On the origin of X-ray disc-reflection steep radial emissivity

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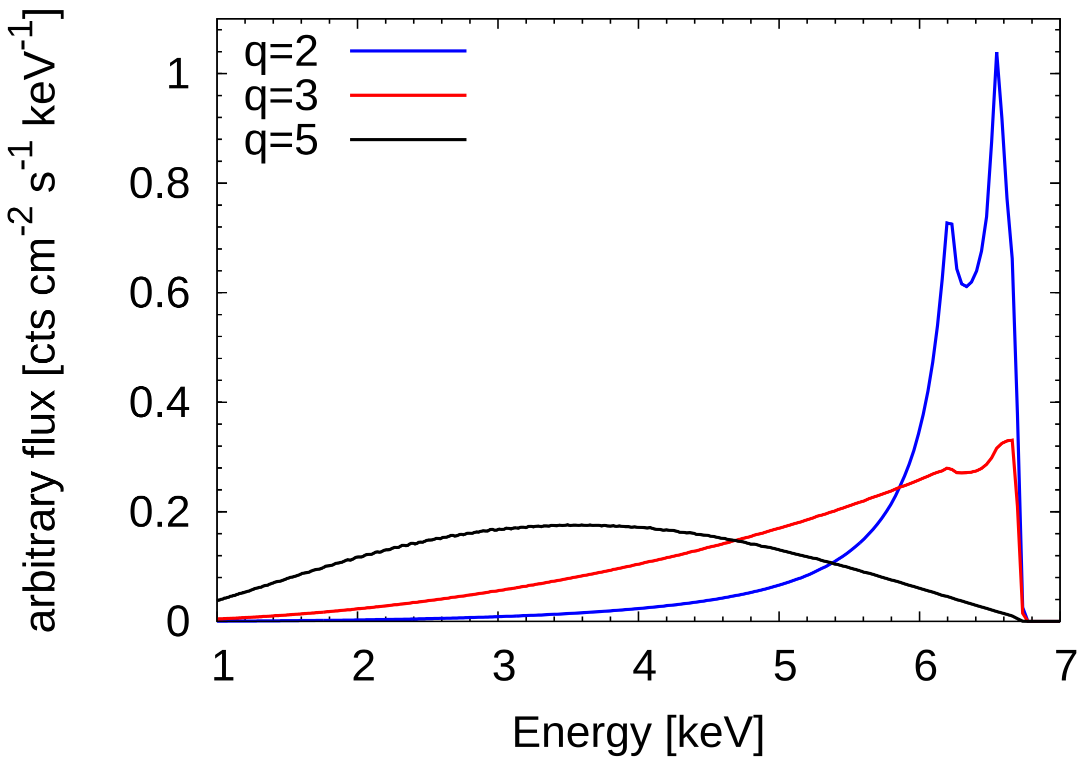
Outline

- Introduction
  - → spin measurements by relativistic iron lines (Laura Brenneman's and Refiz Duro's talk)
  - → radial emissivity in relativistic models of broad iron lines
  - → steep radial emissivity in observations
- Origin of the steep radial emissivity
  - → irradiation by a lamp-post corona
  - → angular directionality
  - → influence of radially dependent ionisation
- Conclusions

Radial emissivity in the relativistic iron lines



- radial dependence: $\mathcal{R}(r_{\mathrm{e}}) \propto r_{\mathrm{e}}^{-q}$ (or a broken power law)
- KYRLINE (Dovčiak et al., 2004), $a = 0.9982$, $\theta_{\mathrm{o}} = 30\,\mathrm{deg}$, $E_0 = 6.4$ keV, $r_{\mathrm{in}} = r_{\mathrm{ms}}(a) = 1.23$, $r_{\mathrm{out}} = 400$, and isotropic angular emissivity

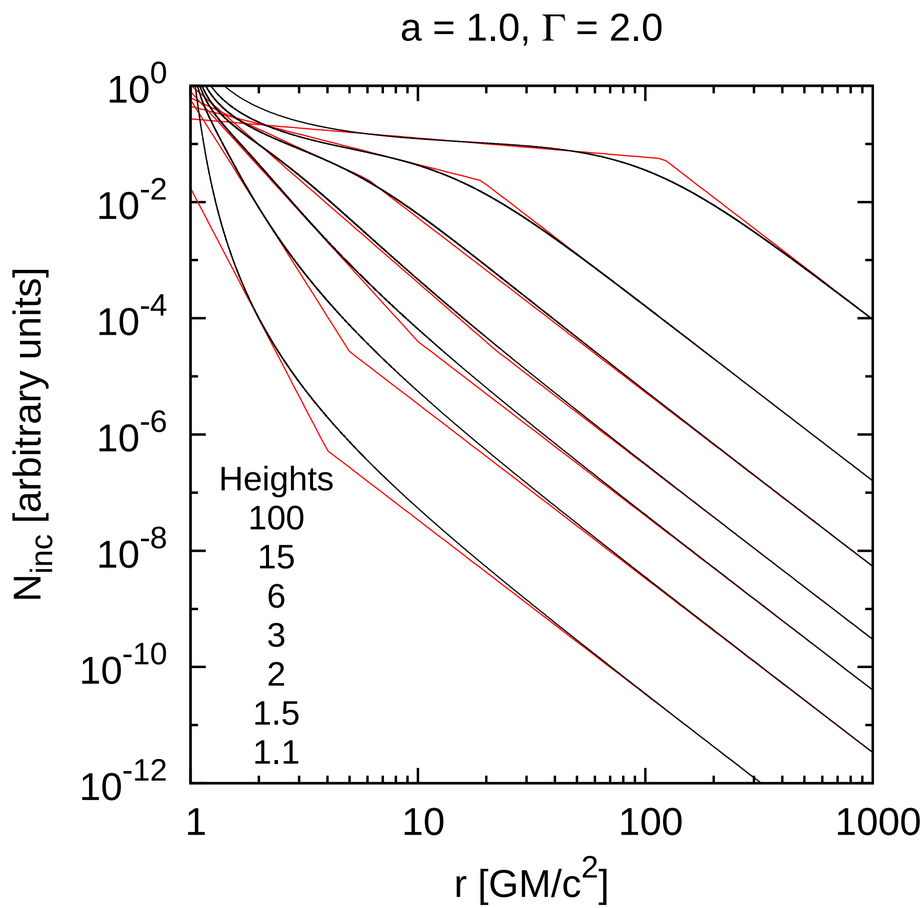
Steep radial emissivity in observations

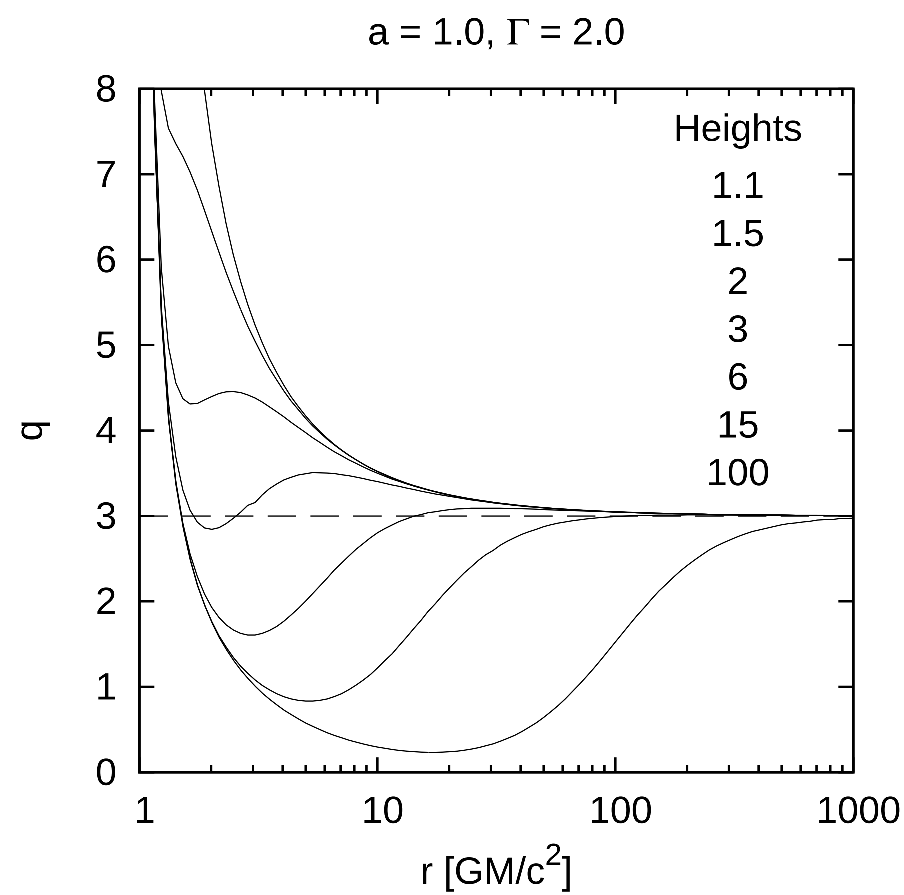
- many observations of active galaxies and Galactic black hole binaries require steep radial emissivity in the relativistic iron line profile than expected (standard value $q = 3$, $I(r_\mathrm{e}) \propto {r_\mathrm{e}}^{-q}$)
- examples:
  - → MCG -6-30-15: $q_1 = 4.8 \pm 0.7$, $r_\mathrm{br} = 6.5^{+4.5}_{-1.4}\, r_\mathrm{g}$ (Fabian et al., 2002)
  - → 1H0707-495: $q_1 \approx 7.5$, $r_\mathrm{br} \approx 4.5\, r_\mathrm{g}$ (Fabian et al., 2009)
  - → IRAS 13224-3809: $q \approx 5 - 9$ (Ponti et al., 2010)
  - → XTE J1650-500, GX 339-4: $q \approx 5.5$ (Miller et al., 2002, 2004)
  - → Cyg X-1 (Duro et al., 2011, Fabian et al., 2012)
- possible explanations:
  - → centrally localised corona ("lamp-post geometry") (Matt et al., 1991, Martocchia et al., 2000, Wilms et al., 2001, Wilkins et al., 2012)
  - → usage of an improper emission directionality (Svoboda et al., 2009)
  - → radially stratified ionisation (Svoboda et al., submitted)

Part I. Lamp-post geometry of the corona

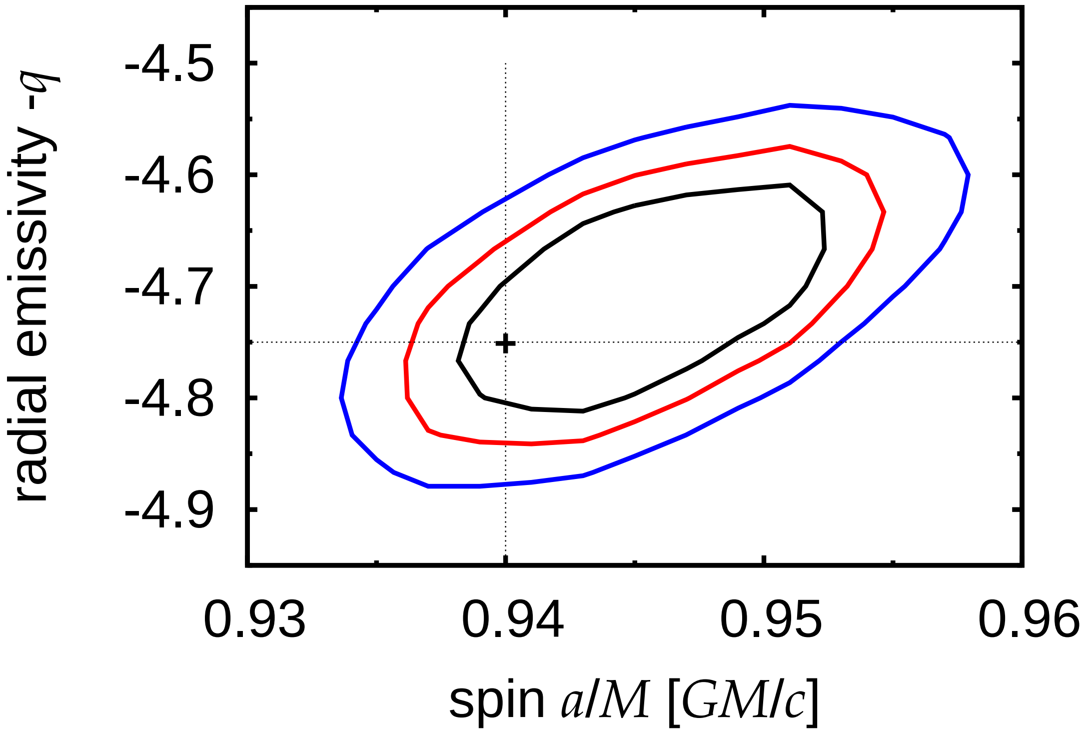
- (point-like) source above the black hole (Dovčiak et al., before submission, see also Wilkins et al. 12 and poster by Dauser et al.)
- radial emissivity: $$q \equiv \frac{\mathrm{d}\log N_{\mathrm{inc}}}{\mathrm{d}\log r}$$

  $\rightarrow$ differs from a broken power law, very steep only for $h < 2\,r_{\mathrm{g}}$





Radial emissivity in the lamp-post geometry



- data simulated by a power law ($\Gamma = 1.9$) and relativistic iron line in the lamp-post geometry with $a_{\mathrm{def}} = 0.94$, $i_{\mathrm{def}} = 30\,\mathrm{deg}$ and $h = 1.5\,r_{\mathrm{g}}$

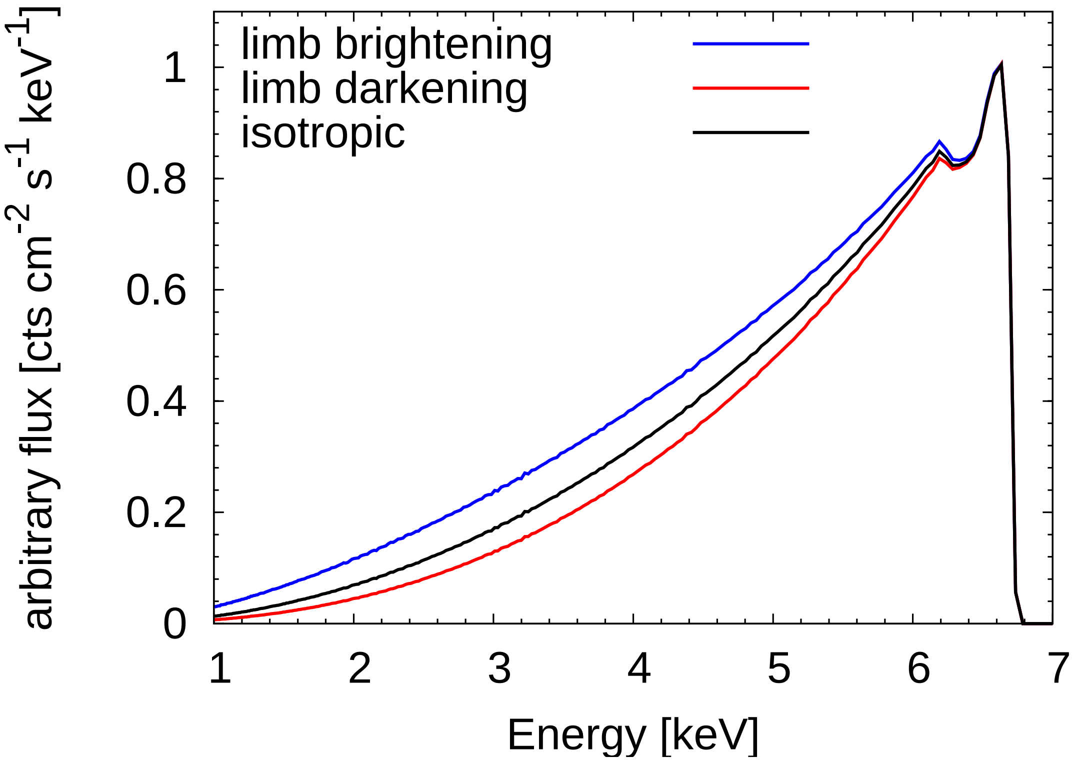
- then fitted by a model with the radial emissivity described as a broken power-law (with $q = 3$ at the outermost disc)

- steep indices, $q \lesssim 5$, found in the inner disc (break radius $r_{\mathrm{b}} \sim 6\,r_{\mathrm{g}}$)

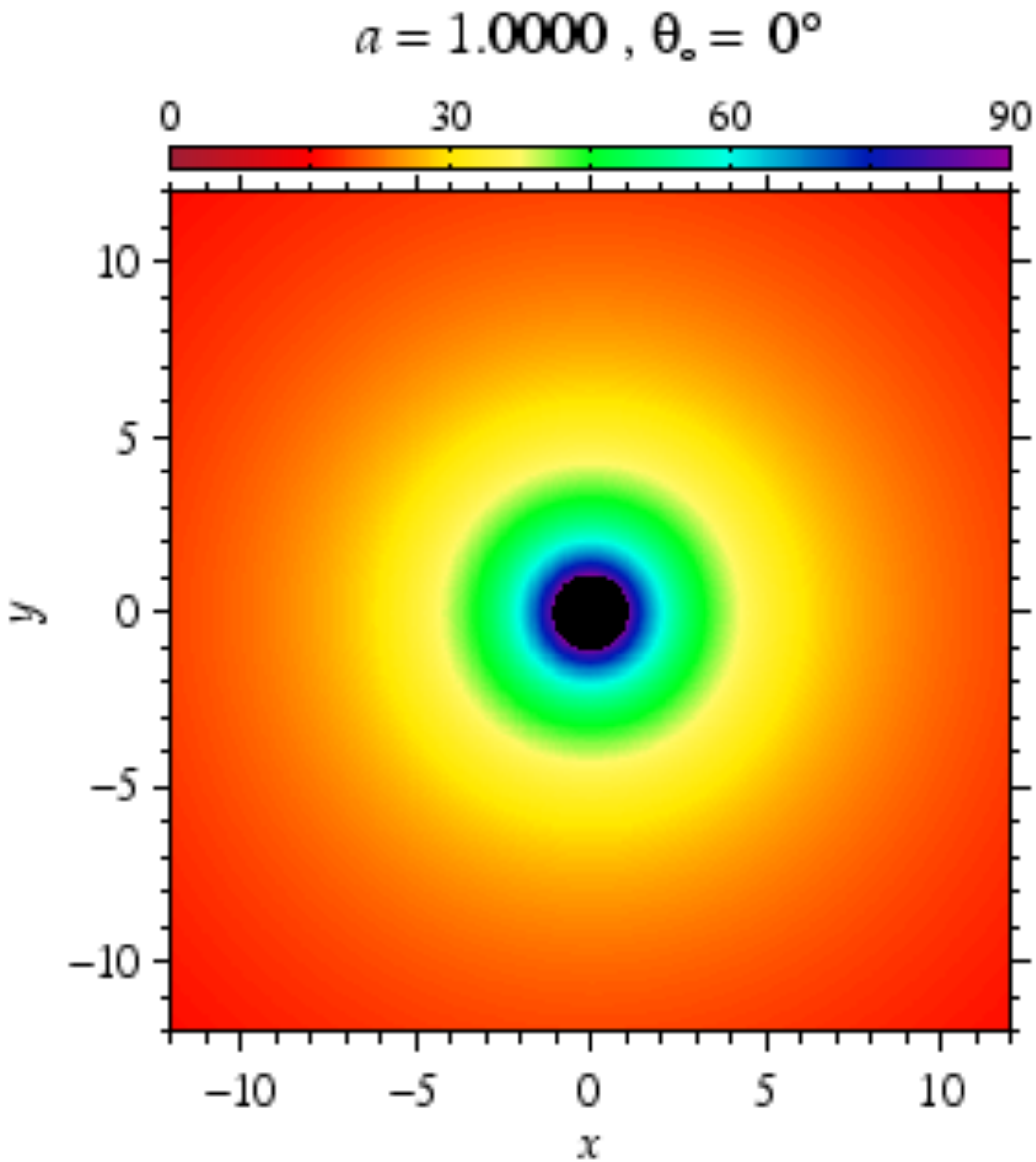
Part II. Emission directionality in reflected radiation

- **emission directionality** $\mathcal{M}(\mu_{\rm e}, r_{\rm e}, E_{\rm e})$ = dependence of the intensity on the emission angle ($\mu_{\rm e} = \cos\theta_{\rm e}$)

$$\mathcal{M}(\mu_{\rm e}) = \begin{cases} \ln(1+\mu_{\rm e}^{-1}) & \text{limb brightening, Haardt 93} \\ 1 & \text{(locally isotropic emission)} \\ 1 + 2.06\,\mu_{\rm e} & \text{limb darkening, Laor 91} \end{cases}$$



Emission angle from a black hole accretion disc

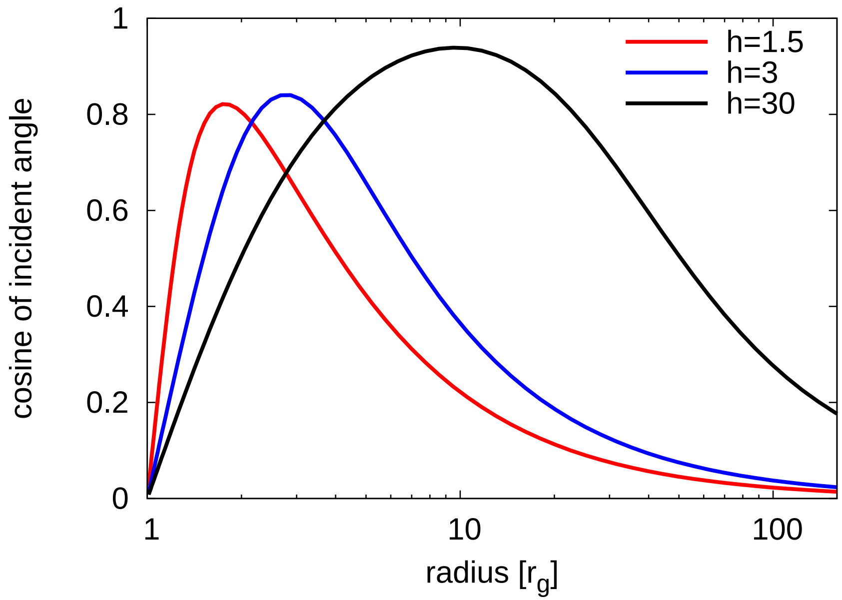


⥀ counter clock-wise rotation

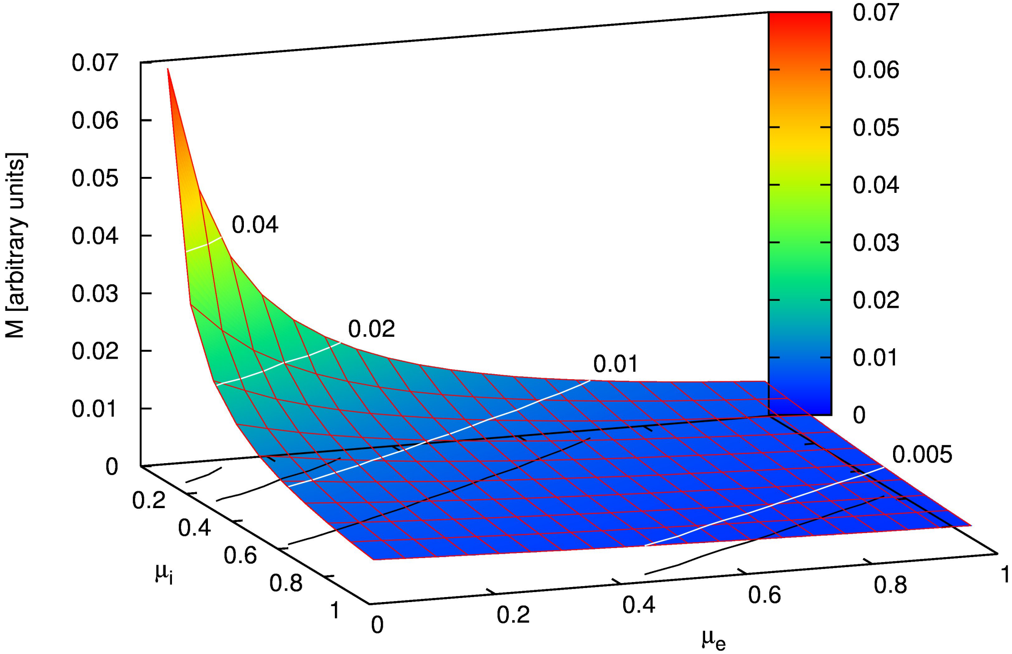
↓ direction to the observer

Lamp-post geometry: incident angle and directionality

incident angle

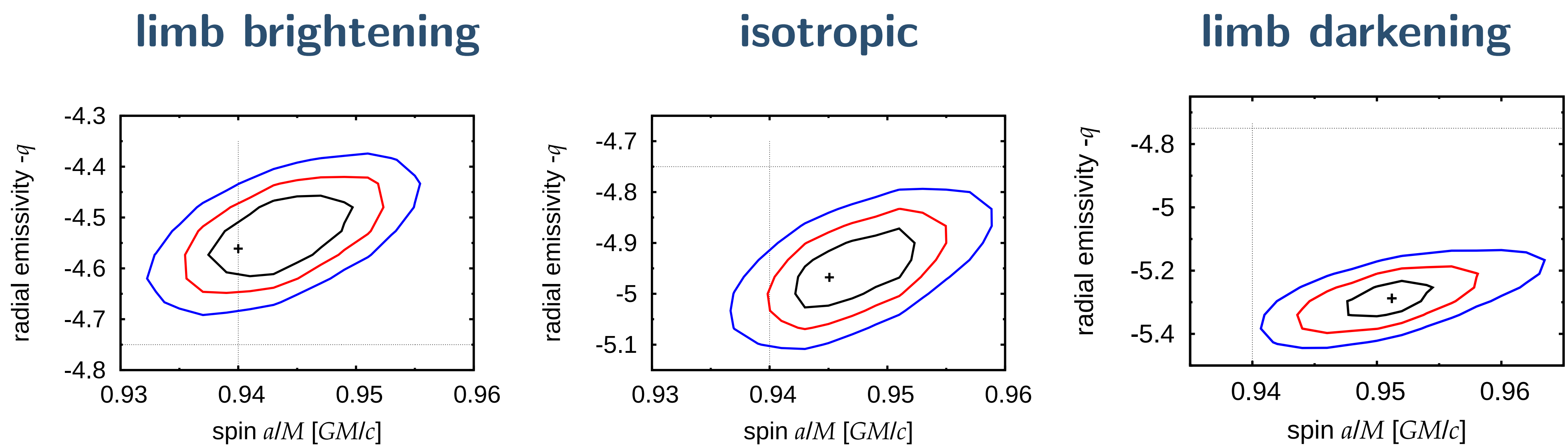


directionality



- at the innermost region: grazing angles of irradiation
- "irradiation from above" occurs at a few gravitational radii
- directionality calculated using Monte-Carlo radiative transfer code NOAR (Dumont et al., 00) for the case of "cold" reflection
- **strong limb-brightening effect at the innermost region**

The effect on radial emissivity and BH spin



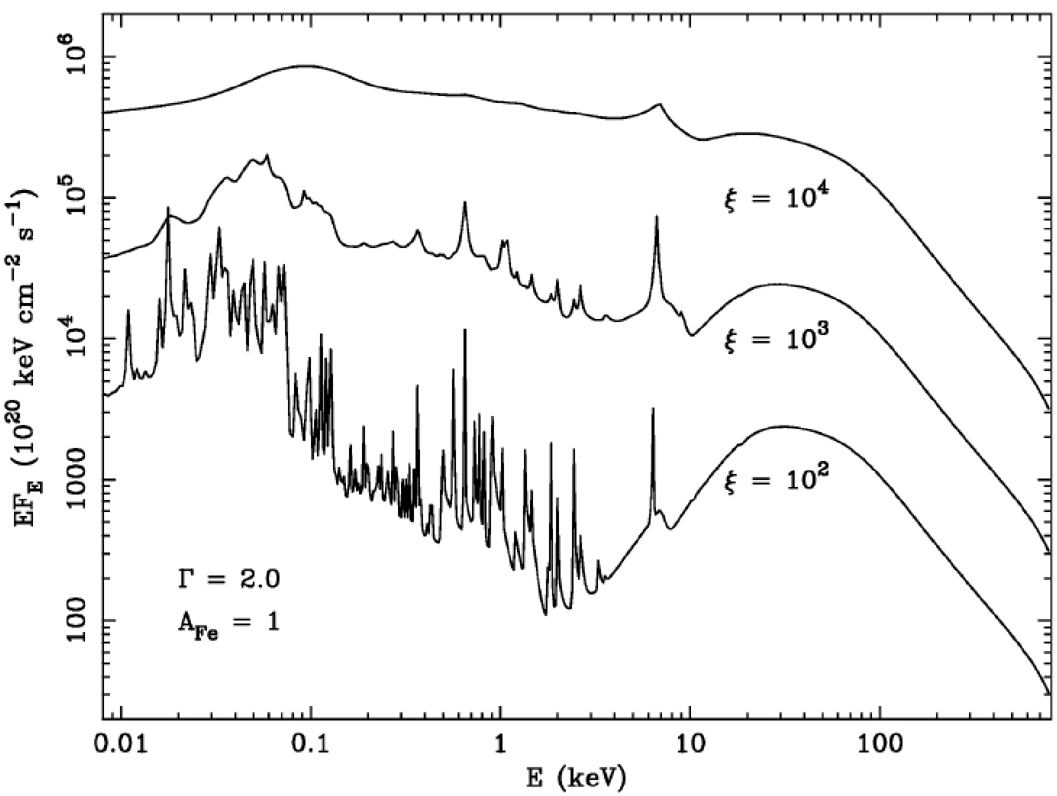
- default parameters: $a = 0.94$, $i = 30\,\mathrm{deg}$, $h = 1.5\,r_{\mathrm{g}}$, and numerical directionality (NOAR)

- **model with limb darkening overestimates the radial emissivity index as well as the spin value**

Part III. Ionised reflection models

- photoionisation dominates in determining the ionisation state of plasma
- ionisation parameter: $$\xi = \frac{4\pi F_{\mathrm{inc}}}{n_{\mathrm{H}}}$$
- REFLIONX (Ross & Fabian, 1993, 2005)

  $\rightarrow$ assumes constant density, no angular dependence

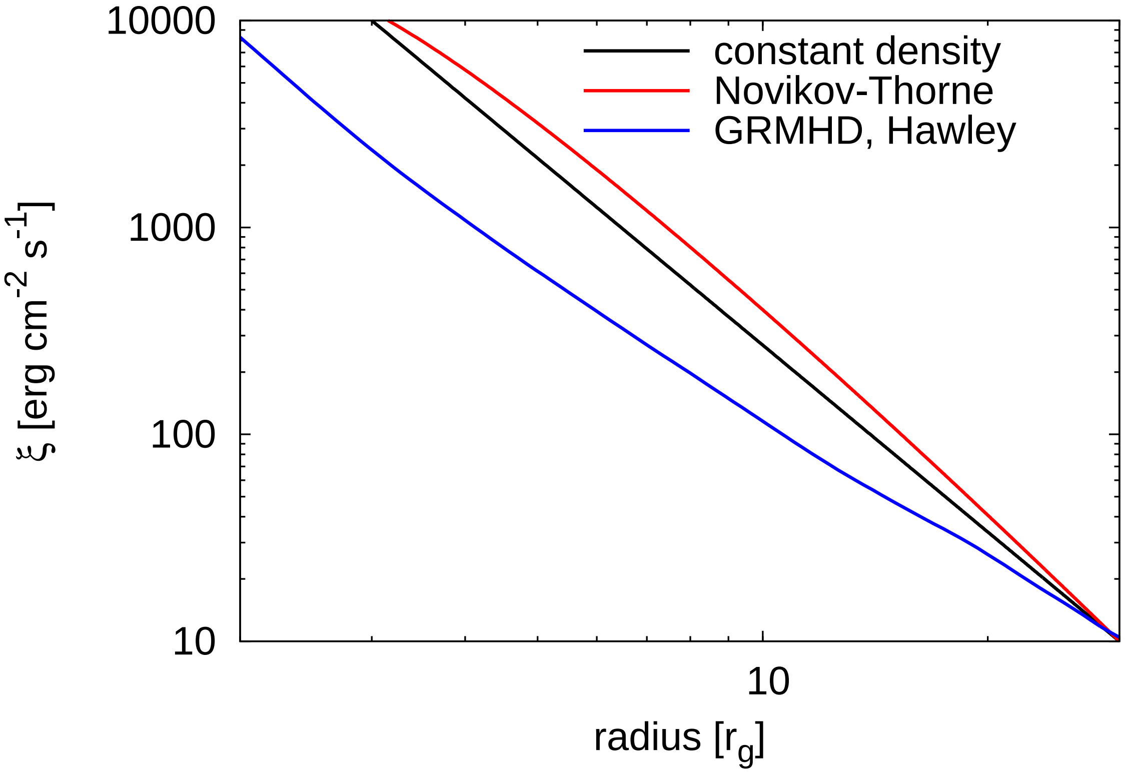


Radial dependence of the ionisation parameter $\xi(r)$

- currently: data are fitted using only one reflection component, i.e. assuming ξ constant over the whole accretion disc
- but (!):

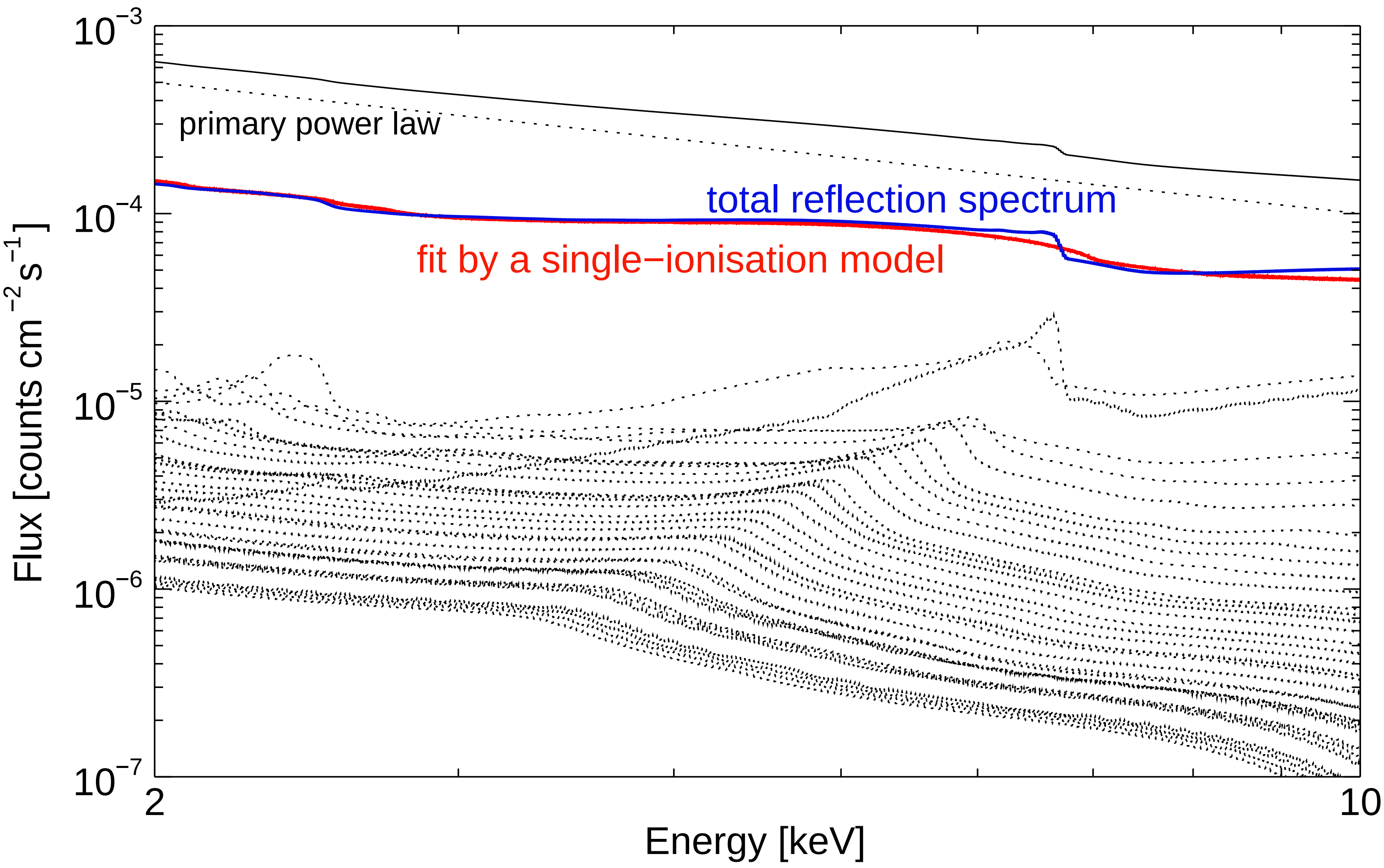
$$\xi(r) = \frac{4\pi F_{\rm inc}(r)}{n_{\rm H}(r)}$$

- assuming $F_{\rm inc}(r) \approx r^{-3}$:

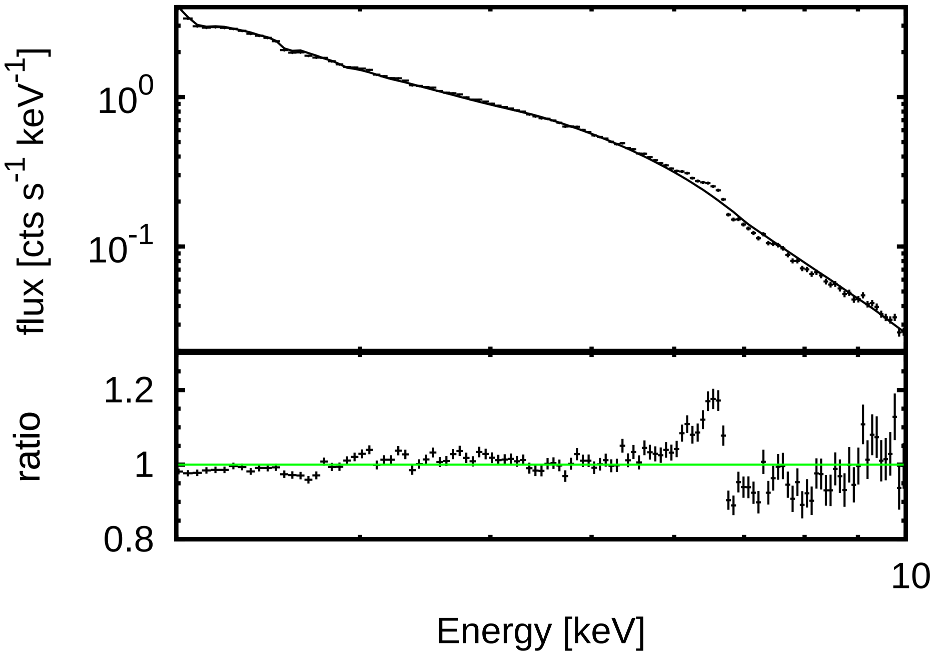


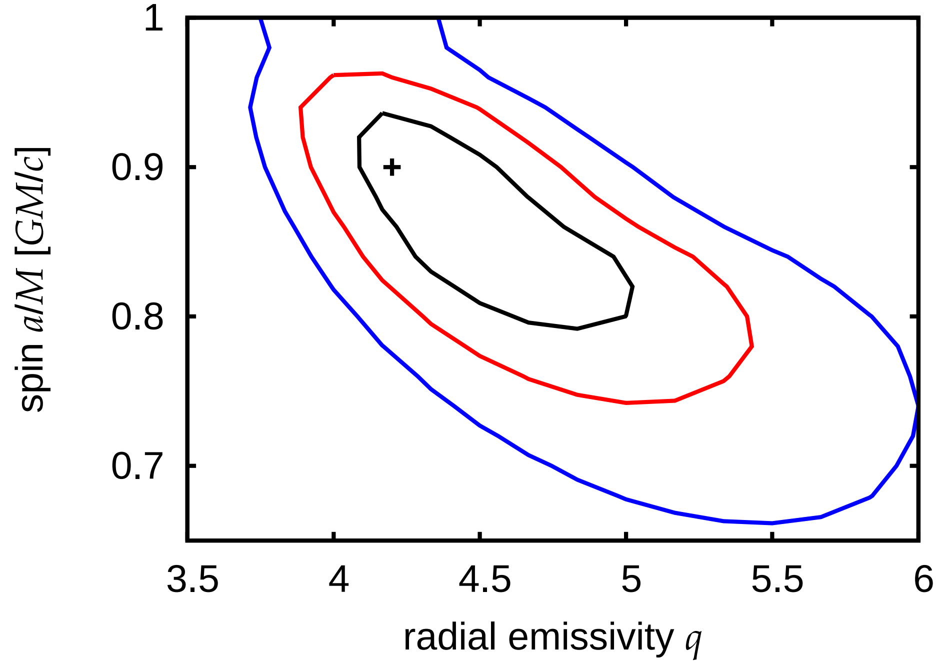
Radially stratified ionisation model

- constant density disc, isotropic irradiation, $a = 0.94$, $q = 3$, $R \approx 1$



Fit with single ionisation model

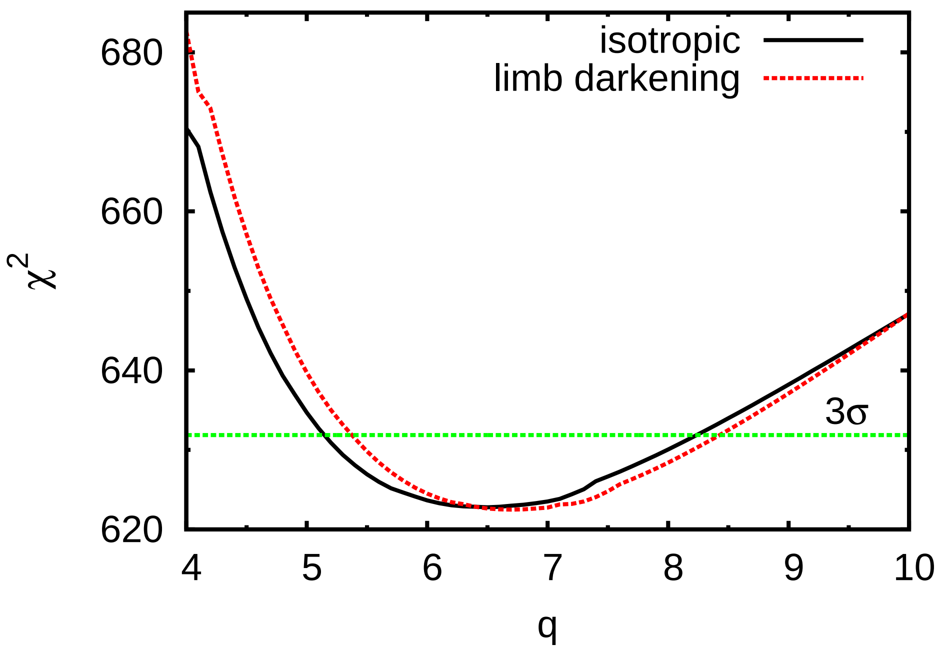


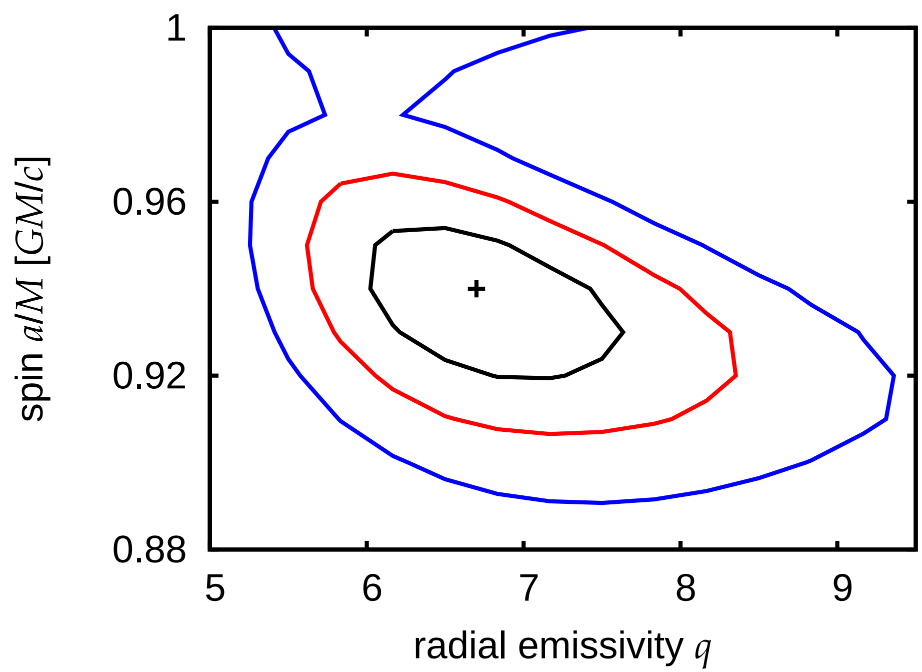


- best-fit results: $\chi^2/\nu \approx 1.35$, $\xi = 310 \pm 10\,\mathrm{erg\,s^{-1}}$, $q = 4.2 \pm 0.1$
- residuals are at the iron line edge (can be fitted by an additional narrow line or may affect equivalent width measurements of a narrow iron line from distant reflector often occuring in the spectra as well)
- radial emissivities $q \approx 4 - 5$ are obtained, i.e. similar values like with the lamp-post model

Combined effect

- simulated data: lamp-post geometry with the height $h = 1.5\,r_\mathrm{g}$, isotropic angular emissivity, and the radially stratified ionisation (with constant density profile)
- fit: single ionisation reflection with limb darkening
- best-fit results: $\chi^2/\nu \approx 1.03$, $a = 0.94 \pm 0.02$, $\xi = 230 \pm 20\,\mathrm{erg\,s^{-1}}$, $q = 6.7 \pm 0.9$ (!)





Conclusions

- relativistic iron lines in X-ray spectra are useful tools for investigation of the innermost regions of black hole accretion discs
- steep radial emissivity in X-ray disc-reflection spectra may be due to:
  - $\rightarrow$ centrally localised corona (*Martocchia et al. 00, Wilkins et al. 12*)
  - $\rightarrow$ the employed definition of the angular distribution of the disc emission (*Svoboda et al. 09*)
  - $\rightarrow$ radially stratified ionisation (*Svoboda et al. 12, submitted*)
- very steep radial emissivities, such as $q \approx 7$, can be naturally explained by the combined result of all three effects

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Thanks a lot for your attention!