Time domain astrophysics with transient sources

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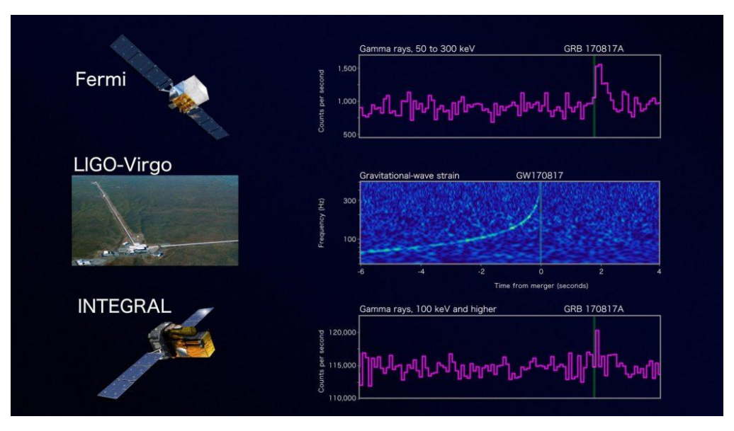
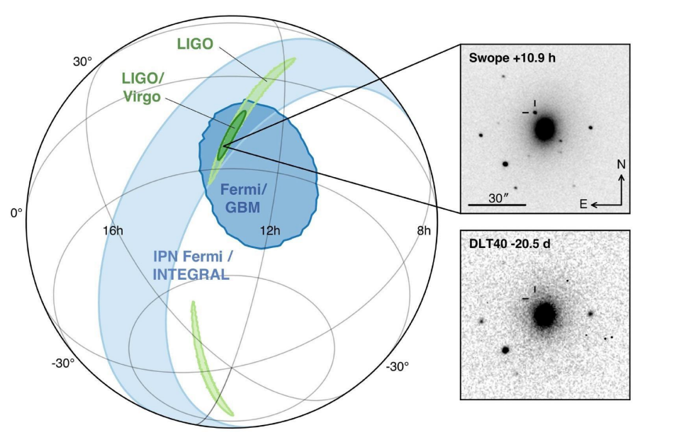
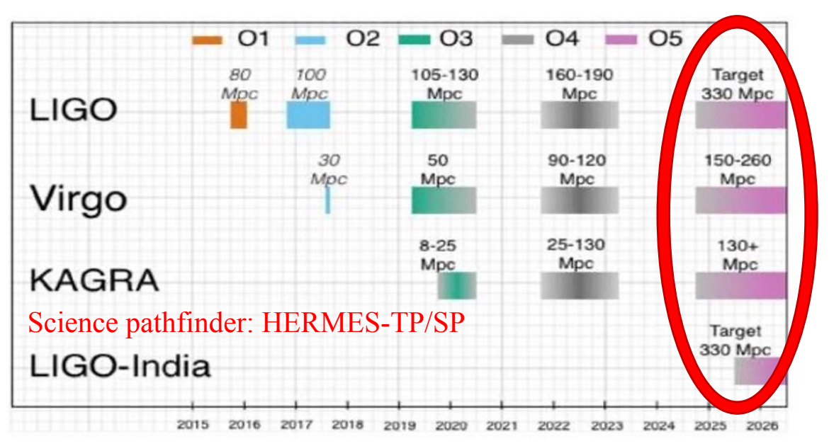
Introduction

Gamma-Ray-Bursts (GRBs) are short, intense and unrepeatable flashes of radiation generated by the collapse of a Massive star or the collision of two Neutron Stars (NSs) in an NS-NS binary system. On the 17th of August 2018, the first joint detection of a Gravitational Wave (GW) signal and its electromagnetic counterpart (short GRB) gave birth to "**Multi-messenger Astrophysics**." Different signals carry different information that can be combined to answer unsolved questions in the physical and astrophysical realms. The described case is, until now, the only joint detection ever observed.



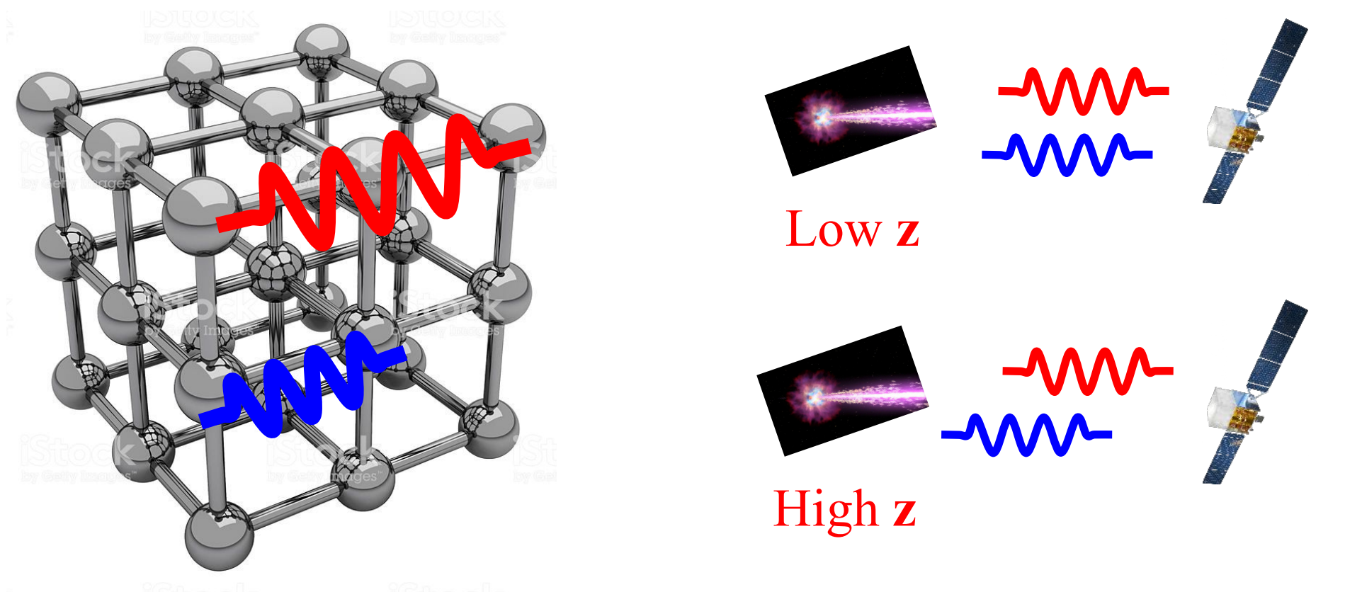


Source localization obtained by LIGO/Virgo and the Fermi/Integral and Fermi/GBM instruments.



HERMES mission operability related to the O5 run of GW interferometer

Detecting and accurately localizing each transient event is crucial for maximizing the likelihood of joint observational detections. The **HERMES constellation**, **launched on March 15, 2025**, aims specifically to achieve this goal through **triangulation method**. This capability greatly enhances the potential for multi-messenger and multi-wavelength follow-up observations. HERMES observes the high energy sky in the 3 keV - 2 MeV energy band.



Higher-energy photons arrive later compared to lower-energy photons

MP or LIV predictions:

$|v_{phot}/c - 1| \approx \xi\, [E_{phot}/(M_{QG}\, c^2)]^n$
$\xi \approx 1$
n = 1,2 (first or second order corrections)
$M_{QG} = \zeta\, m_{PLANCK} \quad (\zeta \approx 1)$
$m_{PLANCK} = (hc/2\pi G)^{1/2} = 21.8\ 10^{-6}$ g

Implications for travel time of photons:

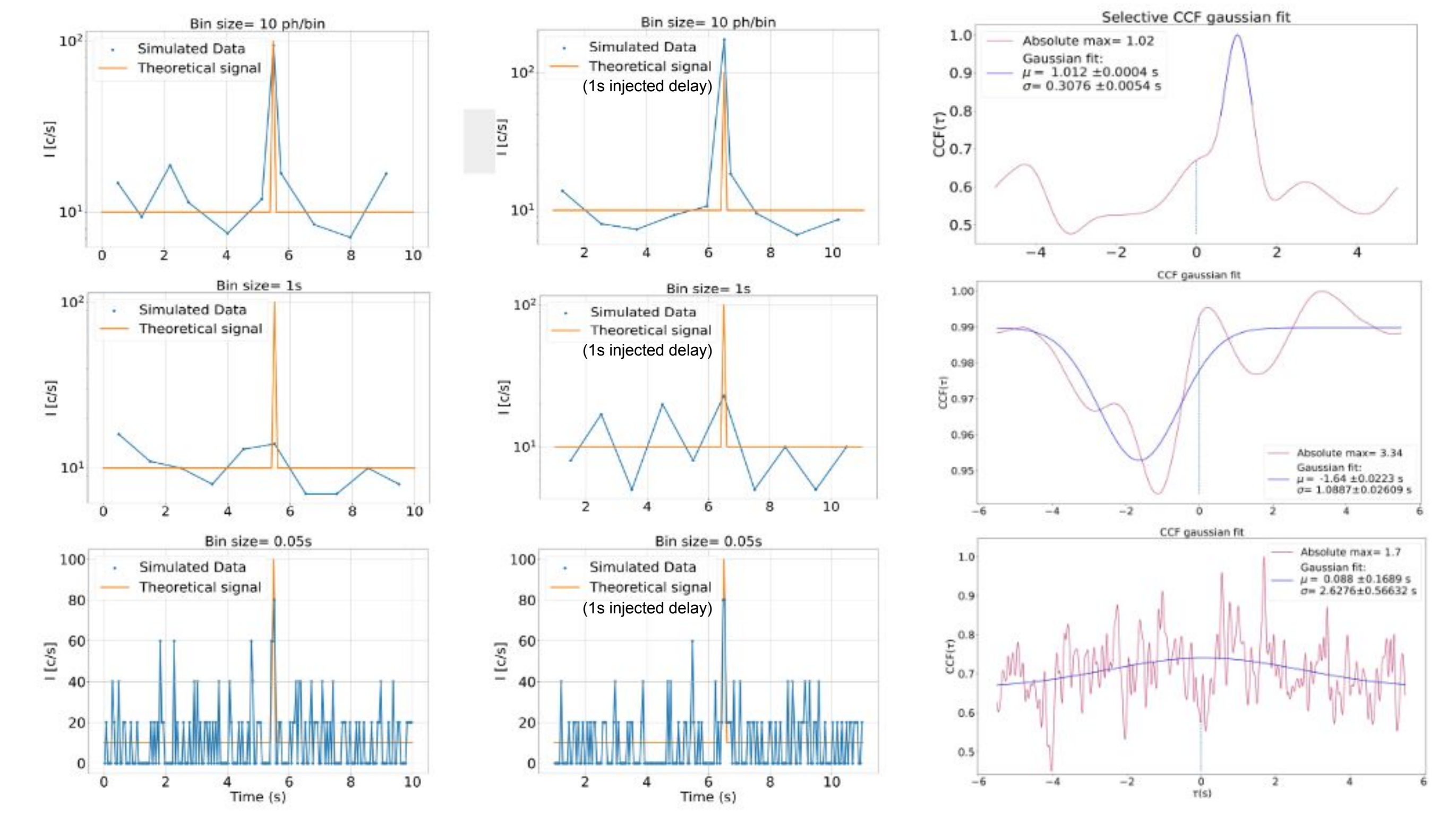
$$\mathbf{\Delta t_{MP/LIV} = \xi\, (D_{TRAV}/c)\, [\Delta E_{phot}/(M_{QG}\, c^2)]^n}$$

$$\mathbf{D_{TRAV}(z) = (c/H_0) \int_0^z d\beta\, (1+\beta)/[\Omega_\Lambda + (1+\beta)^3\, \Omega_M]^{1/2}}$$

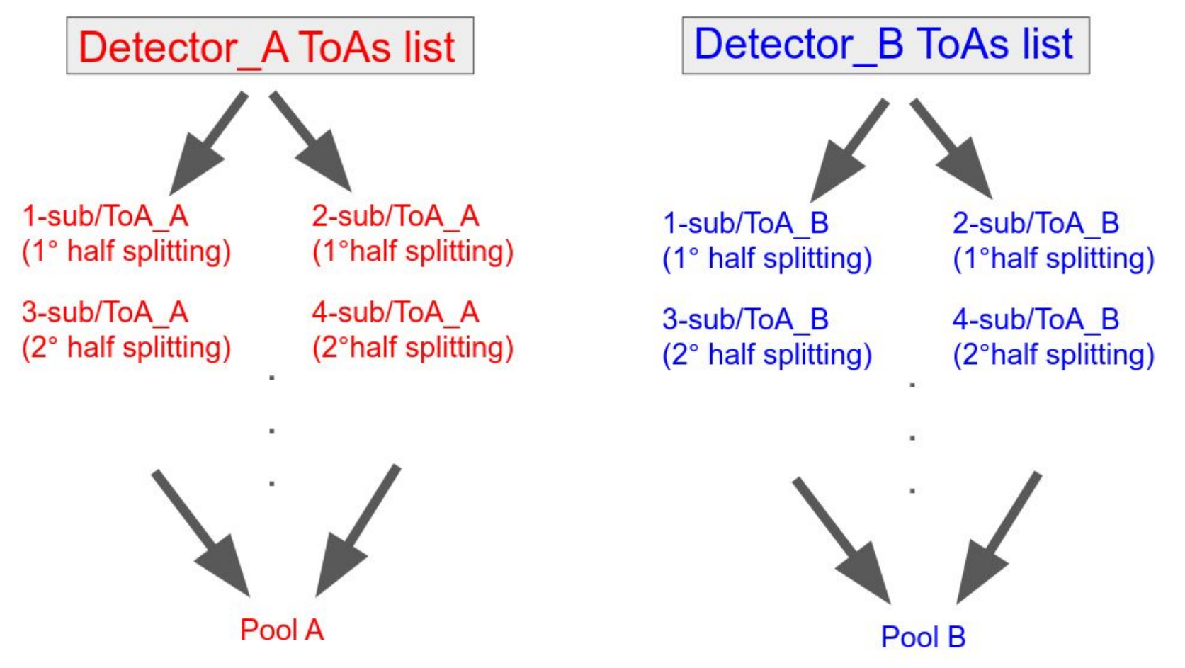
The developed techniques for measuring time delays can be applied to gamma-ray burst (GRB) samples to constrain models in the context of quantum gravity. Within the typical energy range (keV–TeV), delays caused by vacuum dispersion effects would be significantly amplified by cosmological redshift. By assuming that intrinsic emission delays remain constant for each burst, analyzing delay trends between light curves at different energies enables constraints to be placed on quantum-gravity scenarios.

Methodology

The **Cross-Correlation Function** (CCF) requires continuous rate curves, but photon detection instruments provide discrete photon arrival times (Time of Arrival, ToA). Therefore, converting discrete ToA lists into continuous rate functions is crucial and is addressed explicitly in this article. Due to Poisson fluctuations inherent in photon detection, two independently measured ToA lists produce slightly differing rate curves, causing the resulting CCF to fluctuate around the true theoretical delay.



In Leone et al. 2025a (A&A revision in progress), we presented a comprehensive set of mathematical and physical tools necessary for estimating delays and their associated uncertainties between two Time-of-Arrival (ToA) lists using Cross-Correlation Function (CCF) techniques. **Adaptive binning techniques** are essential for accurately characterizing temporal variability and estimating delays in low-count-rate signals typical of high-energy astronomy. Fixed bin-size methods either smooth out significant short-duration events (if bins are too large) or introduce substantial spurious variability due to Poisson noise (if bins are too small). As demonstrated, only adaptive binning methods consistently provide reliable delay measurements.



Detector_A ToAs list

1-sub/ToA_A (1° half splitting)
2-sub/ToA_A (1°half splitting)
3-sub/ToA_A (2° half splitting)
4-sub/ToA_A (2°half splitting)

Pool A

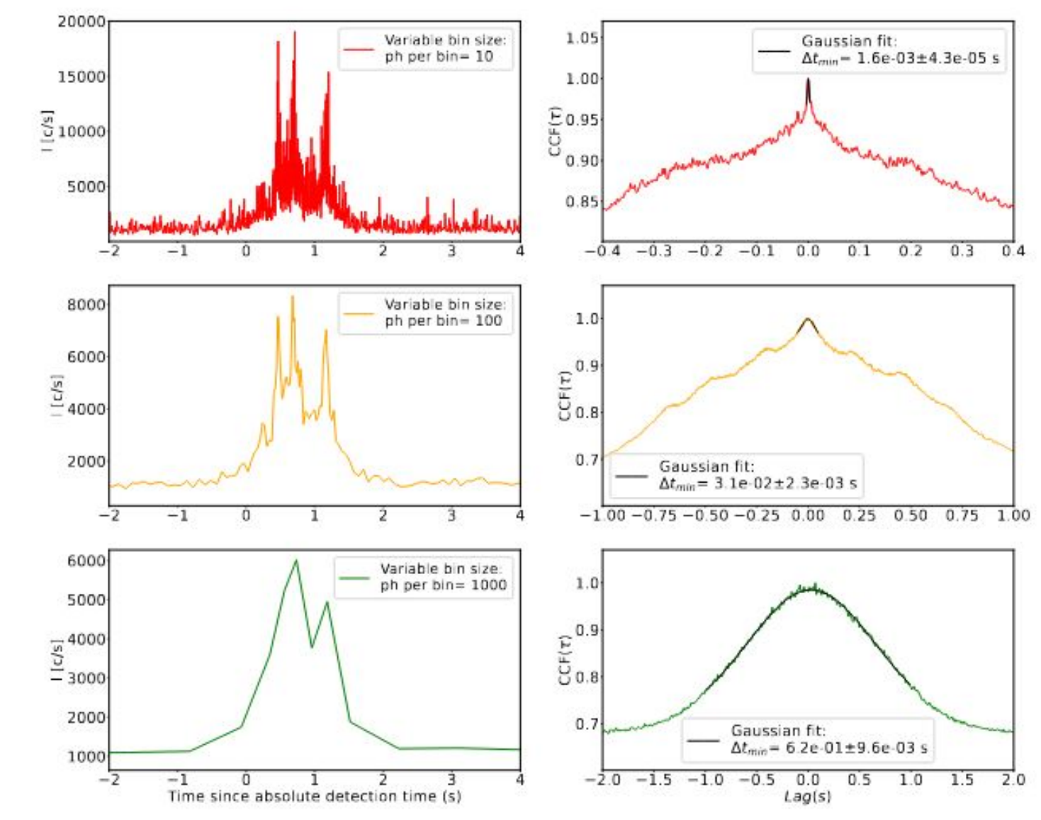
Detector_B ToAs list

1-sub/ToA_B (1° half splitting)
2-sub/ToA_B (1°half splitting)
3-sub/ToA_B (2° half splitting)
4-sub/ToA_B (2°half splitting)

Pool B

In Leone et al. (2025), we introduce the **Modified Double Pool (MDP) method**, an efficient, simulation-free approach to derive delay distributions. Two detector ToA lists are randomly divided into two subsets, simulating independent observations by two identical detectors. Repeating this random division creates multiple, nearly independent pairs of ToA subsets. Numerical studies confirm that the weak statistical dependence does not significantly affect uncertainty estimates. Cross-correlating these subsets yields delay fluctuations of purely statistical origin, related to the original observations. From the two pools we provide a robust delay distribution, with the mean giving the delay estimate and the standard deviation representing its uncertainty. We evaluated the effectiveness of the MDP by using 20 GRBs observed by Fermi/GBM. The data of each GRB were randomly splitted into two independent ToA lists, simulating observations by detectors with half the effective area. The method yields delay estimates consistent with the expected null delay.

Estimating the minimum GRB variability timescale using CCF methods

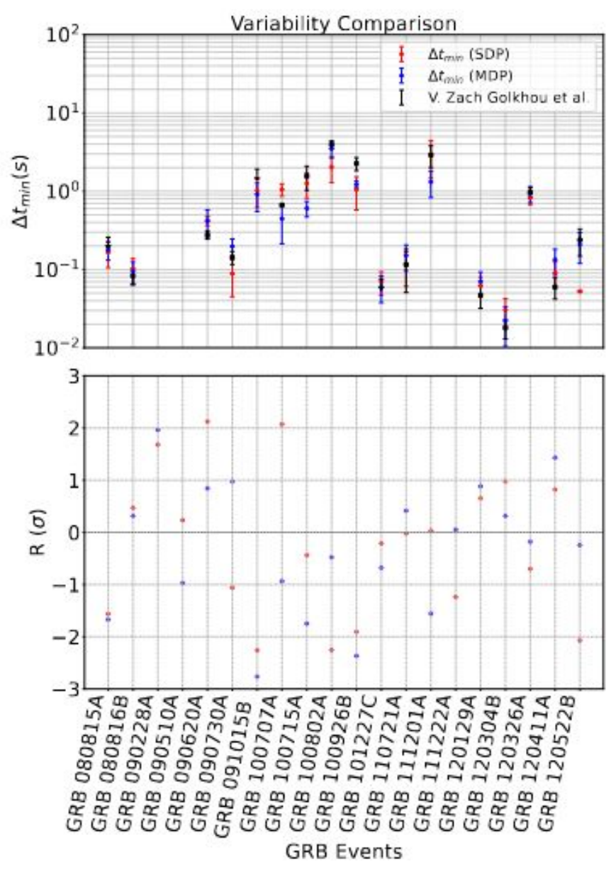


The standard deviation obtained from a Gaussian fit of the CCF peak quantifies how rapidly the correlation decreases with increasing delay. Thus, by applying MDP method to GRB data , we can provide a measure of the characteristic minimal characteristic timescale of the signal (Li et al., 2004). A narrow CCF peak indicates rapid temporal variability in the GRB, while a broad peak (it corresponds to slower, more prolonged variability.

We confirm the existence of a **minimal GRB timescale (~1 ms)** using two independent approaches.

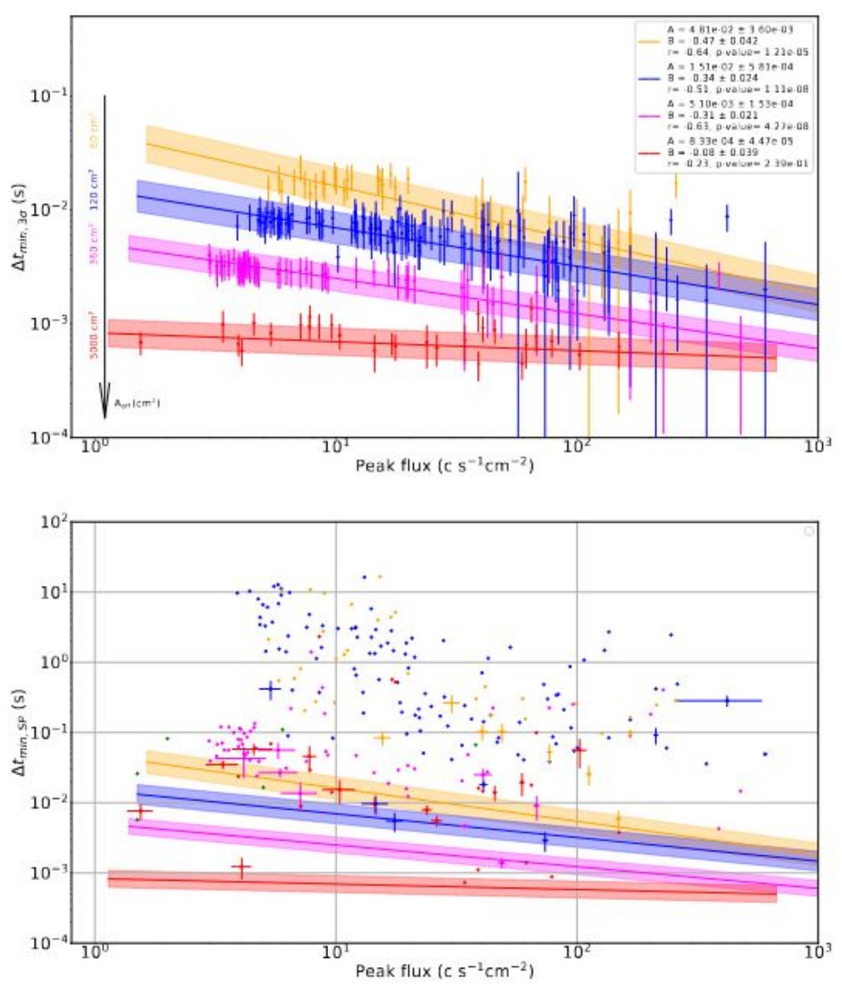
$\Delta t_{3\sigma}$ = average time scale associated to the 3 sigma significant GRB peaks during the T_{90} of the burst. This corresponds to the average explorable temporal resolution of the observation.
Δt_{SP} = minimal time scale as evaluated by the MDP method applied to a single detector.

Analyzing GRBs observed by instruments with different effective areas, we find that increasing effective area allows detection of shorter $\Delta t_{3\sigma}$ at given fluxes. The relationship between $\Delta t_{3\sigma}$ and peak flux flattens at higher sensitivities, stabilizing near the 1 ms limit. On the other hand, instrumental sensitivity strongly influences observed variability where Δt_{SP} differences are confined to the region $\Delta t_{SP} > \Delta t_{3\sigma}$.
Considering smaller effective areas , only short GRBs exhibit variability at the shortest timescales. As the effective area increases, both short and long GRBs display millisecond-scale variability, suggesting that observed timescale differences between GRB types largely depend on instrument sensitivity. We conclude that $\Delta t_{3\sigma}$ defines the **minimal observable GRB variability** for given fluxes and instrument sensitivities.



To assess the validity of the two methods, we estimate Δt_{min} values for 20 GRBs randomly selected from the catalog Golkhou et al. (2015).
MDP method shows the capability to estimate Δt_{min} compatible with the present in literature.

$$R(\sigma) = \frac{\Delta t_{min,MDP} - \Delta t_{min,SF}}{\sqrt{\sigma^2_{\Delta t_{min,MDP}} + \sigma^2_{\Delta t_{min,SF}}}}$$

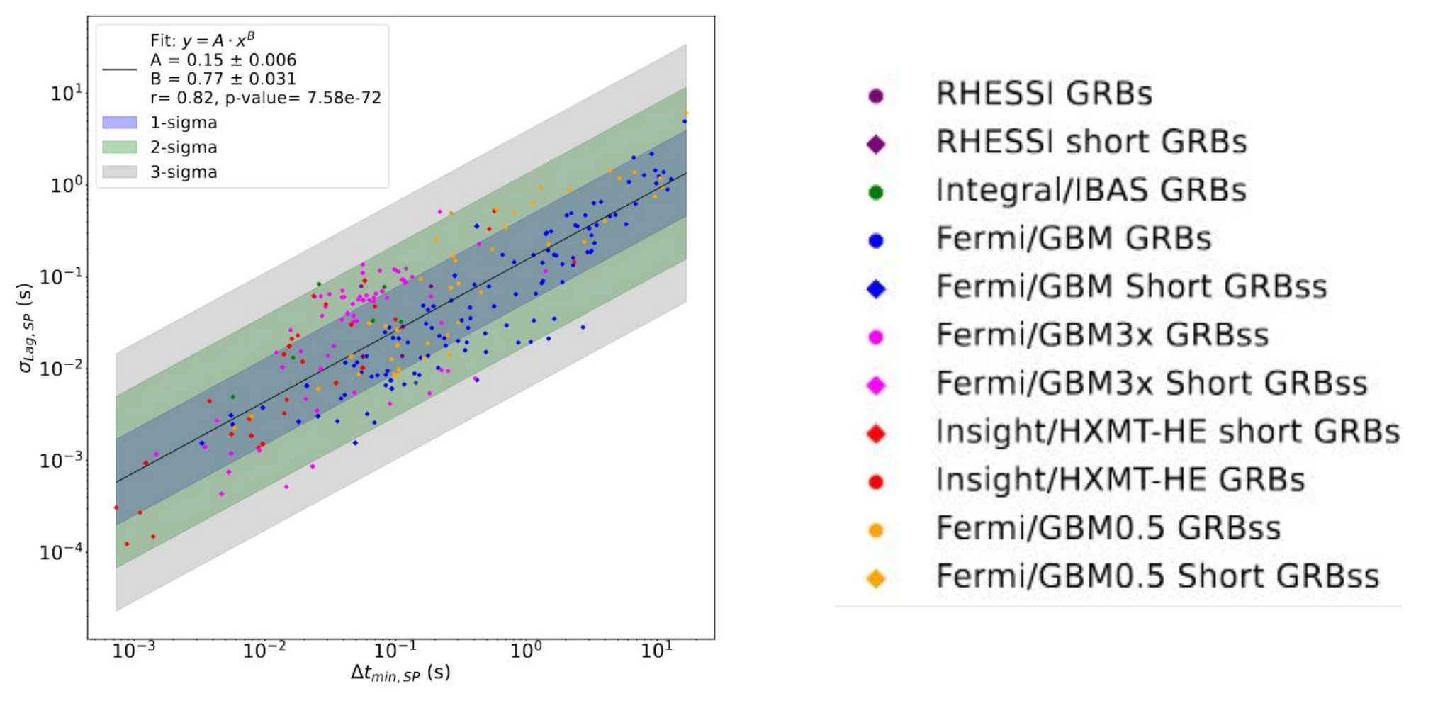


In the bottom plot, the error data points correspond to short GRBs.

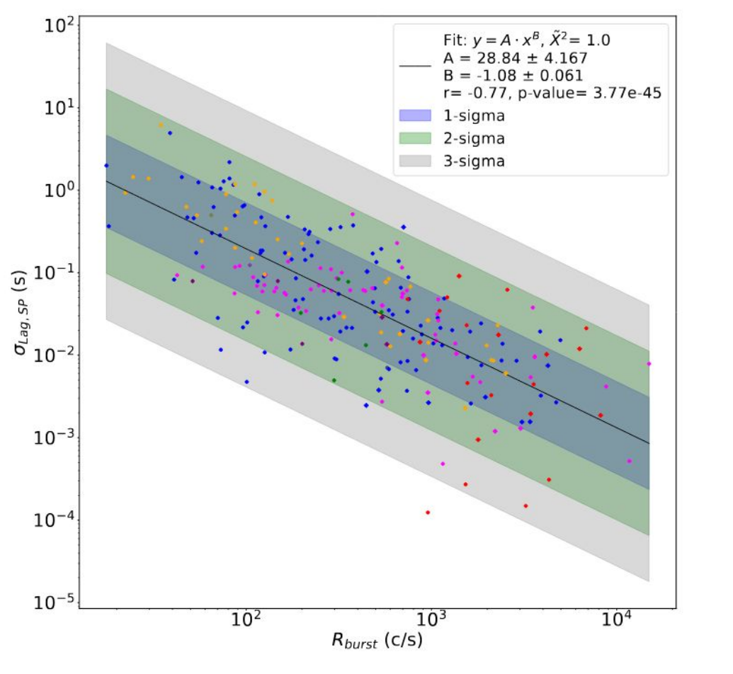
GRB localization for quantum gravity studies

Precise GRB localization via triangulation method also enables effective multi-wavelength follow-up observations, facilitating the measurement of the host galaxy redshift through the detection of the afterglow emission. Accurate redshift determination is essential for **investigating Lorentz invariance violation** effects predicted by quantum gravity theories. Localization precision σ_{pa} strongly depends on the error associated with the lag estimates as shown in Leone et al.,2025b (in preparation).

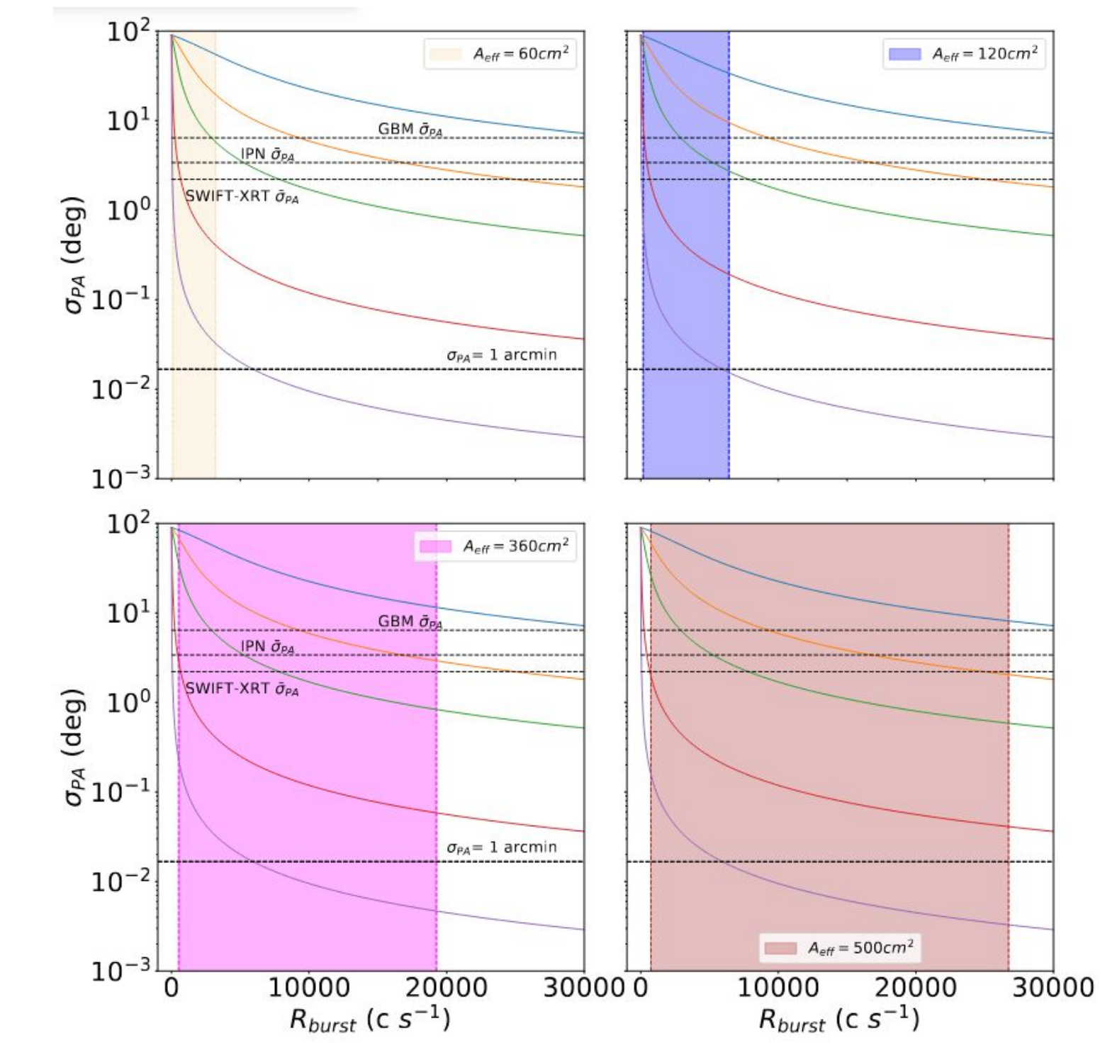
$$\sigma_{PA} = \frac{\sqrt{\sigma^2_{Lag} + \sigma^2_{ipos} + \sigma^2_{time}}}{<Baseline>\ \sqrt{n-1-2}}$$



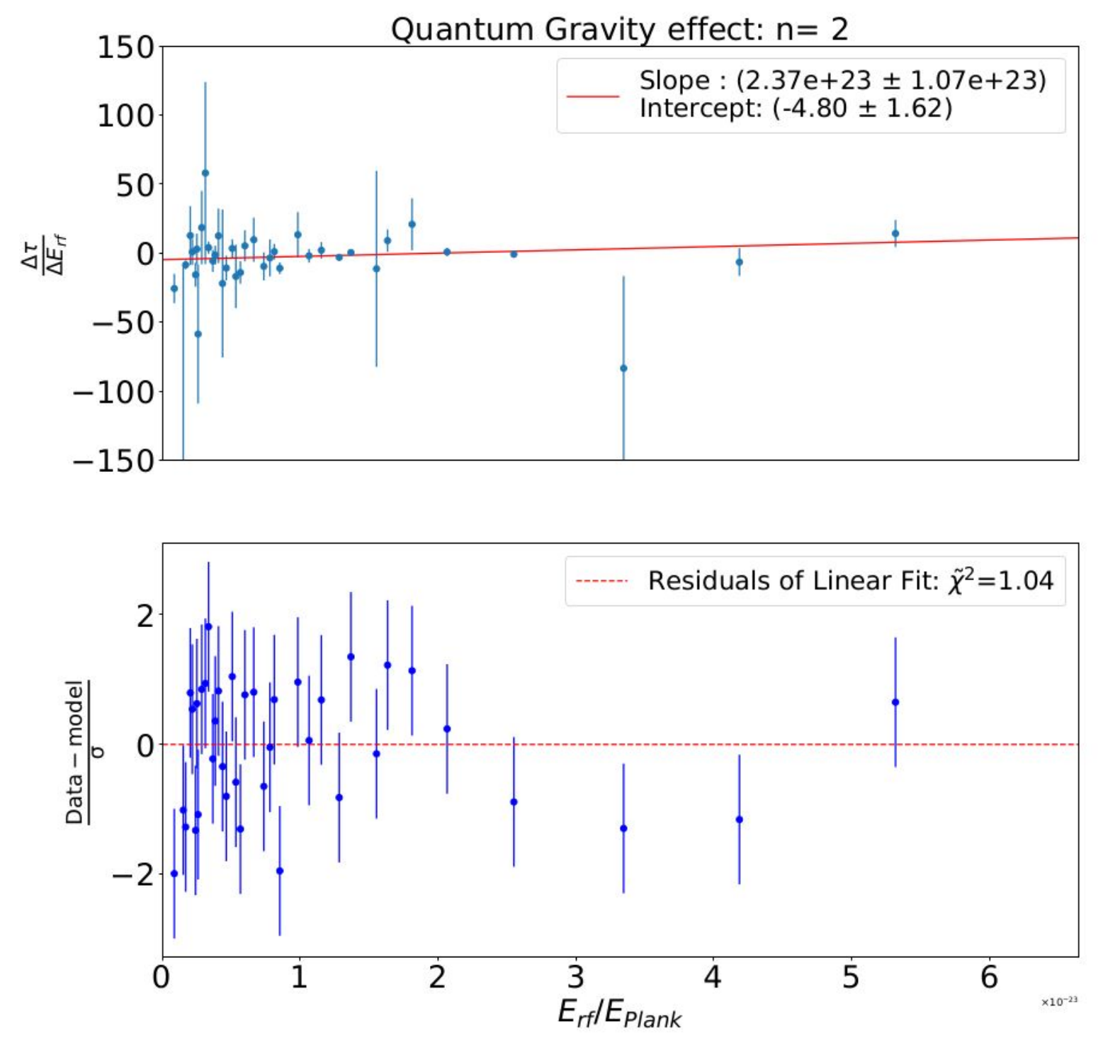
Lag precision as a function of GRB rate for the considered instrument.



Lag precision as a function of the GRB variability for the considered instrument.



Localization precision as a function of the burst Rate for different effective areas. The four panels show the σ_{PA} by considering the expected observed GRB rates for the 68% region of the Fermi/GBM flux distribution. We consider three satellite configurations with increasing baselines: Low Earth Orbit (LEO, ~10^3 km in blue, 4×10^3 km in orange and 1.4×10^4 km in green), Lunar configuration (~4×10^5 km in red), and the Cartwheel configuration proposed by the ALBATROS mission (Burderi et al. 2022, ~2.5×10^6 km in purple).



Linear fit of the **delay per unit energy as a function of the reference-frame energy**, expressed in units of the Planck energy. Each data point is derived from Fermi observations (GBM, LAT, LLE) by estimating the delays between the low- and high-energy light curves of the corresponding GRB and correlating them with the GRB redshift.

Conclusion

The techniques developed represent an innovative and efficient tool for analyzing light curves from transient sources, such as Gamma-Ray Bursts (GRBs). The adaptive method and the Modified Double Pool (MDP) approach allow overcoming the limitations of traditional fixed bin-size methods, providing accurate estimations of experimental delays, especially in low photon-count statistics conditions.

By applying the MDP method to GRB samples observed with various instruments, we confirmed the existence of a minimum variability timescale (~1 ms), consistent with previous literature. At lower effective areas, the minimum observable timescale is strongly influenced by the sensitivity of the instruments employed.

The launch of the HERMES constellation will significantly enhance GRB localization capabilities, thereby expanding scientific opportunities in multi-messenger and multi-wavelength astrophysics. The developed techniques facilitate experimental verification of predictions related to Lorentz invariance violation in cosmological contexts, contributing, for instance, to the proposed quantum gravity study.