# Astro2020 Science White Paper

# Accretion in Stellar-Mass Black Holes at High X-ray Spectral Resolution

**Thematic Areas:** ☐ Planetary Systems ☐ Star and Planet Formation
☒ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics


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**Abstract: Accretion disks around stellar-mass black holes offer unique opportunities to study the fundamental physics of standard thin disks, super-Eddington disks, and structure that may be connected to flux variability. These local analogues of active galactic nuclei (AGN) are particularly attractive for their proximity, high flux, and peak emissivity in the X-ray band. X-ray calorimeter spectrometers, with energy resolutions of 2-5 eV, are ideally suited to study accretion in stellar-mass black holes. The results will make strong tests of seminal disk theory that applies in a broad range of circumstances, help to drive new numerical simulations, and will inform our understanding of AGN fueling, evolution, and feedback.**



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## 1.0 Introduction

Accretion disks are central to the growth and evolution of black holes, and structure in the universe. Mergers and accretion are both likely to be important in black hole mass growth, but accretion may dominate (Croton et al. 2006). The *consequences* of accretion are vast. Disks around massive black holes have likely produced most of the ionizing radiation in the universe since the epoch of reionization (Peebles 2000, Fabian 2001). The most extreme winds driven by accretion disks may be able to seed the bulge of a host galaxy with enough hot gas to halt star formation (e.g., Chartas et al. 2002, Nardini et al. 2015). The hot X-ray gas that dominates the baryonic gas content of clusters can be reshaped by the jets driven by the accretion disk around the massive black hole in the central galaxy (Fabian 2012).

It is crucial, then, that we *observationally* test how accretion disks work. The fundamental analytical treatments of accretion disks are now 40 years old (Shakura & Sunyaev 1973, Blandford & Payne 1982). These seminal models predict that disk accretion is mediated by magnetic processes; this has been verified and bolstered using more recent numerical simulations (Balbus & Hawley 1991, Miller & Stone 2000). Indeed, simulations have rapidly advanced with computing power, and new efforts make detailed predictions of disk structure, variability, winds, and jets (e.g., Ohsuga & Mineshige 2011).

Disks around massive black holes peak in UV light, so measurements are susceptible to neutral hydrogen scattering (both local to the source, and spread within the host galaxy). The long timescales natural to massive black hole accretion further complicate the study of such disks. *Stellar-mass black holes may represent the optimal laboratories for testing fundamental accretion disk physics.* For a broad range of Eddington fractions, disks around stellar-mass black holes peak in X-rays, avoiding scattering by neutral hydrogen. The X-ray band is also fortuitous in that X-ray atomic lines are excited by the X-ray continuum. The ability to measure these simultaneously readily facilitates studies of the physical processes and geometries that define the accretion flow.

The High Energy Transmission Grating Spectrometer (HETGS; Canizares et al. 2005) aboard *Chandra*, and the Reflection Grating Spectrometer (RGS; Den Herder et al. 2001) aboard *XMM-Newton* have demonstrated the ability of high-resolution X-ray spectroscopy to reveal accretion flows (e.g., Boirin et al. 2005, Neilsen et al. 2009). In this white paper, we focus on a subset of particular advances that will be possible using X-ray calorimeters, with resolutions of 2–5 eV. In the critical Fe K-shell band (roughly, 6-10 keV), these instruments will obtain spectra with $R = 1200 - 5000$, comparable to ground- and space-based optical and UV spectrometers.

## 2.0 The Inner Physics of Standard Accretion Disks

Theory shows that disk accretion must be driven by magnetic processes: internal viscosity via the magneto-rotational instability (or, MRI; Balbus & Hawley 1991) and/or magneto-centrifugal winds (Blandford & Payne 1982). In fact, internal viscosity can also give rise to magnetohydrodynamic winds (Proga 2003). Although thermal continuum emission from the disk *does not* bear the imprints of the processes that created it, the line-rich outflows that result *do*. High-resolution X-ray spectroscopy, then, can function as a window into fundamental disk physics.

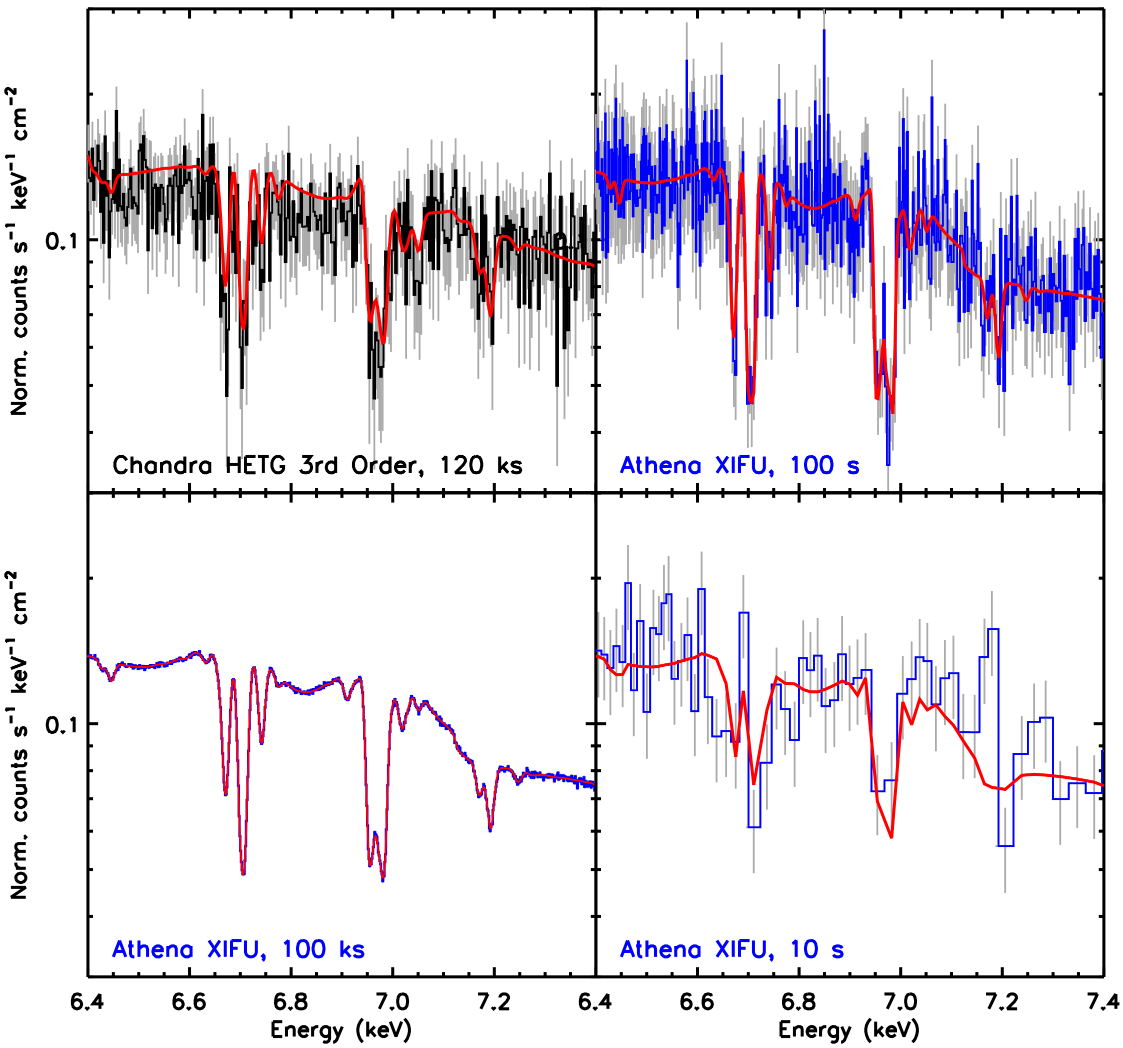


Figure 1: The deep *Chandra*/HETG third-order spectrum of GRS 1915+105 (Miller et al. 2016) and simulated *Athena*/X-IFU (Barret et al. 2018) spectra constructed using the disk wind model for the *Chandra* data. The complex at 6.7 keV is He-like Fe XXV (intercombination and resonance lines), the complex at 6.97 keV is He-like Fe XXVI (a spin-orbit doublet separated by 22 eV). Features at 7.05 keV and 7.2 keV are Fe XXVI at an outflow velocities of 0.01c of 0.03c. Error bars are hardly visible in 100,000 seconds of X-IFU exposure (bottom left), and the level of detail achieved in 100 seconds (top right) and 10 seconds (bottom right) exposures will enable studies of the wind on its *dynamical* time scales ($t \leq 200$ seconds).

Interestingly, feedback between the inner accretion flow and outer disk can influence this process. Irradiation of the outer disk can drive massive thermal winds that can potentially expel more gas than is able to accrete inwards (Begelman et al. 1983); these flows are also line-rich. Heated gas that is unable to escape may supply the ionized gas that gives rise to the non-thermal X-ray corona in black hole systems (Shakura & Sunyaev 1973). Here again, high-resolution X-ray spectroscopy is uniquely able to trace these processes.

Magnetohydrodymamic winds can be differentiated from magnetocentrifugal winds using the run of ionization and density with radius (e.g., the "absorption measure distribution"; Behar 2009,

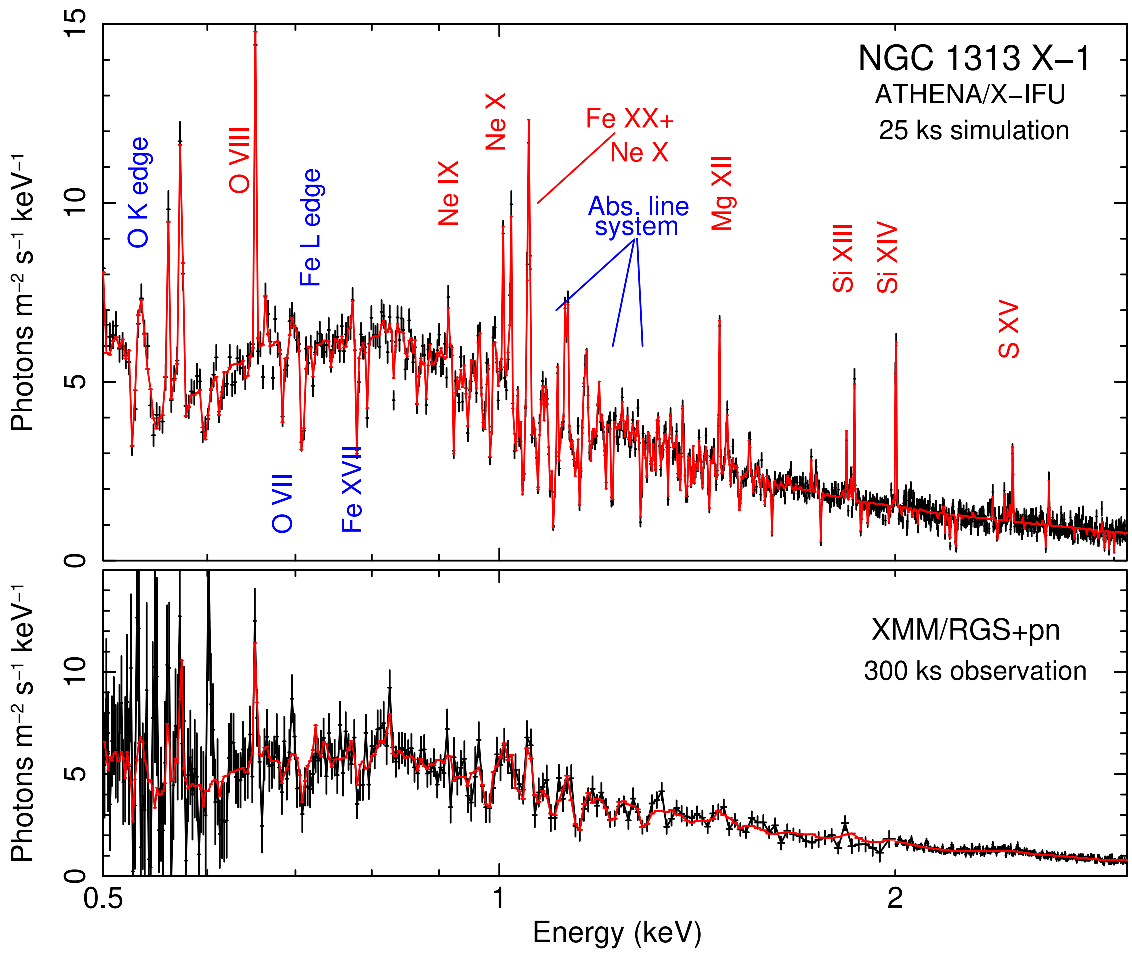


Figure 2: A simulated 25 ks Athena/X-IFU exposure of NGC 1313 X-1, a nearby ULX that may harbor a stellar-mass black hole accreting well above the Eddington limit. Extremely deep XMM-Newton RGS spectra suggest a combination of emission and absorption lines consistent with a $v = 0.2c$ outflow. In just 25 ks of exposure, Athena/X-IFU spectra will reveal fast outflows characteristic of super-Eddington accretion, and examine the variability of such flows. This will be possible in a sample of nearby ULXs, enabling population studies of the source class. The gratings spectrometers envisioned for missions like *ARCUS* and *Lynx* would also excel in studies of ULX outflows.

Fukumura et al. 2017). The resolution of X-ray calorimeters will make such measurements possible in a number of sources, facilitating comparisons across the black hole mass scale. The total mass outflow rate and kinetic power in winds requires measurements of the gas density and volume filling factor; the resolution afforded by calorimeters will also make these determinations routine. The combination of high resolution, high throughput, and large collecting area possible with, e.g., the *Athena* X-ray Integral Field Unit (or X-IFU; Barret et al. 2018), for instance, will enable transformative studies winds on their dynamical timescales ($t \propto r/v$, where $r$ is the wind launching radius and $v$ is the outflow velocity). This will provide an entirely different angle on wind launching mechanisms via velocity variations, density variations, and ionization changes, and will thereby enable quantitatively and qualitatively new comparisons to detailed numerical simulations of accretion disks. **Figure 1** shows simulated *Athena*/X-IFU spectra of the stellar-mass black hole GRS 1915+105 on the *dynamical* timescales of its disk wind, based on a recent deep *Chandra*/HETGS observation (Miller et al. 2016).

## 3.0 Super-Eddington Accretion Disks

Luminous quasars are evident in the early universe (e.g., Fan et al. 2001), implying that some black holes were quickly able to reach masses exceeding a billion solar masses. New detections of quasars at $z \geq 7$ pose even more severe problems: a stellar-mass black hole accreting continuously at the Eddington limit will not reach such masses at the redshifts they are observed (Mortlock et al. 2011, Banados et al. 2018). Thus, although mergers may be important, it is likely that super-Eddington accretion played a key role (Volonteri et al. 2006, 2016). Understanding super-Eddington accretion is therefore fundamental to understanding the evolution of the universe. However, surveys of the low- and moderate- redshift universe reveal that both quasars and super-Eddington accretion are rare (e.g, Hickox et al. 2009). Therefore, we must turn to other settings to understand this critical process. Ultra-luminous X-ray sources (ULXs) are bright, off-nuclear sources that exceed the Eddington limit for 10 solar-mass black holes (Fabbiano et al. 1989). A set of ULXs are known to be pulsars (Bachetti et al. 2014), but other sources may be stellar-mass black holes accreting far above the Eddington limit.

Summing several *XMM-Newton*/RGS observations of ULXs NGC 1313 X-1 and NGC 5408 X-1, emission and absorption lines are finally detected (Pinto et al. 2016). The fastest absorbers indicate velocities of $v = 0.2c$, suggesting that radiation is coupling to moderately ionized gas, as per radiation driving of a super-Eddington wind. Intriguingly, fast winds in these systems - and so-called “ultra-fast outflows” (or, UFOs) in AGN - appear to be transient (Reeves et al. 2018, Pinto et al. 2018). This may be consistent with a radiation force multiplier effect that only operates within a narrow range of gas ionization (Proga 2003).

The resolution of X-ray calorimeter spectrometers is fixed in energy space, so they deliver higher resolution at higher energy. However, they can still deliver revolutionary spectra at low energy, aided by the fact that they are not dispersive spectrometers. This efficiency gain is best leveraged by a large collecting area and high throughput. **Figure 2** shows a simulated 25 ks *Athena*/X-IFU spectrum of NGC 1313 X-1, based on the outflow observed in *XMM-Newton*/RGS data (Pinto et al. 2016). In just 25 ks of exposure, numerous emission and absorption lines can be detected, and the total mass outflow rate and kinetic power of the wind can be measured. The ability to study super-Eddington outflows on short timescales will reveal the physical processes that make them transient. Comparing ULX spectra to SS 433 in the Milky Way may reveal additional disk accretion and ejection physics.

## 4.0 Revealing Disk Structure

Standard disks are expected to be extremely thin close to the innermost stable circular orbit (or, ISCO), and the disk scale height is expected to increase smoothly at larger radii (Shakura & Sunyaev 1973). *However, it is possible that actual disks behave differently.* Radiation pressure on larger radii from dissipation close to the ISCO may give rise to warps that change the local contours of the disk (Maloney et al. 1996). In transitional states, wherein the accretion flow changes from disk-dominated to corona-dominated, and wherein the outflow mode may be changing from wind- to jet-dominated (Gallo et al. 2003), disk “tearing” may cause some annuli to be disconnected and lie out of the broader disk plane (Nixon & Salvesen 2015). Some

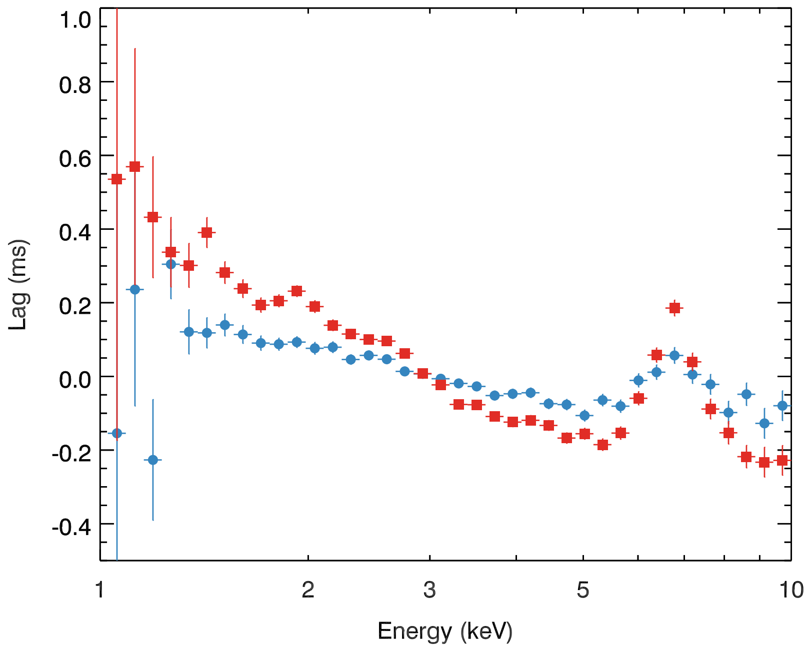


Figure 3: Simulated *Athena*/X-IFU lag spectra of an accretion disk with (red squares) and without (blue circles) heightened reflection from $r = 100 - 300\ GM/c^2$. This simulated exposure is just 4 ks; the dual-reflector model recently considered for MAXI J1535-571 was assumed (Miller et al. 2018). The lag spectra were generated using the methods described in Cackett et al. (2014). The combination of time-averaged spectra and reverberation spectroscopy that is possible with a sensitive, high throughput calorimeter can clearly reveal disk warps and tearing. Similar results would be possible with an instrument like the *Athena* Wide-Field Imager.

quasi-periodic oscillations (QPOs) may be due to structures such as warps, and potentially connected to Lense-Thirring precession (Miller & Homan 2005, Ingram et al. 2016).

X-ray irradiation of a disk with a smoothly varying scale height gives rise to a standard disk reflection spectrum, most prominently revealed through Fe K emission lines (e.g., Miller 2007). However, if specific annuli have anomalous scale heights - as might be the case if the disk is warped or "torn" - this can be revealed through disk reflection. X-ray calorimeters offer unsurpassed spectral resolution, but they can also function as excellent instruments for X-ray timing. If structures like warps or tearing are manifest in stellar-mass black hole disks, they will be detected with an instrument like the *Athena*/X-IFU through time-averaged spectroscopy, and - more importantly - through reverberation lag spectra. Observations with spectrometers with moderate resolution but excellent time resolution, such as the *Athena* Wide-Field Imager (or, WFI; Meidinger et al. 2017), can also capture this science. **Figure 3** shows simulated reverberation lag spectra from a short (4 ks) observation of a bright transient source like GX 339-4, using the dual-reflector model required in recent NICER observations of MAXI J1535-571 (Miller et al. 2018). Following Cackett et al. (2014), reverberation can easily be detected from radii as small as 6 GM/c2 but longer lags accumulate from structure at $r = 100 - 300 GM/c^2$. The combination of time-averaged and lag spectroscopy afforded by X-ray calorimeters will be a powerful means of testing disk structures, and potentially the origins of X-ray QPOs.

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