Orbiting spot around black hole

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Radiative (magneto)hydrodynamical seminar
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Model

Mathematical considerations

Observed spectrum

Local flux

Results

Azimuth and energy shift

Lensing and cosine of emission angle

Delay amplification

Total amplification

Light curves

Averaged spectrum

Fe Kα line

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- Motivation
- Model and approximations used
- Mathematical considerations
- Results
- Summary and future prospects

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- flares in Sgr A* (X-ray, NIR, polarization in NIR) (V. Karas, L. Meyer, A. Eckart, ...)

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- flares in Sgr A* (X-ray, NIR, polarization in NIR) (V. Karas, L. Meyer, A. Eckart, ...)
- variability of X-ray AGN sources (R. Goosmann, V. Karas, T. Pecháček, G. Matt, M. Guainazzi, B. Czerny, ...)

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- spot — part of the accretion disc illuminated by the flare
  — 2D, rigid, circular, moving with Keplerian velocity

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- light rays from the spot to the observer are treated properly, i.e. all general relativistic effects are included
- local flux from the spot is computed by Monte Carlo simulations (multiple Compton scattering, Kα and Kβ fluorescence)

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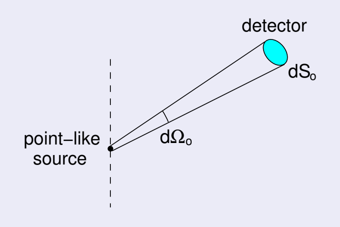
From local to the observed spectrum



$$f(E) \equiv \frac{dn(E)}{dt\, d\Omega_o}$$

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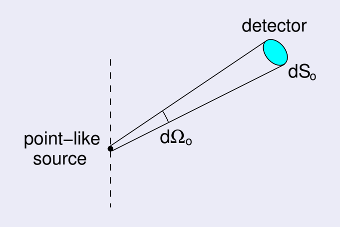
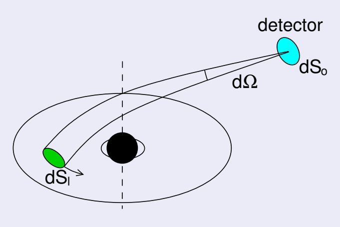
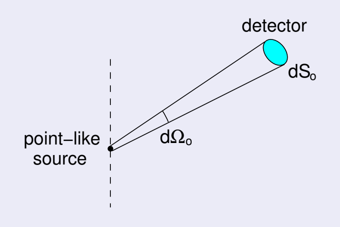


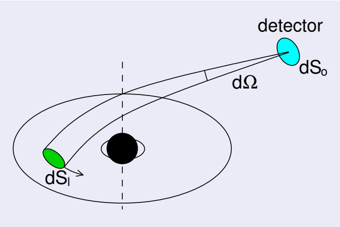


$$f(E) \equiv \frac{dn(E)}{dt\, d\Omega_o}$$

$$f_l(E_l) \equiv \frac{dn_l(E_l)}{d\tau\, dS_\perp\, d\Omega_l}$$

From local to the observed spectrum





$$f(E) \equiv \frac{\mathrm{d}n(E)}{\mathrm{d}t\,\mathrm{d}\Omega_{\mathrm{o}}}$$

$$f_{\mathrm{l}}(E_{\mathrm{l}}) \equiv \frac{\mathrm{d}n_{\mathrm{l}}(E_{\mathrm{l}})}{\mathrm{d}\tau\,\mathrm{d}S_{\perp}\,\mathrm{d}\Omega_{\mathrm{l}}}$$

$$\Delta f(E,\Delta E,t) = \int_{\Sigma} \mathrm{d}S \int_{E/g}^{(E+\Delta E)/g} \mathrm{d}E_{\mathrm{l}}\; f_{\mathrm{l}}(E_{\mathrm{l}};r,\varphi;\mu_{\mathrm{e}},\phi_{\mathrm{e}};t-\delta t)\,F$$

$$F \equiv g^2\, l\, \mu_{\mathrm{e}} \qquad \mathrm{d}S \equiv r\,\mathrm{d}r\,\mathrm{d}\varphi$$

$$F = F_{\mathrm{p}} \equiv g^3\, l$$ for point source

From local to the observed spectrum

$$\Delta f(E,\Delta E,t,\Delta t) = \int_{t}^{t+\Delta t} \mathrm{d}t_{\mathrm{o}} \int_{r_1}^{r_2} \mathrm{d}r\, r \int_{0}^{2\pi} \mathrm{d}\varphi \int_{-\infty}^{+\infty} \mathrm{d}t_{\mathrm{e}} \int_{E/g}^{(E+\Delta E)/g} \mathrm{d}E_{\mathrm{l}}$$

$$\times f_{\mathrm{l}}(E_{\mathrm{l}}; r,\varphi; \mu_{\mathrm{e}},\phi_{\mathrm{e}}; t_{\mathrm{e}})\, F(r,\varphi)\, \delta(t_{\mathrm{o}} - [t_{\mathrm{e}} + \delta t(r,\varphi)])$$

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$$\times f_\mathrm{l}(E_\mathrm{l}; r, \varphi; \mu_\mathrm{e}, \phi_\mathrm{e}; t_\mathrm{e})\, F(r,\varphi)\, \delta(t_\mathrm{o} - [t_\mathrm{e} + \delta t(r,\varphi)])$$

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$$\times f_\mathrm{l}(E_\mathrm{l}; r, \varphi; \mu_\mathrm{e}, \phi_\mathrm{e}; t_\mathrm{o} - \delta t(r,\varphi))\, F(r,\varphi)\, k_\mathrm{t}(r,\varphi)$$

$$\varphi \equiv \varphi(\varphi_\mathrm{l}, t_\mathrm{o}) \qquad \varphi_\mathrm{l} = \varphi - \Omega(r)\,[t_\mathrm{o} - \delta t(r,\varphi)]$$

$$k_\mathrm{t}(r,\varphi) \equiv \left[1 + \Omega(r)\frac{\partial(\delta t)}{\partial \varphi}(r,\varphi)\right]^{-1}$$

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stationary spot:

$$f_\mathrm{l}(E_\mathrm{l}; r,\varphi; \mu_\mathrm{e}, \phi_\mathrm{e}; t_\mathrm{o} - \delta t(r,\varphi)) \equiv f_\mathrm{l}(E_\mathrm{l}; r, \varphi_\mathrm{l}; \mu_\mathrm{e}, \phi_\mathrm{e})$$

Local flux

primary source:

$$f_{\rm p}(E_{\rm l}) \equiv {\rm N_p}\, E_{\rm l}^{-\Gamma} \qquad {\rm N_p} = \left[\int_{E_{\rm min}}^{E_{\rm max}} {\rm d}E\, E^{-\Gamma}\right]^{-1}$$

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reflected component:

$$f_{\rm r}(E_{\rm l},\mu_{\rm i},\mu_{\rm e},\phi_{\rm e}) \equiv f_{0\rm r}(E_{\rm l},\mu_{\rm i},\mu_{\rm e},\phi_{\rm e})\,\frac{\mu_{\rm i}^3}{h^2}\,\frac{1}{\mu_{\rm e}}$$

$$f_{0\rm r}(E_{\rm l},\mu_{\rm i},\mu_{\rm e},\phi_{\rm e}) \equiv \frac{\Delta N_{\rm r}}{\Delta\mu_{\rm e}\,\Delta\phi_{\rm e}\,\Delta E_{\rm l}}$$

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reflected component:

$$f_{\mathrm{r}}(E_{\mathrm{l}},\mu_{\mathrm{i}},\mu_{\mathrm{e}},\phi_{\mathrm{e}}) \equiv f_{0\mathrm{r}}(E_{\mathrm{l}},\mu_{\mathrm{i}},\mu_{\mathrm{e}},\phi_{\mathrm{e}})\,\frac{\mu_{\mathrm{i}}^3}{h^2}\,\frac{1}{\mu_{\mathrm{e}}}$$

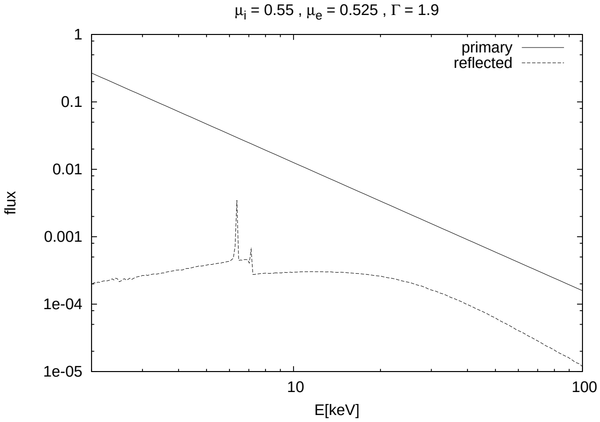
$$f_{0\mathrm{r}}(E_{\mathrm{l}},\mu_{\mathrm{i}},\mu_{\mathrm{e}},\phi_{\mathrm{e}}) \equiv \frac{\Delta N_{\mathrm{r}}}{\Delta\mu_{\mathrm{e}}\,\Delta\phi_{\mathrm{e}}\,\Delta E_{\mathrm{l}}}$$

reflected component averaged over azimuthal angle:

$$\bar{f}_{\mathrm{r}}^{\varphi}(E_{\mathrm{l}},\mu_{\mathrm{i}},\mu_{\mathrm{e}}) \equiv \bar{f}_{0\mathrm{r}}^{\varphi}(E_{\mathrm{l}},\mu_{\mathrm{i}},\mu_{\mathrm{e}})\,\frac{\mu_{\mathrm{i}}^3}{h^2}\,\frac{1}{\mu_{\mathrm{e}}}$$

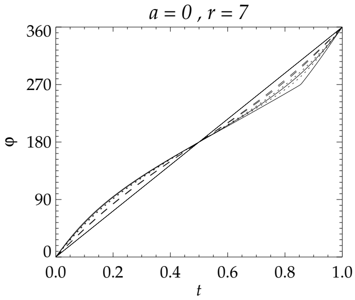
$$\bar{f}_{0\mathrm{r}}^{\varphi}(E_{\mathrm{l}},\mu_{\mathrm{i}},\mu_{\mathrm{e}}) \equiv \frac{\Delta N_{\mathrm{r}}}{2\pi\Delta\mu_{\mathrm{e}}\,\Delta E_{\mathrm{l}}}$$

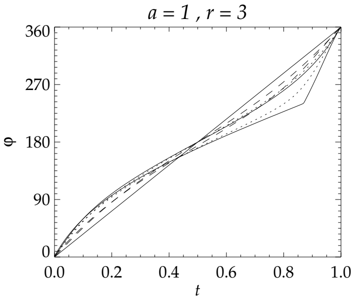
Local flux



μi = 0.55 , μe = 0.525 , Γ = 1.9
primary
reflected
flux
E[keV]
1
0.1
0.01
0.001
1e-04
1e-05
10
100

Azimuth and energy shift





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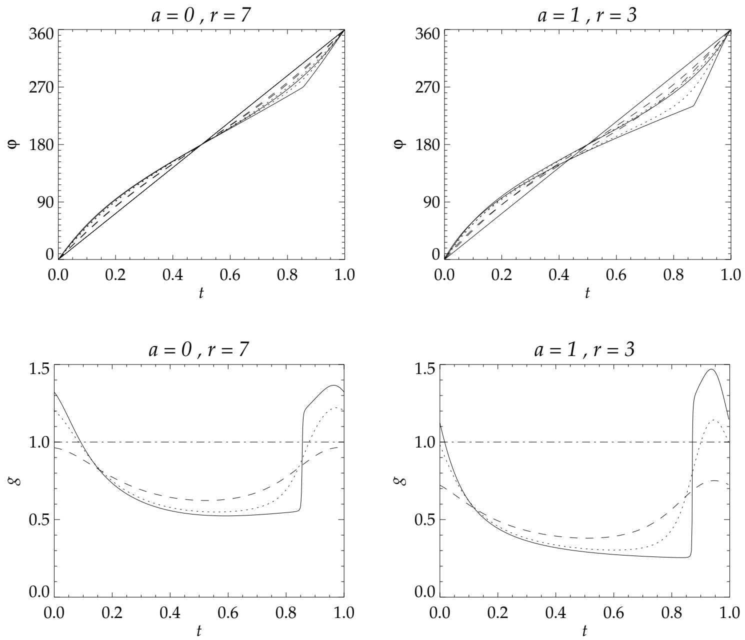
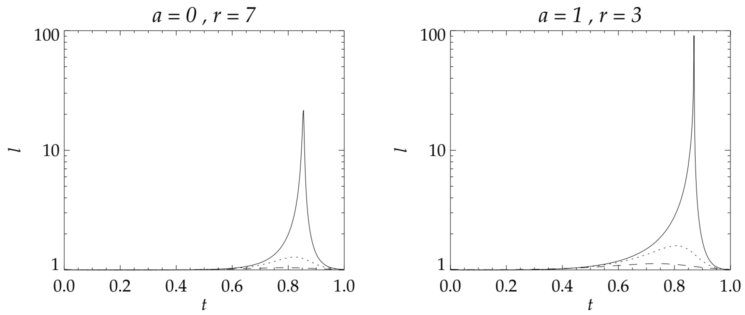


Lensing and cosine of emission angle



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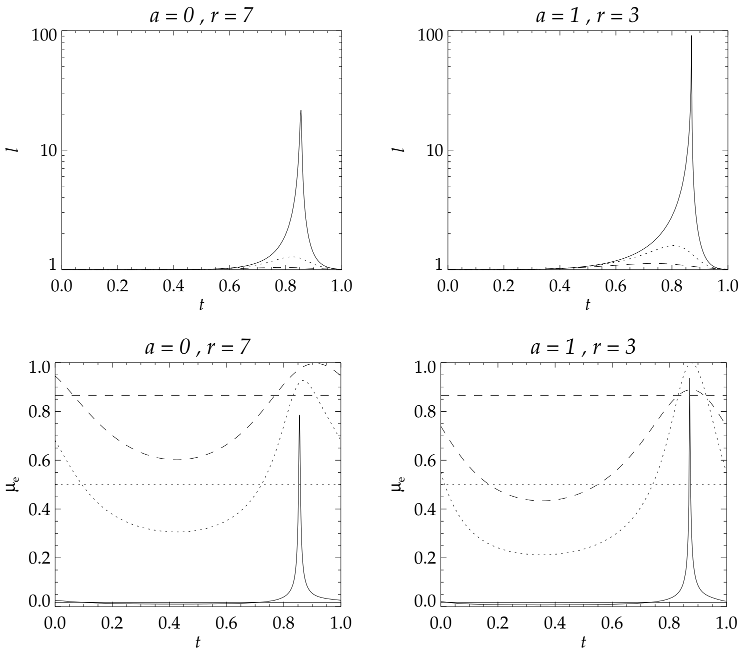

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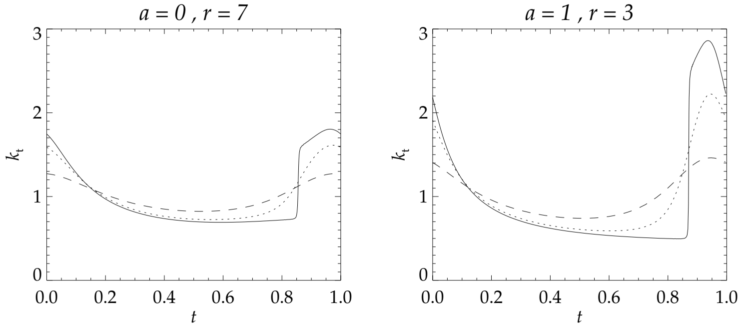

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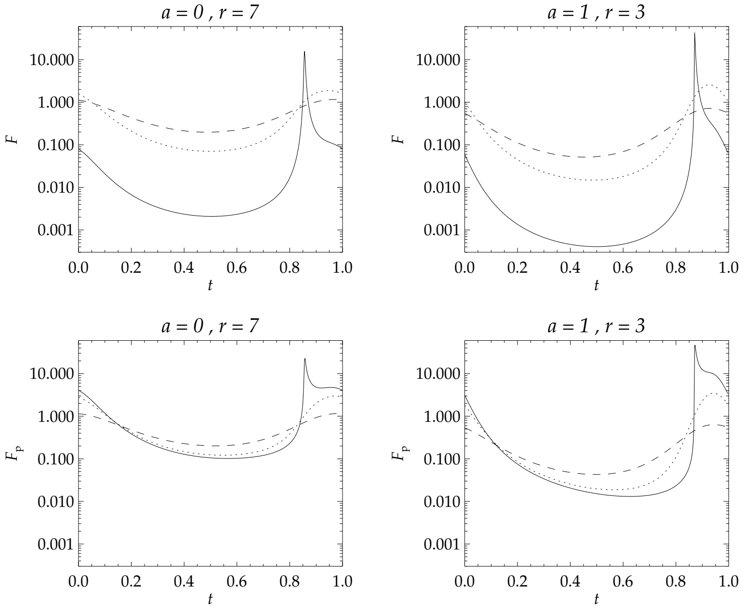
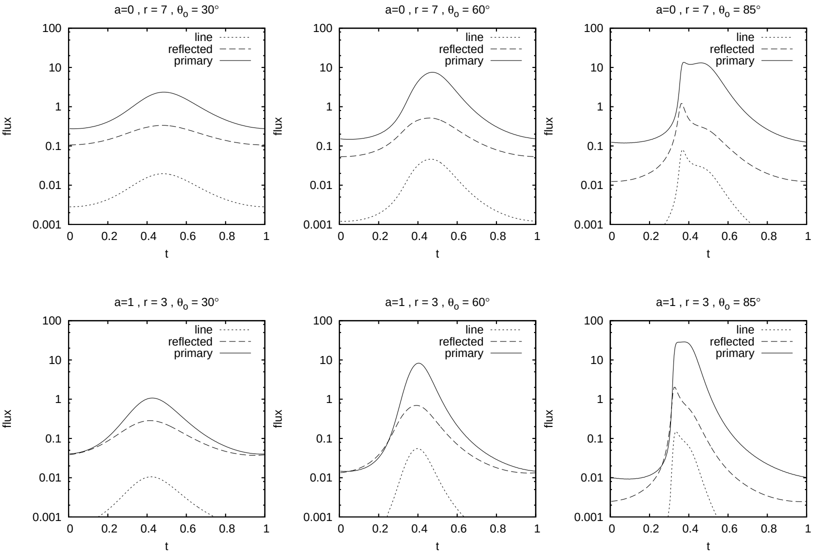
Total amplification for extended and point sources



Light curves



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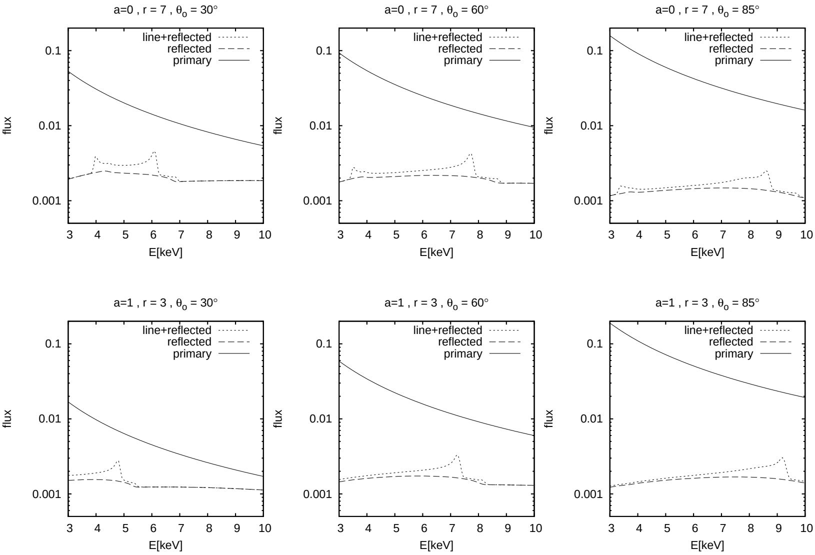
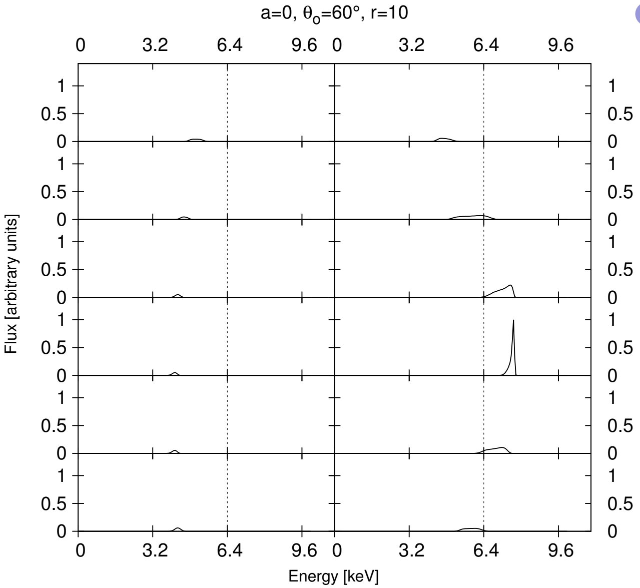


Fe Kα line



line

Animation I
Animation II
Animation III
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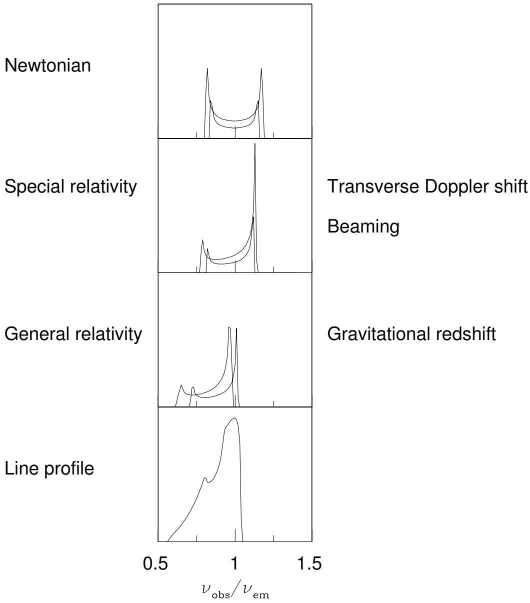
Animation V

Summary and future prospects

- the light curves and spectra changes their shape mainly due to
  - the energy shift g
  - magnification by the total transfer function $F_{\mathrm{tot}} = g^2 l \mu_{\mathrm{e}} k_{\mathrm{t}}$ ($F_{\mathrm{tot}} = g^3 l\, k_{\mathrm{t}}$ for point source)
  - the delay amplification $k_{\mathrm{t}} = \left[1 + \Omega \frac{\partial(\delta t)}{\partial \varphi}\right]^{-1}$ seems to be the most important
- what was done → single spot modelling (polarization as well)
- future → multiple spot modelling of X-ray variability

Relativistic spectral line



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