Significant detection of Quasi-periodic Oscillation in gamma-ray blazar

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Collaborators: Avik Das, Alok C Gupta, and Pankaj Kushwaha

Based on arXiv:2211.00588

Polish-German WE-Heraeus-Seminar

~~Significant~~ A possible detection of Quasi-periodic Oscillation in gamma-ray blazar

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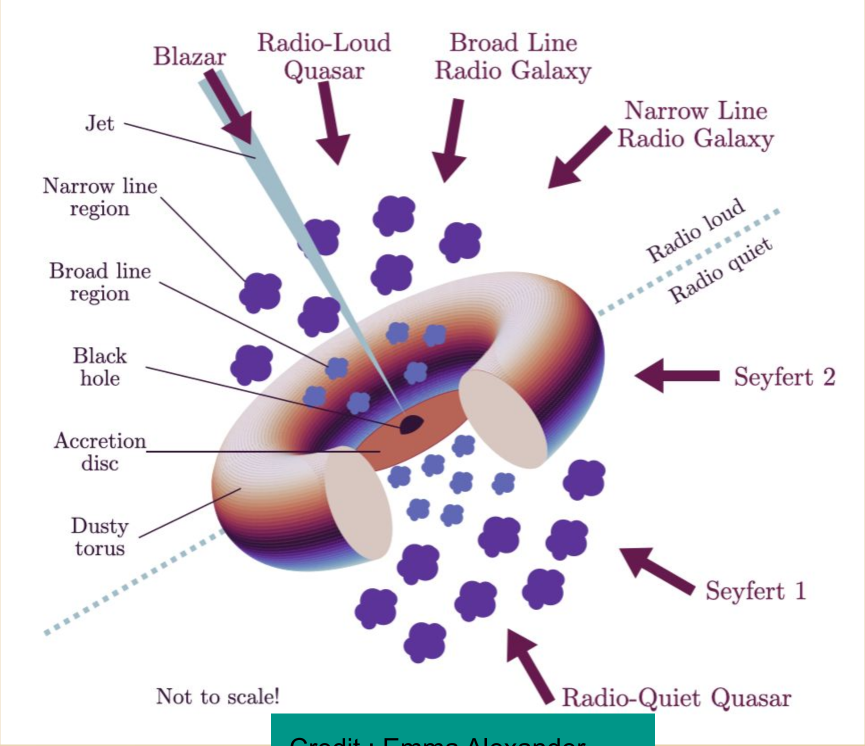
Active Galactic Nuclei and Blazars

- One of the jets is oriented along the observer line of sight
- Relativistic boosting along the jet axis strongly amplifies the observed luminosity of blazar and produces strong variability, polarization, and superluminal motion
- Emission is anisotropic

AGN unification model - Urry & Padovani (1995)

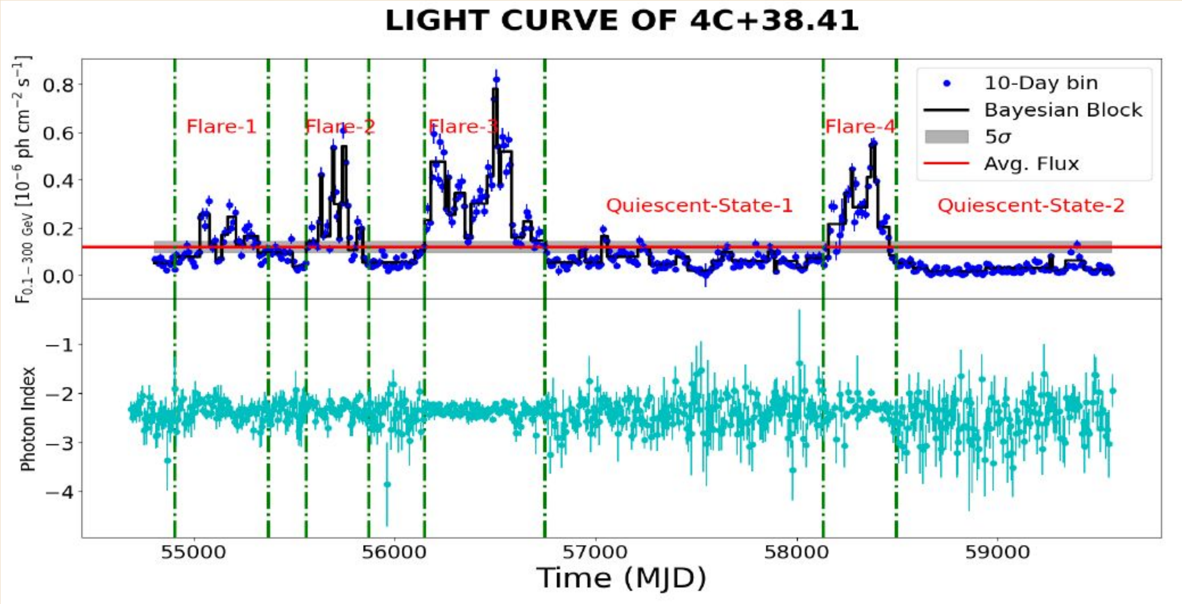


Credit : Emma Alexander

Blazar light curve

- Blazar shows spectacular flares across the entire EM spectrum
- Flare : where flux goes above certain value

10 day binned Gamma-ray LC (~13 yrs)



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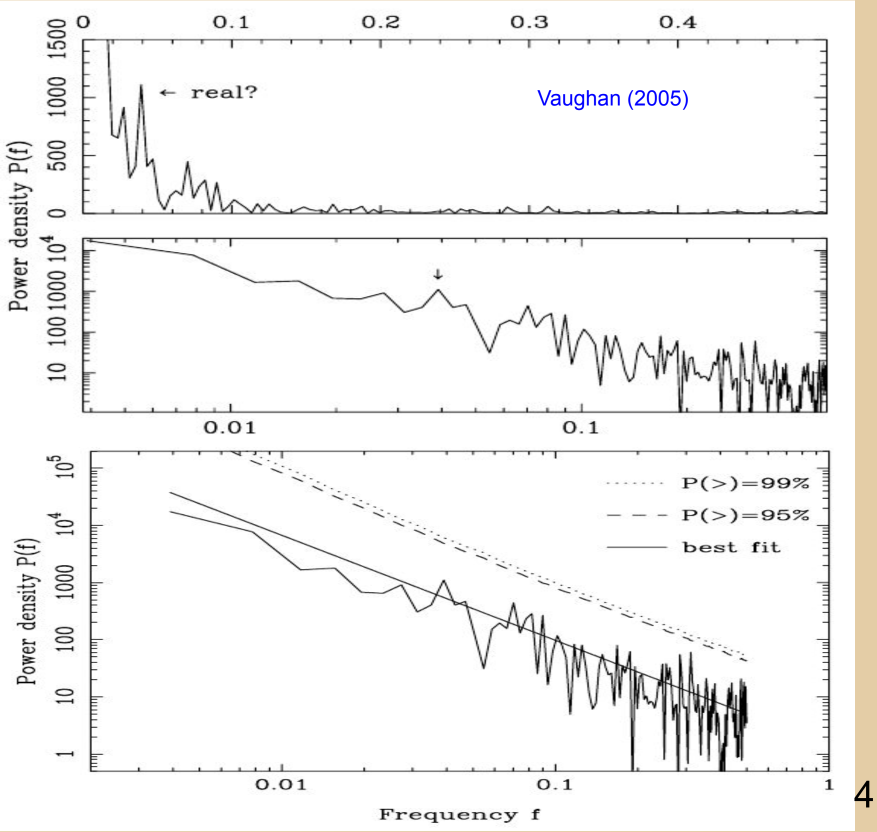
Red-noise

- Many astrophysical sources show erratic, aperiodic brightness fluctuations with steep power spectra. This type of variability is known as red noise. By “noise” I mean to say that the intrinsic variations in the source brightness are random (this has nothing to do with measurement errors, also called noise).
- The periodogram shows a red noise spectrum rising at lower frequencies. But he periodogram also shows a peak at f = 4 × 10^−2 . Is this due to real harmonic (periodic) variation or an artifact of the fluctuating noise spectrum?
- fit the PSD with PL: best fit parameter
- Monte Carlo simulations following Timmer & Konig (1995)



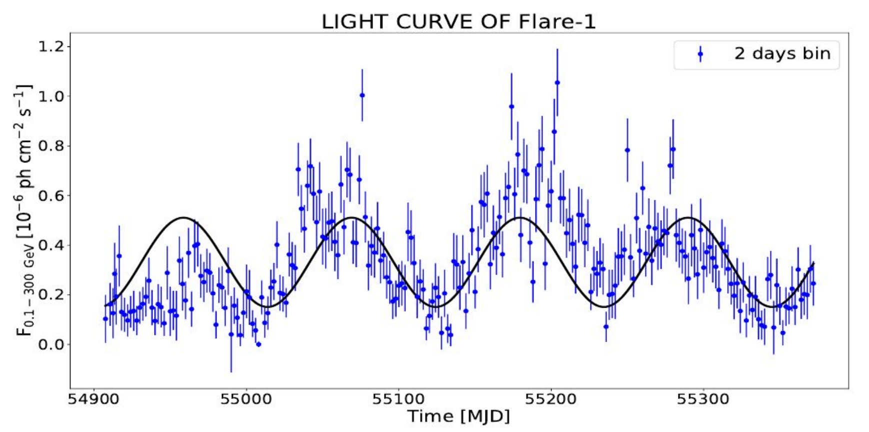
QPOs in Blazar and Challenges

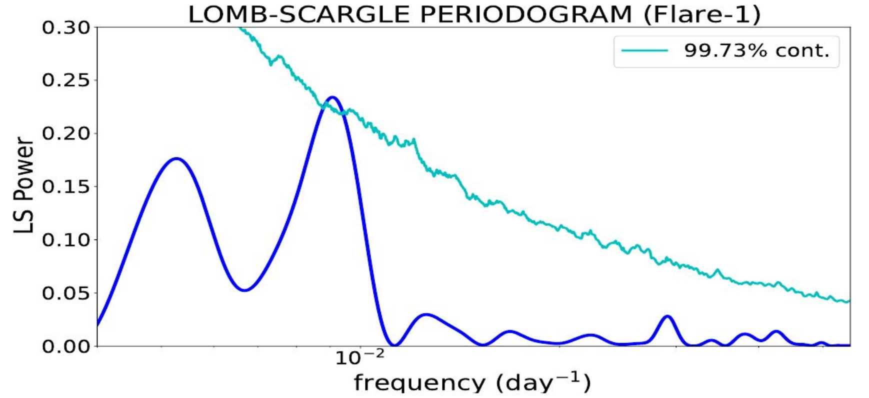
- Generally the flux variability seen in the blazar are aperiodic and random. So detection of any kind of periodicity or quasi-periodicity in random variability will require high statistical significance to claim
- But, over the past decade presence of QPOs in the multi-frequency blazar light curves has been recorded
- The reported periodic timescales range from a few hours to several years and are associated with different processes.

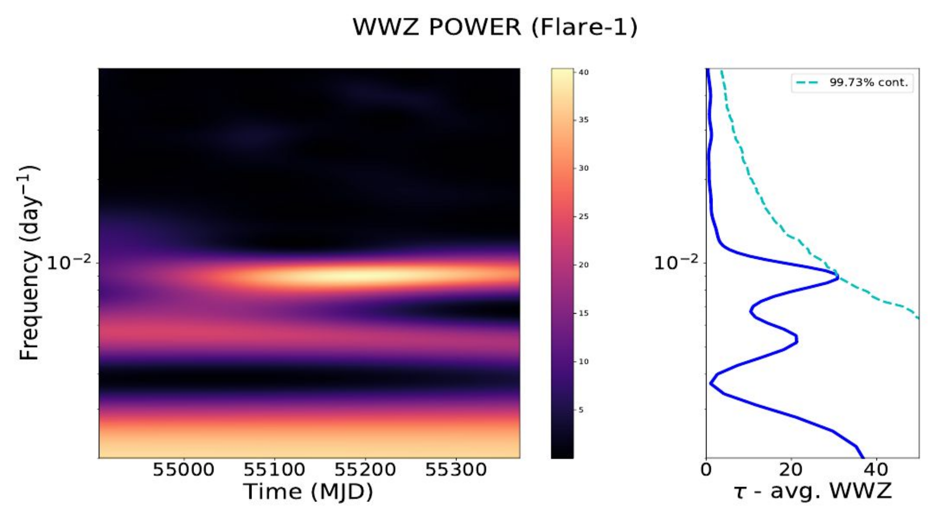
Methods: Many methods are used to detect QPOs

- Lomb-Scargle Periodogram (LSP): Widely used for the uneven light curve
- Power Spectral density (PSD): Estimate the power by sampling the fourier component
- Weighted Wavelet Z-transform (WWZ)
- Discrete Autocorrelation Function (DACF): Works in time domain and free from all the artifacts associated with frequency domain analysis

Flare-1







To estimate the significance PSRESP (Uttley et al. 2002) method is used

Cycle = 4, significance > 99.73%

time scale = 110-111 days

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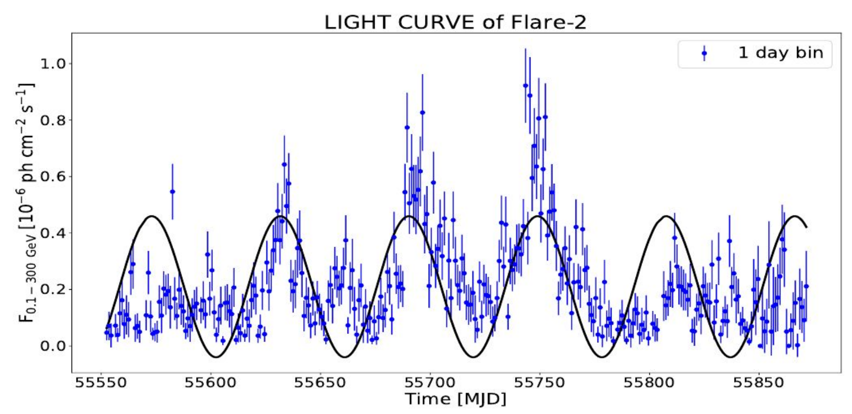
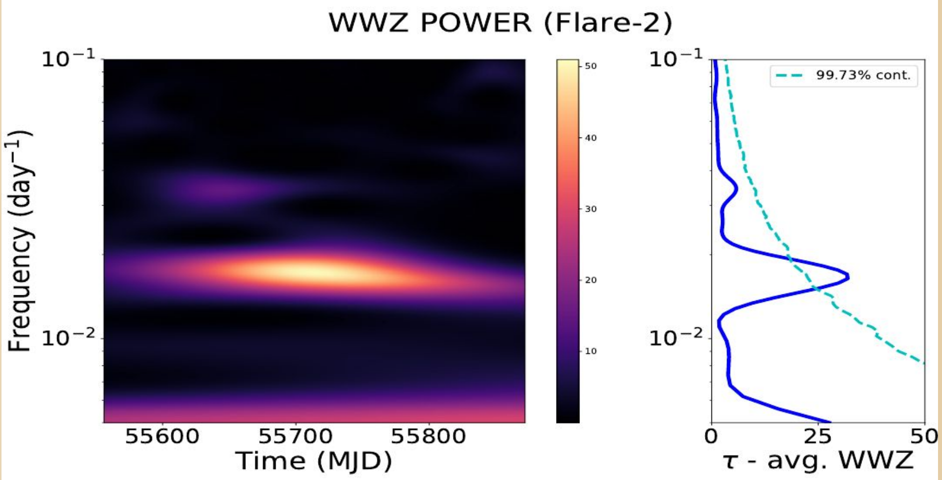
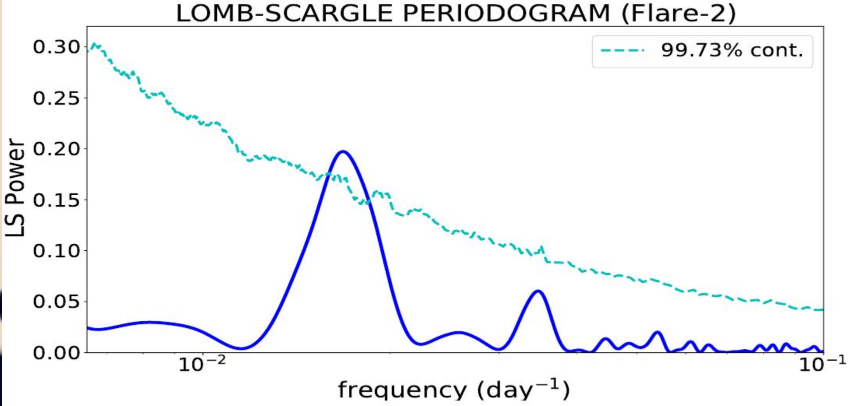
Flare-2







Cycle > 5, significance > 99.73%
time scale = 59-60 days

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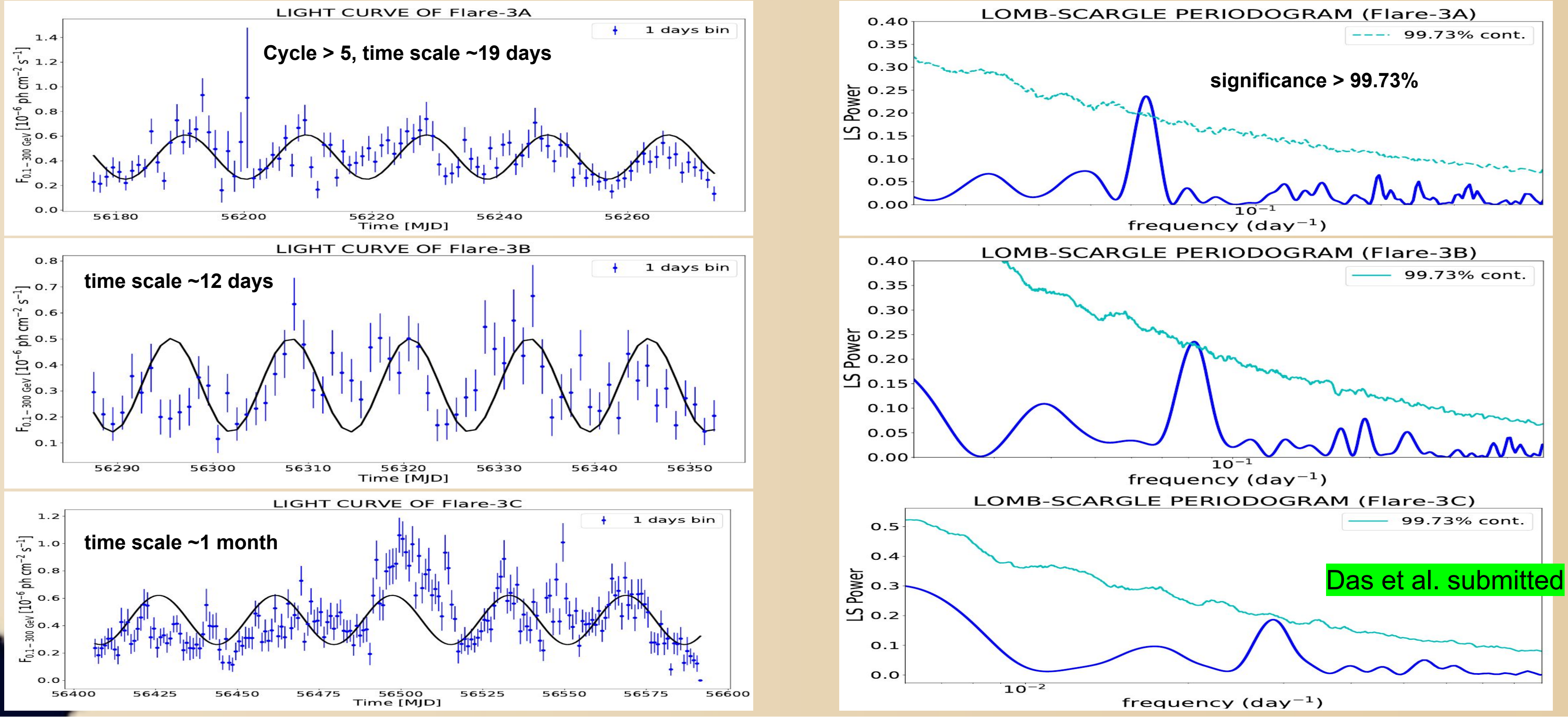
Flare-3



LIGHT CURVE OF Flare-3A
1 days bin
Cycle > 5, time scale ~19 days
Time [MJD]
LIGHT CURVE OF Flare-3B
time scale ~12 days
LIGHT CURVE OF Flare-3C
time scale ~1 month
LOMB-SCARGLE PERIODOGRAM (Flare-3A)
99.73% cont.
significance > 99.73%
LS Power
frequency (day^{-1})
LOMB-SCARGLE PERIODOGRAM (Flare-3B)
LOMB-SCARGLE PERIODOGRAM (Flare-3C)
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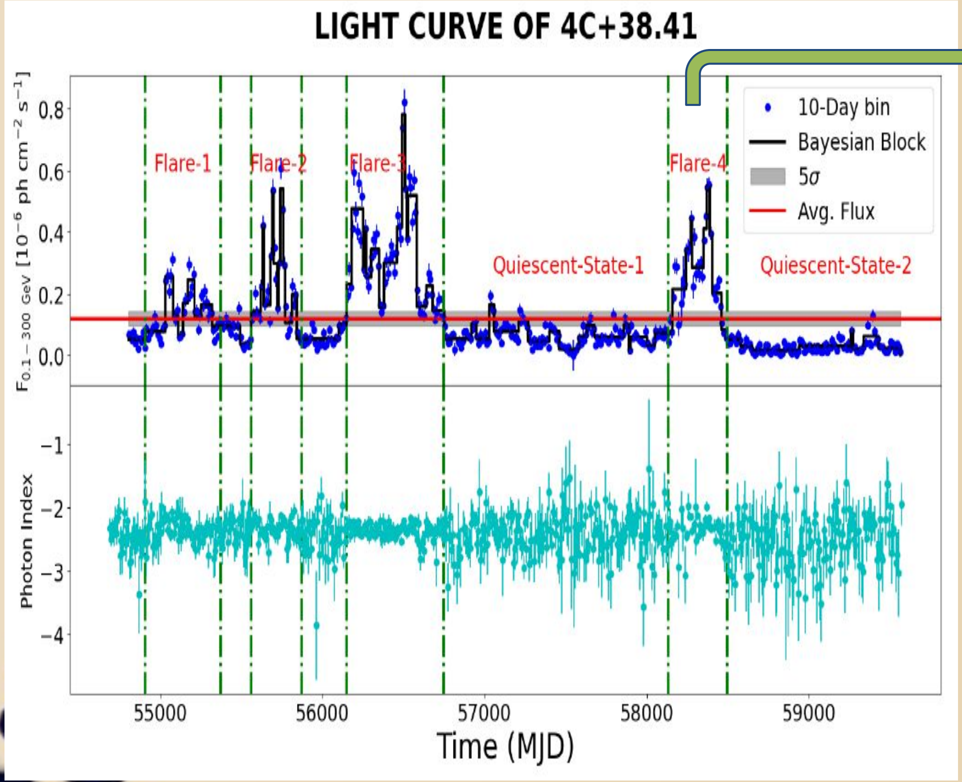
Quiescent States



No significance QPO is detected

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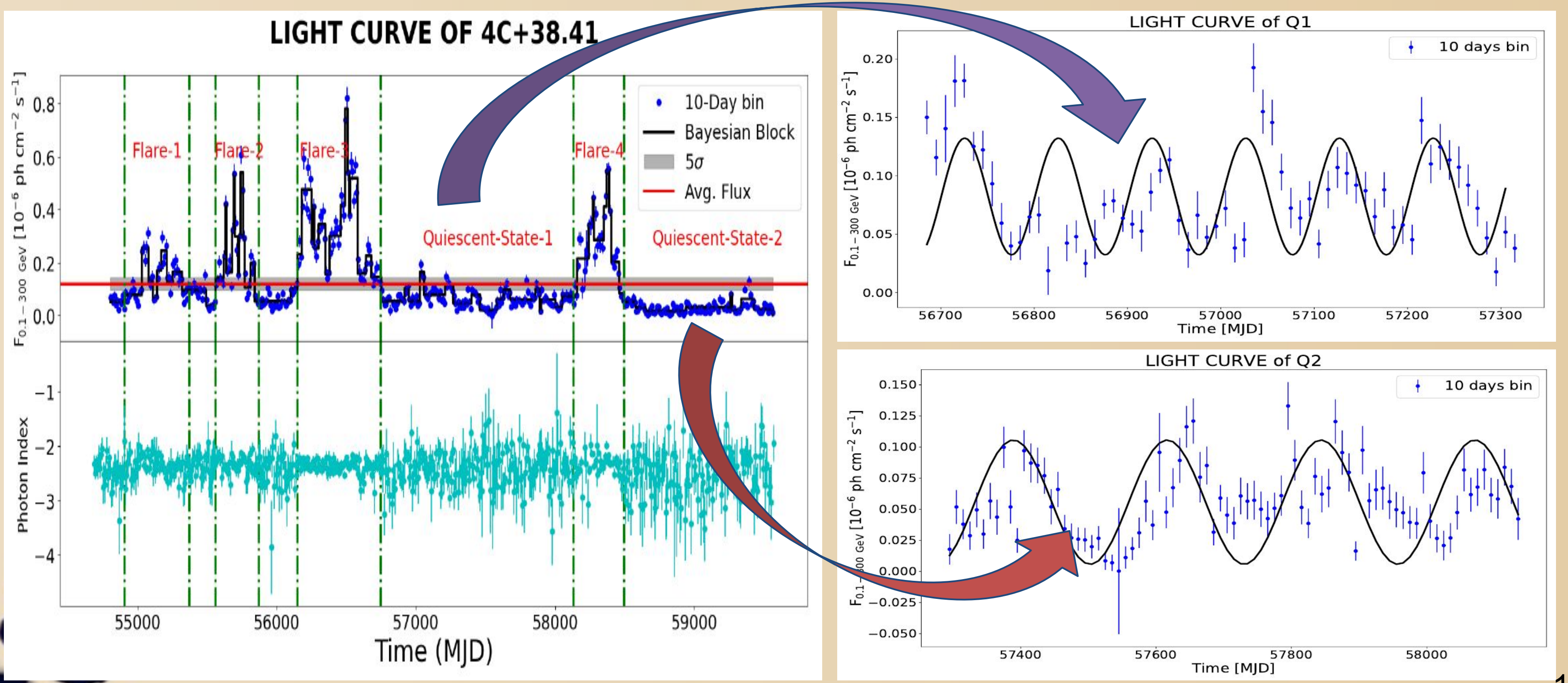
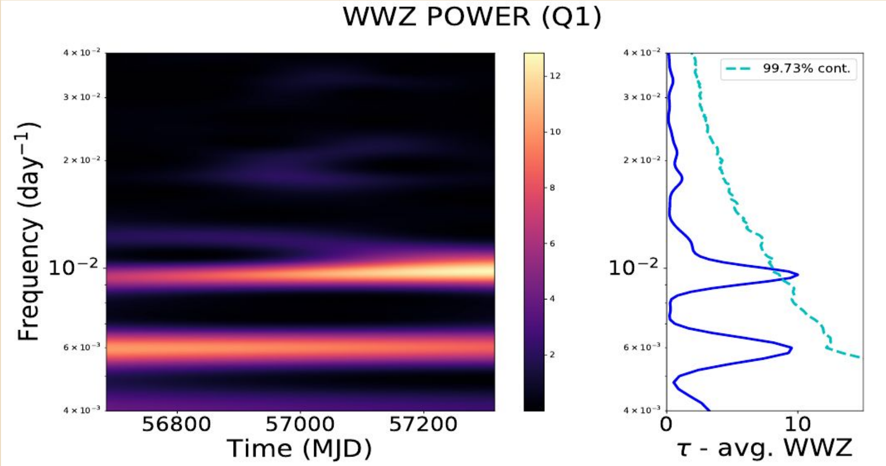
Quiescent States

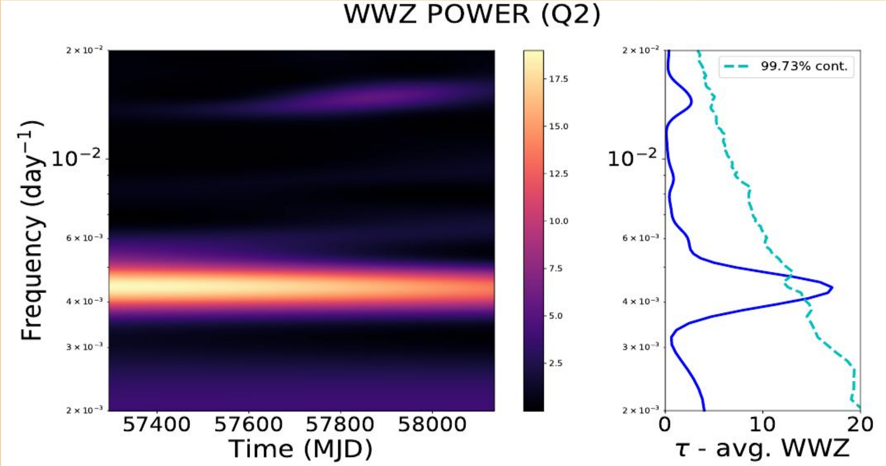


Das et al. submitted

Quiescent States



Q1: Cycle > 6, significance > 99.73%
time scale ~ 104 days



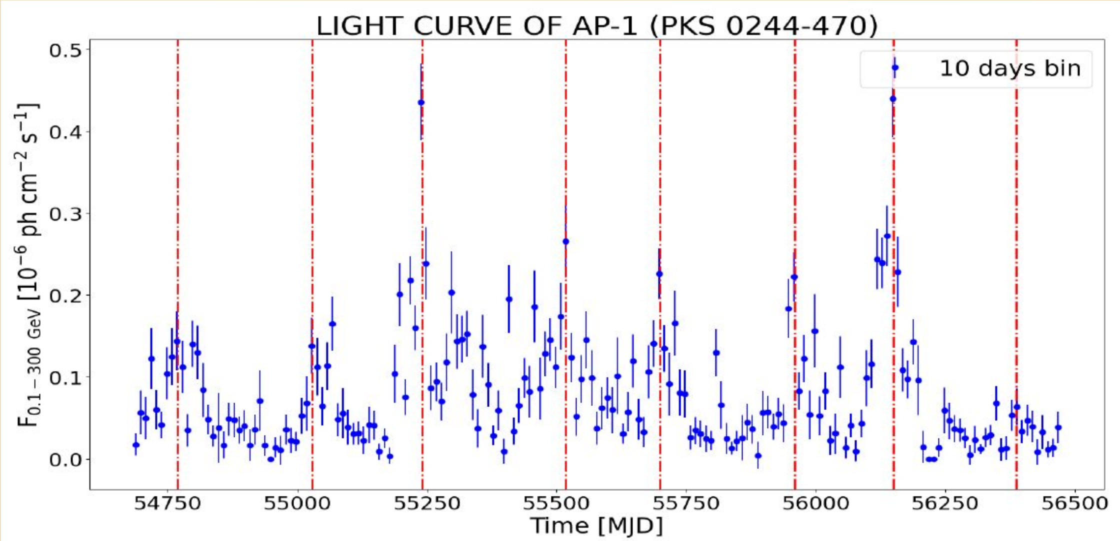
Q2: Cycle ~ 4, significance > 99.73%
time scale ~ 230 days

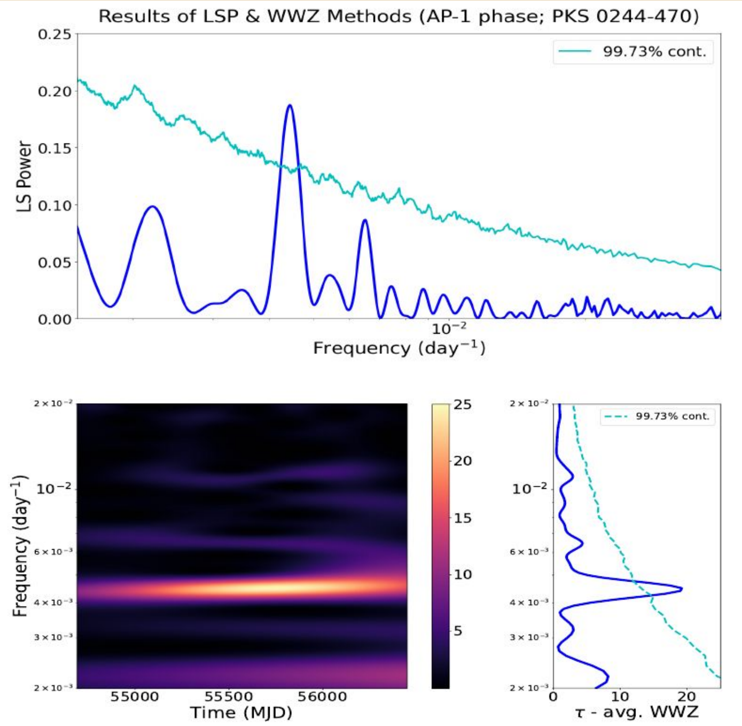
Number of cycles and detection significance

Table 1. Results of LSP & WWZ method for different activity state. Uncertainty on the PSD-slopes result from the HWHM of the gaussian fit.

Activity	PSD-Slope [β]	Method	Observed Period [days]	No. of cycles	Detection Significance (local)	Detection Significance (global)
Flare-1	0.97±0.29	LSP	∼110	4.2	99.82%	97.37%
		WWZ	∼111	4.2	99.77%	97.85%
Flare-2	0.83±0.12	LSP	∼59	5.4	99.90%	99.11%
		WWZ	∼60	5.3	99.85%	99.67%
Flare-3A	0.60±0.29	LSP	∼19	5.1	99.98%	98.74%
		WWZ	∼19	5.1	99.94%	99.34%
Flare-3B	0.80±0.31	LSP	∼12	5.4	99.77%	97.32%
		WWZ	∼12	5.4	99.61%	99.27%
Flare-3C	0.88±0.19	LSP	∼35	5.3	99.60%	94.29%
		WWZ	∼34	5.4	99.54%	98.65%
Q1	0.73±0.40	LSP	∼104	6.1	99.96%	99.21%
		WWZ	∼104	6.1	99.93%	99.86%
Q2	0.60±0.26	LSP	∼227	3.7	99.98%	99.31%
		WWZ	∼223	3.7	99.96%	99.95%

Significant detection of gamma-ray QPO in PKS 0244-470





Activity	PSD-Slope [β]	Method	Observed Period [days]	No. of cycles	Detection Significance (local)	Detection Significance (global)
			PKS 0244-470			
AP-1	0.67±0.21	LSP	∼225	8.0	99.996%	98.164%
		WWZ	∼222	8.0	99.986%	99.941%

Physical Interpretations

- In the past, the QPOs have been detected in many blazars across the wavebands and many possible explanations have been proposed to explain it depending upon the QPO time scale.
- The most recent models are the following:
  - An emission region moving outward along the helical magnetic field lines in curved jet (Camenzind & Krockenberger 1992; Sarkar et al. 2021)
  - A rotating inhomogeneous helical jet with variable pitch angle (Raiteri et al. 2021), and a supermassive binary black hole system (Valtonen et al. 2008; Roy et al.2022a)
  - Persistent jet precession (Rieger 2004, Ackermann et al. 2015)

- However, these possible scenarios predict the QPOs of years time scale (Bhatta & Dhital 2020)

In our study, we have detected multiple QPOs at different time stances with different time scales (< year), suggesting a complex geometry and nature of the source

Physical Interpretations

❖ One of the well-known origins of the transient QPOs is the presence of a relativistic blob moving on a helical trajectory inside the jet. This blob can emit γ-ray radiation via External Compton (EC) and Synchrotron-Self Compton (SSC) process (One-zone leptonic scenario). In this case, the time-dependent viewing angle (θ) in the observer frame is given by (Zhou et al. 2018):

$$\cos\theta(t) = \cos\phi\cos\psi + \sin\phi\sin\psi\cos(2\pi t/P)$$

❖ ϕ=2 deg and ψ = 5 deg as in the case in Zhou et al. (2018) and typical value of Lorentz factor Γ = 20 for FSRQ.
The periodicity in the co-moving frame (P'), distance traversed in one cycle of the helical motion (D'), and total projected distance (S') are estimated.

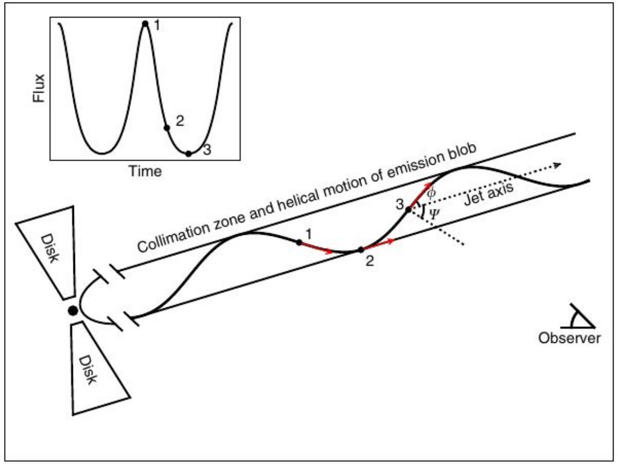


Fig. 4 Schematic illustration of a helical jet that produces periodically modulated emission. The emitting blob's motion has a pitch angle ϕ from the jet's axis, which has an inclination angle ψ from the line of sight. As the emitting blob moves towards the observer, the viewing angle to the blob changes periodically

Well describes the Flare-1, Flare-2, and Q1, Q2 states for 4C +38.41 and QPO of PKS 0244-470

Physical Interpretations

- ❖ Another explanation of the QPO signature is given by Dong et al. (2020). They have identified the blazar emission region inside the jet as the region of strongest kink instability. Due to these instabilities, there is a quasi-periodic conversion of magnetic energy to thermal energy. The observed period, in this case, can be give by:

- ❖ R_KI & v_tr are the size of the emission region & transverse velocity respectively. δ is the Doppler factor of the jet. For typical blazar parameters value, the periodicities is found to be from week to month scale

$$P = \frac{R_{KI}}{v_{tr}\delta}$$

- ❖ One of the recent result from Jorstad et al. 2022, Nature, 609, pages 265–268 (Rapid quasi-periodic oscillations in the relativistic jet of BL Lacertae) strongly approved this scenario

In our case, for Flare-3A, 3B, and 3C we observed the transient QPO with time scale 19, 12, and 35 days.

The kink instability scenario also predicts the Quasi-periodic nature in the polarization. We could not verify this result because of lack of good quality data in optical band

Summary

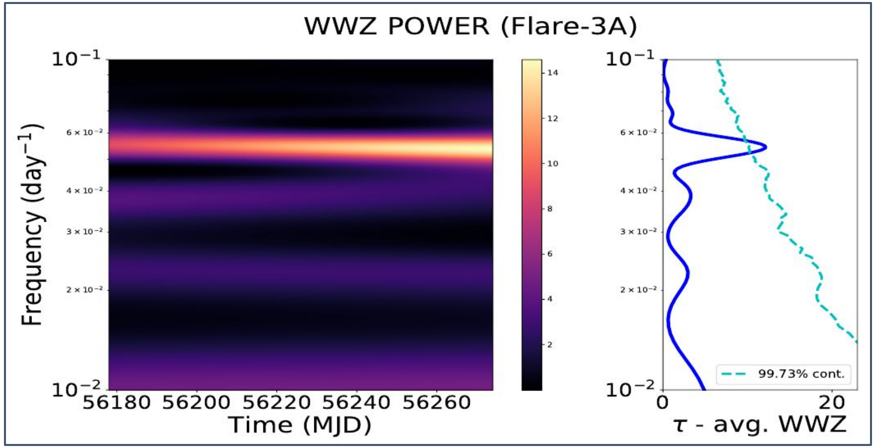
- In the long-term LC of 4C +38.41 four major Flares and two Quiescent states have been identified by the Bayesian Block algorithm

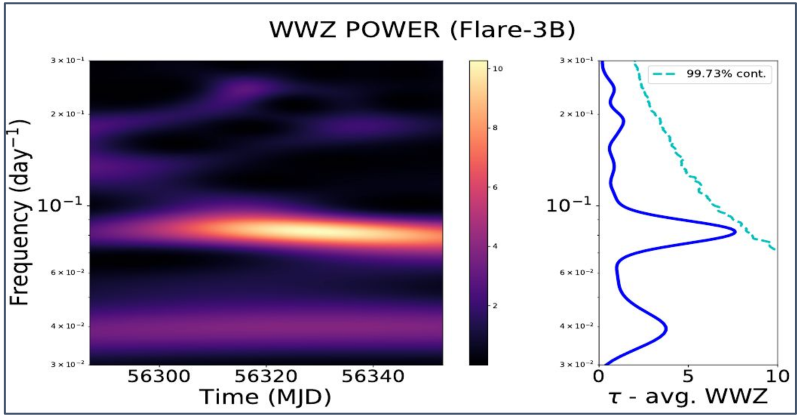
- All the Flares except Flare-4 show significant QPOs in their light curve with four to five complete cycles. Flare-2 shows the QPO with 99.90% and 99.85% local significant level in the LSP and WWZ method respectively. Flare-3 has been further divided into three sub-flares, namely, Flare-3A, Flare-3B & Flare-3C. Each of these sub-flares shows a possible QPO signature.

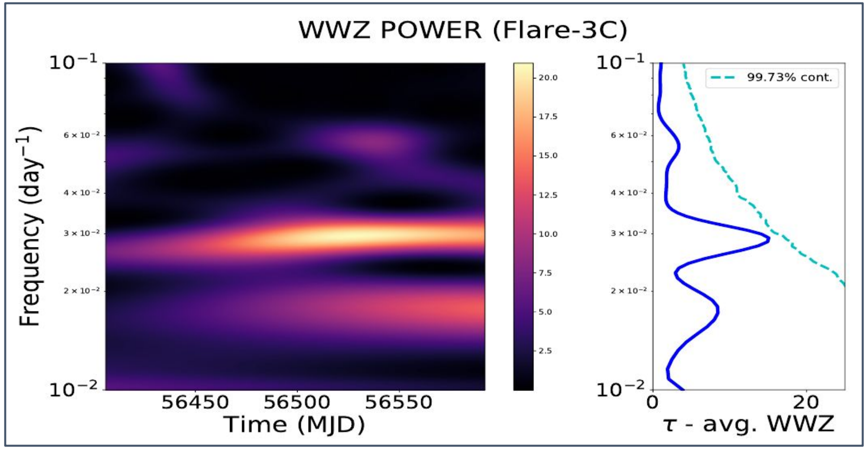
- The quiescent states also show QPO on two different time scales with the local significance level above 99.93%

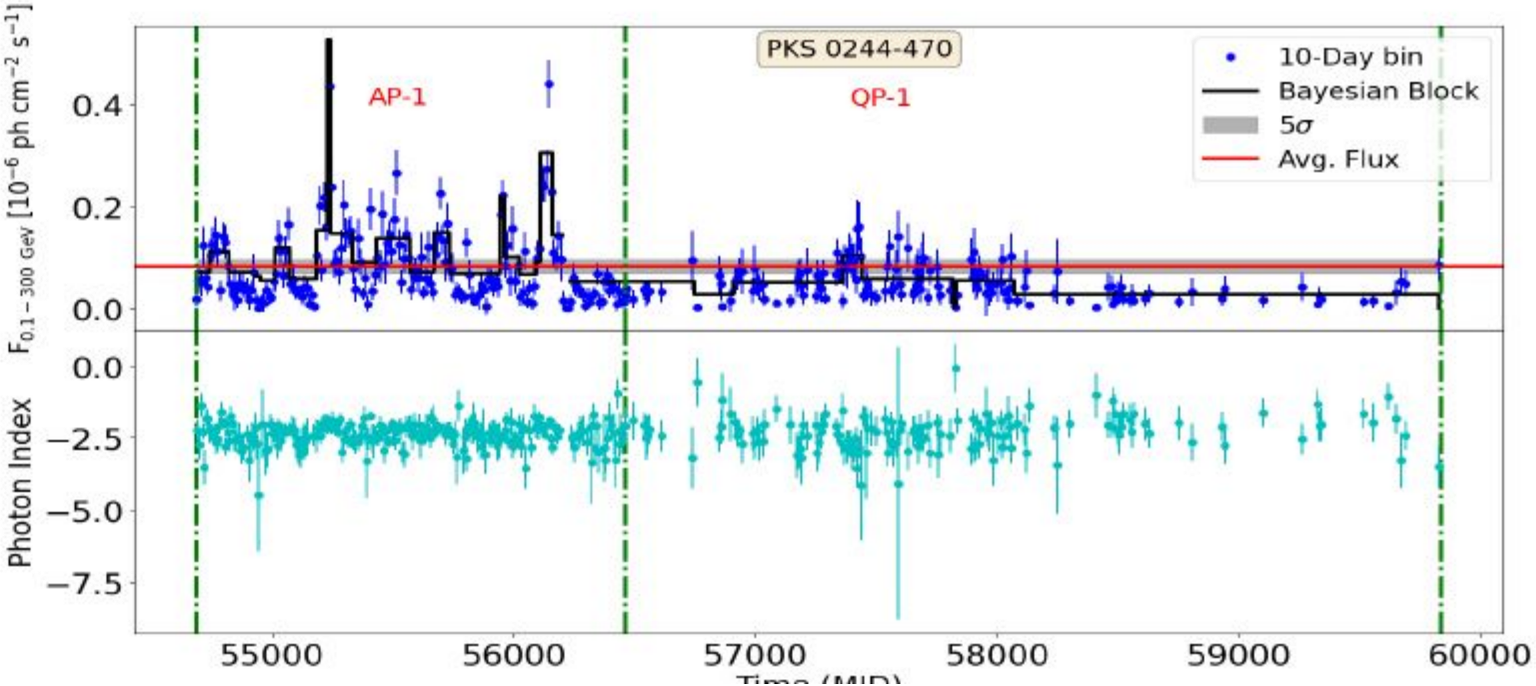
- A significant (> 4sigma) QPO of 225 days has been detected in PKS 0244-470 with 8 cycle

- QPO signatures of Flare-3A, 3B, & 3C can be explained by the jet’s emission region as the strongest kink instability. However, periodicities observed in the light curve for Flare-1, Flare-2, Q1, & Q2 can be well described by the curved helical jet scenario.


WWZ POWER (Flare-3A)
Frequency (day^{-1})
Time (MJD)
τ - avg. WWZ
99.73% cont.


WWZ POWER (Flare-3B)
Frequency (day^{-1})
Time (MJD)
τ - avg. WWZ
99.73% cont.


WWZ POWER (Flare-3C)
Frequency (day^{-1})
Time (MJD)
τ - avg. WWZ
99.73% cont.



PKS 0244-470
AP-1
QP-1
10-Day bin
Bayesian Block
5σ
Avg. Flux
F0.1 − 300 GeV [10−6 ph cm−2 s−1]
Photon Index
Time (MJD)