THE EFFECT OF RETURNING RADIATION ON RELATIVISTIC REFLECTION

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Abstract

Relativistic reflection of X-ray radiation at the inner accretion disk around black holes has been extensively studied in the last decade. The emitted spectrum, which likely originates from a compact corona close to the black hole, is strongly blurred due to gravity effects. Encoded in this blurring of the observed spectrum are important system parameters such as the black hole spin or location and geometry of the primary source of radiation. **While several relativistic reflection models already exist, a crucial effect has so far been neglected: a larger fraction of reflected radiation from the inner regions will inevitably return to the accretion disk and produce additional reflection.** The first implementation of reflection from returning radiation in the RELXILL model suite and a thorough analysis of the implications is presented in Dauser et al. (submitted).

1 - Returning Photon Trajectories

- Photons emitted from the corona (e.g., a lamp post, Dauser et al., 2013) irradiate the accretion disk and create (relativistic) reflection
- A fraction of the reflected **photons return to the disk and create additional reflection** (so far neglected in any relativistic reflection model)

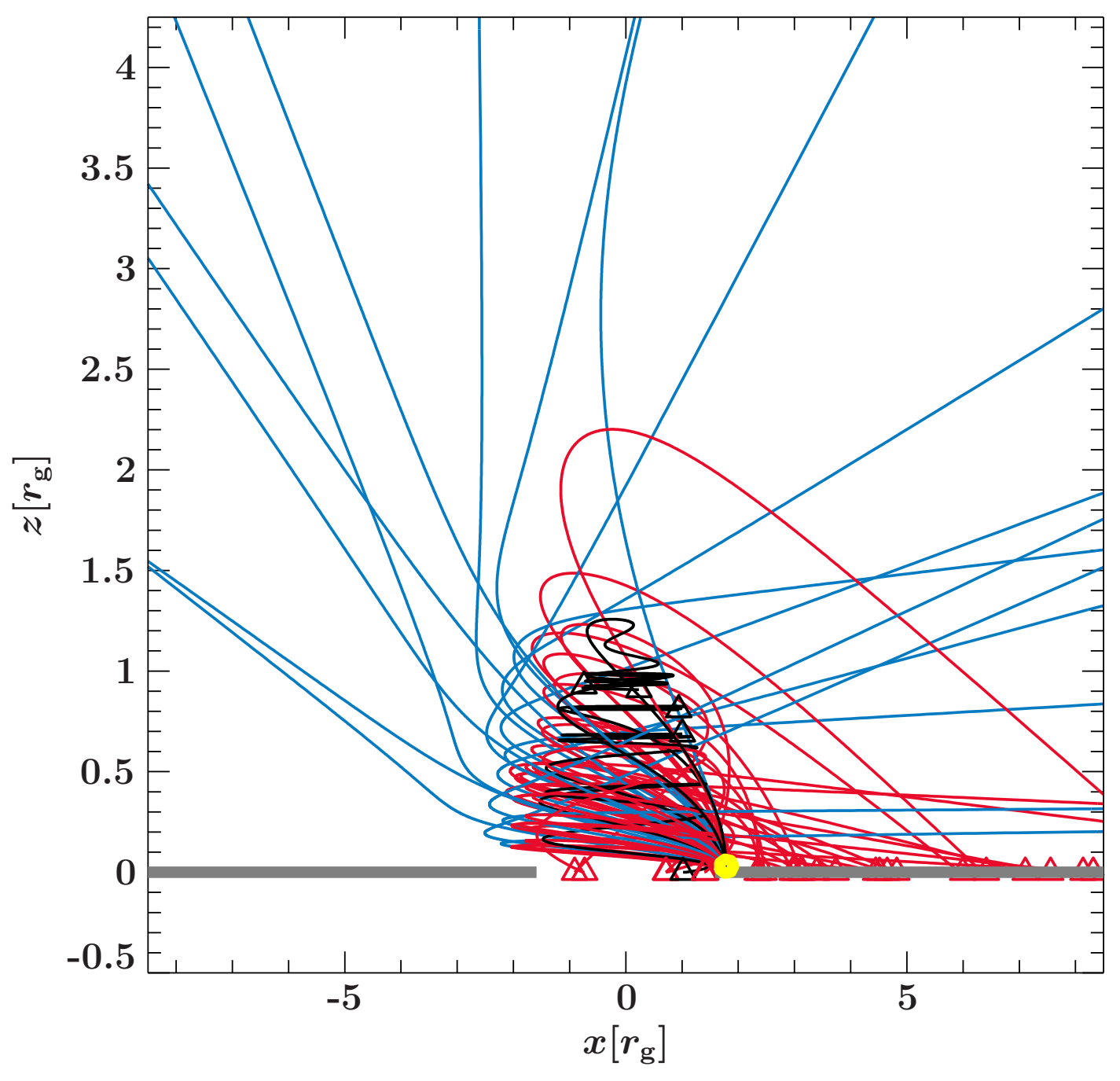


Figure 1: Photon trajectories for black hole spin $a = 0.998$ emitted isotropically at the yellow circle. Triangles indicate the location where the photons hit the disk (red), the black hole (black).

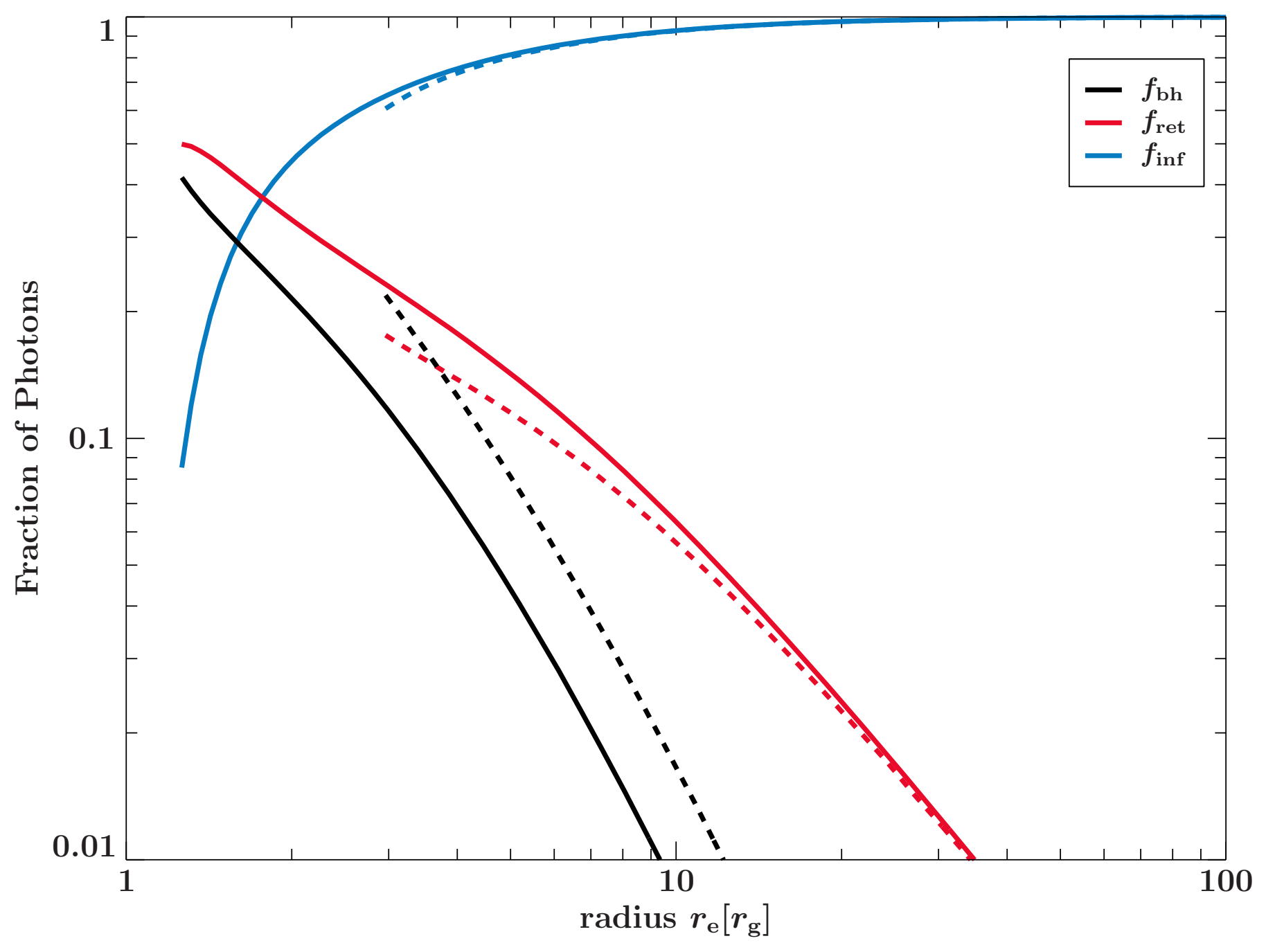


Figure 2: Fraction of photons falling into the black hole, returning to the disk, or reaching infinity as a function of radius of emission, r_e for the case of a maximally spinning black hole ($a = 0.998$, solid lines) and for $a = 0.8$ (dashed).

2 - Returning Emissivity Profile

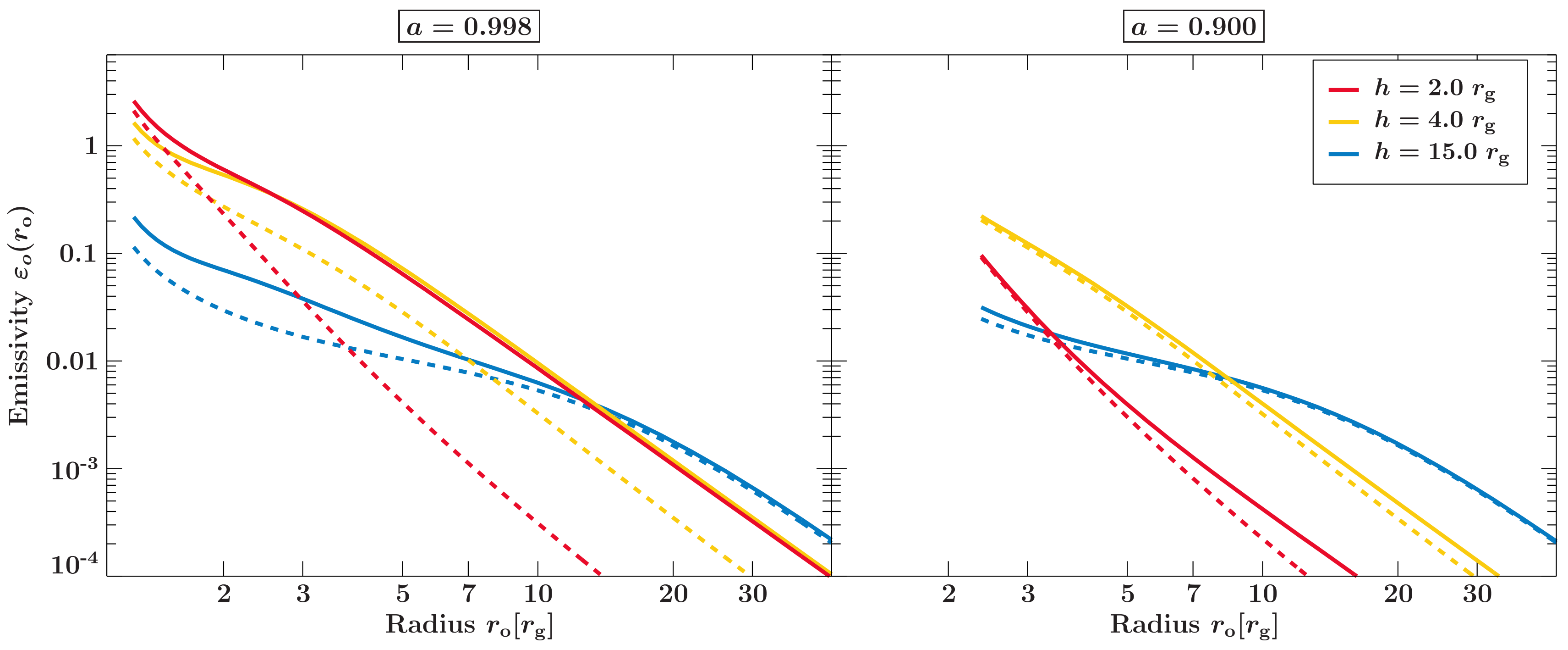


Figure 3: Emissivity Profiles from the Lamp Post Geometry including returning radiation (solid) and without (dashed).

- Returning radiation is primarily important for high spins of $a \gtrsim 0.9$ and compact coronae at heights $h \lesssim 10 r_g$.
- The main effect of returning radiation is to **flatten the emissivity profile**, which is caused by primarily reflected photons from the very inner disk irradiating the outer disk.

3 - Updated RELXILL model

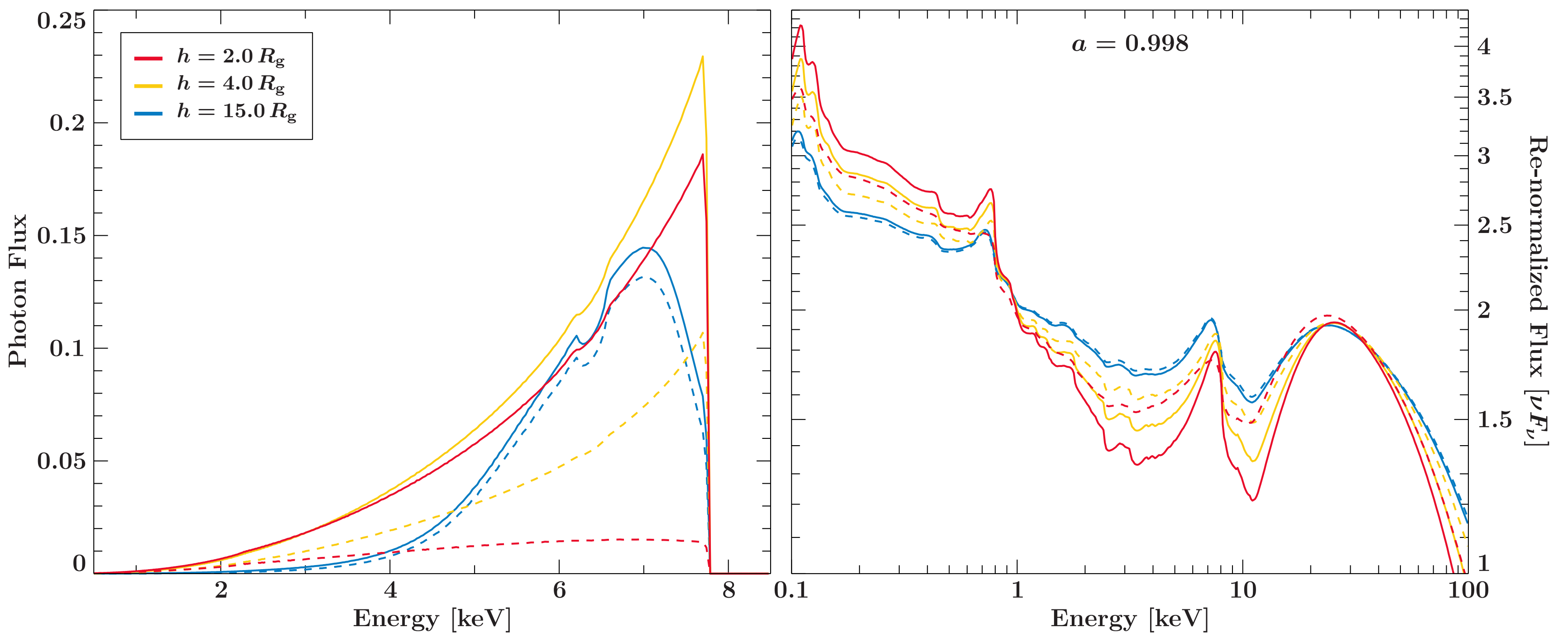
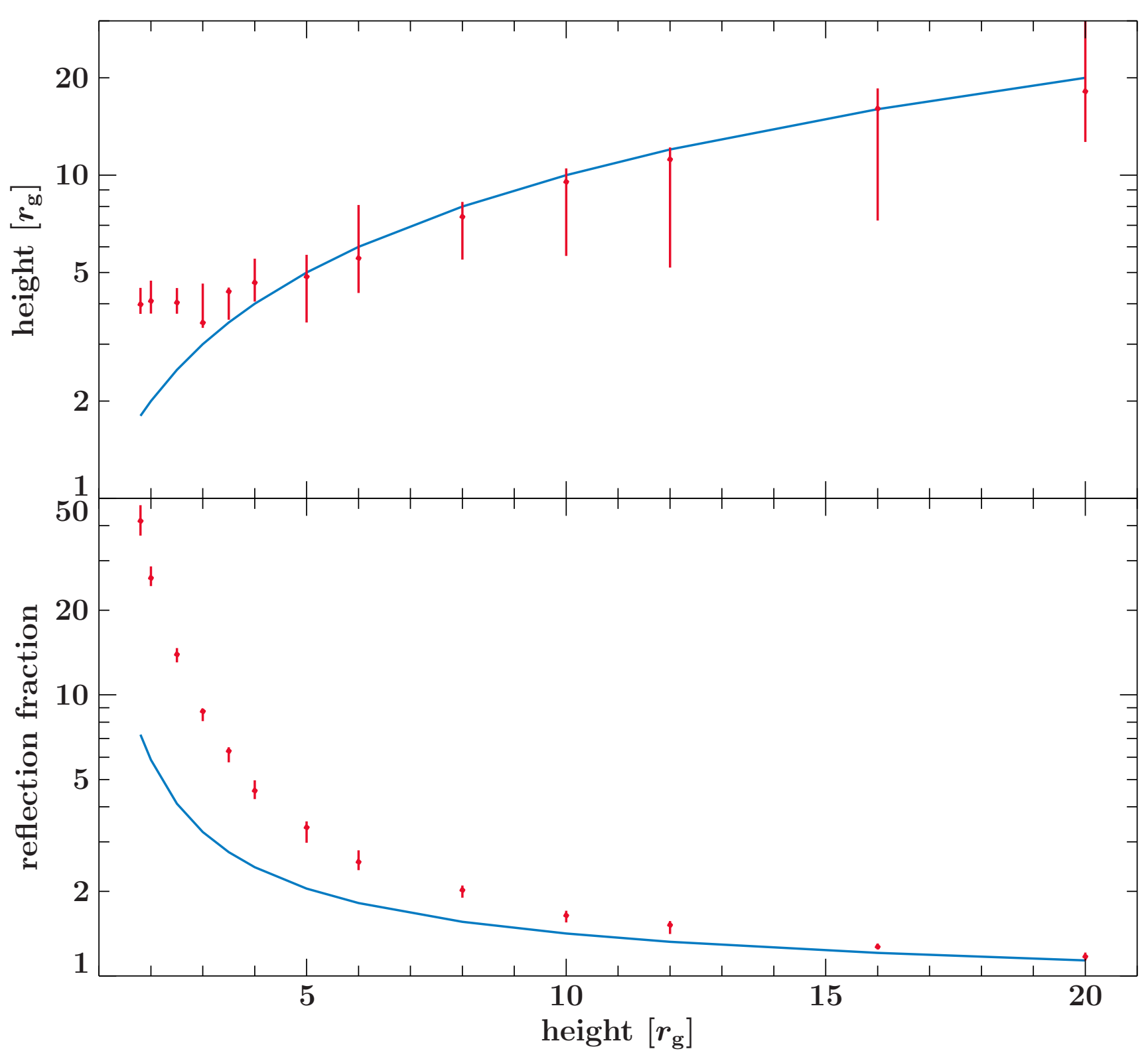


Figure 4: Broadened line profiles (left) and relativistic reflection spectra (right) for a lamp post primary source at height h including returning radiation (solid) and without (dashed). **Including returning radiation leads to stronger and narrower reflection features compared to models neglecting returning radiation. While for an extreme spin of $a = 0.998$ large differences are visible when including returning radiation, for $a = 0.9$ these differences make up only a small contribution to the overall spectrum.**

The increased irradiation of the outer disk leads to a weaker relativistic broadening of the line profile. **For $h \lesssim 4r_g$ the reflection spectra only mildly depend on the coronal height**.

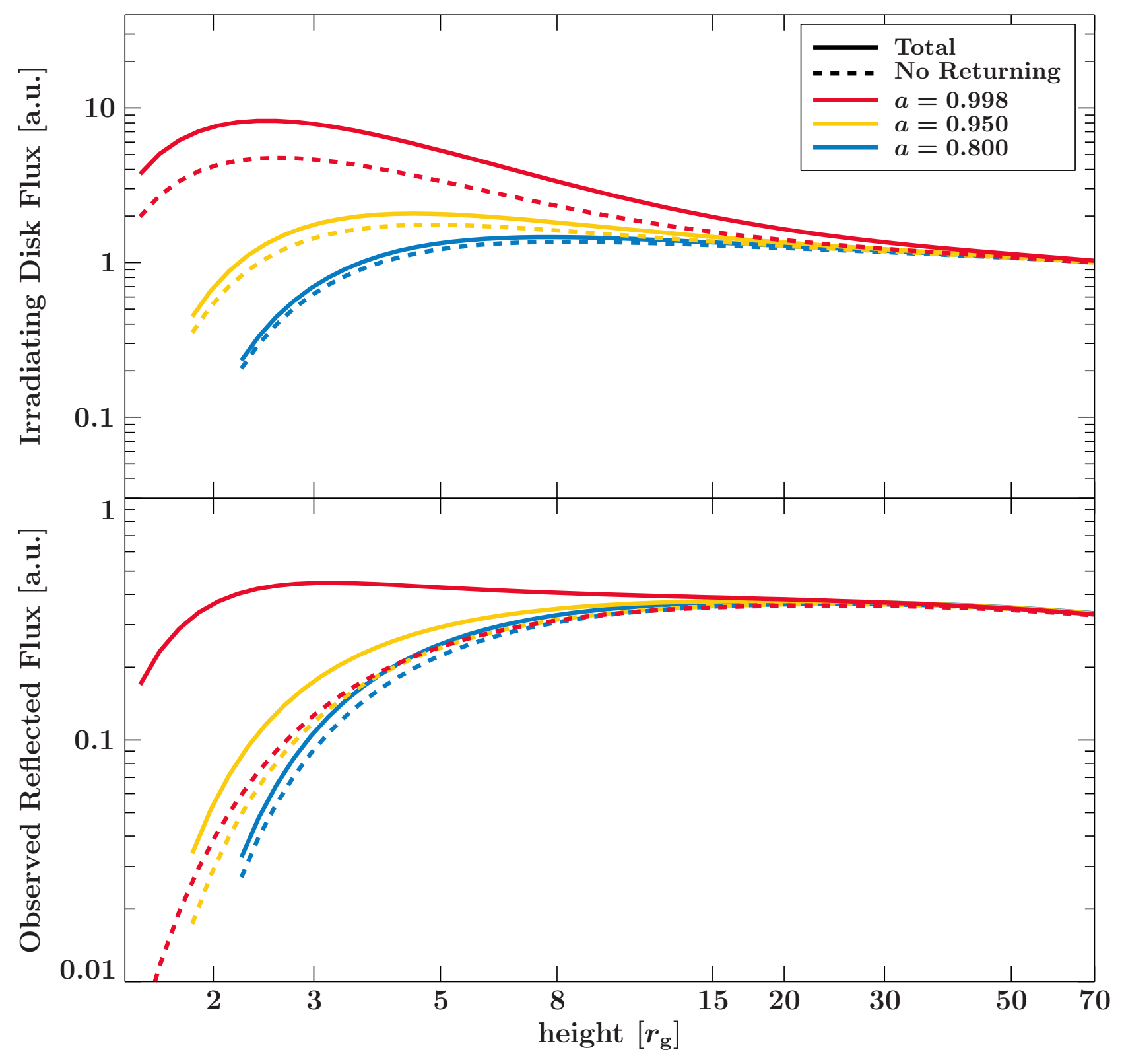
Simulating the Effect on Observations



Simulations of observable spectra show that previous studies that did not include returning radiation likely **overestimated the coronal height**, while simultaneously significantly **underestimating the reflection fraction**.

Figure 5: Results from simulating with the new RELXILL model (blue line) and fitting this data with the normal RELXILL model without returning radiation (rad data points). The spin was set to $a = 0.998$, $\Gamma = 2$, $\log(\xi/\mathrm{erg\,cm\,s^{-1}}) = 3.1$, and the iron abundance $A_{\mathrm{Fe}} = 1.5$

4 - Boosting the Reflection Strength



Returning radiation **boosts the amount of reflection**. For extreme values of compactness and spin, the additional reflection caused by returning radiation dominates the flux of the observed reflection spectrum.

Figure 6: Total flux irradiated onto the disk for an irradiating power law with $\Gamma = 2$. Dashed lines show the contribution of the primary radiation, dotted lines indicate the contribution of the returning radiation. (a) Incident photon flux in the frame of the disk. (b) Observed reflected flux, assuming an inclination of $i = 45°$ and a perfect reflector.

5 - Conclusions

- the apparent discrepancy of the lamp post model under-predicting the reflection strength in some sources that show very strong reflection (e.g., 1H0707−495) can likely be solved by accounting for the large contribution of the returning radiation to the reflected flux.
- returning radiation will lead to an overall increase in the expected time lags (Wilkins et al., 2020) ⇒ explain the discrepancy that the source height found by modeling time lags (e.g., Wang et al., 2021) is generally larger than found from spectral analyses?
- very steep emissivity profiles and low source heights that are often required to describe the spectra are in contradiction with the flatter emissivity profile when including returning radiation ⇒ solved by ionization/density gradient in the accretion disk?

The new RELXILL model (v1.5) will soon be available at `www.sternwarte.uni-erlangen.de/research/relxill/`. Sign up at the mailing list to be notified about the update.

Acknowledgments

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Dauser T., García J., Wilms J., et al., 2013, MNRAS 687
Wang J., Mastroserio G., Kara E., et al., 2021, Astrophys. J., Lett. 910, L3
Wilkins D.R., García J.A., Dauser T., Fabian A.C., 2020, MNRAS 498, 3302