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

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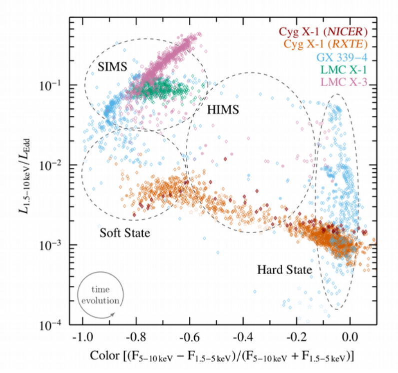
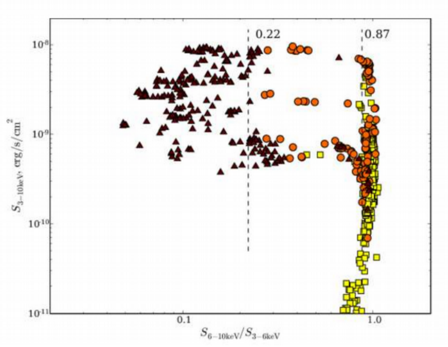
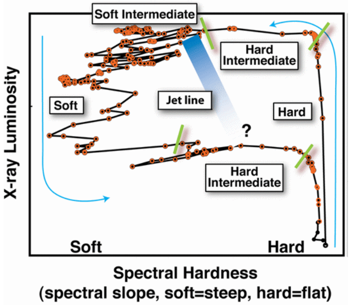
PhD lecture series, 2025, fall semester

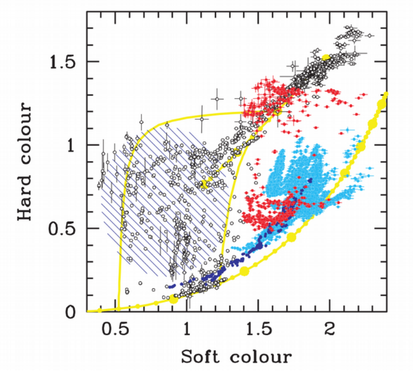
Previous lecture

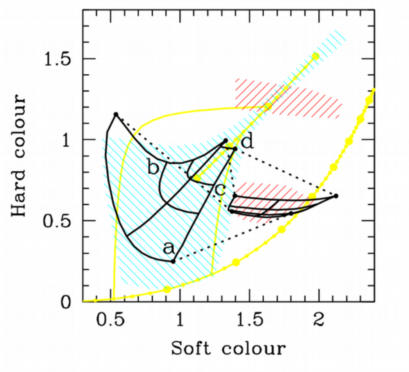
Color-color and color-intensity (HID) diagrams

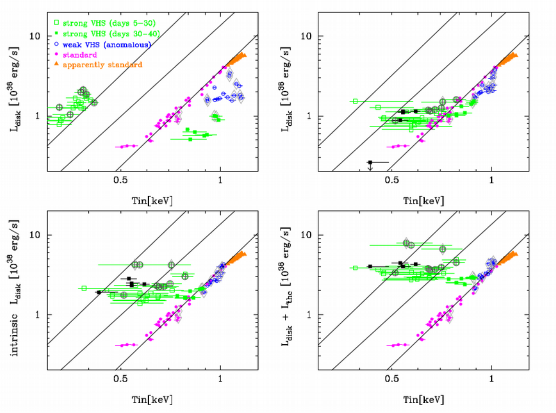




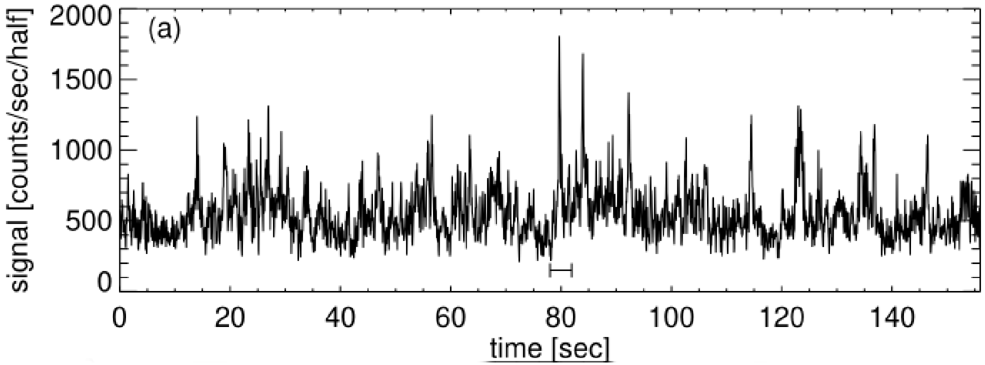








More on X-ray variability



rms = 20-30%

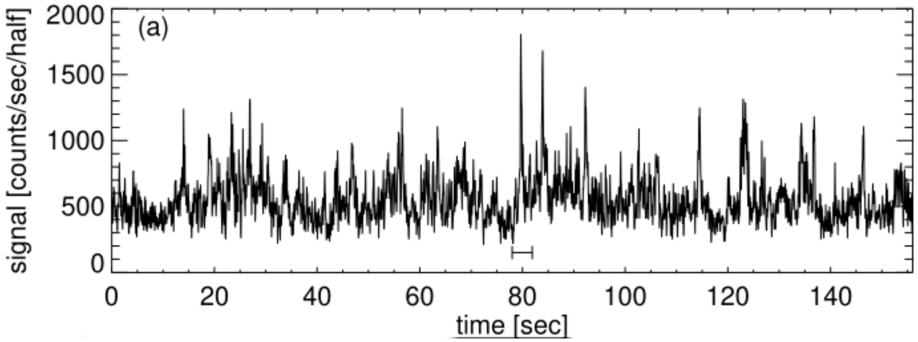
mean value $x_m = \frac{1}{N} \sum_i^N x_i$

std error $\sigma^2 = \frac{1}{N} \sum_i^N (x_i - x_m)^2$

std deviation $\sigma = \sqrt{\sigma^2} = \sqrt{\frac{1}{N} \sum_i^N (x_i - x_m)^2}$

root mean square $\mathrm{rms} = \frac{\sigma}{x_m} = \frac{1}{x_m} \sqrt{\frac{1}{N} \sum_i^N (x_i - x_m)^2}$

More on X-ray variability



rms = 20-30%

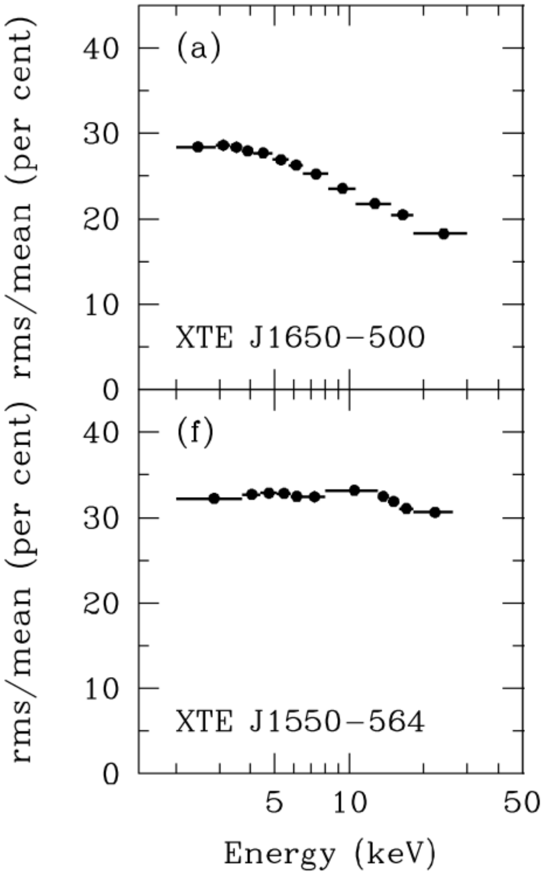
For a small number of events their distribution is given by a Poisson distribution

$$P(n)=\frac{e^{-\lambda}\lambda^n}{n!}, \quad \text{where } \lambda = \text{mean value}$$

The dispersion of the Poisson distribution = it's mean. If e.g. mean=10, then dispersion approx 3 $\rightarrow$ 30%

Note: the variability is not symmetric around the mean value!

Dependence of variability on energy

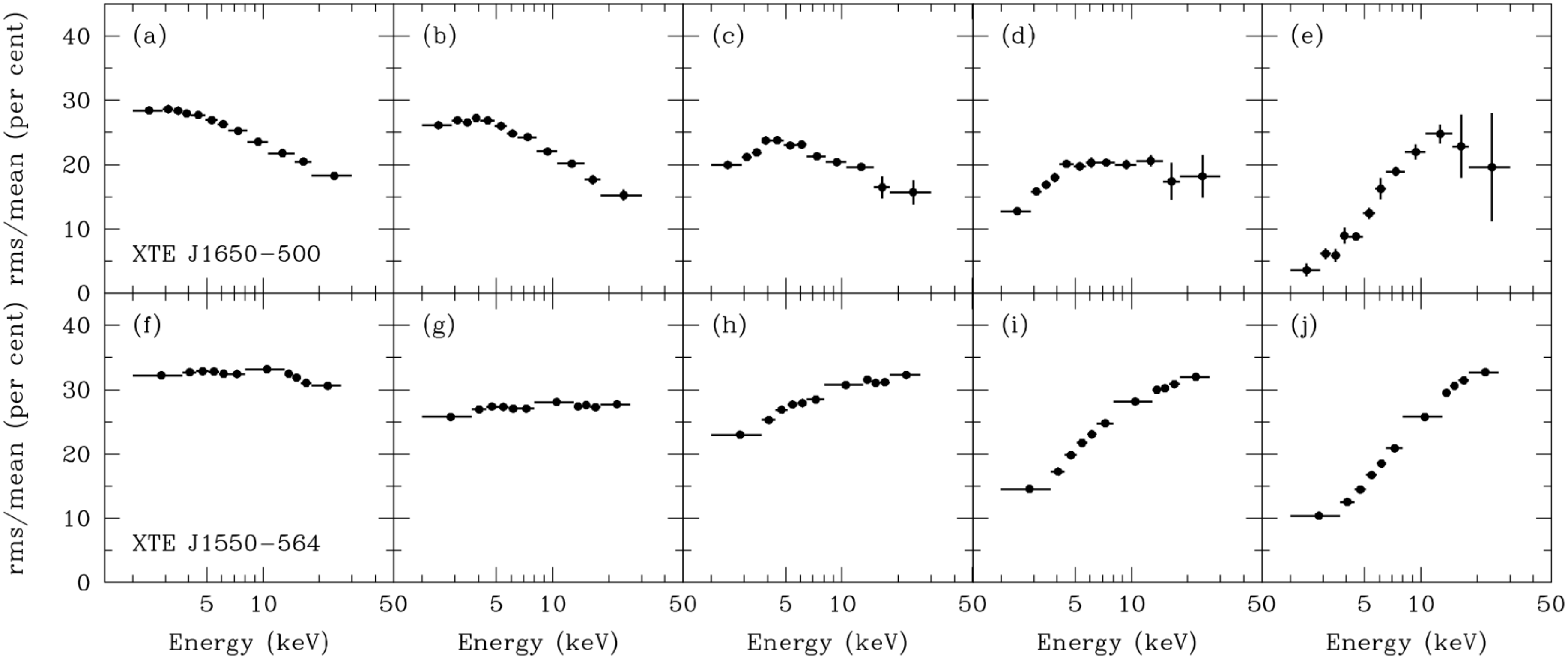


Hard state

Time bin = 1/256 sec; duration = 512 sec

Gierliński & Zdziarski 2005, MNRAS, 363, 1349

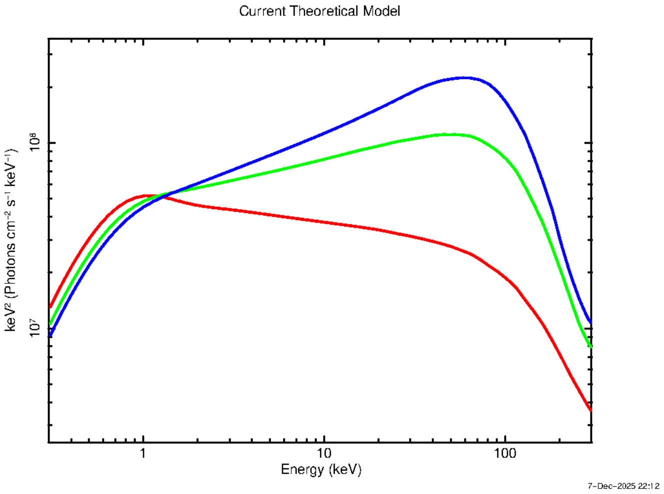
Dependence of variability on energy

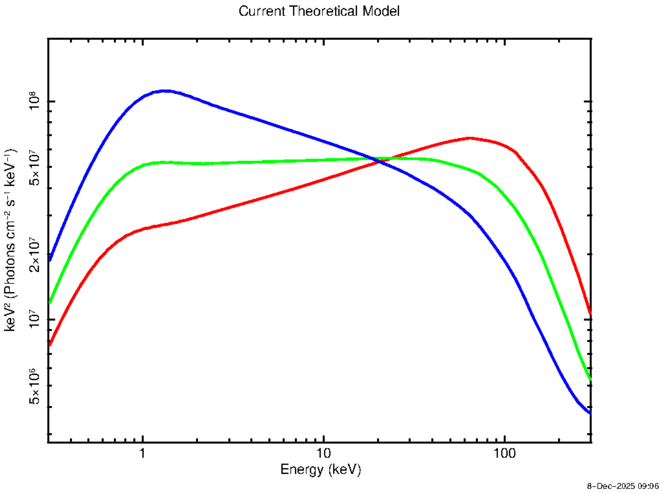


Gierliński & Zdziarski 2005, MNRAS, 363, 1349

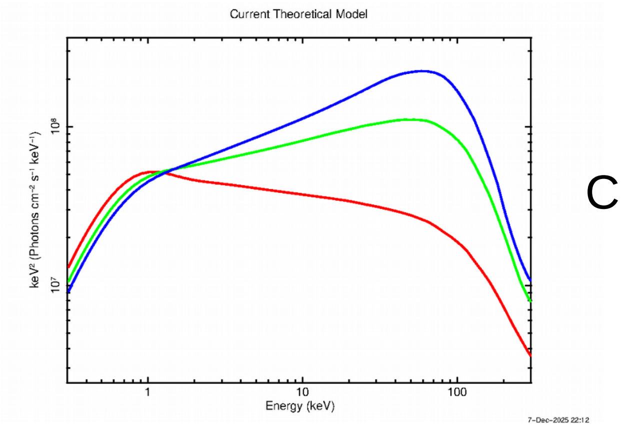
How to understand rms(E)

Changing luminosity together with a change of the spectrum

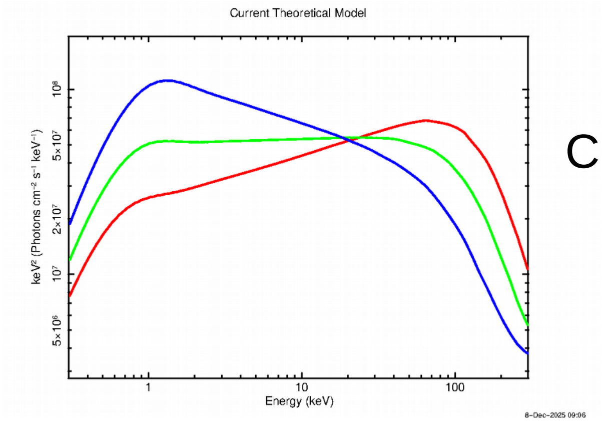




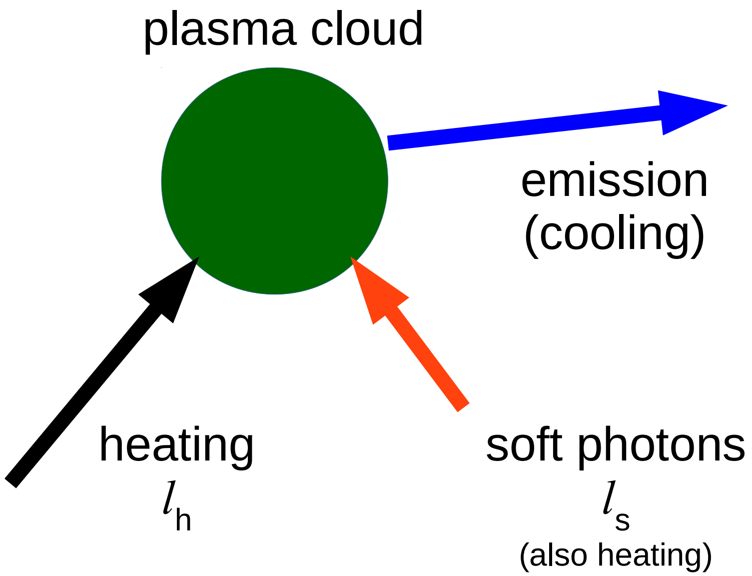
Spectral variability in Comptonized plasma



Changing l_h



Changing l_s



XTE J1650-500 – hard state

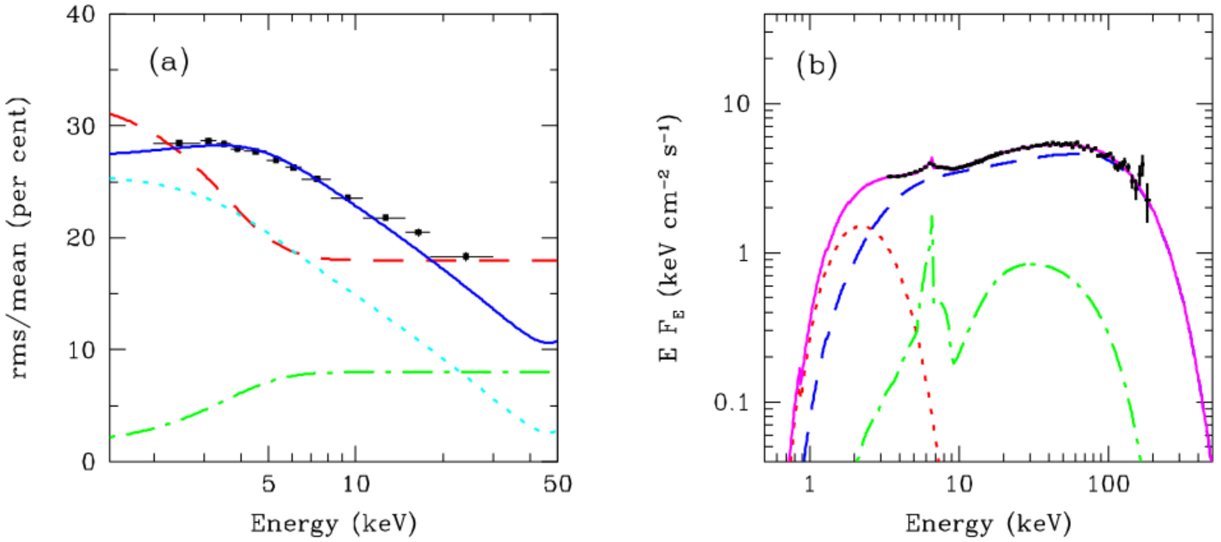
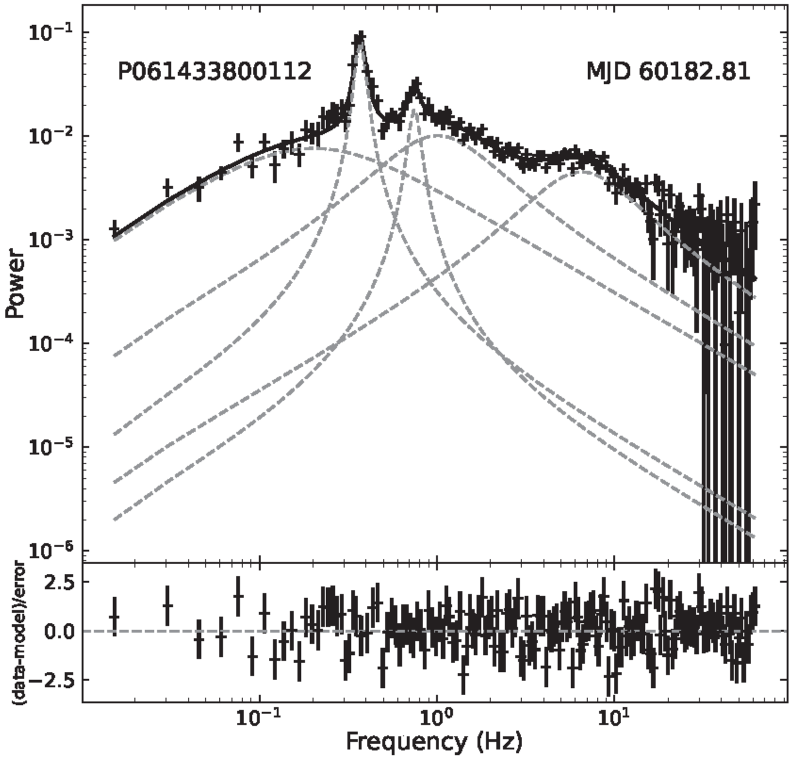


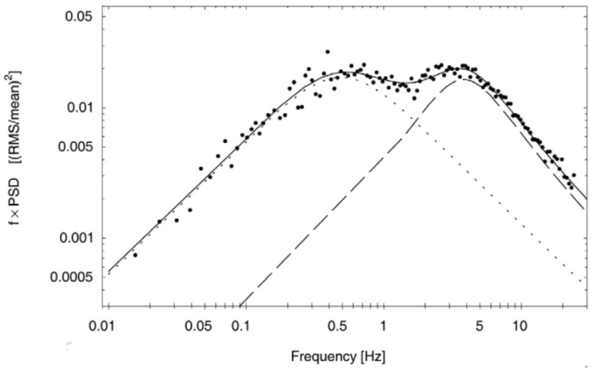
Figure 1. (a) Hard-state (obsid 60113-01-04-00) rms spectrum of XTE J1650–500 observed by *RXTE*. The dashed curve (red in the colour version of the figure online) represents the two-component variability model, with $r(N_s) = 0.36$ and $r(N_h) = 0.18$, clearly not consistent with the data. The solid (blue in colour) curve shows the model with varying soft photon input (dotted curve, cyan in colour) at $r(\ell_s) = 0.25$ plus an additional hard component normalization variability (dash–dotted curve, green in colour) with $r(N_h) = 0.08$. (b) Energy spectrum of the same observation, with the unfolded PCA and HEXTE data together with the best-fitting model. The model consists of the following components: the soft component modelled by DISKBB (dotted curve, red in colour, showing unscattered seed photons only), its Comptonization in thermal plasma (dashed curve, blue in colour) and reflection (dash–dotted curve, green in colour). The solid curve (magenta in colour) shows their sum.

Gierliński & Zdziarski 2005, MNRAS, 363, 1349

Quasi-periodic oscillations



vs



Yi Wen et al., 2005

Quasi-periodic oscillations in AGN

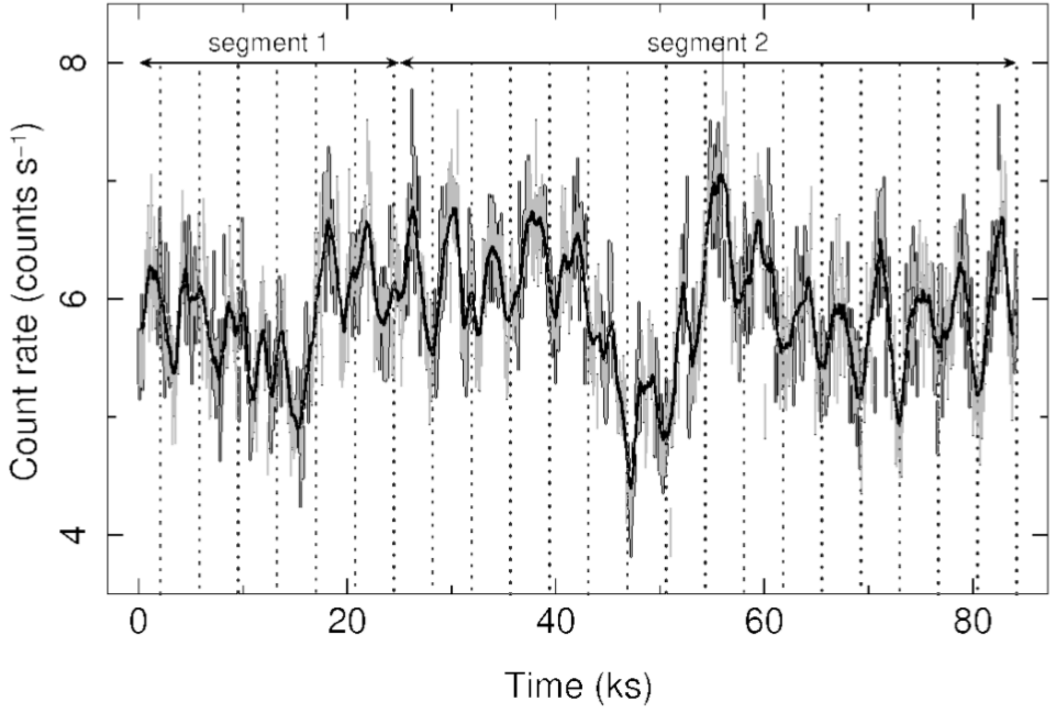


Figure 1 | XMM-Newton light curve of RE J1034+396.

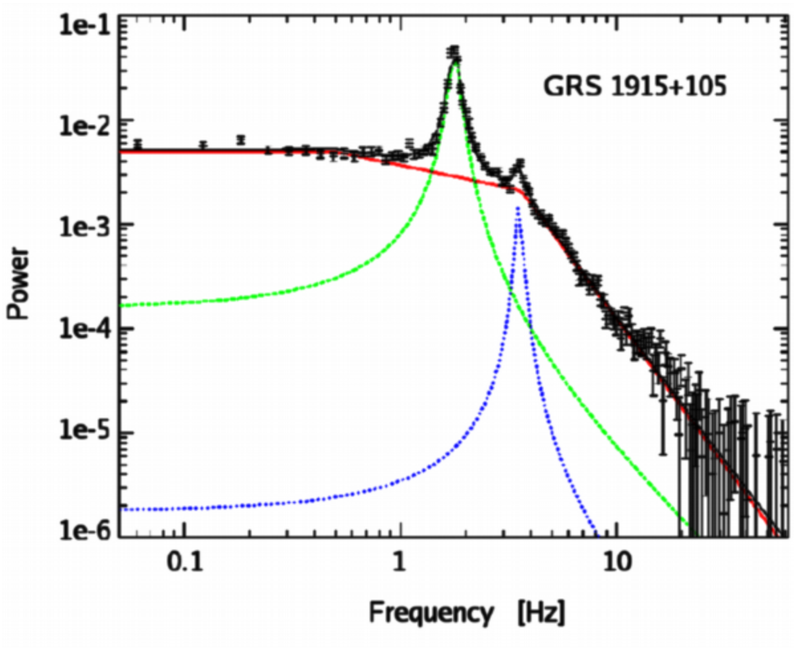
Gierlinski et al., 2008, Nature, 455, 369

The mechanism of quasi-periodic oscillations

Some kind of disk oscillations, vertical or radial (diskoseismology)
(Robert Wagoner et al., 1990-ies – early 2000)

If so, then it would be the disk emission that would be oscillating

Energy spectra of Quasi-periodic oscillations

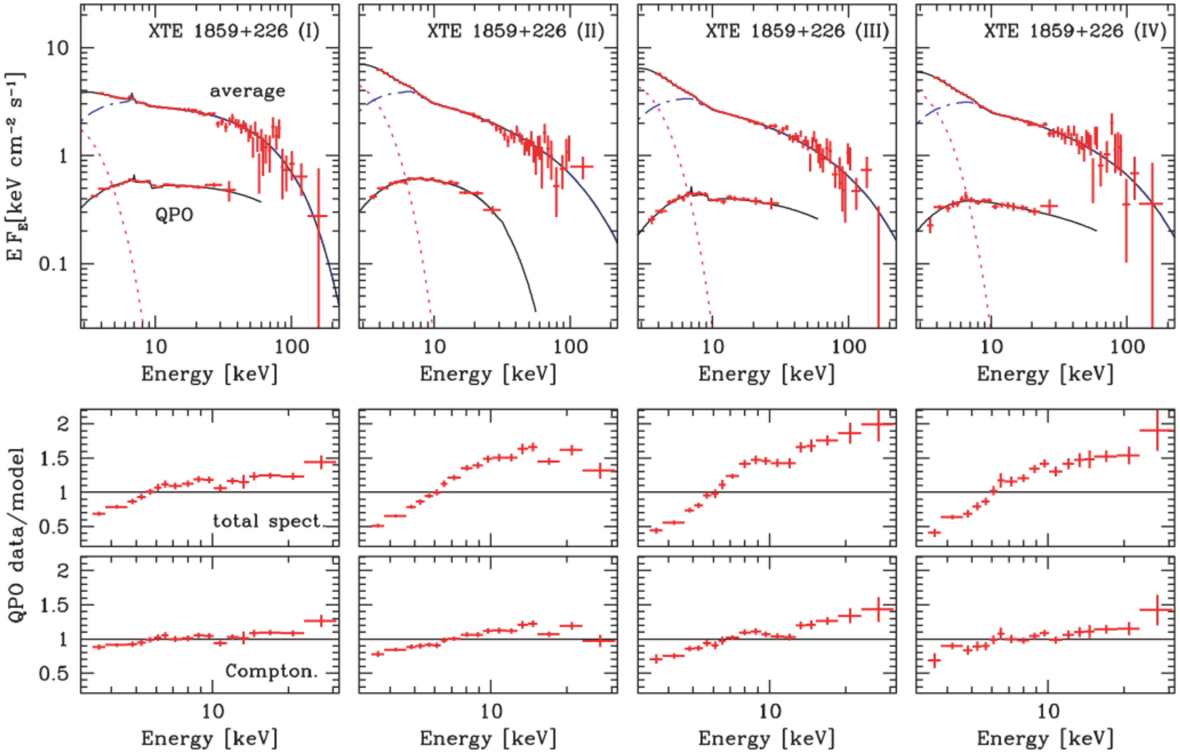


Model the power spectrum: power law or a sum of Lorentz functions for the continuum, and a Lorentzian for the QPO, **as a function of energy**.

Integrate the QPO Lorentzian over frequency to obtain its total variability amplitude.

$\sigma(E) = x_m * \mathrm{rms}(E)$ - QPO energy spectrum

What oscillates in QPO?



Sobolewska & Życki, 2006, MNRAS, 370, 405

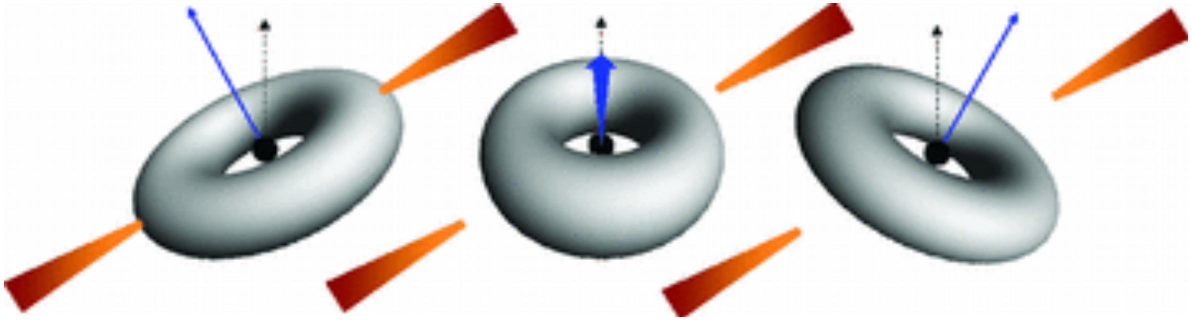
What oscillates in QPO?

It is the **hard X-rays** that oscillate in QPO in X-ray binaries.

The disk emission does not participate in these oscillations.

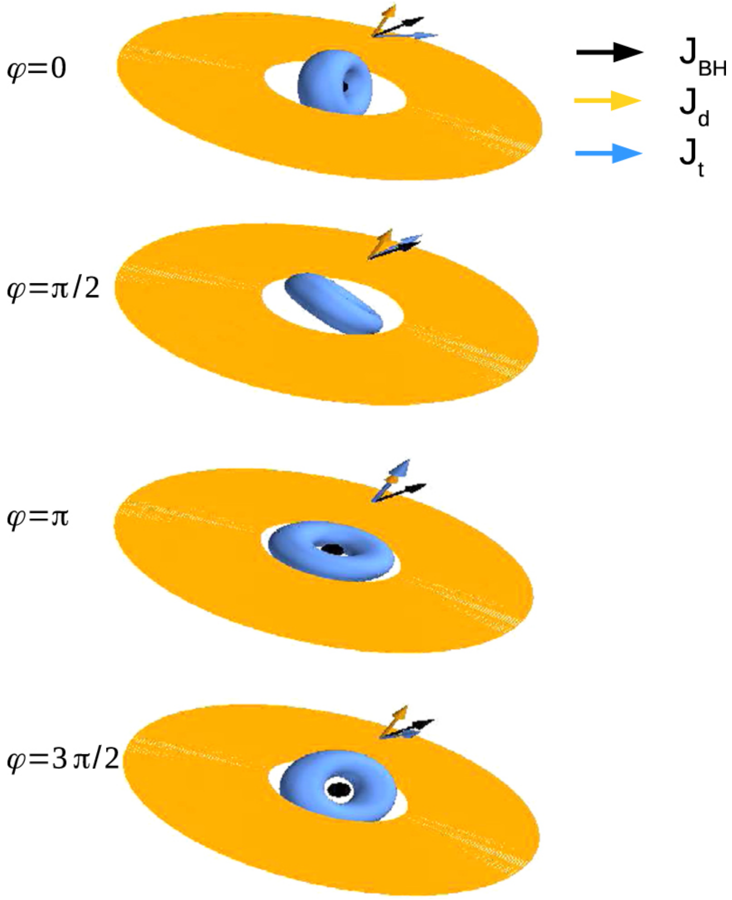
Sobolewska & Życki, 2006, MNRAS, 370, 405

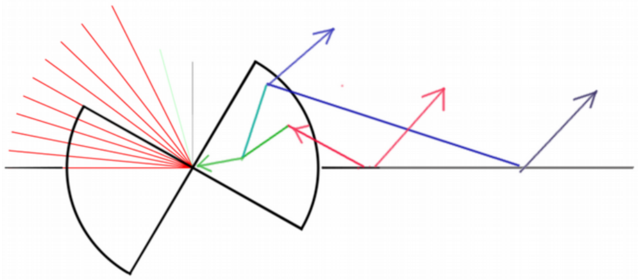
Lense-Thirring precession model



C. Done, A. Ingram, C. Fragile

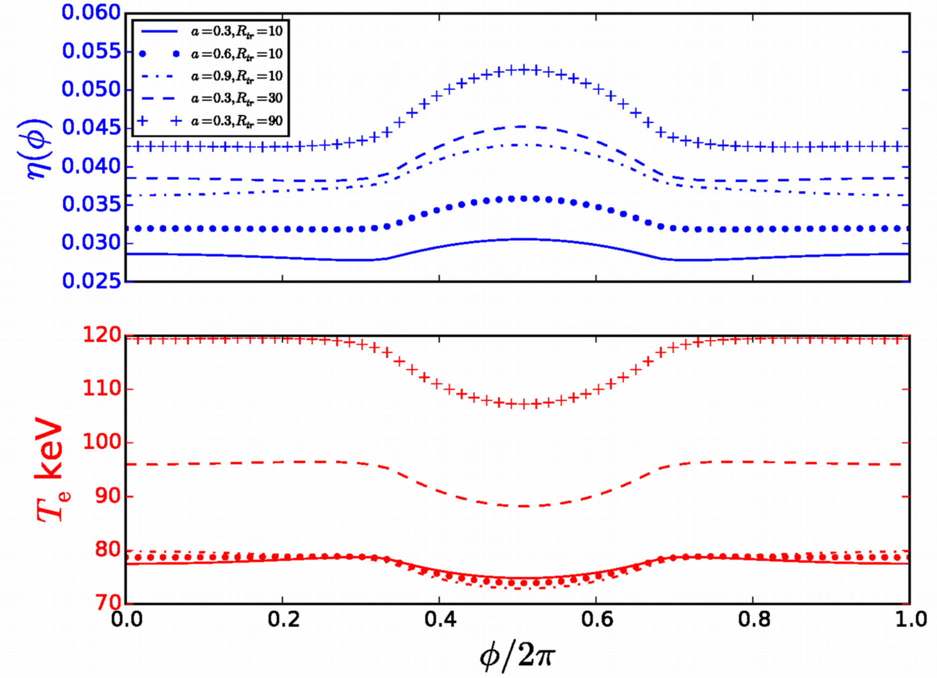
Lense-Thirring precession model





B. You, M. Bursa, P. Życki, 2018, ApJ, 858, 82

Lense-Thirring precession model

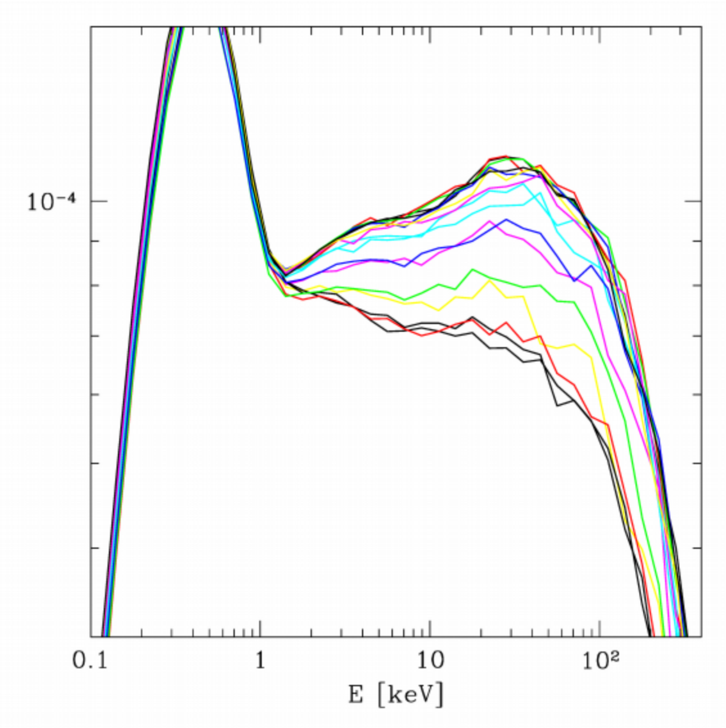


Fraction of the disk emitted energy intercepted by the hot torus

Electron temperature

B. You, M. Bursa, P. Życki, 2018, ApJ, 858, 82

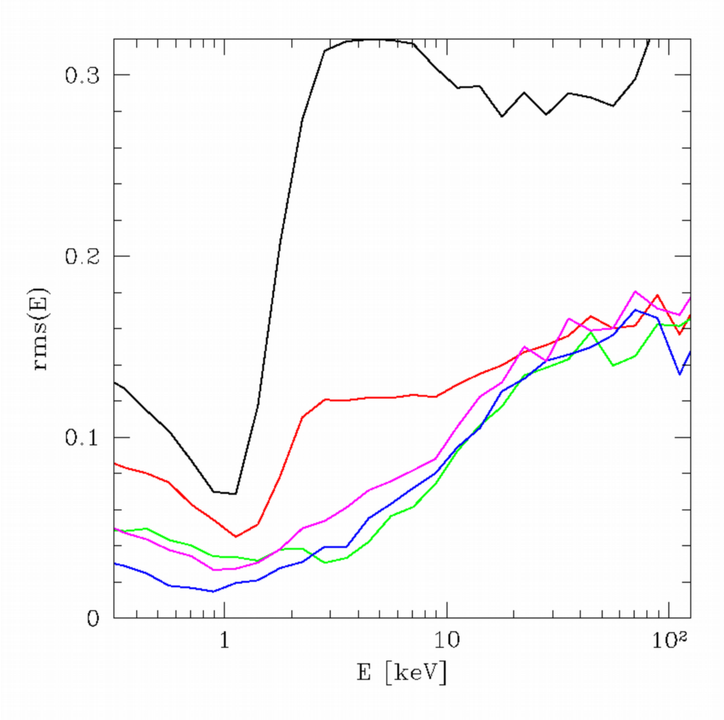
Lense-Thirring precession model



Evolution of the spectrum during a QPO cycle

B. You, M. Bursa, P. Życki, 2018, ApJ, 858, 82

Lense-Thirring precession model



rms(E)

B. You, M. Bursa, P. Życki, 2018, ApJ, 858, 82