Aspects of X-ray data analysis for accreting compact objects: theory and results

Piotr Życki

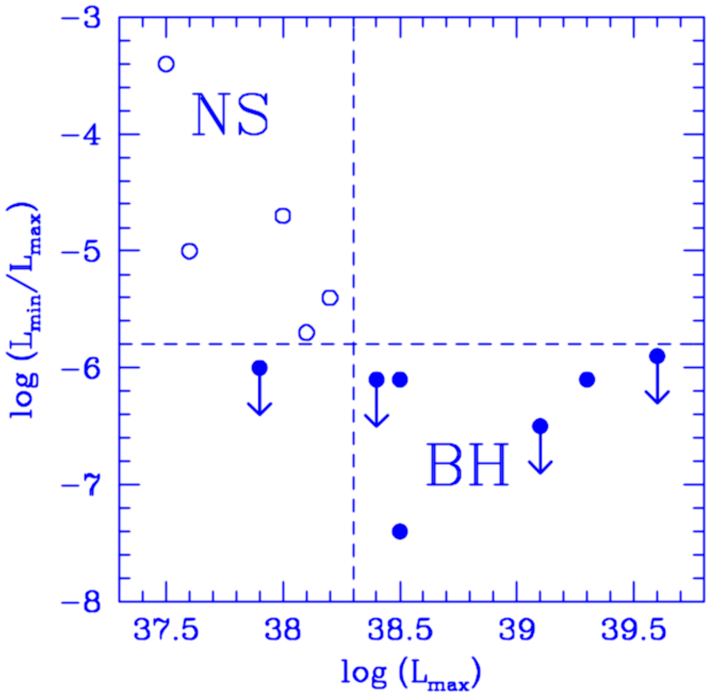
Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences

Lecture 11, 13.01.2026

PhD lecture series, 2025/26, fall semester

Previous lecture

Neutron star soft X-ray transients in quiescent state are brighter than black hole systems, because of additional emission from the surface of the neutron star



R. Narayan et al., 1997

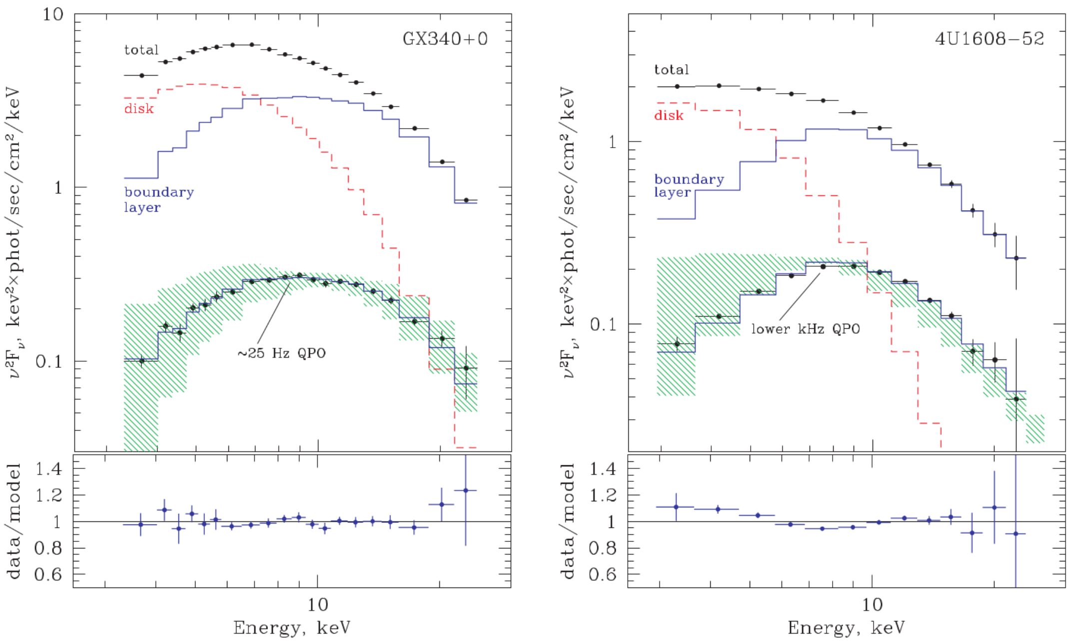
Previous lecture

Eastern vs Western model of the emission:

Disk black body emission from the accretion disk

Comptonized emission from the boundary layer

Revealed by Fourier-frequency analysis



Gilfanov et al., 2003, A&A, 410, 217

Black hole mass determinations from X-ray variability

Characteristic timescales scale with black hole mass

$$r_g = \frac{GM}{c^2} \qquad t_g = \frac{r_g}{c} = \frac{GM}{c^3} \qquad \tilde{r} = r/r_g \qquad v_K = \sqrt{\frac{GM}{r}} = \sqrt{\frac{GM}{\tilde{r}\, r_g}} = \frac{c}{\sqrt{\tilde{r}}}$$

$$t_{ph} \sim t_g; \quad t_{ph} = t_g \times F(\tilde{r}, disk\ parameters)$$

example: Keplerian time scale @ given r: $t_K(r) = \frac{2\pi r}{v_K} = 2\pi r \frac{\sqrt{\tilde{r}}}{c} = \frac{2\pi}{c} \tilde{r} \frac{GM}{c^2} = \frac{2\pi G}{c^3} \tilde{r}^{3/2} \times M$

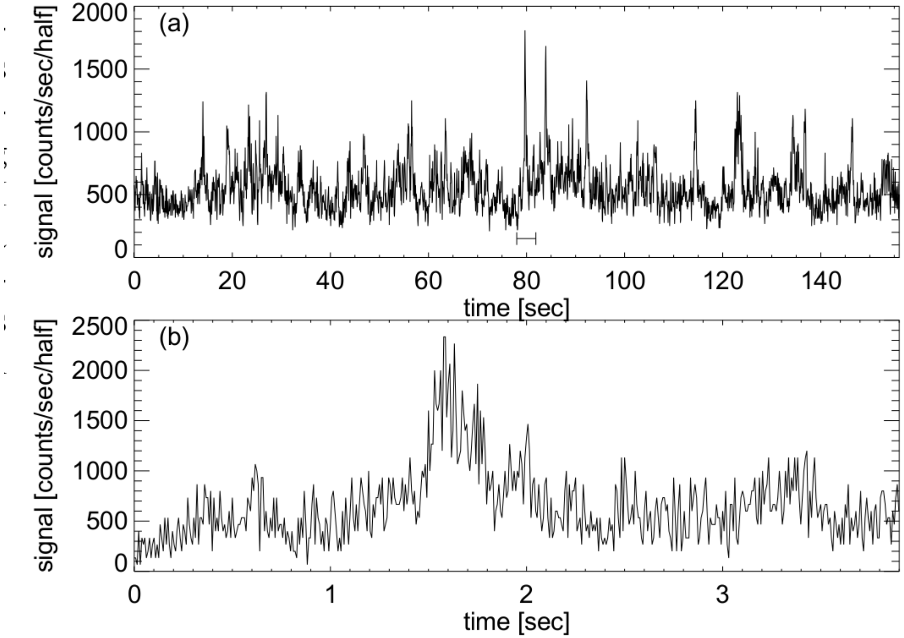
$$t_{ph} \sim M$$

So, in this (simple) picture:

an AGN with 10^8 solar mass black hole is just a scaled up version of a 10 solar mass X-ray binary

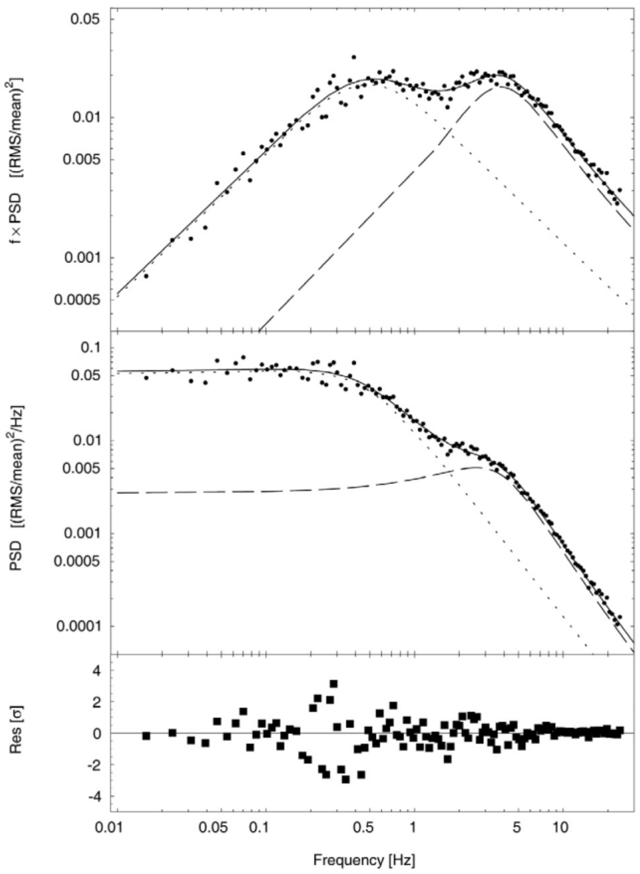
Characteristic timescales

Not easy to notice any characteristic timescale in a lightcurve



Characteristic frequencies in power spectra

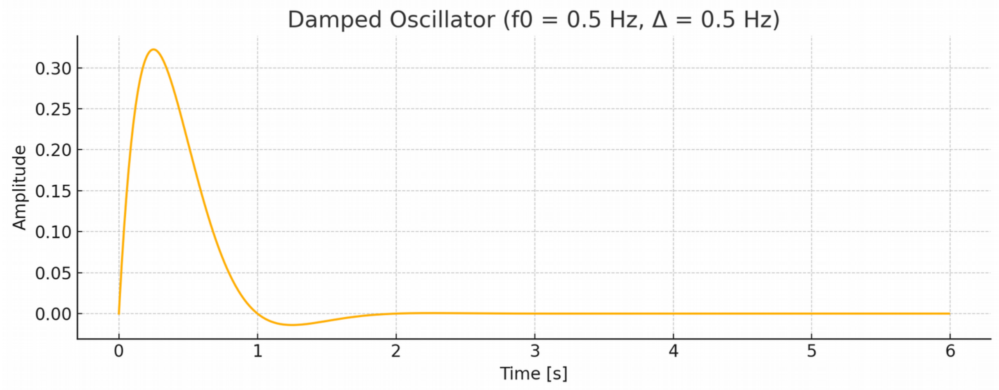
We do see characteristic frequencies in power spectra

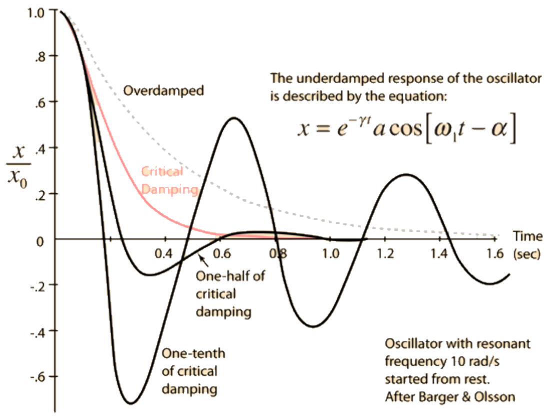


Characteristic frequencies in power spectra

The frequencies of the Lorentzians have to represent some physical timescales (e.g. dynamical, thermal – heating/cooling)

$$F(t) = A\,\mathrm{e}^{-t/t_d}\cos(2\pi\,\omega\,t + \phi_0)$$





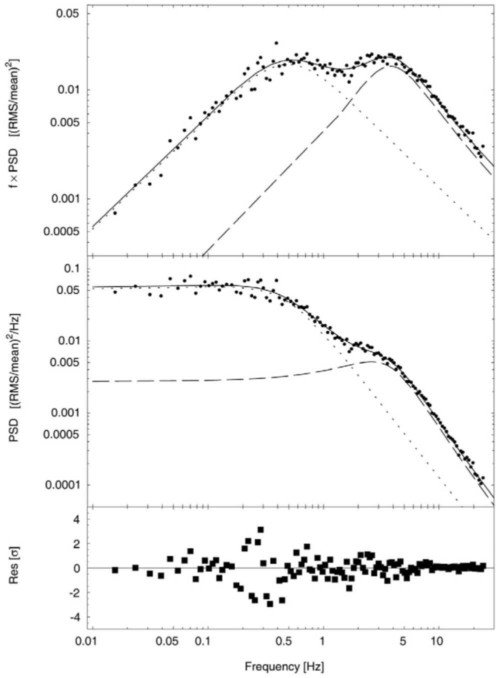
Characteristic frequencies in power spectra

Characteristic frequencies scale with the inverse of the black hole mass

$$f = \frac{1}{t_{ph}} \sim \frac{1}{M}$$

Any break in the power spectrum indicates a characteristic frequency, hence the timescale.

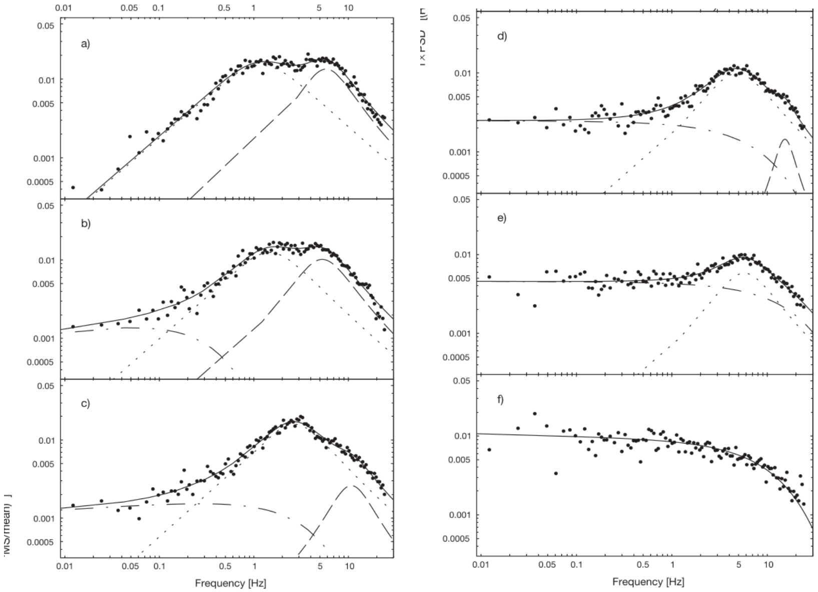
The break will scale with black hole mass: the higher the BH mass, the lower the break frequency. In fact, the entire PSD will shift with the changing BH mass



Scaling/shifting of the power spectrum

The problem:

Power spectra are not universal: a power spectrum from an X-ray binary changes it’s shape and break frequencies, even though the black hole mass is constant.



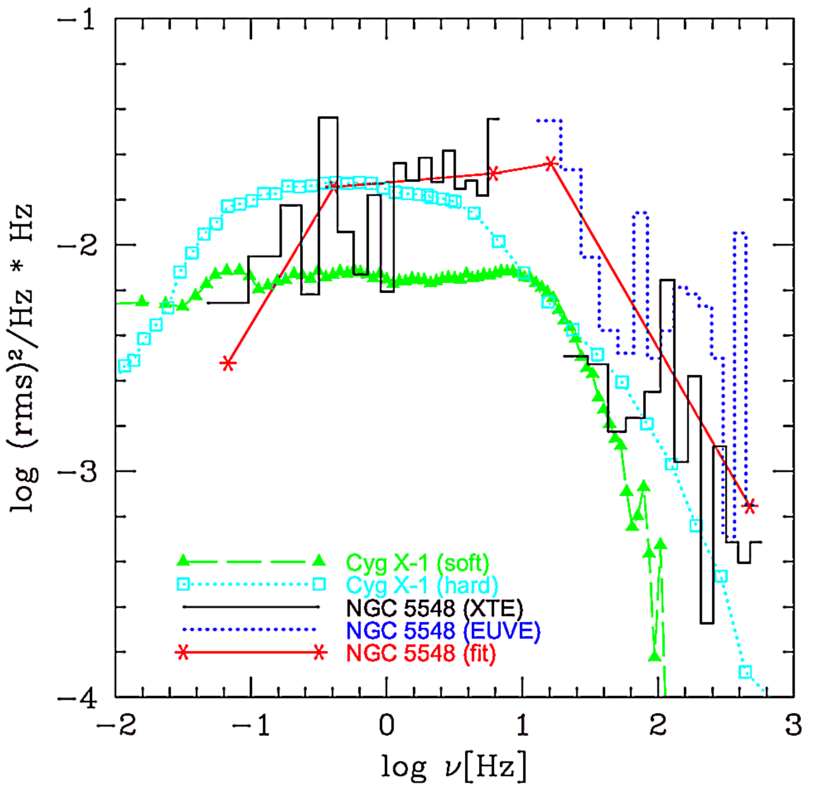
Axelsson et al., 2005, A&A, 438, 999

Scaling/shifting of the power spectrum

Seyfert galaxy NGC 5548 used as a reference source, since it’s mass is quite well known: $6.8*10^7$ M_{SUN}

Assuming 10 M_{SUN} BH mass in Cyg X-1, the PSD has to be shifted by 6.83 in log(f).

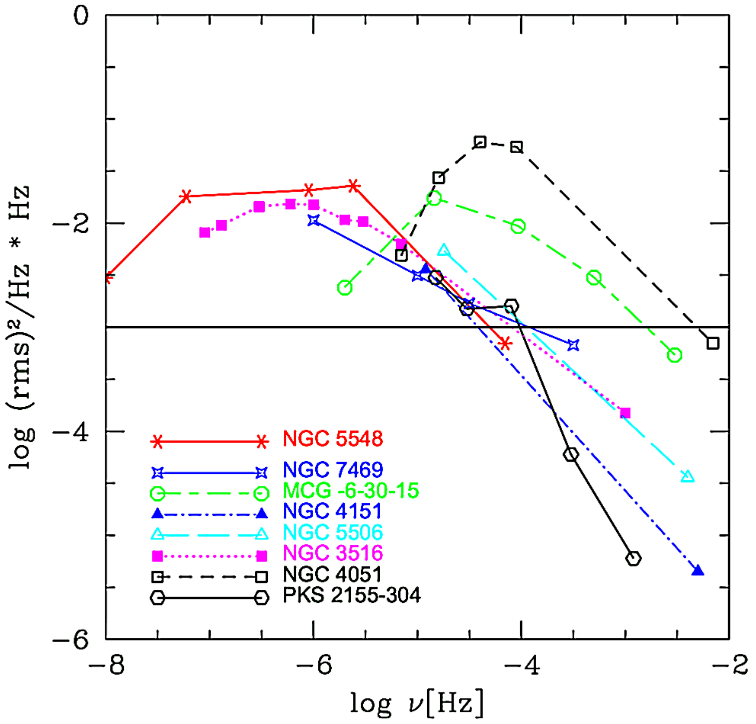
Location of the break frequency matches well the soft state spectrum of Cyg X-1, but normalization in NGC 5548 is higher



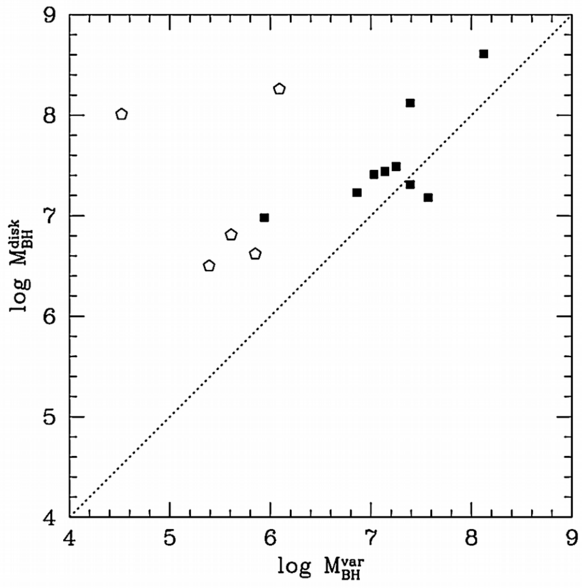
Czerny et al., 2001, MNRAS, 325, 865

BH mass determination for other AGN

Power spectra of a sample of AGN



Comparison of masses determined by the PSD method and the spectral fitting method – discrepancies for NLSy1 galaxies

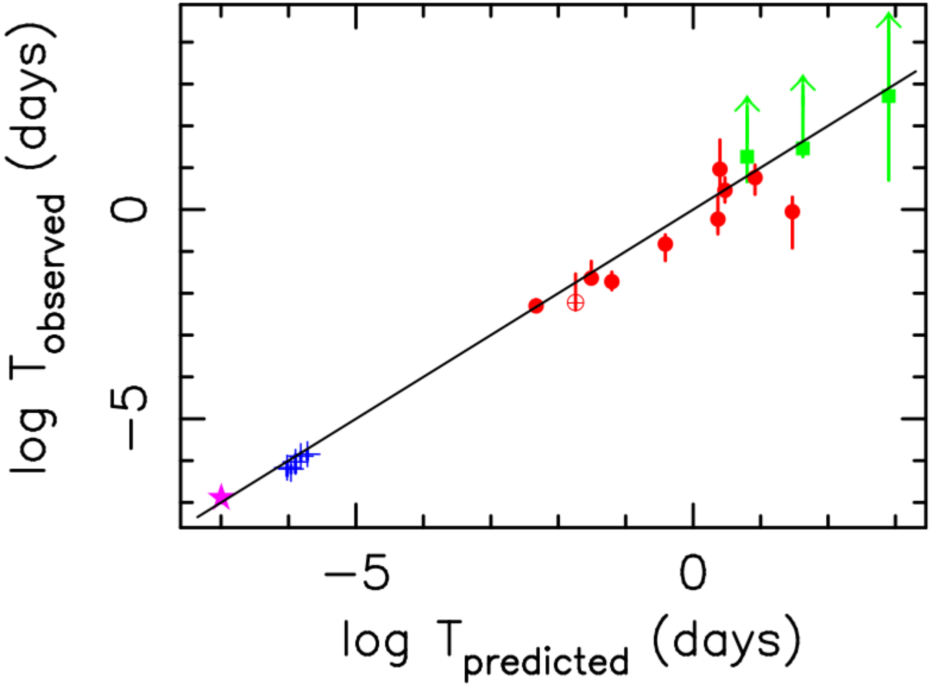


Czerny et al., 2001, MNRAS, 325, 865

A modified scaling

Further research led to a modified scaling, involving also accretion rate

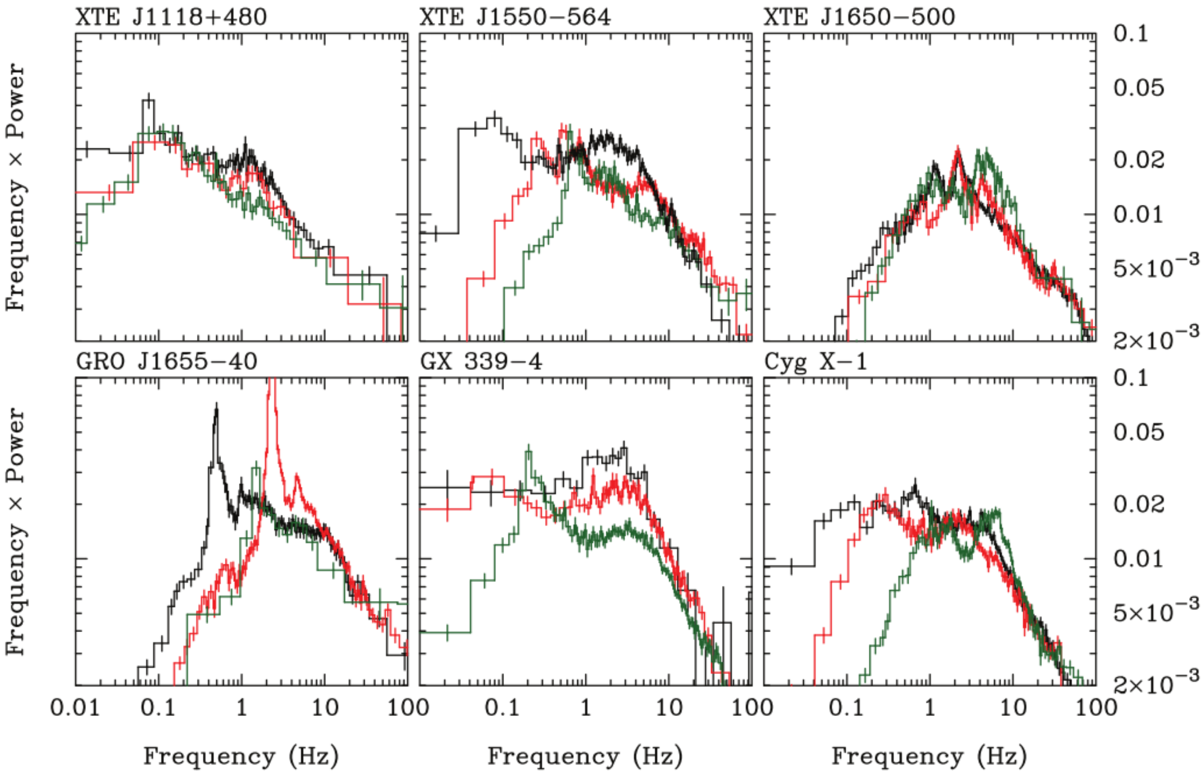
$$T_B = \frac{M_{BH}^{1.12}}{\dot{m}_E^{0.98}}$$



McHardy et al., 2006, Nature, 444, 730

A different method

High-frequency part of PSD does NOT depend on spectral state



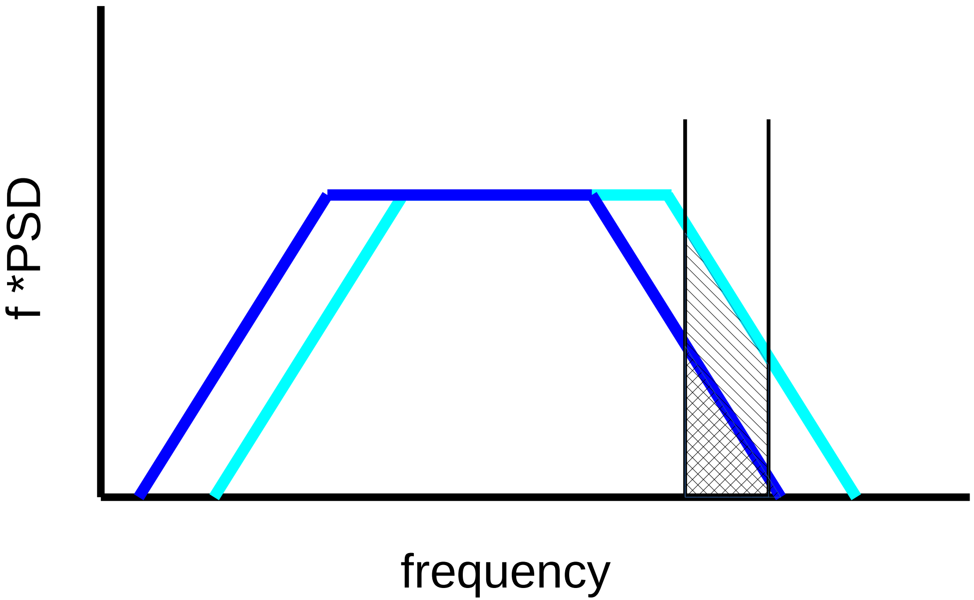
Gierliński et al., 2008, MNRAS, 383, 741

The variance method

The amplitude of variability – the integral of PSD over the marked frequency range – scales with BH mass.

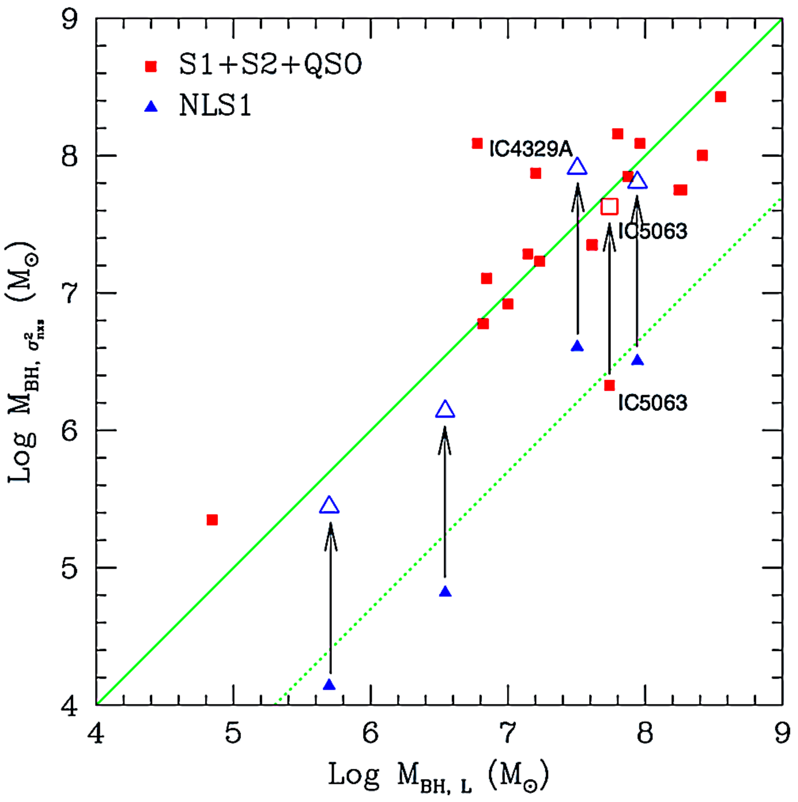
Need to assume:

- Universal shape of power spectrum
- The same frequency range for all sources
- In practice: use σ from lightcurve rather than integrate PSD



The variance method

Using the variance method vs. other methods



M. Nikolajuk et al., 2004, MNRAS, 350, L26