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

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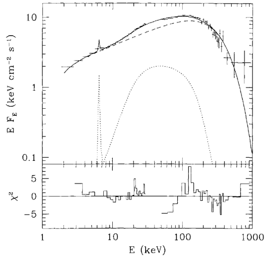
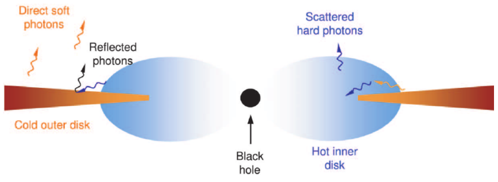
Lecture 5

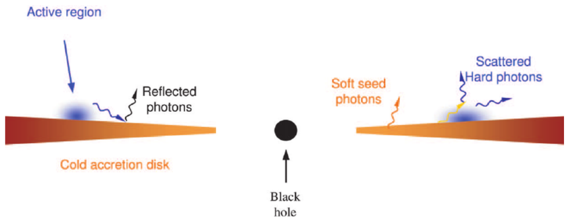
PhD lecture series, 2025, fall semester

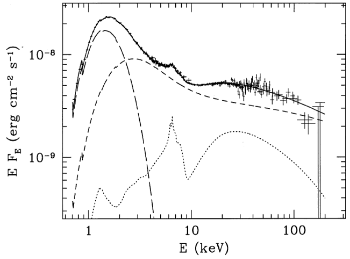
Previous lecture

State transitions

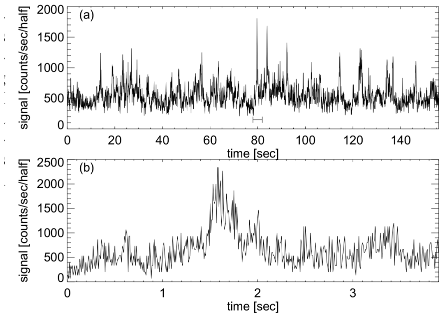


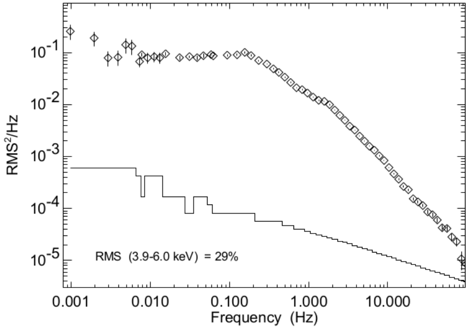


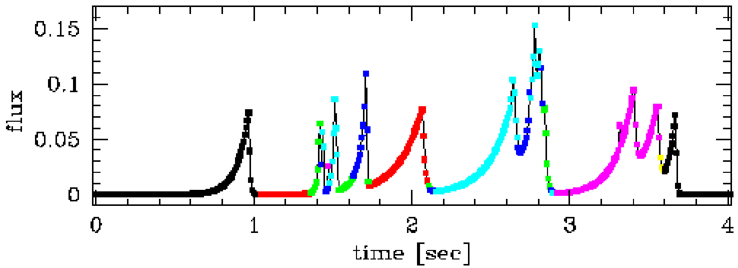




X-ray variability

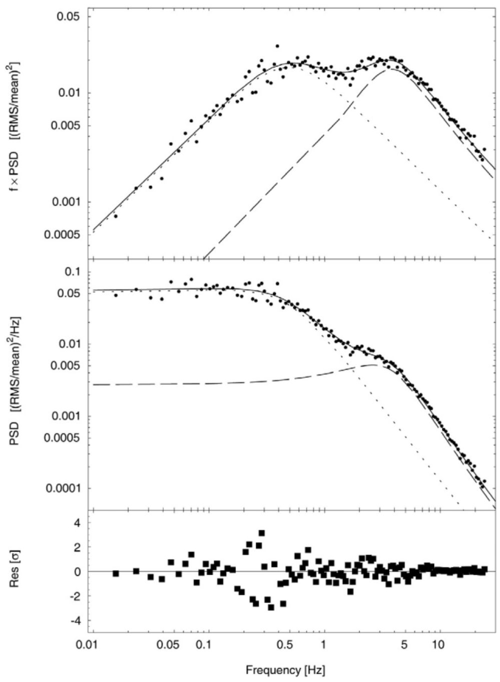


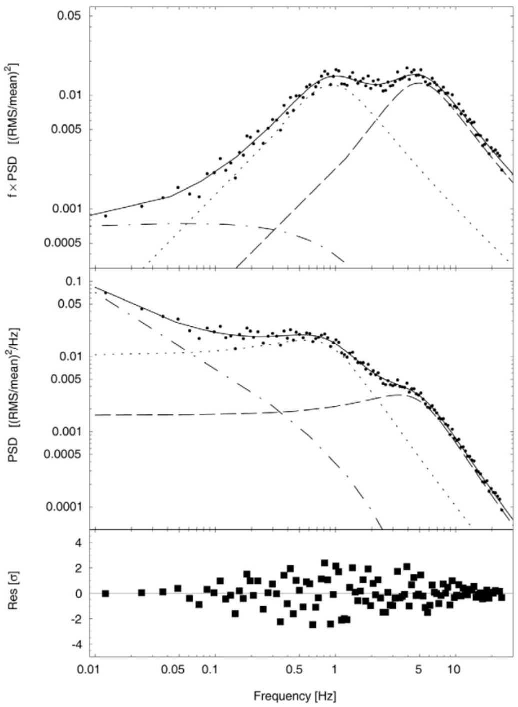




A different description of the PDS

Lorentzian function





$$L(f) = \frac{H\,W\,\nu_i}{(f-\nu_i)^2 + f\,W\,\nu_i}$$

Power law with a cutoff

$$P(f) = A\,f^{-\alpha}\ \mathrm{e}^{-f/f_c}$$

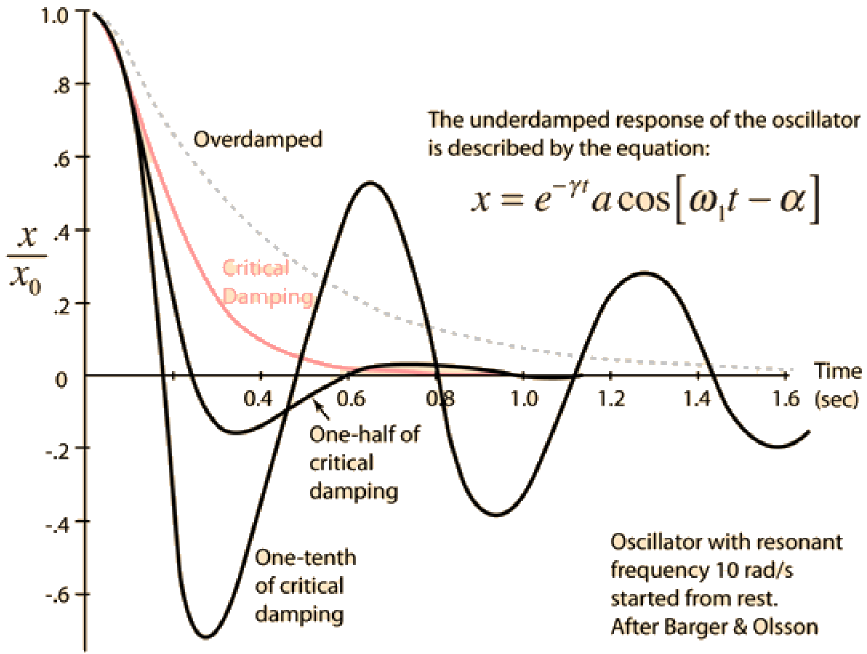
Similar to decomposition of energy spectra into components

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

Lorentzian description of the PDS

Lorentzian function describes power spectrum of a **damped harmonic oscillator**

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



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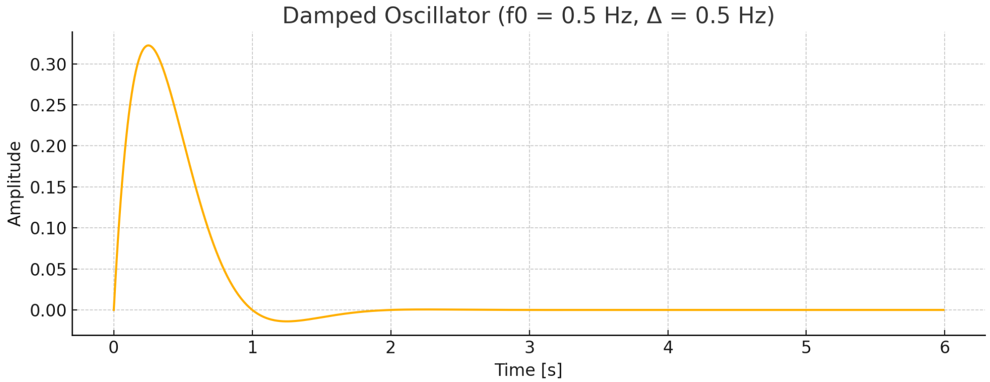
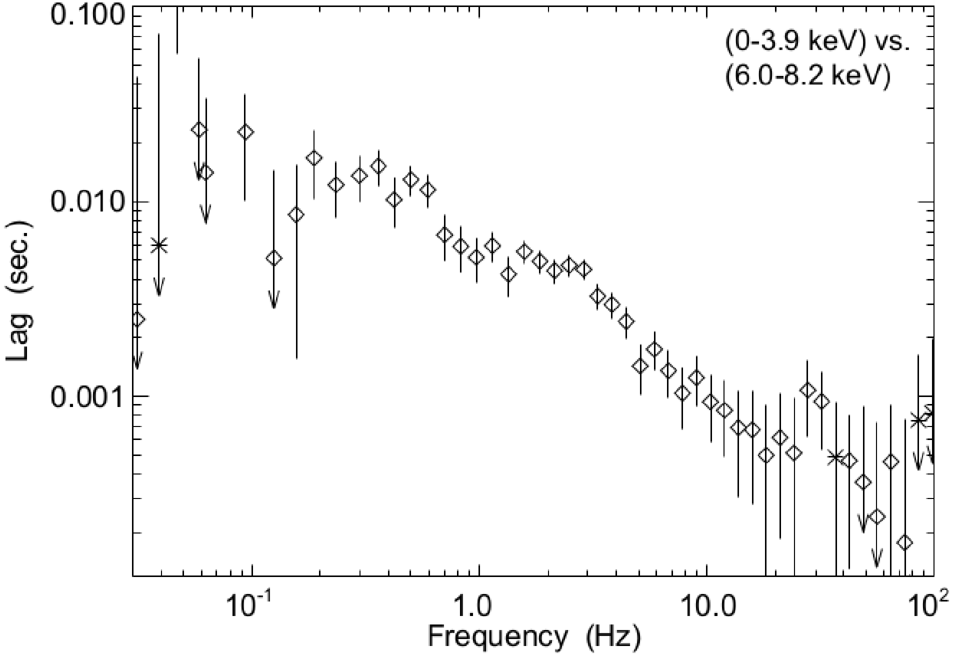


Flares have a different shape than in previous model, but the physical processes are just as mysterious.

The case of broad band noise – time lags

Observations: Cyg X-1



$$\phi(f) = \arg[C(f)] = \arg[\hat{S}(f) H(f)]$$

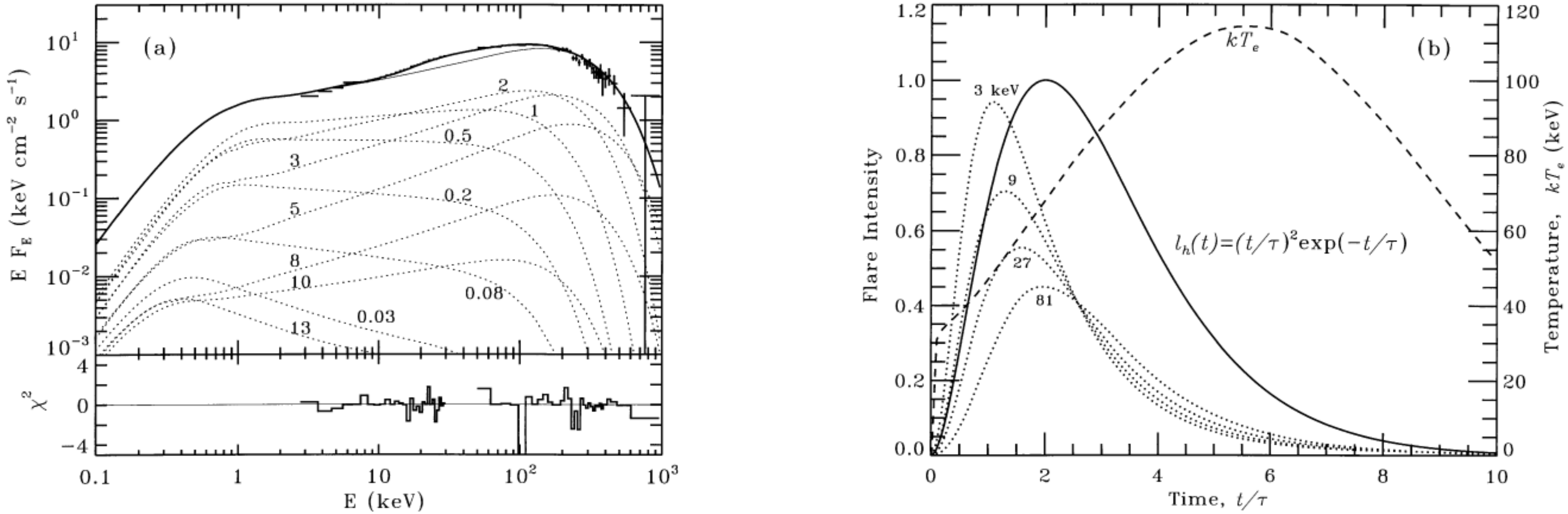
$$\tau(f) = \frac{\phi(f)}{2\pi f}$$

$$\tau \times c = 0.01\,\mathrm{s} \times 3 \times 10^{10}\,\mathrm{cm/s} =$$
$$= 3 \times 10^{8}\,\mathrm{cm} = \mathbf{200}\,\boldsymbol{R_g}(10\,M_{\mathrm{SUN}}/M)$$

M. Nowak et al., 1999, ApJ, 510, 874

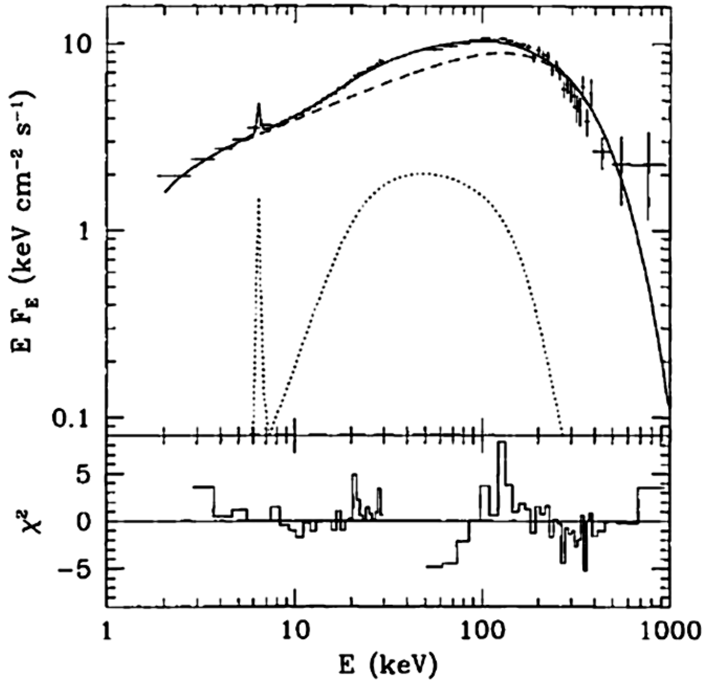
Time lags in the flare model

Spectral evolution!



Poutanen & Fabian, 1999, MNRAS, 306, L31

Back to energy spectra – correlations between parameters



Long observation → sequence of spectra → set of pairs of parameters, e.g.

(spectral slope, amplitude of reflection)
(Γ, R)

or

data for a number of sources

Ergodic theorem?

Back to energy spectra – correlations between parameters

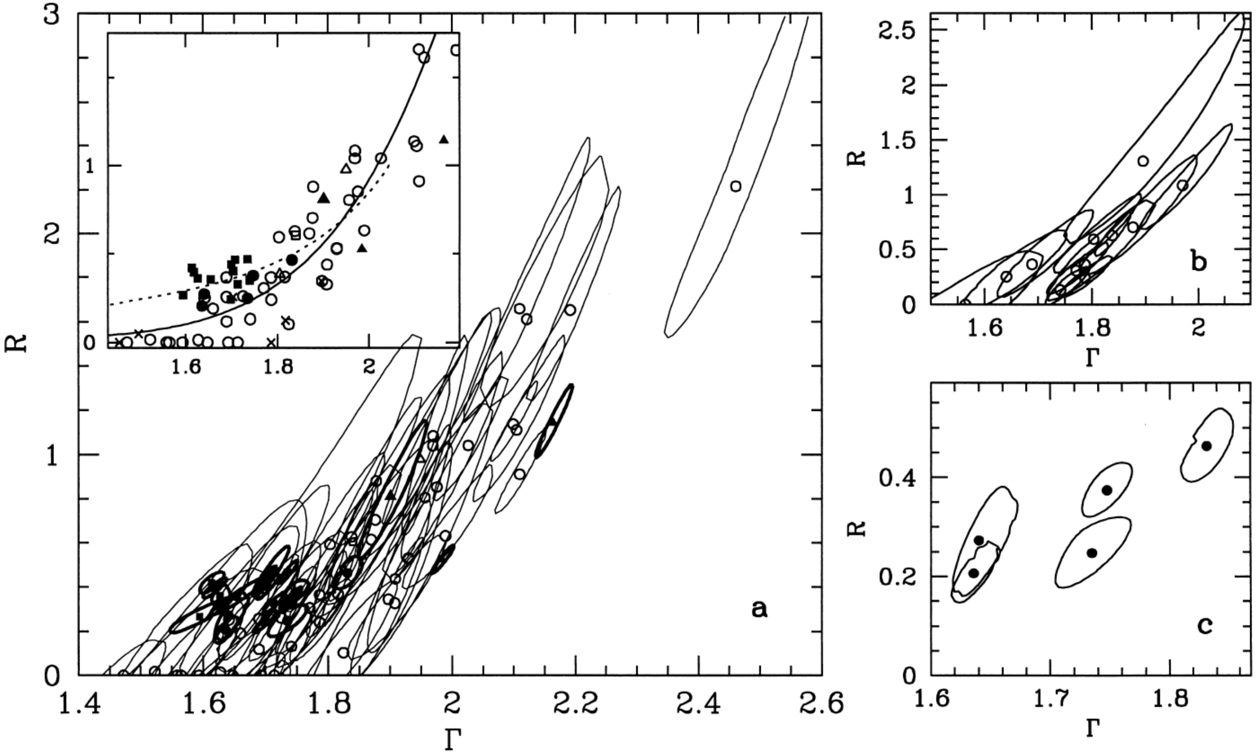
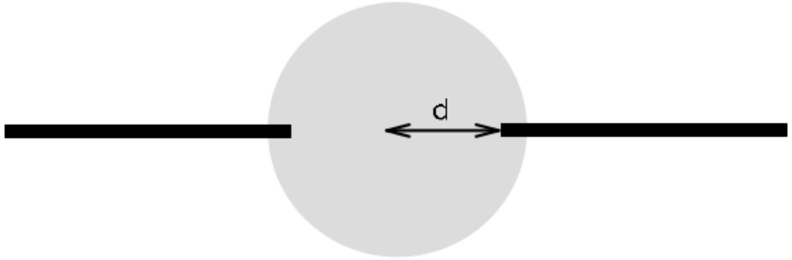


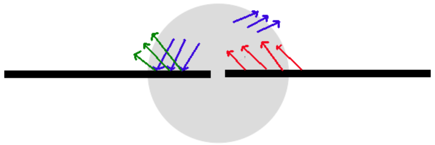
Figure 1. The $R(\Gamma)$ correlation in Seyferts and X-ray binaries in the hard state. Panel (a) shows the data and models (curves in the inset); see Sections 2 and 4, respectively. Examples of the correlation for NGC 5548 and GX 339-4 are shown in panels (b) and (c) respectively.

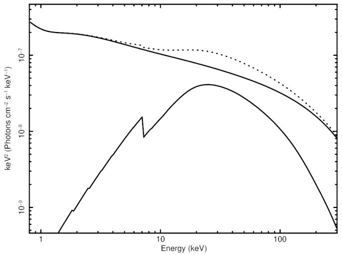
A. Zdziarski, P. Lubiński, D. Smith

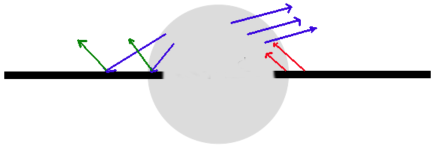
Correlations between parameters – interpretation

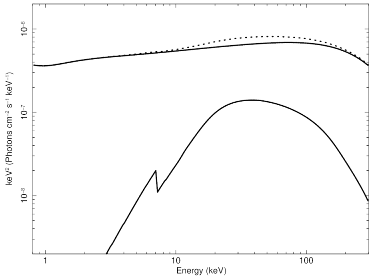
Hot accretion flow model











d – controls the amount of overlap between the disk and the corona

Small d – large overlap: stronger soft flux, softer spectrum, larger reflection amplitude
Large d – small overlap: weaker soft flux, harder spectrum, smaller reflection amplitude

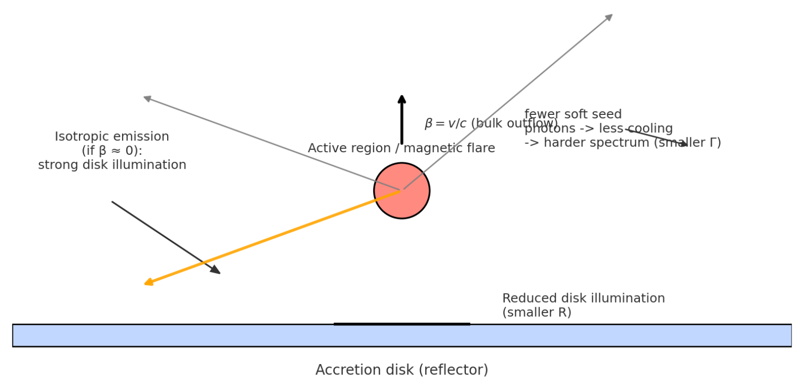
It's a smooth transition between the hard and soft states discussed earlier

A. Zdziarski, P. Lubiński, D. Smith, 1999, MNRAS, 303, L11

Alternative explanation

Outflow model

Schematic: Outflowing active region (Beloborodov 1999) — reduced reflection R and harder Γ



*C*ontrol parameter – velocity of outflowing plasma in the active regions

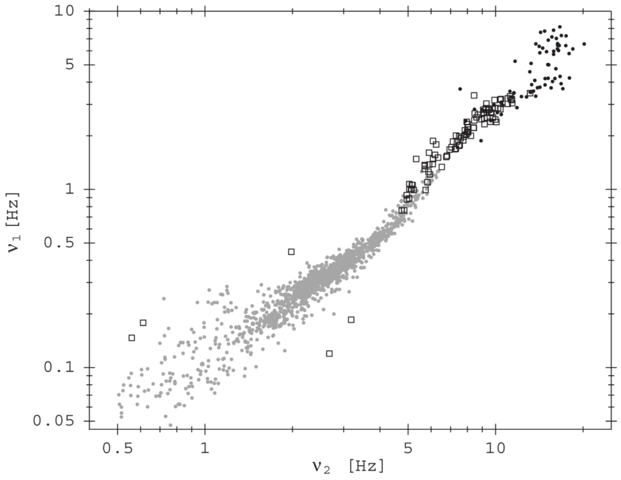
Small *v* – emission close to isotropic: more hard X-rays going towards the disk → stronger soft flux from reprocessing → softer spectrum, larger reflection amplitude
Large *v* – emission focused away from the disk (relativistic beaming) → fewer hard X-rays going towards the disk → weaker soft flux from reprocessing → harder spectrum, smaller reflection amplitude

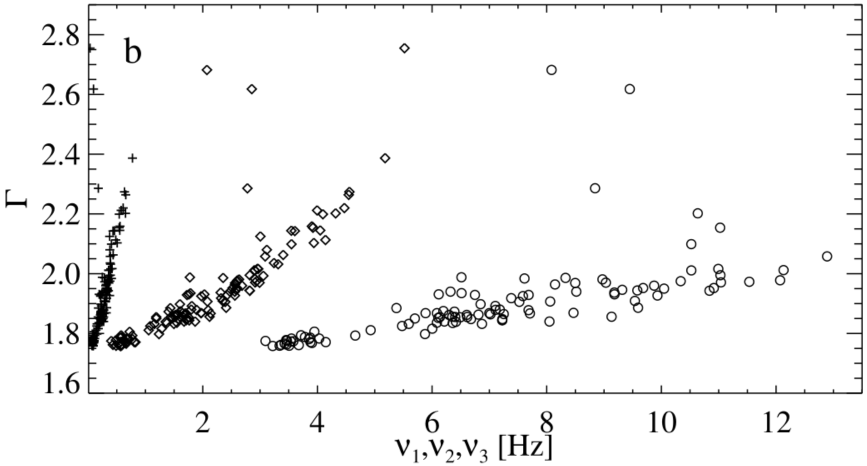
A. Beloborodov, 1999, ApJ, 510, L123

Non-uniqueness of the model

The phenomenological approach put some constraints on possible models but cannot uniquely determine the right model. Need more physical approach, exploring the physical possibilities, simulations, etc

Correlations between spectral and timing parameters



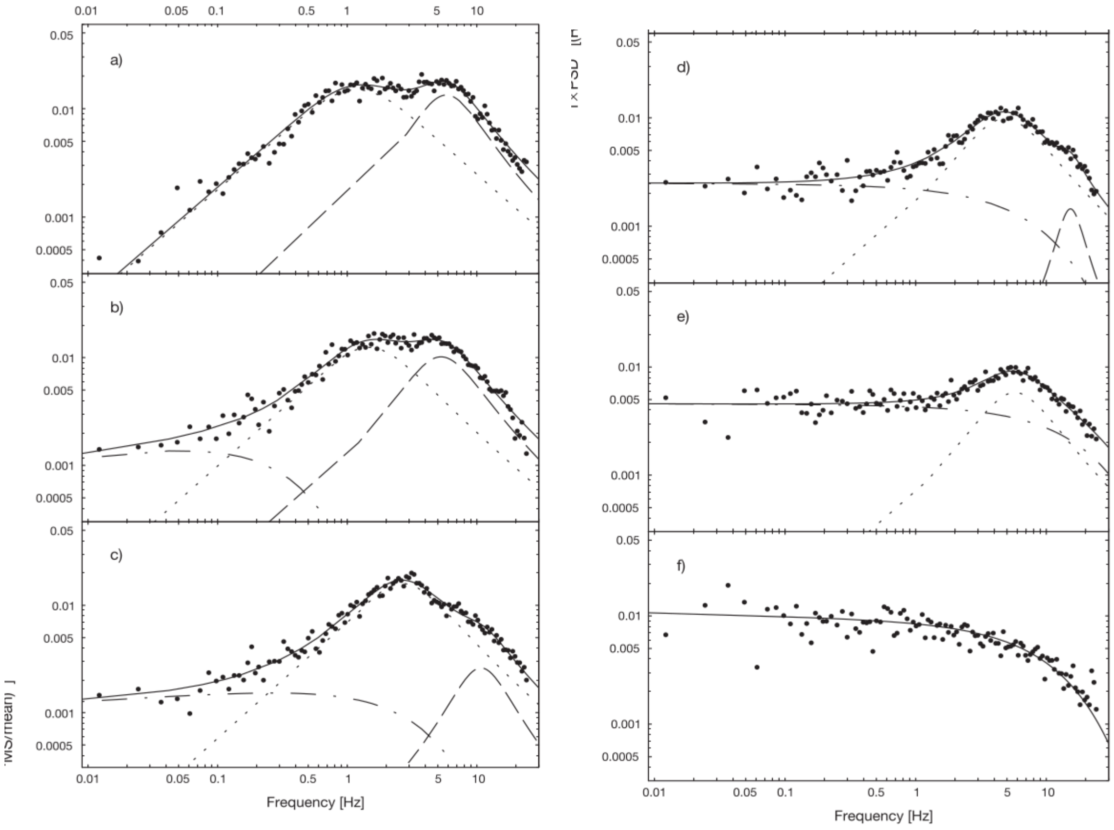


As the spectrum becomes steeper (softer), the characteristic frequencies increase

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

Pottschmidt et al., 2003, A&A, 407, 1039

Sequence of power spectra



Evolution of PDS: from a multiple-Lorentzian to a cutoff power law

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