

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

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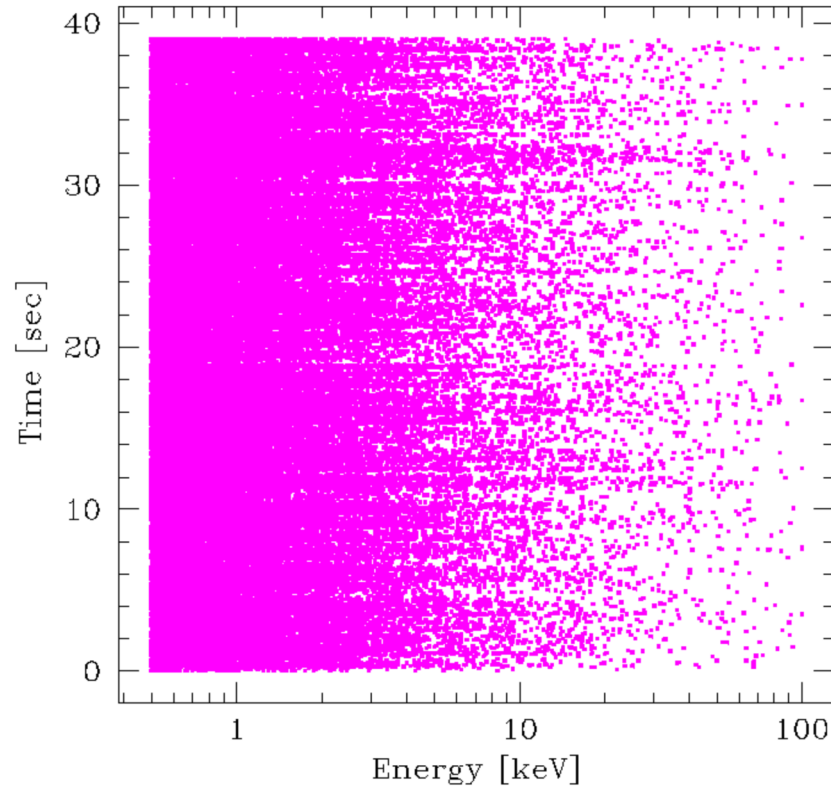
PhD lecture series, 2025, fall semester

Lecture 1

The idea of this course

- Present/recall the basics of radiative processes of X-rays emission relevant to accreting compact objects (Comptonization, atomic interactions)
- Present ideas and tools to compute the emission (spectra, variability)
- Analyse what the observational data are telling us, and attempt to constrain our ideas by confronting model predictions with data
- Use real published research papers

The idea of this course



X-ray data: collection of events:
(energy; time)
(and *polarization*, recently)

- Spectra
- Time variability
- Spectral-temporal analysis

The idea of this course

X-ray spectra

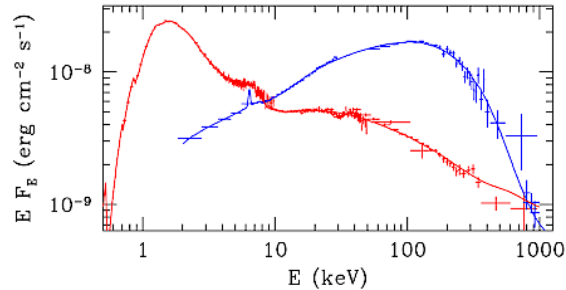


Fig. 8 X/ γ -ray spectral states in Cyg X-1. Classical soft (red) and hard (blue) states taken from Gierliński et al. (1999).

Done, Gierliński, Kubota, 2007, AARv, 15, 1-66

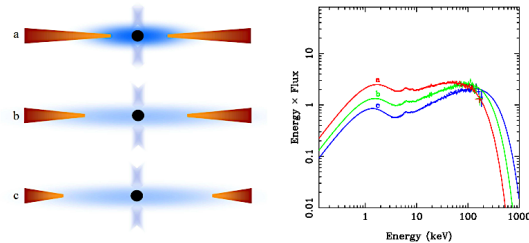


Fig. 12 Range of low/hard state geometries in the truncated disc model, together with their predicted spectra. When the disc is truncated far from the black hole, few disc photons are intercepted by the hot flow. Thus the Comptonized spectrum is hard, while a large fraction of disc photons are seen directly. As the disc extends further underneath the hot flow the larger fraction of disc photons intercepted means the spectrum becomes softer as the electron temperature is cooler, while the disc is hotter but less distinct.

time variability

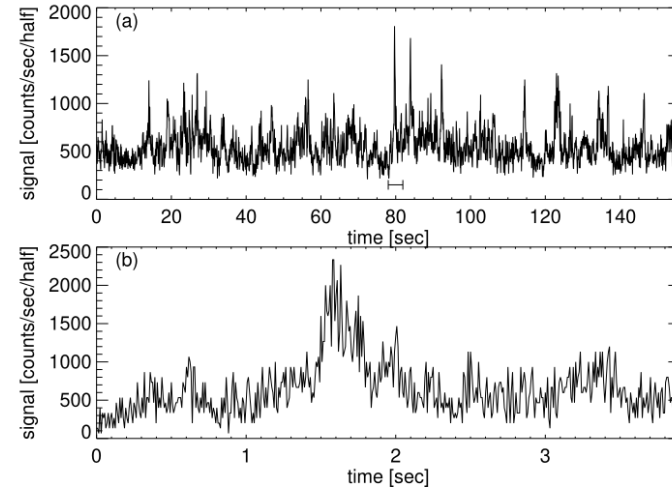


Fig. 1. **a** X-ray lightcurve of Cyg X-1, showing a part of the fifth observation on FOT Nr. EE8087 (No. 1 of Table 1, energy range=1–20 keV, bin time=62.4 ms, length=156 s). **b** Blow-up of the marked segment of subfigure a with a length of 3.9 s and the original bin time of 7.8 ms, showing a typical shot structure. Both lightcurves are plotted without error bars for reasons of clarity.

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

The idea of this course

Correlations between spectral parameters

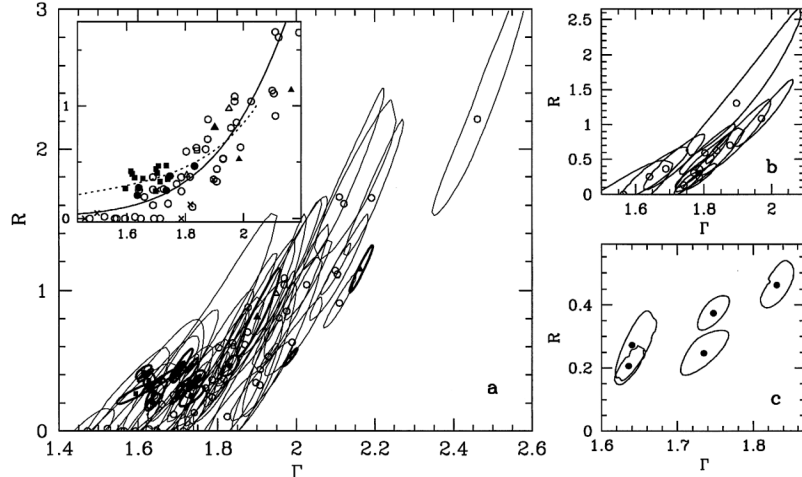
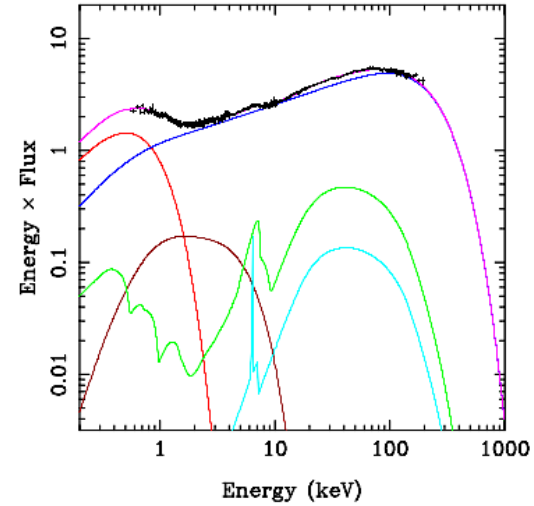


Figure 1. The $R(\Gamma)$ correlation in Seyferts and X-ray binaries in the hard state. Panel (a) shows the data and models (curves in the inset); see Sections 2 and 4, respectively. Examples of the correlation for NGC 5548 and GX 339-4 are shown in panels (b) and (c) respectively.

© 1999 RAS, MNRAS 303, L11–L15

Zdziarski, Lubinski, Smith, 1999, MNRAS, 303, L11

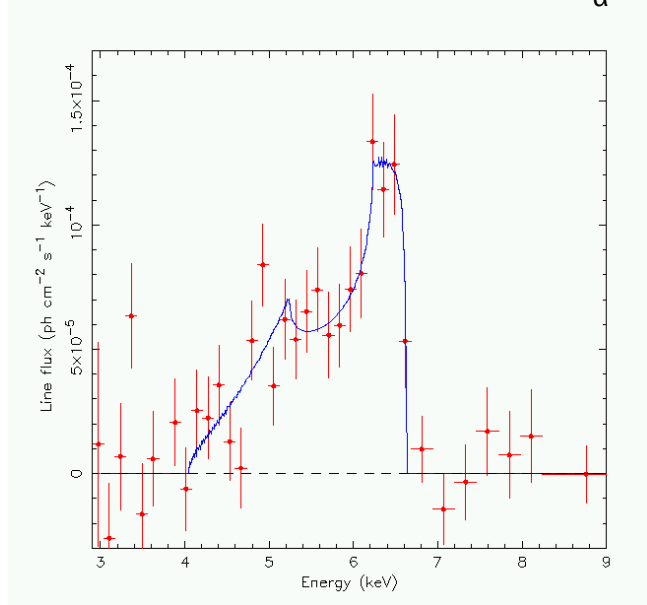
reflection/reprocessing



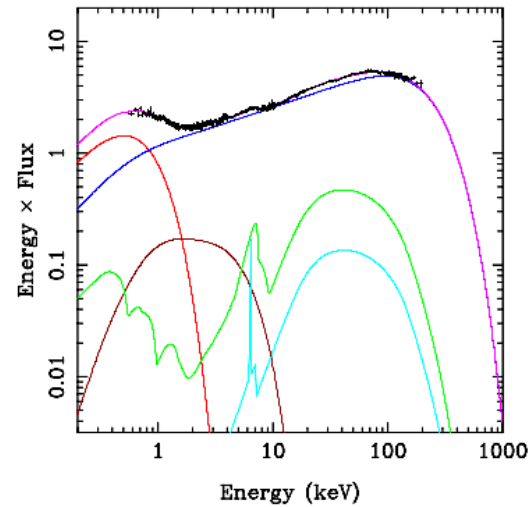
Done, Gierliński, Kubota, 2007, AARv, 15, 1-66

The idea of this course

Broad emission line (Fe K_α) – disk reflection



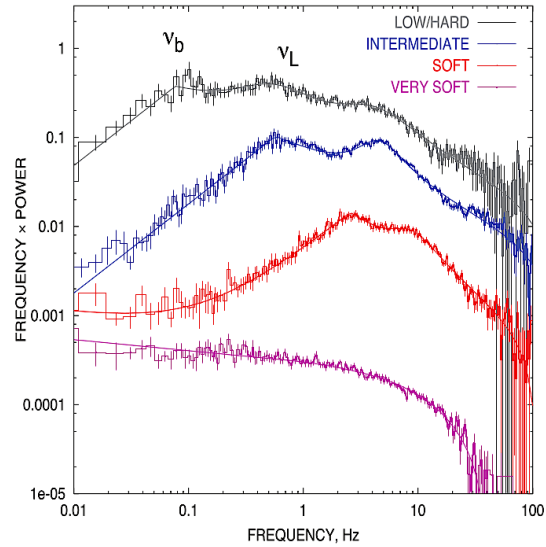
Tanaka et al, 1995, Nature, 375, 659



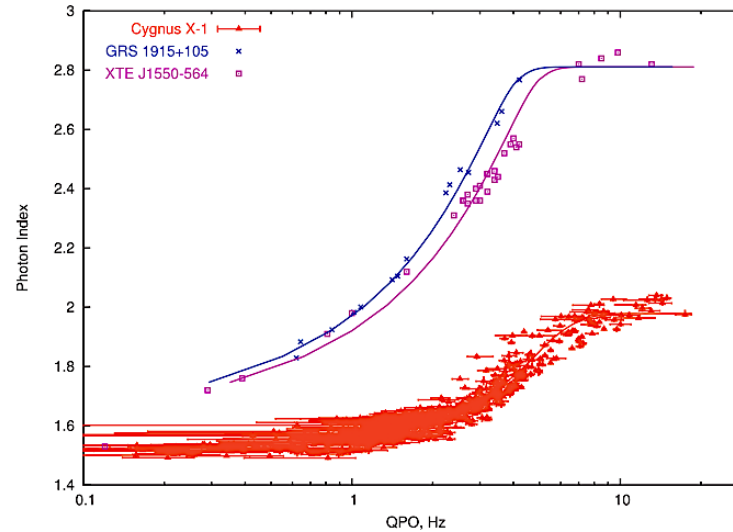
Done, Gierliński, Kubota, 2007, AARv, 15, 1-66

The idea of this course

Power spectrum (variability)



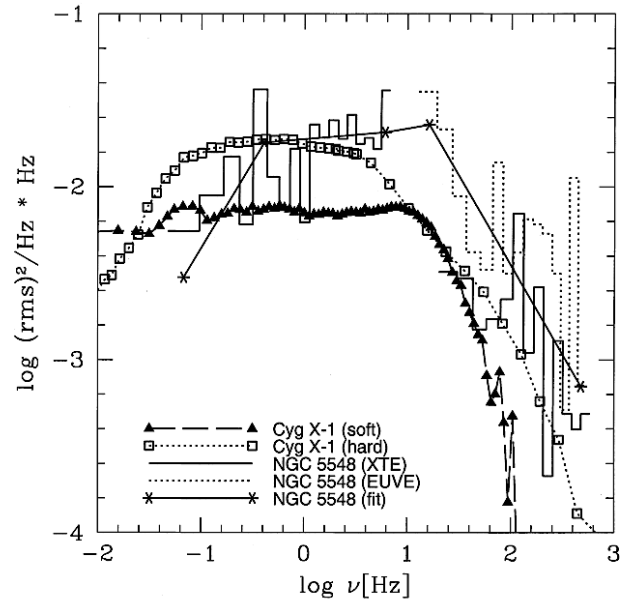
correlation between spectral and timing params



Shaposhnikov & Titarchuk, 2006, ApJ, 643, 1098

The idea of this course

Variability in the AGN case:



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

scaling with mass

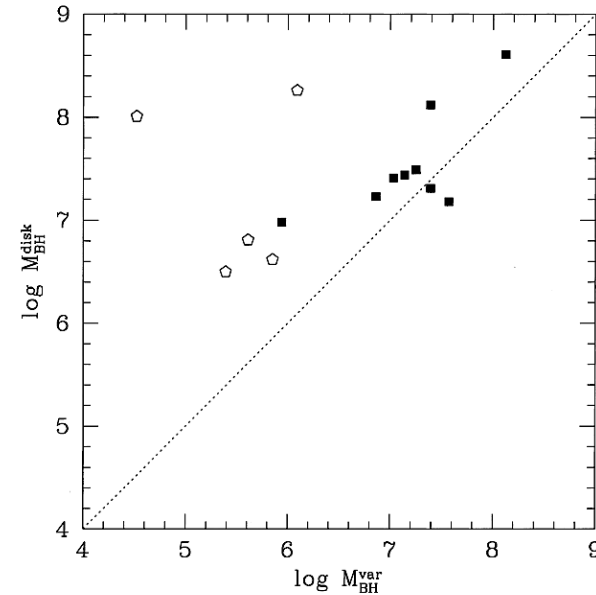
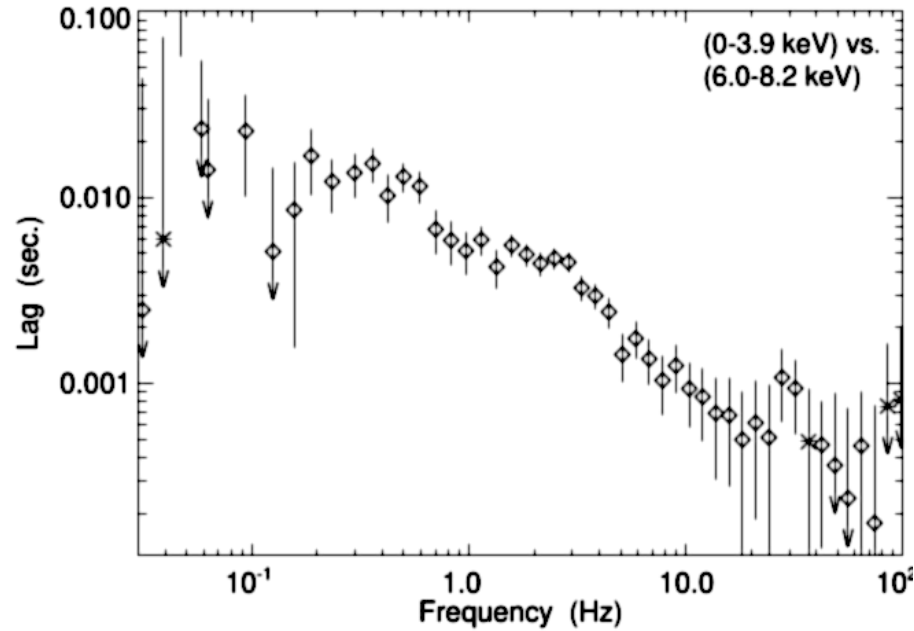


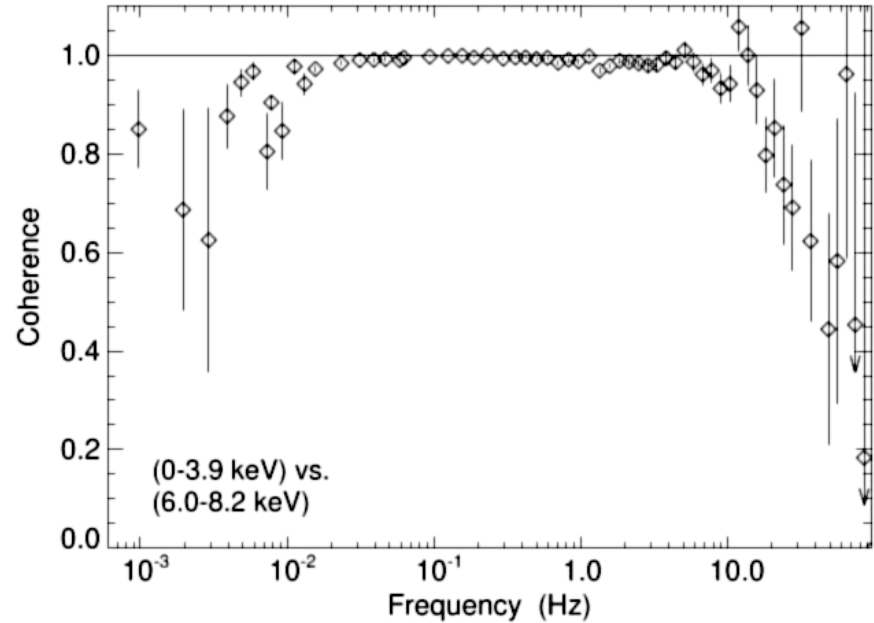
Figure 4. The relation between the mass of the central black hole M_{BH}^{var} , determined from variability, and the mass determined on the basis of accretion disc theory M_{BH}^{disc} : filled squares show S1 galaxies and QSOs, and open pentagons mark NLS1. The dotted line marks the expected relation $M_{BH}^{var} = M_{BH}^{disc}$. This figure is available in colour on *Synergy*, the online version of MNRAS.

The idea of this course

Timing: time lags



coherence



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

The idea of this course

Fourier-frequency resolved spectroscopy

L24

M. Revnivtsev et al.: Frequency resolved spectroscopy: Cyg X-1

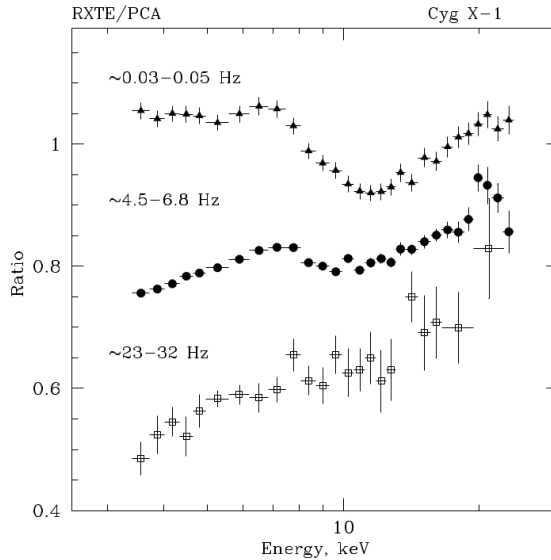


Fig. 1. The ratio of the energy spectra of Cyg X-1 in different frequency bands to a power law model with the photon index $\alpha = 1.8$. Spectra corresponding to 0.03–0.05 Hz and 23–32 Hz were rescaled for clarity.

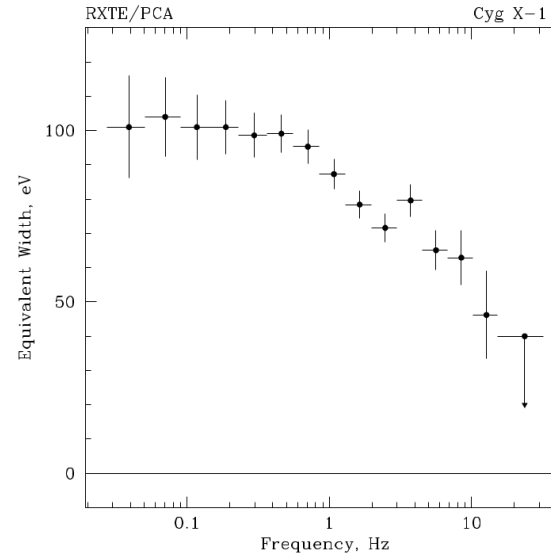


Fig. 2. Dependence of the equivalent width of the fluorescent Fe line on the frequency. For the spectral approximation the powerlaw+gaussian line model was used (3–13 keV energy band, the centroid energy and the width of the line were frozen at the values 6.4 keV and 0.1 keV respectively).

The idea of this course

- **Topics considered:**
 - Continuum spectra and what they say about the main radiative process
 - Reprocessed component, Fe K α line, relativistic effects, evidence for an accretion disk
 - Correlations between parameters and what they tell us about the geometry of accretion
 - X-ray variability: basic concepts, more complex approach
 - Power spectra (PSD), how to understand them
 - PSD, dependence on parameters, application to e.g. black hole mass estimates
 - r.m.s. variability as function of energy

The idea of this course

- **Topics considered** (cont'd):
 - Time lags, interpretation, spectral variability
 - Spectral-timing correlations
 - Fourier-resolved spectroscopy
 - Quasi-periodic oscillations
 - Non-uniqueness of spectral modelling
 - The case of soft X-ray excesses
 - Fe K α line in MCG-6-30-15
 - The case of emission from neutron star X-ray binaries

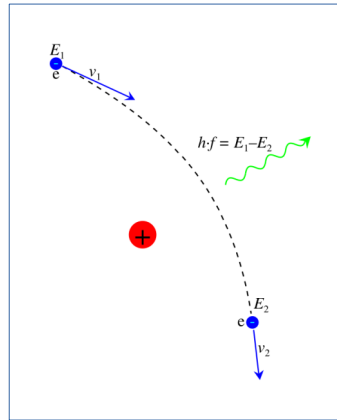
The idea of this course

We will not go through all the thousands of detailed papers on X-ray binaries/AGN

Concentrate on fundamentals

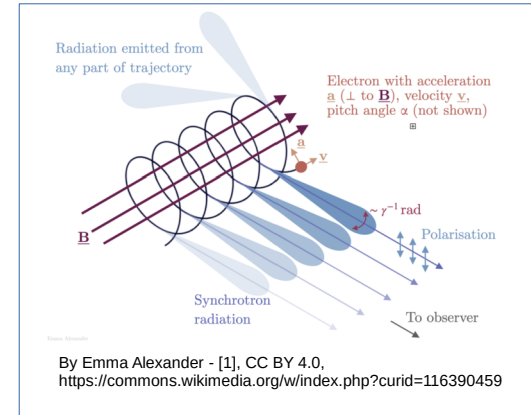
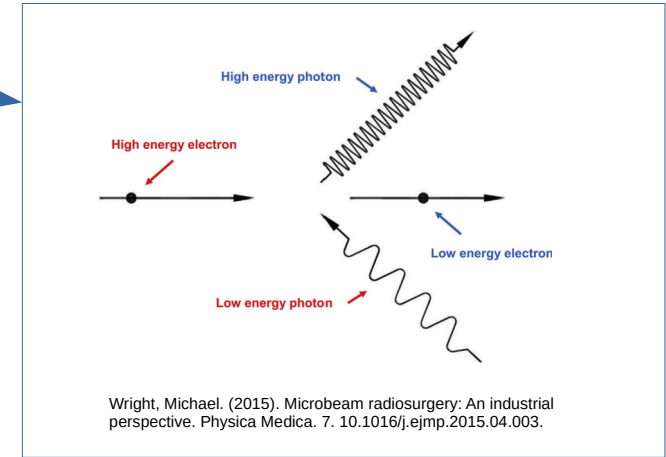
X-ray emission mechanisms. Continuum emission

- Inverse-Compton process



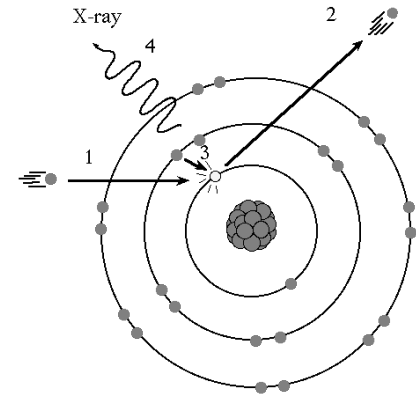
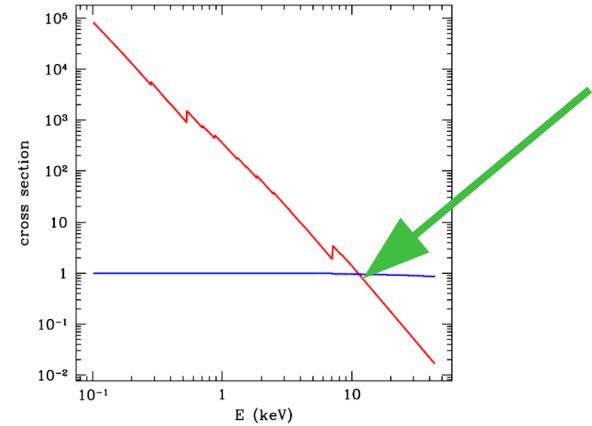
- Bremsstrahlung

- Synchrotron



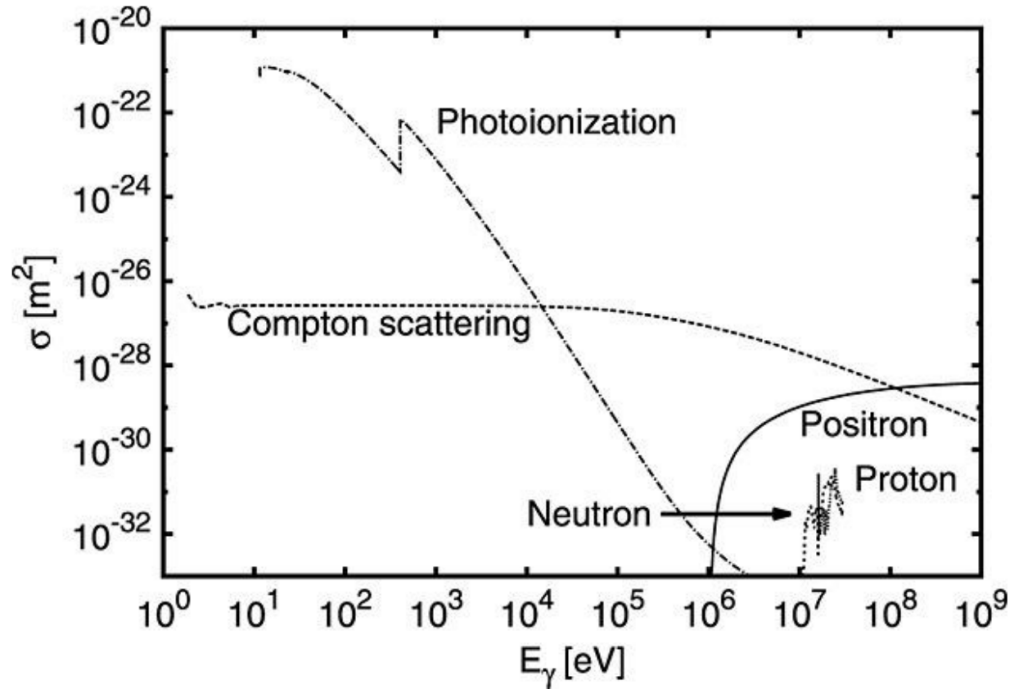
X-ray emission mechanisms. Atomic features

- Photoelectric absorption
- Compton scattering
- Emission/absorption lines
 - Fe K_{α} line (fluorescence; recombination)
 - Recombination edges/continua

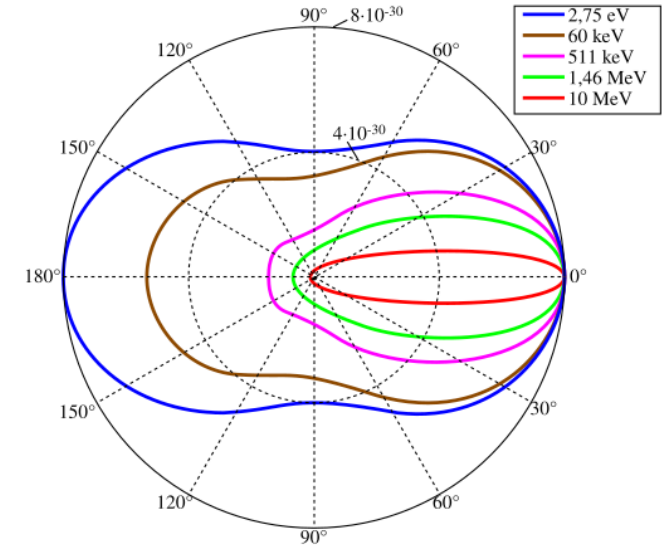


X-ray emission mechanisms. Electron scattering

Cross section

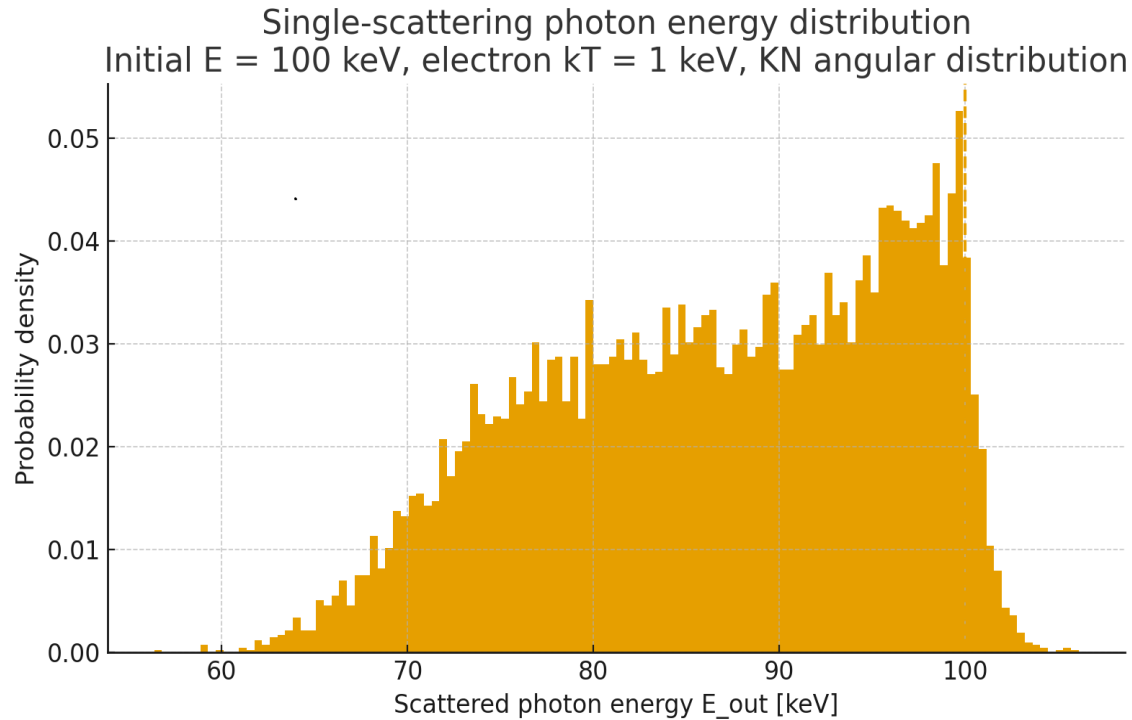


Angular dependence (Klein-Nishina effect)



Wikimedia

X-ray emission mechanisms. Electron scattering



Chat GPT

Realistic case of emitting plasma

- Electron energy distribution + the other agent

→ thermal

→ non-thermal

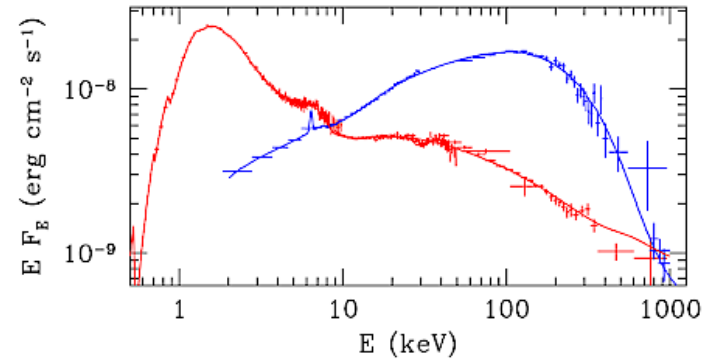


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Realistic case of emitting plasma

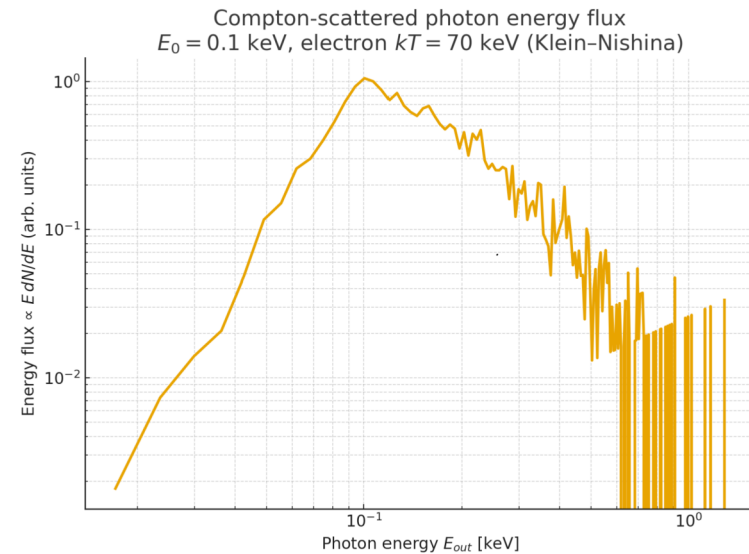
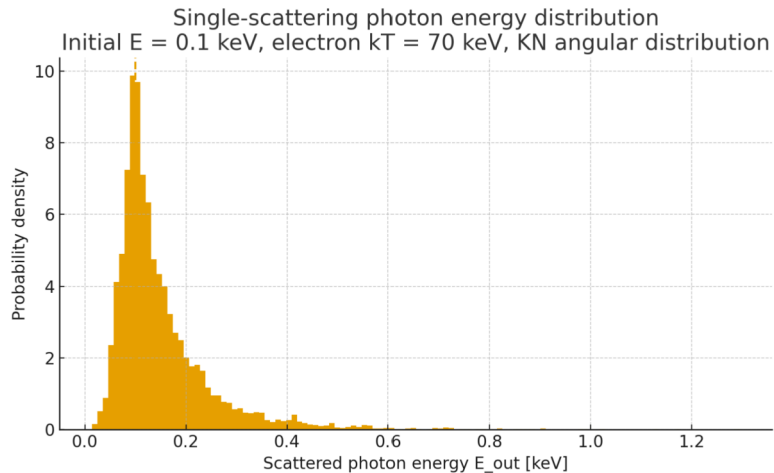
- Why do we think the inverse-Compton is the process responsible for X-ray emission in accreting black holes?

(Ruling out synchrotron and bremsstrahlung)

Topic for one of your presentations!

Realistic case: inverse Compton emission

- Spectra: principles and solutions
 - Single scattering



Chat GPT