X-ray spectra from accreting black holes

A research project on modeling of Fe Kα line profile

Jiří Svoboda, Vladimír Karas, Michal Dovčiak

Astronomical Institute of the Academy of Sciences, Prague
Faculty of Mathematics and Physics, Charles University, Prague

We are carrying out a project to model profiles of intrinsically narrow Fe Kα line broadened due to strong gravitational field and rapid orbital velocities. The main aim of our effort is to trace non-axisymmetric emitting regions (spots) residing on the surface of the disc, taking into account general relativity effects acting on photons along their paths in the gravitational field. For calculation of the frequency shift we are using an approximation, appropriate for the case of non-rotating black holes, which makes numerical computations faster. This approximation allows us to carry out faster checks and comparisons to exact modeling [3].

Introduction

Recent observations from space-based satellites (Chandra, XMM-Newton, etc.) support the idea that supermassive black holes occupy centers of many galaxies and solar mass black holes form non-radiating companions of some X-ray binaries. An appropriate way to study black holes is by observing X-ray spectra of the accreting matter. Disc-type configurations represent an important accretion channel and their properties reflect the global geometry of a source. Photons emerging from the accretion disc and its corona are influenced by gravity of the dark object, so they bear imprints of the source field structure upon arrival to a distant observer. For this reason, X-ray spectral analysis is particularly relevant for astronomical study of strong gravitational fields around black holes. Several routines have been developed and linked with the `XSPEC` package [1] in order to fit the model of a black hole and accretion disk to the satellite data [3, 8, 9]. We focus our investigation on Kα fluorescent line of iron at rest energy at 6.4keV, which is one of the most notable characteristic features of these spectra. We are modeling the spectral line profile taking various approximations of relativistic effects which intend to explain the observed spectral features. The main aim of our effort is to trace non-axisymmetric emitting regions (spots) residing on the surface of the disc, taking into account general relativity effects acting on photons along their paths in the gravitational field.

Model

In our computations we assume a geometrical thin and optical thick disc, where the matter circulates by Keplerian velocities above the marginally stable orbit. We suppose that radial inflow is negligible compared to the orbital movement. We adopt the approximation of geometrical optics in which light rays are null geodesics. Majority of the figures presented here employ approximation for calculation of frequency shift g described in [13]. This approximation is appropriate for non-rotating black holes, the advantage of using it consists in making numerical computations much faster. The results for simple situations are consistent with the precise calculations discussed by other authors in former publications (see [4], [5], etc.). Equations used for computation of presented figures are summarized below. The intensity of point source I is in the relativistic frame scaled by the third power of frequency shift g. This causes strong brightening of the source when moving towards the observer. In employed approximation the frequency shift factor g is determined analytically and it is function of distance from the center R, the azimuthal angle φ and the inclination angle θ. Next two relations express time delay δt and brightening due to the lensing effect.

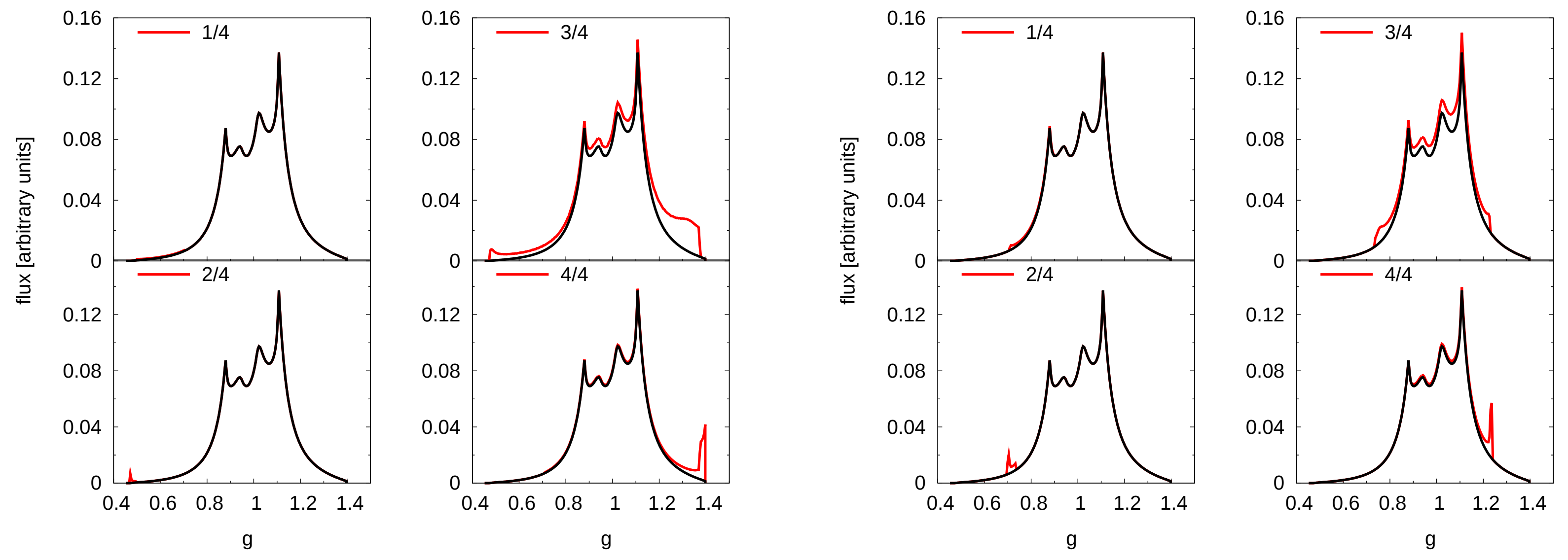


Fig. 2: An example of time modulation of the spectral line profile of the disc due to bright spot residing on its surface. The evolution is illustrated by simulated sequence of four snapshots obtained during the orbital period of the spot. The spot begins to orbit at the nearest point to the observer. The inclination is 85 degrees, the central peak is caused by lensing effect. The spot is located at $R = 6R_g$ (left), respectively at $R = 15R_g$ (right).

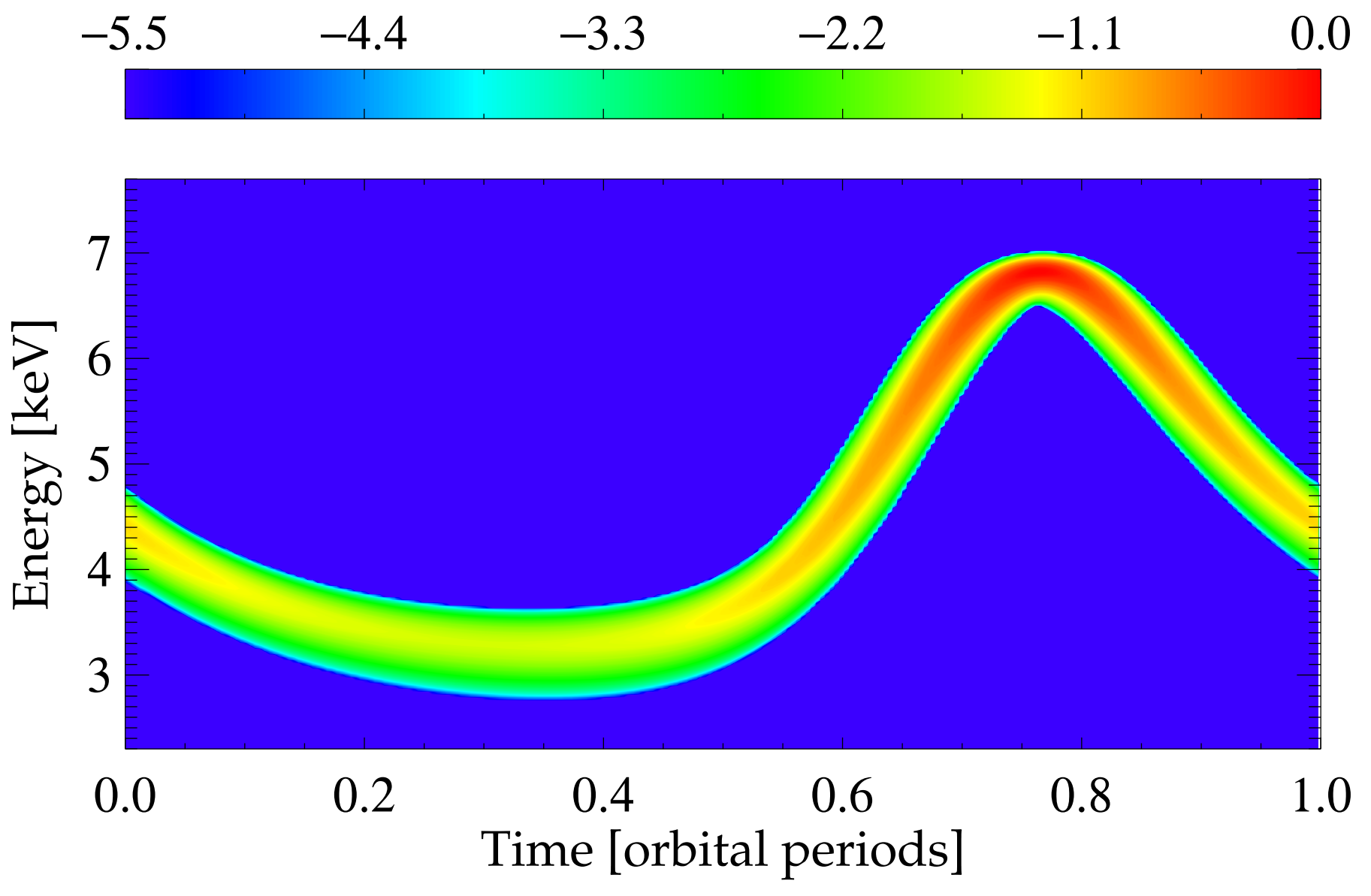
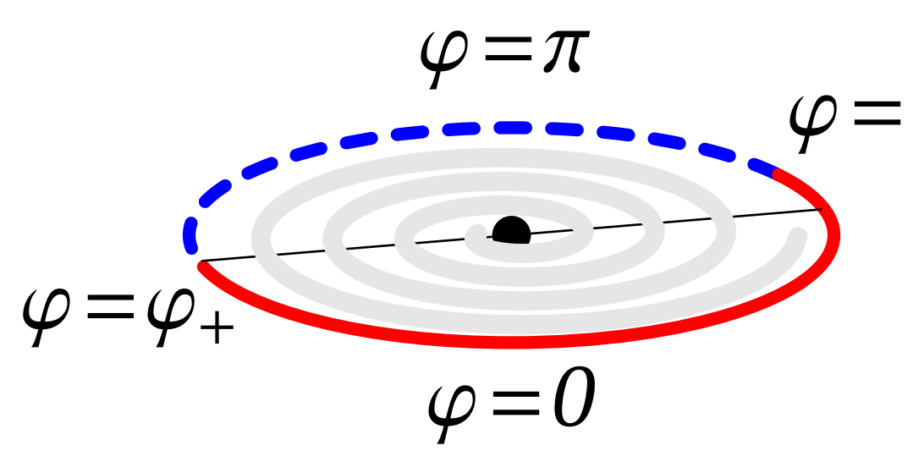
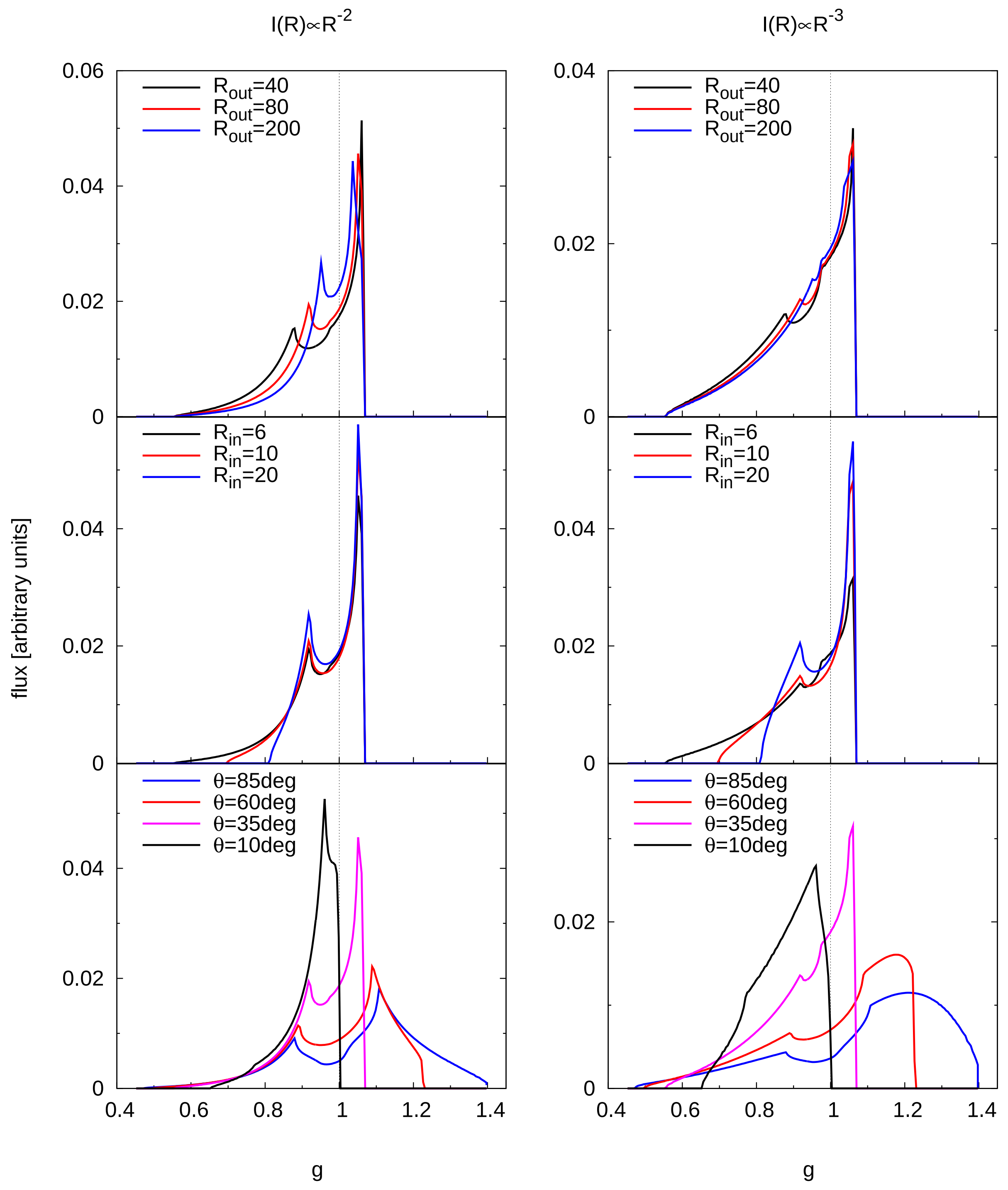


Fig. 3: Color-coded dynamical spectrum of a spot orbiting around a black hole. The interplay between gravitational and Doppler energy shift influences the photon flux and energy at the detector. Polarization degree and the angle also vary as the spot rotates. Near black hole, most of the line emission comes from a small fraction of the orbit. This implies in practice that for observations with a moderate signal-to-noise ratios, only a narrow blue horn can be visible, and only during part of the whole revolution. Large and rapid changes of the line shape get averaged when integrating over the entire orbit, and so an important piece of information is missing in the mean spectra.

Fig. 4: An illustration of the disc, which is divided into the two branches by the azimuthal coordinates $\varphi_{\pm}$ where the frequency shift is extremal.





Some of used relations:

$$\frac{I_{\mathrm{obs}}}{I_{\mathrm{em}}} = \frac{{\nu_{\mathrm{obs}}}^3}{{\nu_{\mathrm{em}}}^3} = g^3$$

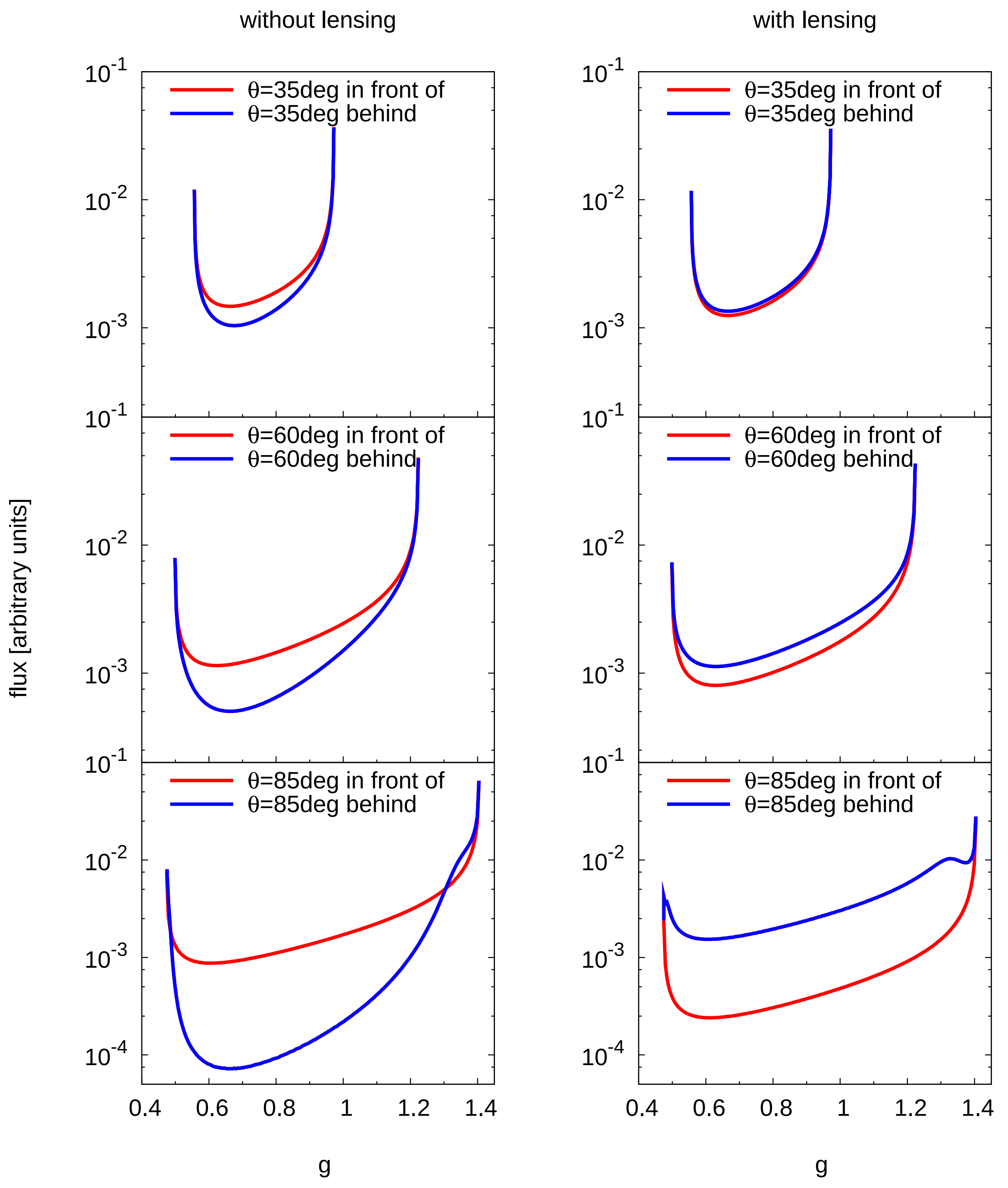
$$g = \frac{\sqrt{R(R-3)}}{R + \sqrt{R - 2 + 4(1+\cos\varphi\sin\theta)^{-1}}\,\sin\varphi\sin\theta}$$

$$\delta t = (R-1)(1-\cos\varphi)\sin\theta + 2\ln\left(\frac{1+\sin\theta}{1+\cos\varphi\sin\theta}\right)$$

$$I_{\,\mathrm{lens}} = I_0\left(R + \frac{1-\cos\varphi\sin\theta}{1+\cos\varphi\sin\theta}\right)$$

⟵ **Fig. 1:** The spectral line profile for accretion discs with $I(R) \approx R^{-2}$ (left panel) and $I(R) \approx R^{-3}$ (right panel) for different values of geometrical parameters, such as inclination, inner and outer edge of the disc. When not specified in labels, the other parameters are fixed at $R_{\mathrm{in}} = 6R_g$, $R_{\mathrm{out}} = 80R_g$ and $\theta = 35\mathrm{deg}$. Lensing is not included.

⟶ **Fig. 5:** The line profile of the spot at $R = 6R_g$ for three different inclination angles, integrated over the front branch (red) and the hind branch (blue) of the orbit. Figures in the left panel do not include lensing, which is counted in profiles in the right panel. The obvious difference is in brightening when the spot orbits behind the hole due to lensing. The effect is stronger for more inclined discs.



Observations

Recently, the broadened profiles of the Fe Kα line have been observed in spectra of both, active galactic nuclei and Galactic black hole candidates. Useful summaries of the analyzed objects with relativistically broadened iron lines are in [10] for Galactic black hole binaries, and in [12] for Seyfert galaxies. The examples of both types are shown in Fig.6. MCG 6-30-15 represents extra-galactic objects, GX 339-4 X-ray binaries.

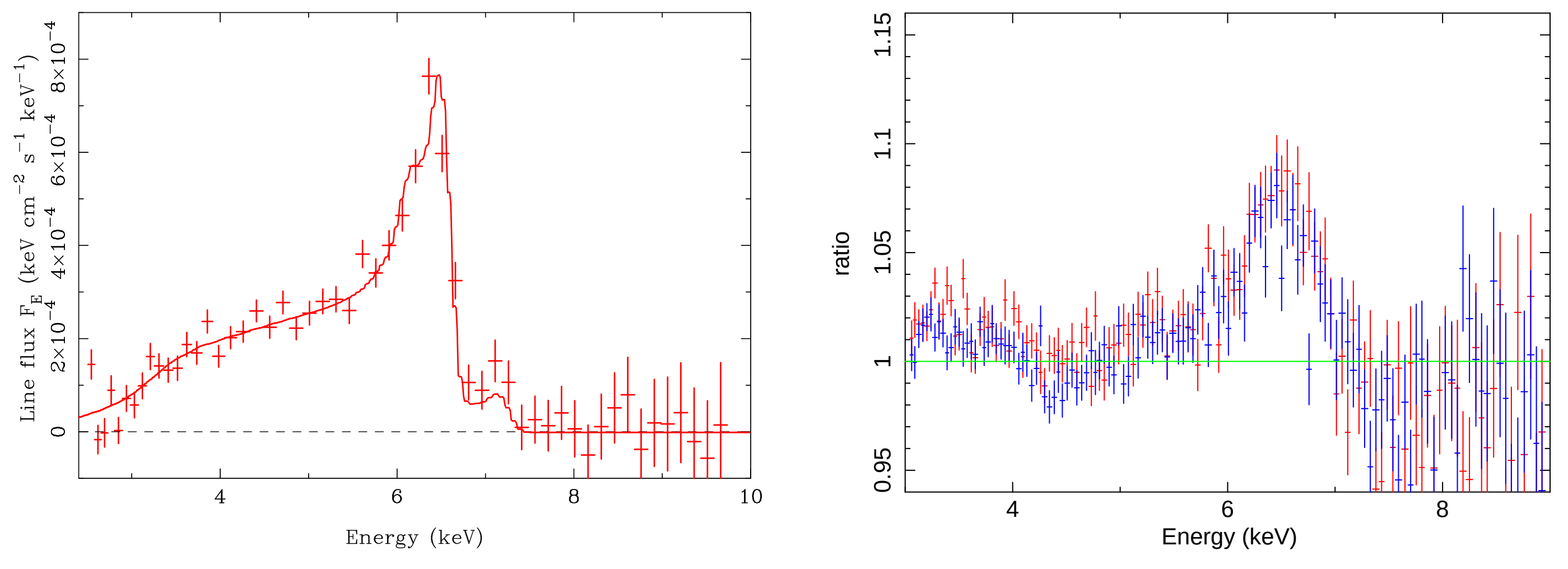


Fig. 6: Observations of broadened Fe Kα line by XMM-Newton. In the left panel there is a spectrum of MCG 6-30-15 observed in August 2001 and analyzed by Fabian et al. [6]. In the right panel we present result of our spectral re-analysis of the GX 339-4 observation from March 2004 (primary analysis was done by Miller et al. [11]).

Discussion and conclusions

We have developed a toy-model for computing spectral line profiles in general relativistic approach. It does not include rotation of gravitational source, but it allows to produce fast calculations and thus to explore extensive space of model parameters. The time-averaged spectra of radiating discs for different values of the parameters are shown in Fig.1 (in the left at the center). The obtained results are consistent with the previously done exact calculations [3]. Further, we concentrate on the time-resolved analysis and modulation of the emitted flux of the disc by orbiting bright spots. The incoming flux is largely non-uniform due to the strong time-delay effect, as seen in the figures Fig.2 and Fig.3. Another significant difference from classical Doppler effect consists in shifting of the values of the azimuthal angle, where the Doppler effect is extremal. They are not opposite in relativistic approximation and moreover, they are shifted unequally depending on the inclination angle. The front path of the orbit is always longer than the hind one (see Fig.4). However, the flux from the hind branch is amplified by the lensing effect, as clearly seen in Fig.5.

Acknowledgements

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e–mail: jirik.svoboda@gmail.com
dovciak@astro.cas.cz
vladimir.karas@cuni.cz