A Systematic Search for Blazar Quasi-Periodic Oscillations: Connecting Jet Variability to Gravitational Wave Sources

Alberto Domínguez
(IPARCOS & UC Madrid)

A. Rico, P. Peñil, M. Ajello, S. Buson, on behalf of the *Fermi*-LAT collaboration
and S. Adhikari, M. Movahedifar

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Why Study Blazar Variability?

- Active Galactic Nuclei (AGN): An accreting supermassive black hole (SMBH) in the center of some galaxies (e.g. Padovani et al. 2017).

- Blazar: AGN with one of the relativistic jets closely aligned with the line of sight. They dominate the gamma-ray sky in number (Abdollahi et al. 2020).

- The most luminous persistent objects in the Universe (e.g, Urry 1996).

- Variable emission across all energies (e.g, Urry 1996).

- Light curves may show patterns, e.g, quasi-periodic oscillations (QPO, e.g, Ackermann et al. 2015; Peñil et al. 2020, 2022, 2023, Adhikari et al. 2024, 2025).

Physical Origins of Periodicity in Blazars

- Helps probe the astrophysical nature of blazars.

- Provides clues about their internal structure and physical processes.

- Periodic behavior in AGN light curves may be linked to:
    - Jet precession (e.g., Camenzind & Krockenberger 1992).
    - Accretion flow instabilities (e.g., Gracia et al. 2003).
    - **Supermassive binary black holes (e.g., Sobacchi et al. 2016; Celoria et al. 2018).**

Expected source of very-low-frequency gravitational waves contributing to diffuse background, maybe a possible individual detection!

Observational and Analysis Challenges

- Blazar light curves are dominated by stochastic variability, flares, and long-term trends that can mask periodic signals (e.g. Peñil et al. 2025).
- Traditional Fourier-based methods are limited by nonstationarity and red noise contamination.
- Obtaining well-sampled light curves requires long-term, continuous monitoring, which is observationally expensive and often incomplete.
- Identifying robust QPOs demands separating overlapping signal components in noisy data.

State of the Art: QPO Searches in Gamma-Ray Blazars

Individual Blazars:

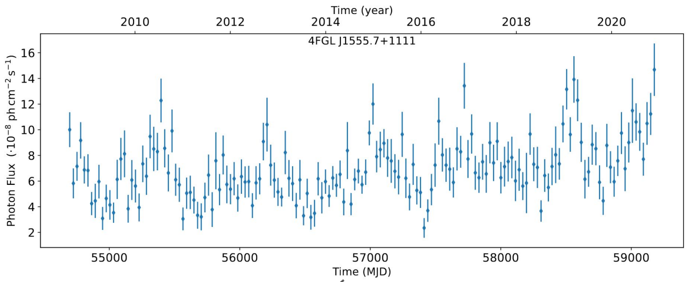
- ***PG 1553+113***: One of the most robust gamma-ray QPO detections. Ackermann et al. (2015) found a ~2.2-year periodicity with Fermi-LAT. Subsequent studies confirmed this signal (e.g., Prokhorov & Moraghan 2017; Peñil et al. 2022).
- ***PKS 0426−380, S5 1044+71, PKS 0208−512***: Periodicity hints detected in gamma rays (e.g., Zhang et al. 2017, Benkhali et al. 2019, Wang et al. 2022, many more). Often show significant peaks in periodograms but with modest global significance due to trial factors.

Larger Samples:

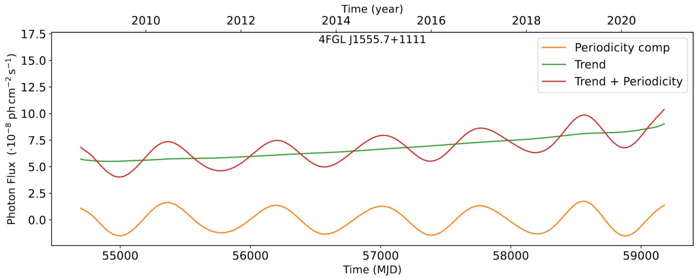
- ***Peñil et al. (2020, 2022)***: First systematic search for periodicity in gamma-ray blazars using 9 years of Fermi-LAT data. Analyzed hundreds of sources using a suite of 10 time-series methods, mostly in the Fourier domain. Identified 11 periodic candidates with local significance ≥ 2σ, but most lacked strong global significance. Highlighted limitations due to noise, trends, and incomplete light curves.
- ***E.g. Gupta et al. (2019), Rueda et al. (2022), Ren et al. (2023), Li et al. (2023)***: Focused on selected bright sources or samples of 10–20 blazars. Reported possible gamma-ray QPOs ranging from days to a few years. Methods often based on Lomb-Scargle, wavelets, or autoregressive modeling.

In the optical, ***3C 66A, S5 0716+71, PKS 2155−304***: Evidence of QPOs in optical light curves with periods from months to a few years. Studies include e.g., Raiteri et al. (2001), Sandrinelli et al. (2014, 2016), Otero-Santos et al. (2020), Cheng et al. (2022). Often show periodicities not (yet) confirmed in gamma rays.

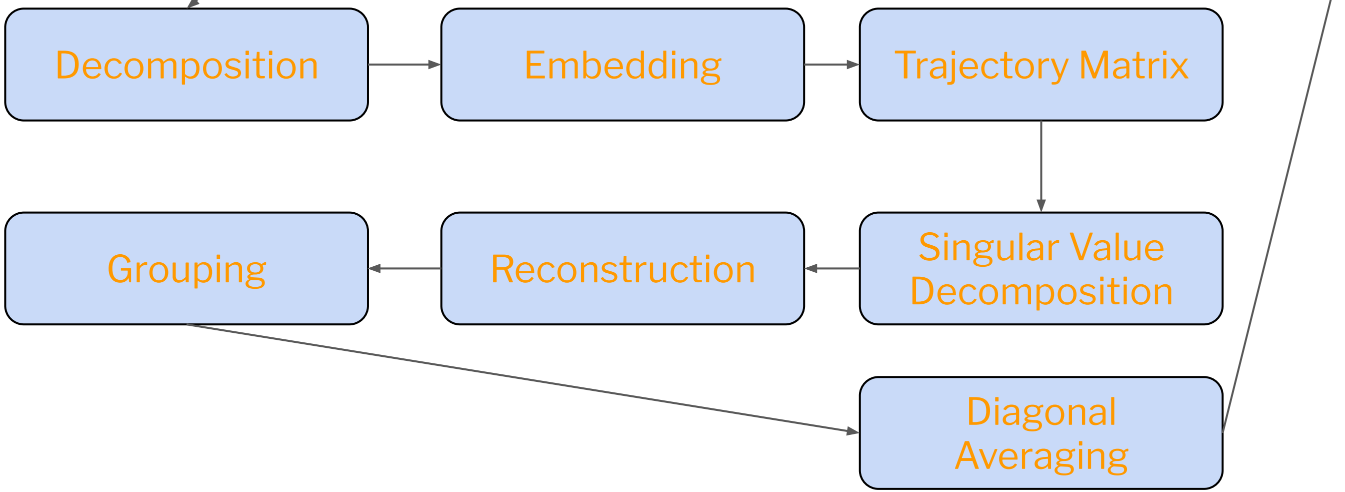
Light Curve Decomposition Using Singular Spectrum Analysis



Input



Output



Gamma-ray Data

Data taken with Fermi Large Area Telescope (LAT):

- Pass 8 SOURCE class data (P8R3_SOURCE_V2)
- Energy range: 0.1 to 800 GeV
- Time span: August 2008 – December 2020 (≈12 years)
- 28-day binning optimized for year-scale periodicities

Light Curve Construction:

- Full likelihood fit for each time bin
- Region of Interest: $15^\circ \times 15^\circ$, centered on each source
- Dynamic fitting strategy: nearby sources fixed or freed based on test statistic (TS)

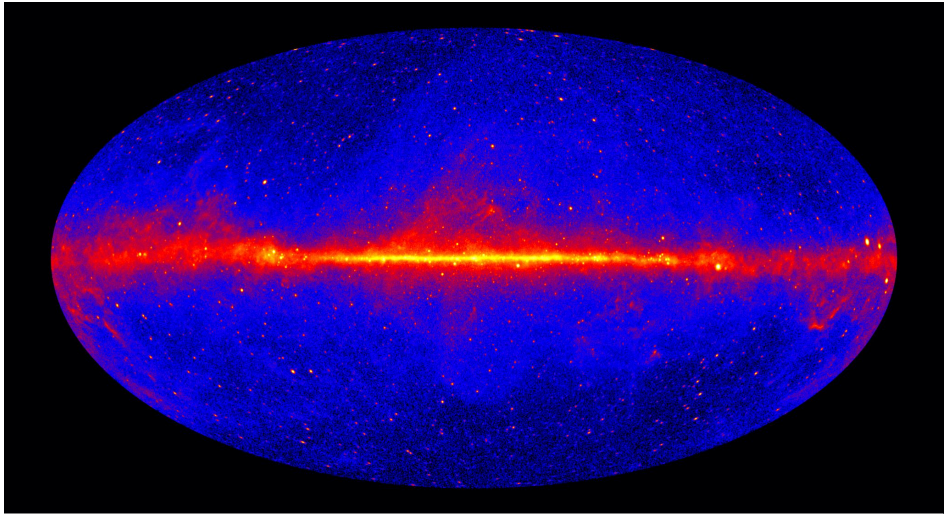
Sample Selection

Based on 4FGL-DR2 catalog (Abdollahi et al. 2020)

- Selected variable sources only:
- Variability index > 18.48 ($p < 0.01$ of constant flux)
- Final sample: 494 variable blazars
- BL Lacs, FSRQs, BCUs, and NLSy1 galaxies included

Treatment of Upper Limits:

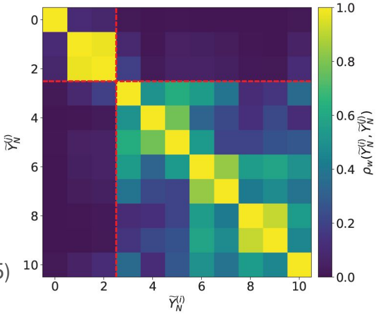
- Time bins with TS < 4 treated as upper limits
- LCs with >50% upper limits excluded



This map shows the entire sky in gamma rays above 1 GeV, captured over 15 years by the Fermi Gamma-ray Space Telescope. Each bright dot marks a powerful cosmic source, many are active galaxies with jets pointed toward us.

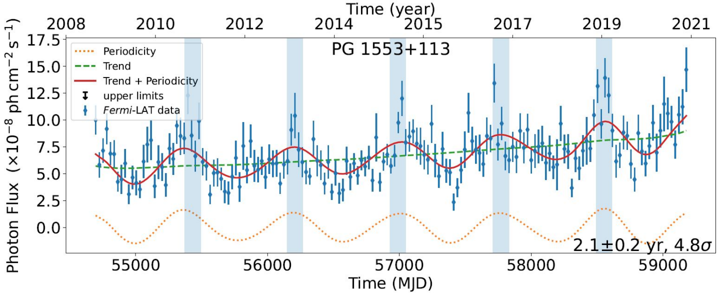
Analysis Pipeline and Benchmark Test Case (PG 1553+113)

1. Apply SSA decomposition to all sources



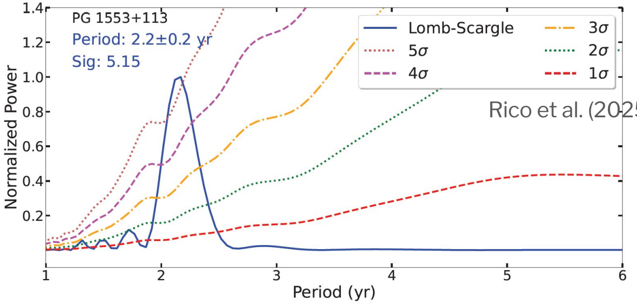
Rico et al. (2025)

2. Decomposed light curve



Rico et al. (2025)

3. Apply Lomb-Scargle all sources and rough significance estimate using Emmanoulopoulos et al. (2013) method



Rico et al. (2025)

4. Local and Global significance calculations

Local significance (σ)	Global significance (σ)
4.8	3.4
4.5	3.0
4.0	2.2
3.5	1.2
<3.0	<1.0

Rico et al. (2025)

Results on Quasi-Periodic Oscillations

4FGL Source Name	RA(J2000)	Dec(J2000)	Association Name	Type	Redshift	Period (yr)	Local Significance	Global Significance
J0137.0+4751*	24.260	47.864	OC 457	fsrq	0.859	1.79 ±0.22	4.8σ	3.3σ
J0407.0−3826	61.763	-38.439	PKS 0405−385	fsrq	1.285	3.01 ±0.43	4.8σ	3.3σ
J0428.6−3756	67.173	-37.94	PKS 0426−380	bll	1.110	3.51 ±0.49	4.8σ	3.3σ
J0457.0−2324	74.261	-23.415	PKS 0454−234	fsrq	1.003	3.57 ±0.43	4.8σ	3.3σ
J0501.2−0158	75.302	-1.975	S3 0458−02	fsrq	2.291	1.00 ±0.04	4.8σ	3.3σ
J0521.7+2112	80.445	21.213	TXS 0518+211	bll	0.108	2.83 ±0.38	4.8σ	3.3σ
J0526.2−4830*	81.571	-48.515	PKS 0524−485	fsrq	1.300	2.07 ±0.20	4.8σ	3.3σ
J0811.4+0146	122.861	1.776	OJ 014	bll	1.148	4.65 ±0.89	4.8σ	3.3σ
J1007.6−3332*	151.912	-33.543	PKS 1005−333	fsrq	1.837	2.61 ±0.34	4.8σ	3.3σ
J1048.4+7143	162.107	71.730	S5 1044+71	fsrq	1.150	3.05 ±0.44	4.8σ	3.3σ
J1146.9+3958	176.740	39.978	S4 1144+40	fsrq	1.089	3.31 ±0.50	4.8σ	3.3σ
J1522.1+3144	230.545	31.740	B2 1520+31	fsrq	1.489	3.37 ±0.56	4.8σ	3.3σ
J1532.7−1319*	233.197	-13.326	TXS 1530−131	bcu	-	1.37 ±0.07	4.8σ	3.3σ
J1555.7+1111	238.931	11.188	PG 1553+113	bll	0.433	2.15 ±0.16	4.8σ	3.3σ
J1637.7+4717*	249.434	47.291	4C +47.44	fsrq	0.735	3.17 ±0.58	4.8σ	3.3σ
J1657.7+4808*	254.438	48.137	4C +48.41	fsrq	1.669	1.47 ±0.08	4.8σ	3.3σ
J1913.0−8009*	288.27	-80.157	PKS 1903−80	fsrq	1.756	2.41 ±0.22	4.8σ	3.3σ
J2201.5−8339*	330.379	-83.663	PKS 2155−83	fsrq	1.865	4.73 ±0.94	4.8σ	3.3σ
J2139.4−4235*	324.855	-42.590	MH 2136−428	bll	-	1.81 ±0.18	4.8σ	3.3σ
J0222.6+4302*	35.670	43.036	3C 66A	bll	0.444	2.31 ±0.20	4.6σ	3.1σ
J1312.8−0425*	198.217	-4.420	PKS B1310−041	fsrq	0.825	2.37 ±0.22	4.6σ	3.1σ
J0721.9+7120	110.488	71.340	S5 0716+71	bll	0.127	2.85 ±0.33	4.5σ	3.0σ
J0210.7−5101	32.695	-51.022	PKS 0208−512	fsrq	1.003	2.47 ±0.26	4.5σ	3.0σ
J2158.8−3013	329.714	-30.225	PKS 2155−304	bll	0.116	1.65 ±0.10	4.5σ	3.0σ
J1427.0+2348*	216.756	23.801	PKS 1424+240	bll	0.604	1.53 ±0.09	4.5σ	3.0σ

Rico et al. (2025)

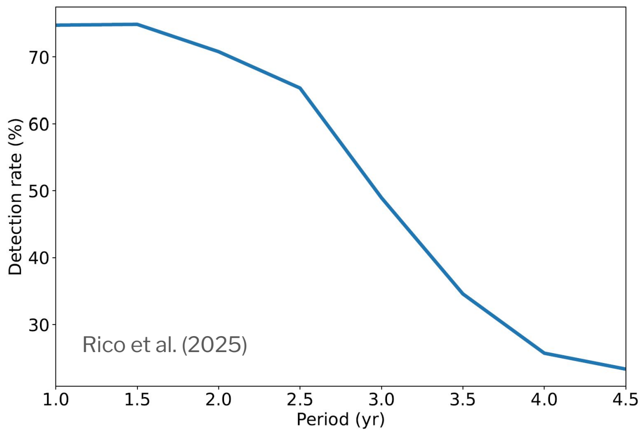
We identify 25 blazars with global significance above 3σ, including 12 not previously reported in the literature.

Robustness Checks and False Positive Rate Assessment

We simulate 100,000 light curves combining a sinusoidal signal and different types of noise (white, pink, red) using the colorednoise Python package.

Results:

- Assessment of the detection rate as a function of period, showing SSA recovers 78% of injected signals with 1 – 2.5 yr periods and 50% improvement over prior methods for 3.5 – 4.5 yr periods.

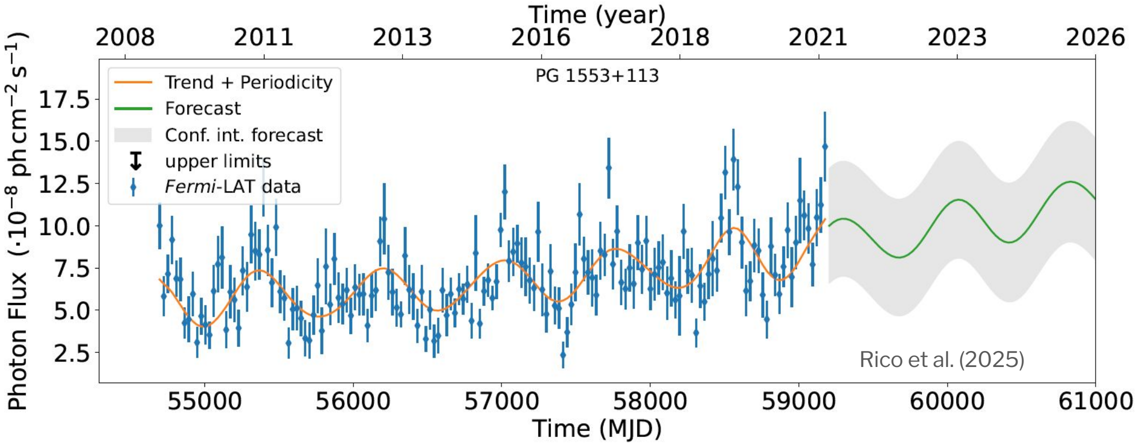


We generate 500,000 pure noise light curves (white, pink, red noise, no signal). SSA and the full detection pipeline are applied.

Results:

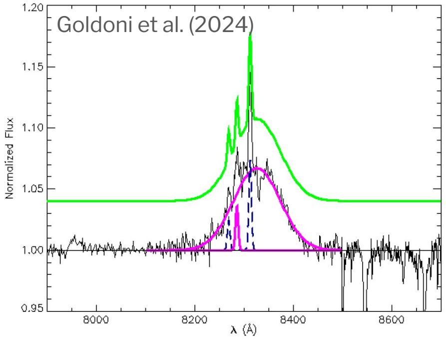
- 0.13% of pure noise LCs show ≥3σ significance.
- 2.27% show ≥2σ significance.
- Therefore, in their sample of 494 sources, about 13 false positives are statistically expected at the 2σ level.

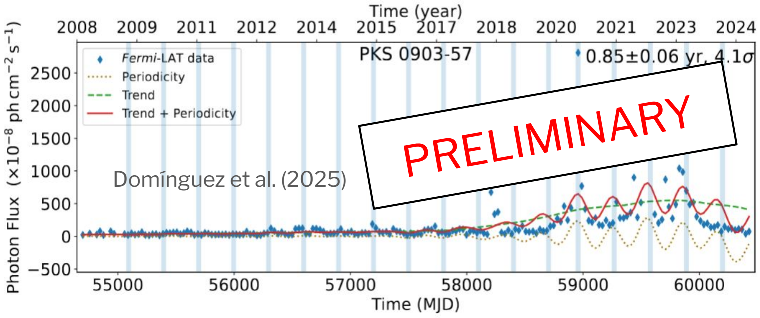
Additional Results: Long-Term Behavior and Forecasting Models



We also analyze long-term trends and provide forecasts of future gamma-ray flux levels.

PKS 0903-57: A Candidate System for Gravitational Wave Emission





- Redshift: $z = 0.2621$; classified as an FSRQ
- Spectroscopy: Broad–narrow Hα offset of 1460 ± 36 km/s (Goldoni et al. 2024)
- QPO Detection: 0.9 ± 0.1 yr periodicity found in Fermi-LAT data using SSA + LSP + WWZ
- Persistence: QPO stable across 16 years, including pre-2018 quiescent phase
- Interpretation: Consistent with SMBBH scenario (see e.g. Sharma et al. 2025); alternatives include jet precession and disk instabilities
- Orbital Separation: Estimated $a \approx 0.07$ pc → firmly in sub-parsec regime
- GW Outlook: Strain $h_c \approx (2.5–5) \times 10^{-16}$ at ~7.5 nHz, near future PTA sensitivity limits

→ **Strong candidate for hosting a sub-parsec SMBBH; excellent multi-messenger target.**

Summary and Conclusions

These findings mark a key step toward population-level studies of QPOs and their connection to the central engines and potential gravitational wave sources in AGNs.

- We conducted a systematic search for quasi-periodic oscillations (QPOs) in 494 gamma-ray blazars using Singular Spectrum Analysis (SSA), applied to 12 years of Fermi-LAT data.
- Our methodology successfully overcomes challenges from red noise and nonstationarity, enabling robust identification of periodic components.
- We detect 25 QPO candidates with global significance $> 3\sigma$, 12 of which are new to the literature , significantly expanding the known sample of gamma-ray QPOs.
- False positive rate tests confirm a low contamination level, with <0.2% of pure noise light curves exceeding the 3σ threshold.
- Forecasting models and long-term trend analysis offer additional tools to characterize blazar variability beyond periodicity.
- PKS 0903-57 stands out as a strong multi-messenger candidate, showing a stable ~0.9 yr QPO consistent with a sub-parsec supermassive binary black hole. It is likely that similar systems exist among the other sources in our sample - this is currently work in progress.