Modelling the Black Hole Reflection Spectrum with Fenrir

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Papers: Taylor & Reynolds 2018a, ApJ, 885, 120; Taylor & Reynolds 2018b, ApJ 865, 109; Taylor, Dauser, & Reynolds (in prep)

The Reflection Spectrum

- The SEDs of AGN are typically dominated by a thermalized disk (~10 eV), as well as a high-energy tail produced by inverse Compton scattering of thermal photons by a hot corona (~ 100 keV)
- The reflection spectrum is created by the reprocessing of the coronal photons by the underlying disk. It is dominated by Fe K (~6.4 keV), a Compton hump (~20 keV), and the soft excess (~0.3 - 1.0 keV).
- These features are very broad and skewed, consistent with the rapid orbital motions and strong gravity of the inner-most accretion flow.
- By fitting reflection models to AGN X-ray spectra, we can estimate black hole spin, the size of the corona, the inclination of the system, and the properties of the accretion disk near the event horizon (Reynolds 2014).
- Past modeling suites (e.g. *RELXILL*, Dauser et al. 2010, 2013, 2014) have assumed that the disk has negligible disk thickness (i.e. "razor-thin").

Fenrir – A New Ray Tracing Suite

- I built new ray tracing software (*Fenrir*) that propagates photons through Kerr spacetime (Taylor & Reynolds 2018a, b).
- While compatible with many disk models, we chose to approximate the disk as optically thick, geometrically thin, and radiation pressure dominated (Shakura & Sunyaev 1973, hereafter SS73).

$$z = H_d \left[1 - \left(\frac{r_{ISCO}}{\rho}\right)\right]^{\frac{1}{2}}, \; H_d = \frac{3}{\eta}\left(\frac{\dot{M}}{\dot{M}_{Edd}}\right) \text{ (SS73)}$$

- We have chosen to approximate the corona as a lamp post: a point source with height *h* along the polar axis (Martocchia & Matt 1996).
- Currently being developed into an XSPEC model to be released soon (Taylor, Dauser, & Reynolds, in prep)

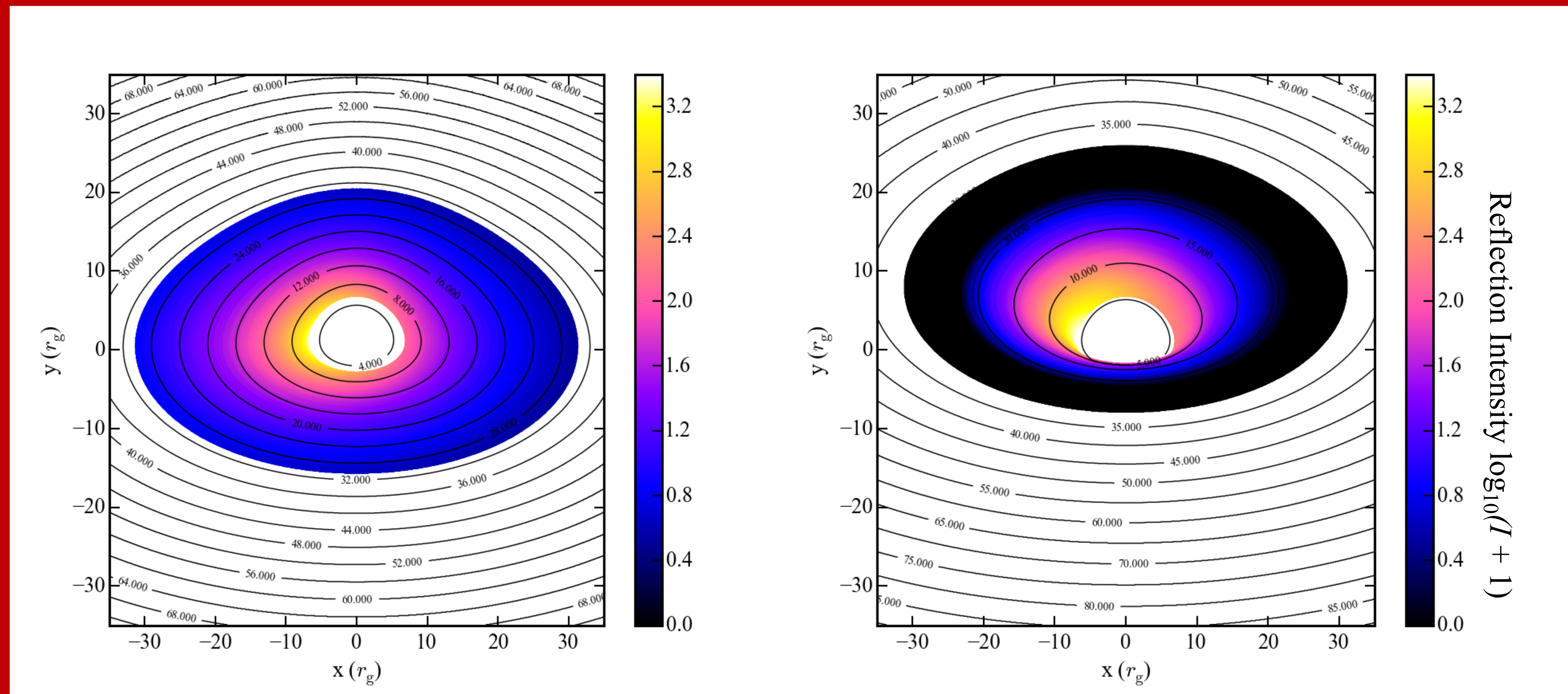

Fig. 1 – Reflection intensity maps produced by Fenrir for an accretion disk around a non-spinning (a = 0) black hole, illuminated by a lamp post at $h = 3\ r_g$ and seen by an observer at an $i = 60^{O}$ angle. The left panel shows the case of a razor-thin disk, ubiquitously used in modelling the reflection spectrum. The right panel uses an optically-thick, geometrically-thin, radiation pressure dominated accretion disk (SS73). For the right panel, the black hole is accretion at $\dot{M} = 0.3\ \dot{M}_{Edd}$. The convex geometry of the disk in the right panel has resulted in "self-shielding", in that the inner regions of the disk shield the outer regions from the corona's X-rays. This results in the outer disk having significantly less (if any) photons to process, thus significantly suppressing the reflection intensity.

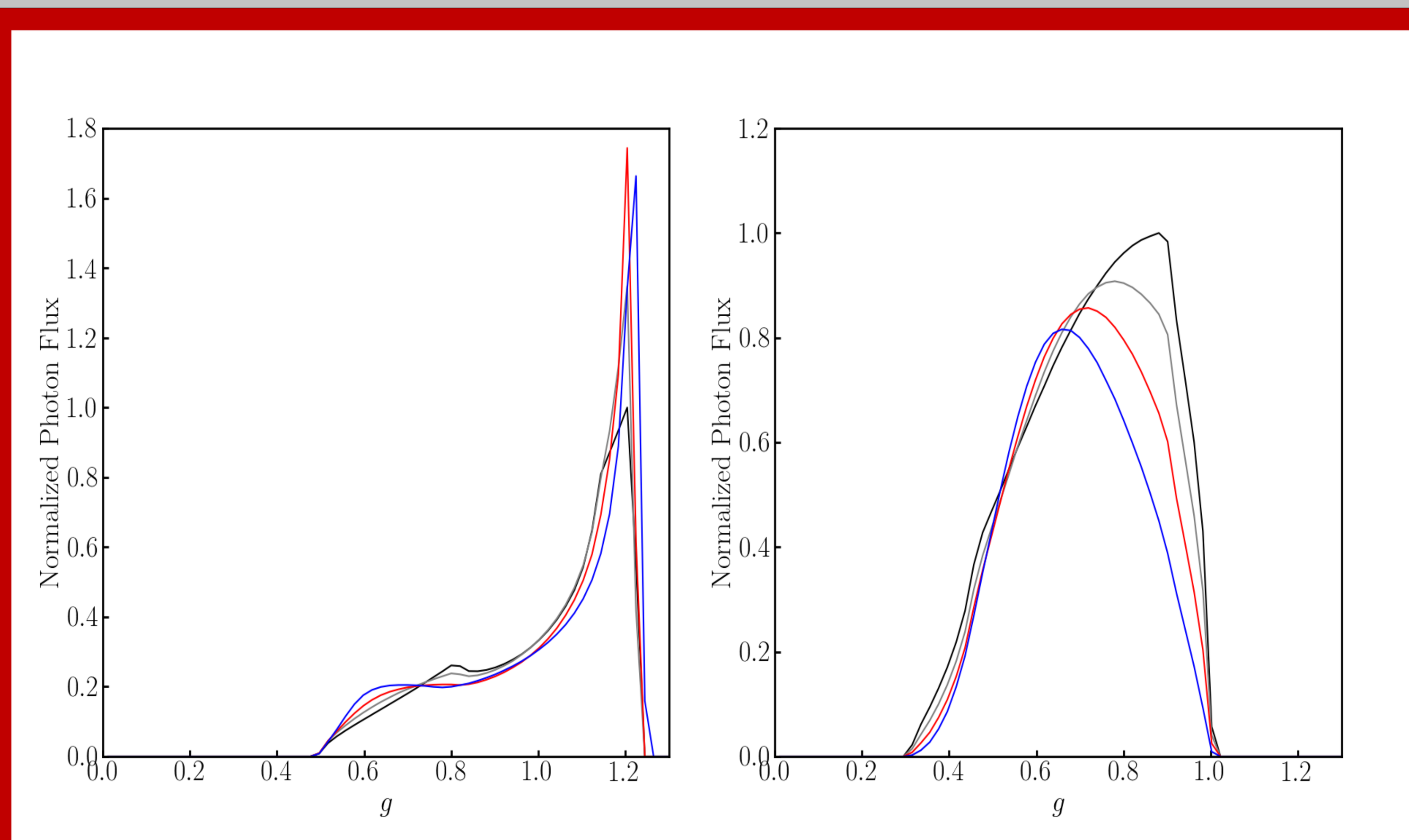

Fig 2 –Example line Fenrir line profiles (e.g. Fe K). The left panel has a black hole with a = 0.0 that has a corona at $h = 3r_g$, seen at $i = 60^{O}$. The right is the same, but with a = 0.9, h = 3, and $i = 15^{O}$. All four panels are color coded to represent different disk geometries: razor-thin (black) and an SS73 disk accreting at $\dot{M}$ = 0.1 (gray), 0.2 (red), and 0.3 $\dot{M}_{Edd}$ (blue). Note that $g = E_{obs}/E_{em}$. Clearly disk geometry has a significant impact on the shape of the broad line profiles observed in AGN.

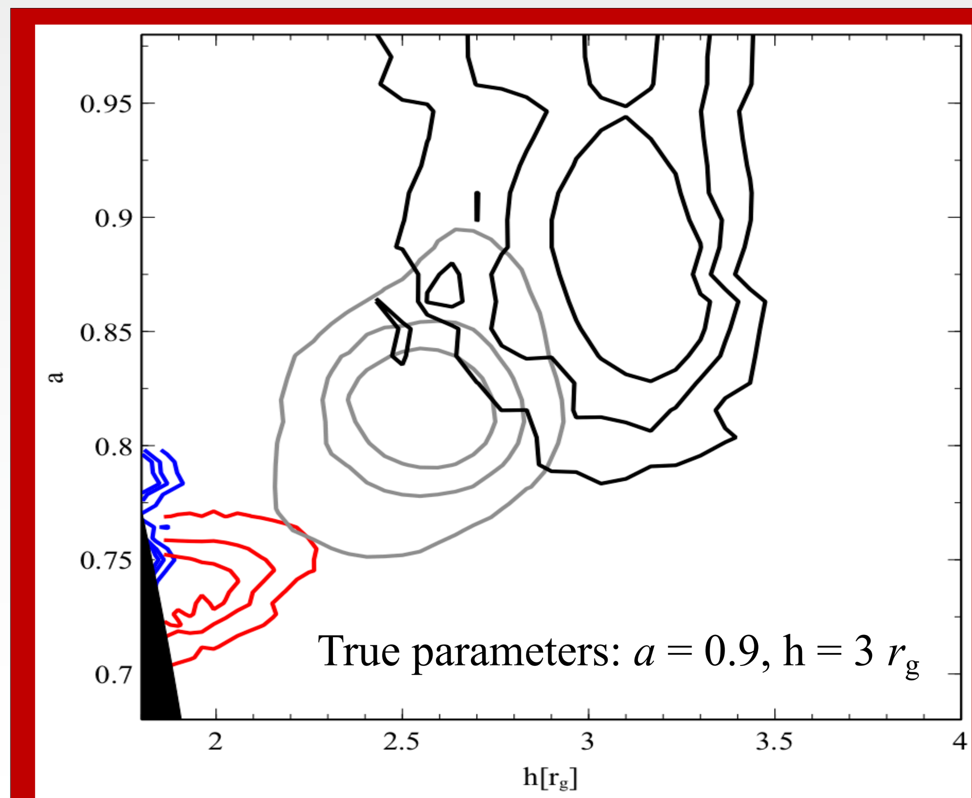

Fig 3 – A first attempt at estimating systematic error in spin measurements. These are MCMC contour plots for corona height (h) and black hole spin (a) for a razor-thin disk (black) and $\dot{M}$ = 0.1 (gray), 0.2 (red), and 0.3 $\dot{M}_{Edd}$ (blue), generated when fitting a razor-thin model (RELXILL) to Fenrir-generated synthetic data. The different levels are 68%, 90%, and 99% significance. The synthetic data was generated using XSPEC, using response matrices to simulate 200 ks of XMM-Newton data. As this was a first attempt, we used the true parameters as the initial parameters of the fit. We find that both a and h are underestimated in this case, but a rigorous analysis of a much broader region of parameter space much be done in order to make any definitive conclusions.

Building The Model

- I am currently working with Thomas Dauser (co-creator of RELXILL) to create a Fenrir XSPEC model.
- It will use H_d as a free parameter, generalizing from a strict SS73 accretion disk.
- An early version of the Fenrir XSPEC model can produce reflection models with a broken power-law emissivity profile (a common alternative to the lamp post). It is consistent with RELXILL at the razor-thin limit.
- I am currently working to implement a lamp-post corona into the XSPEC model, therefore capturing the self-shielding effects.
- Once this is completed, this will be released to the general astronomical community for use (Taylor, Dauser, & Reynolds, in prep).

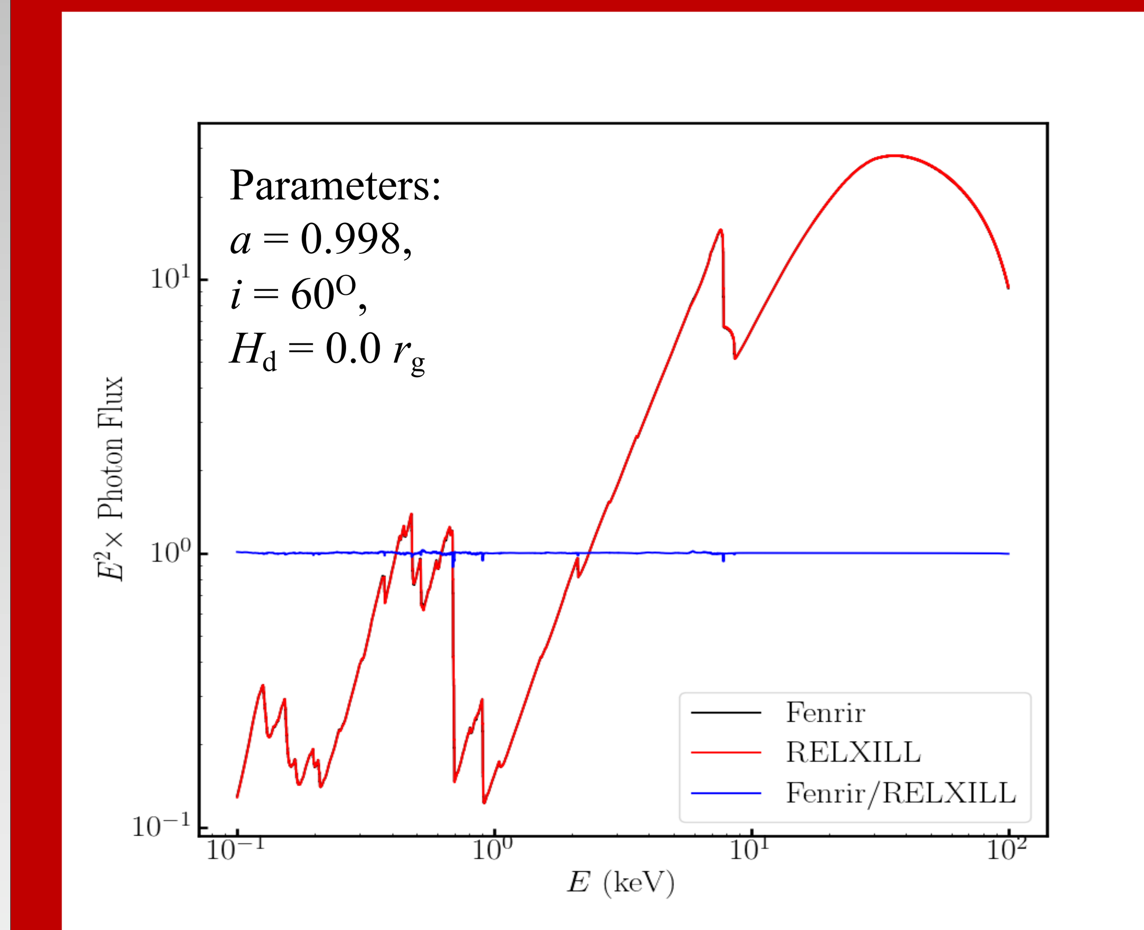

Fig 4 – A direct comparison between the current version of the Fenrir XSPEC model with $H_d = 0\ r_g$ (black) with RELXILL (red), along with their ratio (blue). These were produced using a power-law emissivity profile (index of -3), and one can see that they are nearly identical, giving confidence in the current state of the model.

Dauser et al. 2010, MNRAS, 409, 1534
Dauser et al. 2013, MNRAS, 430, 1694
Dauser et al. 2014, ApJ, 782, 76
Martocchia & Matt 1996, MNRAS, 282, L53
Reynolds 2014, Space Sci. Rev., 183, 277
Shakura & Sunyaev 1973, A & A, 24, 337
Taylor & Reynolds 2018a, ApJ, ApJ, 885, 120
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