THE SCIENCE ENABLED BY ULTRAHIGH ANGULAR RESOLUTION X-RAY AND GAMMA-RAY IMAGING OF BLACK HOLES

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1.0 SUMMARY

Scientists and lay people alike are intrigued by black holes. To the scientist, they provide the ultimate test of Einstein's theory of General Relativity (GR) and underlie exotic phenomena such as particle jets moving at nearly light speed. To the public, black holes are mysterious points of no return that capture the imagination. Both views reflect a fascination with the question: *What happens at the edge of a black hole?*

This question has fundamental physics aspects as well as connections to questions of the structure and evolution of galaxies. In particular super massive black holes have become an essential part of the model of how galaxies form and evolve. It is important to confirm our belief that they actually exist and to understand the role that energetically active BHs play in the centers of Active Galactic Nuclei (AGN).

GR has been validated in many different ways in the weak gravity limit and must be accounted for to understand much of what we see in the universe. Even in the case of the Global Positioning System (GPS) on a terrestrial scale GR is important for our ordinary world. However, Black Holes (BHs) are not ordinary objects in the universe. They are the endpoint of matter and possess the deepest gravitational potentials known. *Is GR as we understand it today valid in the strong gravity environment of BHs?*

We need to understand not just BHs themselves, but how they influence their environment. We know that an accretion disk feeds the BH in an AGN while relativistic jets stream matter and energy away. A torus and other structures complicate the message that we receive when we look at the integrated flux from the region and the details remain unknown. *How is energy released from the accretion disk? How are the relativistic jets of AGN formed? What is the role of BH spin? In summary: What is the detailed anatomy of an AGN?*

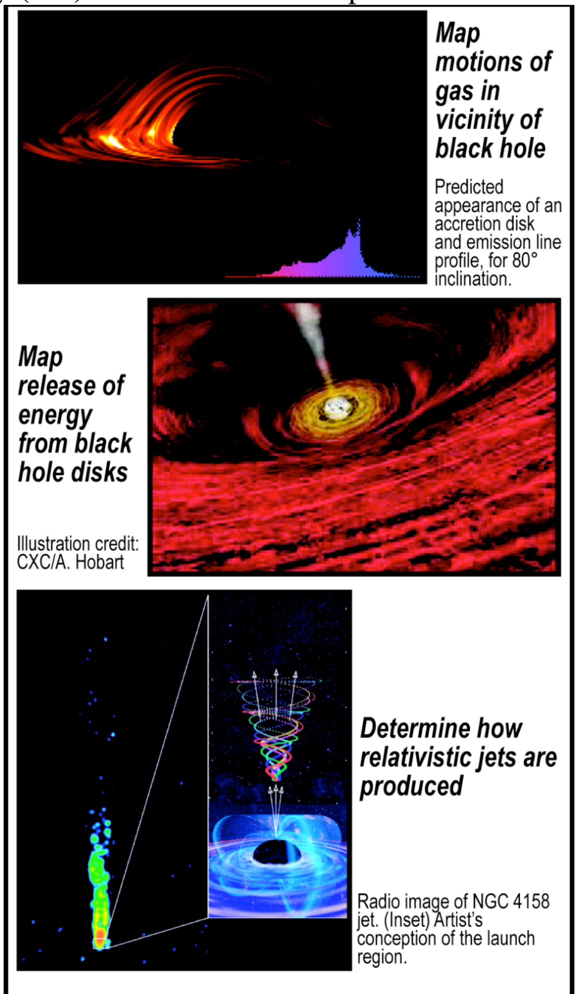

Figure 1. Science potential of ultra high angular resolution imaging.

Below, we discuss these issues and show that combining high resolution imaging and spectroscopy of a BH directly addresses the question: "What happens at the edge of a black hole?" by: 1) directily observing the bending of space-time in its vicinity, 2) mapping the motion of matter in the vicinity of BHs, 3) mapping the release of energy from accretion disks around BHs, and 4) establishing the origin of the relativistic jets formed near BHs (Figure 1).

2.0 BLACK HOLE SCIENCE QUESTIONS

2.1 Is GR Valid in the Strong Gravity Limit?

Most of what is known about gravity comes from experiments where gravity is weak. Testing GR in the strong field limit can be done only in the intense gravity field close to a BH event horizon, utilizing astronomical observations of BHs in our Galaxy or at the center of other galaxies. As well as possessing the deepest gravitational potentials known, BHs provide a powerful test of GR due to their simplicity: according to GR, the space-time surrounding a rotating BH should be precisely described by the Kerr metric[16]. At present, however, no firm and direct evidence exists that this is the case. By tracing the motion of matter falling into the BH, one can map the geometry of space-time near the BH and test the predictions of GR.

Models supported by the timing and spectra of integrated flux from BHs provide indirect evidence. In the coming years, detections of gravitational radiation from BH mergers may provide quantitative data on the Kerr nature of BHs. An image of a Black Hole would be able to complement these studies by uniquely probing the interaction of fundamental fields (in particular, electromagnetic fields) with strongly curved and rotating space-times.

Of course, by their very nature, one cannot see BHs themselves but the extreme effects they have on their immediate surroundings can be observed. Gravitation energy is released by accretion or rotational energy extracted from the BH itself. Space-time is distorted so that one can even image the event horizon itself by looking for the "shadow" formed where emissions from the far-side flow fall into the BH. GR makes clear predictions about the apparent diameter of this shadow. These anticipated shadow diameters are a factor of ~2 greater than their predicted values in the absence of light bending[8], so that strong GR effects act as a lens magnifying the shadow image. GR also predicts that the shadow will appear off center and slightly non-circular if the BH is spinning appreciably; indeed, the precise shape of the shadow gives a detailed test of the Kerr metric[2].

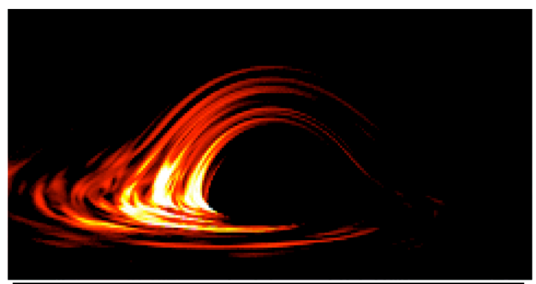

Figure 2. A simulated image[1] of the innermost accretion disk flow around a black hole, inclined at 85°.

Material that falls into a BH is super-heated and, close to the event horizon, emits predominantly in X-rays. The BHs with the largest angular sizes (e.g., Sgr A*and M87) are believed to possess radiatively inefficient accretion flows[20][19]—very hot, optically thin, and quasi-spherical flows that shine in X-rays via thermal bremsstrahlung and Comptonization. Those in AGN produce copious X-rays and gamma-rays as material is heated in an accretion disc and accelerated in jets. X-rays and gamma-rays have the penetrating power to escape through the dense material and plasma close to the BH and they also are least subject to angular resolution limits due to diffraction making them an obvious choice of medium to peer close to the event horizon. In addition, spectral lines in the X-ray band can provide an additional powerful diagnositic tool. With technologies currently under development ultrahigh resolution X-ray and γ-ray imaging of the event horizon region will become possible.

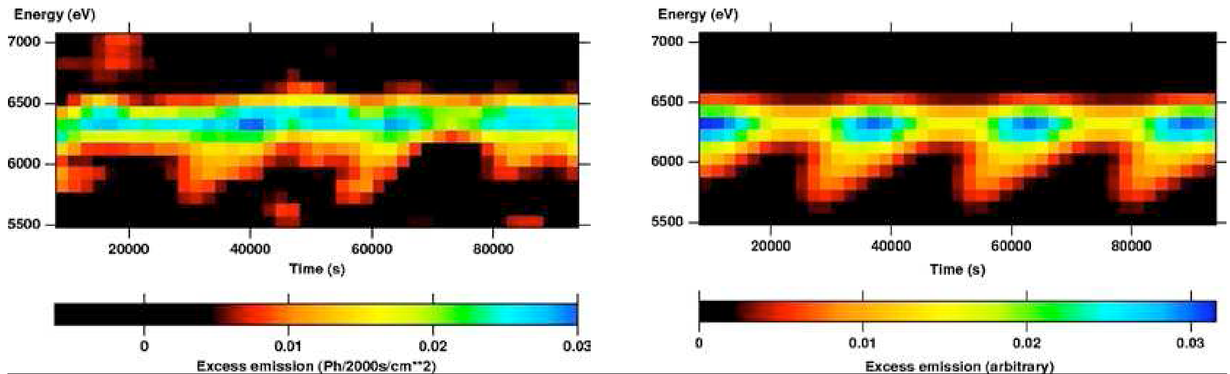

Figure 3. (Left) Smoothed line emission from NGC 3516 as a function of energy and time, as measured with XMM-*Newton*. Pixel size is 2 ks ×100 eV. (Right) Theoretical time-energy map for a coronal flare at $9r_g$ and disk inclination of 20°, in reasonable agreement with the observed emission feature.

Such high resolution imaging will allow for a precision test of the Kerr metric via the mapping of material motions in radiatively efficient systems, most notably the nearby Seyfert galaxies. In these systems, it is believed that irradiation of the accretion disk surface produces fluorescence (e.g., from iron with rest-frame energy of 6.4 keV) and recombination line emission (e.g., from ionized oxygen and iron at rest-frame energies of 0.65 keV and 6.97 keV, respectively). Imaging spectroscopy of these features with spatial resolution of one gravitational radius, $r_g=GM/c^2$ where M is the mass of the BH (corresponding to about 0.01-1 μas for the closest Seyfert galaxies), will allow direct mapping of the gravitational and Doppler red/blueshifts across the accretion disk. Comparing the observed "redshift map" with that calculated from GR gives a powerful and quantitative test of the Kerr metric and strong-field GR. It is expected that the combined effect of gravitational redshift and transverse Doppler shift will become significant (i.e., > 10%) at radii of about $20r_g$, with additional contributions from line-of-sight Doppler shifts expected in any disk that is not viewed face-on. These redshift effects become extreme at $6r_g$ (0.12–0.30 μas), at which point relativistic frame-dragging associated with BH spin also begins to affect material motions. The radial behavior of these effects is illustrated in Figure 2.

Observations with exisiting instrumentation coupled with models provide strong evidence for our picture of accretion onto a BH. For example, Iwasawa et al. (2004)[13] demonstrate the time and energy modulation of a 6-keV spectral feature from NGC 3516 (Figure 3), consistent with Fe K emission arising from a spot on the accretion disk, illuminated by a corotating flare located at a radius of $(7\text{–}16)r_g$, modulated by Doppler and gravitational effects as the flare orbits around the black hole. While impressive, in the absence of spatially resolved information, the interpretation of these data depends on modelling. The validity of this view could be tested by direct imaging with an imaging spectrometer of sufficient angular and energy resolution.

The X-ray continuum from the accretion disk corona is likely to be significantly polarized, and GR makes clear predictions about how polarization vectors are rotated as the photons propagate through the Kerr metric. Detailed polarization maps could be even more powerful than imaging spectroscopy.

Comparison of such data with GR theory requires a deeper understanding of the nature of the environments of BHs. While the singularity of a BH may be simple, interpreting the data will involve taking into consideration the detailed anatomy of the AGN which host SMBHs. The details of this anatomy are interesting in their own right as they include accretion in extreme environments and the most powerful particle accelerators in the universe.

2.2 What Is the Anatomy of an AGN?

BH systems shine by releasing gravitational potential energy (i.e., accretion) or through extraction of BH rotational energy. Either way, copious X-ray production seems to be generic. The spectrum and time variability of the emitted X-rays are currently our major tools in deciphering the structure of the BH environment. Models have been developed to explain the data and describe the environment of the BH- but they are only models validated by imperfect data. Imaging data is currently only useful for the largest scales of the BH environment and has revealed jets of particles at the highest energies.

Below we review some aspects of the current view of AGN structure and point out how ultra-high resolution imaging can bring clarity to the picture.

2.2.1 Accretion Disk Physics

X-ray emission is a prominent and generic signature of BH accretion. There are two known modes of accretion. Radiatively efficient accretion disks, probably present in Seyfert nuclei and other luminous AGN, are powerful X-ray sources due to thermal Comptonization in a disk-corona.[11][21] In this case, irradiation of the accretion disk by the coronal X-rays produces a spectrally rich "reflection signature."[19][10] Conversely, low-luminosity sources (e.g., Sgr A* and M87) seem to operate in a radiatively inefficient mode[20][19] in which much of the accretion power is trapped as thermal energy in the very hot and quasi-spherical accretion flow. It is expected that bremsstrahlung and Comptonization in the body of the optically thin accretion disk places a large fraction of the emitted energy in the X-ray band. These two accretion modes provide distinct ways in which BH physics and GR can be probed.

X-ray images of the disk can be corrected for light-bending effects in order to obtain a true image of the X-ray continuum source. Even this "correction" process is interesting in its own right since the light bending can be extremely strong, with some photons possibly executing multiple orbits around the BH. With the corrected accretion disk images, where and how the accretion energy is released can be mapped. The location and geometry of the continuum X-ray-emitting corona can be determined: is it a disk-hugging or geometrically thick structure, and how patchy is it? Individual flaring regions in the corona can be identified and tracked, thereby giving vital clues to the impulsive and violent physics at play.

Rapid and large-amplitude X-ray variability is a widespread property of AGN and is of fundamental relevance to accretion physics. Imaging of these disks with enough area to see flares will expose the nature of the accretion flow as it crosses the radius of marginal stability (which, in nearby Seyfert galaxies, would appear at 0.2–0.3 μas depending on the spin parameter of the BH).

The Galactic Center is a particularly important target for accretion physics. It provides a unique opportunity for probing the uncertain physics of very inefficient accretion disks. As well as being a source suitable for mapping the radial dependence of energy release (still a fundamental unknown for such disks), it is known to experience huge X-ray flares that may well dominate the overall energy budget.[3] Observing the spatial evolution of a flare will revolutionize our understanding of this enigmatic phenomenon.

2.2.5 Jet Formation and Physics of Black Hole Spin

A fundamental component of GR is the description of how electromagnetic fields interact with the strongly curved and rotating space-time near a Kerr BH. An important prediction of BH astrophysics theory is that the rotational energy of a BH is extractable via the action of magnetic fields[4]—this is the leading contender for a theory of relativistic jet production. Current observations of BL-Lac objects, AGN that possess jet-dominated spectra, already reveal that the inner regions of relativistic jets are strong X-ray sources. This X-ray emission is likely to continue all of the way into the magnetosphere of the BH and innermost accretion disk. High resolution imaging will provide a unique opportunity to study these magnetospheres and thereby probe strong-field BH electrodynamics.

High resolution imaging of these disks could provide robust measurements of BH spin in several sources. In Sgr A* and M87, this will be accomplished via the offset of the event horizon's shadow and in nearby Seyfert nuclei this can be achieved through the spectral detection of frame-dragging effects in the "redshift maps" . Given these measurements, one can examine the astrophysical manifestation of frame-dragging as a function of BH spin. In addition to the formation of relativistic jets, BH spin may also energize the innermost accretion disk and act as a natural and very powerful particle accelerator. AGNs are a leading candidate for the accellerator of ultra-high energy cosmic rays, particles with observed energies exceeding 10^{20} eV.

It is now becoming possible[6] to build sophisticated computer models, using a full Kerr metric, of the processes that could accelerate particles and jets near a rotating BH, providing a basis with which imaging data could be compared.

Imaging with the Chandra X-ray Observatory has demonstrated that quasar jets emit X-rays on kpc scales[12]. The two most cited X-ray production mechanisms are synchrotron emission from TeV electrons with lifetimes of order a year[14][22] or Compton up-scattering of cosmic microwave background photons by electrons in highly relativistic bulk motion. Both mechanisms should also operate on sub-parsec scales as the magnetic fields are stronger and the ambient radiation density is substantially higher due to starlight and accretion disk emission. Jets are already known to extend closer to the event horizon than the current limits of VLBI observations, so these jets should also be X-ray sources on the very smallest spatial scales. Again, X-rays are free to escape these jets, so micro-arcsecond imaging will reveal the connection between gas inflow (which also generates X-rays) and jet formation.

3.0 What is Required of a Black Hole Imager?

Addressing the questions described in section 2.0 by BH imaging will require (1) angular resolution fine enough to resolve the gravitational radius of a SMBH, (2) sufficient collecting area, spectral bandpass, and energy resolution to perform imaging spectroscopy of known line features; and, (3) a sufficiently wide field of view (FOV), or the ability to reconfigure baselines, so as to capture the various different sizes of BH event horizons as well as jet forming regions. Imaging polarization sensitivity could also provide for unique constraints on GR.

Table 1: Representative SMBHs. θ_h is the lensed angular diameter of a Schwarzschild event horizon.

Target	Mass (10^8 Msun)	Distance (Mpc)	θ_h (μas)	log (M/M_{edd})
Galactic Center	0.04	0.008	50	-10.3
M87	32	19.5	16.4	-5.8
NGC 4594	10	9.2	10.8	-5.6
Cen A	2	3.6	5.56	-3.6
NGC 4258	0.36	7.2	0.5	-3.8
NGC 3227	0.36	17.6	0.2	-3
NGC 5548	0.68	75.9	0.09	-1.3
NGC 4151	0.12	17	0.07	-1.2
MCG-6-30-15	0.1	30.9	0.032	-1

Table 1 lists several SMBHs with current mass and distance estimates. Angular resolutions of a microarcsecond put some exciting BH science within reach for about 5 known objects. Going to 0.05 microarcseconds brings more objects into consideration. The Galactic Center and nearby elliptical galaxies are radiatively inefficient accretors and excellent candidates for observing the shadow of the event horizon. The Seyfert galaxies present smaller apparent event horizon sizes but allow the most constraining test of the Kerr metric to be performed. We anticipate that this list will grow over the next decade.

4.0 The Road to a Black Hole Imager

Seeing is believing. While LISA will "hear" the ringing of space time as black holes merge, there are many additional tests and experiments that can be performed when we can "see" the behavior of light and matter in the deepest depths of a gravitational well. It is likely that multiple approaches to studying strong gravity will be needed before it is fully understood.

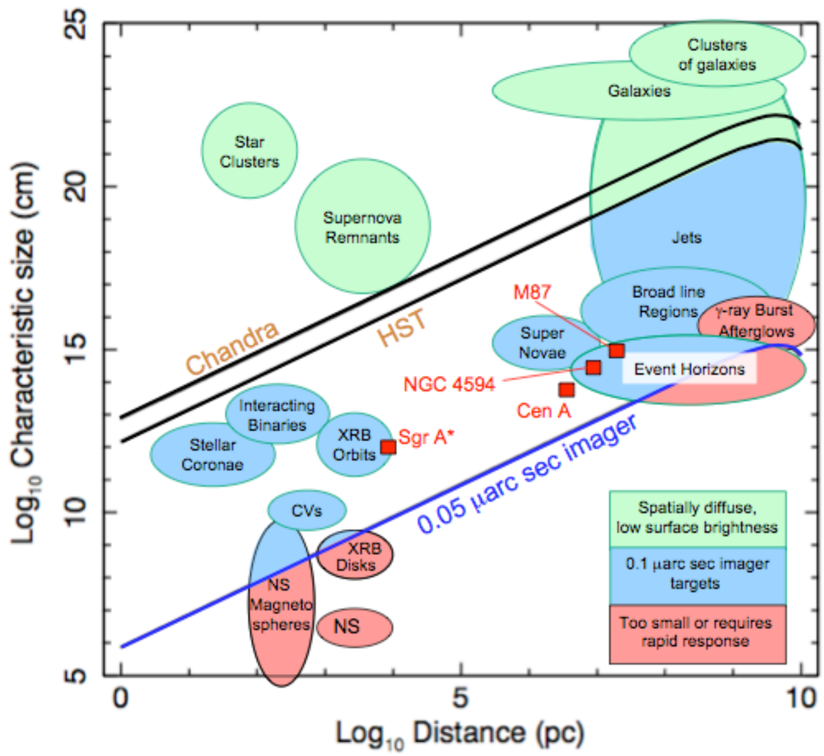

Figure 4. Characteristic angular scales of classes of imager targets. The Schwarzschild radii of some particular SMBHs are shown. The imaging resolutions of Chandra (0.5 arcsec), the Hubble Space Telescope (0.1 arcsec) and a proposed ultrahigh angular resolution imager are shown by lines that are straight except for cosmological effects at high-z.

In the case of the nearest SMBH—Sgr A* at the center of our galaxy, for which the expected shadow is 37^{+16}_{-10} μas[7], it may become possible within a decade to achieve the angular resolution necessary to view these phenomena using ground-based sub-mm radio interferometry. The observations possible at these wavelengths would conceivably confirm the existence of event horizons. However, the observations will be limited by diffraction and scattering in the ISM and the absence of spectral lines precludes measurements of spatially varying Doppler and gravitational shifts. Furthermore it is difficult to imagine that this technique can be pushed to significantly higher resolution. To go beyond what can be done in the radio/sub-mm bands one must consider the X-ray and γ-ray band where the surface brightness is high, spectral lines are available, and there is potential for much better angular resolution.

An X-ray/γ-ray Black Hole Imager's unprecedented angular resolution would benefit many fields of astrophysics beyond the core science of imaging a BH. Its exceptional ability to resolve the geometry of astrophysical objects would propel fundamental advances in myriad topics such as the magnetic activity of normal stars, the structure of pulsar emission regions, relativistic jet production, the geometry of the accretion flow onto cataclysmic variables (CV) and neutron stars

(NS), and the cosmological distance scale.

In the X-ray/γ-ray bands, there are several anticipated approaches to building a Black Hole Imager (BHI). The short wavelength of the radiation means that the required instrument aperture is ~1000 times smaller than that in the visible. Examples for 0.1 μas are 6000m at 0.5 keV, 500m at 6 keV and 30 m at 100 keV. Key components of architectures involving grazing- and normal-incidence optics as components of an interferometer, as well as diffractive/refractive optics at higher energies, have already been demonstrated in the laboratory[5][9][15][18], but further technology development is needed to optimize the strategy for building a BHI. BHI will also require developments over the next decade of technology related to formation flying and precision alignment, both of which are also required by other "vision" missions.

The size and distance scales of several classes of astrophysical objects are compared with the angular resolution of BHI in Figure 4. However, the tremendous jump in angular resolution will, no doubt, lead to discoveries we cannot yet imagine. Even a pathfinder mission with more modest angular resolution, making a step towards an eventual BHI, would yield fantastic discoveries.

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