ELMA – Transient Monitoring Framework for Very High Energy Gamma-Ray AGNs

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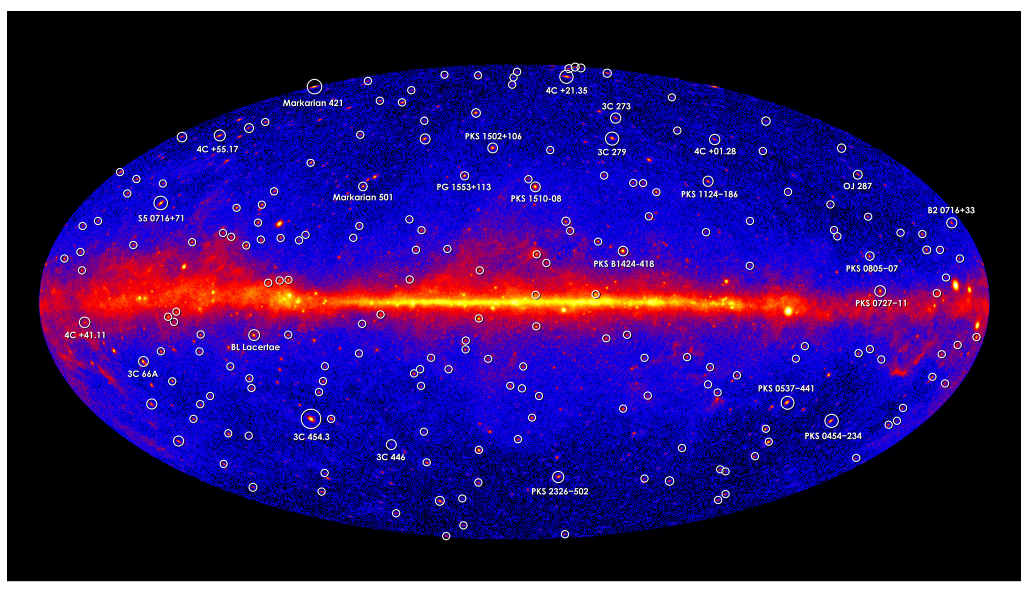
Abstract

High-energy gamma-ray observations provide a unique window into the most extreme astrophysical environments, where particles are accelerated to relativistic energies. The *Fermi* Large Area Telescope (LAT) has established blazars as the dominant class of extragalactic gamma-ray sources, exhibiting pronounced variability that encodes essential information on emission mechanisms and particle acceleration processes. In the era of Time-Domain and Multi-Messenger Astrophysics, the rapid identification and characterization of flaring sources are critical to enable prompt, coordinated multi-wavelength and multi-messenger follow-up observations. We present **ELMA** (**E**xtended **LAT** **M**onitoring of **A**GNs), a fully automated, FAIR-compliant framework designed for the systematic extraction, analysis, and dissemination of time-dependent **LAT** data. Employing an aperture photometry approach, ELMA provides rapid, background-independent flux estimates and generates real-time alerts for a predefined list of active galactic nuclei. The pipeline produces a comprehensive suite of primary and derived data products–including light curves, spectral energy distributions, sky maps, variability metrics, and high-energy photon analyses–all accessible through a dedicated web interface and preserved within a long-term archival system. The framework is optimized for scalability, transparency, and reproducibility, enabling sustained, large-scale monitoring of γ-ray active galactic nuclei. Planned developments include the integration of machine learning–based variability detection, Bayesian uncertainty quantification, and an AI-driven agent for autonomous pipeline management. These enhancements will support intelligent, real-time operations within the broader landscape of multi-messenger astrophysics.

Introduction

High-energy gamma-ray observations provide a unique probe of the most extreme astrophysical environments, where particles are accelerated to relativistic energies under physical conditions inaccessible to terrestrial laboratories. The *Fermi* Large Area Telescope (LAT) [1], a space-based pair-conversion detector operating since 2008, has been the principal instrument exploring this energy regime through continuous all-sky monitoring. Over more than a decade of observations, *Fermi*-LAT has firmly established blazars—active galactic nuclei (AGNs) whose relativistic jets are closely aligned with our line of sight—as the dominant population of extragalactic gamma-ray sources [2].



All-sky γ-ray map from the *Fermi*-LAT in Galactic coordinates. The bright central band traces diffuse emission from the Milky Way, while circled sources mark extragalactic blazars, which constitute the dominant class of identified LAT γ-ray emitters.

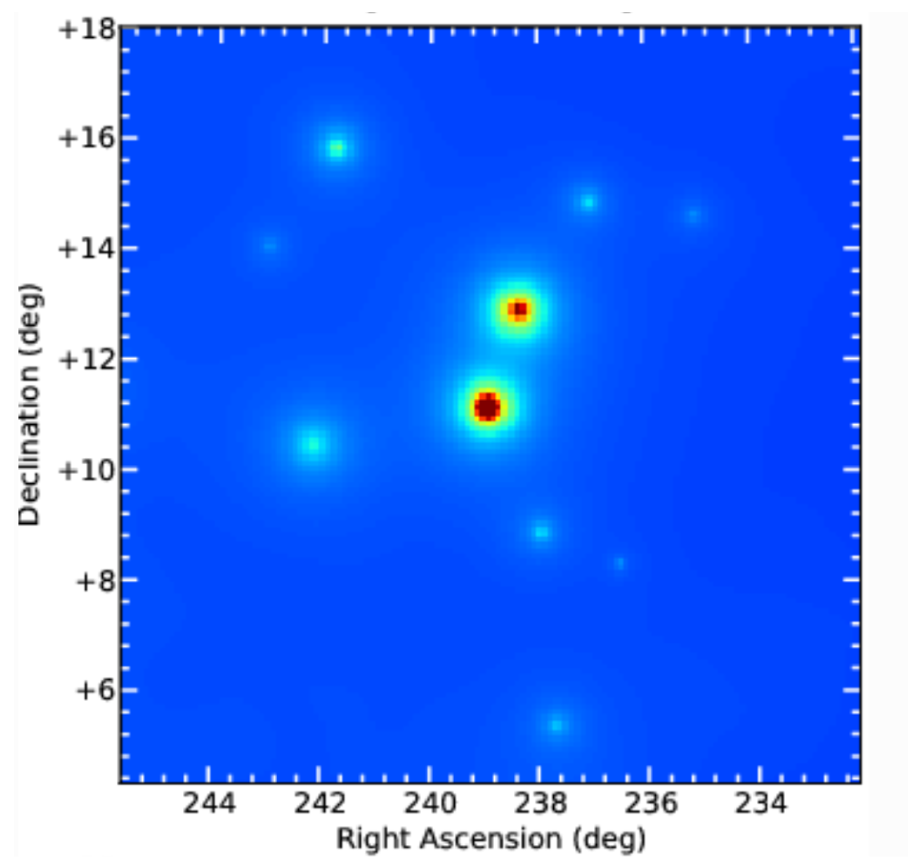
Blazars exhibit rapid and pronounced variability [3], offering stringent constraints on the size, geometry, and location of the emitting regions via causality arguments. Their temporal behavior provides valuable insights into the underlying particle acceleration processes, including relativistic shocks, magnetic reconnection, and plasma turbulence. In the current era of Time-Domain and Multi-Messenger Astrophysics (MMA), gamma-ray transients play a pivotal role as triggers for coordinated, multi-wavelength and multi-messenger observations. The timely identification and characterization of flaring sources are therefore crucial to maximizing the scientific return of observational campaigns. Achieving this objective requires robust, automated analysis pipelines capable of delivering statistically reliable alerts with minimal latency and high reproducibility.

Architecture and Implementation

The monitoring framework is a fully automated FAIR-compliant system designed for the systematic extraction and analysis of time-dependent *Fermi*-LAT data. Its modular and distributed architecture ensures reproducibility, scalability, and seamless integration with time-domain and multi-messenger astrophysical studies. Implemented in PYTHON, the framework employs a multithreaded design capable of processing thousands of sources per day. The workflow is organized into four coordinated layers: (1) **Data Acquisition**, responsible for retrieving and validating photon and spacecraft data files; (2) **Analysis Engine**, which performs energy-dependent aperture photometry using the *Fermi* Science Tools; (3) **Statistical Processing**, which applies robust variability diagnostics—such as χ^2 tests—to identify significant flux changes; and (4) **Database Management**, which stores and organizes all outputs, including catalogs, light curves, sky maps, and spectral energy distributions, into structured, queryable data products. This architecture supports fully automated monitoring campaigns with minimal manual intervention, while preserving data integrity and methodological reproducibility. The system is optimized for computational efficiency and scalability: parallel execution and distributed processing enable large-scale analyses, balanced workload distribution, and consistent statistical reproducibility across multiple observational datasets.

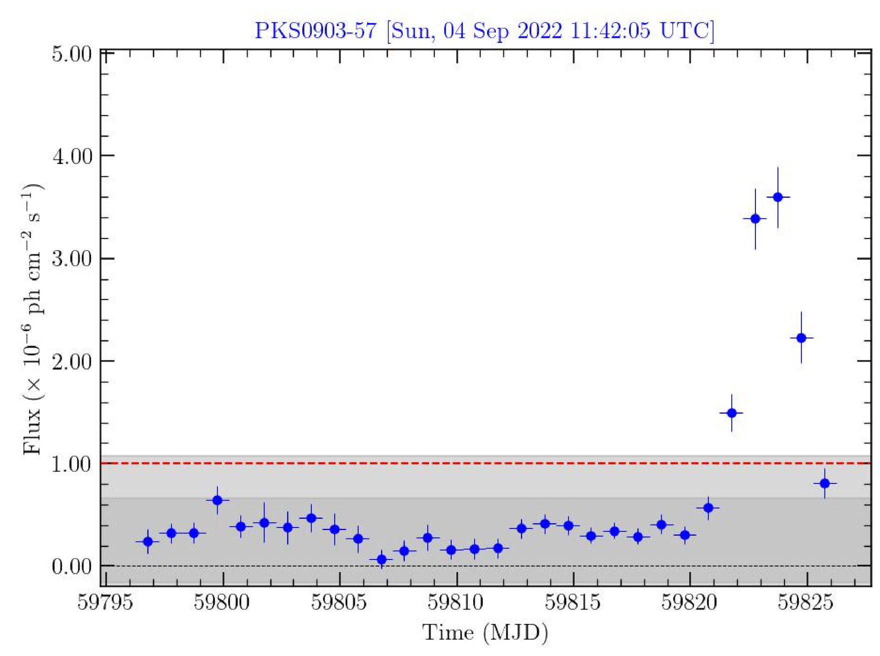
Methodology and Data Products

Time-dependent γ-ray fluxes are measured using an aperture photometry approach [4]. For each source, photon events are extracted within a 1° radius and an energy range of 100 MeV–500 GeV, applying standard quality cuts to minimize contamination from Earth's atmospheric γ rays and solar flares. Good Time Intervals (GTIs) are computed to ensure data integrity and to exclude periods of high instrumental background. Fluxes are then estimated by summing photon counts within the aperture, weighted by the instrumental exposure, providing a rapid, background-independent measure of source variability. This method enables the timely generation of alerts for a predefined source list without the need for full-sky searches, making it particularly well suited for large-scale, automated monitoring campaigns. The pipeline produces a comprehensive suite of primary and secondary data products. Primary outputs include light curves, diagnostic plots, detailed analysis reports, and variability metrics that systematically characterize temporal behavior–including flares and state transitions–with associated test statistics and configurable alert metadata.



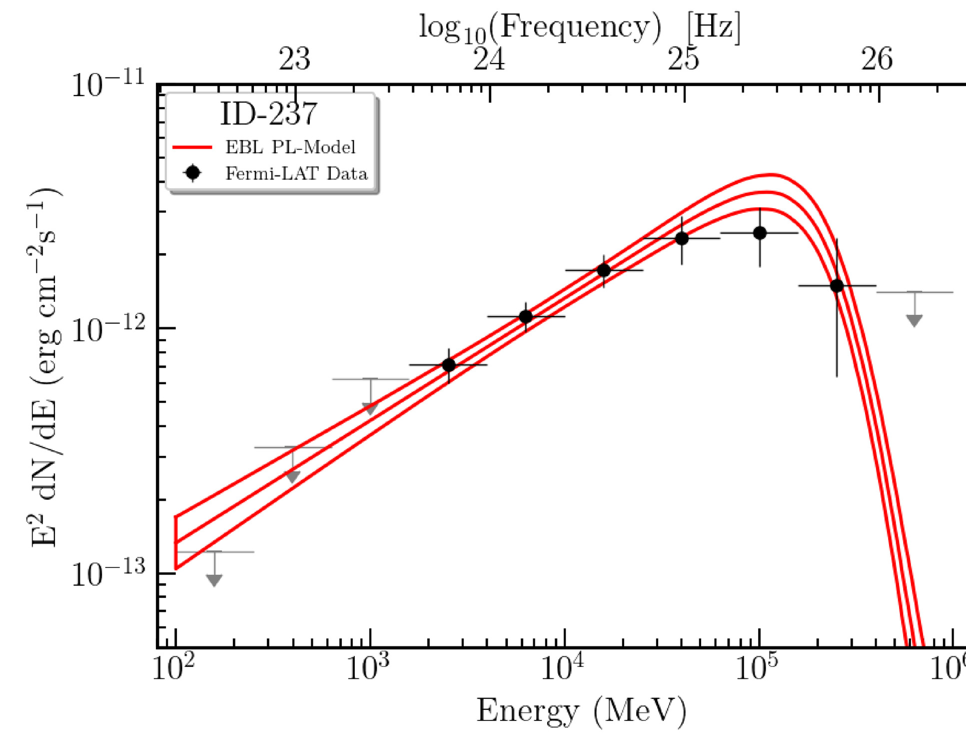
Fermi-LAT γ-ray count map in the vicinity of the BL Lac object PG 1553+113 ($z = 0.5$), shown in units of counts per pixel and smoothed by a Gaussian kernel.

For flaring sources, a dedicated likelihood-analysis framework performs automated, binned spectral fits using both `PowerLaw` and `LogParabola` models, providing detailed spectral characterization of the γ-ray emission. The system dynamically generates configuration templates and executes analyses across high-performance computing environments with optimized resource allocation and fault tolerance. Temporal segmentation is managed through adaptive time-windowing algorithms that align the analysis intervals with trigger epochs, ensuring accurate characterization of transient emission. Comprehensive quality-assurance protocols govern all stages of data processing, including event validation, job monitoring, and systematic error propagation. Outputs such as spectral energy distributions (SEDs), fit diagnostics, and variability metrics are automatically consolidated and structured for scientific interpretation.



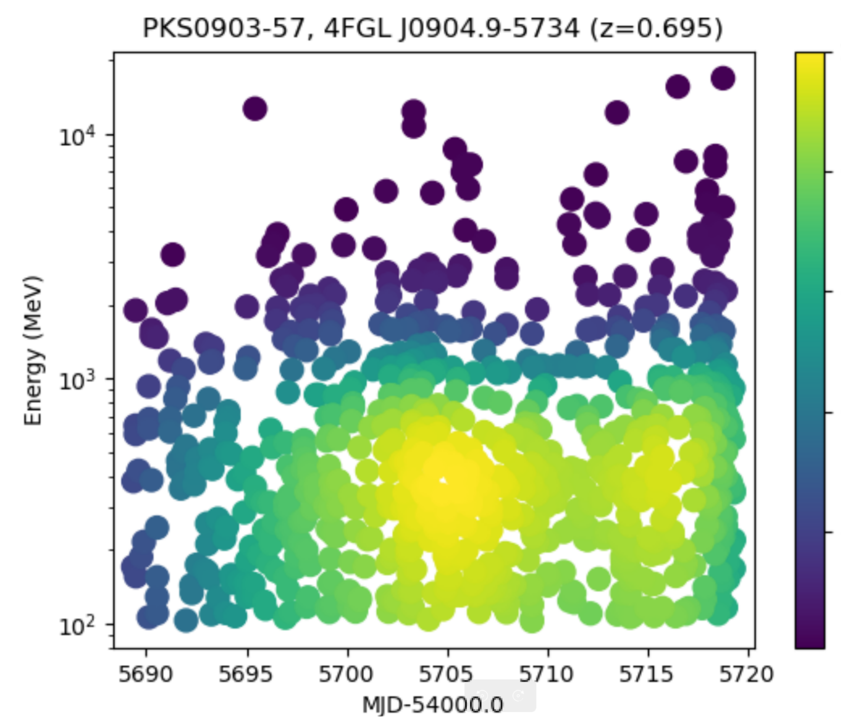
Daily Fermi-LAT light curve of the blazar PKS 0903-57 ($z = 0.69$) in the 100 MeV–500 GeV energy range. Data points were derived using 1° aperture photometry. A prominent flare triggers an automated alert from the ELMA pipeline as the flux rises sharply above the historical quiescent level (grey band) and exceeds the predefined alert threshold (red dashed line). Error bars represent 1σ statistical uncertainties.

Secondary data products focus on the characterization of high-energy photons, typically above 100 GeV, where background contamination is minimal. Event-level analyses enable precise source localization and identification of temporal clustering among very-high-energy (VHE) events. Automated association algorithms evaluate the probability that each photon originates from a known γ-ray source rather than the Galactic or extragalactic diffuse background, based on positional and temporal likelihood criteria. A dedicated alert system disseminates these results through multiple channels, including email, web interfaces, and other formats. Notifications include flux estimates and detection significance, customizable according to source type, flux threshold, and temporal cadence. In addition to real-time alerts, users can access data products via a web portal that provides interactive visualization, statistical tools, and data export functionality.



Spectral Energy Distribution (SED) of PKS 0903-57 in the 100 MeV–1 TeV range, extracted from the full *Fermi*-LAT dataset and fitted with a log-parabola model corrected for extragalactic background light (EBL) absorption.

All results are also archived in a long-term database to enable historical variability and population studies. The archive maintains compatibility with evolving analysis methodologies by recording all processing parameters and systematic uncertainty estimates. To ensure scientific integrity, the framework generates comprehensive processing logs for every automated operation, guaranteeing traceability and reproducibility.



Energy versus arrival-time distribution for *Fermi*-LAT events associated with PKS 0903-57. The color scale represents a Gaussian kernel-density estimate of photon density. Vertical clustering of yellow points indicates a high-intensity flaring episode.

Conclusions

The presented framework provides a robust and scalable solution for the automated monitoring of *Fermi*-LAT γ-ray sources, enabling rapid and statistically reliable flux estimation and alert generation. Its modular design ensures efficient parallel processing, reproducibility, and flexible access to comprehensive data products, including light curves, spectral analyses, and high-energy photon characterizations. By facilitating detailed investigations of source variability and enabling prompt multi-wavelength and multi-messenger follow-ups, the system maximizes the scientific return of time-domain γ-ray observations. Future developments will focus on the integration of machine learning techniques for enhanced variability detection, advanced Bayesian methods for uncertainty quantification [5], and an AI-driven agent [6] for autonomous pipeline management. These enhancements will enable fully automated, intelligent monitoring and real-time response to transient γ-ray phenomena, strengthening the framework's role within the rapidly evolving landscape of multi-messenger astrophysics.

Future Development

Ongoing work aims to incorporate machine learning approaches for improved variability detection and classification, together with Bayesian techniques to refine parameter and uncertainty estimation . A dedicated AI agent is being developed to autonomously manage the workflow, including data processing, event prioritization, and alert dissemination. These upgrades will transform the framework into an intelligent, self-adaptive system capable of real-time decision making and optimized scientific responsiveness to transient high-energy astrophysical events.

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