Tools for period searching in AGN in the era of "Big Data"

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Introduction

- AGN emission is dominated by stochastic, aperiodic variability that overwhelms any potential periodic/quasi-periodic signal (QPO) that can be present due to e.g; jet emission from blazars, similar accretion mechanisms with BHXBs, SMBH binary mechanisms etc.
- While using different statistical tools to search for QPOs one needs to account for this red noise, since it can spuriously mimic few-cycle sinusoid-like periods and impact statistical significances of detection of periods and calibration of the false alarm probability (FAP).
- Moreover, we have entered the era of "Big Data," wherein current and near-future large-area monitoring programmes facilitate data trawls for period searches; developing the proper know-how for period searching is thus essential.
- In our project we examine several statistical tools — the autocorrelation function (ACF), phase dispersion minimization (PDM), wavelets, and CARMA modeling — to assess how QPO detection and the FAP depend on broadband continuum PSD shape when a mixture of red noise and a QPO is present and provide guidelines on the proper use of these statistical tools to the community. We determine how QPO detection sensitivity depends on QPO strength and broadband red noise shape for evenly-sampled and for realistically-sampled data (e.g., with data gaps).
- We present here the results from analysis using the ACF and PDM. We also compare the results on using the PDM and the periodogram. We apply the results to realistic systems, namely gravitational lensing from highly-inclined binary supermassive black hole systems, to check the conditions under which a periodic flux signal can be robustly separated from the red noise using these statistical tools.

Simulating AGN light curves

- We simulate time series similar to AGN light curves by using the algorithm developed by Timmer & Koenig 1995.
- We perform Monte carlo simulations for combinations of rednoise of unbroken power law PSD model and different strengths of QPO signal for a modest range of sampling patterns (baseline and some realistic monitoring sampling patterns) for three test frequencies of QPO and empirically test the statistical tools.

ACF & PDM analysis for period searching

- We use the Discrete Correlation Function method by Edelson & Krolik 1988 to determine the auto-correlation (ACF) between the light curves. We track the cosine like feature in the ACF to determine the period of the signal.
- The Phase Dispersion Minimization (PDM) method can be used for searching for non-sinusoidal pulsations (Stellingwerf 1978). The test statistic θ parameter of the PDM, which follows a beta distribution (Schwarzenberg-Czerny 1997), gives the measure of fit quality between the observations & the model at each test frequency, with a deep minimum indicating the frequency corresponding to a periodic/QPO signal.

Results & Discussion

- **ACF for pure red noise** light curves of unbroken power-law PSD model for 100 MCS is estimated.
  - In Figure. 1 Pure random stochastic red noise process causes bumps and wiggles in the ACF e.g, green line; similar to what expected from a quasi-periodic signal can possibly misinterpreted as an intrinsic signal.

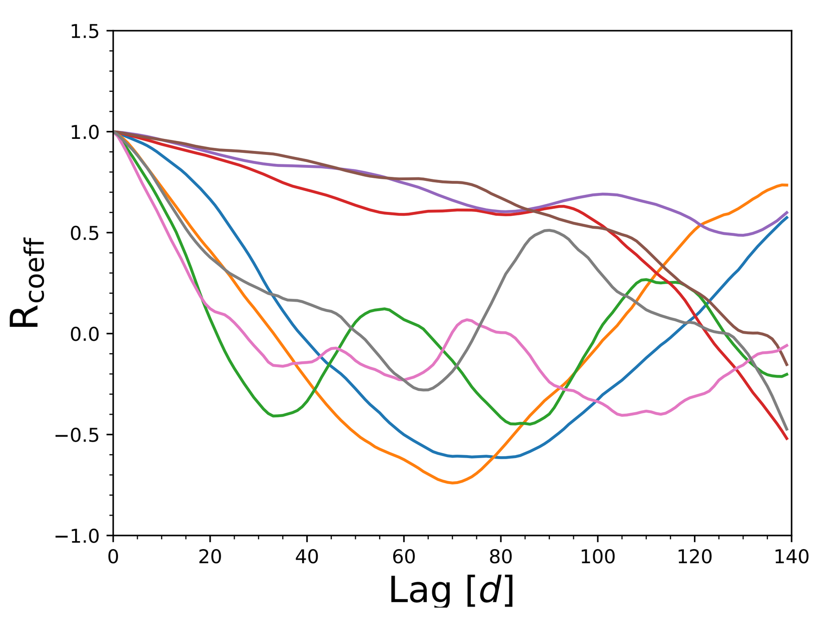


Fig. 1: The ACF of pure red noise light curves of unbroken power-law model.

Results & Discussion (cont..)

- Significant detection with 97% reliability using the ACF & PDM of QPO mixed with red noise increases with increasing strength of the QPO against the unbroken power law PSD slope (P_{rat}) and with decreasing steepness of the spectral slope (β).
  - **ACF:** occurs only when $\log(\mathrm{P_{rat}}) \gtrsim 4$ at $\beta \lesssim 2.0$ and at much steeper slopes of $\beta > 2.0$, we need $\log(\mathrm{P_{rat}}) > 5$ for all three test frequencies of QPO.
  - **PDM:** occurs only when $log(P_{rat}) \gtrsim 5$ at $\beta \lesssim 2.0$ and at much steeper slopes of $\beta > 2.0$, we need $\log(\mathrm{P_{rat}}) > 5$ for all three test frequencies of QPO.

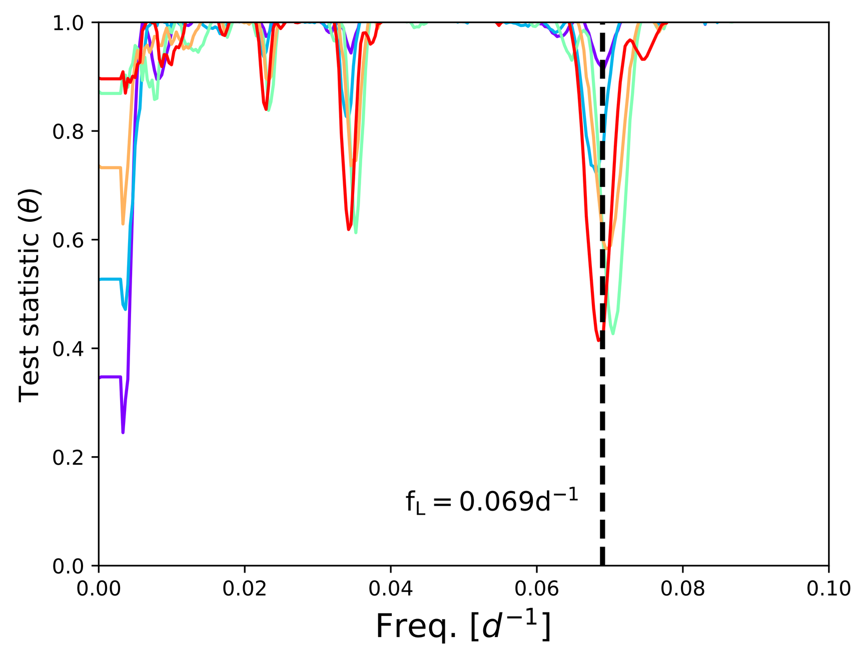


Fig. 1: PDM of QPO ($log(P_{rat}) \sim 5$) mixed with red noise of $\beta \sim 3.0$.

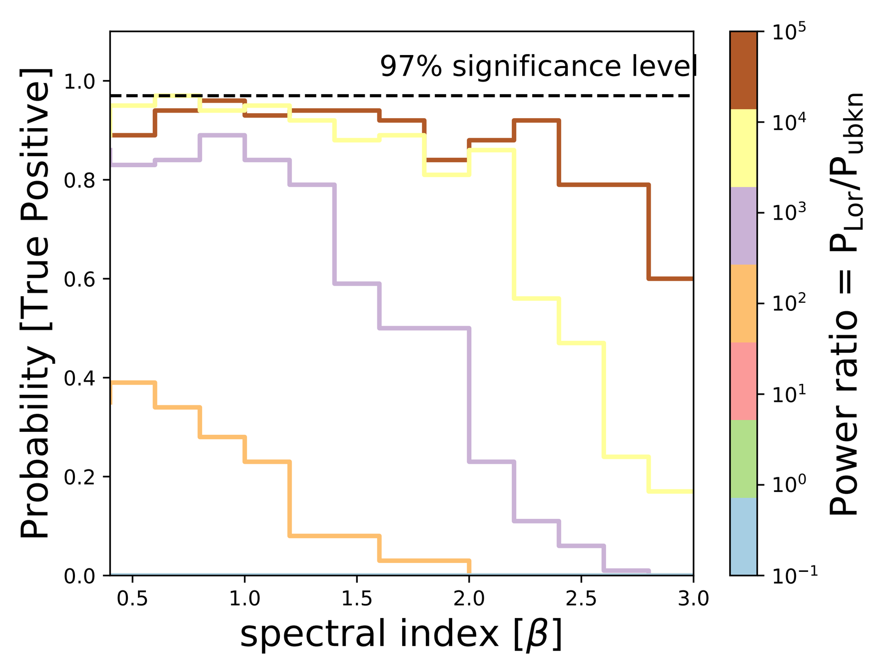


Fig. 2: Detection probability of the period corresponding to QPO signal as a function of spectral index slope and power ratio using PDM.

Reducing the effect of red noise processes

We use a simple pre-filtering technique where we first smooth the light curve using a moving average and subtract it from original light curve and reduce the effect of red noise.

CONCLUSIONS
It increased the significance of detection of the period of QPO both along the power ratio of QPO against the red noise background and along the spectral index slope on using ACF & PDM. The significance of detection of QPO signal with 97% reliability:

- **using ACF:** improved by a factor of $\log(\mathrm{P_{rat}}) \sim$ 2-3 along all spectral index slope β.
- **using PDM:** improved by a factor of $\log(\mathrm{P_{rat}}) \sim 2$ along all spectral index slope β.

Realistic uneven sampling patterns

We do Monte carlo simulations of 10 year long light curves similar to LSST AGN monitoring : different yearly sun gaps and/or irregular sampling patterns for pure red noise and QPO mixed with red noise.

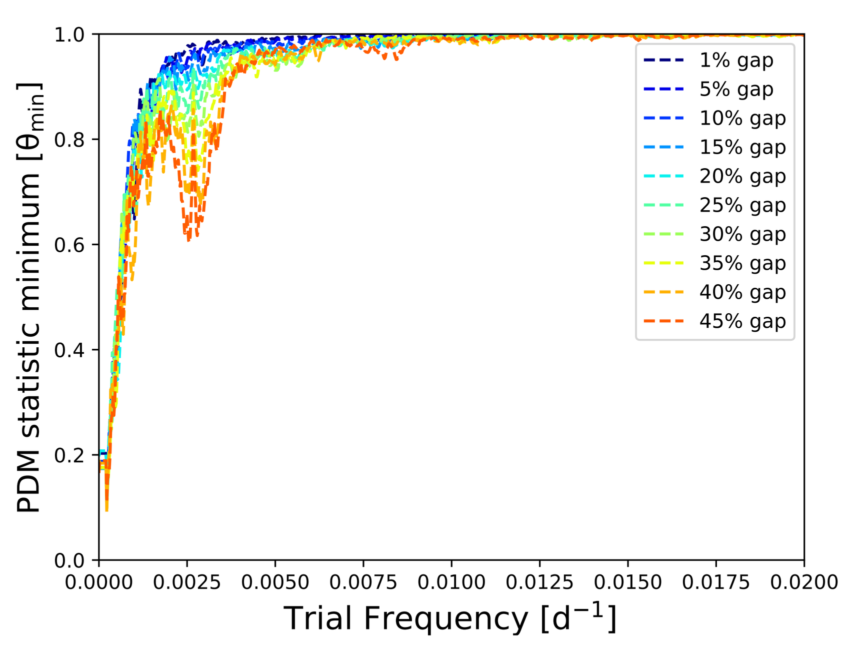


Fig. 3: PDM of pure red noise light curves having $\beta \sim 2.0$ with different Sun gaps.

Realistic uneven sampling patterns (cont..)

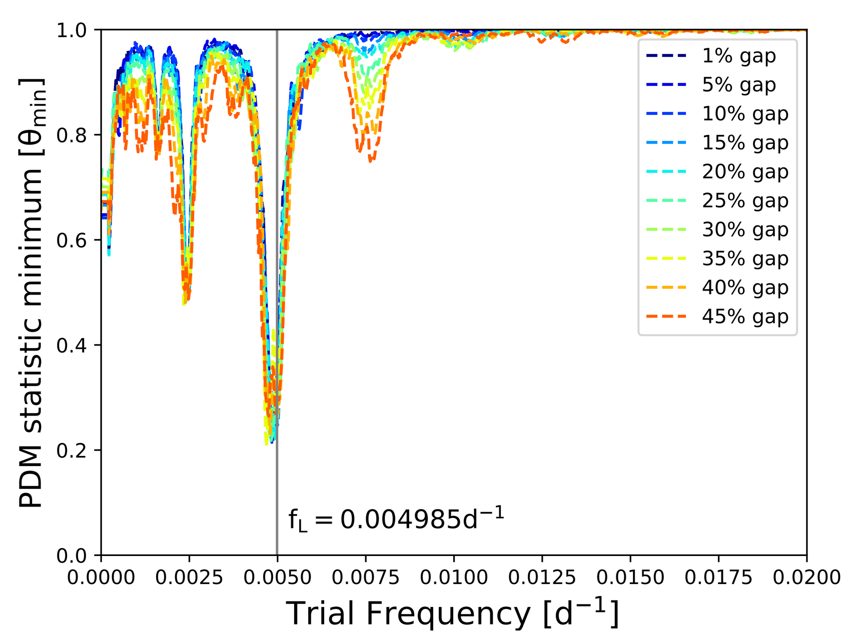


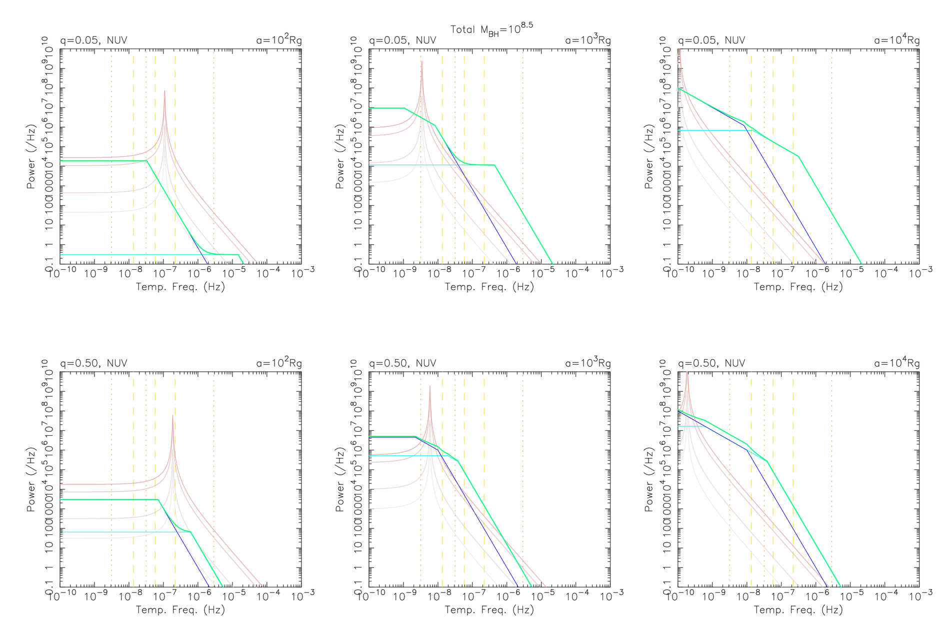
Fig. 4: PDM of QPO mixed with red noise of $\beta \sim 2.0$; LSST monitoring type with different Sun gaps.

CONCLUSIONS

- Pure red noise light curves with sun gaps can cause deep minimum in PDM at timescales $\sim$ 1/3-1/4th of duration.
- uneven sampling doesn't affect the PDM much in terms of the detection probability of the signal.
- **PDM vs Periodogram:**
  - evenly sampled data periodogram is preferred.
  - uneven sampling causes aliasing in periodogram, so PDM is preferable but only for large values of P_{rat} for significant detection.

Application to realistic systems

- We consider periodic signals expected from gravitational self-lensing of accreting massive BHs in highly inclined binary systems (D'Orazio et al. 2017).
- We compare periodic signal strength against the expected broadband red noise variability from optical emitting accretion disks with LSST-style sampling for a a range of $M_{\mathrm{BH,tot}}$ & BH separation r



CONCLUSIONS & Future Work

- Any claim of detection of a QPO using ACF or PDM implies claiming a detection of a strong QPO signal of power $\sim \log(\mathrm{P_{rat}}) \gtrsim 4$ - 5 against underlying red noise.
- The filtering technique improves significance of detection of underlying QPO signal by a factor of $\log(\mathrm{P_{rat}}) \sim$ 2-3.
- Applications to Gravitationally lensed accreting BHs in highly inclined binary systems detection for LSST type monitoring over 10 years:
  - likely only if $r \lesssim 10^{2-3} R_g$, $M_{tot} \sim 10^{7.5-8.5} M_{sun}$ & $N_E < 0.5$ Einstein radius.
- Work in progress with Wavelet analysis & CARMA Bayesian time-domain fitting.

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