

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

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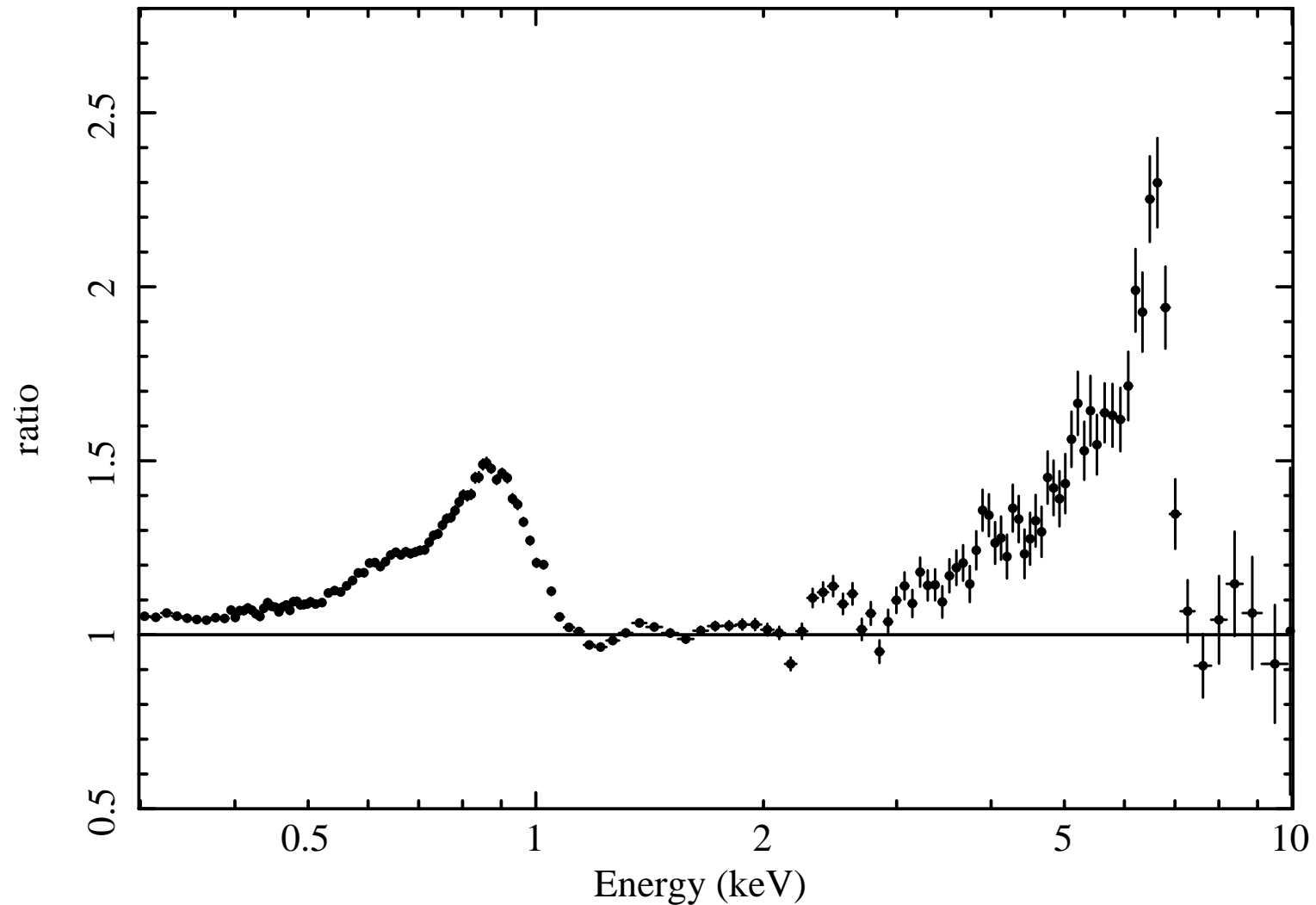
# Outline

- Introduction
  - spin measurements by relativistic iron lines
  - 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

# Energy shift and relativistic line profile

- KYRLINE (Dovčiak et al., 2004)
- inner edge of the disc coincides with the innermost stable circular orbit

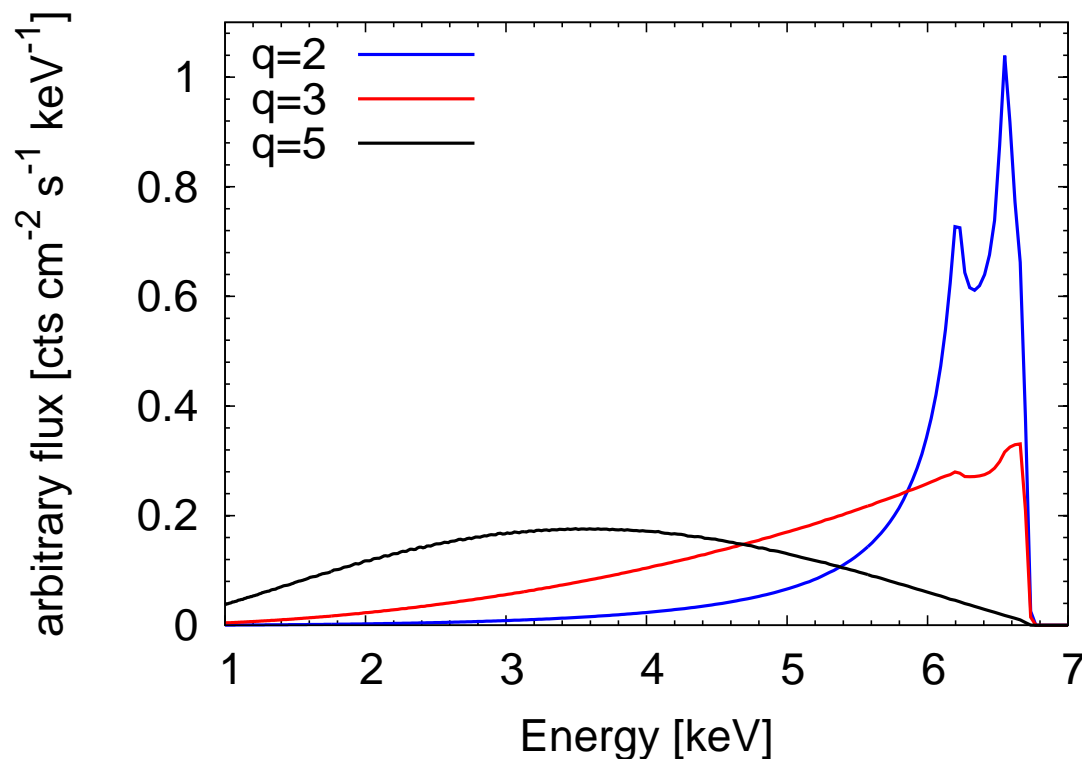
# Observed relativistic iron lines



- $K\alpha$  and L iron line in the XMM-Newton observation of narrow-line Seyfert 1 galaxy 1H 0707-495 (Fabian et al., 2009)



# Radial emissivity in the relativistic iron lines



- radial dependence:  $\mathcal{R}(r_e) \propto r_e^{-q}$  (or a broken power law)
- “standard” value  $q = 3$  ( $\propto$  thermal dissipation of the accretion disc in the isotropic corona, or Newtonian limit for a point source on the rotational axis)

# Steep radial emissivity in observations

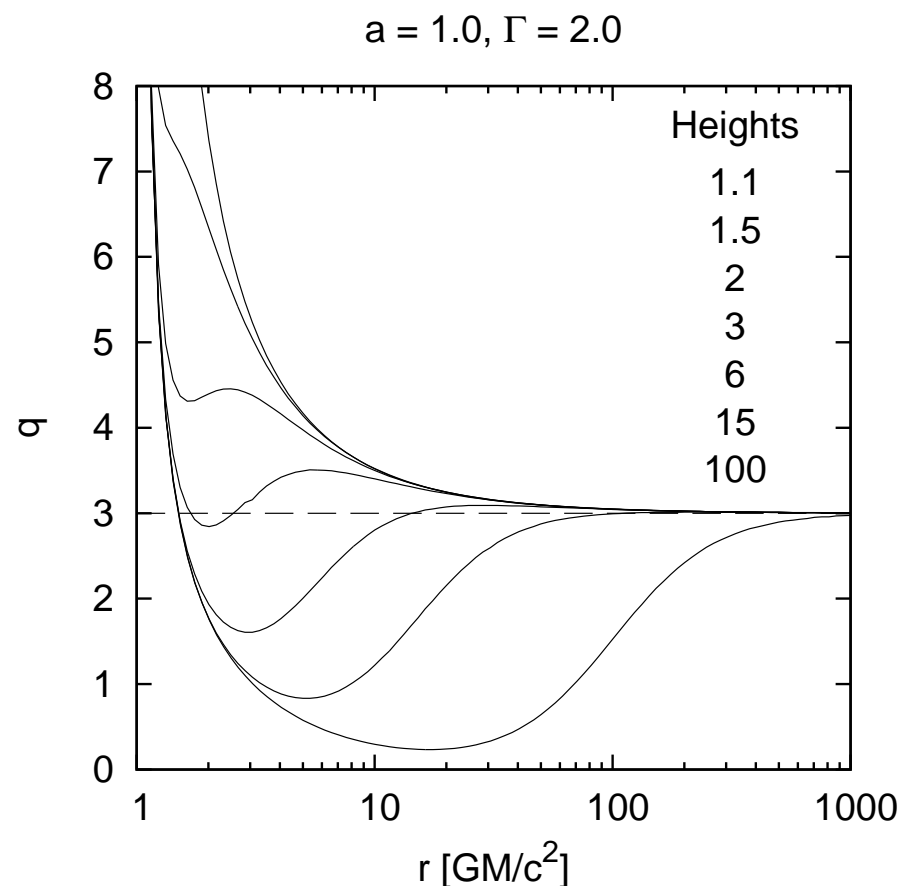
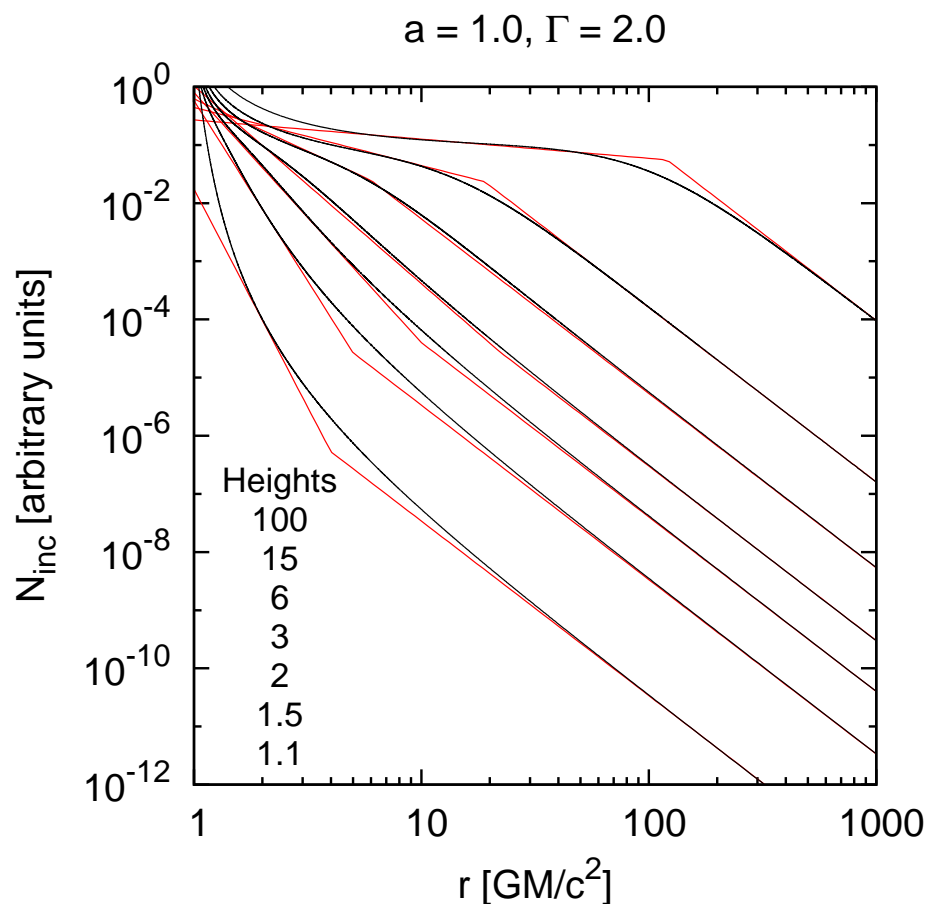
- many observations of active galaxies and Galactic black hole binaries require steep radial emissivity in the relativistic iron line profile than expected (standard value  $q = 3$ ,  $I(r_e) \propto r_e^{-q}$ )
- examples:
  - MCG-6-30-15:  $q_1 = 4.8 \pm 0.7$ ,  $r_{\text{br}} = 6.5^{+4.5}_{-1.4} r_g$  (Fabian et al., 2002)
  - 1H0707-495:  $q_1 \approx 7.5$ ,  $r_{\text{br}} \approx 4.5 r_g$  (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

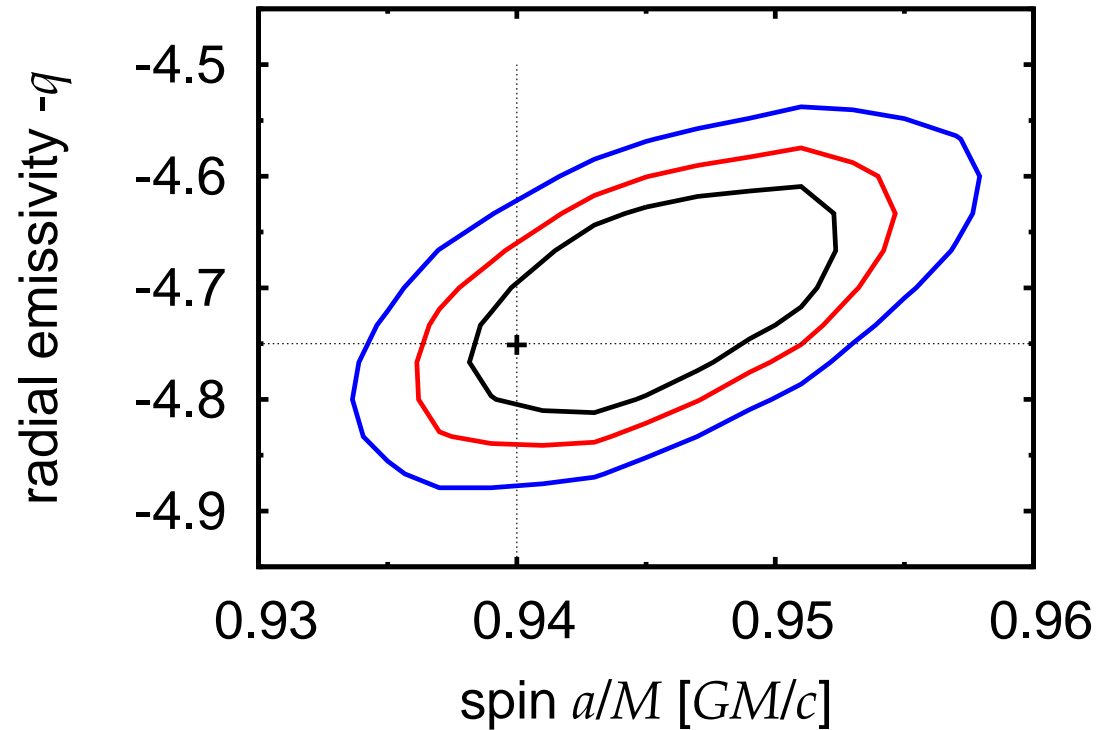
- (point-like) source above the black hole (Dovčiak et al., before submission, see also Wilkins et al. 12)

- radial emissivity:  $q \equiv \frac{d \log N_{\text{inc}}}{d \log r}$

→ differs from a broken power law, very steep only for  $h < 2 r_g$



# Radial emissivity in the lamp-post geometry

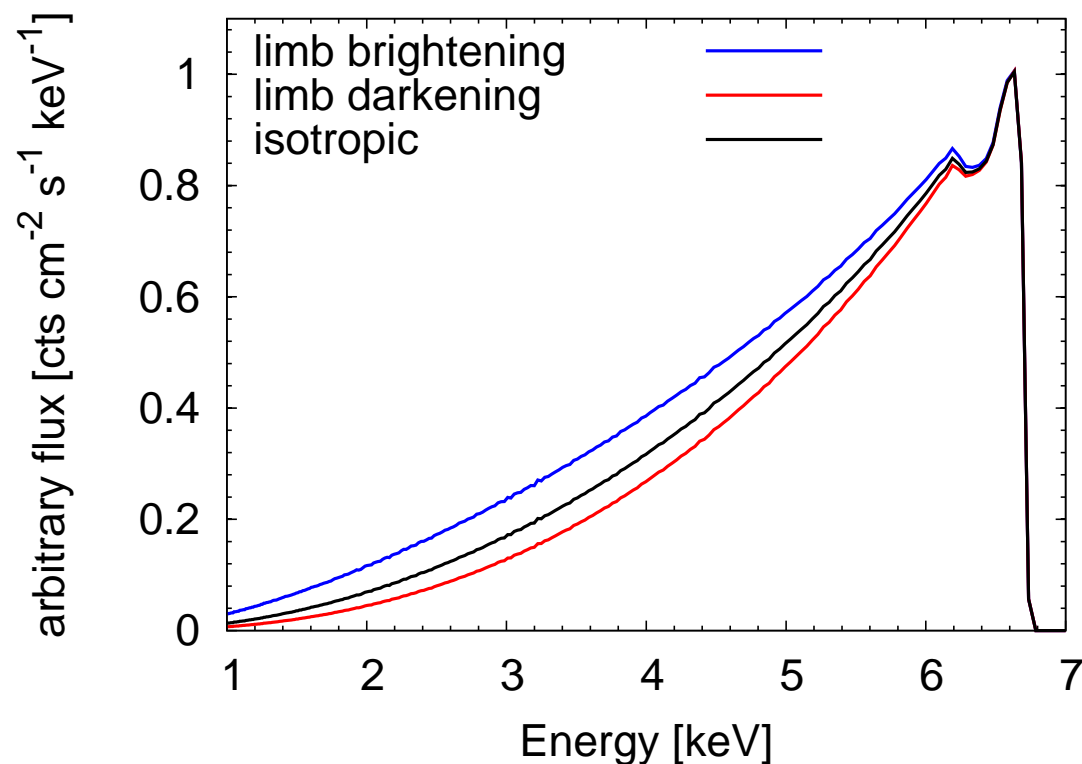


- data simulated by a power law ( $\Gamma = 1.9$ ) and relativistic iron line in the lamp-post geometry with  $a_{\text{def}} = 0.94$ ,  $i_{\text{def}} = 30^\circ$  and  $h = 1.5 r_g$
- then fitted by a model with the radial emissivity described as a broken power-law (with  $q = 3$  at the outermost disc)
- steep indices,  $q \lesssim 5$ , found in the inner disc (break radius  $r_b \sim 6 r_g$ )

## Part II. Emission directionality in reflected radiation

- **emission directionality**  $\mathcal{M}(\mu_e, r_e, E_e)$  = dependence of the intensity on the emission angle ( $\mu_e = \cos \theta_e$ )

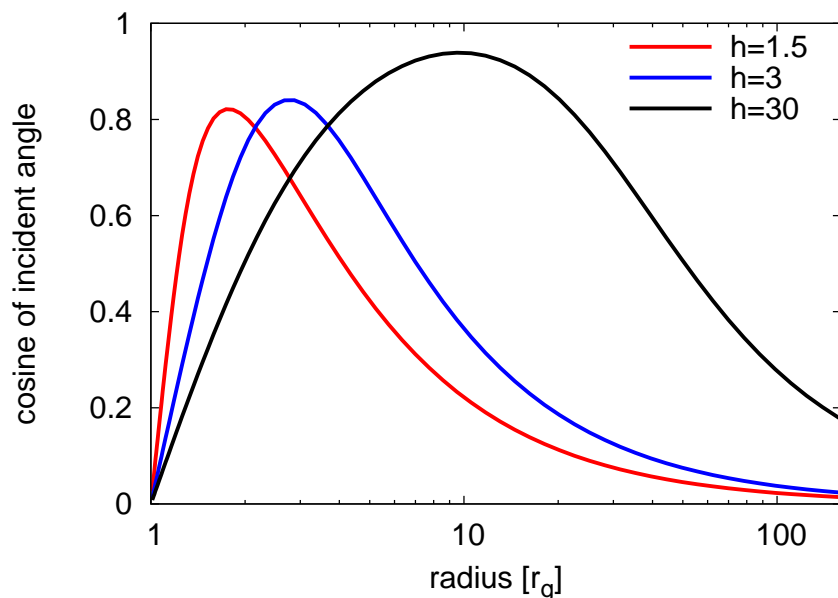
$$\mathcal{M}(\mu_e) = \begin{cases} \ln(1 + \mu_e^{-1}) & \text{limb brightening, Haardt 93} \\ 1 & \text{(locally isotropic emission)} \\ 1 + 2.06 \mu_e & \text{limb darkening, Laor 91} \end{cases}$$



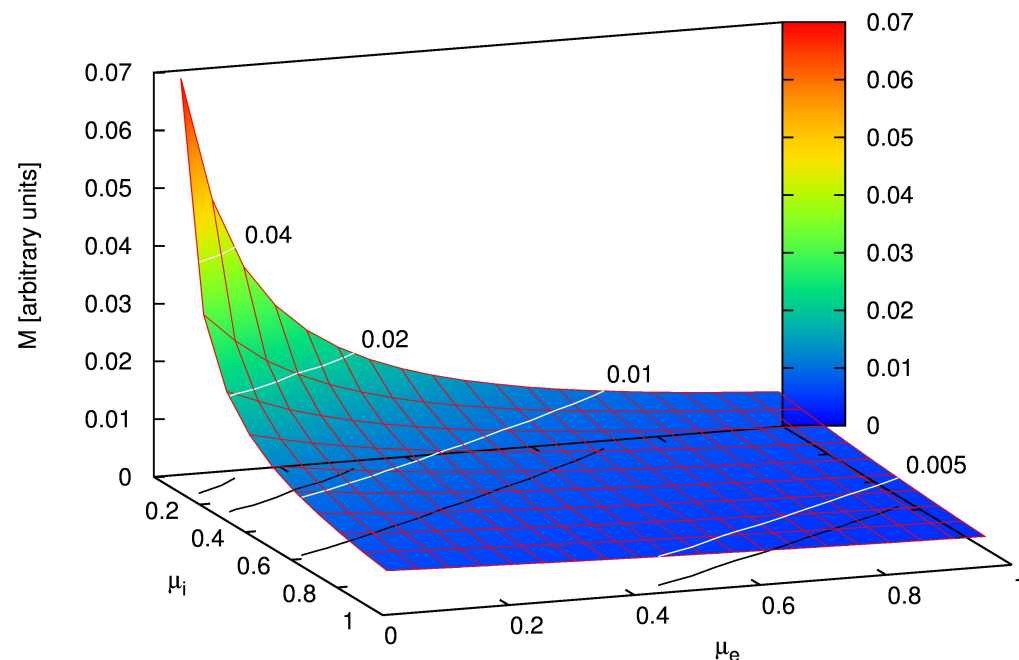


# Lamp-post geometry: incident angle and directionality

incident angle



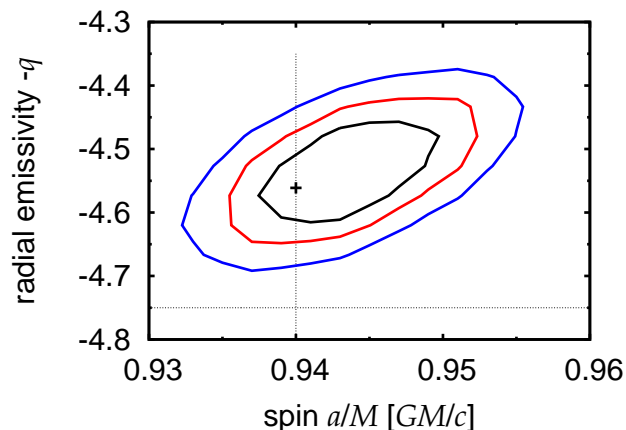
directionality



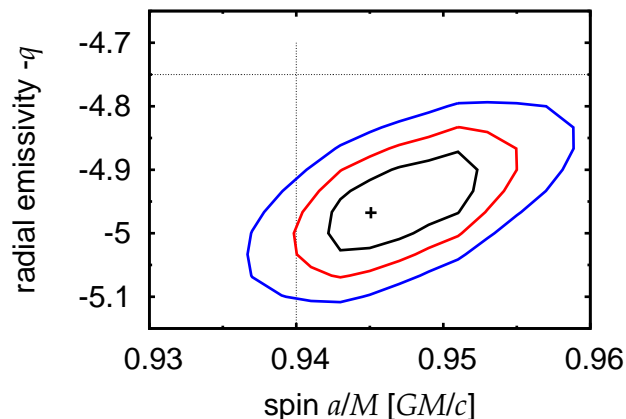
- at the innermost region: grazing angles of irradiation
- “irradiation from above” occurs at a few gravitational radii
- directionality calculated using Monte-Carlo radiative transfer code NOAR (Dumont et al., 00) for the case of “cold” reflection
- **strong limb-brightening effect at the innermost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

# The effect on radial emissivity and BH spin

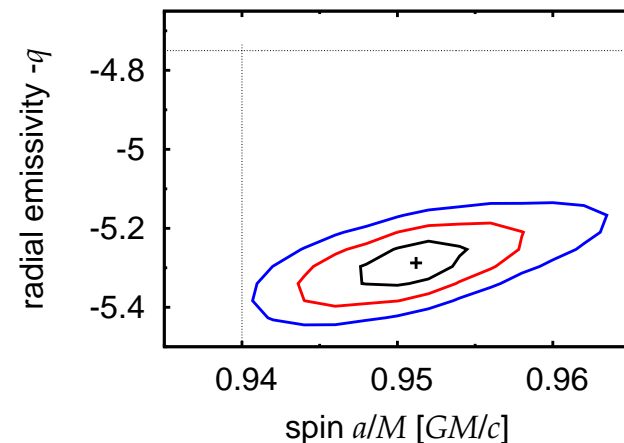
limb brightening



isotropic



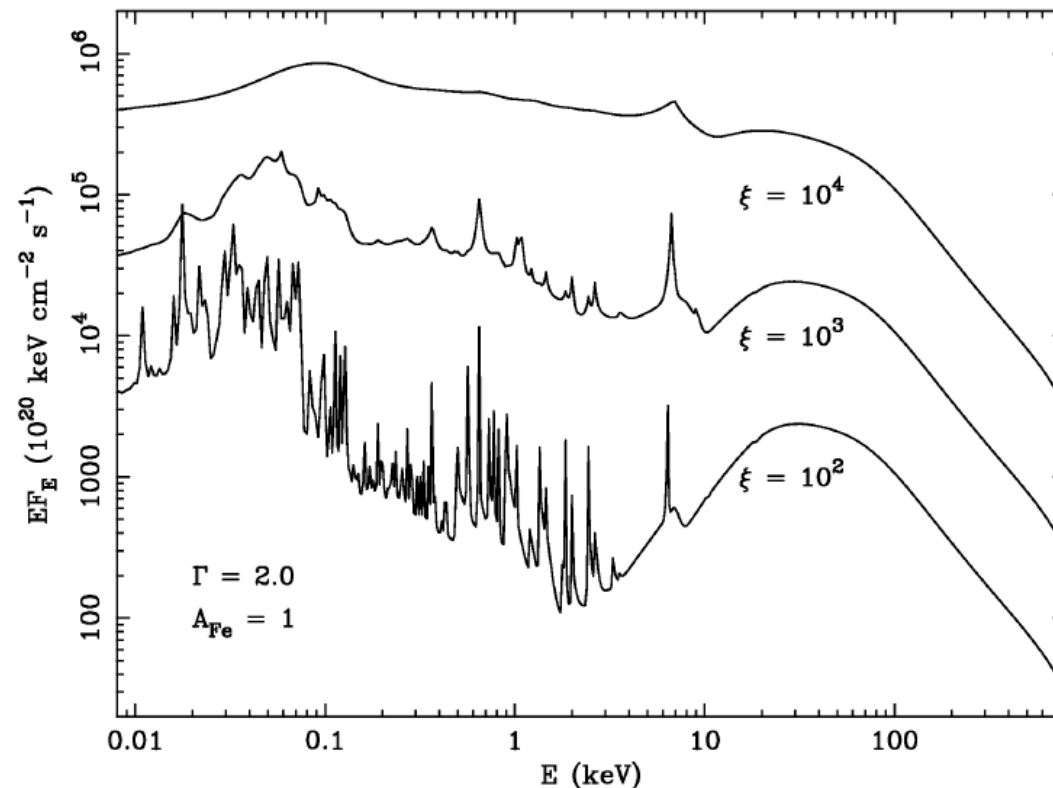
limb darkening



- default parameters:  $a = 0.94$ ,  $i = 30$  deg,  $h = 1.5 r_g$ , 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: 
$$\xi = \frac{4\pi F_{\text{inc}}}{n_{\text{H}}}$$
- REFLIONX (Ross & Fabian, 1993, 2005)
  - assumes constant density, no angular dependence



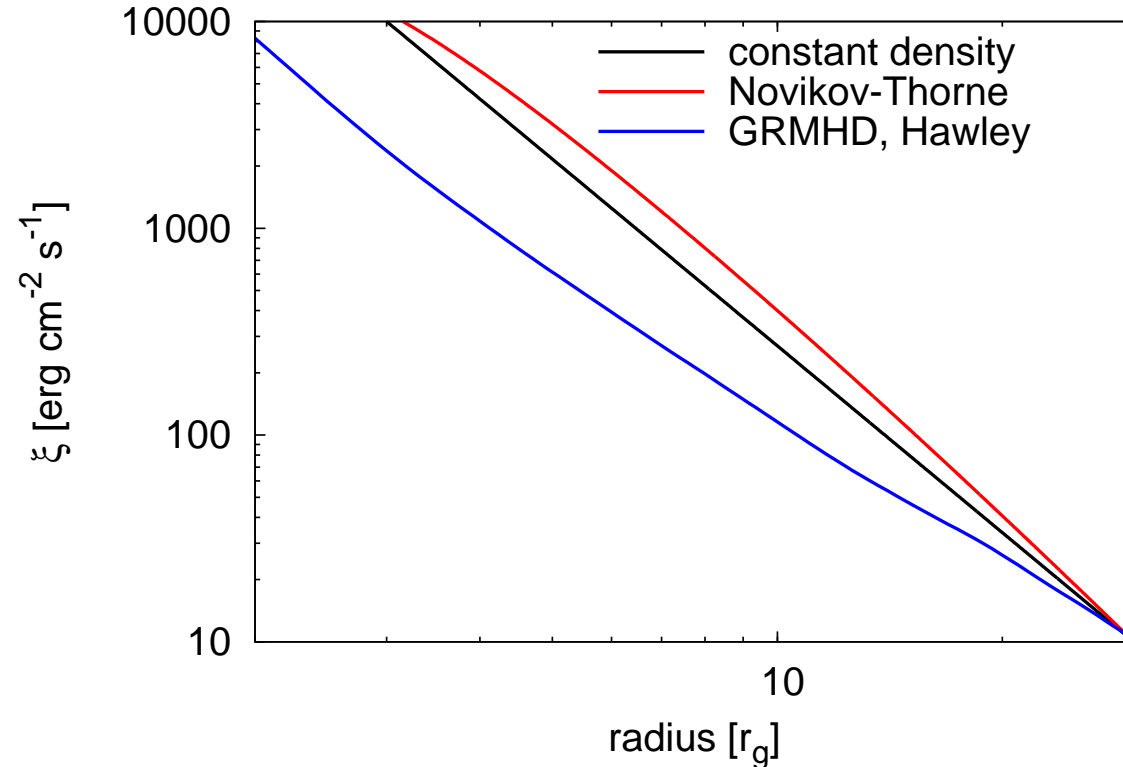
# Radial dependence of the ionisation parameter $\xi(r)$

- currently: data are fitted using only one reflection component, i.e. assuming  $\xi$  constant over the whole accretion disc

- but (!):

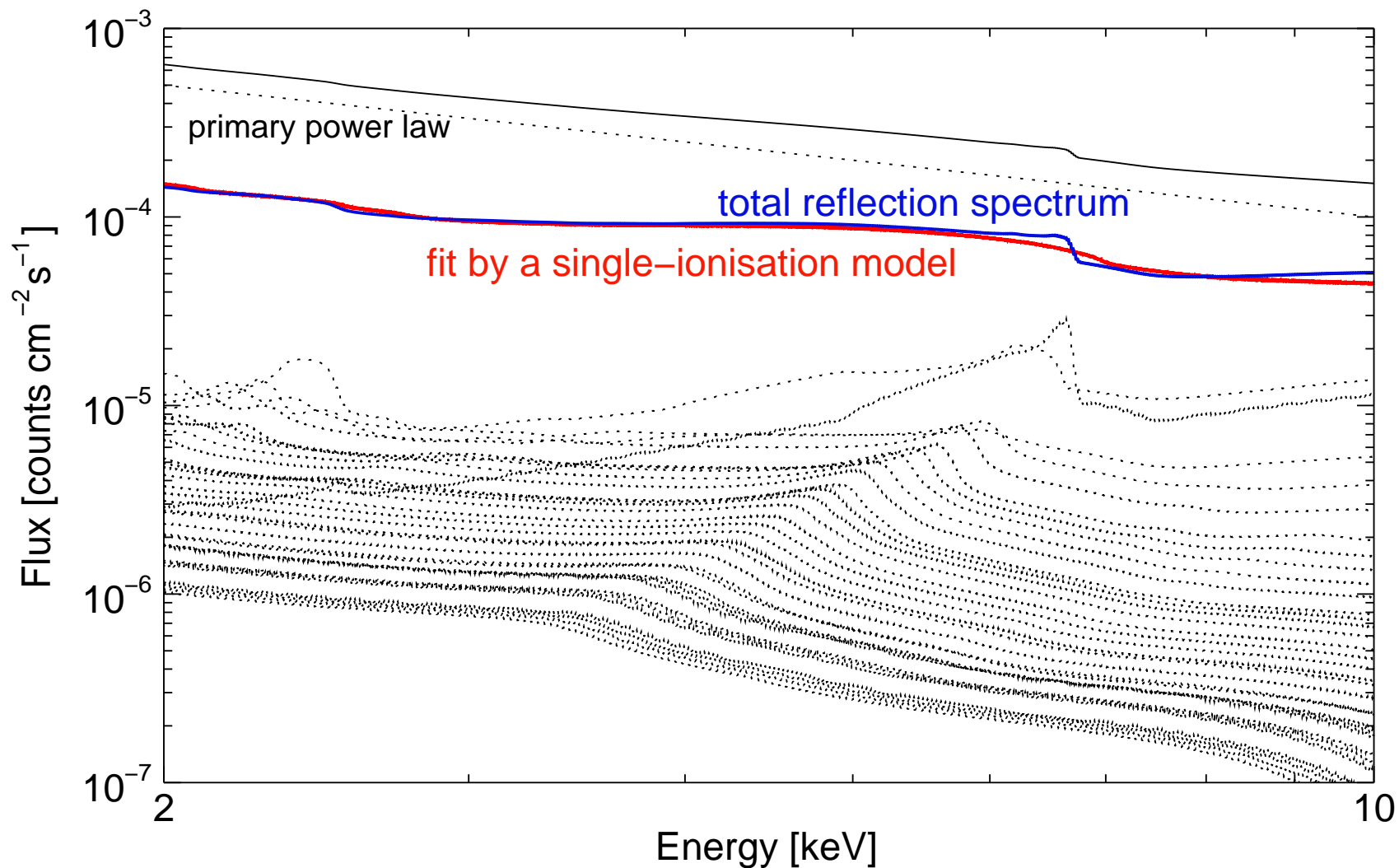
$$\xi(r) = \frac{4\pi F_{\text{inc}}(r)}{n_{\text{H}}(r)}$$

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



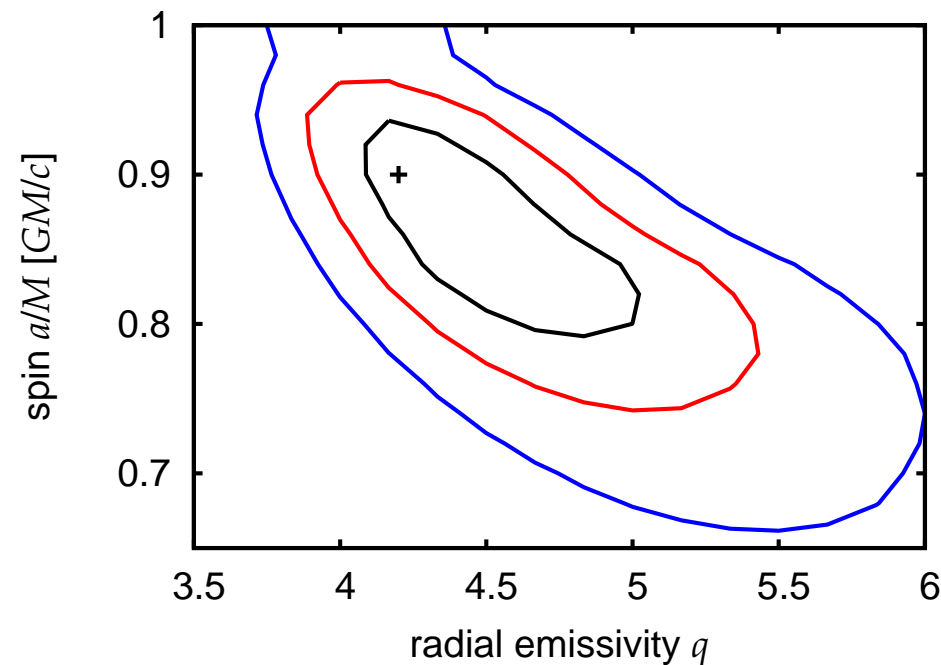
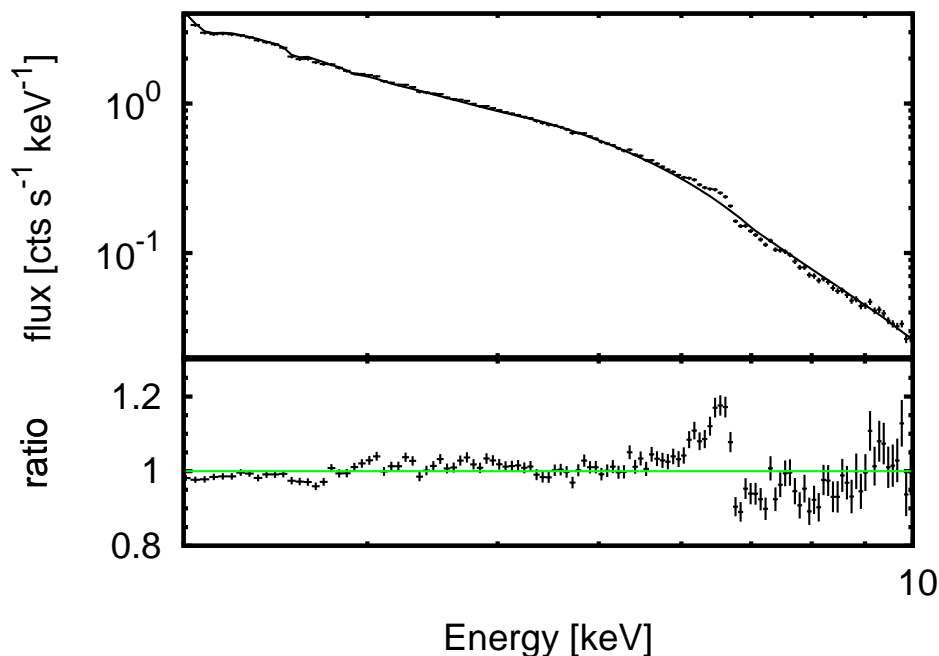
# Radially stratified ionisation model

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





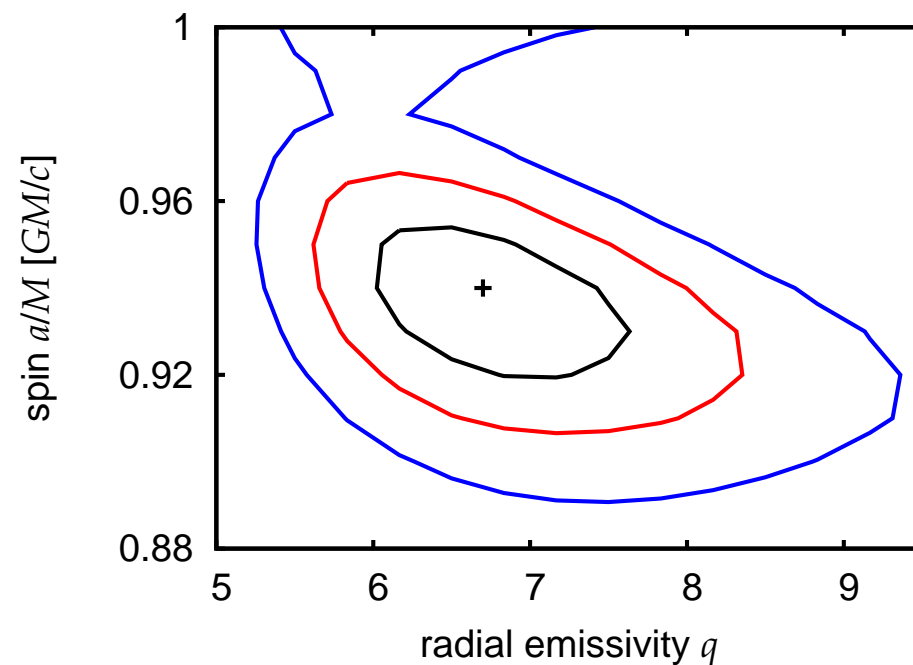
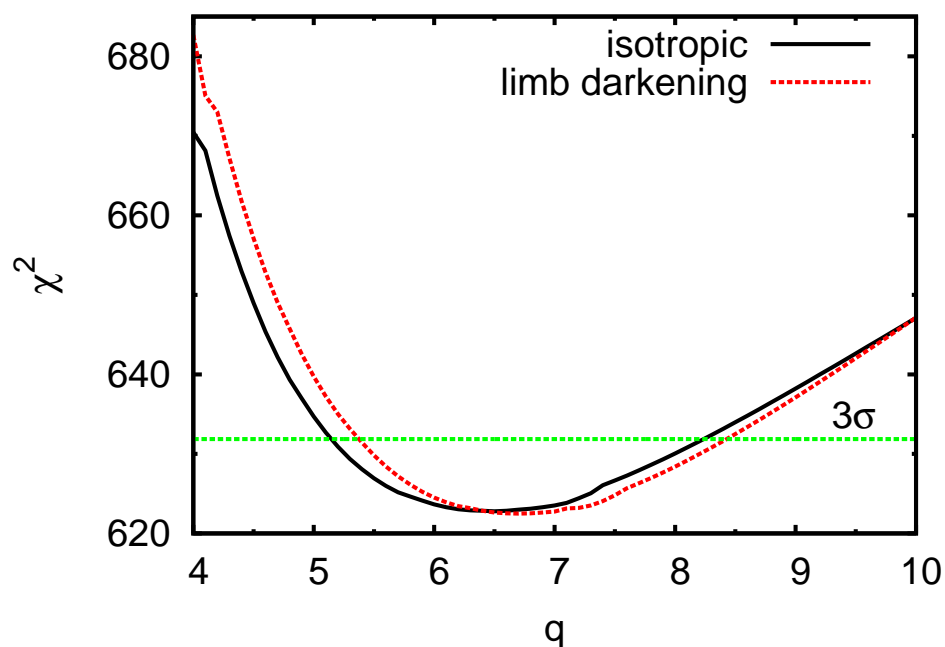
# Fit with single ionisation model



- best-fit results:  $\chi^2/\nu \approx 1.35$ ,  $\xi = 310 \pm 10 \text{ erg s}^{-1}$ ,  $q = 4.2 \pm 0.1$
- 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 occurring 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  $h = 1.5 r_g$ , isotropic angular emissivity, and the radially stratified ionisation (with constant density profile)
- fit: single ionisation reflection with limb darkening
- best-fit results:  $\chi^2/\nu \approx 1.03$ ,  $a = 0.94 \pm 0.02$ ,  $\xi = 230 \pm 20 \text{ erg s}^{-1}$ ,  $q = 6.7 \pm 0.9$  (!)



# 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:
  - centrally localised corona (*Martocchia et al. 00, Wilkins et al. 12*)
  - the employed definition of the angular distribution of the disc emission (*Svoboda et al. 09*)
  - 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!