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

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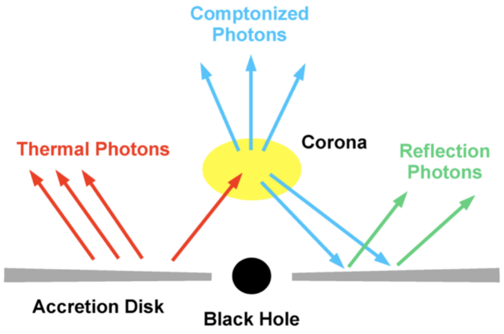
Lecture 4

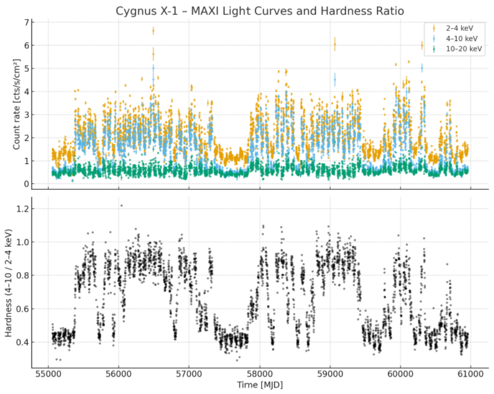
PhD lecture series, 2025, fall semester

Previous lecture

Summary of the radiative processes



Cyg X-1, hard state



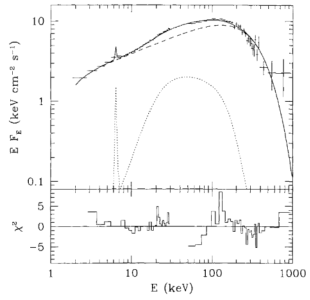
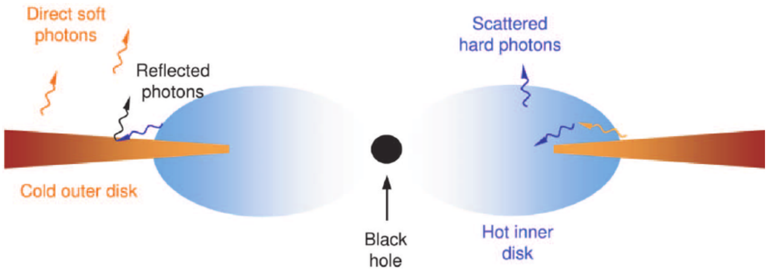


Figure 3. The isotropic one-temperature thermal Comptonization model fitted to the data set 2. The upper panel shows the data (crosses), the thermal Comptonization continuum (dashed curve) and the reflection component (dotted curve). The solid curve shows the sum. This model yields $\chi^2_\nu < 1$, but there is still a systematic residual pattern for the OSSE data (the lower panel).



Heating – cooling balance

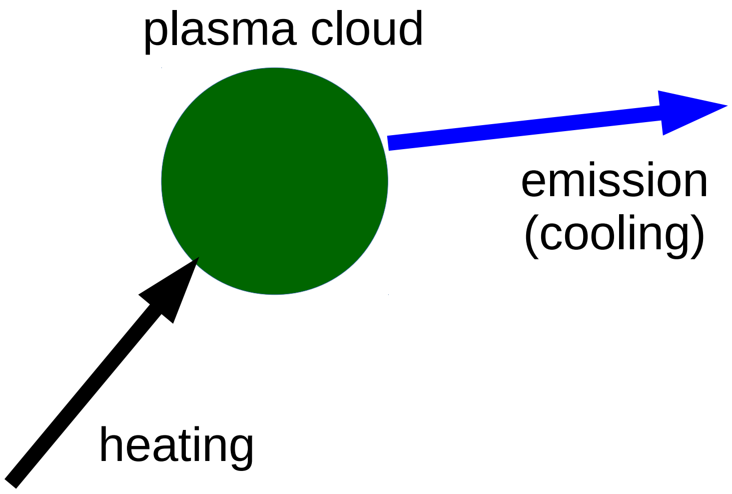
Heating-cooling balance – fundamental concept

Emission from a cloud – cooling ==> need heating process

Example:

a star: heating due to thermonuclear reactions inside – cooling by emission of electromagnetic radiation

a plasma cloud (planetary nebula, BLR cloud): heating by incident radiation (photoionization) – cooling by emission (lines, recomb. continua, etc)



Comptonization – the amplification factor

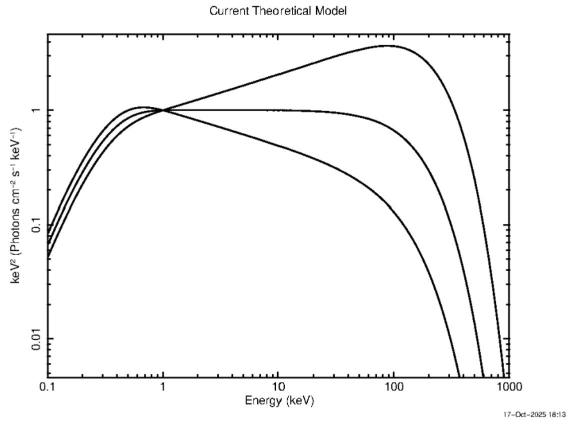
X-ray emitting plasma in accreting sources:

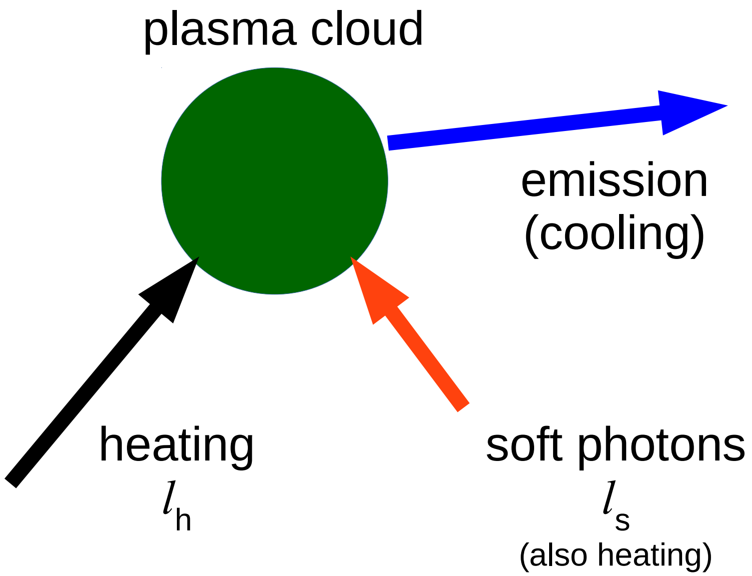
Heating: unspecified form – we simply don't know how it works!

Heating = cooling = $l_h + l_s$

$$\Gamma \approx \frac{7}{3} A^{-1/6}$$

Amplification $A = \frac{l_h}{l_s}$

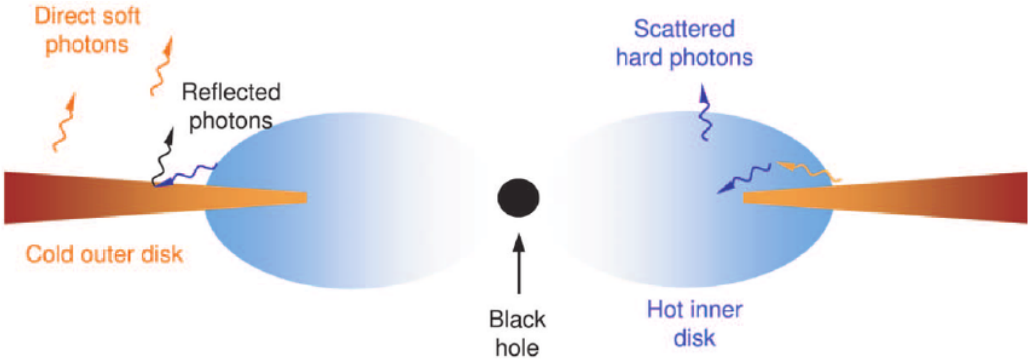




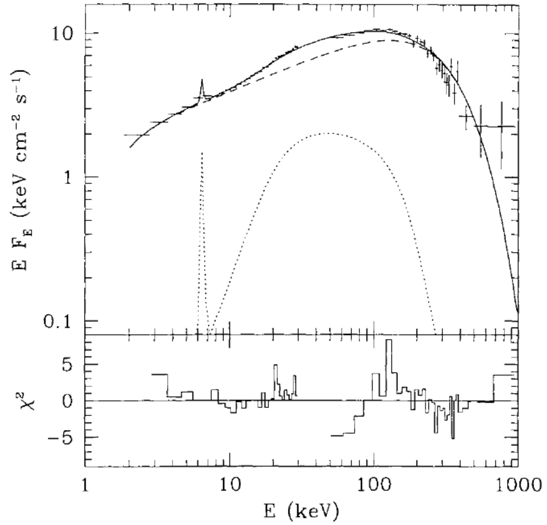
Spectra of Cygnus X-1 in the hard state

„Photon-starved plasma” - cannot be a simple slab disk-corona geometry

Low amplitude of reflection, R=0.3, confirms the above



Inner hot accretion flow model



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 Gierliński et al.

Spectra of Cygnus X-1 in the soft state

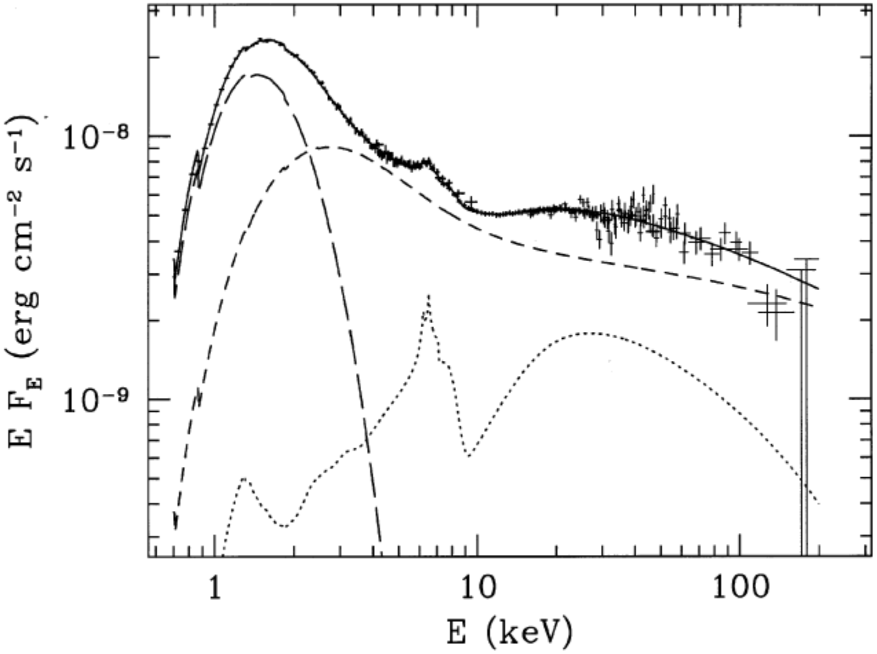


Figure 9. The simultaneous *ASCA* and *RXTE* observation of Cyg X-1 in the soft state on 1996 May 30 (observation No. 3). The short dashes, dots and long dashes show the Comptonization continuum, the component reflected from the cold disc, and the disc emission, respectively. The solid curve shows the sum. The fit parameters are given in Table 2. The Comptonization continuum is dominated by thermal and non-thermal scattering below and above, respectively, ~15 keV, with the resulting spectral break at that energy.

Gierliński et al., 1999, MNRAS, 309, 496

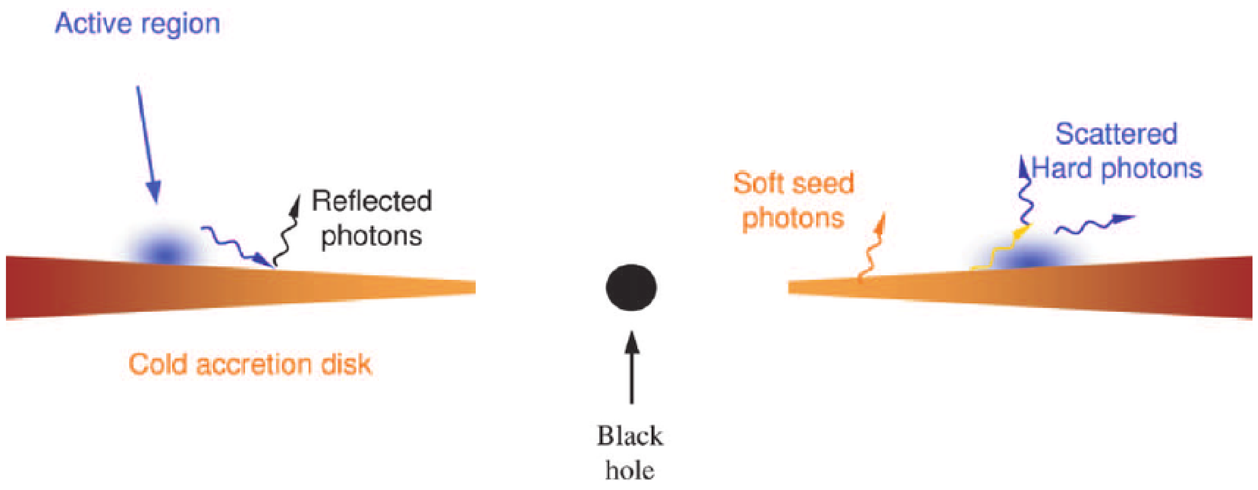
Spectrum dominated by the thermal emission from accretion disk

The Comptonized component is *soft*, and it requires a *hybrid plasma*

Reflected component has larger amplitude than that in hard state

Fe Kα line is broad

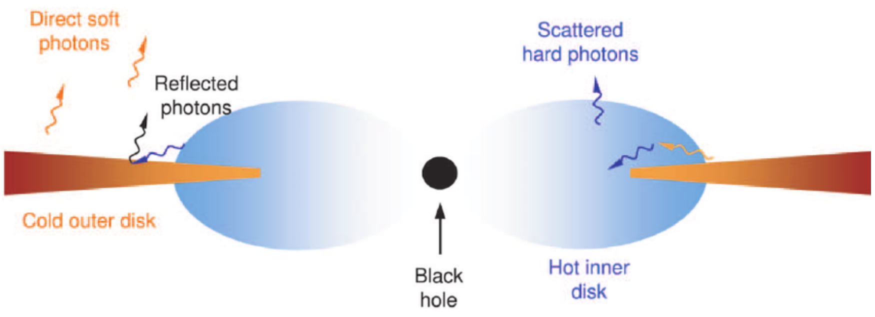
Accretion geometry in the soft state

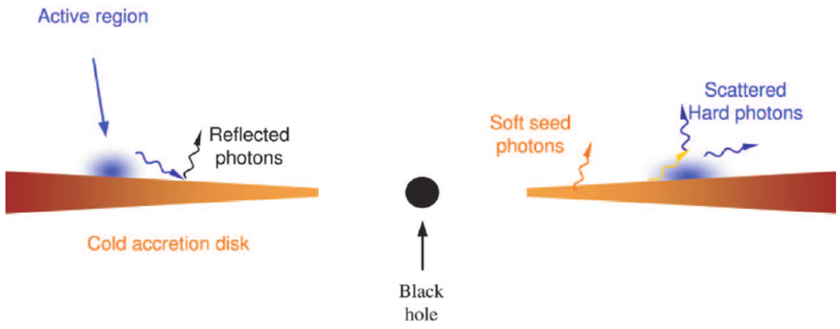


- Spectrum dominated by the thermal emission from accretion disk
- The Comptonized component is *soft*, and it requires a *hybrid plasma*
- Reflected component has larger amplitude than that in hard state
- Fe Kα line is broad

Gierliński et al., 1999, MNRAS, 309, 496

Accretion geometry and physical processes in the hard and soft state

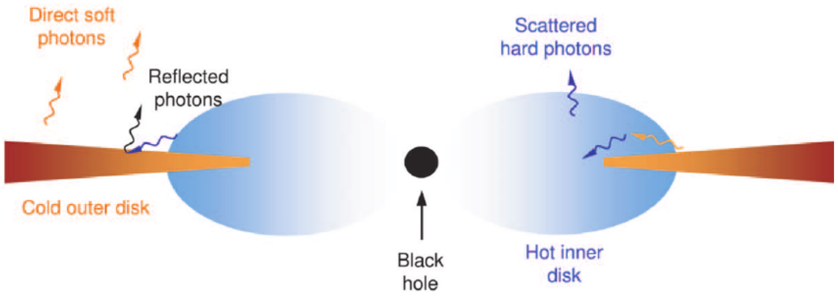


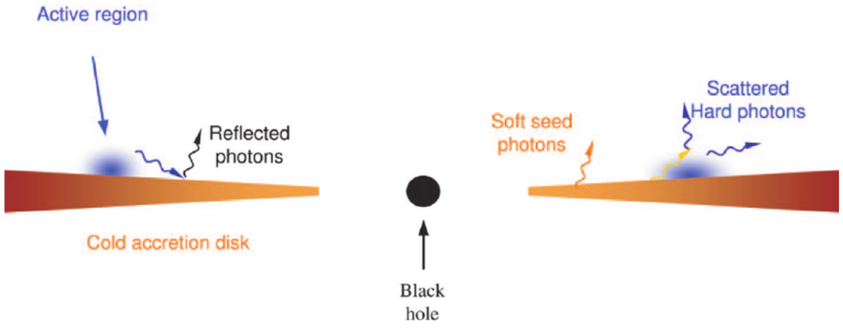


- Hot inner flow, outer standard accretion disk truncated at $r>r_{ISCO}$
- Thermal Comptonization, hard spectra from the hot flow
- Small amplitude of reflection

- Standard accretion disk extending to ISCO
- Active regions producing X-rays, hybrid plasma (conditions not sufficient to thermalization)
- Soft spectra
- Large amplitude of reflection

What is the mechanism of transition between the states?



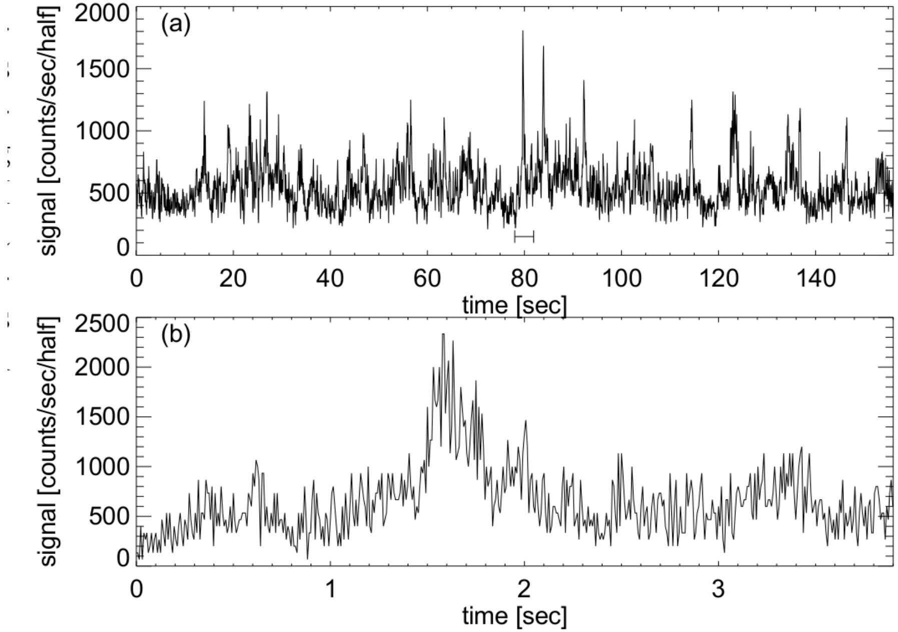


- For Cyg X-1 situation is somewhat ambiguous because the inferred accretion rate in the two states is not very different.

- Observations of so called soft X-ray transient sources clearly indicate that at lower $\dot{m}$ the spectra are hard, while at high $\dot{m}$ spectra are soft.

X-ray variability

Cyg X-1



K. Pottschmidt et al., 1998, A&A, 334, 201

- X-ray variability of XRB/AGN looks random/chaotic
- Mathematically speaking, random and chaotic are not the same (possible subject for a presentation)
- Side note: the time scale will scale linearly with the mass of the black hole
- How do we analyze the variability? What can we learn from it?

Power density spectrum (PDS)

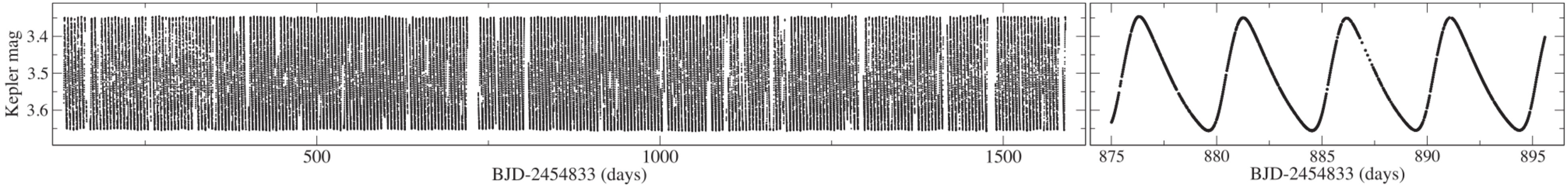
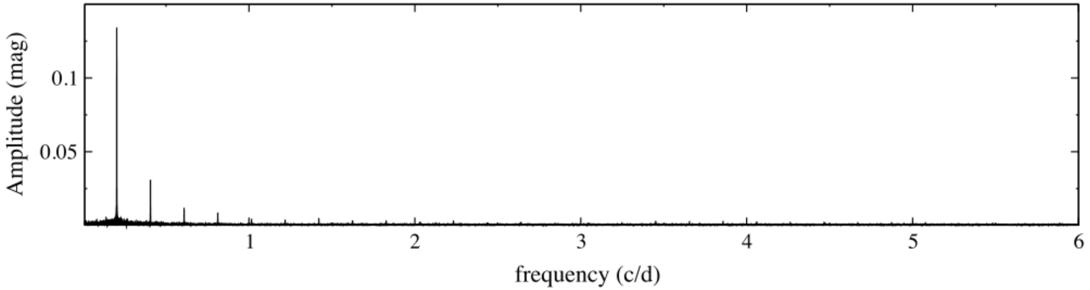
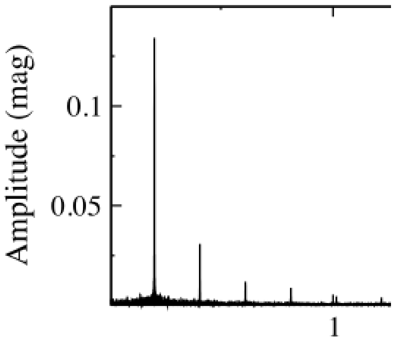


Figure 1. Left panel: detrended LC *Kepler* observations of V1154 Cyg. Right panel: zoom in four cycles of LC data.

PDS → Square of the Fourier transform $P(f) = |F(f)|^2$



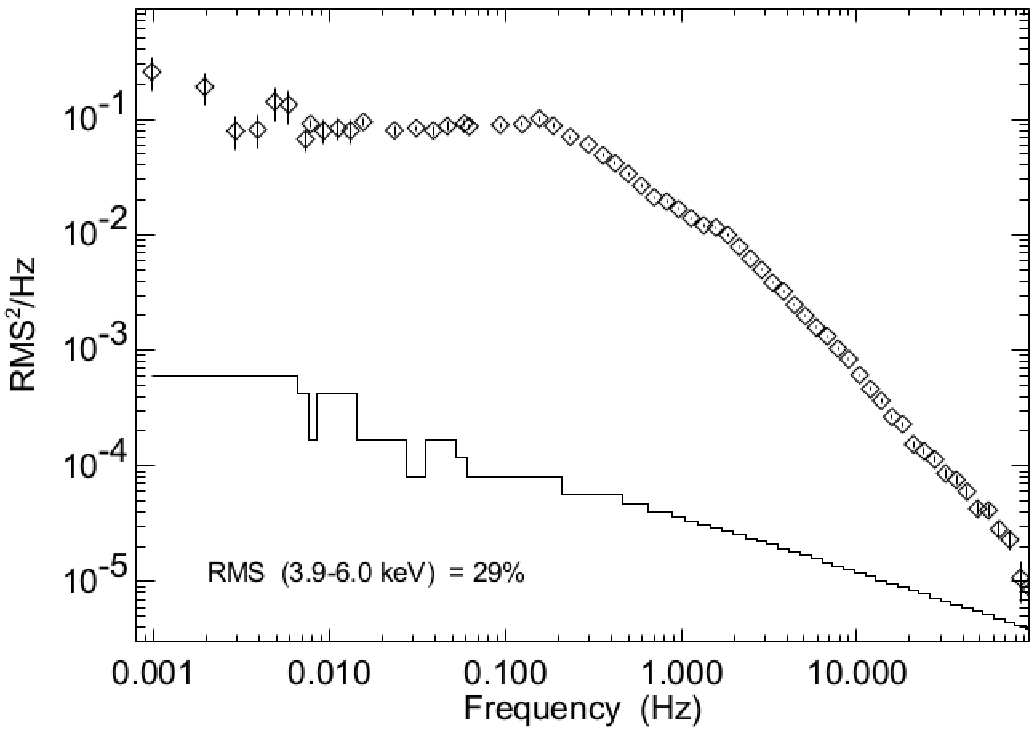


Observables: set of frequencies and the amplitude of PDS at these frequencies

Derkas et al., 2017, MNRAS 464, 1553

PDS for an X-ray light curve from X-ray binary – **broad band noise**

Cyg X-1



Slope: 0 for $f < 0.1$ Hz,
-1 for $0.1 < f < 1$ Hz
-2 for $f > 1$ Hz

So, observables:

Values of the slope exponent and the break frequencies

Minimum and maximum frequency related to the length of observation and the time bin.

M. Nowak et al., 2019, ApJ, 520, 874

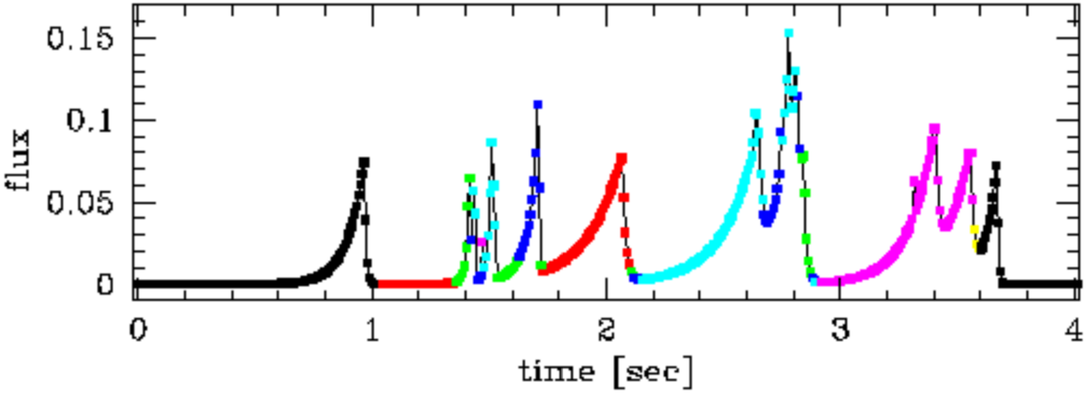
PDS – what do we learn from it?

- In analogy to the energy spectra, the theory should predict the variability, so a comparison of theory and data should tell us something about the “reality” (or actually about the *model* we use)

- For a periodic signal (not necessarily sinusoidal) the domain of PDS is a set of discrete frequencies. For example, for a light curve of a pulsating star we hope that the theory of pulsations will predict the frequencies and the power of variability at these frequencies. These may depend on, e.g., chemical abundances, so the estimation of the abundances may be possible from variability.

The case of broad band noise – PDS

- We imagine that the **X-rays are emitted in the form of flares** – short emission events.
- The form of PDS imply that flares are correlated
- Avalanches of flares

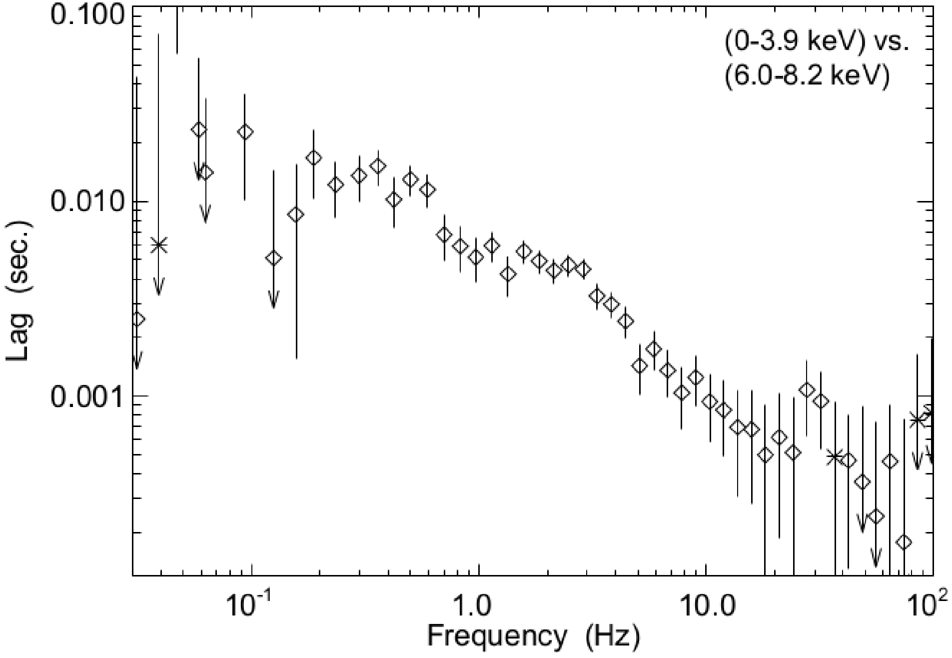


Parameters: probability of stimulating a ‘baby’ flare and it’s time delay

Poutanen & Fabian, 1999, MNRAS, 306, L31

The case of broad band noise – time lags

Observations: Cyg X-1



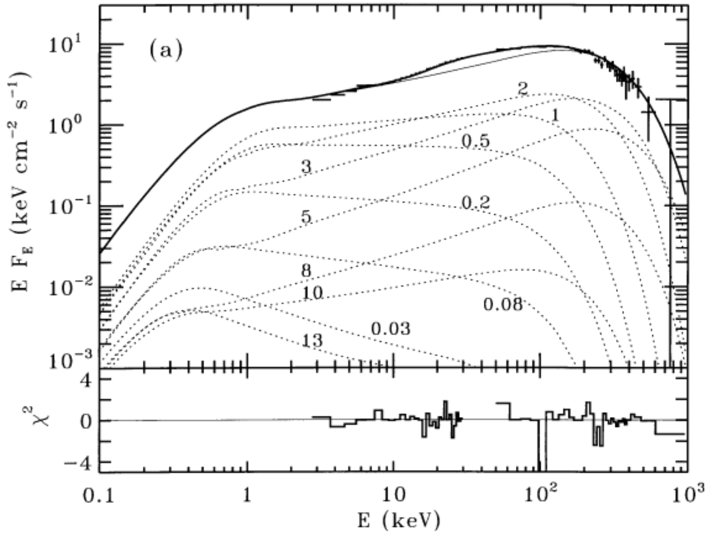
$$\phi(f) = \arg[C(f)] = \arg[\hat{S}(f) H(f)]$$

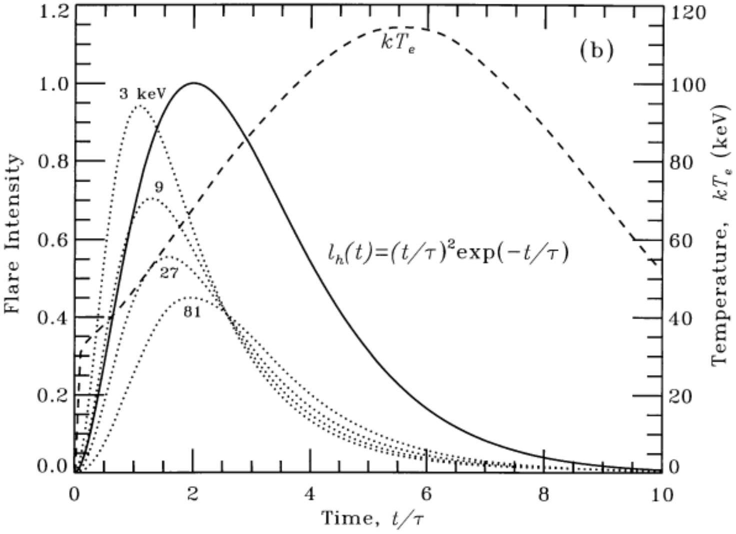
$$\tau(f) = \frac{\phi(f)}{2\pi f}$$

M. Nowak et al., 2019, ApJ, 520, 874

Time lags in the flare avalanche model

Spectral evolution!





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