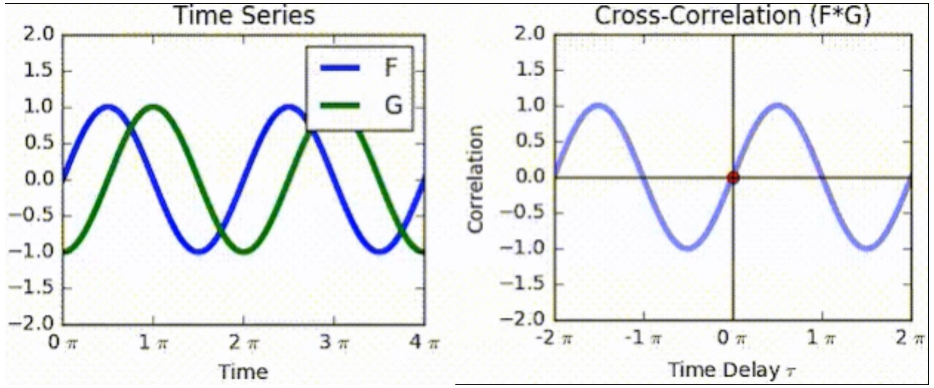
- The variable bin size method (with N > 10) ensures the construction of consistent light curves associated with uniform statistics. The proposed TOAs list simulation method is in accordance with the given rate definition.
- The detector's quantum measurement process results in each light curve being a particular Poissonian realization. The 'one-shot' delay between two experimental light curves is just a particular Poissonian realization of the true delay.
- The experimental delay closest to the true theoretical delay is the average of multiple experiments. The Modified Double Pool simulation method allows for the estimation of the correct **statistical delay** and its associated standard deviation.
- The detectors' data autocalibration sets the lower limit for the achievable accuracy in any temporal analysis.

THANKS FOR YOUR ATTENTION!

Localization of transient events using triangulation method

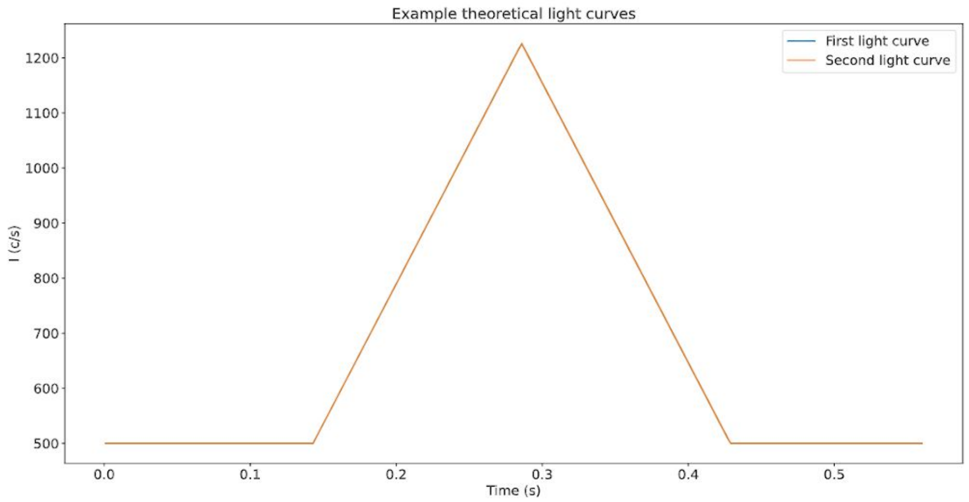
- By analysing the cross-correlation function, we can effectively discern and quantify time shifts or delays between two signals.
- Each value of the cross-correlation function denotes the degree of correlation between two signals at a particular time lag.

$$CCF(\tau) = \int_{-\infty}^{+\infty} x^*(\tau) \cdot y(t+\tau)d\tau$$

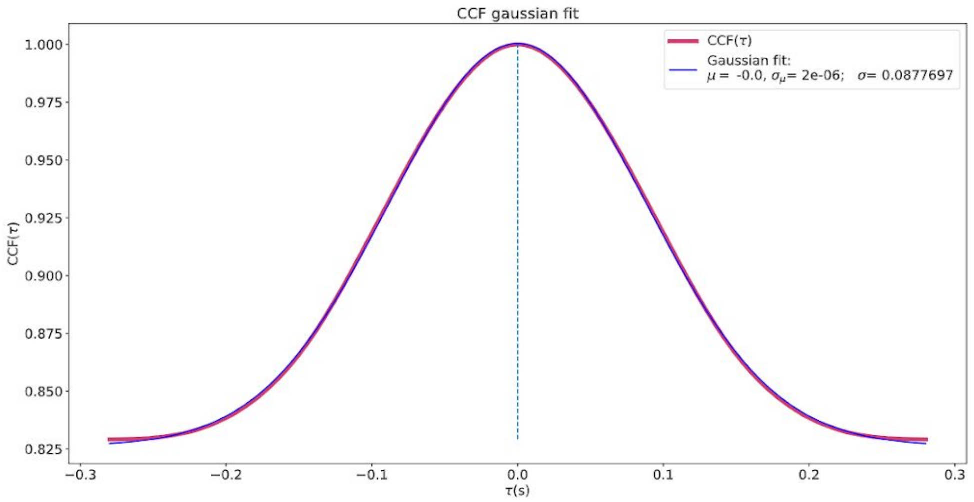


How to deal with CCF errors?

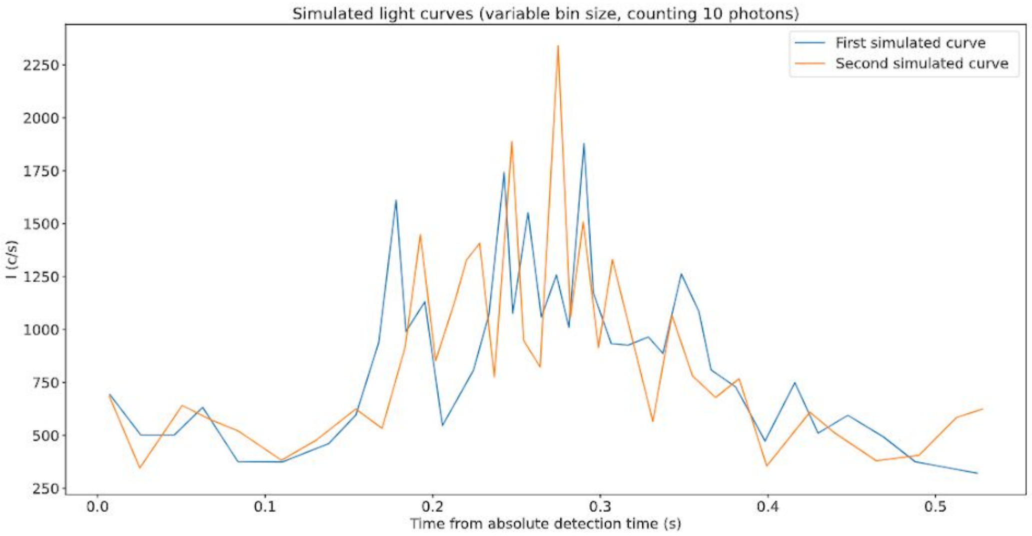
Missing the true theoretical curve associated to the source

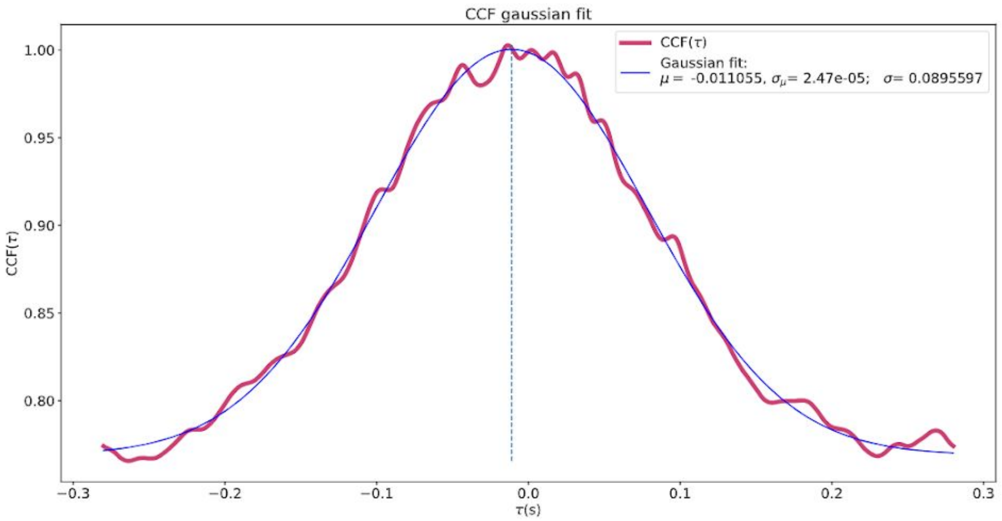


(a) Identical overlapping example signals.



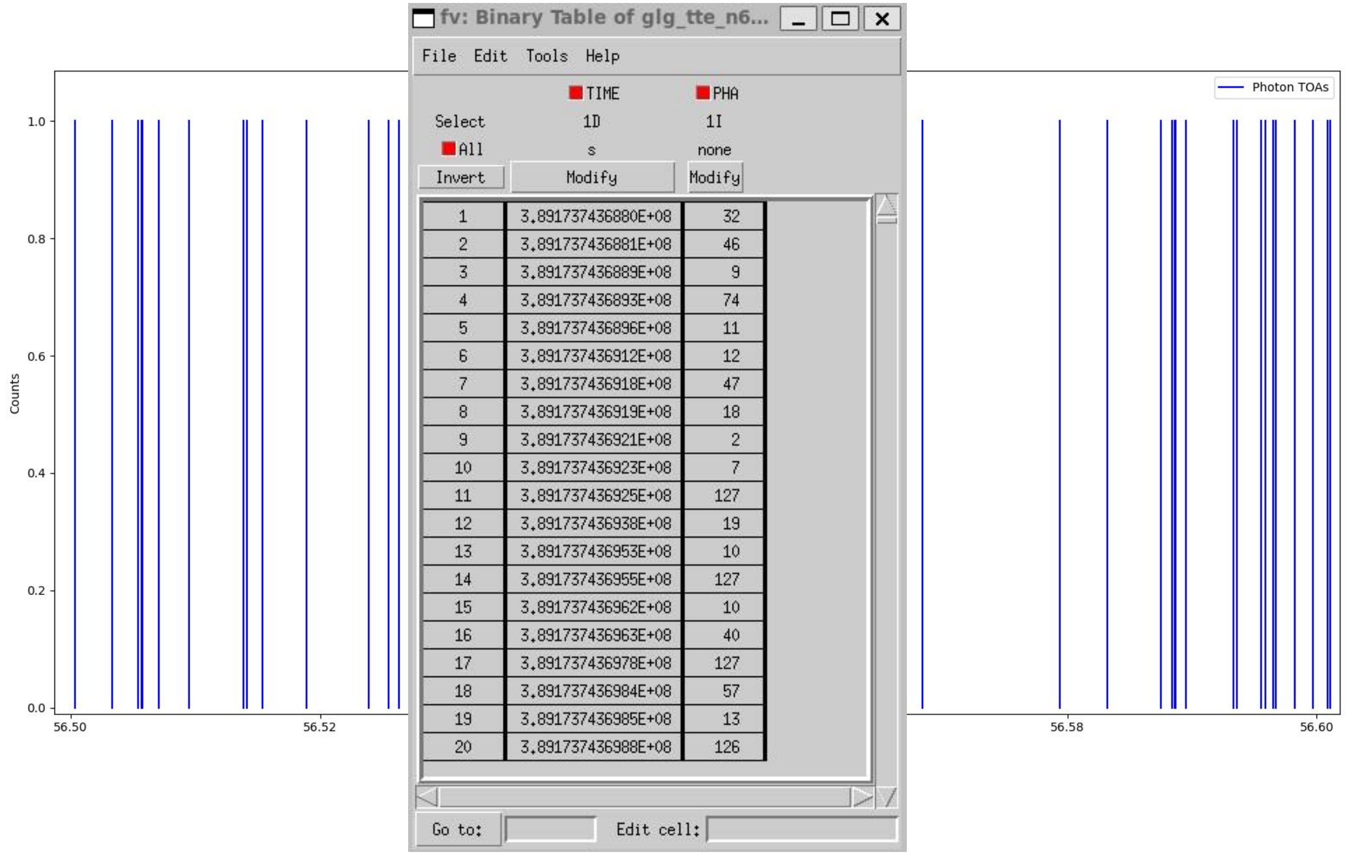
(b) Gaussian best fit of the CCF.





Standard simulation procedure

Leone et al., 2024a



	TIME	PHA
1	3.891737436880E+08	32
2	3.891737436881E+08	46
3	3.891737436889E+08	9
4	3.891737436893E+08	74
5	3.891737436896E+08	11
6	3.891737436912E+08	12
7	3.891737436918E+08	47
8	3.891737436919E+08	18
9	3.891737436921E+08	2
10	3.891737436923E+08	7
11	3.891737436925E+08	127
12	3.891737436938E+08	19
13	3.891737436953E+08	10
14	3.891737436955E+08	127
15	3.891737436962E+08	10
16	3.891737436963E+08	40
17	3.891737436978E+08	127
18	3.891737436984E+08	57
19	3.891737436985E+08	13
20	3.891737436988E+08	126

- Counting the number (n) of photons per bin

- I(t) = n / Δt (Δt is the time interval to count n photons)

- To simulate you need to sample the light curve by the instrument resolution and call a poissonization for each bin
- For example by considering 1 μs time resolution:
  - 10s / 1 μs = 10^7 light curve sampled point
  - 10^7 poissonization to simulate just 30 000 TOAs
- Now your memory stores 30 000 TOAs (integer value =1) and 9.97 10^6 no detection times (integer value =0)