Multiwavelength Analysis of Periodic *Fermi*-LAT Blazars Exhibiting Hints of Periodicity

**P. Peñil, M. Ajello,
S. Buson, A. Domínguez,
L. Marcotulli, J. Becerra,
A. Rico on behalf of the
Fermi-LAT
collaboration with
J. Otero-Santos,
R. Westernacher-Schneider,
N. Torres-Alba,
J.A. Acosta-Pulido,
J. Zrake**

11th Fermi Symposium
Clemson University (Clemson, SC, USA)
9-11-2024

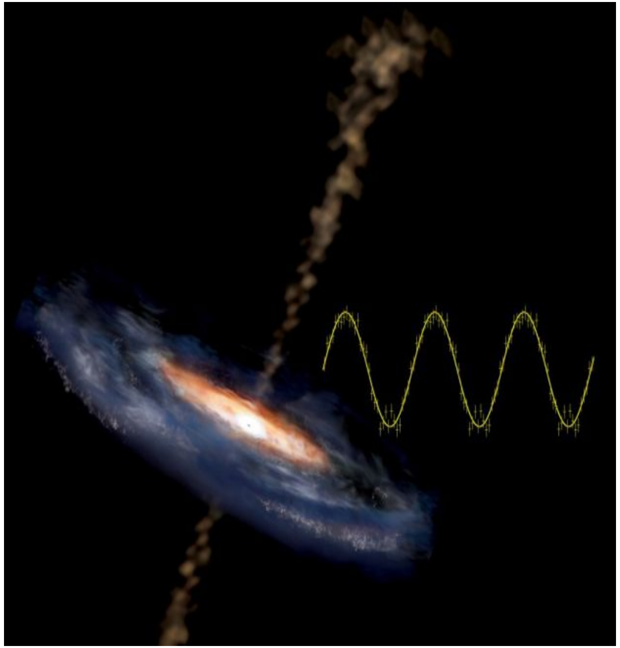
Introduction

- Detecting of long-term periodic oscillations in γ rays is an important step for identifying potential Binary-SMBH (e.g. Rieger & Volper, 2010)

- Similar periodic emission in other energy bands point to a common origin:
  - Traditional indicator for Binary-SMBH Candidate

- Infer the physical parameters of the putative binary, e.g:
  - eccentricity (e.g., Zrake et al., 2021), primary SMBH mass (e.g., Westernacher-Schneider et al., 2022)

- Single SMBH:
  - Jet precession (Ostorero et al., 2004)
  - Accretion Disk Instabilities (Gracia et al., 2003)



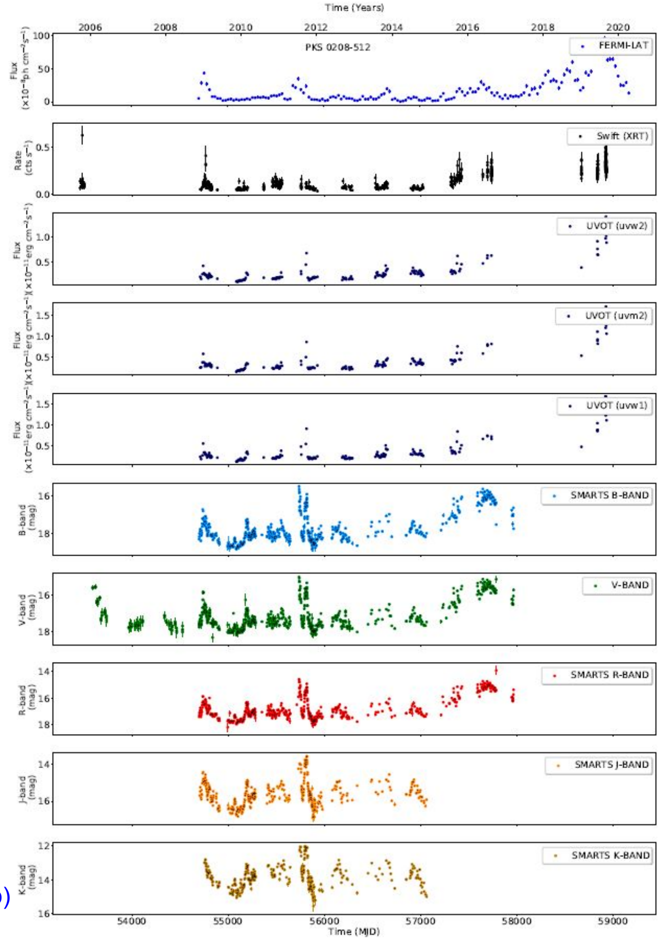
Blazar Sample

- **24 blazars** with evidence of periodicity (>2σ pre-trial) in a sample of 351 sources (Peñil et al., 2020)
- Re-analysis with 3 extra of *Fermi*-LAT observations, in total 12 years (Peñil et al., 2022)
- **5 objects: periods significance >3σ** (pre-trial) (Peñil et al., 2024a)
- **19 objects: period significance >2.0σ** (pre-trial) (Peñil et al., 2024b)

4FGL Source Name	RA(J2000)	Dec(J2000)	Type	Redshift	Association Name	P20 Period (S/N) [yr]	Period (S/N) [yr]
J1555.7+1111	238.93169	11.18768	bll	0.433	PG 1553+113	2.2 (>4.0σ)	2.2 (4.4σ)
J2158.8−3013	329.71409	-30.22556	bll	0.116	PKS 2155−304	1.7 (>3.0σ)	1.7 (3.5σ)
J0811.3+0146	122.86418	1.77344	bll	1.148	OJ 014	4.3 (>3.5σ)	4.1 (3.1σ)
J0457.0−2324	74.26096	-23.41384	fsrq	1.003	PKS 0454−234	2.6 (>2.5σ)	3.6 (3.1σ)
J0721.9+7120⋆	110.48882	71.34127	bll	0.127	S5 0716+714	2.8 (>2.5σ) 0.9 (>2σ)	2.7 (3.1σ) 0.9 (1.9σ)
J0043.8+3425	10.96782	34.42687	fsrq	0.966	GB6 J0043+3426	1.8 (4.0σ)	1.9 (2.8σ)
J0521.7+2113	80.44379	21.21369	bll	0.108	TXS 0518+211	2.8 (>3.0σ)	3.1 (2.8σ)
J0449.4−4350	72.36042	-43.83719	bll	0.205	PKS 0447−439	2.5 (3.0σ)	1.9 (2.7σ)
J0252.8−2218	43.20377	-22.32386	fsrq	1.419	PKS 0250−225	1.2 (>2.5σ)	1.2 (2.7σ)
J1146.8+3958	176.73987	39.96861	fsrq	1.089	S4 1144+40	3.3 (> 3.0σ)	3.3 (2.3σ)
J0303.4−2407	45.86259	-24.12074	bll	0.266	PKS 0301−243	2.0 (3.0σ)	2.1 (2.2σ)
J0428.6−3756	67.17261	-37.94081	bll	1.11	PKS 0426−380	3.4 (3.0σ)	3.6 (2.1σ)
J2056.2−4714⋆	314.06768	-47.23386	fsrq	1.489	PKS 2052−47	1.7 (>2.5σ)	3.1 (1.7σ) 1.7 (2.1σ)
J1248.2+5820⋆	192.07728	58.34622	bll	–	PG 1246+586	2.0 (3.0σ)	2.1 (1.9σ) 1.4 (1.7σ)
J2258.0−2759⋆	344.50485	−27.97588	fsrq	0.926	PKS 2255−282	1.3 (>3.5σ)	2.8 (1.9σ) 1.4 (1.8σ)
J1903.2+5541	285.80851	55.67557	bll	–	TXS 1902+556	3.8 (>2.5σ)	3.3 (1.8σ)
J0818.2+4223	124.56174	42.38367	bll	0.530	S4 0814+42	2.2 (3.5σ)	2.2 (1.8σ)
J0211.2+1051	32.81532	10.85811	bll	0.2	MG1 J021114+1051	1.7 (>3.5σ)	2.9 (1.8σ)
J0501.2−0157	75.30886	-1.98359	fsrq	2.291	S3 0458−02	1.7 (>2.5σ)	3.8 (1.8σ)
J1303.0+2435	195.75454	24.56873	bll	0.993	MG2 J130304+2434	2.0 (>2.5σ)	2.1 (1.6σ)
J0102.8+5825	15.71134	58.41576	fsrq	0.644	TXS 0059+581	2.1 (3.0σ)	4.0 (1.4σ)
J1454.5+5124	223.63225	51.413868	bll	–	TXS 1452+516	2.1 (>3.5σ)	2.1 (1.2σ)
J0210.7−5101	32.68952	-51.01695	fsrq	1.003	PKS 0208−512	2.6 (>3.0σ)	3.8 (1.1σ)
J1649.4+5238	252.35208	52.58336	bll	–	87GB 164812.2+524023	2.7 (>2.5σ)	2.8 (1.1σ)

Multiwavelength Data

- X-ray band: *Swift*-XRT
- UV bands: UVOT
- Optical data:
  - Katzman Automatic Imaging Telescope (KAIT)
  - Catalina Sky Survey (CSS)
  - Tuorla blazar monitoring program
  - American Association of Variable Star Observers (AAVSO)
  - Small and Moderate Aperture Research Telescope System (SMARTS)
  - Astronomy & Steward Observatory
- Radio data:
  - Owens Valley Radio Observatory (OVRO)



(Peñil et al., 2024b)

Methodology

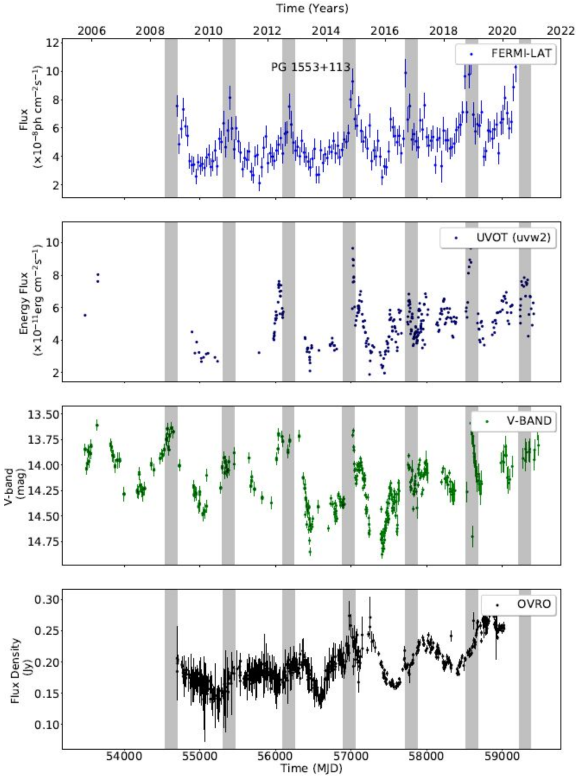
- Periodicity:
  - *Fermi*-LAT LCs over 12 years telescope time binned 28-days intervals
    - MWL data binned 28-days intervals
  - Methods:
    - Generalized Lomb-Scargle periodogram
    - Phase Dispersion Minimization
    - Weighted Wavelet Z-transform

- Multiwavelength Correlation:
  - Z-Transformed Discrete Function:
    - Time lags in γ rays

- Significance:
  - Emmanoulopoulos method: same PSD and PDF as the original
  - PSD model: power-law with indices [0.8-1.6]
  - Trial-factor correction: 0σ global significance for <4.5σ pre-trial significance

Results(I): Blazars with Periods at >3σ

- Periodicity:
  - PG 1553+113 (period 2.2 years in γ rays)
    - Same period in optical, and radio (5σ pre-trial) (Ackermann et al., 2015)
    - X-ray: 1.5 yr (2σ pre-trial) (Aniello et al., 2024)
      - Secondary peak at 2.2 yr (2σ pre-trial) (Huang et al., 2021)
  - PKS 2155-304 (period 1.7 years in γ rays):
    - Same period in X-ray and optical (2.5σ pre-trial) (Battha & Dhital, 2020)

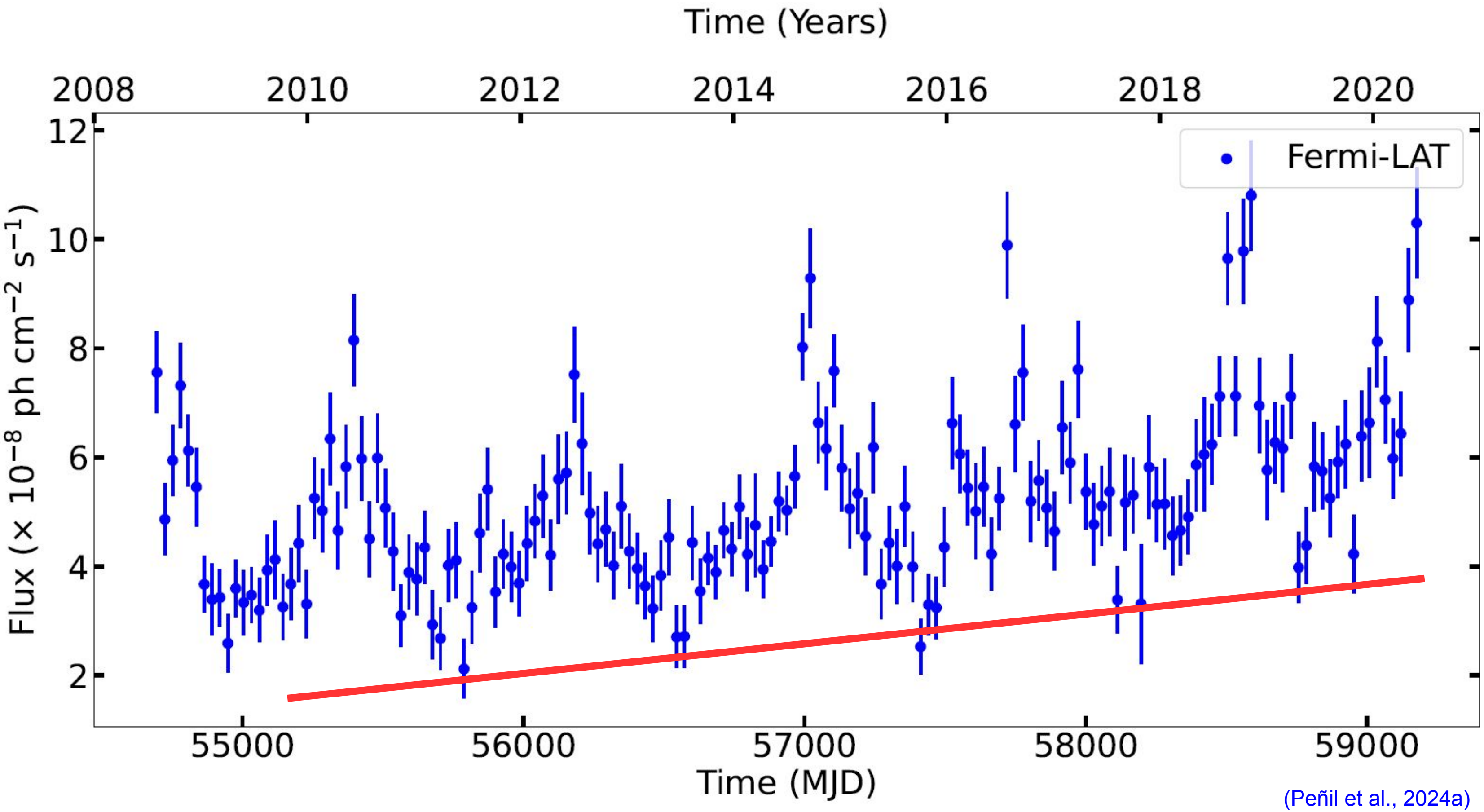


(Peñil et al., 2024a)

Results(I): Blazars with Periods at >3σ

- Correlation:
  - X-ray: Time lag <28 days (3.0σ)
    - Suggested co-spatial origin. γ rays may be produced via external Compton scattering on either the photons from the BLR or those from the dusty torus, which also dominates the X-ray emission (Sikora et al., 2013)
  - Optical: Time lag <28 days (2.0σ-4.0σ)
    - Co-spatial origin of both emissions, typically expected from leptonic models (e.g., Liodakis et al., 2018)
  - Radio: Time lag -200 days (2.0σ)
    - Observed in jet regions further away from the central engine (γ rays generation); high opacity and self-absorption in the inner regions (e.g., Ackermann et al., 2015)

Results (II): Long-Term Trend in the LC of PG 1553



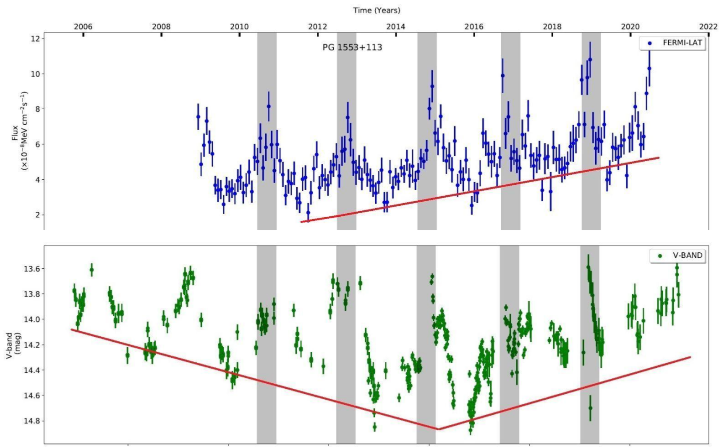
(Peñil et al., 2024a)

Results (II): Long-Term Trend in the LC of PG 1553

- Long-term trend is an increase or decrease of the flux over extended epochs of time

- Compatible slope of a linear fit of MWL emissions

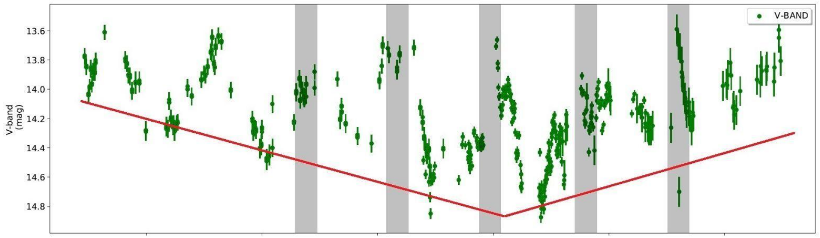
- Two questions:
    - **What can be causing this long-term trend?**
    - **Are long-term trends common in blazars?**



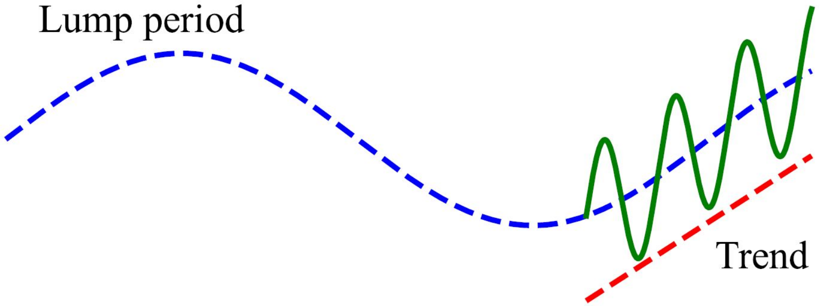
(Peñil et al., 2024a)

Results (II): Long-Term Trend in the LC of PG 1553

- What can be producing this long-term trend?
    - Hypothesis:
      Section of a larger period
- DASCH Historical Optical data (100 years):
    - Evidences of **period 22 years** (Adhikari et. al, 2024):
        - Binary-SMBH hypothesis:
          Lump scenario
    - See the poster 5:
      Decades Long Periodicity in 2FHL Blazar PG 1553+113? (Sagar Adhikari)



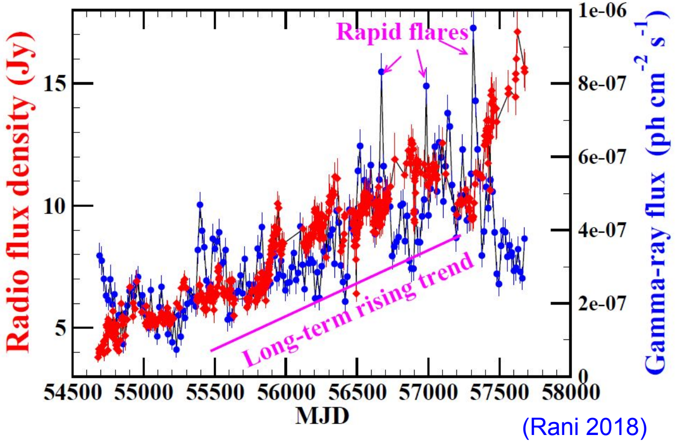
(Peñil et al., 2024a)



(Adhikari et al., 2024)

Results (II): Long-Term Trend in the LC of PG 1553

- Are long-term trends common in blazars?
  - Observed in a few objects:
    - Radio+γ rays:
      - 3C 84 (Rani 2018)
    - γ rays
      - 1ES 1215+303 (Valverde et al., 2020)

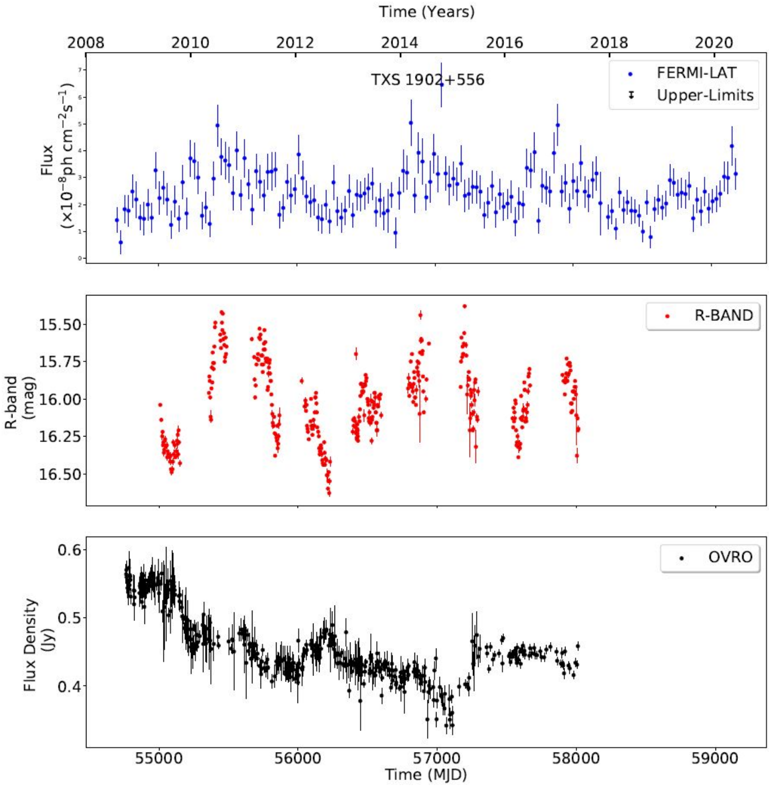


(Rani 2018)

- Systematic Search for Long-Term Trends in Fermi-LAT Jetted Active Galactic Nuclei (submitted to ApJ)
  - See the poster 6:
    A Systematic Search for Periodicity of *Fermi*-LAT AGN using Singular Spectrum Analysis
    (Alba Rico)

Results(III): Blazars with Periods at >2σ

- Periodicity:
  - Limited data available
  - 9 blazars analyzed
- Compatible with γ-ray period:
  - Optical:
    - PG 1246+586: 2.2 yr (2.5σ pre-trial)
    - S4 0814+42: 2.3 yr (2.5σ pre-trial)
    - PKS 0301-243: 2.1 yr (3.0σ pre-trial)
    - TXS 1902+556: 3.3 yr (3.0σ pre-trial)
  - Radio:
    - S4 1144+40: 3.3 yr (2.5σ pre-trial)



(Peñil et al., 2024b)

Results(III): Blazars with Periods at >2σ

- Correlation:
  - X-ray: 1 blazar analyzed
    - Time lag <28 days (4.0σ)
      - Co-spatial origin of both emissions
  - Optical: 18 blazars analyzed
    - Time lag <28 days (2.0σ-4.0σ)
      - Co-spatial origin of both emissions
  - Radio: 2 blazars analyzed
    - Radio Delayed of 150-250 days (2.0σ-3.0σ)
      - Observed in jet regions further away from the central engine

Summary

- Periodicity:
    - 24 blazars with periods ≥2σ in γ rays
    - 7 of them similar period than γ rays with (2.5σ-5.0σ): Binary-SMBH Candidate
- Correlation, co-origin with γ rays:
    - X-ray: 3 sources time lag <28 days (2.5σ-4.0σ)
    - Optical: 23 sources <28 days (2.5σ-4.0σ)
    - Radio: 3 sources with delays 150-250 days (2.0σ-4.0σ)
- First detection and characterization of a long-term trend in the MWL emission of PG 1553+113
- Follow-up these sources with new MWL observations
- Improve the analysis methodology:
    - Singular Spectrum Analysis: see the poster 6
      A Systematic Search for Periodicity of *Fermi*-LAT AGN using Singular Spectrum Analysis
      (Alba Rico)

Papers

Peñil et al., 2022

Peñil et al., 2024a

Peñil et al., 2022

Adhikari et. al, 2024

Peñil et al., 2024b