

# Time lags and reverberation in the lamp-post geometry of the compact corona illuminating a black-hole accretion disc

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Title: **Probing Strong Gravity by Black Holes Across the Range of Masses**

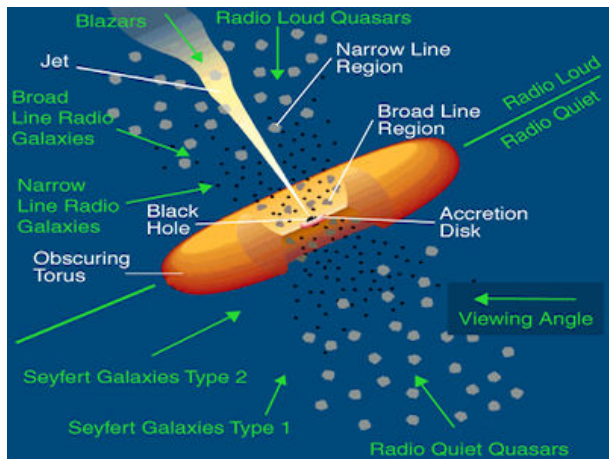
Institutes: AsU, CNRS, UNIROMA3, UCAM, CSIC, UCO, CAMK

Webpages: <http://stronggravity.eu/>

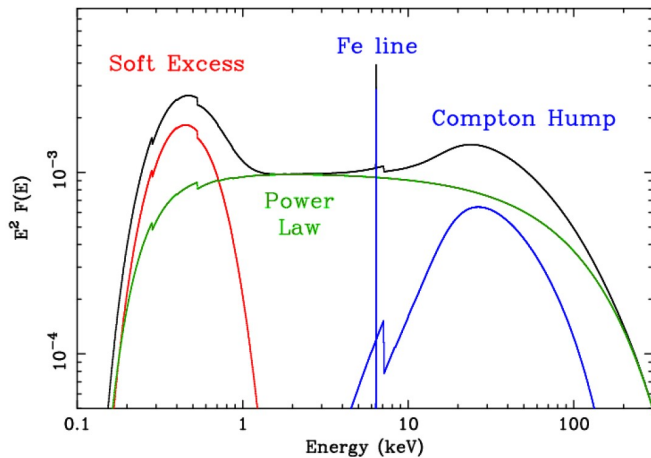
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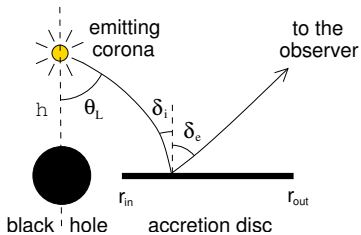
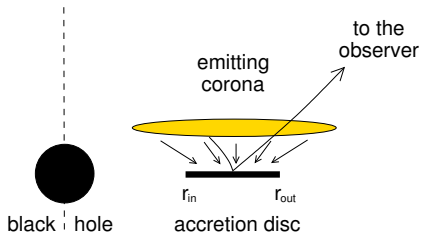
# Active Galactic Nuclei – scheme



# Active Galactic Nuclei – X-ray spectrum

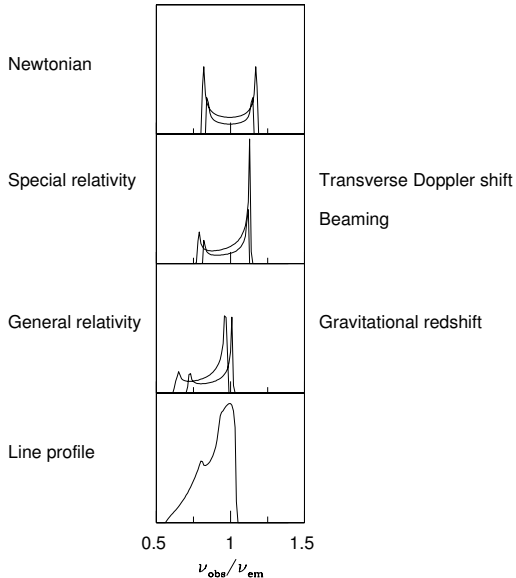


# Innermost part of AGN – scheme



# Relativistic iron line

$$G(g) = \sqrt{\frac{g_+ g_-}{(g_+ - g)(g - g_-)}} g^2 \cos[\theta_e(g)] \ell(g) \left[ \frac{\partial \psi}{\partial \varphi}(g) \right]^{-1}$$



Fabian et al. (2000)

$$g = 1 - \frac{v_k}{c} \sin \theta_o \sin \varphi$$

$$\theta_e = \theta_o \quad \ell = 1 \quad \psi = \varphi$$

$$g = \left[ \gamma \left( 1 + \frac{v_k}{c} \sin \theta_o \sin \varphi \right) \right]^{-1}$$

$$\theta_e = \theta_o \quad \ell = 1 \quad \psi = \varphi$$

$$g = [U_k^t (1 - \Omega_k \sin \theta_o \alpha)]^{-1}$$

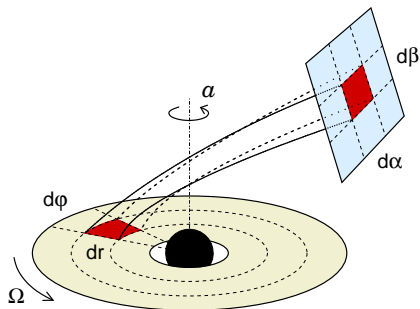
$$\cos \theta_e = \sqrt{\beta^2 + (\alpha^2 - a^2) \cos^2 \theta_o} / r$$

$$\ell = \frac{dS_o}{dS_{\text{loc}}}$$

$$\sin \psi = \frac{2(\alpha - \bar{\alpha})}{\alpha_+ - \alpha_-}$$

$$F(g) = \int_{r_{\text{in}}}^{r_{\text{out}}} dr r R(r) \sum_{j=1}^2 G_j(g) M_j(\mu_i, \mu_e)$$

# Transfer function for spectrum



$$\Delta I = \int_{\Sigma_{\alpha,\beta}} d\alpha d\beta \underbrace{g^\gamma}_{\text{transfer function } G} I_{\text{loc}}(\alpha, \beta)$$

$$\Delta I = \int_{\Sigma_{r,\varphi}} r dr d\varphi \underbrace{g^{\gamma-1} \mu_e \ell}_{\text{transfer function } G} I_{\text{loc}}(r, \varphi)$$

transfer function  $G$

$$g = \frac{E}{E_{\text{loc}}}$$

$$\mu_e = \cos \theta_e$$

$$\ell = \frac{dS_0}{dS_{\text{loc}}^\perp}$$

$$\gamma = 4 \quad \text{for} \quad \frac{dE}{dt d\Omega dS}$$

$$\gamma = 3 \quad \text{for} \quad \frac{dE}{dt d\Omega dS dv} \quad \text{or} \quad \frac{dN}{dt d\Omega dS}$$

$$\gamma = 2 \quad \text{for} \quad \frac{dN}{dt d\Omega dS dv}$$

$$\frac{d\alpha d\beta}{r dr d\varphi} = \frac{dS_0}{dS_{\text{loc}}^\perp} \times \frac{dS_{\text{loc}}^\perp}{dS_{\text{loc}}} \times \frac{dS_{\text{loc}}}{dS} = \frac{\ell \mu_e}{g}$$

# Energy shift and amplification



# Dependence on spin

$$F_{\text{loc}} = r^{-3} \times \delta(E - E_{\text{rest}})$$

# Dependence on inclination

$$F_{\text{loc}} = r^{-3} \times \delta(E - E_{\text{rest}})$$

# Historical note on relativistic Fe $K\alpha$ line

## Spectrum from the black hole inner accretion disc:

Cunningham C. T. (1975) *The effects of redshifts and focusing on the spectrum of an accretion disk around a Kerr black hole*, ApJ, **202**, 788

## Relativistic broad line profiles:

Fabian A. C., Rees M. J., Stella L. & White N. E. (1989) *X-ray fluorescence from the inner disc in Cygnus X-1*, MNRAS, **238**, 729

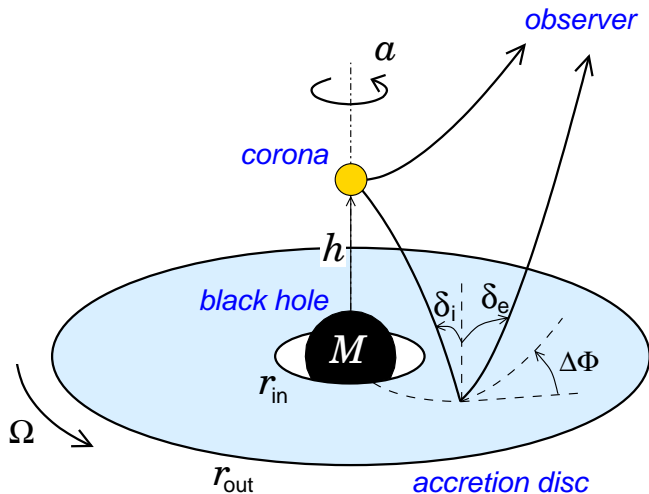
## Observations:

Tanaka Y. et al. (1995) *Gravitationally redshifted emission implying an accretion disk and massive black hole in the active galaxy MCG-6-30-15*, Nature, **375**, 659

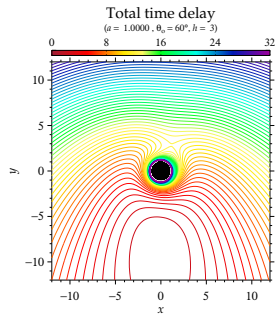
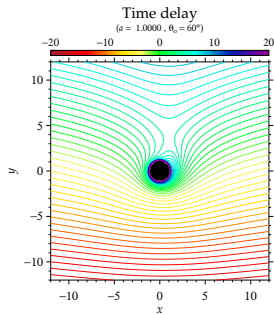
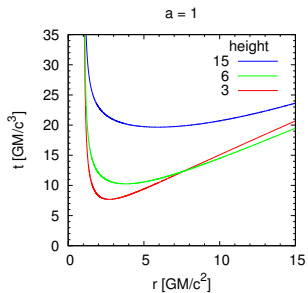
Fabian A. C. et al. (2002) *A long hard look at MCG-6-30-15 with XMM-Newton*, MNRAS, **335**, L1

Miller J. M. (2007) *Relativistic X-Ray Lines from the Inner Accretion Disks Around Black Holes*, Annual Review of Astronomy & Astrophysics, **45**, 441

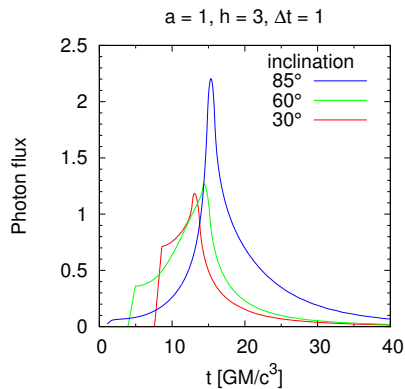
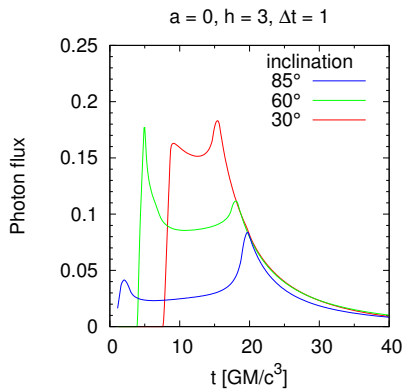
# Scheme of the lamp-post geometry



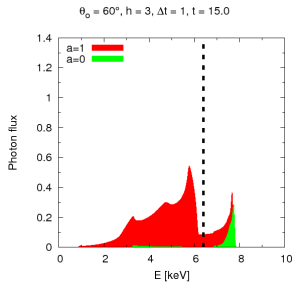
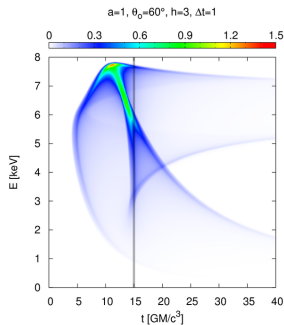
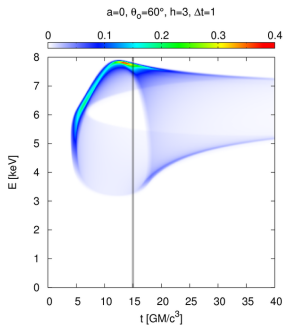
# Time delay



# Light curve



# Dynamic spectrum



# Transfer function for reverberation

Stationary emission from the accretion disc:

$$F(E) = \int r dr d\varphi G(r, \varphi) F_1(r, \varphi, E/g)$$

Response to the on-axis primary emission:

$$F(E, t) = \int dt' \int r dr d\varphi G(r, \varphi) \times \\ N_p(t') N_{\text{inc}}(r) M(r, \varphi, E/g, t' + t_{\text{pd}}) \delta([t - t_{\text{do}}] - [t' + t_{\text{pd}}])$$

Line reverberation:

$$F(E, t) = \int dt' N_p(t') \int r dr d\varphi \psi_0(r, \varphi) \delta(E - gE_{\text{rest}}) \delta([t - t'] - \underbrace{[t_{\text{pd}} + t_{\text{do}}]}_{\Delta t})$$

Transfer function  $\rightarrow$  response to a flare [ $N_p(t') = \delta(t')$ ]:

$$\psi(E, t) = \sum_{\substack{g = E/E_{\text{rest}} \\ t_{\text{pd}} + t_{\text{do}} = t}} \psi_0 \frac{r}{E_{\text{rest}}} \left| \frac{\partial(g, \Delta t)}{\partial(r, \varphi)} \right|^{-1}$$

$$F(E, t) = \int dt' N_p(t') \psi(E, t - t')$$

$$\frac{\partial(g, \Delta t)}{\partial(r, \varphi)} = \frac{\partial g}{\partial r} \frac{\partial(\Delta t)}{\partial \varphi} - \frac{\partial g}{\partial \varphi} \frac{\partial(\Delta t)}{\partial r} \neq 0 \quad \Rightarrow \quad \nabla g \nparallel \nabla(\Delta t)$$

$$G = g \mu_e \ell$$

$$g = \frac{E}{E_1}$$

$$\mu_e = \cos \delta_e$$

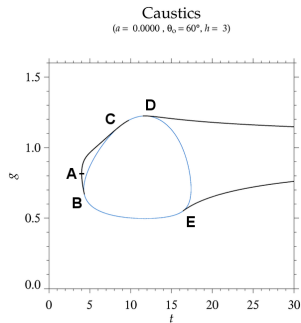
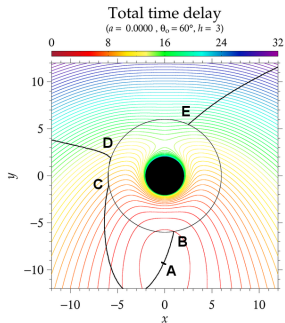
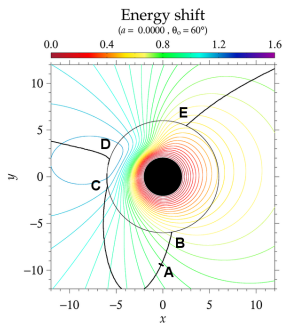
$$\ell = \frac{dS_o}{dS_1^\perp}$$

$$N_{\text{inc}} = g_{\text{inc}}^\Gamma \frac{d\Omega_p}{dS_{\text{inc}}}$$

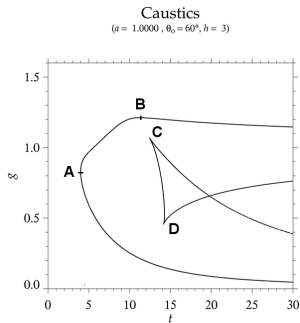
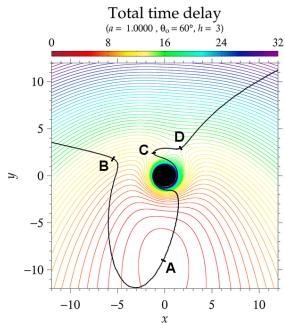
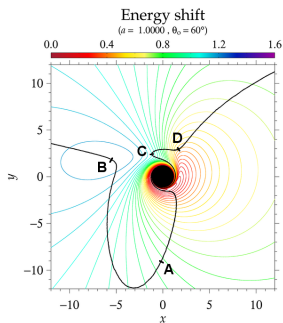
$$\psi_0 = g G N_{\text{inc}} M$$



# Caustics – Schwarzschild case

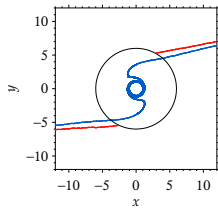


# Caustics – extreme Kerr case

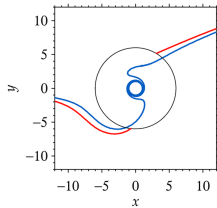


# Caustics

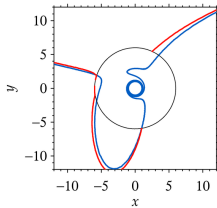
$\theta_0 = 5^\circ, h = 3$



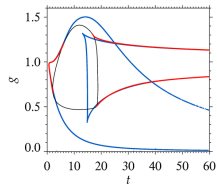
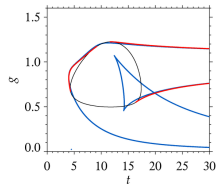
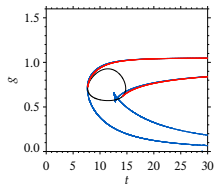
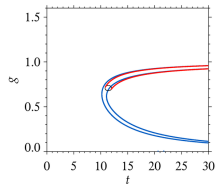
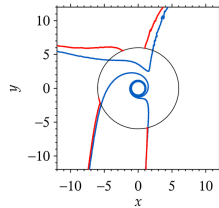
$\theta_0 = 30^\circ, h = 3$



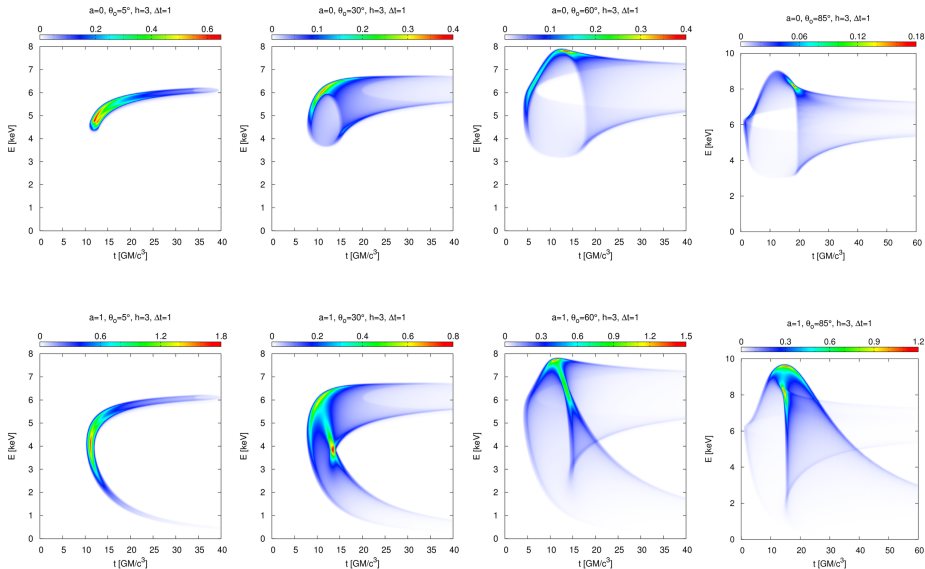
$\theta_0 = 60^\circ, h = 3$



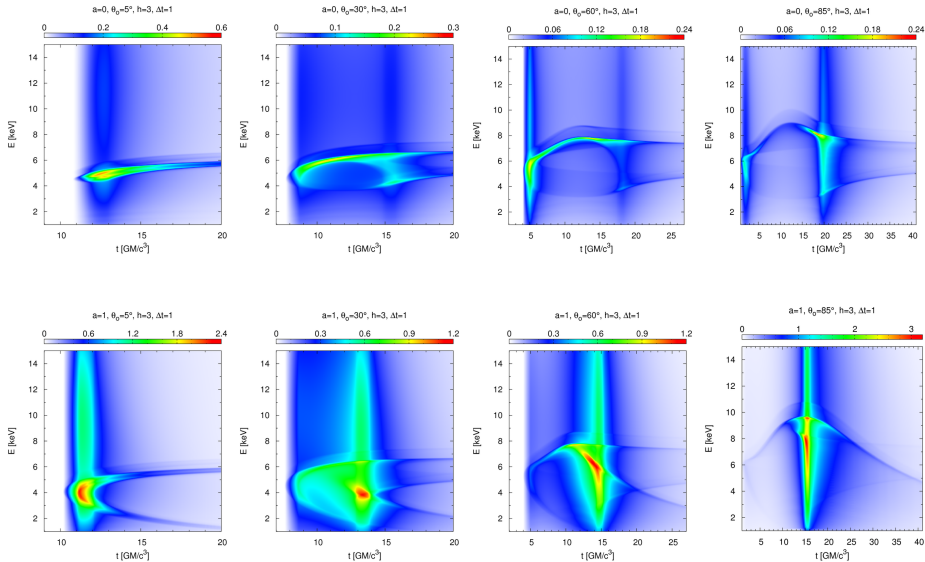
$\theta_0 = 85^\circ, h = 3$



# Dynamic spectrum – narrow spectral line

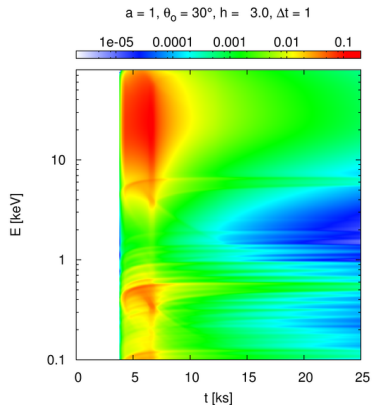
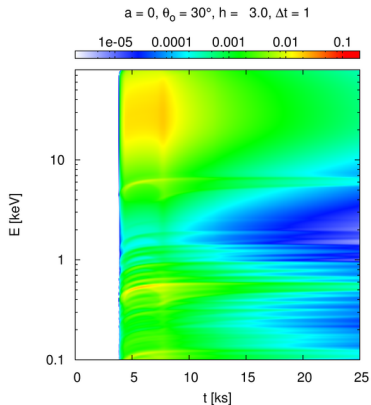


# Dynamic spectrum – the whole reflection



# Dynamic spectrum – ionised disc

$$E^2 \times F(E)$$



# Summary

- ▶ X-ray reverberation mapping of inner parts of AGN is a topical research
- ▶ measuring lags and their frequency and energy dependence may uncover the geometry of corona and properties of the black hole (spin)
  
- ▶ studying AGN is very exciting research
- ▶ using X-rays is inevitable
- ▶ bright future – Athena mission  
(<http://www.the-athena-x-ray-observatory.eu/>)