Ensemble Power Spectral Density of Quasars in optical bands

Vincenzo Petrecca

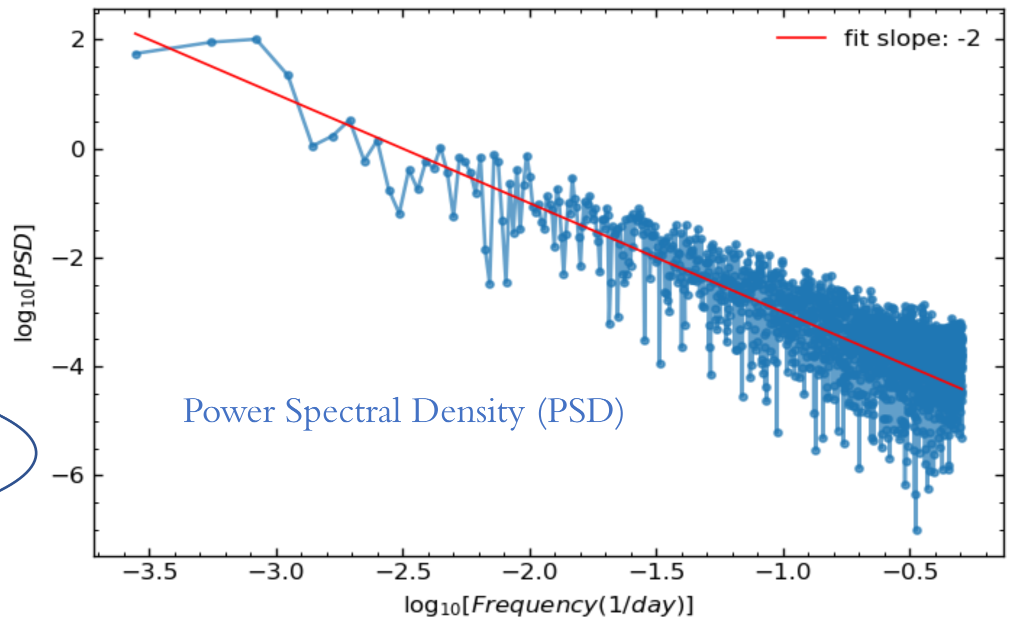
PhD student (Università di Napoli Federico II – INAF OACN)

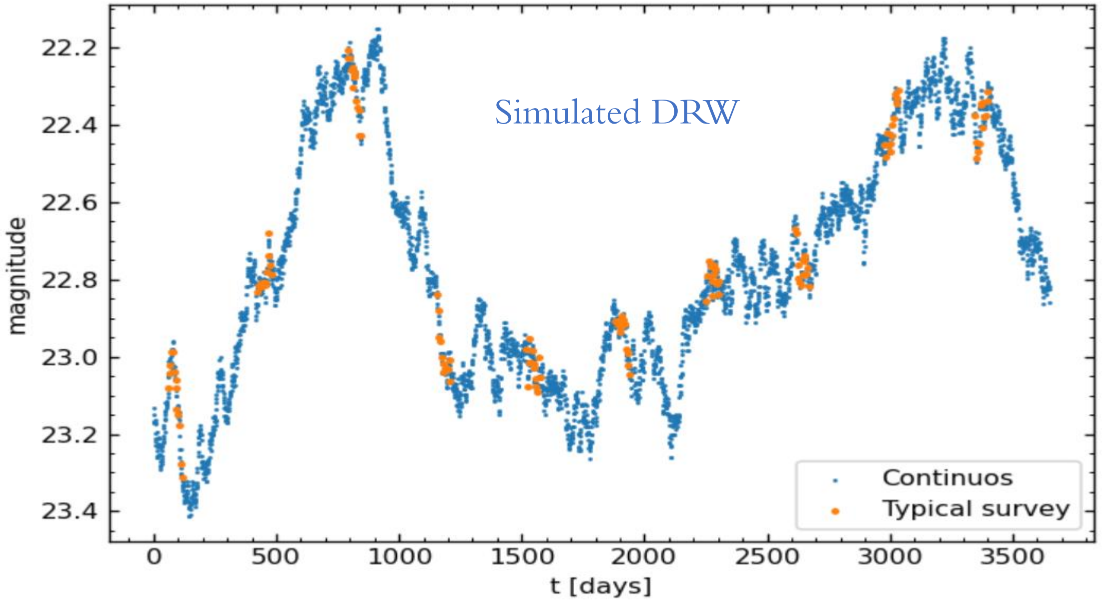
Main collaborators: M. Paolillo, I. Papadakis, F. Bauer, D. De Cicco

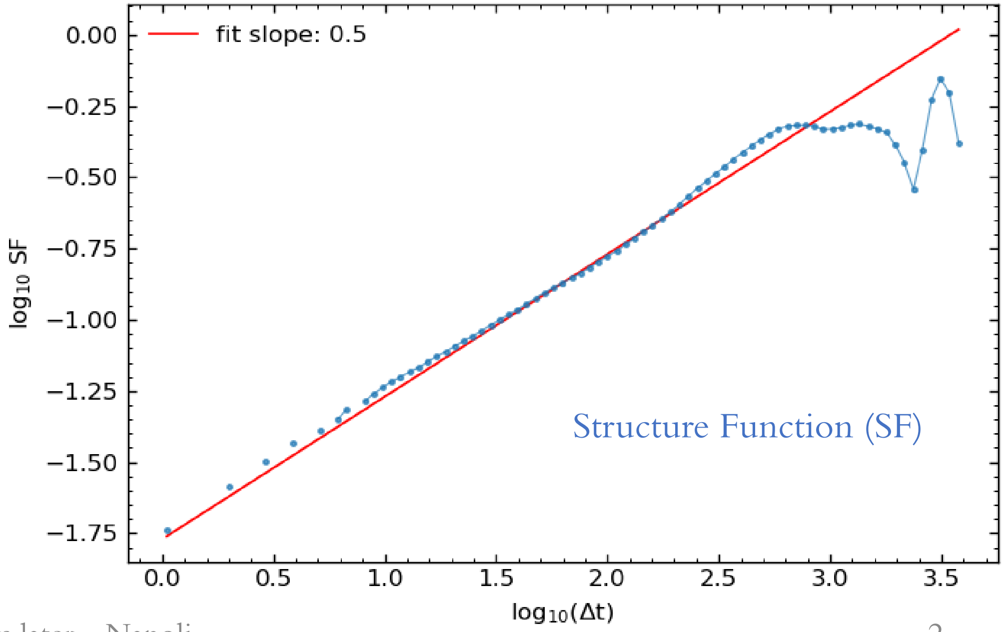
Modeling optical variability

- Light curves are completely stochastic and characterized by a red noise trend in their power spectra
- Usually described by a **Damped Random Walk** (DRW) (Kelly et al. 2009)

DRW model is consistent with data from SDSS Stripe 82 data (MacLeod et al. 2010) and OGLE (Zu et al. 2014), but there are deviations both on longer and shorter timescales (Mushotzky et al. 2011; Guo et al. 2017)



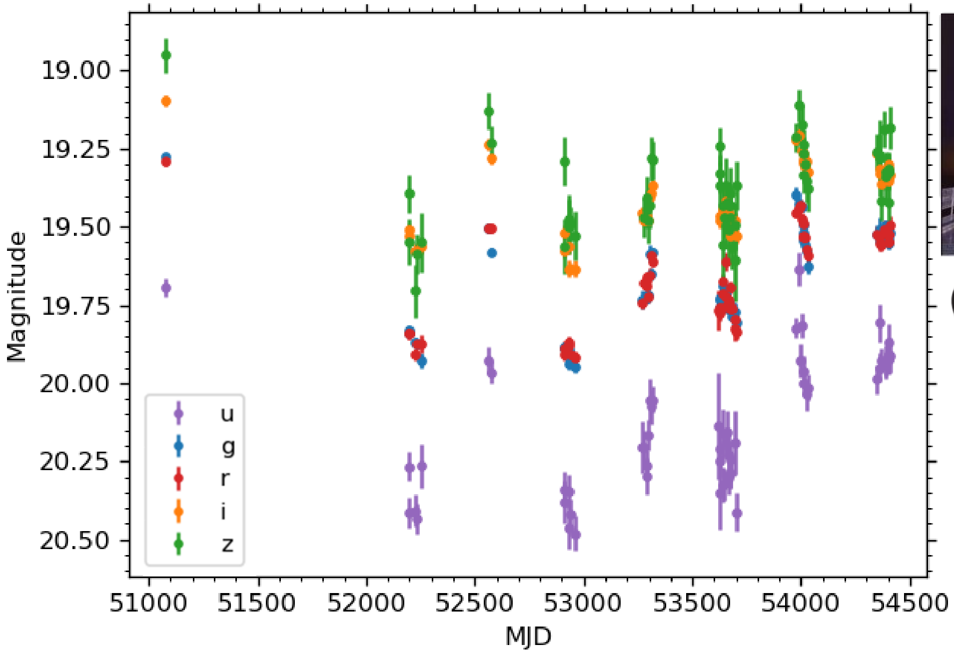


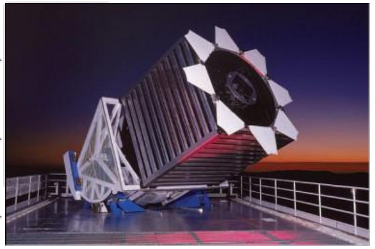


Quasars from SDSS Stripe-82

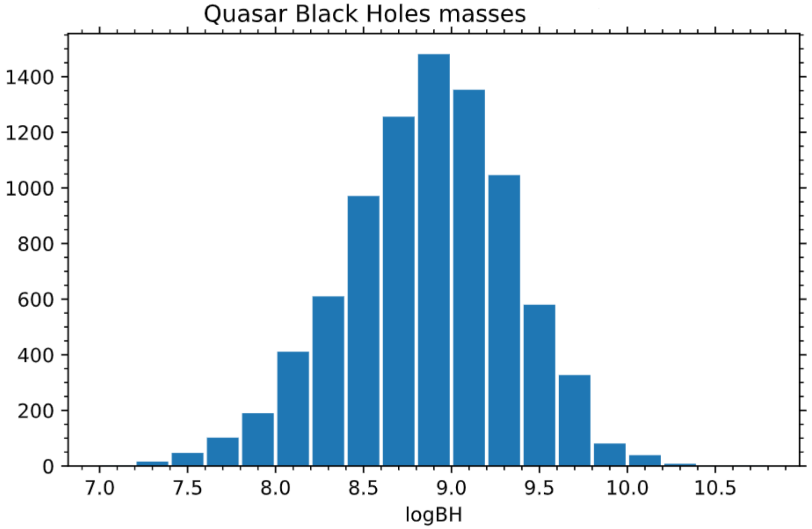
- 9186 spectroscopically confirmed Quasars
- Light curves with ~ 60 visits for 10 years in 5 bands *ugriz* (nearly simultaneous)
- Estimates of Mass and Bolometric Luminosity

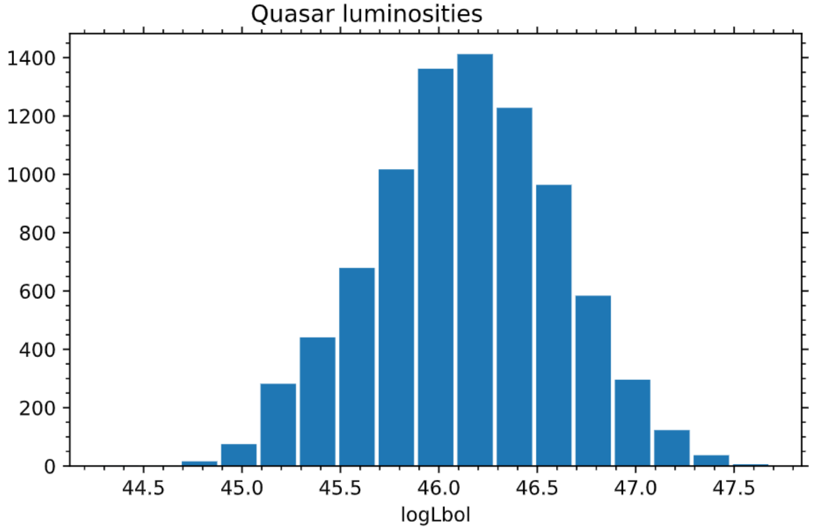
(MacLeod et al. 2010)

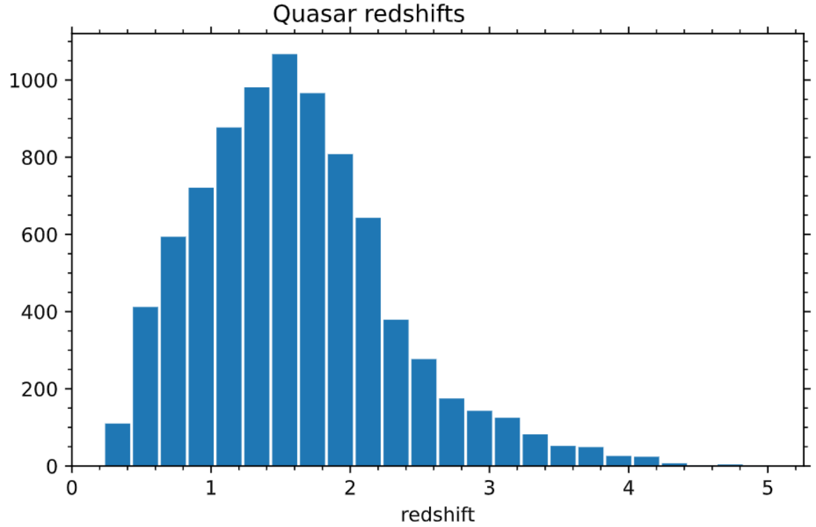




SDSS

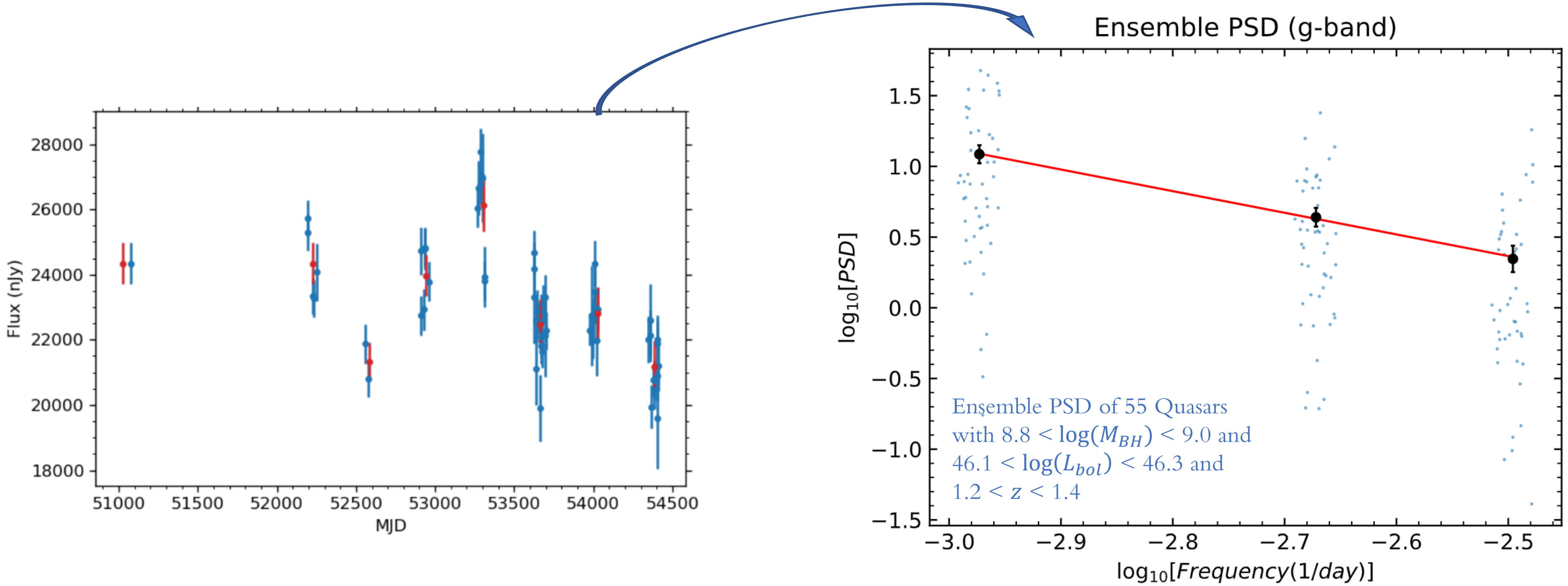




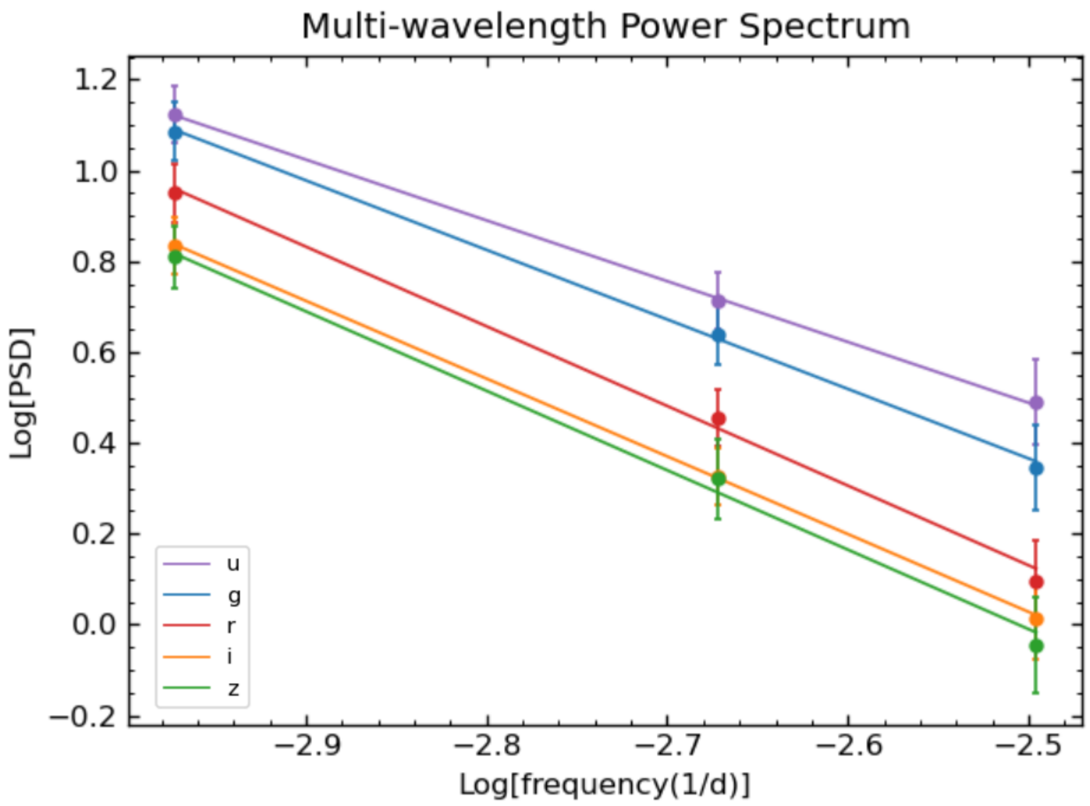


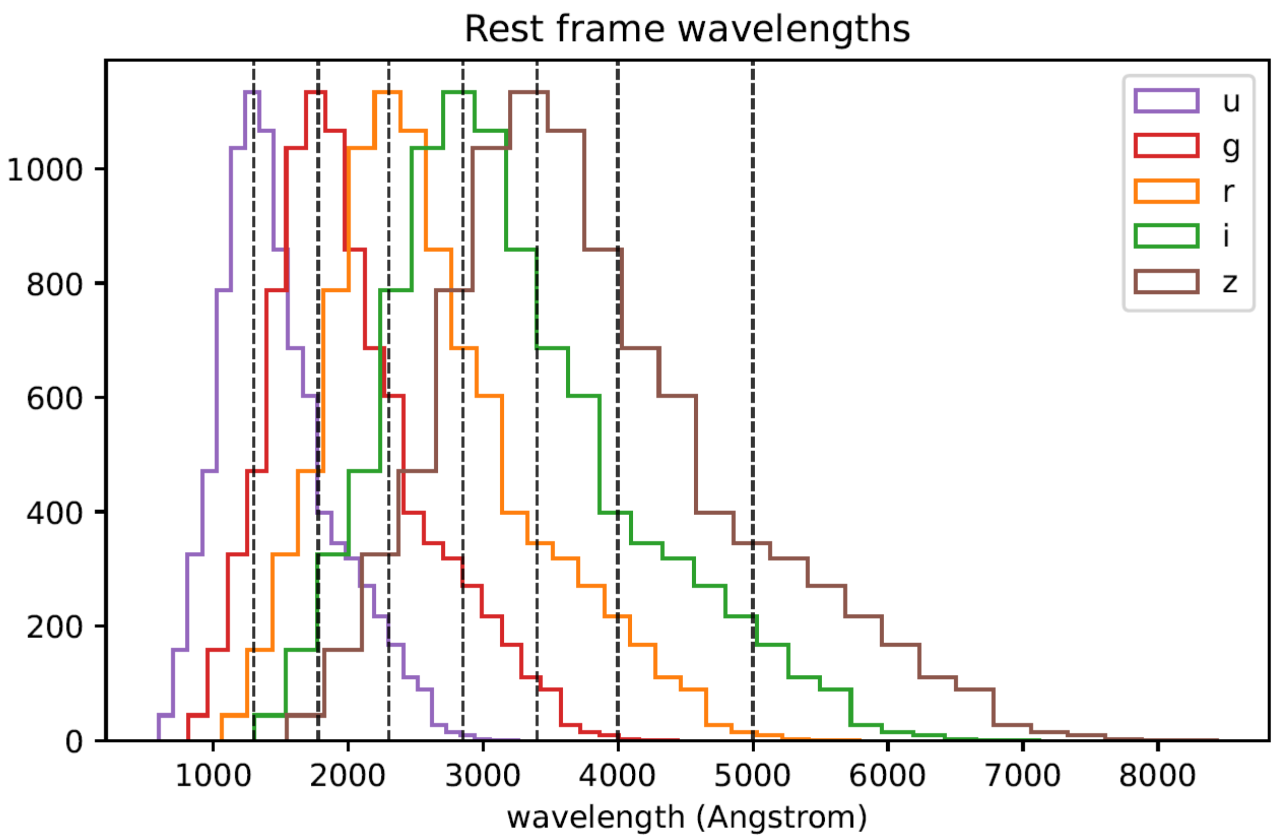
Ensemble PSD of SDSS quasars

- Bin the light curve (evenly sampled with sampling period $\Delta T = 1\ yr$ observer frame)
- Periodogram as estimator of the PSD
- White noise subtraction from non-variable SDSS stars (in different magnitude ranges)



Dependence of PSD on Wavelength





Dependence of PSD on Redshift

Ensemble PSD of quasars with with $8.8 < \log(M_{BH}) < 9.0$ and $46.1 < \log(L_{bol}) < 46.3$ in different redshift bins

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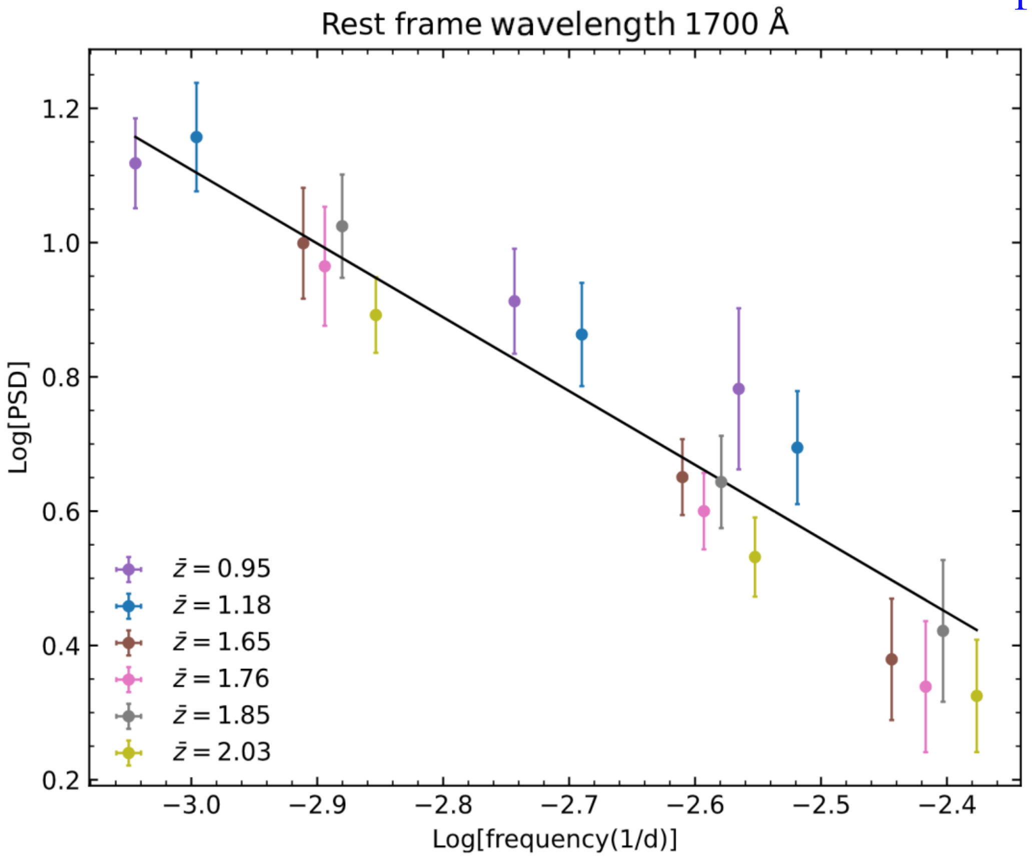
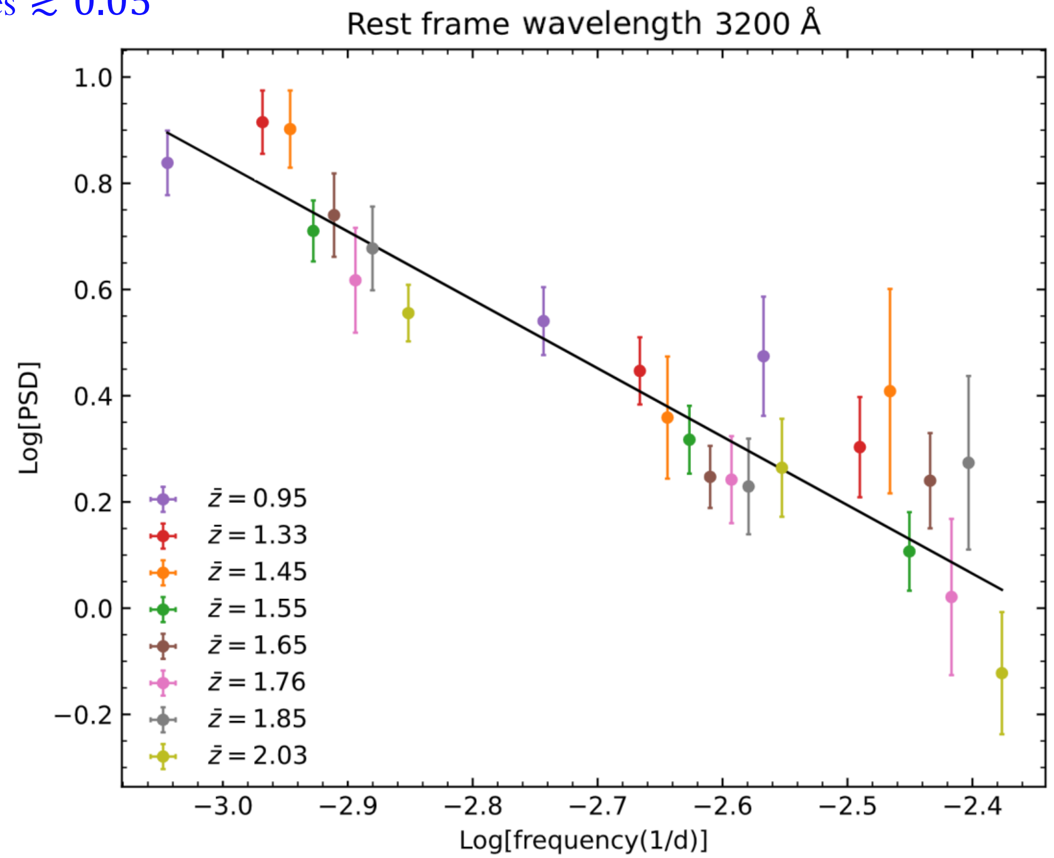
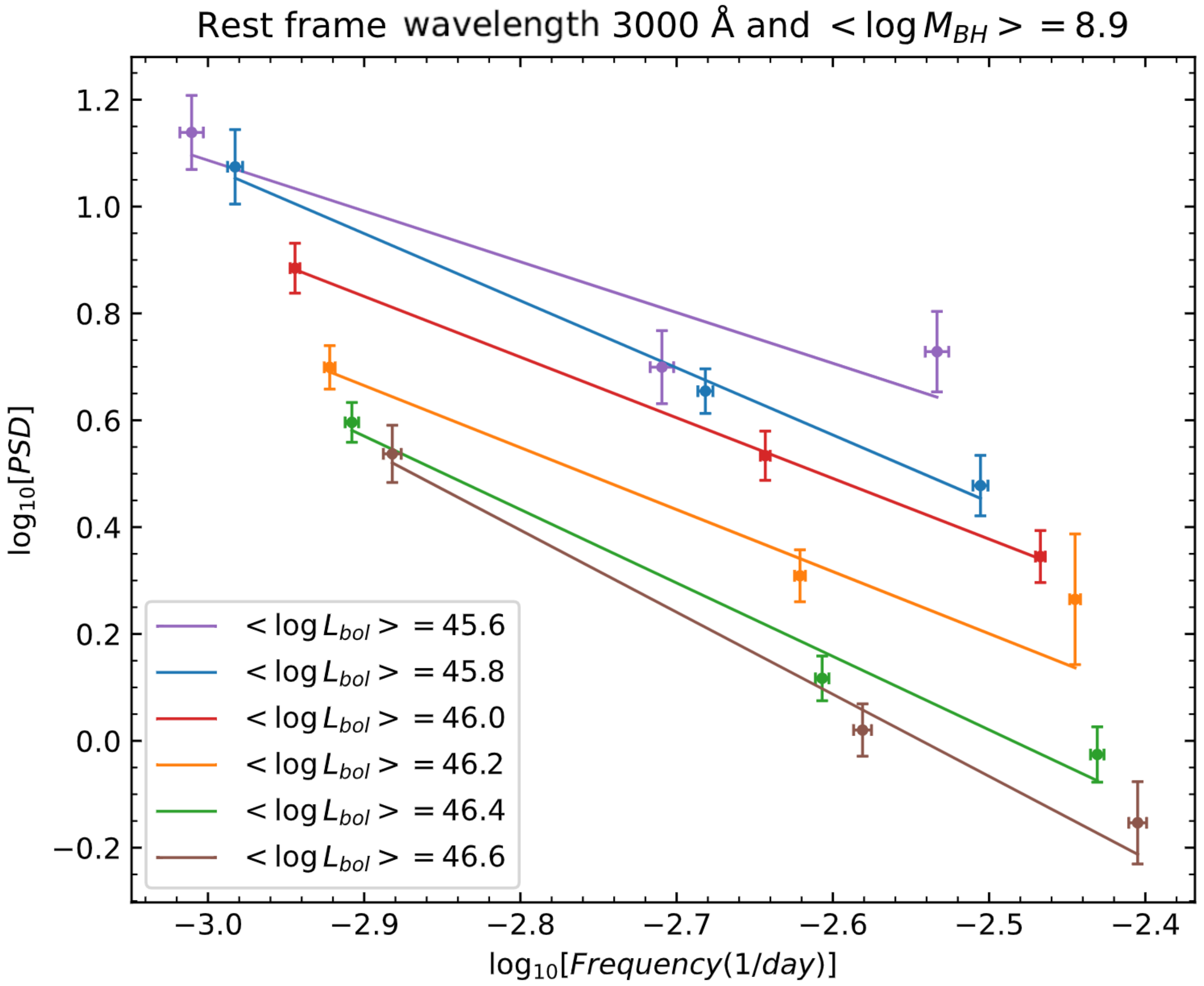
No significant evidence for a trend with redshift

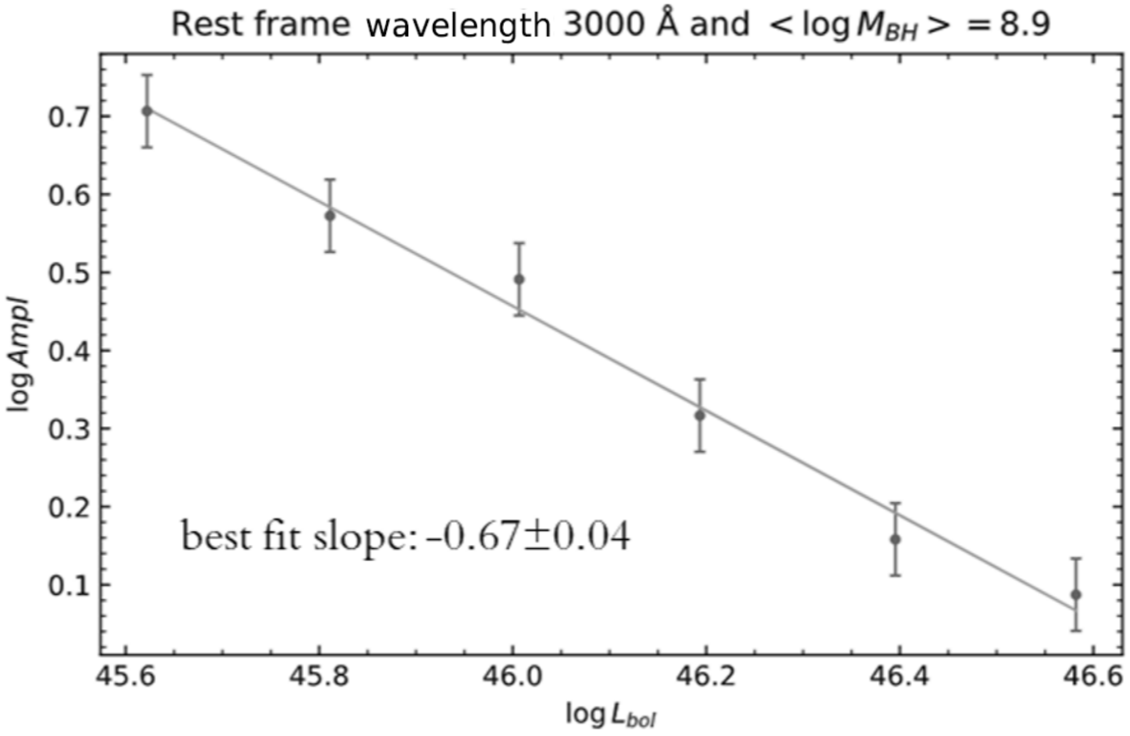
P-values $\gtrsim 0.05$



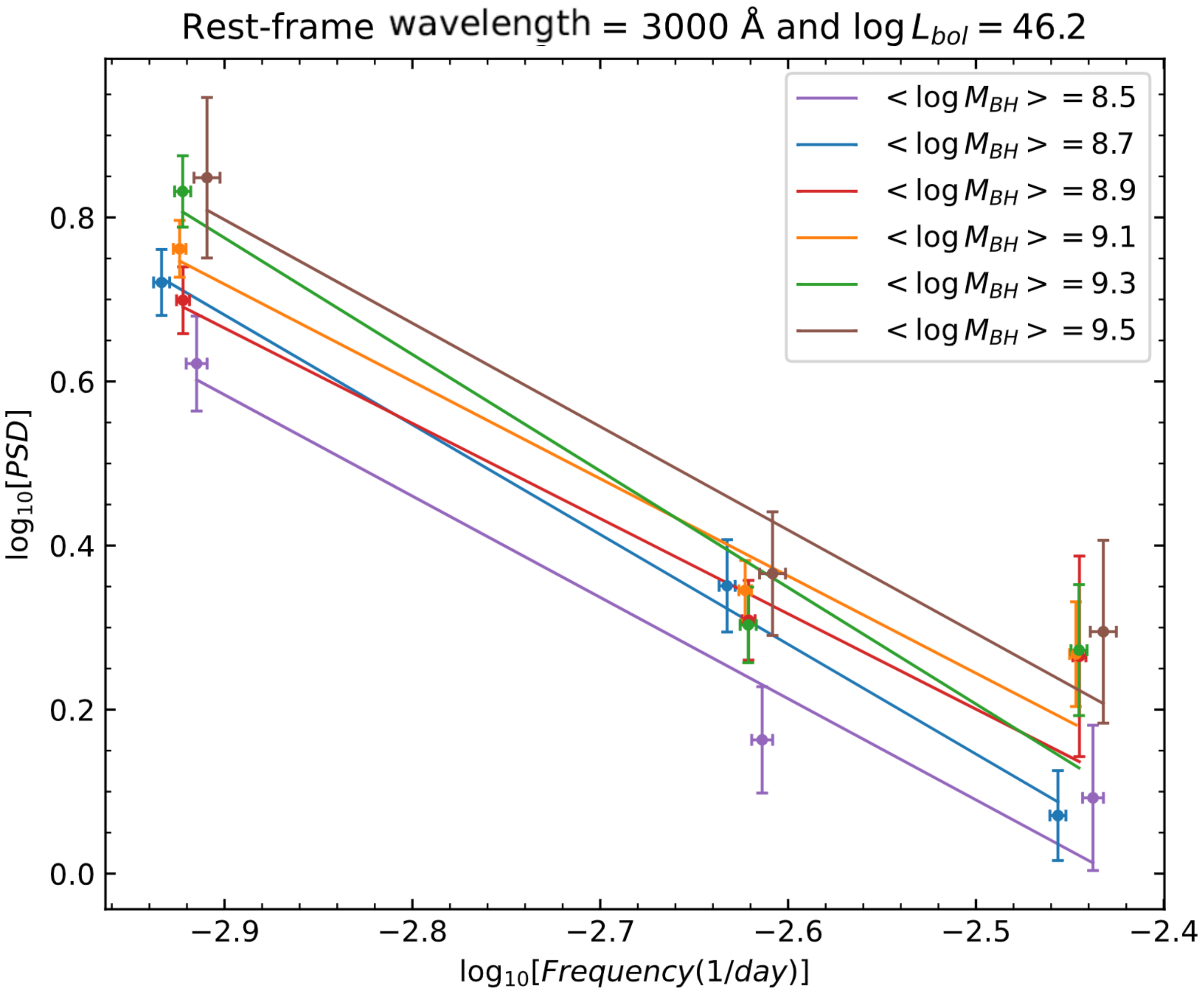


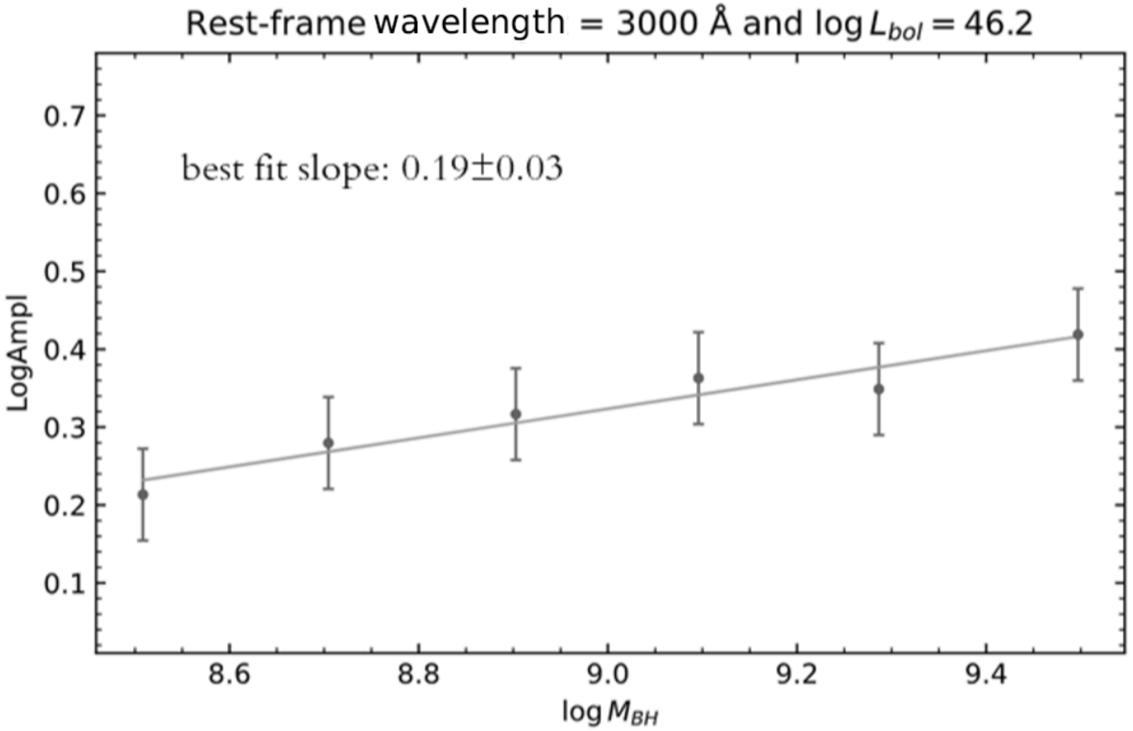
Dependence of PSD on Luminosity (fixed mass)



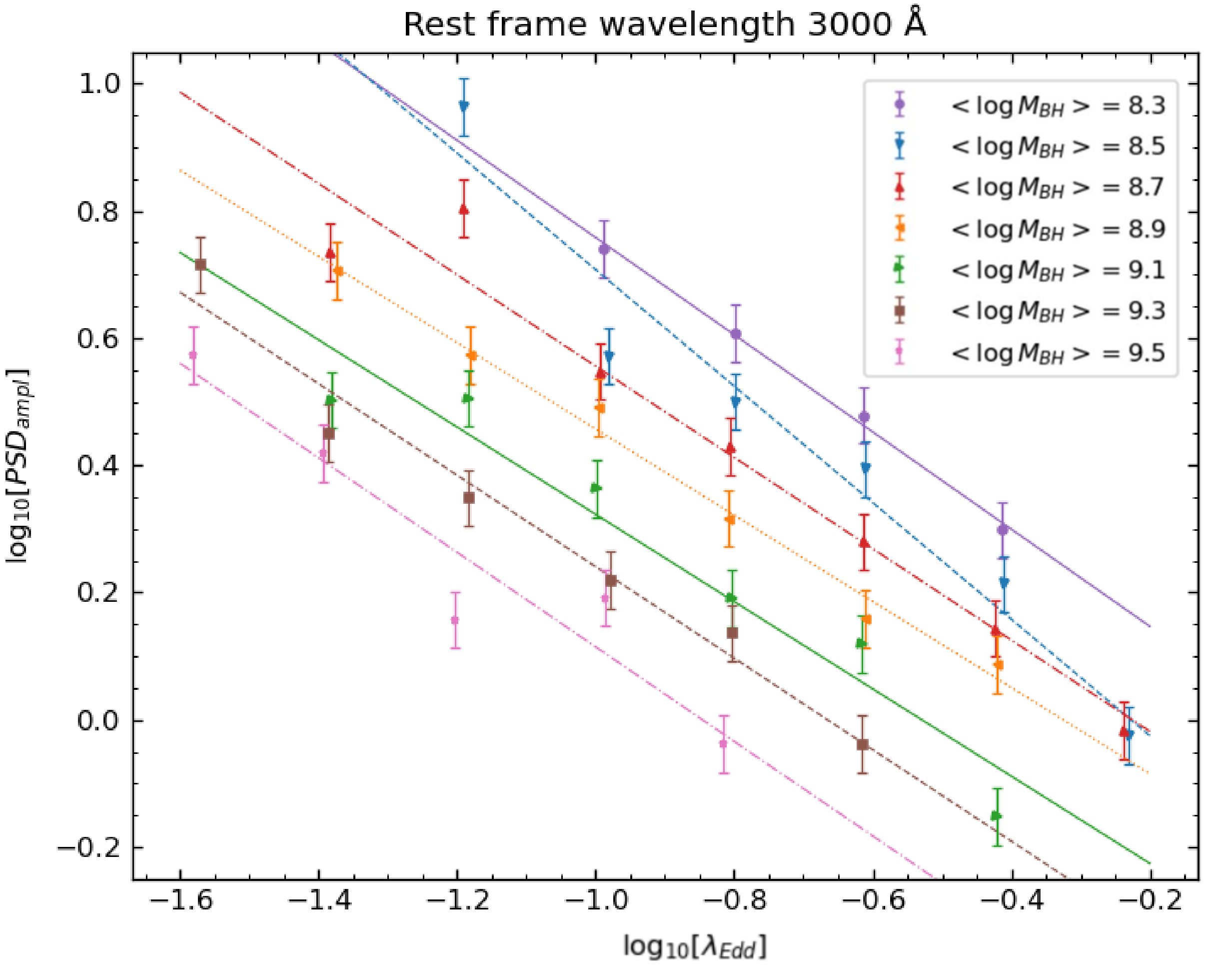


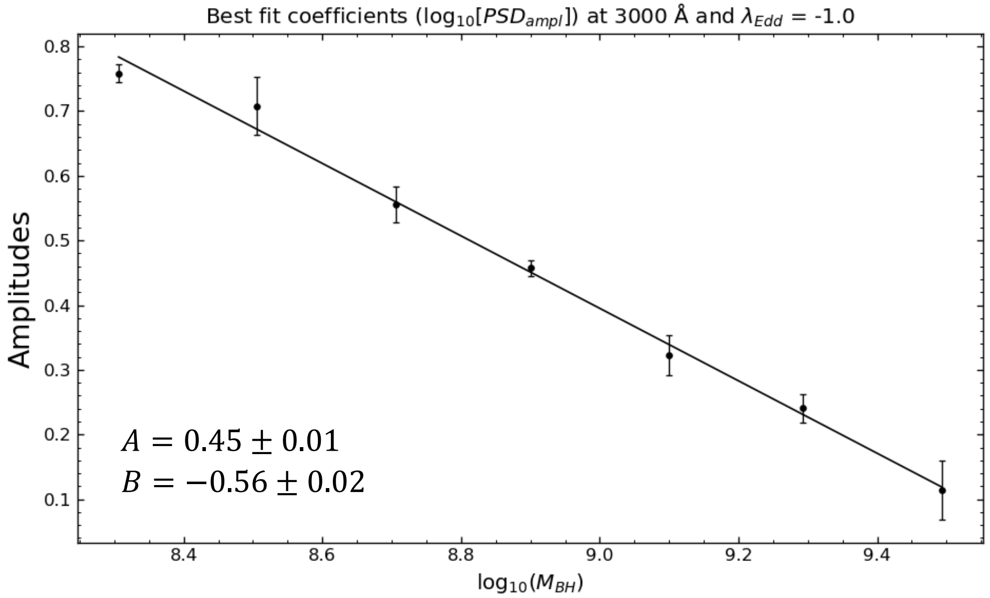
Dependence of PSD on Mass (fixed luminosity)

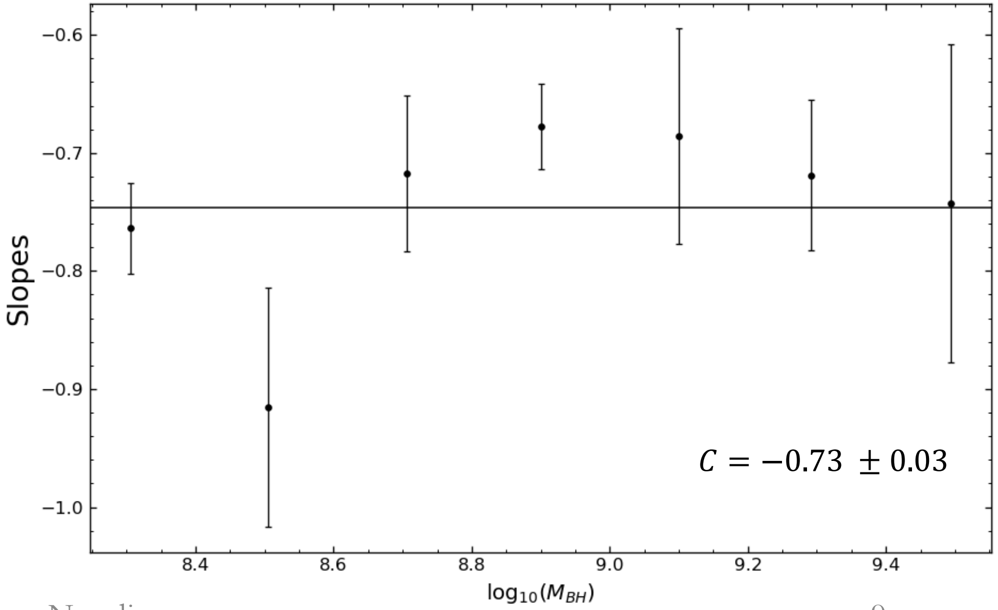




Dependence of PSD on Mass and Accretion rate

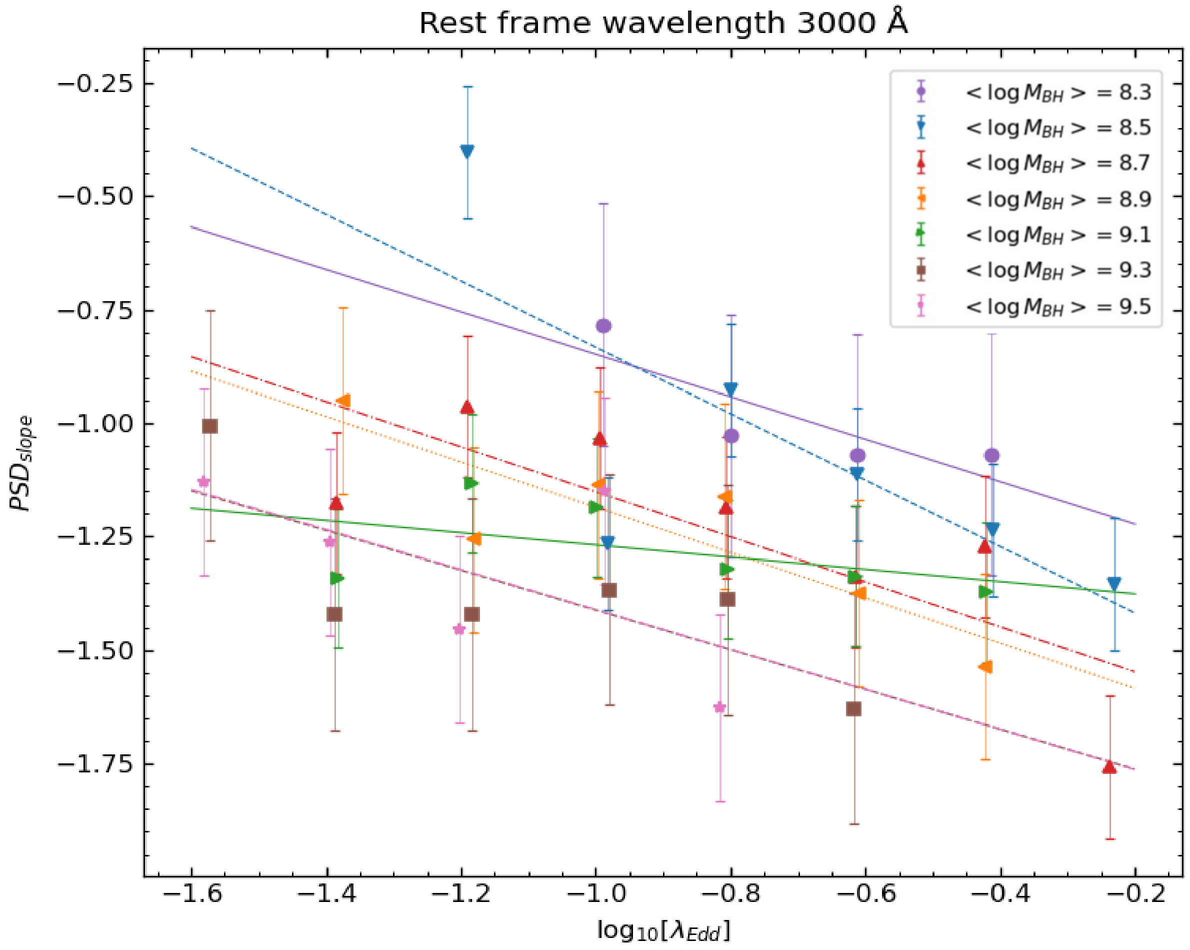


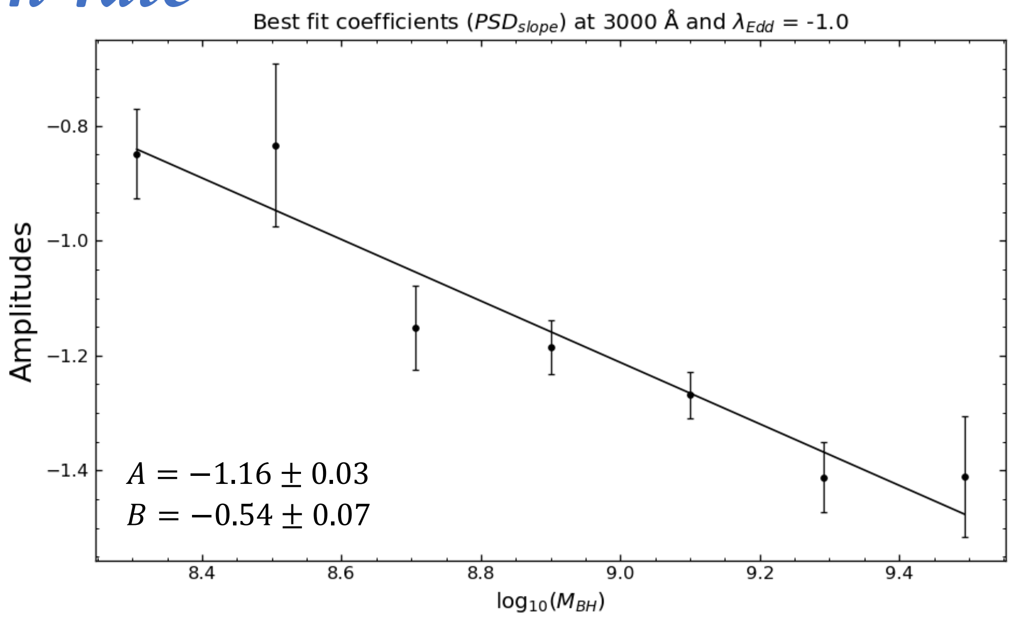


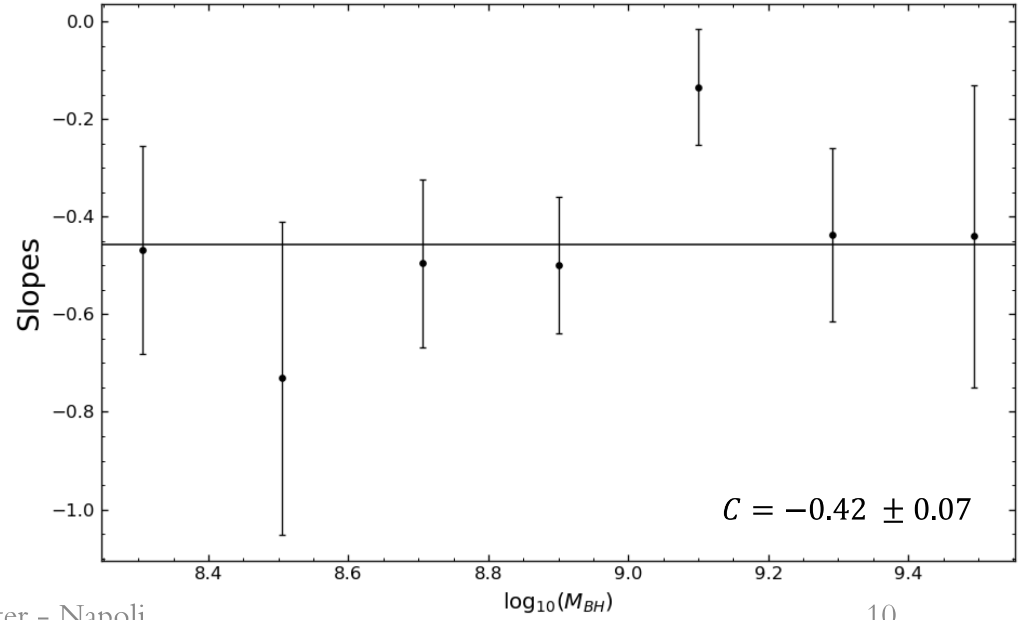


$$\log_{10}(PSD_{ampl.}) = A + B \cdot \log_{10}\left(\frac{M_{BH}}{7.9 \times 10^8}\right) + C \cdot \log_{10}\left(\frac{\lambda_{Edd}}{0.1}\right)$$

Dependence of PSD on Mass and Accretion rate

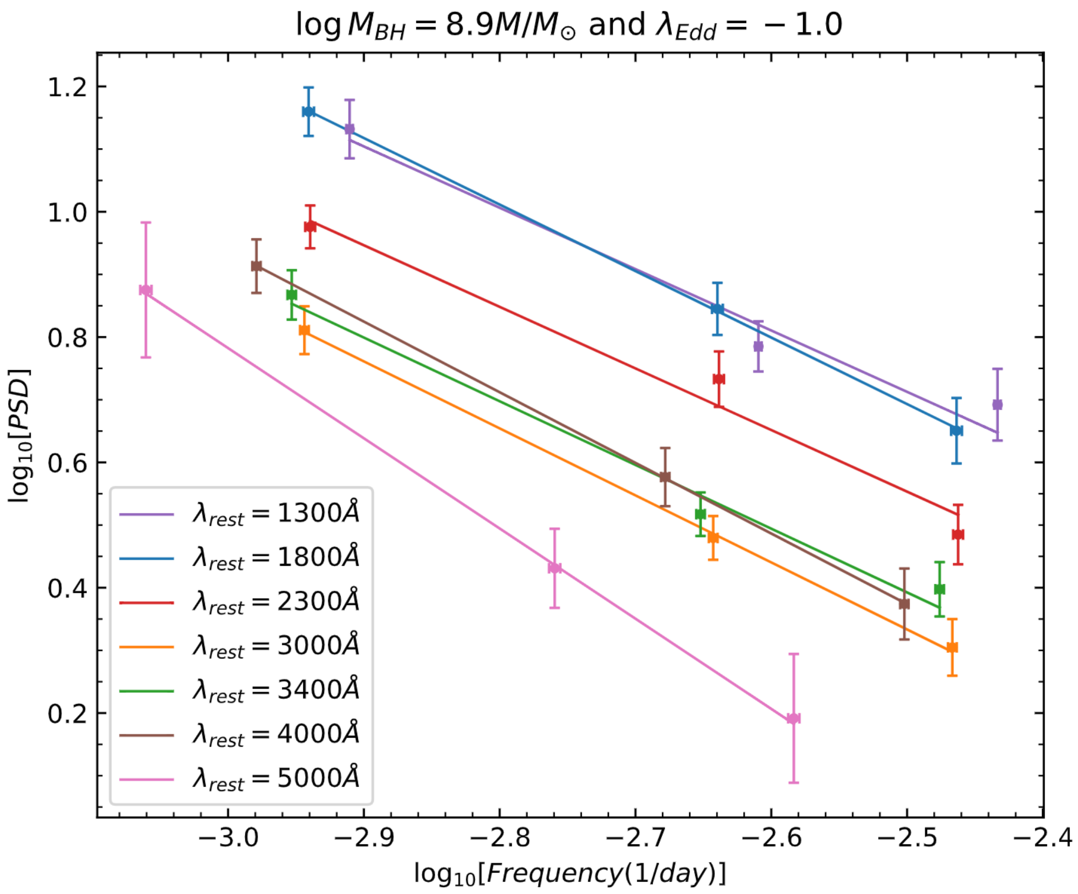


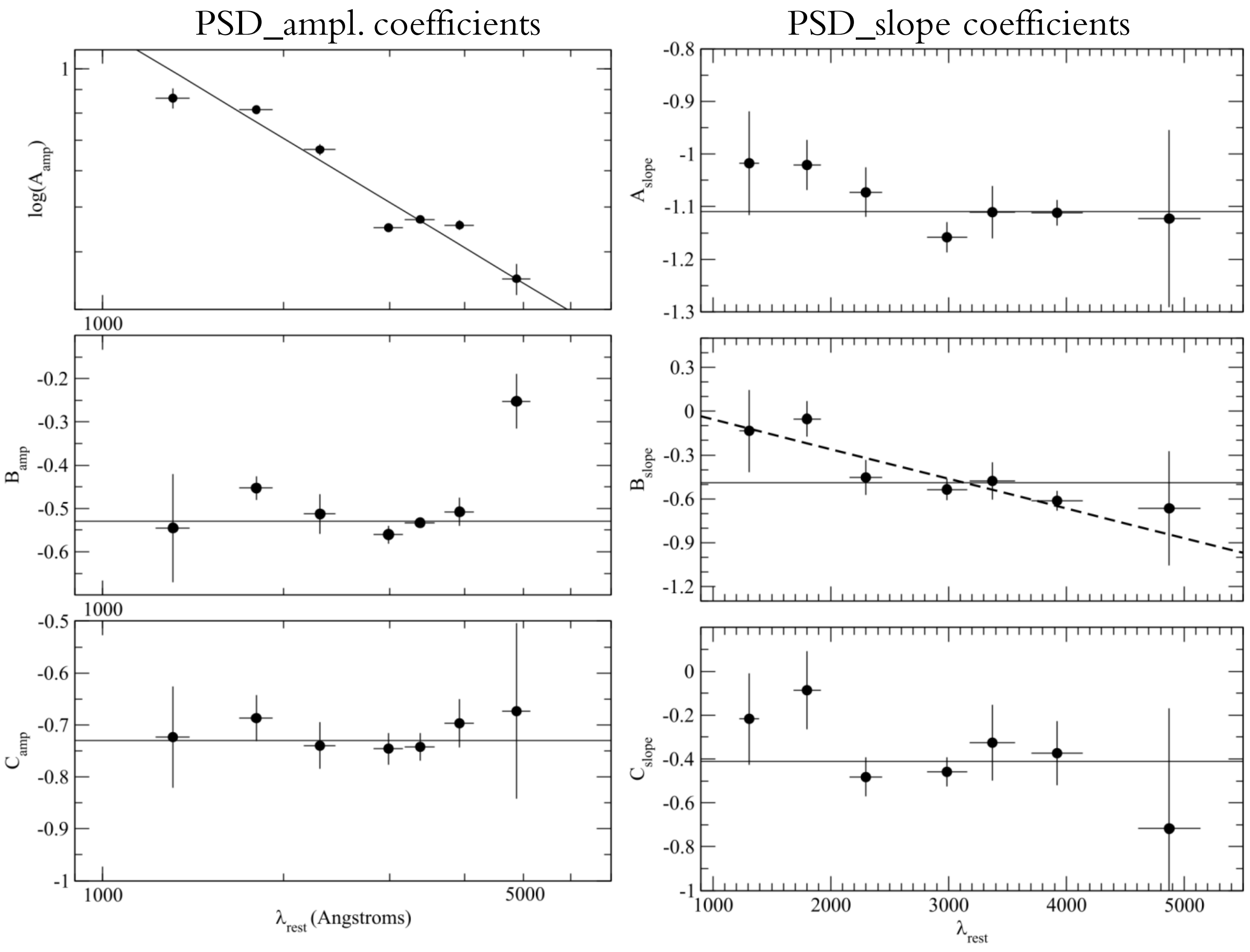




$$PSD_{slope} = A + B \cdot \log_{10}\left(\frac{M_{BH}}{7.9 \times 10^8}\right) + C \cdot \log_{10}\left(\frac{\lambda_{Edd}}{0.1}\right)$$

Dependence of PSD on rest-frame Wavelength





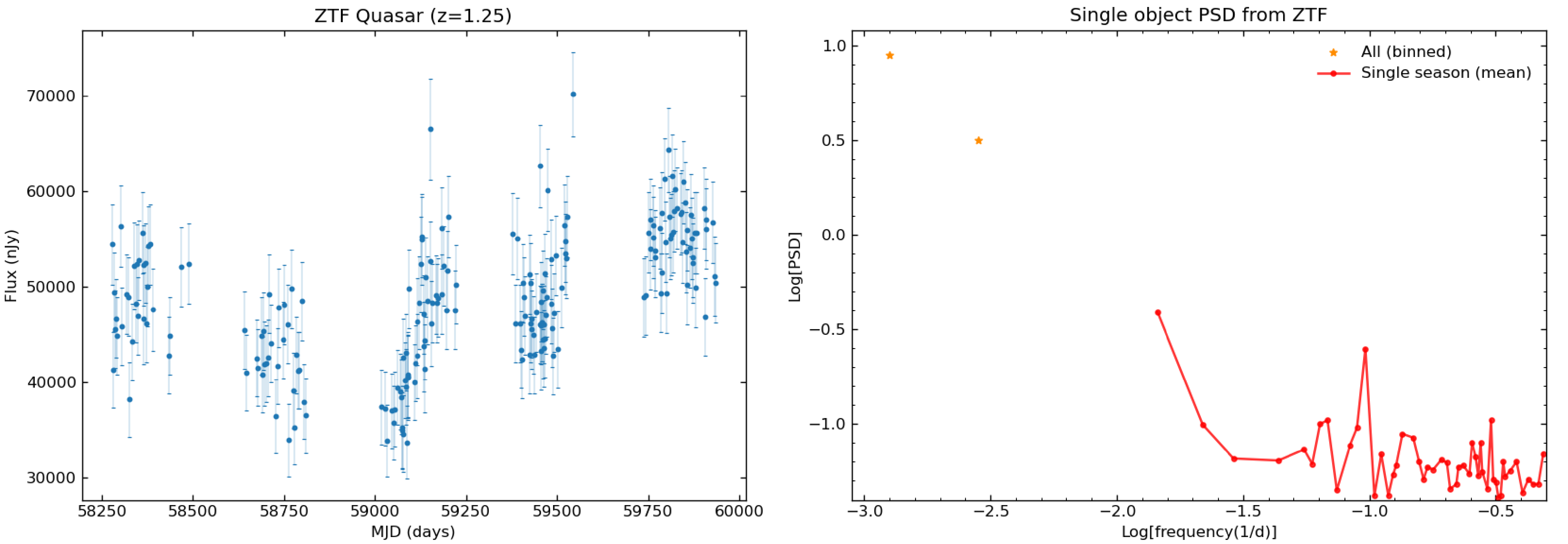
PSD scaling relations

From ~ 9000 quasars in the frequency range $[10^{-2}-10^{-3}]$ days (rest-frame)

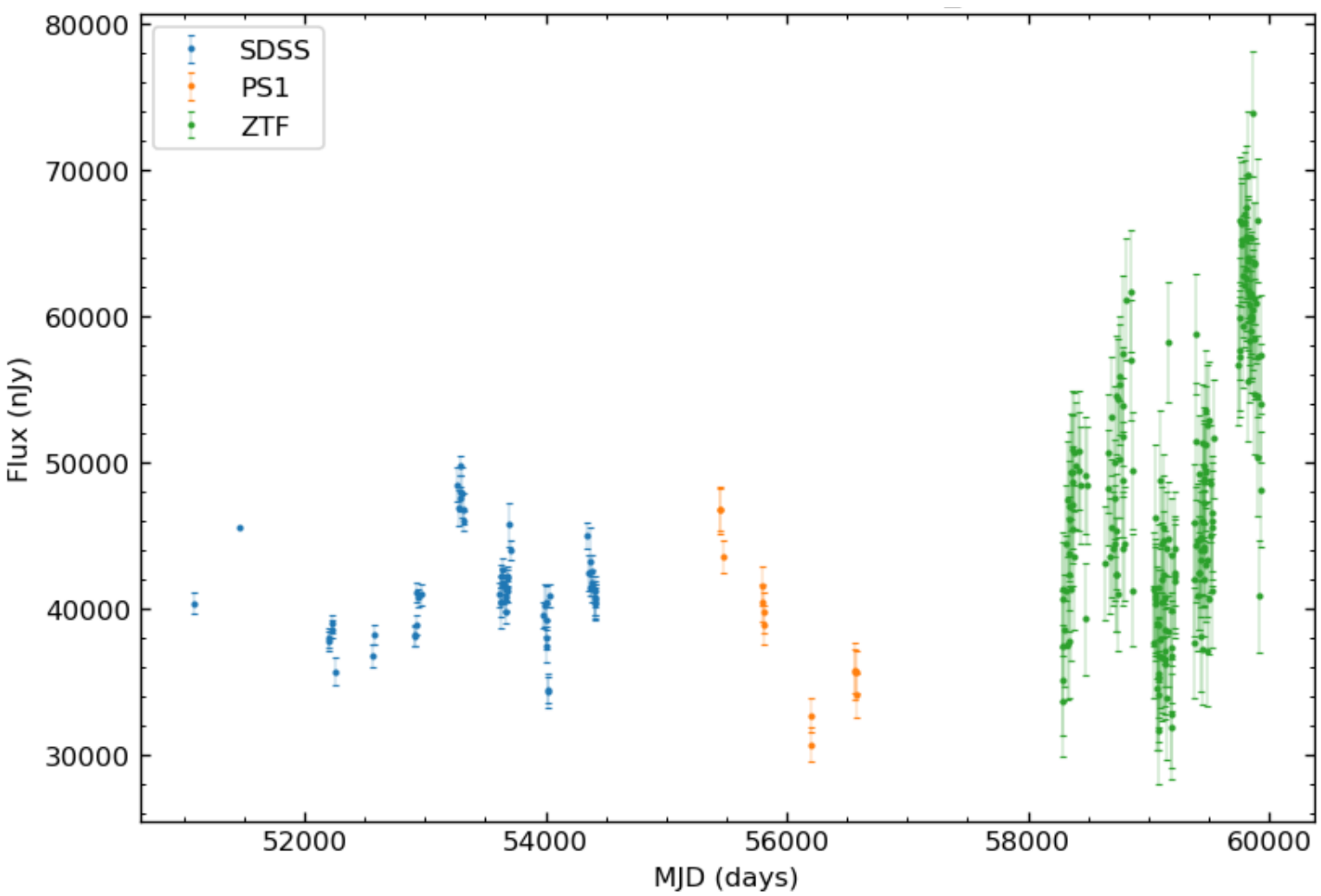
$$\log_{10}(PSD_{ampl.}) \propto \lambda_{rest}^{-1} \frac{\lambda_{Edd}^{-0.7}}{\sqrt{M_{BH}}}$$

$$|PSD_{slope}| \propto \frac{\lambda_{Edd}^{-0.4}}{\sqrt{M_{BH}}}$$

Expanding the frequency range: SDSS + ZTF



Expanding the frequency range: SDSS + ZTF + Pan-STARRS



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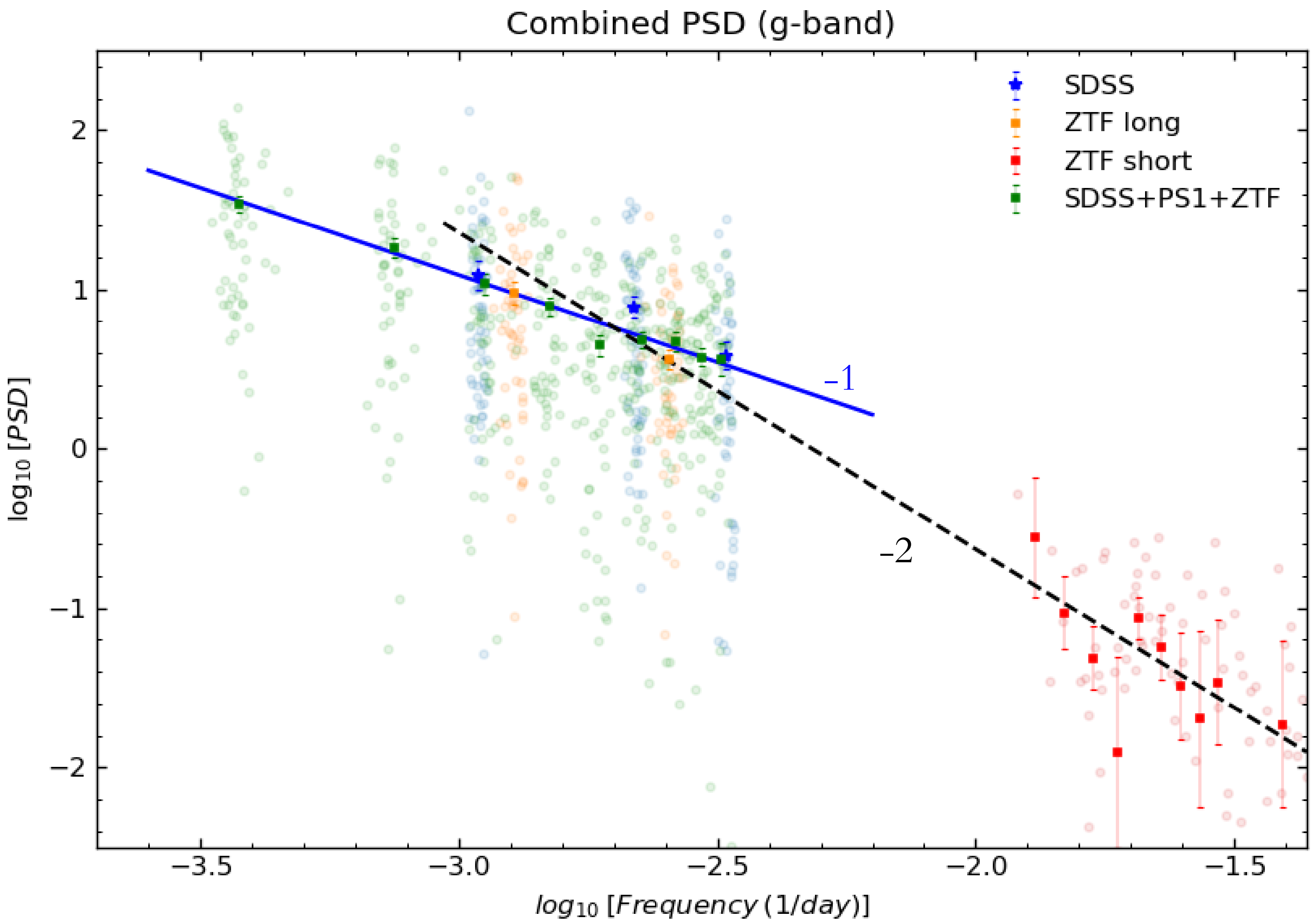

PRELIMINARY

Ensemble PSD of 56 Quasars with $8.7 < \log(M_{BH}) < 8.9$ and $45.9 < \log(L_{bol}) < 46.1$ and $1.25 < z < 1.45$

Summary

- Ensemble PSD analysis provides a valid framework to study AGN variability with big surveys
- Completely model independent analysis
- Variability amplitude is strongly anti-correlated with Luminosity and correlated with Mass
- PSD Amplitudes and Slopes depending on both Accretion rate and Mass (at rest-frame wavelength)
- Combination of different surveys enables to reach timescales of ~ 20 years (observer frame)

… Further Steps

- Extend the analysis of the combined PSD to different subsets of Quasars to look for differences in the PSD shape
- Use simulations for additional checks on possible measurement biases