

Self-Consistent X-ray Spectra from Accreting Black Hole Binaries

Jeremy D. Schnittman and Christopher S. Reynolds

University of Maryland

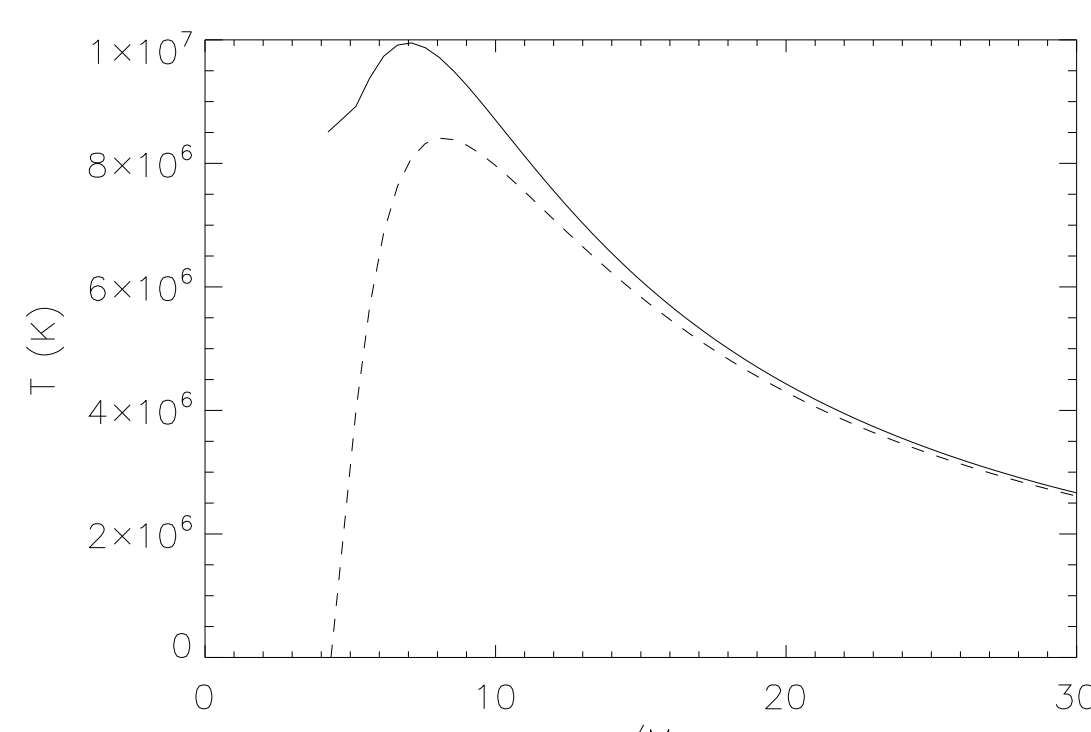
Abstract

We have developed a Monte Carlo ray-tracing code in the Kerr metric to calculate the observed spectra from accreting black hole binaries. The accretion disk is modeled as a steady state Novikov-Thorne disk with a non-zero torque at the inner-most stable circular orbit (ISCO). The emitted photons then propagate through a spherical corona of hot electrons, getting boosted in energy through inverse-Compton scattering. Some photons are scattered back to the disk, producing relativistically broadened fluorescent emission lines. Thus a single integrated model can account for all major feature of the X-ray spectrum: the thermal peak, power-law slope, and iron emission line. These self-consistent spectral models will help interpret observations to measure black hole parameters such as mass, spin, accretion rate, and inclination, as well as the corona temperature and optical depth.

Methods

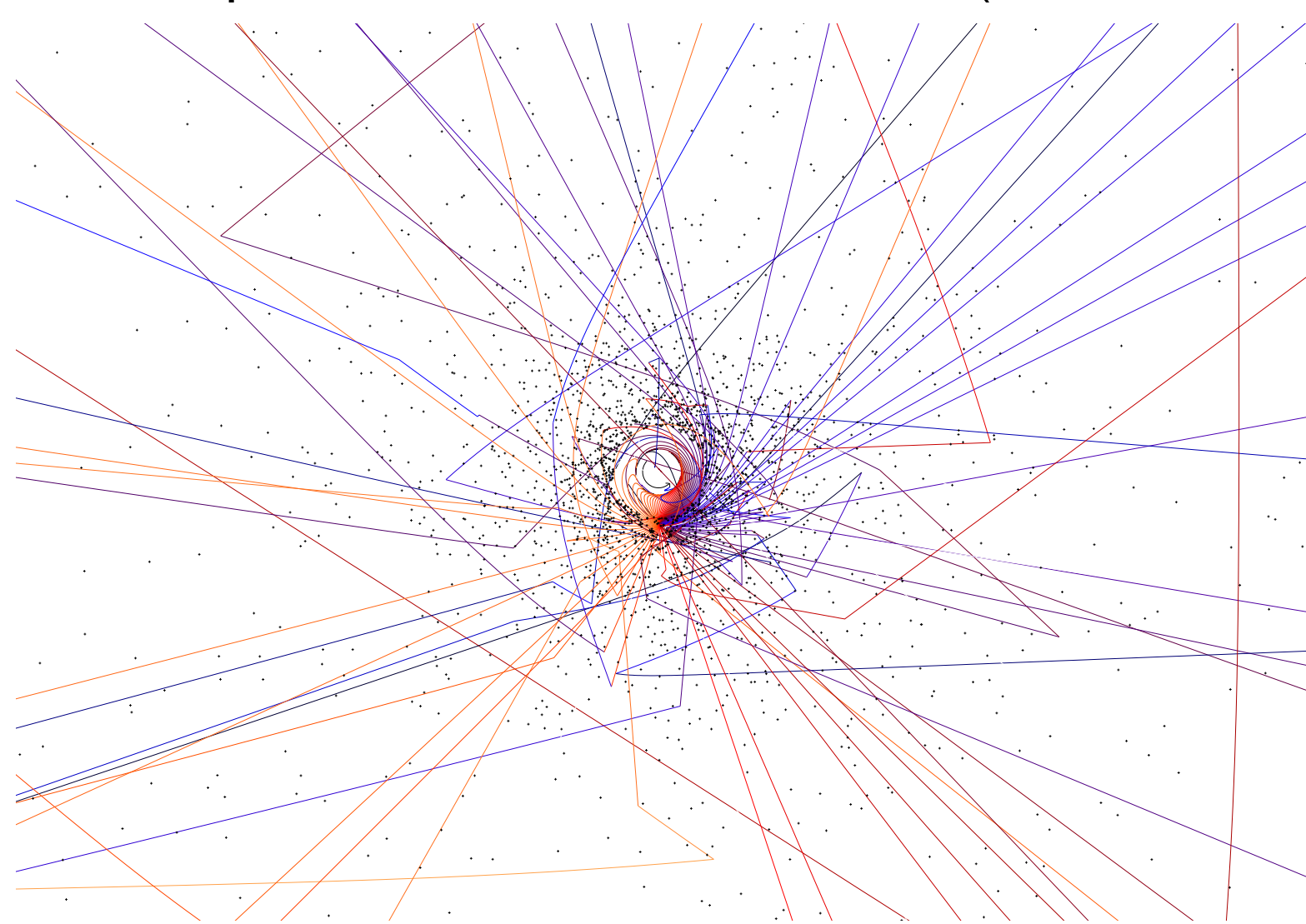
We begin by calculating the surface temperature of a steady state Novikov-Thorne accretion disk (Novikov & Thorne, 1973) with a non-zero torque at the inner boundary (Agol & Krolik, 1999). The parameters for such a disk are (nominal values in parentheses):

- M_{BH} : black hole mass ($10 M_{\odot}$)
- a/M : BH specific angular momentum (0.5)
- \dot{M} : mass accretion rate ($10\% \dot{M}_{\text{Edd}}$)
- α : dimensionless stress parameter (0.1)
- η : "excess" efficiency due to torque at ISCO (0.01)

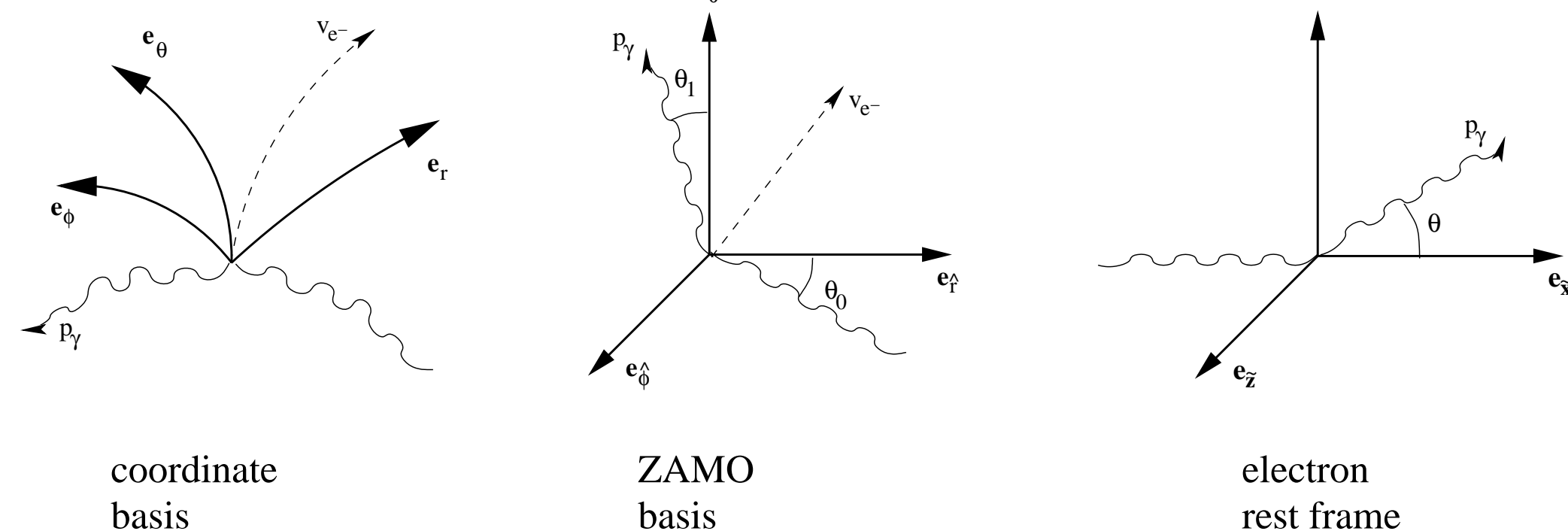


A torque at the ISCO increases the surface temperature of the inner disk (solid line) compared to a no-torque Novikov-Thorne disk (dashed line).

For the scattering corona, we assume a hydrostatic equilibrium around a point-mass Newtonian gravitational potential, which gives $\rho_e \sim r^{-3/2}$ and $T_e \sim r^{-1}$, similar to an ADAF distribution. A Monte Carlo code is used to trace the photons (typically $\sim 10^8 - 10^9$ per calculation) through the corona from a disk made up of isotropic emitters on circular orbits (Schnittman 2005).

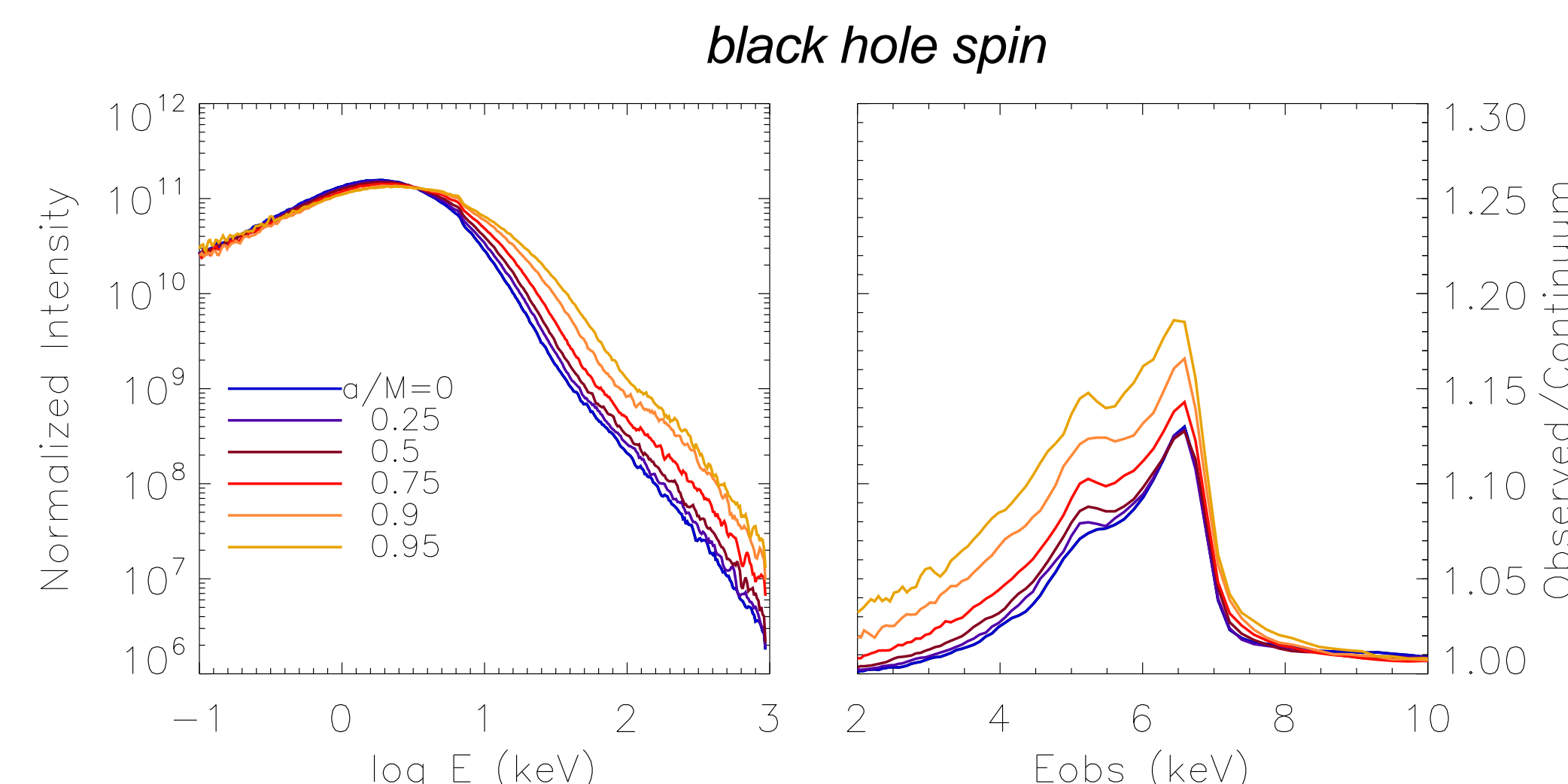


The electrons have an isotropic thermal velocity distribution, as measured in the frame of a zero-angular momentum observer (ZAMO). In this locally flat frame, the scattering processes can be treated as classical inverse-Compton scattering, which generally transfers energy from the hot electrons to the cool (disk) photons (Rybicki & Lightman, 1979). Some photons scatter back to the disk, where they may excite Fe $K\alpha$ lines if the effective energy is > 6.4 keV.

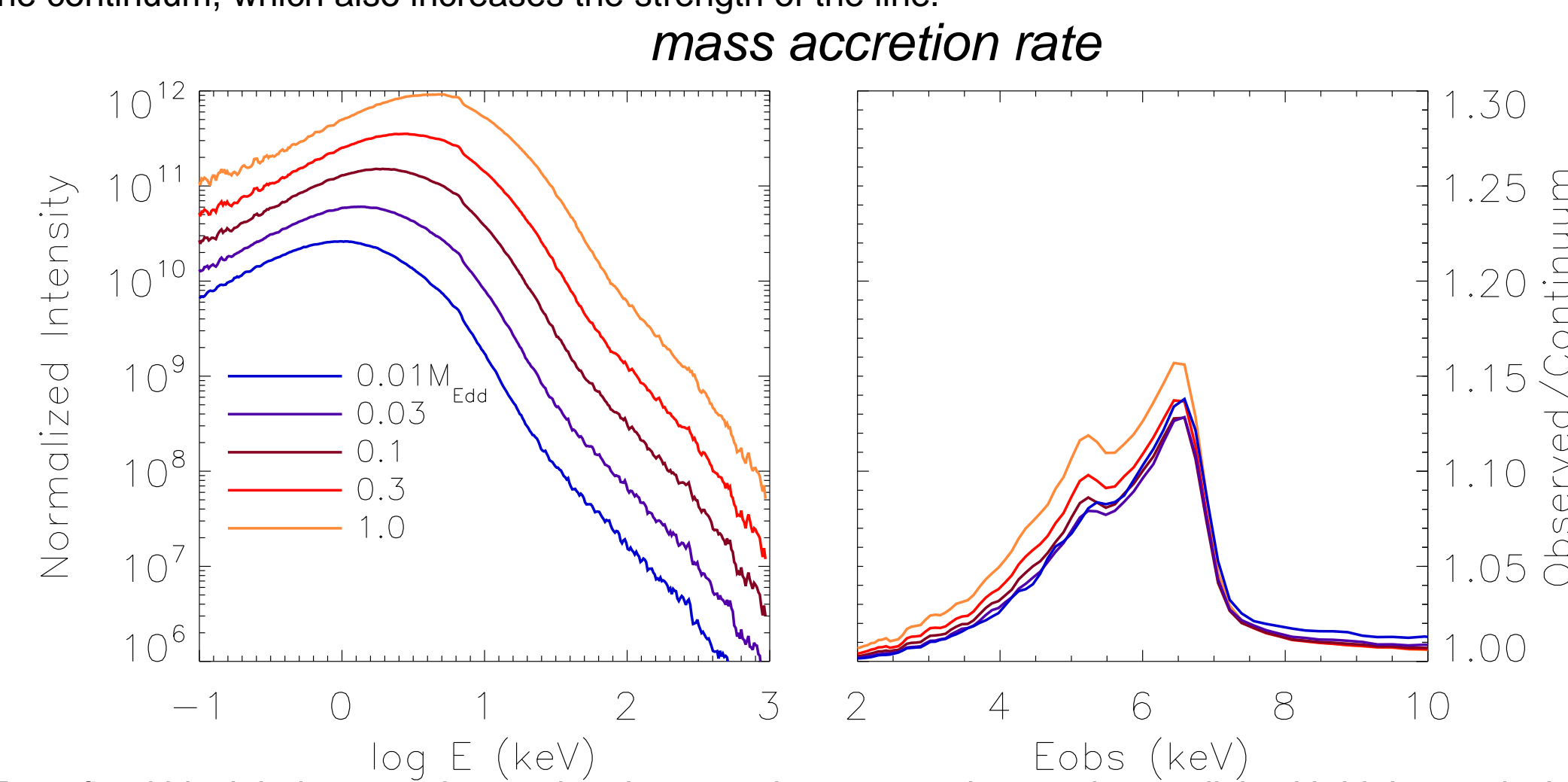


Results

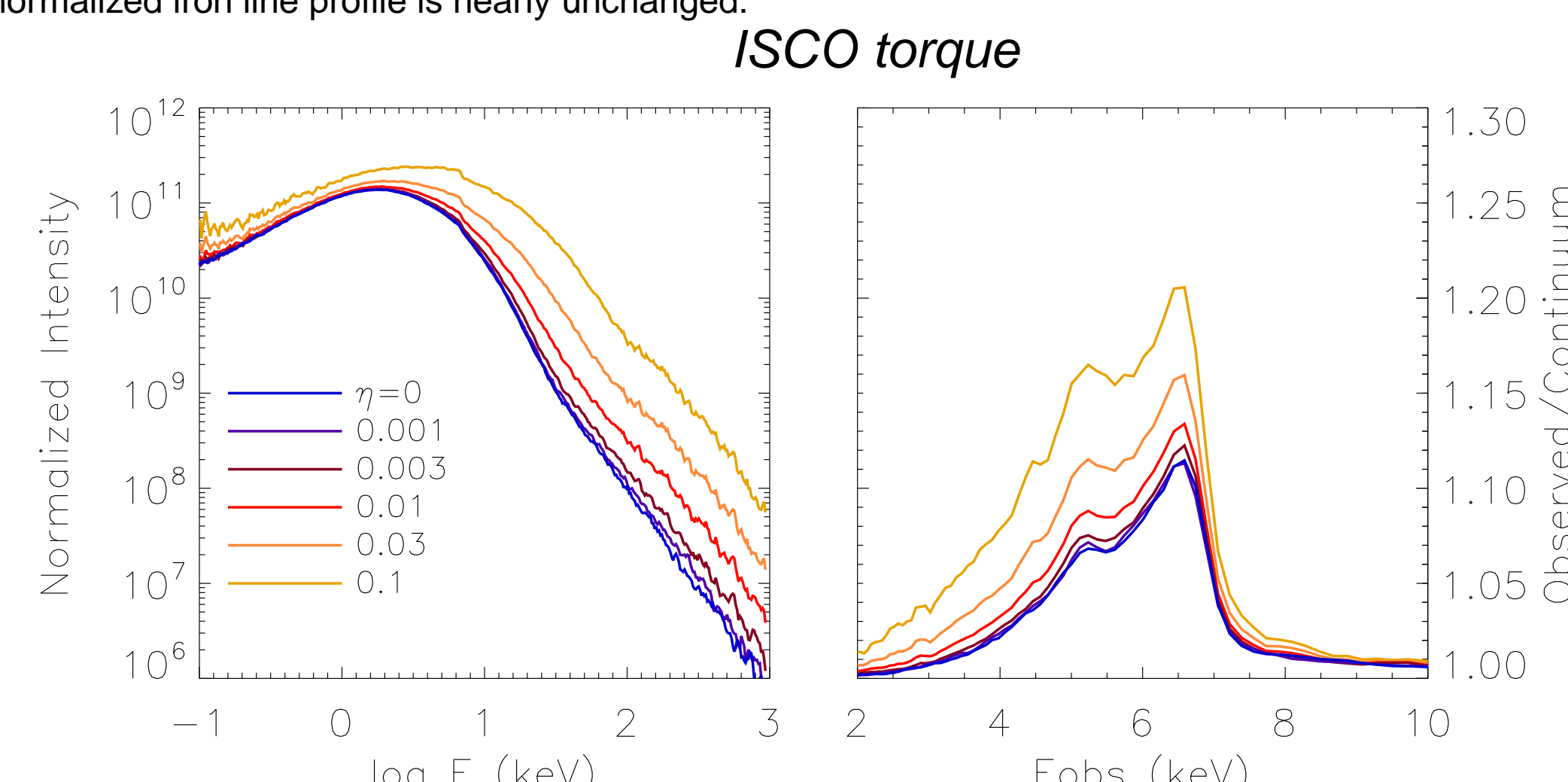
To investigate the effects on the spectrum of each of the model variables, we explore each "dimension" around a central fiducial point in parameter space. The baseline model spectrum has: $M = 10 M_{\odot}$, $a/M = 0.5$, $\dot{M} = 10\% \dot{M}_{\text{Edd}}$, $i_{\text{disk}} = 60^\circ$, $\eta = 0.01$, $\alpha = 0.1$, $\tau_{\text{es}} = 1$, $T_e = 200(r/r_{\text{ISCO}})^{-1}$.



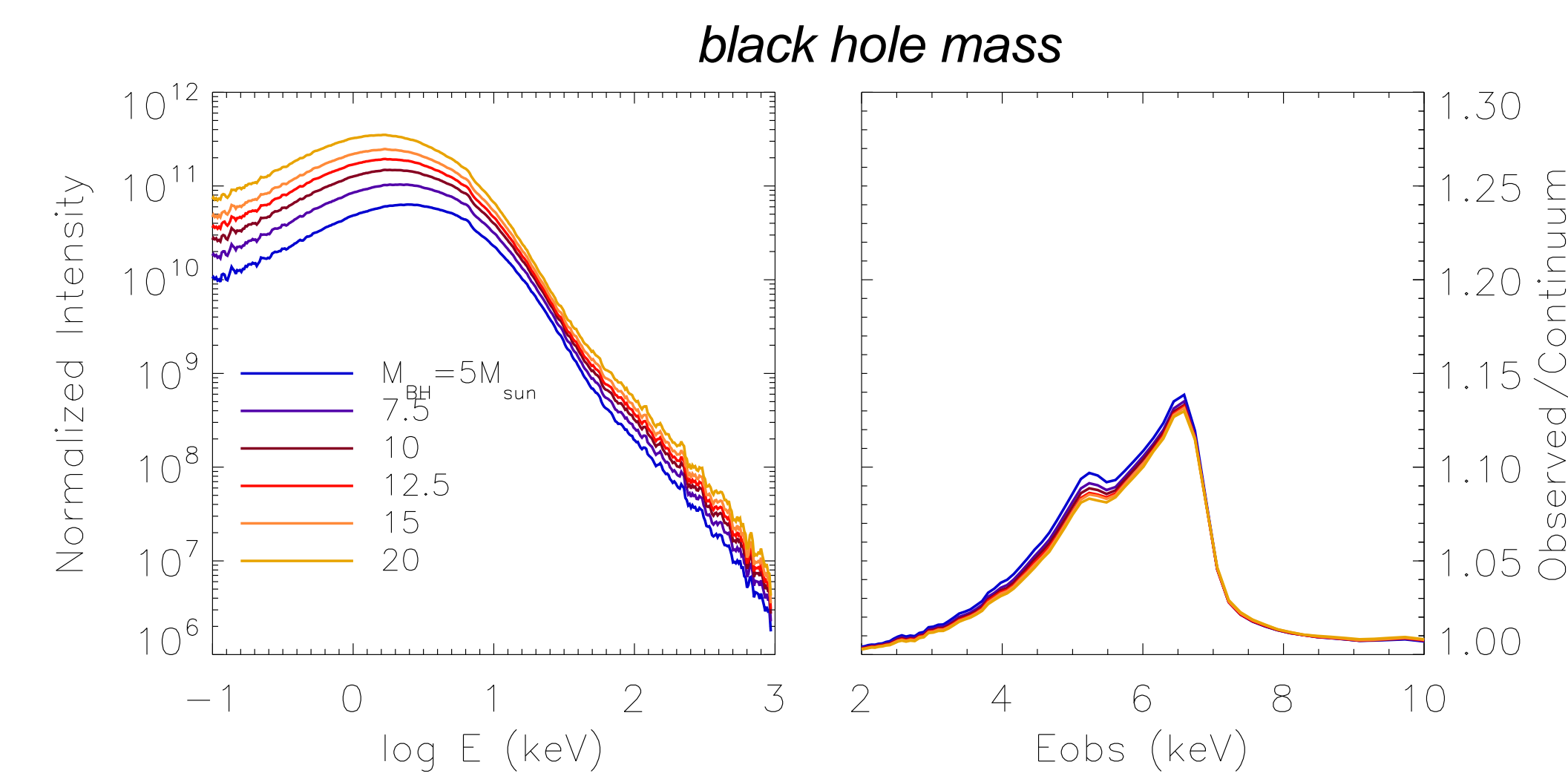
Increasing the black hole spin moves the ISCO closer to the horizon, increasing the strength of the red-shifted tail of the iron line. Additionally, for large spins, the hotter inner disk produces more high-energy photons in the continuum, which also increases the strength of the line.



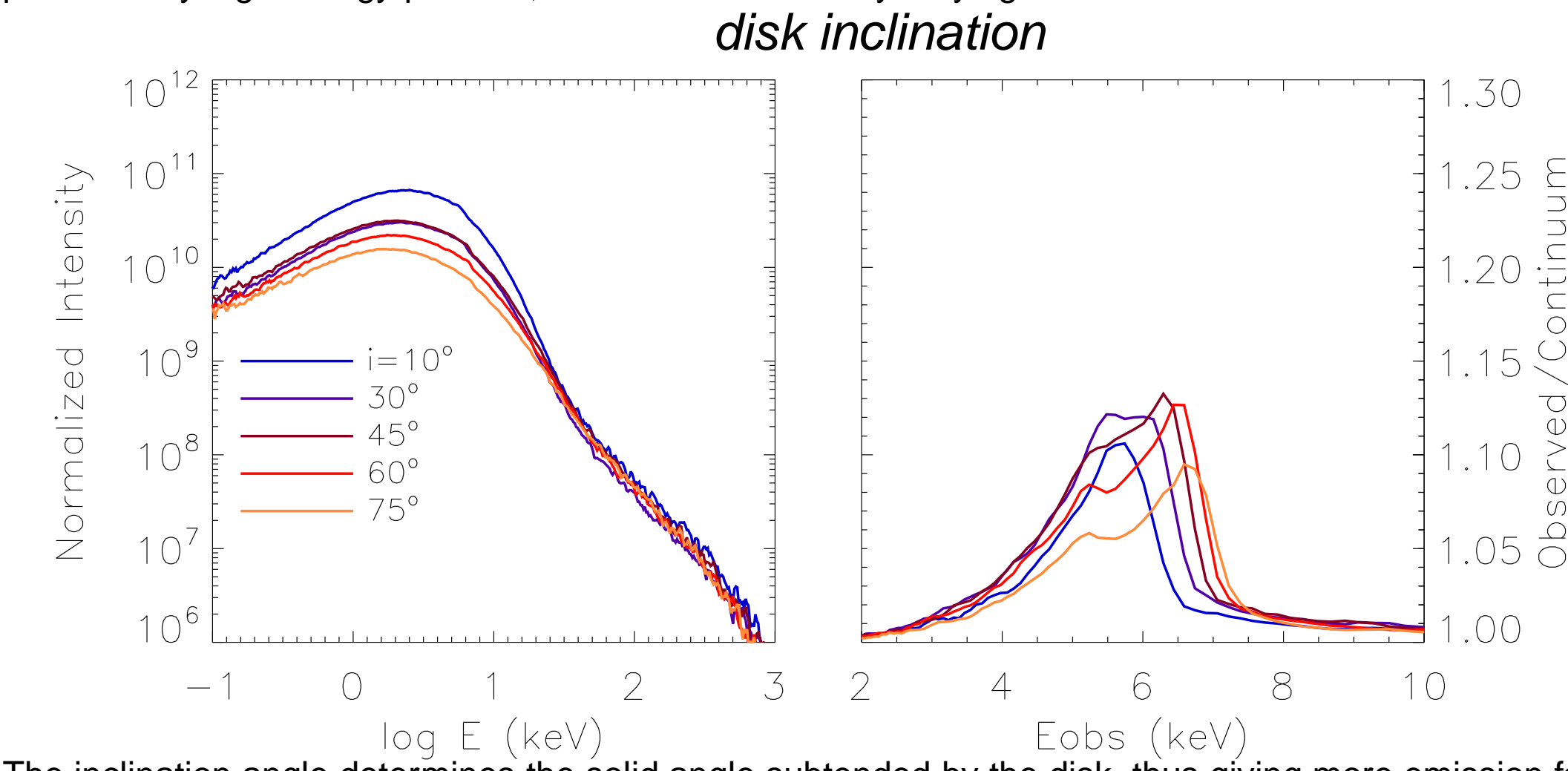
For a fixed black hole mass, increasing the accretion rate produces a hotter disk with higher emission, yet the normalized iron line profile is nearly unchanged.



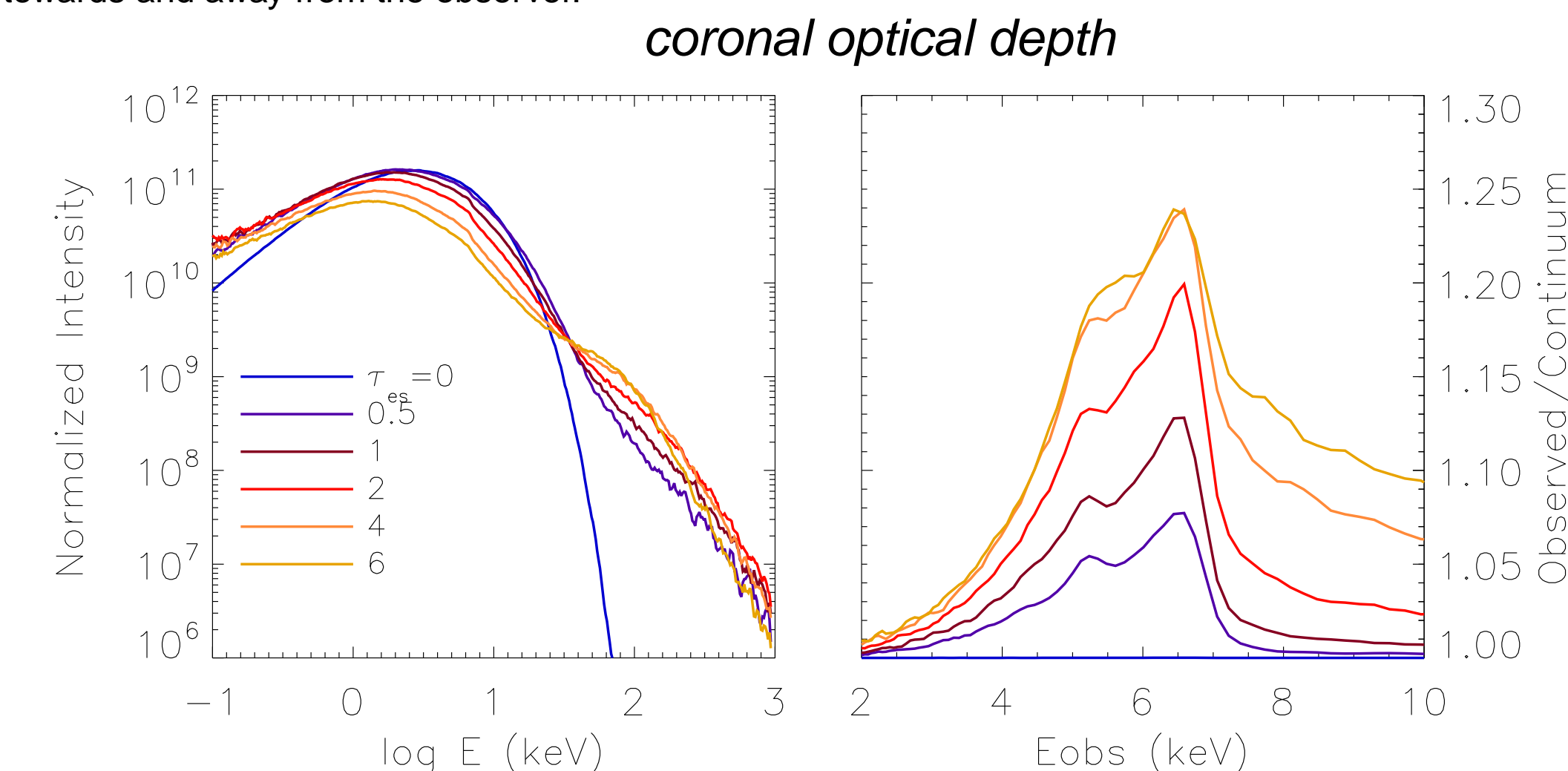
Increasing the torque at the ISCO boundary increases the efficiency of the disk, and raises the temperature of the inner regions, giving more high-energy photons in the continuum and increasing the strength of the iron line. In this manner, a torqued inner disk can resemble that of a rapidly spinning black hole.



For a fixed Eddington accretion rate, increasing the black hole mass decreases the temperature of the disk while increasing its size, thus affecting the low-energy part of the continuum spectrum. The iron line, which is produced by high-energy photons, is thus not affected by varying the black hole mass.



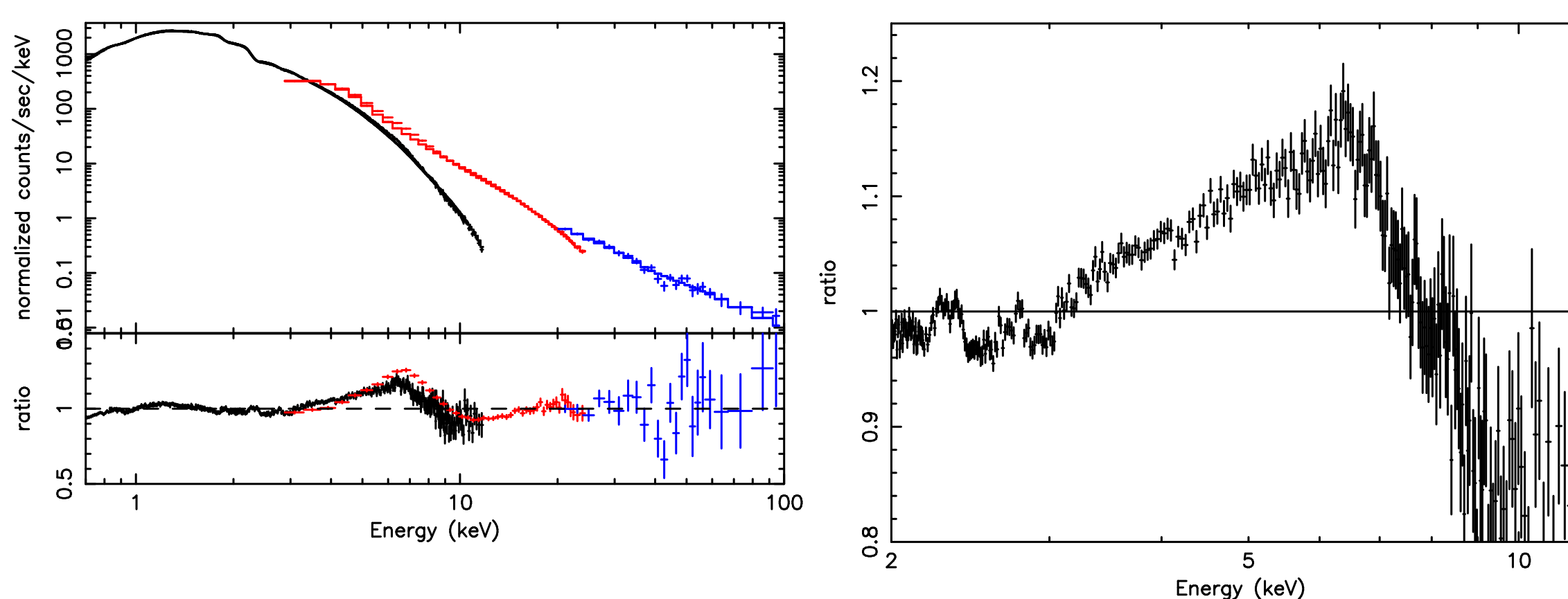
The inclination angle determines the solid angle subtended by the disk, thus giving more emission from a face-on disk. However, the Compton-scattered photons come from a spherical corona that appears the same size regardless of inclination. For higher inclinations, the iron line is broader due to relativistic beaming of photons towards and away from the observer.



The optical depth of the corona determines the shape and magnitude of the power-law tail in the continuum spectrum. Just as the thermal disk photons get upshifted in energy from Compton scattering, so does the fluorescent iron line, showing large blue-shifted tails for coronae with large optical depths.

Applications

We hope to apply these integrated methods to fitting *RXTE* and *XMM-Newton* observations of galactic black holes such as GX 339-4 (Miller et al. 2004).



Future Work

- Include emission from inside of the ISCO
- Use plunge orbits to solve for surface density and ionization fractions
- Develop efficient procedures to fit data to model with 6+ parameters

REFERENCES

- Agol, E., & Krolik, J. H. 1999, *ApJ*, 528, 161
 Miller, J. M., et al. 2004, *ApJ*, 606, L131
 Novikov, I. D., & Thorne, K. S. 1973, in *Black Holes*, ed. C. DeWitt & B. S. DeWitt (New York: Gordon and Breach)
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 Schnittman, J. D. 2005, in *Proceedings of the 22nd Texas Symposium on Relativistic Astrophysics*, pre-print astro-ph/0502048

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