GR Models of the X-ray Spectral Variability in MCG-6-30-15

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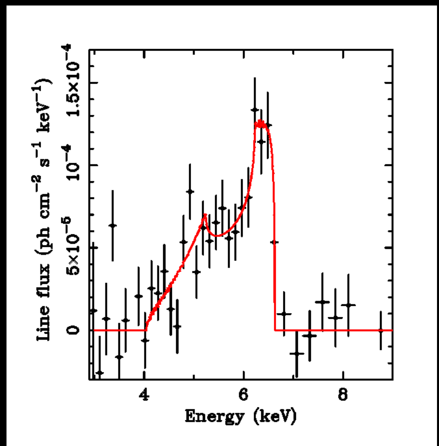
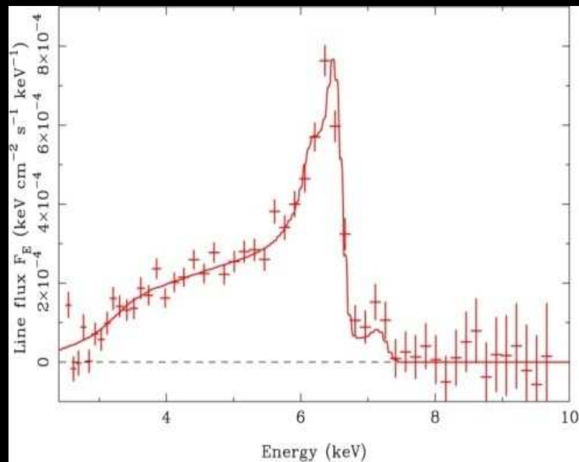
MCG−6-30-15 is a Seyfert 1 galaxy, well known for showing a broad, skewed Fe Kα emission line. The line most likely originates from the innermost regions of an accretion disc and its profile is shaped by gravitational redshift and Doppler shifts.

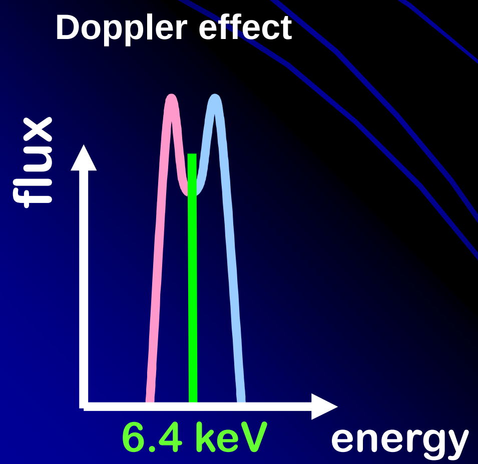
In some observations, the elongated red tail of the line extends to energies much lower than 6.4 keV, indicating strongly enhanced fluorescent emission from a few grav. radii.

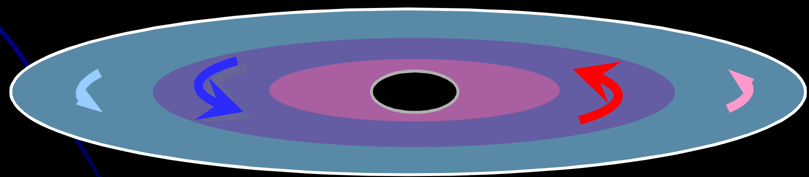
ASCA
Tanaka et al. (1995)

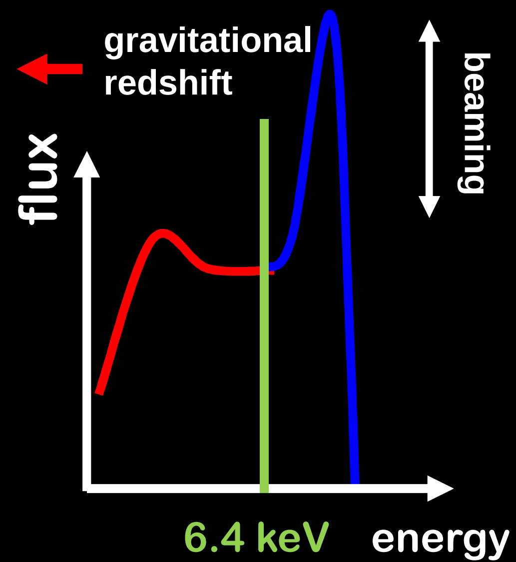




XMM
Fabian et al. (2002)



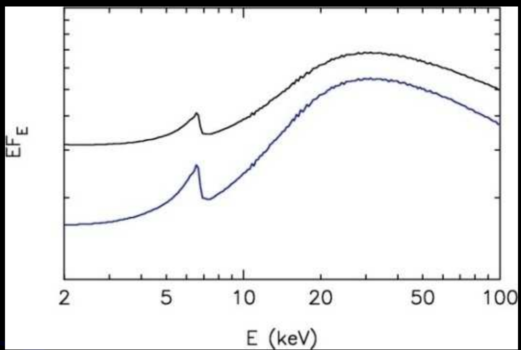




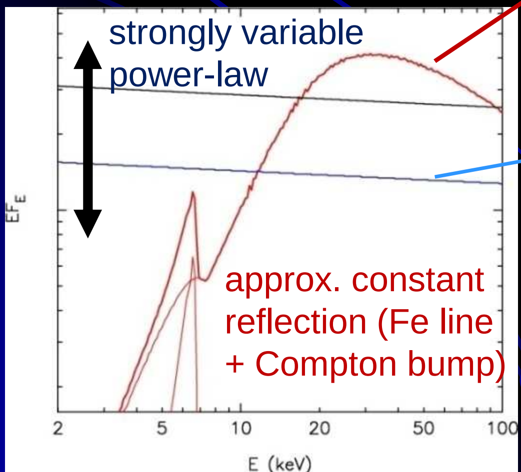
Additional hints for GR effects:

- large values of both the equivalent width of the Fe line and the normalization of the Compton reflected component
- systematic spectral changes with variations of the X-ray flux - indicating strong reduction of the variability of the reflected component

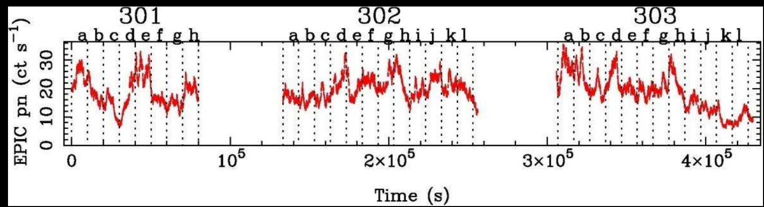
spectral evolution with changes of the X-ray flux ...

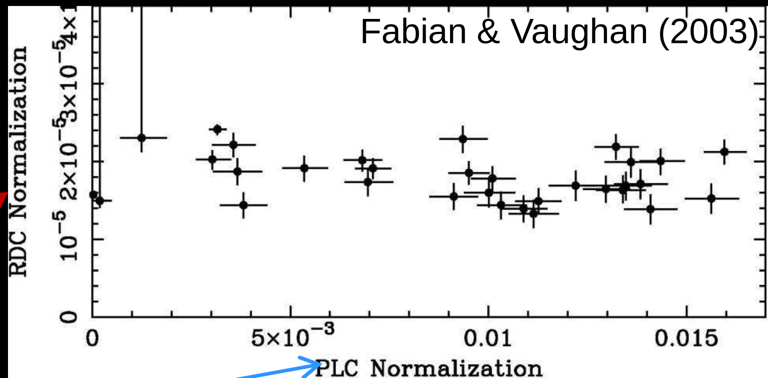


... may be explained by two spectral components with different variability:

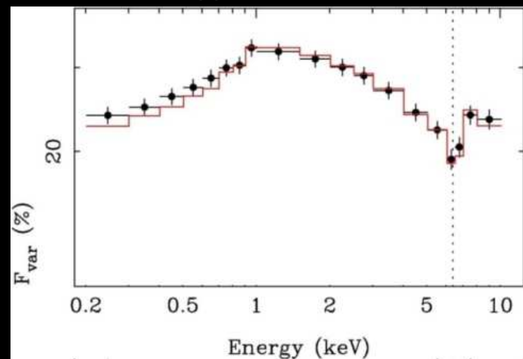


light curve for the 2001 XMM observation



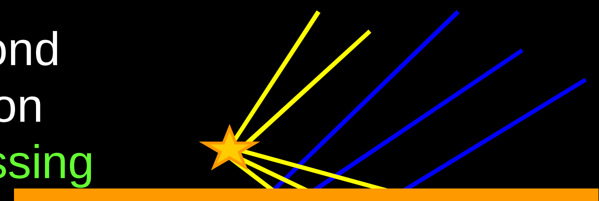


suppressed fractional variability around the Fe line energy

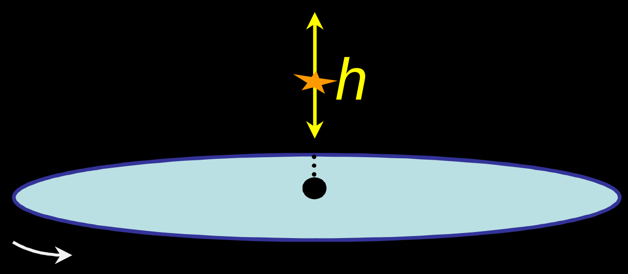


Vaughan & Fabian (2004)

If the observed power-law continuum component gives rise to the reflection component then the latter should respond to variations in the incident continuum on timescales comparable to the light-crossing time: **< 1 ks** for BH mass: (3-6)×$10^6 M_{sun}$

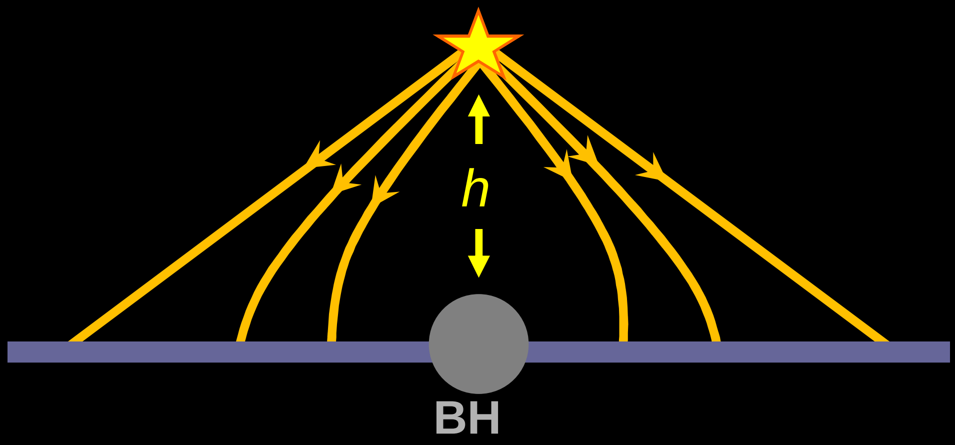


If the observed radiation is generated close to the event horizon, GR effects should increase amplitude of reflection (gravitational focusing toward the disc; Martocchia & Matt 1996), furthermore, variations of the position of the primary X-ray source may result in variability pattern characterized by reduced variability of reflection (Fabian & Vaughan 2003).



Lamp-post geometry: the source located on the symmetry axis, at a varying height.

Changes of the observed primary flux and the illuminating flux seen by the disc are not correlated because of the bending of photon trajectories near the black hole.



For such location of the source: bending toward the center dominates and the enhanced illumination is concentrated within $R < h$. Then, the reflected emission is subject to similar reduction (by GR effects) as the primary emission ...

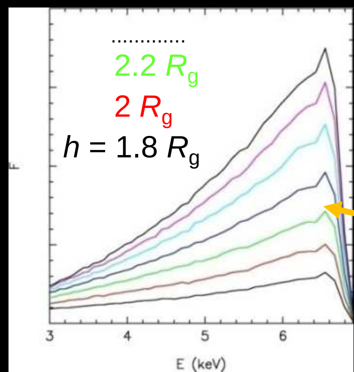
... and variations of both components are strictly correlated:

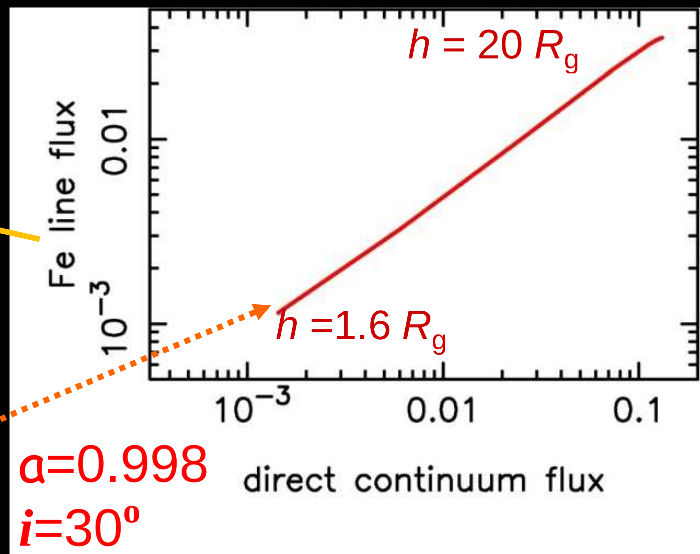
$$a = \frac{J}{cMR_g}$$ – BH spin parameter

$$R_g = \frac{GM}{c^2}$$ – gravitational radius

M – BH mass

J – BH angular momentum

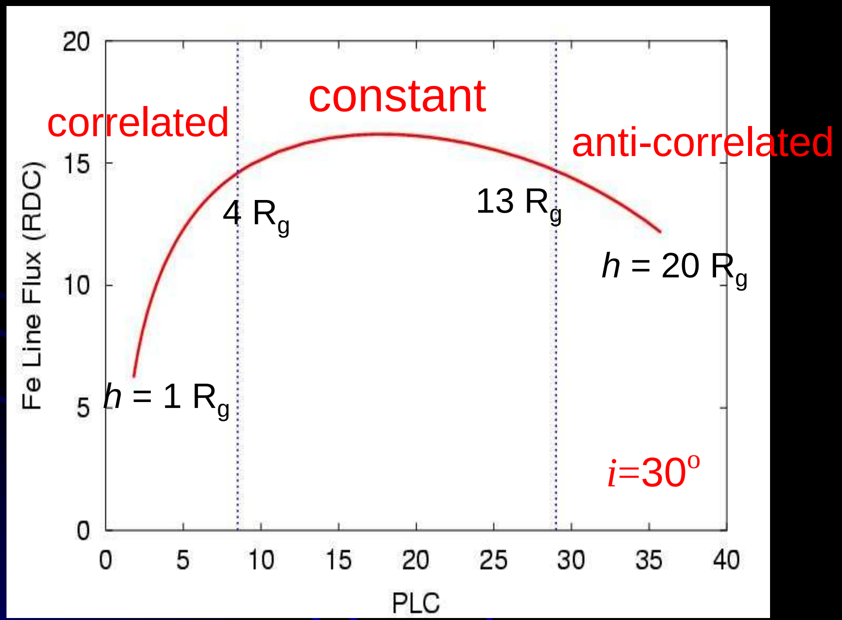




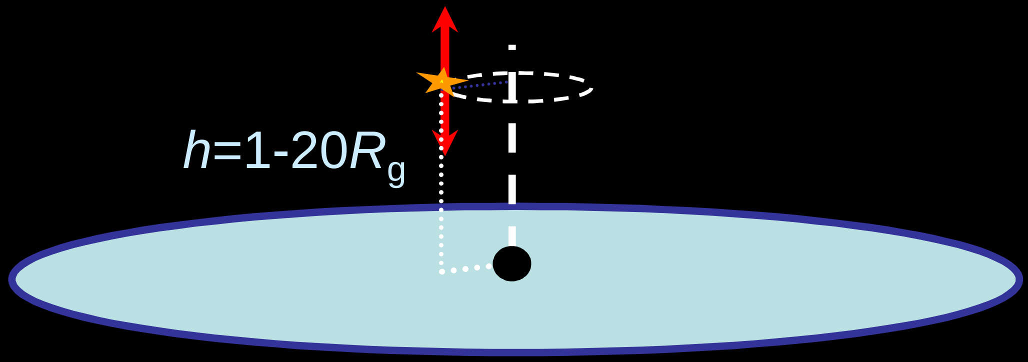
Constant intrinsic luminosity of the primary source; variability of observed fluxes results from varying height of the source

The light bending model (Miniutti et al. 2003, Miniutti & Fabian 2004) – including rotation of the source around the axis and the resulting beaming of its emission toward the outer regions of the disc – predicts that the Fe line flux is:

- correlated with the power-law continuum during low flux states
- constant during intermediate flux states
- anti-correlated during high flux states



Miniutti & Fabian (2004)



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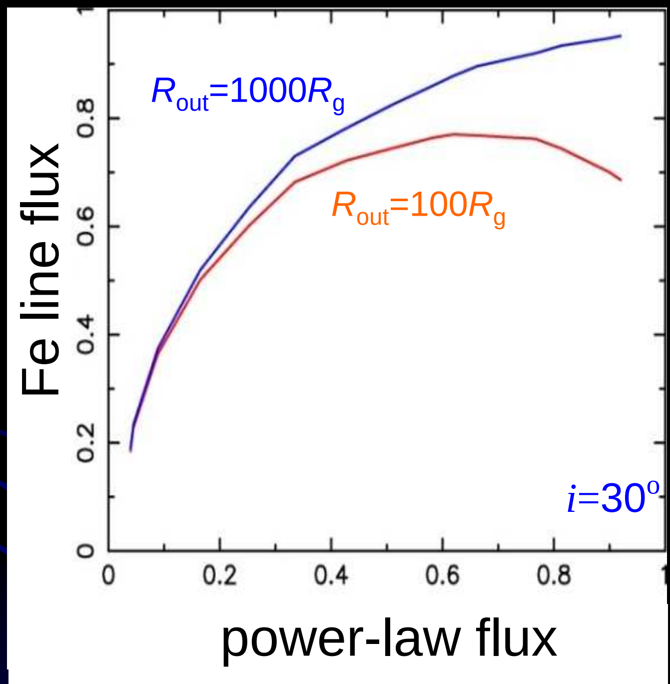
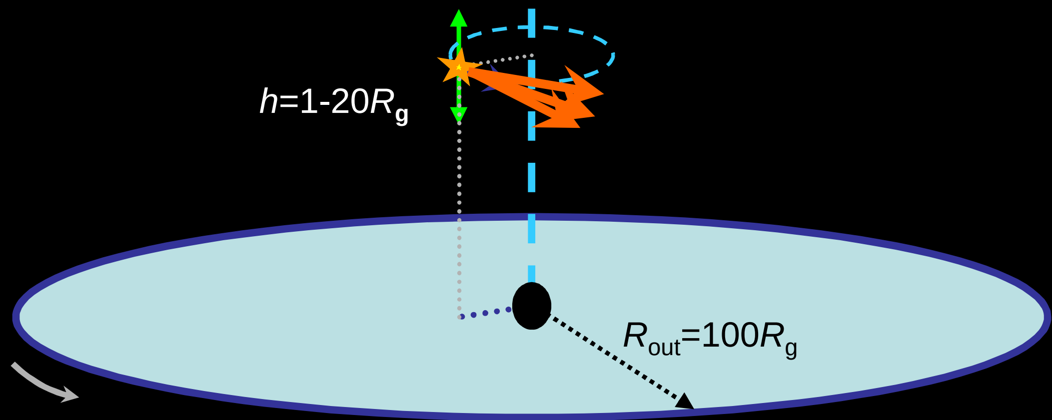


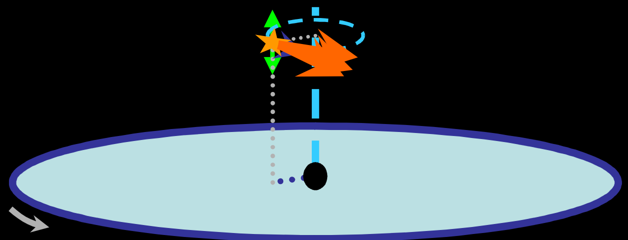


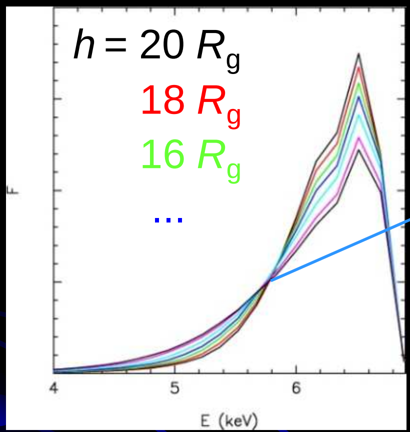
Deviations from strict correlation between the Fe and PL fluxes result primarily from a small extent of the accretion disc (R_{out}=100R_g)

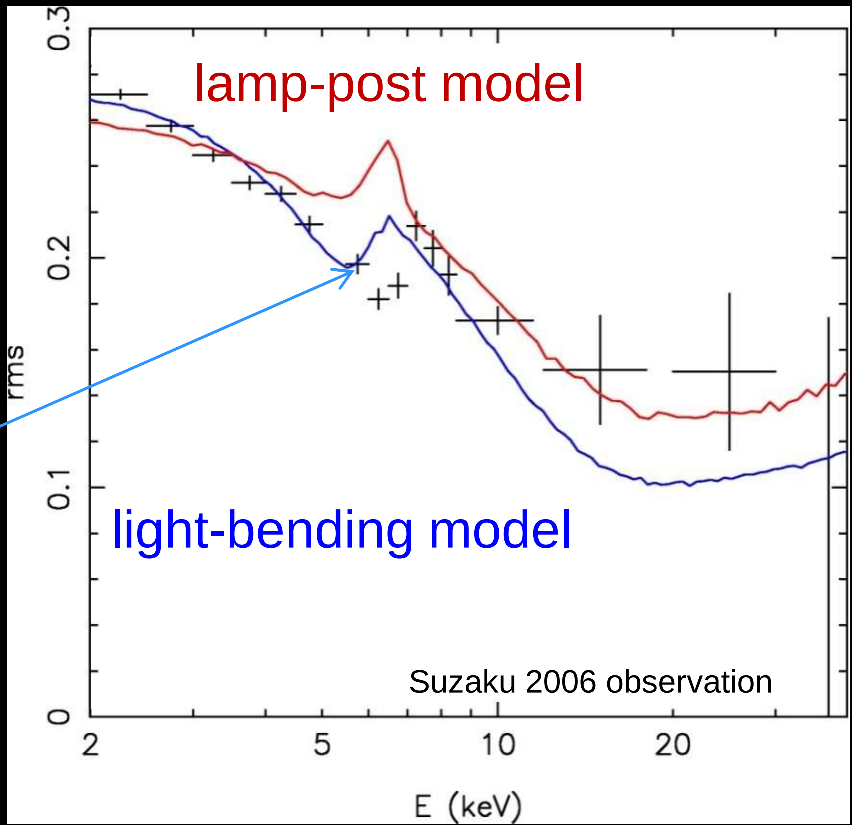
An additional effect involves a non-trivial relation between V and Ω in the Kerr metric (for assumed parametrization V(h) is not a monotonic function)

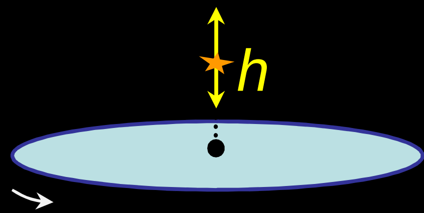
Root mean square spectrum – the fractional variability of observed spectra as a function of energy

$$RMS(E) = \frac{\sqrt{\sum_{i=1}^{N} \frac{[x(E,\Delta t_i) - \langle x(E) \rangle]^2}{N-1}}}{\langle x(E) \rangle}$$









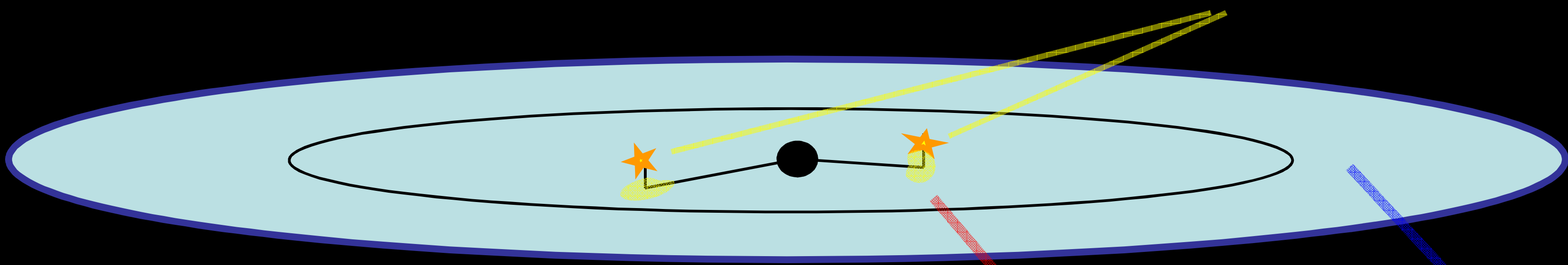
Models involving vertical motion of the X-ray source do not reproduce the observed rms(E) spectrum

The observed variability pattern may be fully explained under assumption that the primary hard X-ray emission is subject to bending to the equatorial plane (a distinct property of the Kerr space-time, strongly affecting trajectories of photons emitted at distances $< 4\ R_g$ from a rapidly rotating, $a > 0.9$, black hole). Variability is than reproduced by models with varying radial position of the X-ray source (Niedzwiecki & Zycki 2008)

$$a = \frac{J}{cMR_g}$$

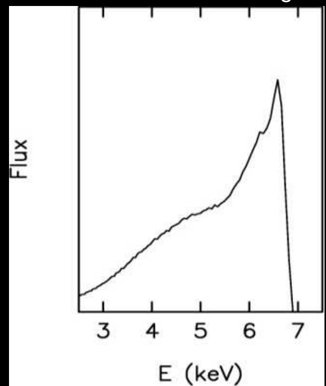
$$R_g = \frac{GM}{c^2}$$

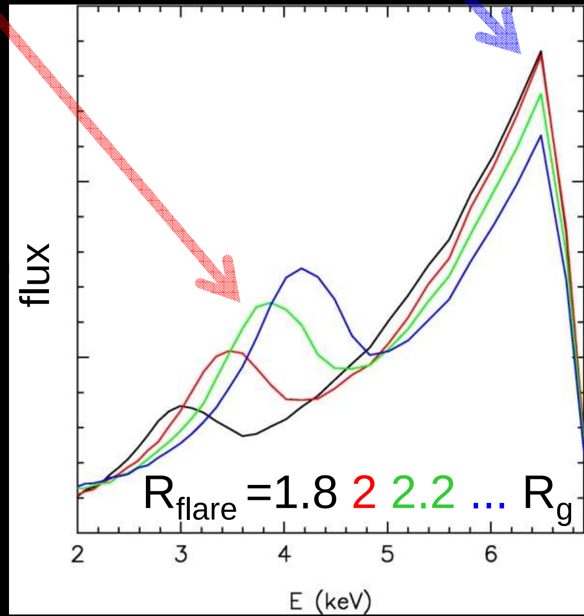
compact flares occurring at various radial distances R_{flare}

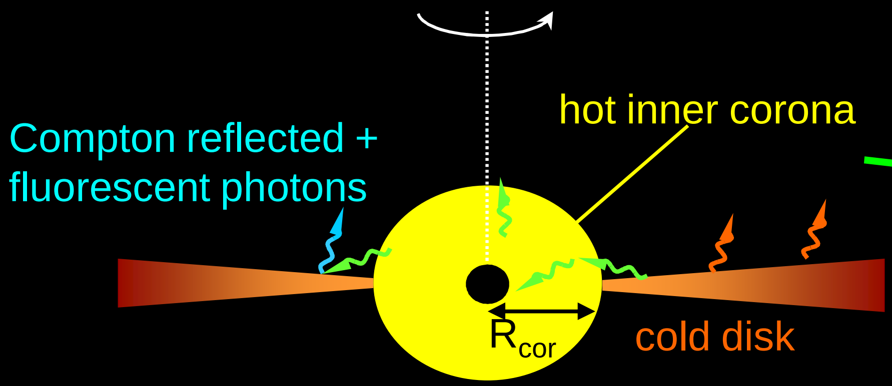


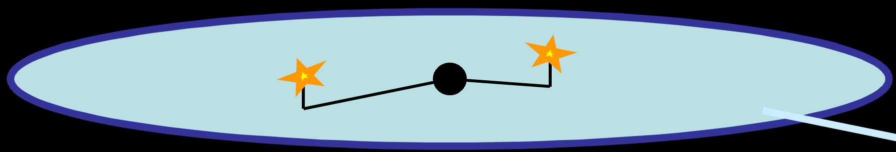
Decrease of R_{flare} results in (*i*) strong reduction of the observed primary flux; and (*ii*) more efficient bending to outer regions of the disc. The latter gives rise to approximately constant illumination of the disc surface at ≥ 10 R_g - where photons forming the blue peak originate

Smooth tail in profile averaged over several flares with distances between R_{flare} = 1.8 and 3 R_g

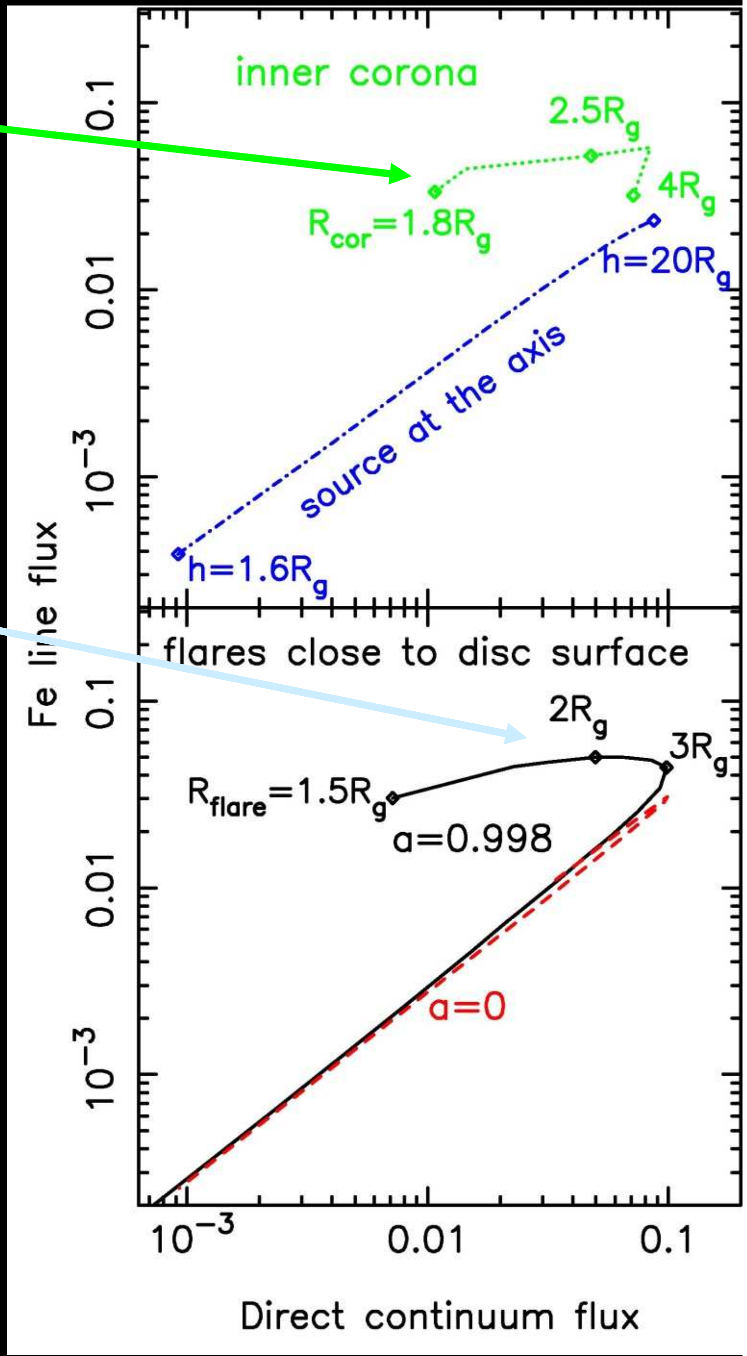






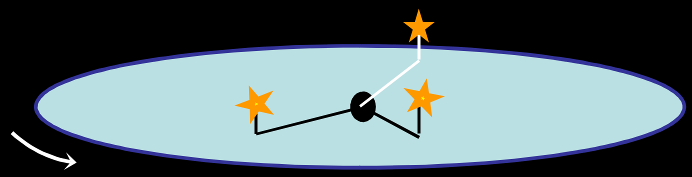


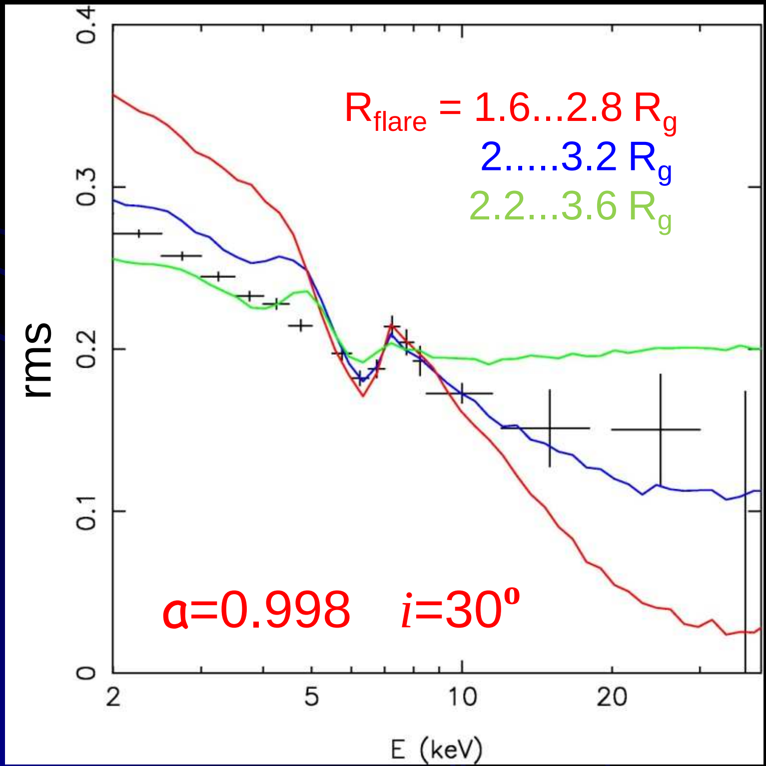
Bending to the equatorial plane, coupled with changes of the radial distance, gives rise to reduction of the variability of reflected component for various geometries of the X-ray source located within 4 R_g

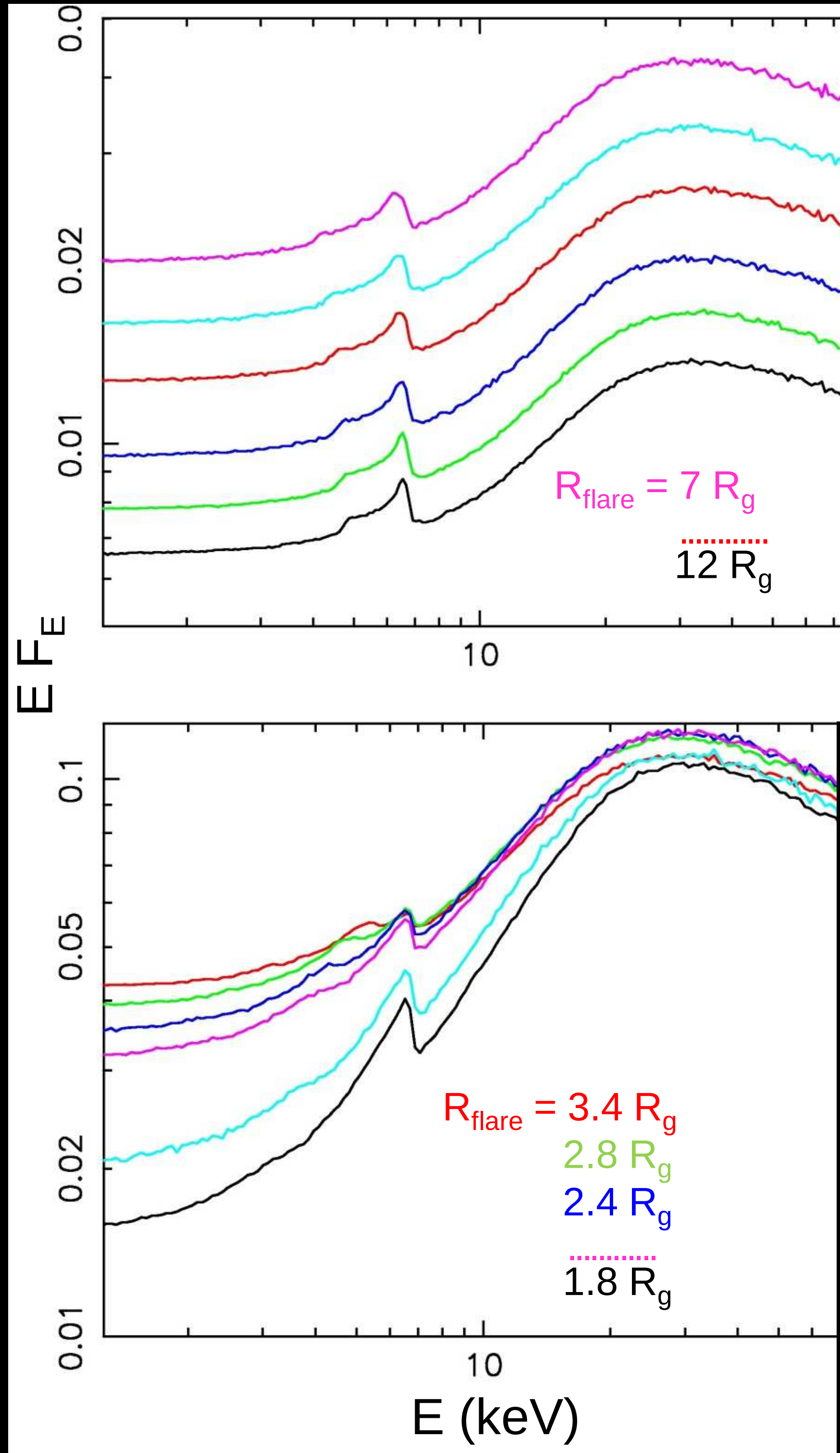


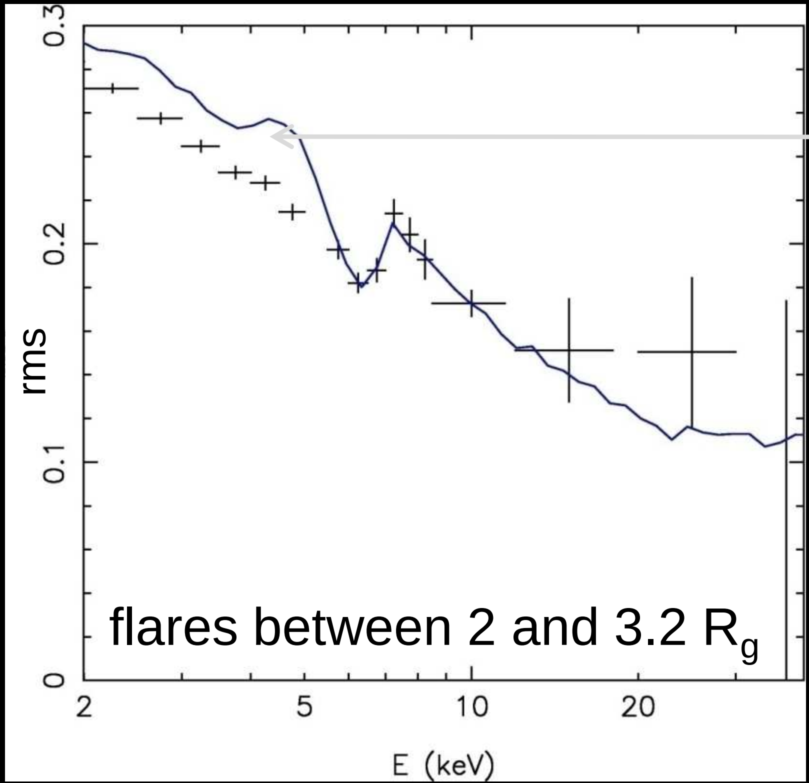
Intrinsic luminosity of flares related to dissipation rate in the Keplerian disc at R_{flare}

Suppressed variability around 6.4 keV reproduced only in models involving changes of radial position in the Kerr metric

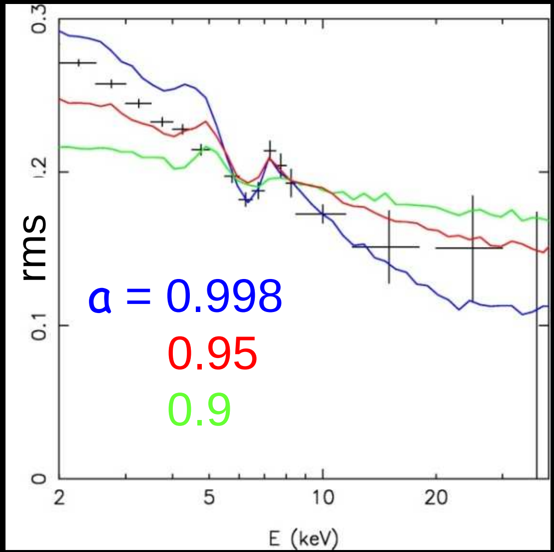


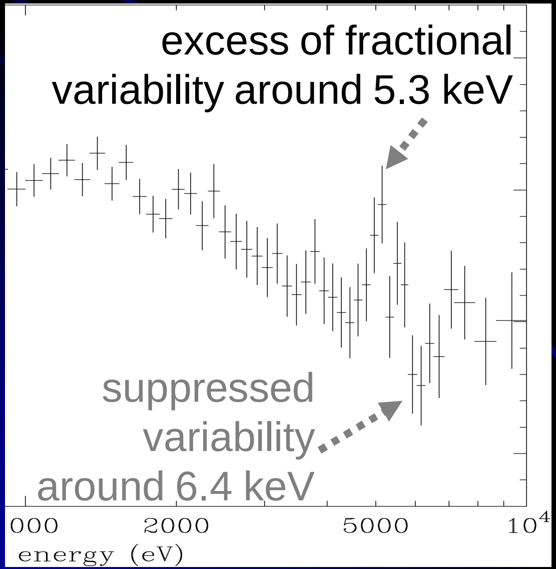




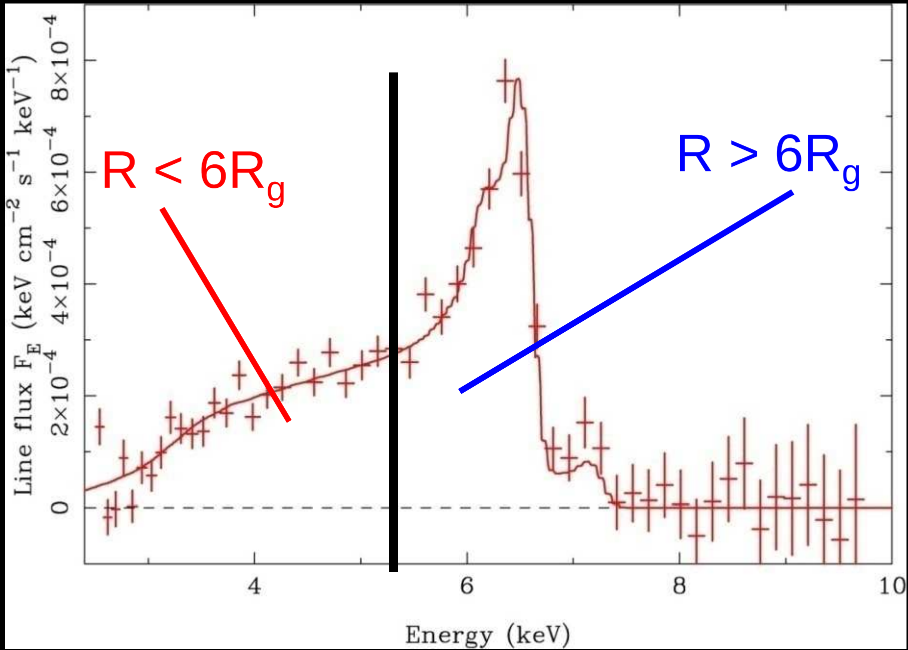


Excess resulting from changes in the shape of the red wing of the line (ionization; spin parameter ???)





Ponti et al. (2004): evidence for additional variability around 5 keV in the 2000 *XMM observation*



Fabian et al. (2002):

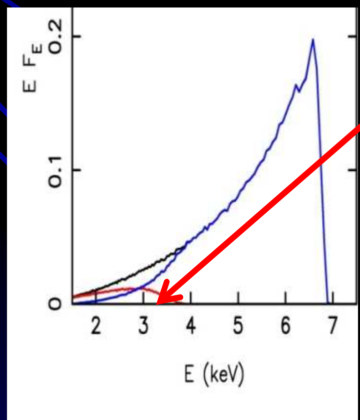
radial emissivity of Fe emission, $\varepsilon(R) \sim R^{-\beta}$:

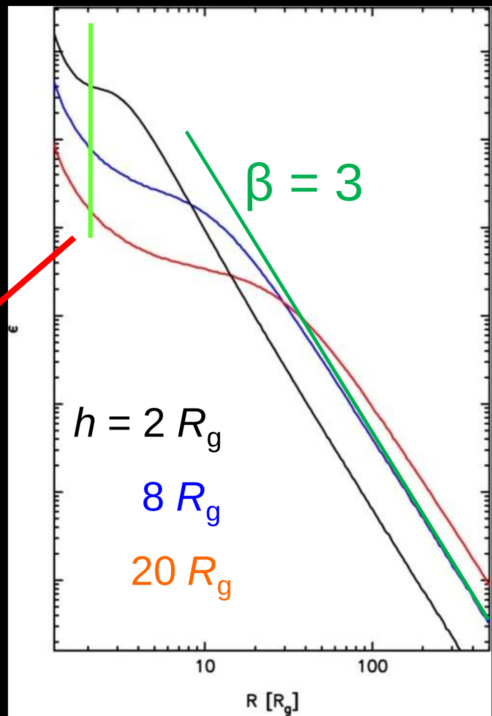
a broken power-law with:

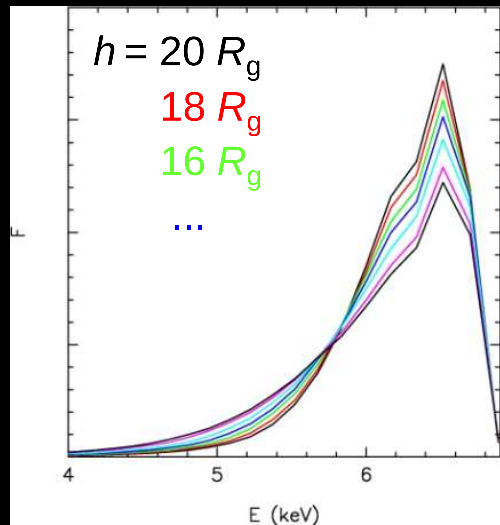
$R > 6R_g$ $\beta_1 \approx 3$

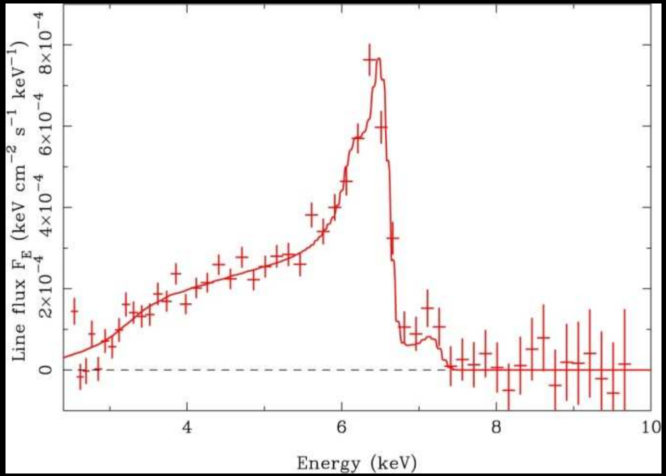
$R < 6R_g$ $\beta_2 > 4$

$\beta > 3$ ONLY within 2 R_g – not relevant for the line profile at E > 3 keV

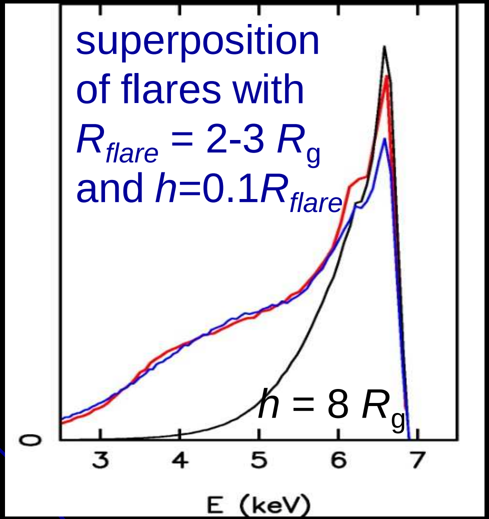


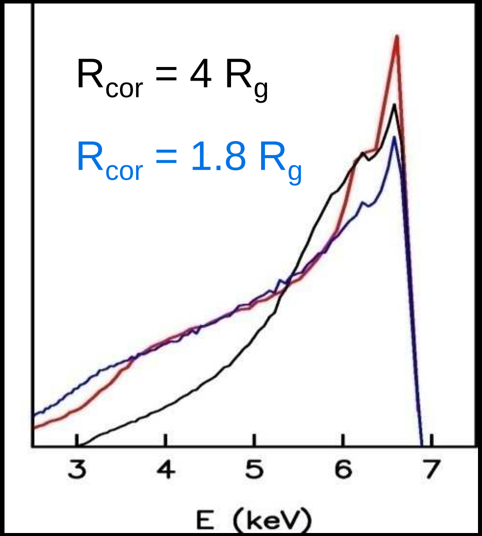




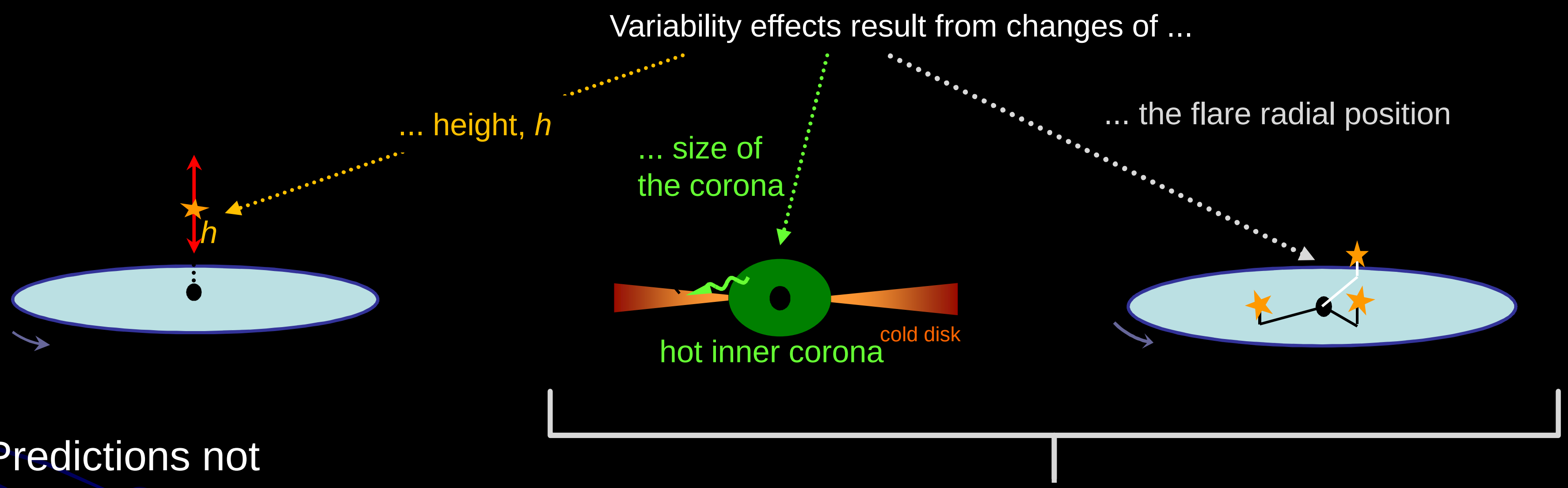


Modeling of the red tail requires illumination of the disc by an X-ray source located within 4 R_g





Summary: the observational data - we already have - put strong constraints on the geomtry of the X-ray source and properties of the space-time metric



Predictions not consistent with observed properties

OK; require rapid rotation of the black hole

Both the time-averaged Fe line profile and the variability pattern observed in MCG-6-30-15 independently indicate that the hard X-ray source must be located very close (within 4 R_g) to the black hole, i.e. in the region where Kerr metric effects become crucial.