

# Probing the Evolving X-ray Sources of Accreting Black Holes

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Detailed analysis of observed reflection features in the X-ray spectrum and of the variability of the emission showing reverberation time lags between the directly observed continuum and reflection from the disc has made it possible to probe the innermost regions of accreting black holes, down to the innermost stable orbit and the event horizon. Comparing detailed analysis of energy and lag spectra to theoretical predictions constrains the locations of the X-ray sources in a number of AGN including 1H 0707-495, IRAS 13224-3809 and MCG-6-30-15.

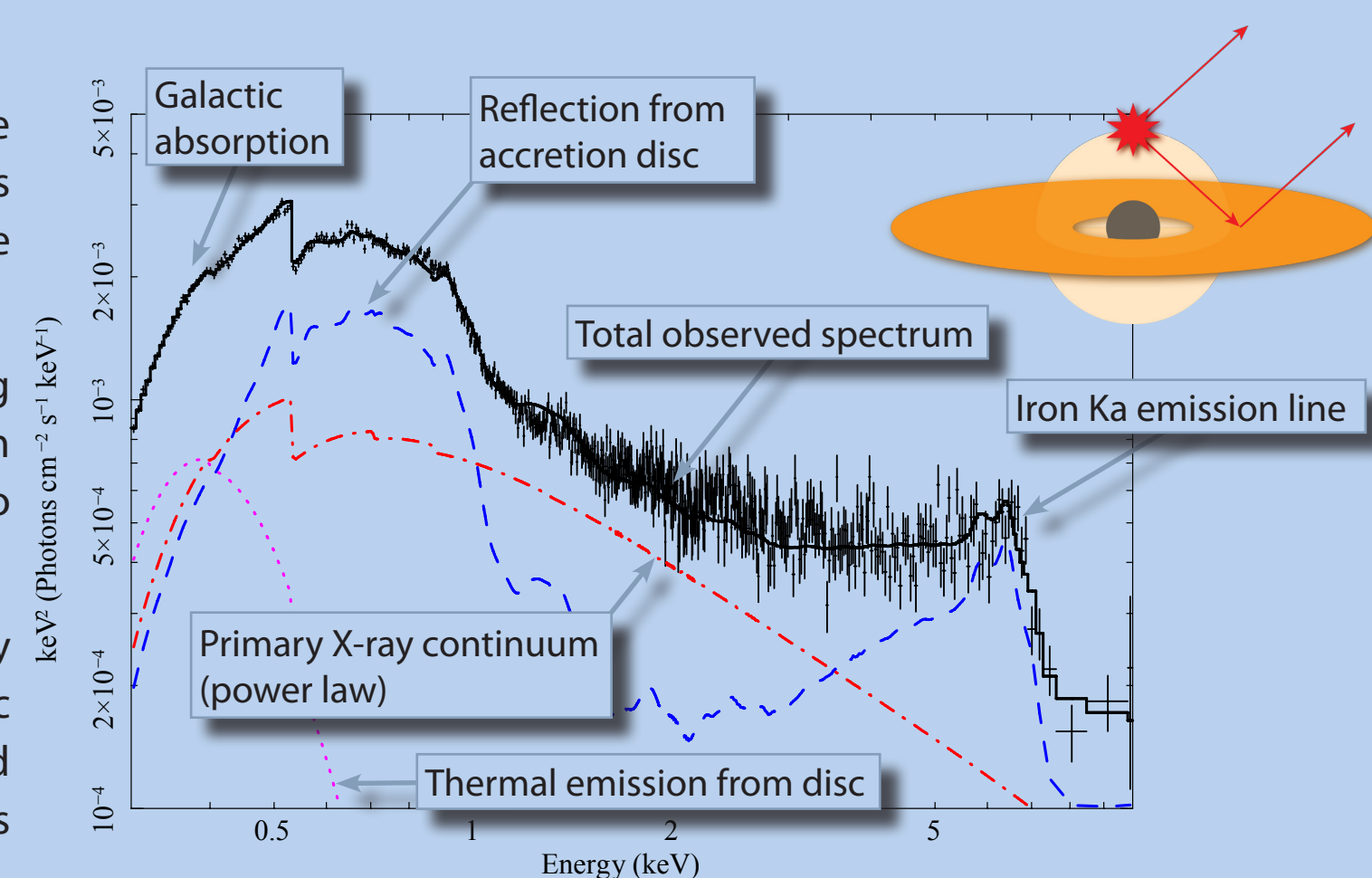
With high quality data from long X-ray observations of these sources, it has, for the first time, been possible to follow the evolution of the coronal X-ray source as the luminosity of the source goes up and down. We are able to find evidence that the size and other properties of the X-ray source change on the timescale of a few hours, giving rise to the extreme variability seen in these sources with the source increasing in size as the luminosity increases. Such detailed analysis of observations (both of spectra and variability) and studies of how the X-ray source is changing is paving the way to the science that will be possible with the next generation of X-ray instruments (NuSTAR and Astro-H) and will allow us to understand the processes at work in the innermost regions of accreting black holes, releasing energy from the inflowing material to power some of the brightest objects in the Universe.

## X-ray Emission from Accreting Black Holes

When the X-ray continuum originating from a source in the corona surrounding the central black hole of an AGN is incident upon the accretion disc around that black hole, the incident X-rays will be reflected. This causes a number of absorption and emission features to be imprinted on the spectrum of the X-rays reflected from the accretion disc, the most prominent of which is the  $K\alpha$  emission line of iron, at 6.4keV (as measured in the rest frame of the emitting material).

An emission line originating from an accretion disc around a black hole will be affected by relativistic effects due to the Doppler shifting of the emission as the material in the accretion disc orbits around the black hole as well as gravitational redshift of the emission from material closer to the central black hole. This causes the emission line to be greatly broadened with an extended redshifted wing to lower energies originating from the innermost parts of the disc, as close as  $1.235r_g$  ( $GM/c^2$ ), to rapidly spinning black holes.

The X-ray emission from AGN is extremely variable and measurements of this variability have added a further dimension to the study of accreting black holes. Most notably, reverberation lags are detected, where variability in the X-rays reflected from the accretion disc lags behind that in the continuum emitted from the corona, owing to the additional light travel time between the X-ray source and reflector. These lag times correspond to the light travel time across just a few gravitational radii, so measurement of these lags probes the innermost regions, right down to the innermost stable orbit and event horizon.



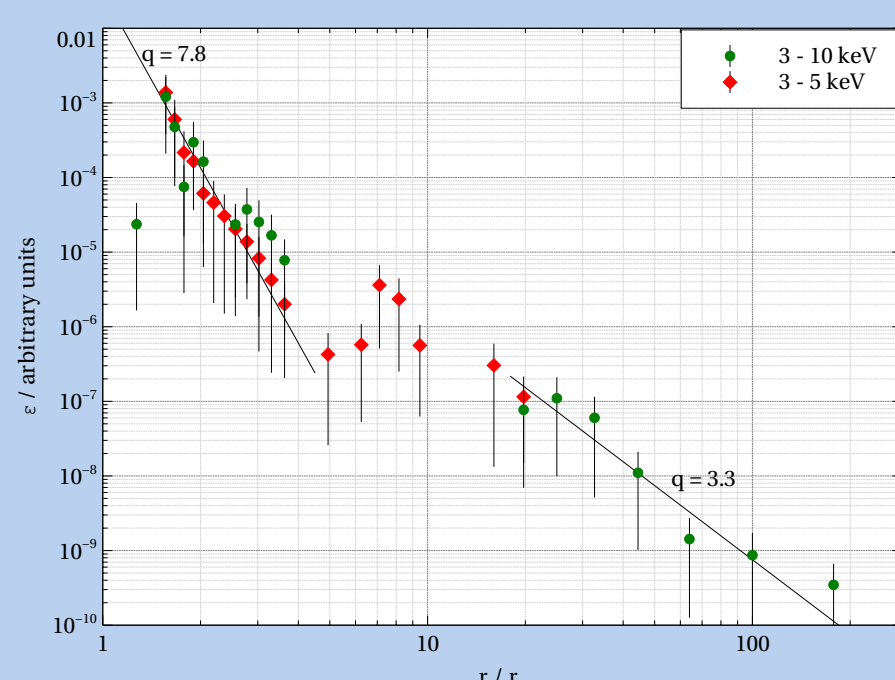
## Observational Probes of Black Hole Structure

Detailed analysis of the X-rays detected from accreting black holes allows thier structure to be probed down to just a few gravitational radii from the event horizon and the innermost stable orbit. This is achieved through analysis of both time-averaged X-ray spectra and the variability of the X-ray emission.

### Resolving the Accretion Disc through Spectral Observations

The illumination pattern of the accretion disc (and thus the relative reflected fluxes from different parts of the disc) is characterised by the *emissivity profile*, defined as the reflected flux (per unit area) as measured in the local rest frame on the disc.

The profile of a relativistically broadened emission line is different from successive radii in the disc, due to the change in the orbital velocity and gravitational redshift moving further from the black hole. It is therefore possible to determine the emissivity profile of the accretion disc by fitting the relative contributions to the profile of the relativistically broadened iron  $K\alpha$  emission line of the blurred reflection spectrum from each radius (Wilkins & Fabian 2011).

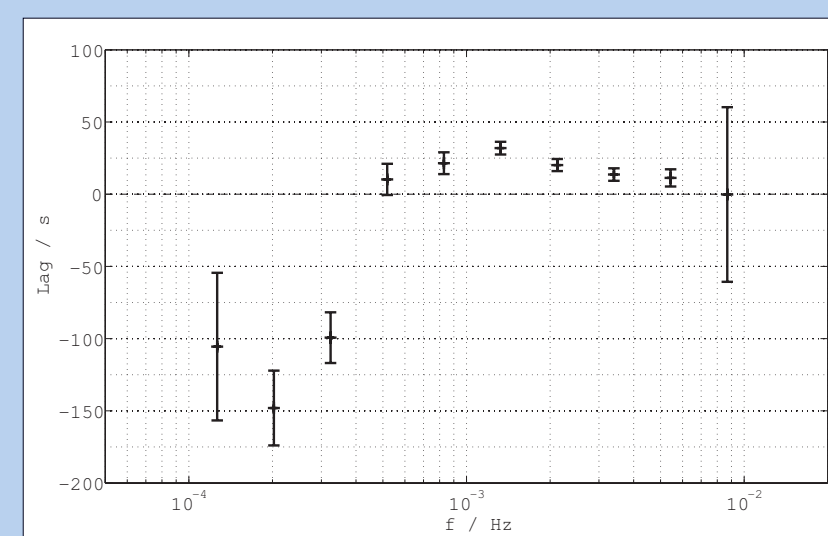


*The emissivity profile of the accretion disc in 1H0707-495, determined by fitting the reflection from successive radii to the profile of the relativistically broadened iron  $K\alpha$  line.*

### Measurement of Reverberation Time Lags

The innermost structure of the accreting black hole can be probed by measuring the time lags between variability in an energy band dominated by direct continuum emission from the corona and one dominated by reflection from the disc. These time lags correspond to the additional light travel time between the source and reflector.

The time lags are found by taking the Fourier transforms of the light curves and the time lag is calculated for each frequency component to produce a lag spectrum (Zoghbi et al 2010, Kara et al 2012).



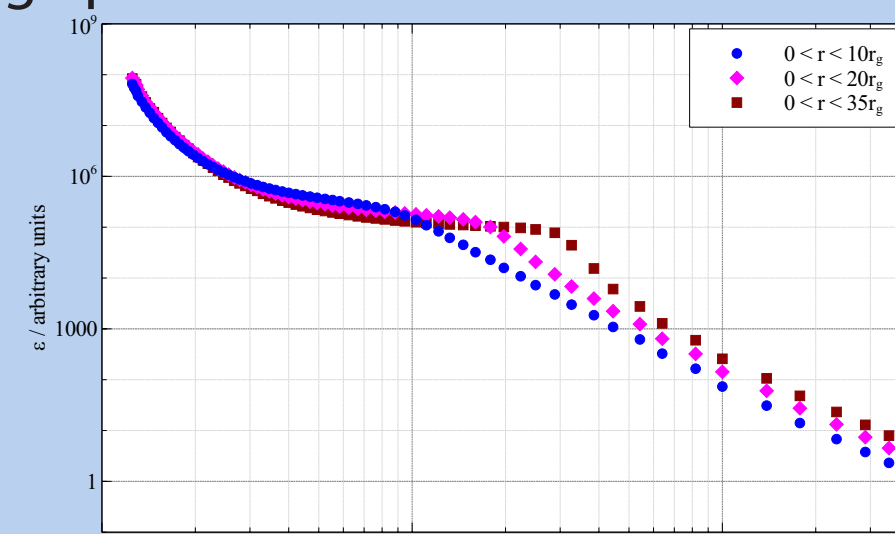
*The lag spectrum between the continuum-dominated 1.0-4.0keV band and reflection-dominated 0.3-1.0keV band of 1H0707-495. The positive time lag around 10⁻³ Hz indicates the variability in the reflection lags behind the continuum.*

## Understanding and Interpreting Observations

In order to interpret the detailed spectral and timing observations of the X-ray emission from accreting black holes, general relativistic ray tracing simulations were carried out. Emissivity profiles, lag spectra and other observables that would arise from the reflection off the accretion disc were simulated for coronae in different configurations, varying properties of the X-ray source including its location, geometry and extent. Ray tracing simulations are carried out on graphics processing units (GPUs) using the NVIDIA CUDA framework for efficient computation of the hundreds of rays in parallel.

### Understanding Emissivity Profiles and Lag Spectra

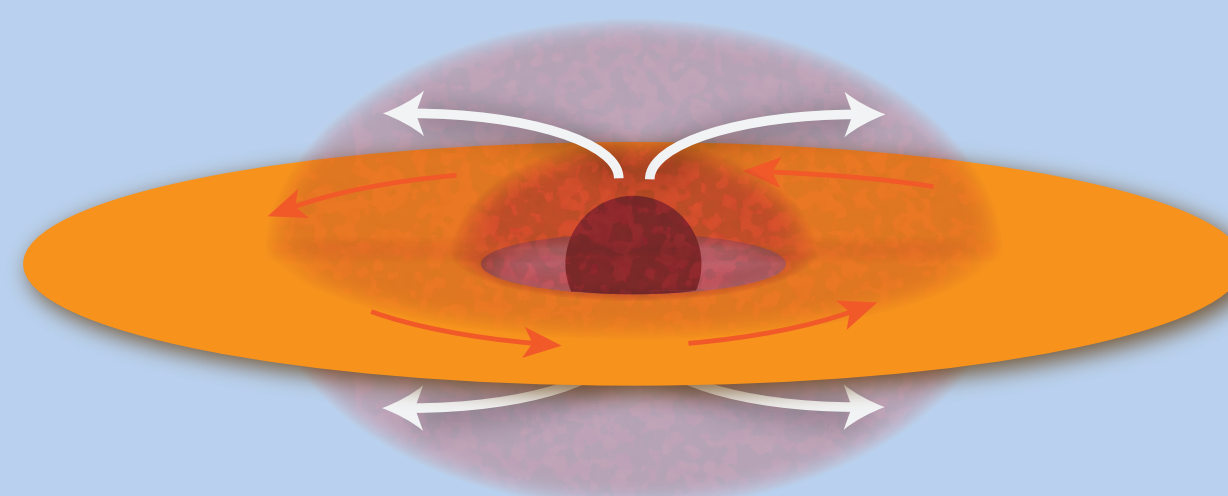
Theoretical emissivity profiles are computed by tracing rays from their source in the corona until they hit the accretion disc where their location is recorded. When extended X-ray sources are considered, the outer break point of the emissivity profile, where the flat middle region becomes an inverse-cube fall-off over the outer part of the disc, is identified with the outermost radial extent of the X-ray source (Wilkins & Fabian 2012).



Observable lag spectra may be simulated by computing the reverberation response from the accretion disc to an instantaneous flash in the corona. Counting the number of rays arriving as a function of time gives the transfer function. Convolving this with the intrinsic variability of the X-ray source (or the light curve observed in the continuum-dominated band) gives the light curve of the reflected band, and theoretical lag spectra between these bands can be calculated. It is necessary to know the arrival time of direct rays from the source and the fractions of continuum and reflected emission seen in each energy band as 'mixed' bands will dilute the observed lag (Wilks & Fabian 2013).

### Locating the Corona

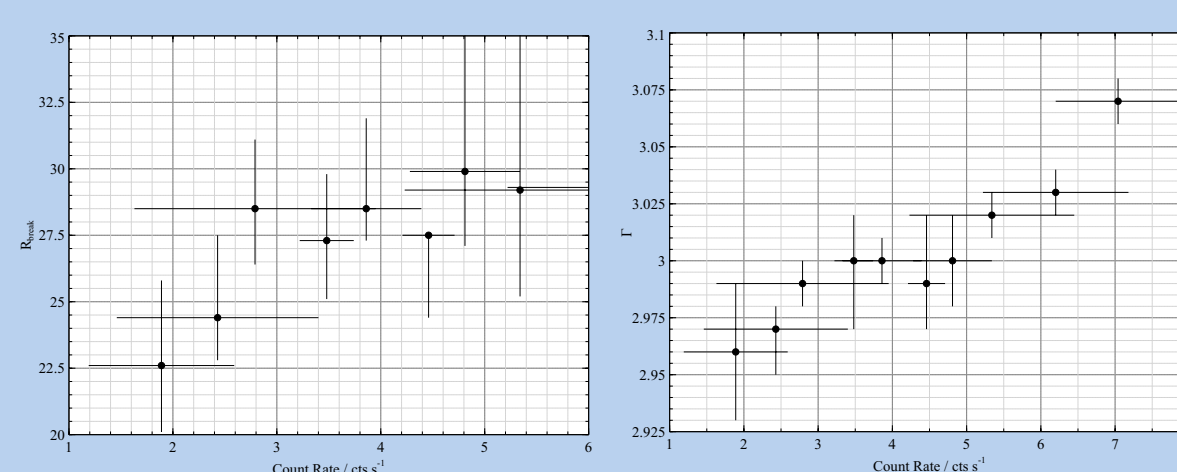
From both the accretion disc emissivity profile and lag spectrum, the X-ray emitting coronae in AGN are found to extend over the inner parts of the accretion disc (out to around  $35r_g$  in 1H 0707-495 and around  $10r_g$  in IRAS 13224-3809 and MCG-6-30-15) and extend vertically to around  $2r_g$  above the plane of the accretion disc.



## Time Evolution of the X-ray Source

In addition to analysing integrated data sets from long observations, it is possible to analyse spectra extracted from separate time intervals of the observation. Spectra were produced using the photons that arrive during time periods of varying count rate, found from the lightcurve of the source.

Fitting the emissivity profile of the iron  $K\alpha$  line as a twice-broken power law and identifying the outermost break point with the radial extent of the corona, we see evidence that as the count rate increases, the corona expands to a larger volume around the black hole.



*(Left) The outer break radius in the emissivity profile, identified with the outermost radial extent of the X-ray emitting corona and (Right) the photon index of the power law continuum, for times of varying total count rate of 1H 0707-495. Parameters are derived by fitting a model spectrum consisting of emission from the corona (power law) and relativistically blurred reflection from the accretion disc with a twice-broken power law emissivity profile.*

If X-rays are emitted from the corona by Comptonisation of thermal photons from the accretion disc, the increased size of the corona increases its cross-section for scattering photons from the disc, thus increasing the count rate.

As well as the extent of the corona changing, spectral analysis reveals that as the count rate increases, the continuum spectrum becomes softer (a more steeply falling power law). This may indicate that as the corona expands to increase the count rate, the energy per particle in the larger corona decreases.

## Conclusions

- Through detailed X-ray observations (spectral and timing) it is possible to probe the innermost regions of accreting black holes.
- It has been possible to locate the X-ray emitting corona in 1H 0707-495, IRAS 13224-3809 and MCG-6-30-15.
- Studying the X-ray spectrum in changing flux states reveals that increases in X-ray count rate are associated with an expansion of the corona and a softening continuum spectrum.
- Observable data products produced from ray tracing simulations let us understand what the data are telling us about the black hole.

### References

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