PSD ANALYSIS OF OPTICAL QSO LIGHT CURVES

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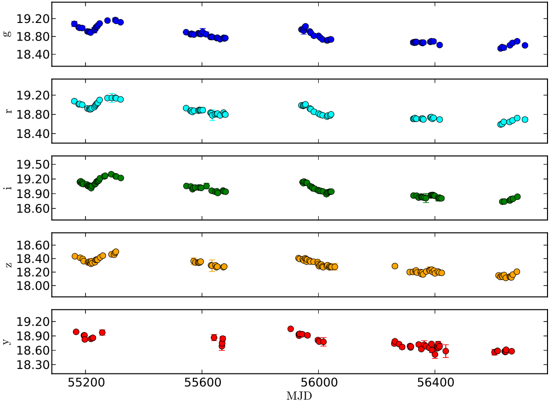
Optical Variability of QSOs

- flux variations are aperiodic and of stochastic nature
- $\sim$ 10%–20% fractional amplitude on timescales of months to years
- variability highly correlated across optical bands



QSO multi–band magnitude light curves (Simm et al. 2015)

Variability tools

Power spectral density (PSD) estimators:

- Fourier techniques: periodogram (even sampling), Lomb–Scargle periodogram (uneven sampling) (Priestly 1981, Scargle 1982, Vio et al. 2010)
- normalized excess variance (Nandra et al. 1997, Ponti et al. 2012) and structure functions (MacLeod et al. 2010, Kozlowski 2016)
- continuous-time modeling via stochastic differential equations:

  → put unknown physics (complex processes with large number of degrees of freedom, e.g. magnetic turbulence) into Gaussian white noise process (Vio et al. 2005)

  → Damped Random Walk (DRW) process (Kelly et al. 2009)

  → Continuous-time AutoRegressive Moving Average (CARMA) process (Kelly et al. 2014)

PSD estimation via CARMA process

For a time series $y(t)$ the variability is assumed to be driven by a continuous-time white noise process $\epsilon(t)$ with zero mean and variance σ^2

DRW = CARMA(1,0) process:

$$\frac{dy(t)}{dt} + \alpha_0 y(t) = \epsilon(t) \quad \leftrightarrow \quad \mathrm{PSD}(\nu) = \sigma^2 \frac{1}{\alpha_0^2 + (2\pi\nu)^2}$$

General CARMA(p,q) process:

$$\frac{d^p y(t)}{dt^p} + \alpha_{p-1}\frac{d^{p-1} y(t)}{dt^{p-1}} + .. + \alpha_0 y(t) = \beta_q \frac{d^q \epsilon(t)}{dt^q} + \beta_{q-1}\frac{d^{q-1}\epsilon(t)}{dt^{q-1}} + .. + \epsilon(t)$$

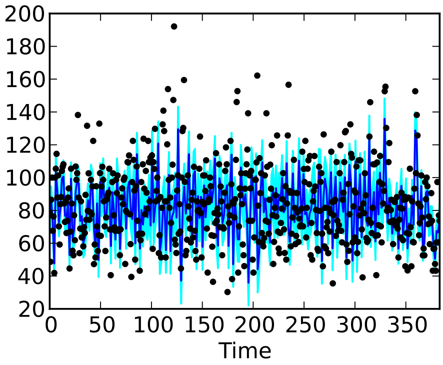
with autoregressive coefficients α_p and moving average coefficients β_q

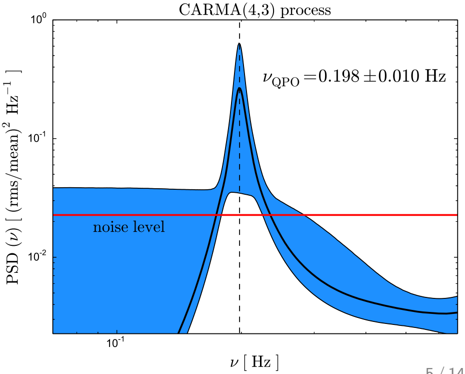
Stationary CARMA(p,q) process with $q < p$ has the PSD:

$$\mathrm{PSD}(\nu) = \sigma^2 \frac{|\sum_{j=0}^{q} \beta_j (2\pi i\nu)^j|^2}{|\sum_{k=0}^{p} \alpha_k (2\pi i\nu)^k|^2}$$

Example: high frequency PSD of X–ray binary H1743–322
(137 ks count rate light curve from XMM–Newton)

- has well defined QPO at $\nu_{\rm QPO} \sim 0.20\,$Hz (obtained from Fourier spectrum analysis by B. De Marco)
- original light curve has $\Delta t = 0.02\,$s $\rightarrow$ use downsampled light curve with $\Delta t = 0.75\,$s $\rightarrow$ $\nu_{\rm Nyquist} = 3.3 \times \nu_{\rm QPO}$





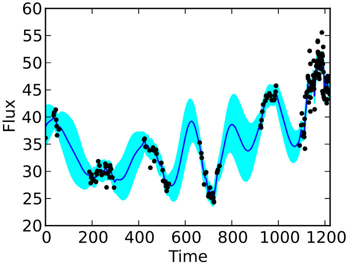
Variable QSO sample

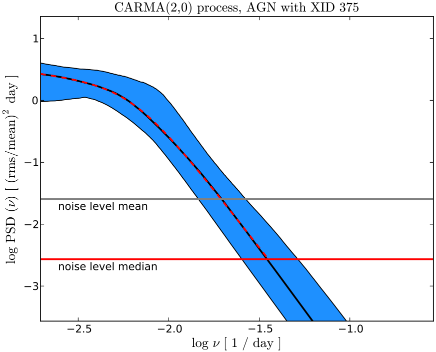
XMM–COSMOS catalogue (Brusa et al. 2010):

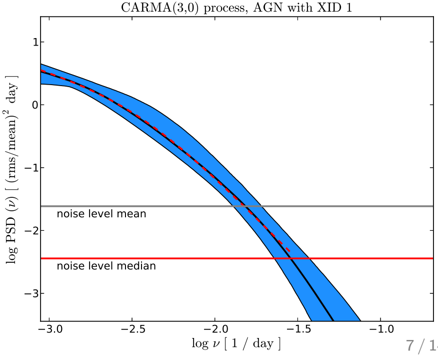
- X–ray selected AGN with $0.3 < z < 2.5$ (100% redshift complete)
- consider point–like and isolated QSOs with known L_{bol} and M_{BH} (Lusso et al. 2012, Trakhtenbrot and Netzer 2012, Rosario et al. 2013)
- 5 band (g, r, i, z, y) multi-epoch light curves from the Pan-STARRS1 (PS1) Medium Deep Field survey
- sample of 187 (g), 184 (r), 165 (i), 135 (z), 76 (y) variable QSOs
- CARMA PSD analysis done in g, r, i, and z bands (Simm et al. 2016)

PSD SHAPE – BROKEN POWER LAW

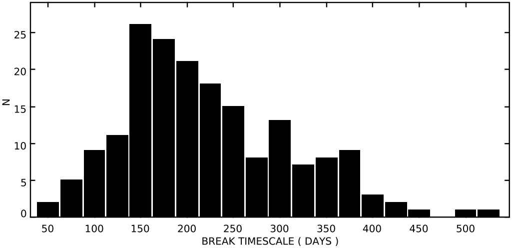
$$\mathrm{PSD}\,(\nu) = \frac{A\,(\nu/\nu_{\mathrm{br}})^{\alpha}}{1 + (\nu/\nu_{\mathrm{br}})^{\beta-\alpha}}$$

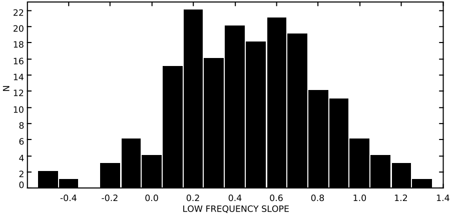


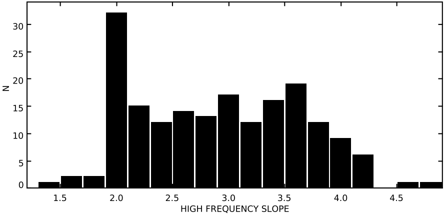




PSD SHAPE – DEVIATIONS FROM DRW MODEL

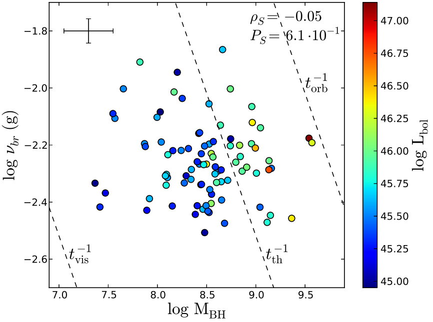


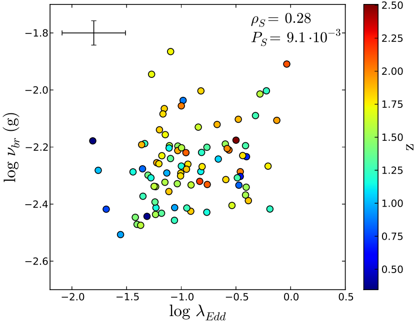




Scaling of the optical break frequency

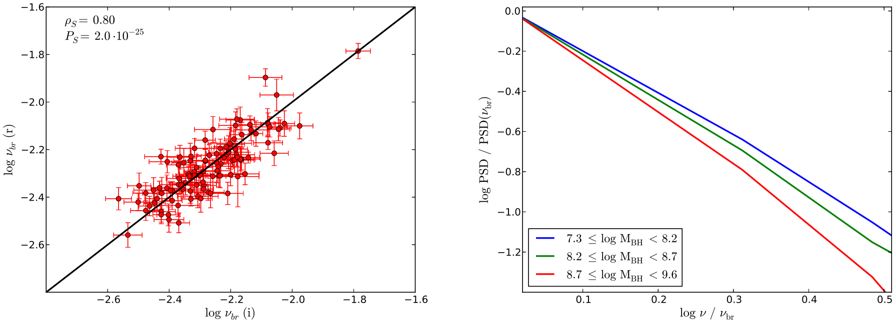
X–ray variability studies found: $\nu_{\rm br} \propto M_{\rm BH}^{-1}$ (e.g. McHardy et al. 2006)





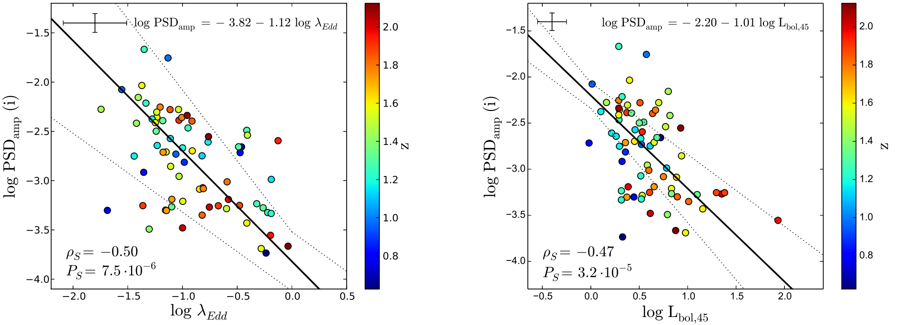
$\rightarrow$ the optical break frequency does not scale with $M_{\rm BH}$, $L_{\rm bol}$ and $\lambda_{\rm Edd}$!?

Scaling of the high frequency PSD slope



$\rightarrow$ the break frequency does not depend on radiation wavelength $\lambda_{\rm rad}$!?

$\rightarrow$ the high frequency PSD slope seems to be anti-correlated with $M_{\rm BH}$

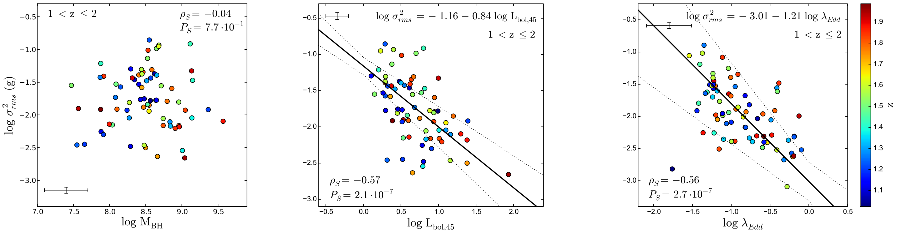


→ $\mathrm{PSD_{amp}} = A\nu_{\mathrm{br}}$ scales inversely with Eddington ratio λ_{Edd} and luminosity with slope ~ -1

Sanity check: excess variance analysis

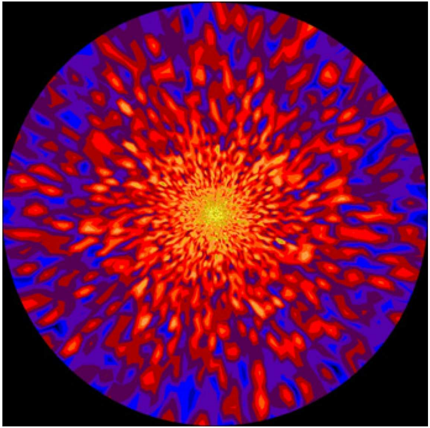
$$\mathrm{PSD} = \begin{cases} A\left(\frac{\nu}{\nu_{br}}\right)^{-1} & \nu \leq \nu_{br} \\ A\left(\frac{\nu}{\nu_{br}}\right)^{-2} & \nu > \nu_{br} \end{cases} \leftrightarrow \quad \sigma^2_{rms} = \frac{s^2 - \langle \sigma^2_{err} \rangle}{\langle f \rangle^2} = \int_{\nu_{min}}^{\nu_{max}} \mathrm{PSD}\mathrm{d}\nu$$

$$\rightarrow \sigma^2_{rms} = \begin{cases} \mathrm{PSD}_{\mathrm{amp}}\left(\nu_{min}^{-1} - \nu_{max}^{-1}\right)\nu_{br} & \nu_{min} > \nu_{br} \\ \mathrm{PSD}_{\mathrm{amp}}\left[\ln\left(\frac{\nu_{br}}{\nu_{min}}\right) - \frac{\nu_{br}}{\nu_{max}} + 1\right] & \nu_{min} < \nu_{br} < \nu_{max} \end{cases}$$



Strongly inhomogeneous accretion disc?

Temperature map of accretion disc



Toy model of Dexter and Agol 2011 (revised model see Cai et al. 2016):

- disc divided into N independent zones of fluctuating temperature
- variability amplitude $\propto 1/N$
- larger $L_{\rm bol}$ $\rightarrow$ radiation pressure instability enhanced $\rightarrow$ larger number of zones N?
- $M_{\rm BH}$–timescale relation smeared out by many zones with same temperature at different radii?

CONCLUSIONS

- for the first time we derived optical PSDs for a large QSO sample in a wide redshift range
- the optical PSD resembles a broken power law with a low frequency slope of -0.5 and a high frequency slope ranging between -2 and -4 $\rightarrow$ significant deviations from simple DRW model
- the PSD amplitude scales inversely with $L_{\rm bol}$ and $\lambda_{\rm Edd}$ with the same logarithmic slope of ~ -1
- the magnitude of the break timescale ($T_{\rm br}$ $\sim$200 days) is consistent with the thermal timescale, but seems to be uncorrelated with the AGN parameters $M_{\rm BH}$, $L_{\rm bol}$, and $\lambda_{\rm rad}$?

$\rightarrow$ with more sophisticated accretion disc models and big observational programs such as eROSITA/LSST we may be able to understand the physical origin of these variability correlations