Tools for Period Searching in AGN in the Era of "Big Data"

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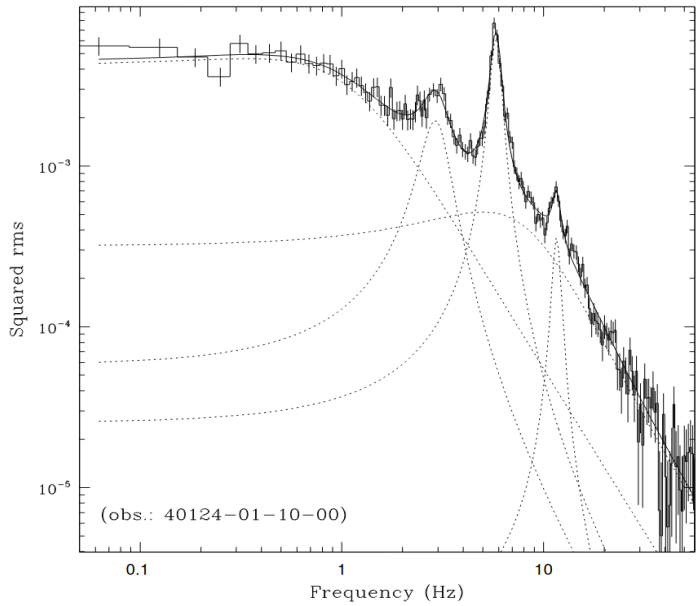
Introduction

- Quasi Periodic Oscillations (QPOs) from inner disk routinely detected in BH XRBs. Seyferts & BH XRBs have very similar accretion properties ("fundamental plane" relations, Merloni et al. 2003; disk reflection & winds, Miller et al. 2006)



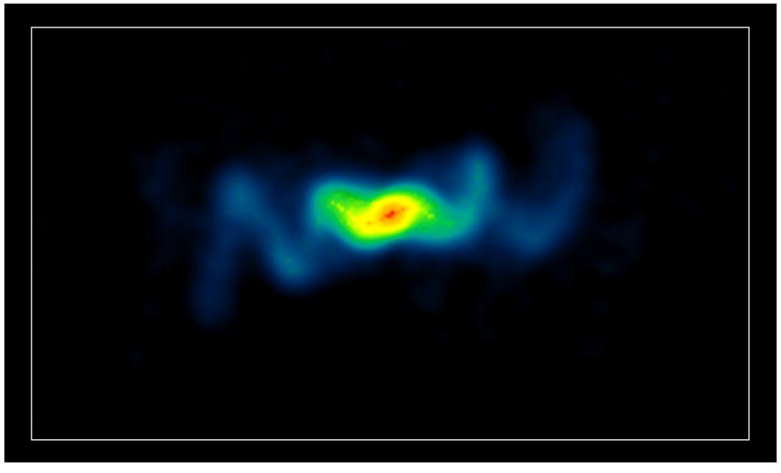
PSD of the BHXRB XTE J1859+226 (Casella et al. 2004)

What to expect in the power spectrum?

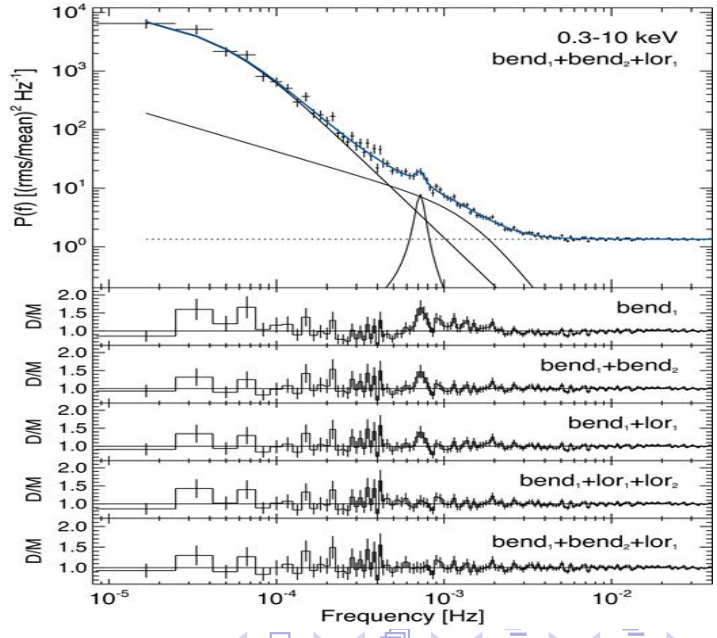
- similarities of broadband X-ray PSD shapes, hence variability components present in BHXRBs should appear in AGNs.
- Low freq. QPOs which evolve in frequency as source luminosity and inner disk size evolve
- High freq. QPOs with frequencies scaling as the inverse of M_{BH}

- Searches for QPOs in AGN are conducted across all wavebands.
- Provide testing grounds for General Relativity via the dynamical accretion flows in the region of extreme gravity (e.g., Lense-Thirring precession of inner disk, super-massive black hole binaries).
- In the case of blazars, interpretations also include precessing jets, with emission being beamed in/out of the line of sight (e.g., Villata & Raiteri 1999).
- Claims of strict- or quasi-periods in AGN are made using a variety of statistical methods, so far only a few robust claims based on the X-ray PSD (e.g.,Gierliński et al. 2008; Alston et al. 2014, Alston et al. 2019).

VLA Image of Microquasar SS 433, credit: Blundell & Bowler, NRAO/AUI/NSF



QPO in IRAS 13224-3809 Alston et al. 2019



Motivation - Era of Big Data

- Big Data: Current/Future large-area monitoring programmes $\rightarrow$ PanSTARRS, ZTF, LOFAR, LSST, SKA allows period searches over 10^3 to 10^6 AGN.

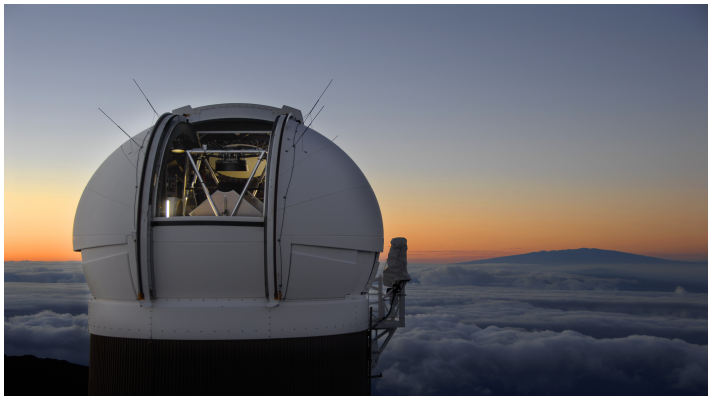


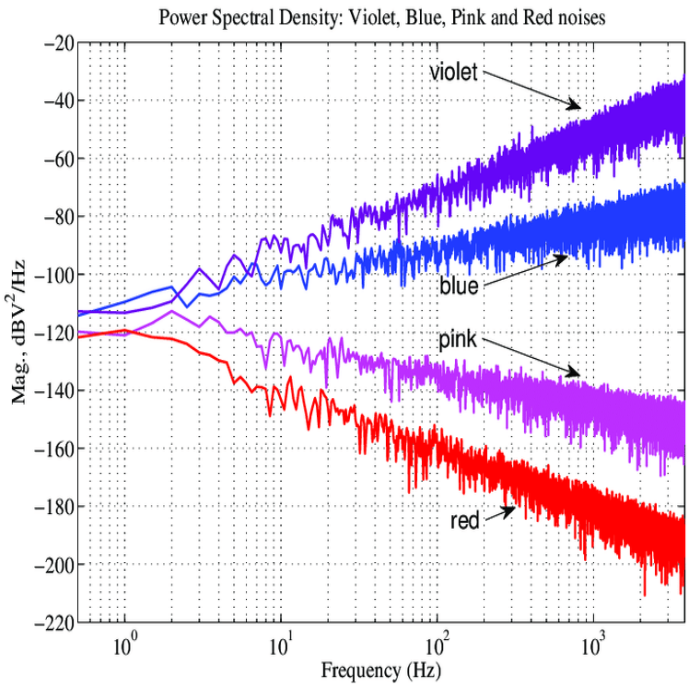
Figure: PanSTARRS and SKA

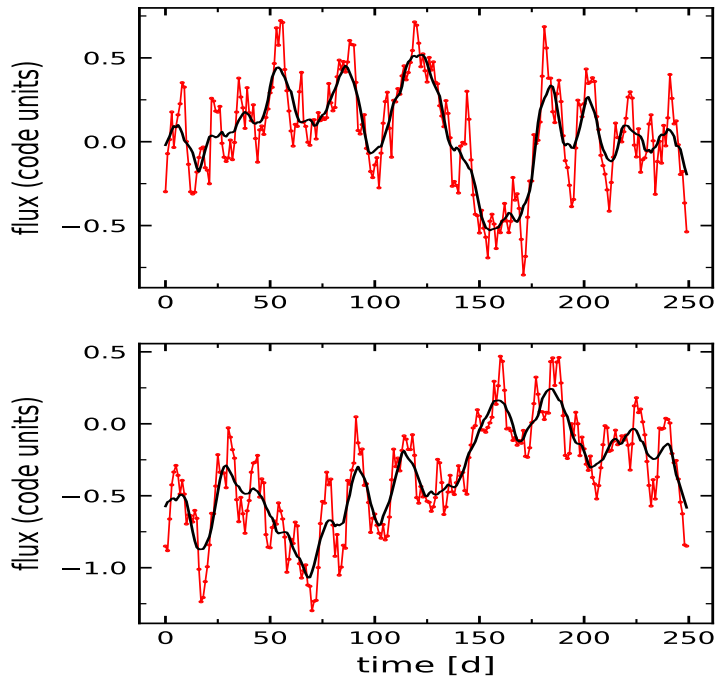
- Low data quality: most of the times the AGN data quality is too poor to measure a PSD.

- Methods generally used in the literature: wavelets, time-domain Bayesian fitting (CARMA), epoch folding, auto-correlation function and direct sinusoidal fitting.

- Robust claims of any QPO must include CLEANLY SEPARATING RED NOISE AND QPOs.

- No robust claims
  - Multiple claims resulting from database trawls exist in the literature (e.g., Graham et al. 2015; Liu et al. 2015), but there are severe doubts regarding null hypothesis model testing (red noise only).
  - no physically-consistent picture based on these periods has emerged.
- Red noise
  - most claims of periods are likely spurious and are due to ordinary red noise.
  - can mimic few-cycle sinusoid-like variability (Vaughan et al. 2016).





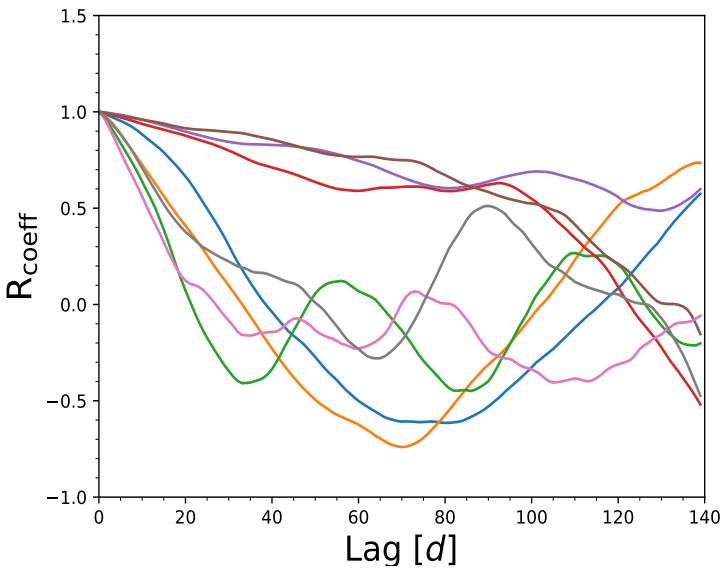
- Research Focus: **To provide guidelines on the proper use of statistical methods (ACF & PDM) to robustly distinguish between pure stochastic red noise (no QPOs) and a mixture of red noise plus a QPO signal.**

Auto-Correlation Function (ACF) for QPO detection?

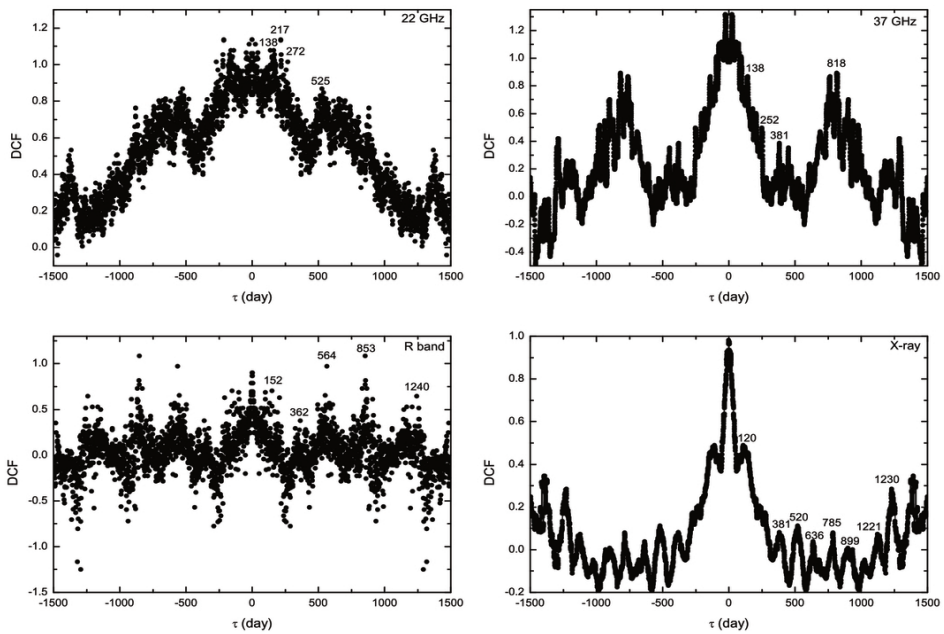
- The successive peaks after the zero lag indicates the time at which the signal is correlated with itself.
- In the case of a purely periodic signal (no red or Poisson noise), the ACF will be cosine-like, with peaks at the corresponding period.

- Watch out for red noise !?
  - pure red-noise processes (especially with steep PSD power-law slopes) cause spurious bumps and wiggles in the ACF.
  - some occasionally interpret it as a deterministic signal.

ACFs from pure red noise (simulations)



Spurious claims of multiple periodic signals in 3C279 from Li et al. (2009)

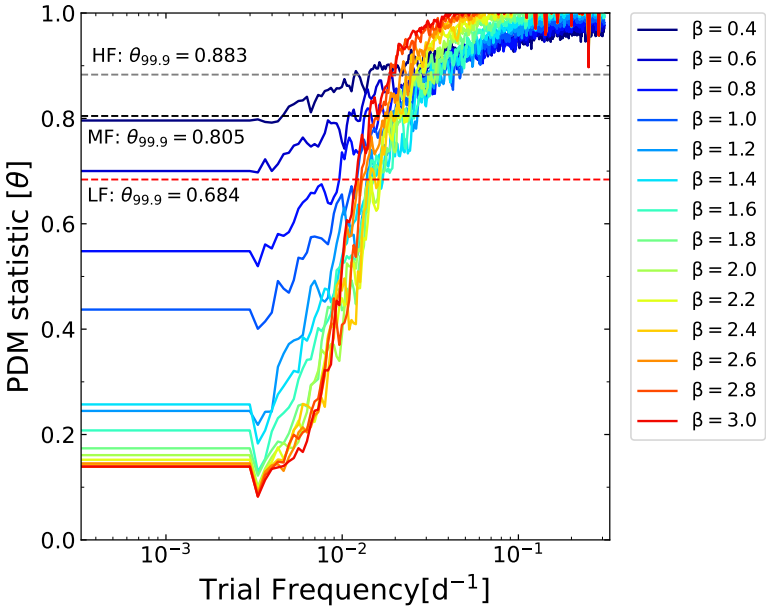


Phase Dispersion Minimization (PDM) for QPO detection

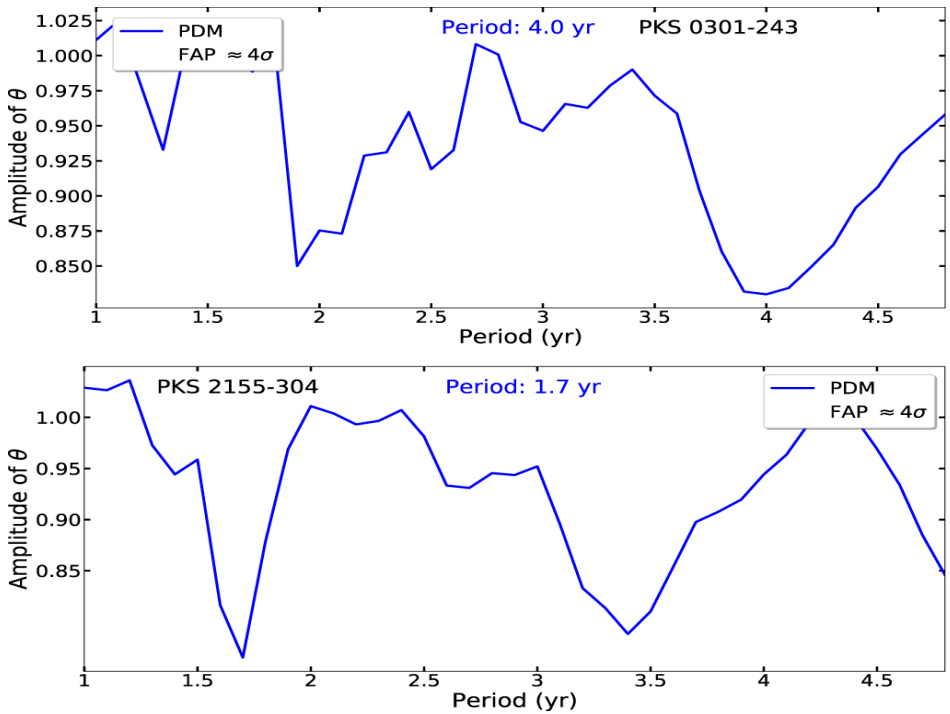
- periodogram statistic $\theta = s^2/\sigma^2$
  $s^2 \rightarrow$ sample variance, $\sigma^2 \rightarrow$ overall variance of the lightcurve.
- For a true period: θ to approach zero at that frequency.

- Again, watch out for red noise !?
  - A pure rednoise process can produce θ of 0.6 or lower values in PDM and can be misintepreted as quasi-periodic signals.

PDM of pure red noise simulated light curves

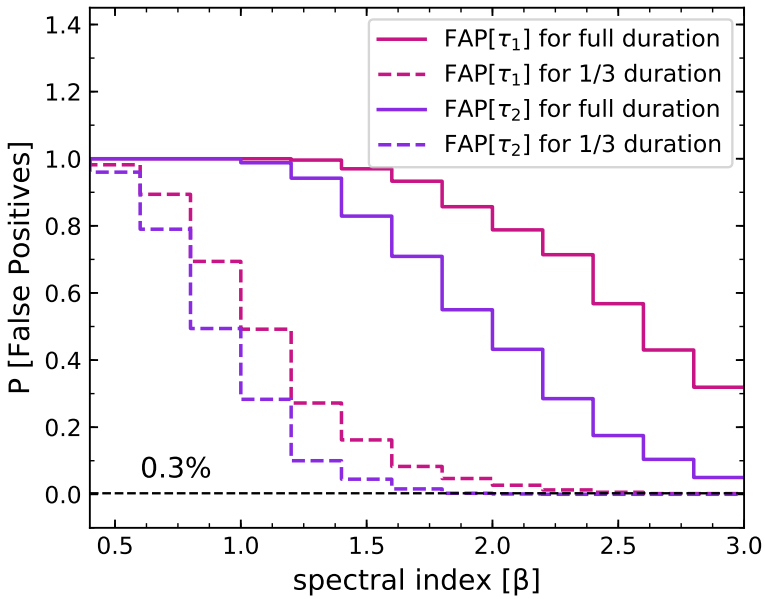


Claims of period using PDM [P. Peñil et al 2020]

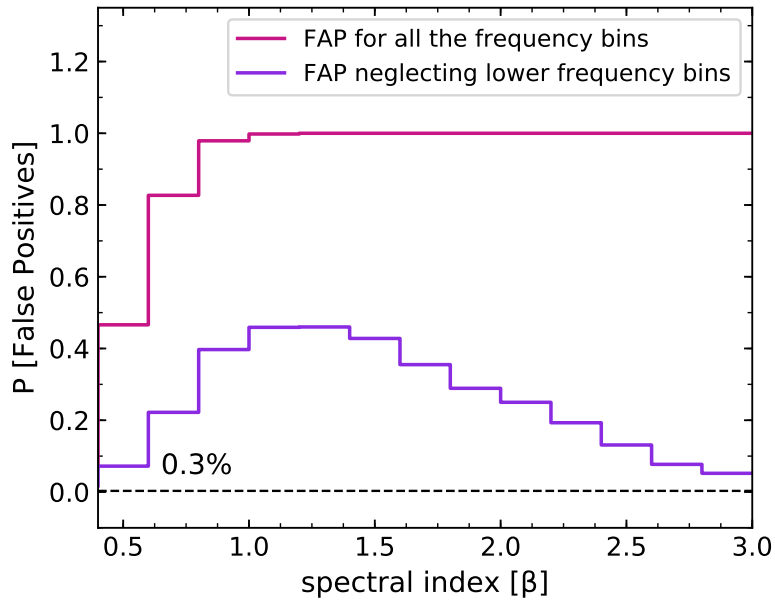


False Alarm Probabilities

- Monte carlo simulations of continuous evenly sampled light curves for broadband rednoise of unbroken power law PSD model(Duration = 250 days,$\Delta T = 1$ day) for 1000 MCS (Timmer & Koenig 1995).

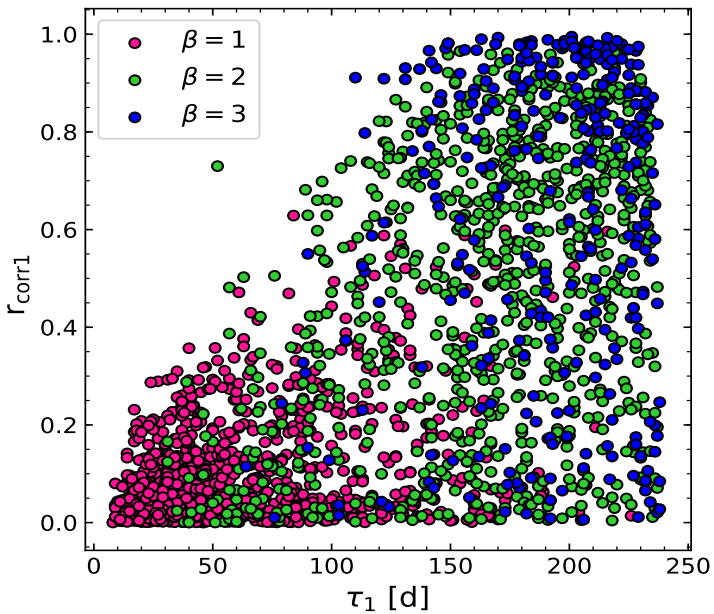


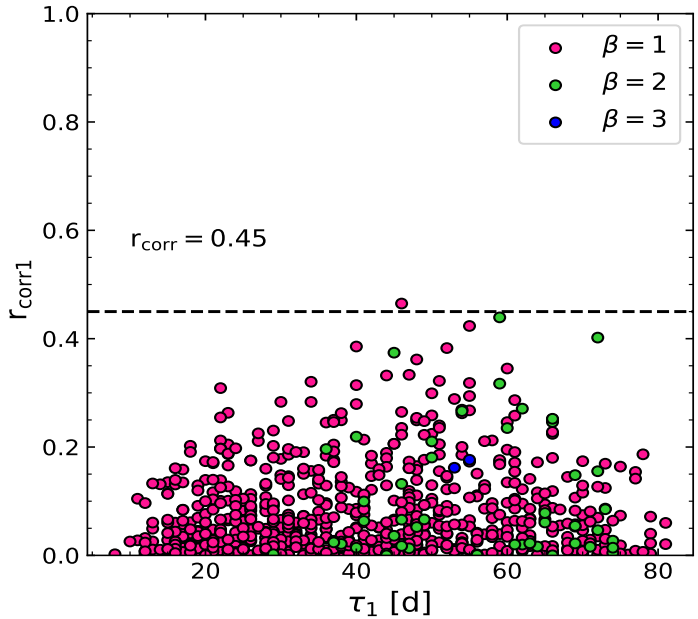
FAP for ACF



FAP of PDM

- simply disregarding timescales greater than $\sim 1/3$ of the full duration is an effective way to reduce false positives.
- It also suggests that features occurring at the longest timescales/lowest frequencies in previously-published ACFs/PDMs may have been consistent with pure red noise instead of being due to QPOs, as claimed.





- For ACF:
  - The distribution of the time scales of the first peak after the zero lag against the corresponding correlation coefficient of false positives.
  - $< 0.3\%$ of the false positives has $\mathrm{r_{corr}} > 0.45$.

- For PDM: after neglecting the lower frequency bins $< 0.3\%$ of the false positives has the local minimum statistic $\theta < 0.6$

Detection of QPO mixed with red noise

- Monte carlo simulations for combinations of rednoise of unbroken power law PSD model and different strengths of QPO signal using realistic sampling patterns (sun gaps/LSST; uneven sampling/OVRO).

- Detection of the period with statistical significance ($\gtrsim 99.7\%$) depends strongly on both the strength of the QPO against the red noise and the steepness of the red noise PSD slope

- On using **the ACF & PDM:** for detecting the period with high significance of 99.7% reliability after neglecting timescales greater than $\sim 1/3$ of the full duration.

ACF	PDM
$log_{10}(P_{rat}) \gtrsim 5$ at $\beta \gtrsim 2.2$	$log_{10}(P_{rat}) \gtrsim 5$ at $\beta \gtrsim 2.0$

- Application to realistic systems: For highly inclined SMBHB model requires extereme parameter space: mass ratios $q = 0.05$,0.5 requires the number of einstein radii between source and lens to be only $\sim$ 0.05–0.1, for high values of RMS.

Results

- Monte carlo simulations: broadband rednoise of unbroken power law PSD model and different strengths of QPO signal for even & realistic sampling patterns (sun gaps/LSST; uneven sampling/OVRO).

- On using the ACF & PDM: True positive detection (99.7% significance) requires the relative strength of the QPO against the red noise defined as log(PR) to be extremely large. e.g; log(PR) $\gtrsim$ 4–5 for evenly sampled data.

- community should be cautious and refrain from publishing claims of QPO using the ACF/PDM (until they have a reliable and significant detection considering proper null hypothesis), since the detection rate is generally low and not significant until one reaches very high values of power of QPO against the red noise continuum.

- *Submitted the manuscript to the MNRAS, Co-authors: Alex Markowitz, M.J. Middleton (Southampton), A. Schwarzenberg-Czerny (NCAC-PAS) (the referee, the editor and us are all converging and we are likely very close to getting this paper accepted, so please look for it on arXiv soon!).*

THANK YOU

NOTE: we are here to work with you and assist you if are working with AGN/quasar light curves (at any wavelength) and have questions/concerns about null hypotheses/red noise, FAP calibration, etc. so feel free to contact us!