Minimum X-ray source size for a lamppost corona in light-bending models for AGN

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From the Dolomites to event horizon: Sledging down the Black Hole potential well (3rd ed.)

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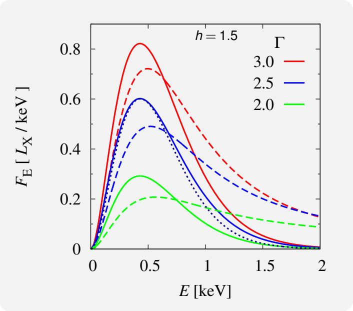
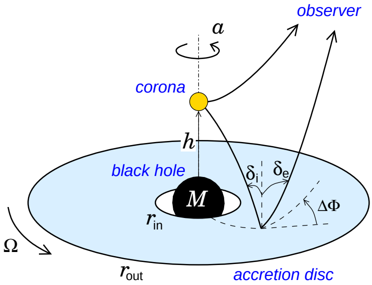
Scheme of the lamp-post geometry

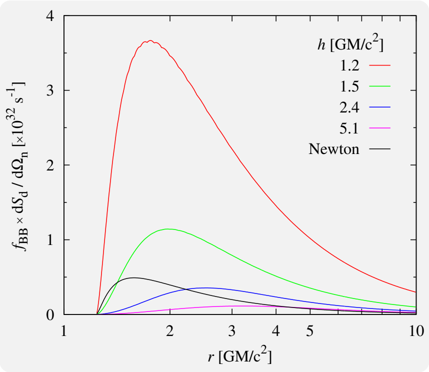
- central black hole – mass, spin
- accretion disc
  → Keplerian, geometrically thin, optically thick
  → Novikov-Thorne thermal emission
  (T_{NT}, M, $\dot{M} = \frac{L_b}{\eta c^2}$, a, f_c)
- compact corona with isotropic emission
  → height, luminosity, size (radius),
  optical depth (h, L_X or L_{obs}, R, τ)
- up-scattering in the corona
  → `nthcomp`(E; Γ, E_c, T_{BB})
- relativistic effects:
  → Doppler and gravitational energy shift
  → light bending (lensing)
  → aberration (beaming)

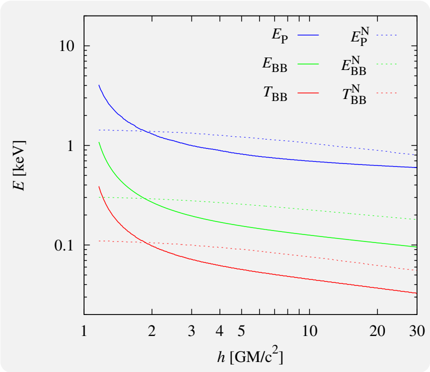
$M = 10^7 M_\odot$, $L_b = L_{Edd}$,
$a = 0.998$, $\eta = 32.4\%$, $f_c = 2.4$





Thermal photon flux arriving at corona





$$f_{\rm in} = \frac{8\pi\zeta(3)k^3}{f_{\rm c}^4\, h^3\, c^2} \int_{r_{\rm in}}^{r_{\rm out}} {\rm d}r\, r\, \frac{{\rm d}\Omega_{\rm L}}{{\rm d}S_{\rm d}}\, (g\, T_{\rm NT})^3$$

$$F_{\rm in} = \frac{4\pi^5 k^4}{f_{\rm c}^4\, 15\, h^3\, c^2} \int_{r_{\rm in}}^{r_{\rm out}} {\rm d}r\, r\, \frac{{\rm d}\Omega_{\rm L}}{{\rm d}S_{\rm d}}\, (g\, T_{\rm NT})^4$$

$$\frac{{\rm d}\Omega_{\rm n}}{{\rm d}S_{\rm d}} = \frac{h}{D^3}, \quad g = \frac{E_{\rm L}}{E_{\rm d}}$$

$$T_{\rm BB} = \frac{E_{\rm peak}}{2.82}, \quad E_{\rm BB} = \frac{F_{\rm in}}{f_{\rm in}}, \quad E_{\rm P} = \frac{L_{\rm X}}{f_{\rm out}}$$

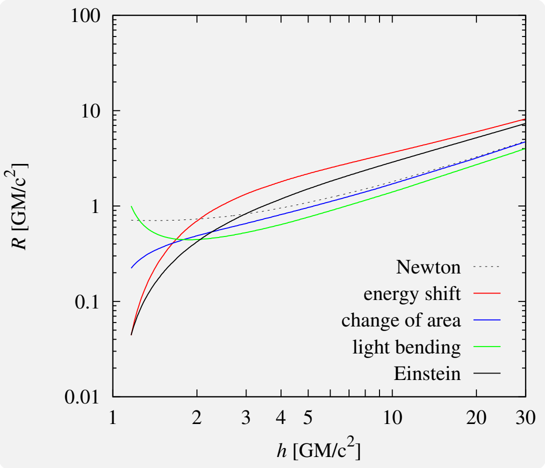
$$F_{\rm th}(E_{\rm peak}) = {\rm MAX}[F_{\rm th}(E)]$$

$$f_{\rm out} = \int_0^\infty \texttt{nthcomp}(E; \Gamma, E_{\rm c}, T_{\rm BB})\, {\rm d}E$$

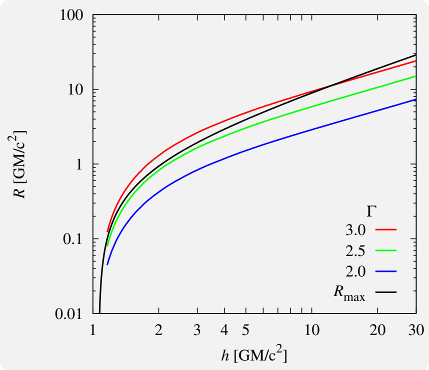
Size of the corona - components

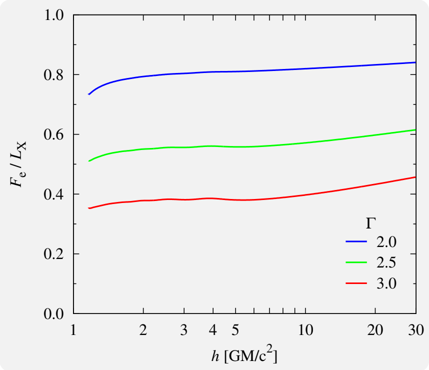
$$(1 - e^{-\tau})\, f_{\rm in} \mathrm{d}S_{\rm L} = f_{\rm out}$$

$$R = \sqrt{\frac{1}{\pi} \frac{g_{\rm L}}{1 - e^{-\tau}} \frac{f_{\rm out}}{f_{\rm in}}}$$



Size of the corona – constant intrinsic luminosity





$L_X = 0.031\, L_{Edd}$
$(L_{obs} = 0.02\, L_{Edd}$ at $h = 10\, GM/c^2)$

$$\Sigma_e = \frac{\tau}{\sigma_t} \sim 10^{23} - 10^{24}\,\mathrm{cm}^{-2}$$

$$n_e = \frac{\Sigma_e}{l} \sim 10^{9} - 10^{12}\,\mathrm{cm}^{-3}$$

Γ	τ
2	0.85
2.5	0.4
3	0.2

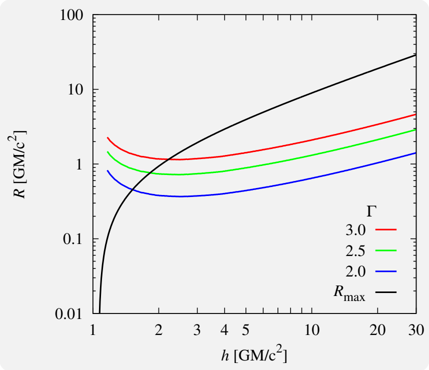
computed with `compps`

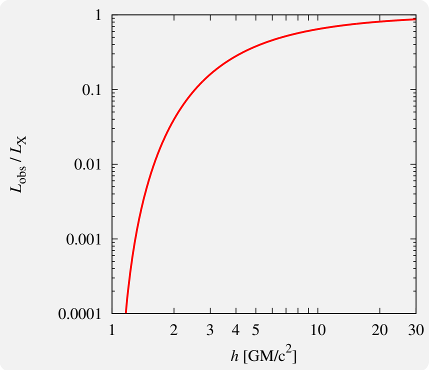
$$\frac{F_e}{L_X} = 1 - \frac{F_{in}}{L_X}\frac{f_{out}}{f_{in}}$$

$$(1 - e^{-\tau})\, f_{in} dS_L = f_{out}$$

$$R = \sqrt{\frac{1}{\pi}\frac{g_L}{1-e^{-\tau}}\frac{f_{out}}{f_{in}}}$$

Size of the corona – constant observed luminosity



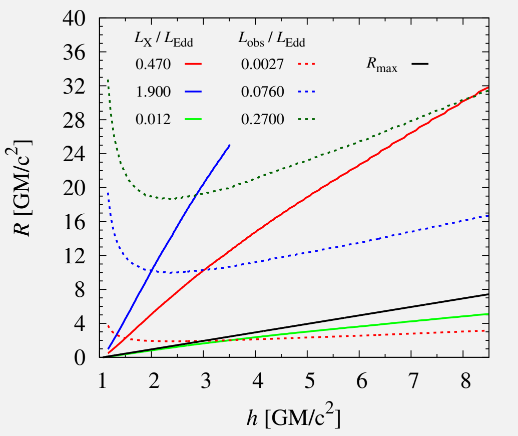


$L_{obs} = 0.001\, L_{Edd}$

$$\frac{L_{obs}}{L_X} = g_L^2 \frac{d\Omega_L}{d\Omega_o}$$

What size of the corona is needed for the given observed luminosity if the corona is at height h?

Application to 1H0707-495



- dotted red $\rightarrow$ size for the minimum L_{obs}
- solid red $\rightarrow$ size for the light bending scenario, L_X set from the minimum L_{obs} at $h = 1.5$
- dotted dark green $\rightarrow$ size for the maximum L_{obs}
- dotted blue $\rightarrow$ size for the average L_{obs}
- solid blue $\rightarrow$ size for the light bending scenario, L_X set from the average L_{obs} at $h = 2$
- solid green $\rightarrow$ size for the light bending scenario, L_X set from the minimum L_{obs} at $h = 3.5$ $\rightarrow$ pure light bending scenario cannot reach maximum L_{obs}

$F_o(0.3 - 10\mathrm{keV}) =$
$2 \times 10^{-13} - 2 \times 10^{-11}$
$\mathrm{erg\,cm^{-2}\,s^{-1}}$

$$L_{obs} = 4\pi D^2 F_o(0.3 - 10\mathrm{keV}) \frac{\int_0^\infty E\,\mathtt{nthcomp}(E;\Gamma,E_c,T_{BB})\,\mathrm{d}E}{\int_{0.3/g_L}^{10/g_L} E\,\mathtt{nthcomp}(E;\Gamma,E_c,T_{BB})\,\mathrm{d}E}$$

Conclusions

General conslusions:

- for reasonable assumptions the corona is not tiny but still may be quite small (even of the order of $1 - 10\, r_{\rm g}$),
- in light bending scenario with inverse Compton the corona has to change size (geometry), it scales with height,
- for larger Γ we need smaller τ and both increase R,
- point-source approximation is not valid, **3D** computations with **non-spherical** geometry and corona **rotation** are needed for more accurate corona size (and shape) estimation.

Conclusions

Conslusions on 1H0707-495:

- due to high observed flux in 1H0707-495, in the pure light bending scenario the small spherical patch of corona does not fit above the horizon,
- **Wilkins & Fabian (2012)** reproduce the steep radial emissivity with an extended corona (up to $30R_g$) at low height ($2R_g$),
- such an extended corona probably cannot change its emissivity to $100\times$ larger luminosity either through light bending scenario or by extending it even further outside,
- thus could the inner accretion have higher temperature to produce more photons? (the disc in our assumptions already shines at $L_{\rm Edd}$),

Conclusions

- however, the steep decrease of radial emissivity might be artificial due to wrong assumptions on local emission directionality and radial decrease of ionisation, see **Svoboda et al (2012)** and his poster,
- thus the extension may be much smaller ($2\,r_{\rm g}$ at height $2-3\,r_{\rm g}$) and maybe the maximum flux could be explained by changing corona size and geometry, e.g. by extending it further outside ($20\,r_{\rm g}$ at height $2-3\,r_{\rm g}$)?
- **3D** computations with **non-spherical** geometry and corona **rotation** are needed for more accurate estimations.