International X-ray Observatory (IXO)

Black Hole Physics and Strong Gravity with IXO

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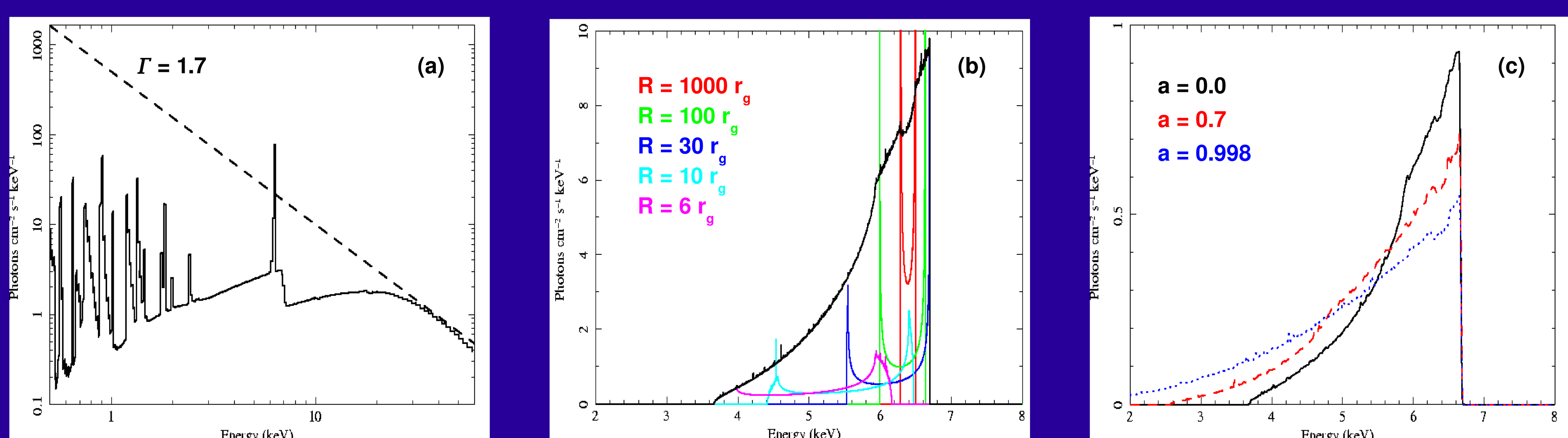
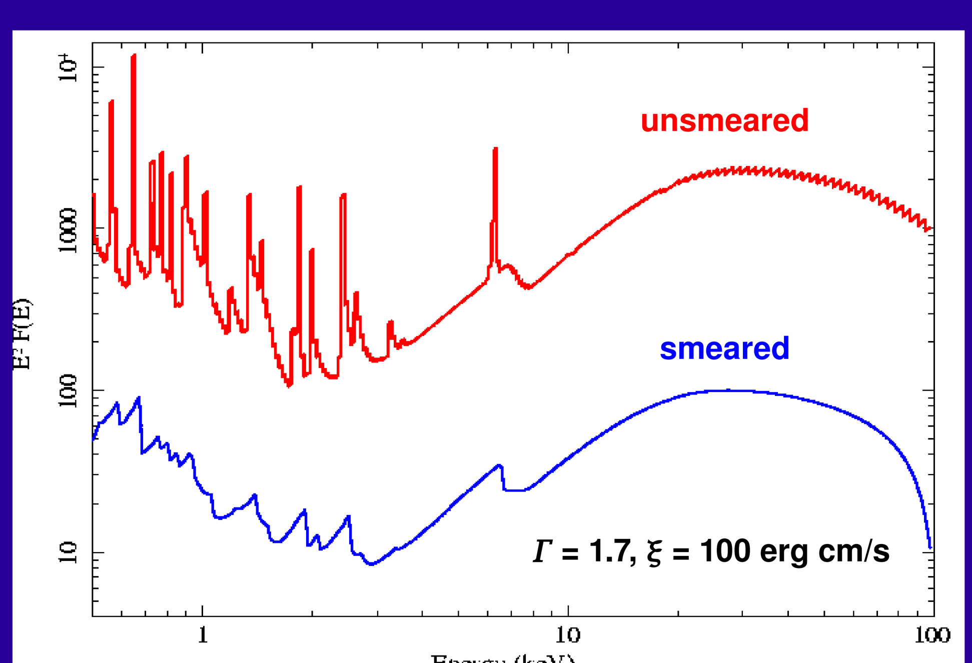
Introduction: **Studies of black holes are at a threshold. There is compelling evidence for the existence of both stellar-mass and supermassive black holes, and research is now focused on determining their properties and environmental effects. Most importantly, we are starting to realize the long-held promise of black holes as the ultimate laboratories for studying gravity in the strong-field limit. X-ray observations are already providing probes of the strong-gravity region around black holes, including evidence for the effects of black hole spin. However, a dramatic increase in collecting area and spectral resolution is required if we are to fully realize the potential of broad iron lines as probes of the strong-gravity region around black holes. Here, we will describe how the IXO will allow detailed studies of relativistic accretion, open the observational window on the astrophysics of black hole spin, and provide the first X-ray tests of strong-field General Relativity.**

The Importance of Black Hole Spin: Black hole spin has long been recognized for its role as an energy source, likely playing a fundamental part in the powering of relativistic jets such as those seen from radio-loud active galactic nuclei (AGN) or Galactic microquasars. Unlike measurements of black hole mass, spin measurements require us to examine observables that originate within a few gravitational radii of the black hole. A powerful probe of this region is obtained through the study of relativistically-broadened spectral features that are produced in the surface layers of the inner accretion disk in response to irradiation by the hard X-ray source (Tanaka et al. 1995). The strongest feature in this "reflection" spectrum is the Fe Kα line. For moderate accretion rates (between ~1-30% of the Eddington rate), we expect the iron line emitting part of the disk to extend down to, but be truncated by, the innermost stable circular orbit (ISCO) of the black hole potential (e.g., Reynolds & Fabian 2008). This ISCO-truncation imparts a spin-dependence to the reflection spectrum: black holes with higher (prograde) spin have an ISCO at smaller radius and hence the maximum redshift experienced by the reflection spectrum and the iron line is increased, broadening the overall line profile.



Left to Right: (a) The spectrum (solid) reflected from the surface layers of a neutral accretion disk by an incident hard X-ray spectrum of power-law shape (dashed). Note the fluorescent emission lines: iron is the most prominent due to its high energy and fluorescent yield. Note also the "Compton hump" created above 10 keV by downscattering of high energy photons in the disk atmosphere. (b) The broad Fe Kα line gets its shape as a result of emission contributions from a continuous series of annuli in the disk, with the emission from annuli closest to the black hole experiencing the greatest relativistic effects as well as greater Doppler broadening. The black line represents the resulting summed profile over all the annuli in the disk for a Schwarzschild black hole inclined 30° to the viewer's line of sight. (c) As the (prograde) black hole spin increases the resulting line profile becomes broader, since the disk can support stable orbits closer to the black hole, pulling in the ISCO to smaller radii. The material from this region thus experiences enhanced relativistic effects such as gravitational redshift.



Above: Comparison of an ionized disk reflection spectrum (Ross & Fabian 2005) both with and without the effects of relativistic smearing from the inner accretion disk near a maximally spinning black hole.

Measuring Spin: High signal-to-noise spectra across a wide band-pass are required to obtain robust spin measurements. It is especially important to obtain data above 10 keV in order to accurately measure the amplitude of disk reflection present and break degeneracies that exist between the reflection parameters and the spacetime parameters near the black hole, such as spin. The effects of spin on the disk reflection spectrum are not subtle, but the disk spectrum must be decomposed from other complexity in the spectrum such as continuum curvature or the effects of photoionized absorbers. For this reason, current black hole spin estimates (with *XMM-Newton* and *Suzaku*) have been limited to a handful of GBHBs (Miller et al. 2009) and one AGN (MCG-6-30-15; Brenneman & Reynolds 2006).

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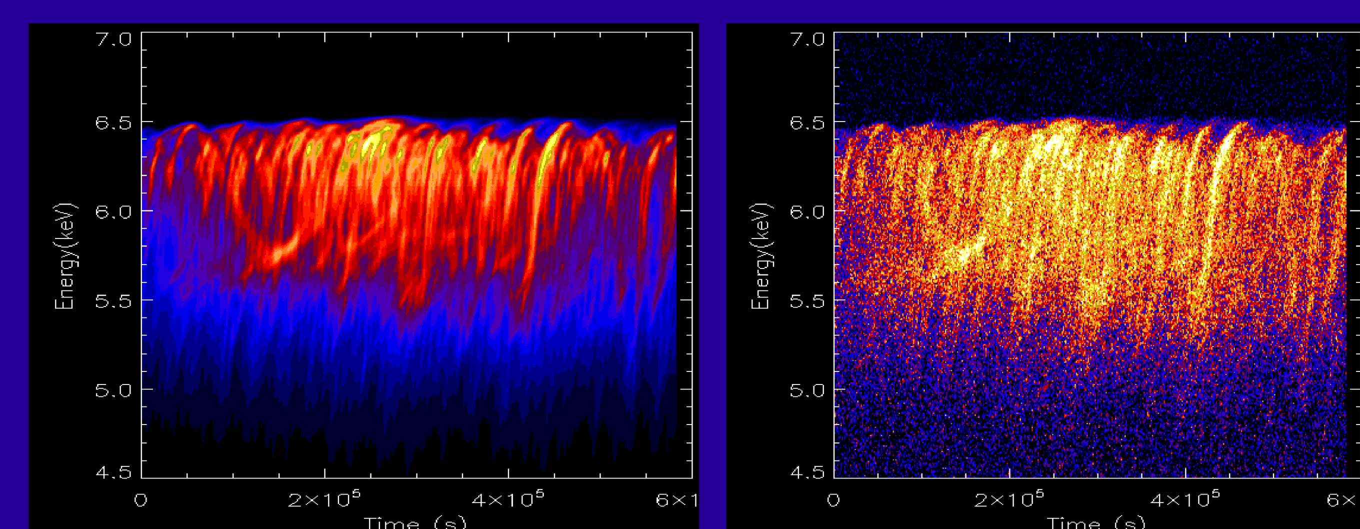
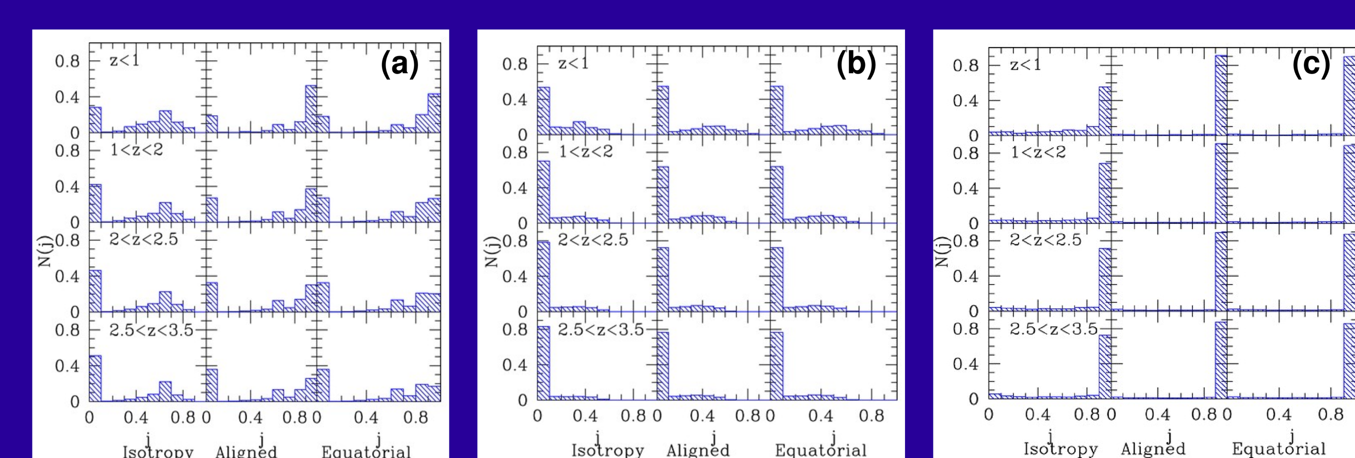
Other Methods for Measuring Spin: The disk reflection (i.e., broad Fe Kα) methodology outlined here is powerful since it can be applied uniformly to black holes across the whole range of masses. However, there are other mass-specific techniques that lead to spin constraints, which can be used to provide crucial consistency checks. In GBHBs, detailed examination of the spectrum and polarization of the thermal X-ray emission from the accretion disk both give independent measurements of the ISCO and hence the spin (e.g., McClintock et al. 2006, Dovčiak et al. 2008). GBHBs also occasionally display high-frequency quasi-periodic oscillations (HFQPOs) which provide a third (albeit model-dependent) spin constraint (e.g., Strohmayer 2001). Interestingly, the first AGN-QPO has recently been reported (Gierlinski et al. 2008) and opens up the possibility of timing-based measurements of supermassive black hole spin. For the brightest dozen AGN, rapid iron line variability is expected from orbiting structures within the disk (see below) and/or the reverberation of X-ray flares across the disk. Both of these phenomena have well defined spin-dependence and would be well-suited to IXO's observing capabilities.

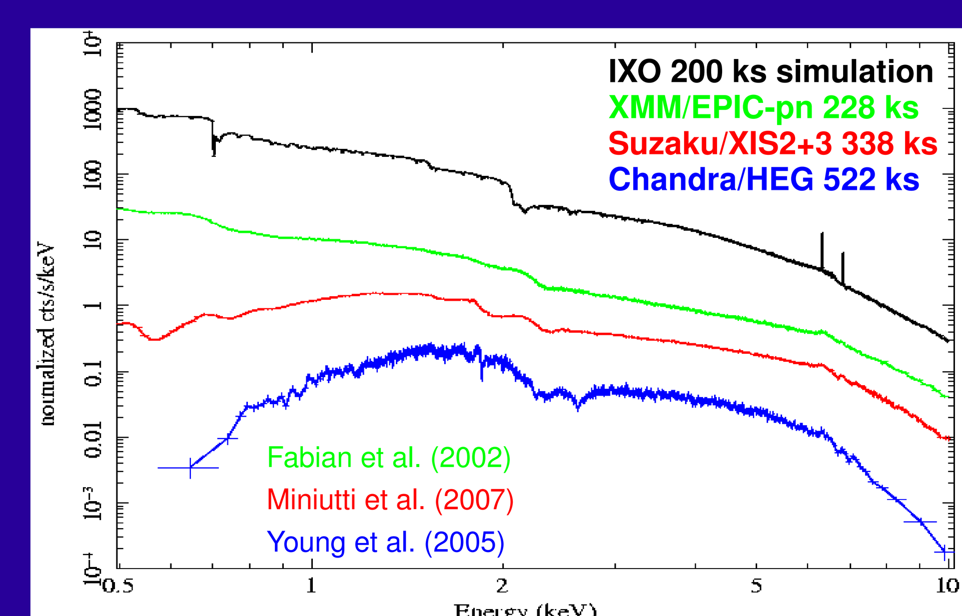


Above Left: Theoretical simulation of the variation of the centroid energy of the Fe Kα line with time. This emission originates from a "hot spot" in the inner disk around a 3 x 10^7 $M_\odot$ black hole inclined at 20° to the viewer's line of sight. The line energy varies in accordance with GR predictions as the hot spot orbits the black hole within the disk. *Above Right:* IXO simulation of the theoretical line energy variation. The pattern of "arcs" seen in the simulation can be used to check the accuracy of GR predictions.

Black Hole Spin and AGN Evolution: The IXO census of spins will revolutionize black hole astrophysics. The spins of stellar-mass black holes in GBHBs are natal and hence give a direct window into the birth of these objects. This provides a glimpse into the workings of the most powerful explosions in the Universe – at least some stellar mass black holes are believed to be born in long Gamma-Ray Bursts. For AGN, the IXO spin census will allow us to determine the distribution of black hole spins as of host galaxy type and redshift. Comparisons with detailed theoretical calculations will determine whether supermassive black hole growth has been dominated by accretion or mergers.



Left to Right: Histograms from Berti & Volonteri (2008) showing the results of numerical simulations of black hole spin evolution in AGN for the cases of (a) black hole mergers only; (b) mergers as well as chaotic accretion episodes; and (c) mergers as well as "standard" (i.e., long-lived, prograde) accretion. Results are shown according to redshift (top to bottom) and merger scenario (left to right) within each plot. IXO will allow us to probe the demographics of black hole spin for the first time, enabling these theoretical results to be tested observationally.



Above: 0.5-10 keV, 200 ks IXO simulation of the spectrum of MCG--6-30-15 as compared with *XMM-Newton*, *Suzaku* and *Chandra* observations.

IXO's Black Hole Spin Legacy: The IXO μ-calorimeter array will make constraining black hole spin a matter of routine, revolutionizing our knowledge of spin-related astrophysics. With ~20 times the effective area of *XMM* and *Suzaku* in the Fe K band and ≥3 times better energy resolution than *Chandra*/HETG (~100 times better than *XMM* and Suzaku), coupled with hard X-ray sensitivity, IXO will enable the disk spectrum to be decomposed from other complexities in the spectrum in a completely unambiguous manner. In the planned black hole spin survey, IXO will measure the spin of 200-300 supermassive black holes in the local (z<0.2) universe and a handful (5-10) of supermassive black holes out to z~1. IXO will also easily determine the spin of every accessible GBHB in the Galaxy or the Magellanic Clouds that enters into outburst during the mission lifetime.