gammapy_SyLC: A Package for Simulating and Fitting Variability in High-Energy Light Curves

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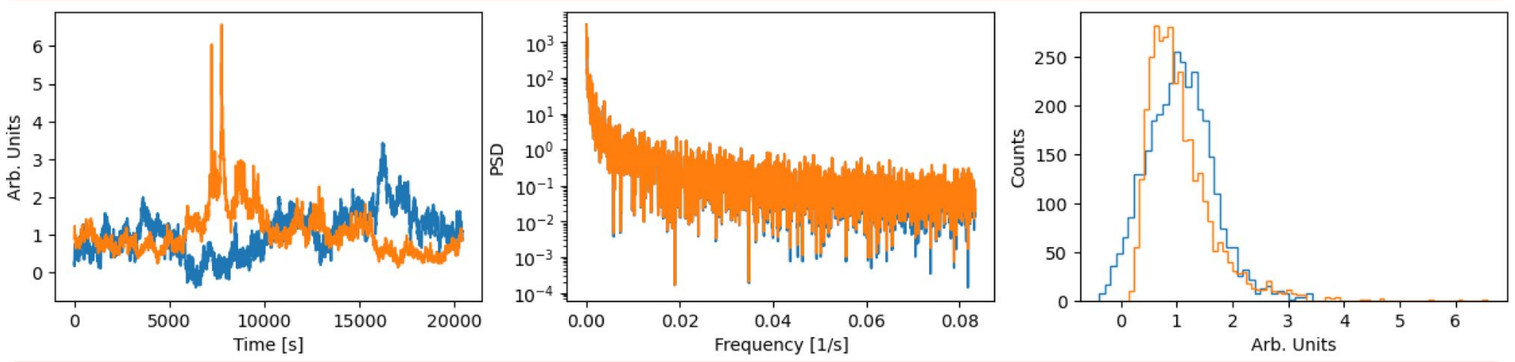
Characterizing the **temporal variability of astrophysical sources** is key to understanding the underlying physical processes driving their emission. However, the **stochastic and often non-Gaussian** nature of the variability requires advanced tools for simulation and fitting.

Gammapy_SyLC was developed to **bridge the gap between models and observational data,** enabling quantitative time-domain analysis in a simple and accessible way for all users in the high-energy astrophysics field, keeping compatibility with Gammapy. [1][2]

Core feature: light curve simulation

The package implements two powerful algorithms for generating synthetic light curves, allowing for testing of variability models, statistical properties and observational biases.



*A comparison of a **TK**-simulated curve with a power law PSD with a **EMM**-simulated curve following the same PSD and a lognormal PDF. Left - Light curves, middle - periodograms, right - histograms. The amplitudes and their distribution clearly differ, while the periodograms are indistinguishable.*

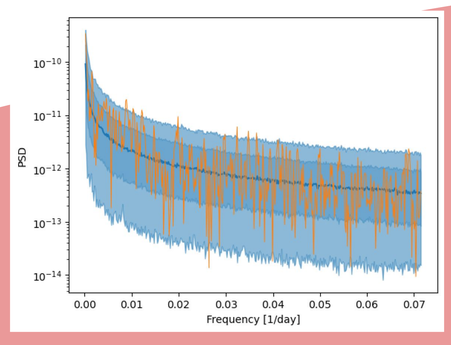
Timmer-Koenig (TK) [3] Algorithm: Generates Gaussian-distributed light curves that conform to a specified Power Spectral Density (PSD) model. Fast and efficient for processes where the flux distribution is assumed to be normal.

Emmanoulopoulos (EMM) [4] Algorithm: Extension of TK that generates light curves matching both a target PSD and a custom flux amplitude distribution (PDF). Essential for accurately modeling the non-Gaussian, skewed variability often seen in AGNs at high energy.

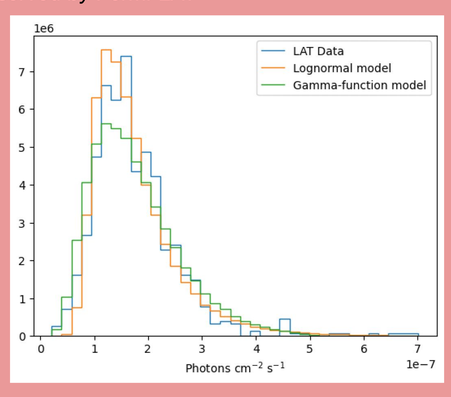
Core feature: fitting to models

PSD fitting

1. **Simulate:** A large ensemble of light curves is simulated based on a trial PSD model.
2. **Construct Envelopes:** The statistical distribution of the simulated periodograms is computed, forming confidence envelopes.
3. **Minimize & Fit:** The parameters of the PSD model are optimized by minimizing a chi2-like statistic that compares the observed periodogram to the simulated envelopes.
4. **Estimate Uncertainty:** The fitting process is repeated on batches of simulated to estimate parameter uncertainties via the Neyman construction method.



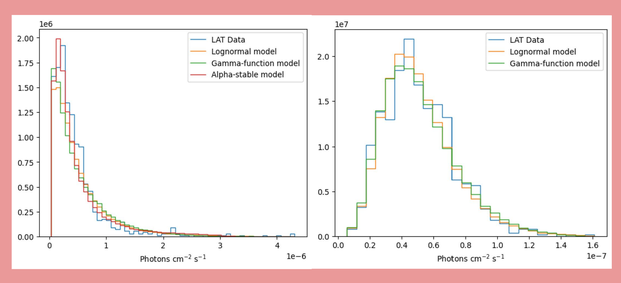
Top: periodogram and best-fit PSD envelope for BL Lac observed by Fermi-LAT. Bottom; histogram and best-fit PDF models assuming an underlying gamma or lognormal distribution for Markarian-421 as observed by Fermi-LAT



PDF fittting

1. **Simulate:** A large ensemble of light curves is simulated with the EMM algorithm according to the test PDF.
2. **Interpolate PDF:** An empirical amplitude distribution is constructed from the histogram of the ensemble.
3. **Fit:** data is fitted to the model by minimizing to find the best-fit parameters for the chosen PDF model, accounting for measurement uncertainties. $\mathrm{NLL} = -\sum_{i=0}^{n} \log\left(\prod_{j=0}^{m} \mathrm{PDF}_{interp}\left(N_j(x_i, xerr_i)\right)\right)^{\frac{1}{m}}$
4. **Compare models:** The package includes likelihood ratio tests to statistically quantify whether a given model (e.g., Lognormal) is preferred over an alternative (e.g., Normal or Gamma distribution).

A test on Fermi-LAT data

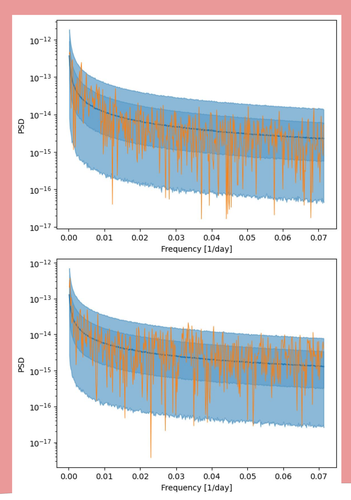


Histogram and best-fit PDF models assuming an underlying gamma or lognormal distribution for BL Lac (left) and Markarian-501 (right) as observed by Fermi-LAT

Object Name	Spectral Index (PSD)	P(Lognormal/Normal)	P(Lognormal/Gamma)
BL Lac	-0.91±0.04	0.03	0.13
Mkn 421	-0.83±0.05	0.0014	0.08
Mkn 501	-0.75±0.04	0.45	0.78

The package was tested for PSD fitting, PDF fitting and PDF model comparison using public weekly-binned light curves of AGNs from the Fermi-LAT Light Curve Repository.

- PSD Fitting: Effectively reconstructs the **underlying red-noise power-law behavior** and index, and derives robust parameter uncertainties.
- PDF Analysis: Identifies **best-fit amplitude distributions**. However, the model discrimination tools reveal that even with large datasets, **distinguishing between similar skewed models remains a challenge.**



Periodogram and best-fit PSD envelope for Markarian 421 (top) and 501 (bottom).

Future and conclusions

- **Realistic Simulation:** Generation of synthetic light curves that reproduce both the power spectrum and the non-Gaussian flux distributions seen in astrophysical sources.
- Quantitative Analysis: Robustly **constrains PSD parameters** from observed data and quantifies the statistical challenge of **discriminating between competing skewed PDF models**, especially in the case of smaller datasets.

Gammapy_SyLC provides a simple, accessible framework to bridge theoretical models and observational data in time-domain astrophysics.
Future developments: incorporating more complex models and a direct integration with gammapy objects, positioning gammapy_SyLC as an accessible community tool for maximizing the scientific return from current and future facilities like the CTAO.

Resources

[1]A. Donath et al., 2023, Gammapy: A Python package for gamma-ray astronomy, A&A, 2024 arXiv:2308.13584 [2]https://github.com/gammapy/ [3] Timmer, J and Koenig, M, 1995, On generating power law noise, https://ui.adsabs.harvard.edu/abs/1995A%26A...300..707T/abstract [4] Emmanoulopoulos, D. et al., 2012, Generating artificial light curves: revisited and updated, https://academic.oup.com/mnras/article/433/2/907/1746942?login=true