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INWARD BOUND: AN INVITED WHITE PAPER ON ACTIVE GALACTIC NUCLEI SUBMITTED TO CANADA'S LONG RANGE PLAN 2010 COMMITTEE

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ABSTRACT

AGN research in Canada should during the next decade strive to achieve the following goals: 1) Measure the masses of the nuclear supermassive black holes (SMBHs) in galaxies within a distance of 100 Mpc; 2) Determine how active galactic nuclei (AGN) are powered, and how their power output is related to the structure of the central engine; 3) Understand how SMBHs and their host galaxies formed and evolved over cosmic time; 4) Understand the accretion history of AGN, and how AGN feedback operates. AGN research, by its nature, relies on observations made across the entire electromagnetic spectrum. These goals will be achieved through strong commitments to ALMA, TMT, and JWST, and by securing a stake in future, earth-orbiting X-ray observatories. Canadian partnership in LSST and associated data analysis infrastructure will transform Canadian AGN research, and will provide leverage for winning observing time on the world's premier observing facilities. Canada will reap the benefits of these marvelous facilities only if funding beyond the Discovery Grant process is made available to Canadian researchers on a competitive basis.

Subject headings:

1. AGN: WORK HORSES OF THE UNIVERSE

Since the suggestion in the 1960s that quasars are powered by accretion onto massive black holes, AGN research has concerned itself primarily with understanding the structure of the nucleus and its host galaxy, and with the evolution of AGN over cosmic time. The picture that emerged is a universal central structure composed of a black hole surrounded by a thin accretion disk that is fed by a gaseous torus (Fig. 1). This perception has changed in recent years. The structure of an AGN is now thought to depend on the black hole's mass, its accretion rate, and the evolutionary stage of its host galaxy. Rather than being a brief but remarkable phase in the lives of a minority of galaxies, AGN are now thought to play a central role in the formation and evolution of essentially all massive galaxies (Bower et al. 2006).

During the assembly of galaxies through the infall of stars and gas, a small fraction of this gas is able to accrete onto the central SMBH. This process releases an enormous amount of gravitational binding energy in the form of radiation and mechanical outflows that couple to the ambient gas. This coupling forms a feedback loop that regulates the rate of star formation and accretion onto the black hole. The most energetic AGN may drive gas out of the galaxy, quenching star formation entirely.

Fossil evidence for early feedback was discovered in the $M_{\rm BH} - M_{\rm bulge}$ relation, that was presumably imprinted by so-called "quasar-mode" feedback during the early development of galaxies. Direct evidence for AGN feedback occurring in mature galaxies at late times is seen in X-ray observations of the hot halos of elliptical galaxies and clusters. In the so-called "kinetic mode" or "radio mode" feedback, mechanically-driven outflows couple to hot halos (Fig. 2) and prevent them from cooling into stars. In recent years, AGN feedback has become widely viewed as essential new physics in galaxy formation that may solve outstanding problems, such as the dearth of big blue galaxies at late times, the red sequence–blue cloud dichotomy, excess energy in cluster halos, and several other major problems in galaxy formation.

Understanding how SMBHs formed, what their distributions of mass and spin are, how they are related to their host galaxies, how AGN jets and winds are powered and collimated, and how feedback operates over cosmic time should become central themes of LRP 2010. Addressing these issues will require sensitive, large aperture observations and high spatial and spectral resolution over a broad bandwidth. A commensurate theoretical and computational effort will be needed to understand the dynamics of accretion and outflows and how they couple to host galaxies.

2. TWO FRONTIERS

An AGN can be thought of as a structure bounded by two frontiers: the SMBH's gravitational radius of influence, R_g, and the event horizon lying more than 5 decades in radius below (Fig. 1). $R_g \approx GM_{\rm BH}/\sigma_{\rm gal}^2 = 10$ pc $M_{\rm BH,8}\sigma_{200}^{-2}$, where $M_{\rm BH,8}$ is the black hole mass in units of 10^8 $M_\odot$, and σ_{200} is the stellar velocity dispersion of the bulge outside of R_g in units of 200 km s^{-1}. Within R_g, the motions of gas and stars are governed by the black hole's mass and not the mass of the host galaxy. Measurements made near to the Schwarzschild radius (event horizon), $R_s = 2GM_{\rm BH}/c^2 \simeq 10^{-4}$ pc $\rm M_{BH,8}$, are key to understanding the effects of strong gravity and AGN power output.

Spatial resolution near to and below R_g is required to probe the structure of AGN and to measure black hole masses using gas and stellar motions. Dynamically-determined black hole masses have been measured in three dozen nearby galaxies lying within roughly 30 Mpc. This number will increase dramatically when the Thirty Meter Telescope (TMT) becomes operational later in the decade. Apart from the Milky Way and M87, the event horizon lies below the resolving power of all existing and planned telescopes for the next decade, with the exception of the VLBA. Conditions near the innermost stable circular orbit (ISCO), which is a few times larger than R_s, may be probed indirectly using X-ray emission from high temperature gasses there, and eventually using gravitational waves.

3. STRUCTURE ON THE SCALE OF R_G

The Atacama Large Millimeter Array (ALMA), which will soon see first light, will image molecular gas and dust continua with an angular resolution below 0.1 arcsec. This corresponds to a linear size of 10 pc at the distance of the Virgo cluster, which is smaller than M87's R_g and its Bondi radius for spherical accretion. ALMA will probe the inner cold gas structure in nearby galaxies near to or within their gravitational radii of influence and Bondi radii. These measurements in parallel with X-ray observations will test hot (Bondi) and cold (disk) accretion models. Black hole masses are central parameters in accretion models. Their masses will be measured using JWST and TMT. TMT with adaptive optics will deliver nearly diffraction limited imaging of $\simeq 0.015$ arcsec resolution at 2 microns. This capability will extend the region of space within which SMBH masses can be directly measured to a distance exceeding 100 Mpc, and will produce images of AGN that are several times sharper than HST in the infrared band.

4. PROBING THE HORIZON USING X-RAYS AND GRAVITY WAVES

Space near the event horizon will be probed using optical/UV variability studies, X-ray observations of hot gasses in the surrounding accretion disk, and eventually, using gravity waves. X-ray observations are able to probe the conditions in the accretion disk and corona near the SMBH, and in some systems, the black hole's spin.

Spin alters the structure of spacetime near the horizon by moving the ISCO inward, thus increasing the power output per gram of accretion. A SMBH is endowed with its spin through gas accretion and black hole mergers (Volonteri & Gnedin 2009). Therefore, SMBH masses and their spins are sensitive to large scale structure formation. Black hole spin will be measured in AGN using the relativistically Doppler shifted Fe Kα line at ~ 6.4 keV (e.g. Brenneman & Reynolds 2006). Sensitive, high-resolution spectra of this line will be obtained with the International X-ray Observatory's (IXO) grating and microcalorimeter spectrometers. (See Fig. 3 and the LRP-WP by Gallo et al.)

Eventually, gravitational wave observations with LISA will reveal the details of black hole binary mergers and their spin parameters. Gravity waves may reveal essential clues to a variety of other problems including, the powering and collimation of cosmic radio jets, SMBH kicks from the anisotropic emission of gravity waves during black hole mergers, and the last parsec problem where binary black holes release their binding energy before a merger is possible.

5. OUTFLOWS & RADIATION: QUASAR MODE FEEBACK

Powerful outflows of ionized and neutral gas are found in distant, young radio sources (Morganti et al. 2009, Nesvadba 2009). Outflow rates of $50-100$ $M_\odot$ yr^{-1} are observed. In addition, winds associated with broad absorption lines toward quasars have apparent kinetic powers of $\gtrsim 10^{44}$erg s^{-1} (e.g., Chartas et al. 2007, Dunn et al. 2010). These may be the signatures of quasar-mode feedback that imprinted the $M_{\rm BH}-M_{\rm bulge}$ relation on galaxies. Their kinetic power output is poorly determined, largely because the outflows themselves are unresolved. Theoretical models of the dusty component of disk winds are able to account for their mid-infrared spectral energy distributions (Everett et al. 2010, in prep). But the viability of the models require knowledge of the geometry and dynamics of the cold outflows, which will be directly observable in nearby AGN with ALMA. IXO will spectrally resolve outflow velocities of the thick, highly ionized gas closest to the central black hole (Gallagher et al. 2006). Together, with theory, these observations will reveal the dynamics and kinetic powers of quasar outflows, which are key to understanding the role of quasar-mode feedback in galaxy evolution (Gallagher & Everett 2007). TMT and IXO will provide the dramatically improved sensitivity and resolution in the optical, near-IR, and X-ray bands are needed to address these issues.

6. RADIO-MECHANICAL MODE FEEDBACK

X-ray images of elliptical galaxies and galaxy clusters have revealed direct evidence for AGN feedback in the hot, X-ray halos surrounding them. Recent discoveries of cavities and shock fronts in hot halos have yielded direct and reliable estimates of the total jet energy per outburst and their mean jet power (McNamara & Nulsen 2007). The *mechanical* energy emerging from what were once regarded as modest AGN is surprisingly large, often comparable to the radiative output of powerful quasars. New cosmic microwave background (CMB) experiments with the South Pole Telescope show a deficit in the amplitude of the Sunyaev-Zeldovich signal suggesting that 30-40% of baryons are missing from hot gas phase in cluster halos. These baryons may have been driven out of nascent clusters by AGN feedback, suggesting AGN are shaping structure on the largest virialized scales.

Mechanically dominated radio jets are thought to be powered by radiatively inefficient accretion flows (e.g., ADAFs) accreting at a few percent or less of the Eddington value. Systems accreting near to the Eddington rate form thin accretion disks that radiate their accretion energy in the form of a quasar. Mechanical feedback from relativistic jets couples to hot, X-ray halos, while radiation and winds couple to colder gas. AGN are able to switch modes, perhaps in response to changes in accretion rate. In order to maintain a feedback loop, the AGN must be tightly coupled to the thermodynamic state of the surrounding gas extending more than ten decades in distance from the AGN. Understanding this coupling will be an important thread of AGN research through the next decade. The high spectral resolving power of IXO will detect outflow and turbulent velocities of the hot gas in cluster halos, providing a new means to measure the kinetic power output of AGN and how kinetic energy is converted to thermal energy of the hot gas. Measurements of the nuclear structure of these systems with TMT and ALMA will reveal how this structure is related to AGN power output and to accretion rate.

7. LARGE SURVEYS

Large area sky surveys are the traditional means of discovering and characterizing AGN. The Sloan Digital Sky survey not only opened up a vast landscape of discovery, it has revolutionized how astronomy is done. The Large Synoptic Survey Telescope, which is expected to become operational later in the decade, will be a boon to AGN research. With an 8.4-m primary mirror and a 10 square degree field of view, LSST will scan 20,000 square degrees of sky in six filters from the ultraviolet to the infrared bands, down to a depth of 27th magnitude. Because the sky will be scanned repeatedly, AGN will be discovered by color and by variability on time scales of minutes to years. LSST will yield 10 million AGN with a million-fold range in luminosity (Brandt et al. 2009). LSST will reveal the accretion history of AGN to redshifts beyond 6, and will determine the evolution of the quasar luminosity function. Through variability it will enable the statistical study of the structure of accretion disks, and will identify rare, transient accretion processes. LSST will enable the study of AGN feedback through statistical studies of AGN and their host galaxies throughout most of the Universe (e.g., Hopkins et al. 2007). Whether star formation peaks during the peak of AGN activity or whether AGN activity lags star formation, indicating SMBHs and galaxies do not form in lock-step, is an important question that LSST will be able to address.

A partnership that provides direct and timely access to LSST data would make Canadian AGN research competitive on the international stage. Partnership in LSST would optimize Canada's financial investment and prestige by providing the best astrophysical targets for detailed observation with TMT, JWST, and ALMA. The LSST, like Sloan before it, will require an investment in fast and efficient computers and algorithms to mine its treasures. This effort would benefit other large survey instruments such as LIGO and LISA, which will also require the development of fast and efficient analysis techniques.

8. FORMATION & EVOLUTION OF SMBHS

Understanding SMBH seeding and the evolution of their host galaxies at $z > 10$ is the domain of TMT, ALMA, JWST, the EVLA, LOFAR, and ultimately IXO and the Square Kilometer Array (SKA). This endeavor will demand high resolution (< 0.1 arcsec) imaging and spectroscopy in the infrared band to measure star formation rates and gas velocities indicative of inflow, outflow, and ordered motion. Measurements of neutral hydrogen and molecular gas using ALMA, and eventually SKA, will probe the earliest development of galaxies. The ubiquity of SMBHs in galaxies shows that the seeding process was efficient. Whether they were seeded by single massive stars, star clusters, or by massive cloud collapse is unknown. The answers will emerge from measurements of black hole accretion rates and star formation rates in nascent galaxies (see Fig. 4). Measuring the growth rates of low mass black holes at early times will reveal the role of AGN in cosmic reionization at $z \sim 10$ (Madau et al. 2004; Volonteri & Gnedin 2009).

9. THEORY & COMPUTATION

Our understanding of AGN, like most areas of astrophysics, sees its greatest advances when theories are put to test. The complexity of structure within R_g can only be understood using a combination of theoretical intuition and numerical simulation that reliably predicts the emergent properties of AGN. Advances in algorithms and increased computational power will be required to model accretion dynamics, jet launching mechanisms, emission processes, and so forth. Petascale computing will provide exciting opportunities to model the structure of AGN and related systems from first principles to compare with observations. A strong Canadian presence in AGN research will require a continued investment in powerful computing facilities at the peta-scale, and funding for new faculty and postdoctoral fellows.

10. FUTURE OF AGN RESEARCH IN CANADA

Canadian astronomy enjoys a strong legacy in several areas of AGN research. The Canada-France-Hawaii Telescope (CFHT) produced the first major studies of quasar host galaxies, and has enabled major studies of galaxy evolution in the distant Universe. Canadian engineers pioneered turnkey, high resolution adaptive optics (AO) for the CFHT and Gemini observatory. HST's STIS spectrograph is the work-horse instrument used for measuring black hole masses in galaxies and for mapping ionized gas kinematics in AGN. Much of this work was done in collaboration with Canadian astronomers. Nevertheless, AGN research has not had a strong tradition in Canada. With the growing recognition of the important role AGN play in the development of large scale structure, and with the recent influx of young astronomers interested in AGN research, Canada could develop into a world-leader in this area. In order to achieve the goals set out in this White Paper, we make the following recommendations:

1) Maintain Canada's partnership in TMT, JWST, EVLA, and ALMA. These telescopes and their instrumentation will provide a panchromatic, high angular resolution view of AGN from ultraviolet to centimeter wavelengths. The development of AO systems for TMT will provide the high resolution imaging and spectroscopic capabilities needed to tackle the problems set forth in this WP.

2) Canada should seek partnership in LSST. Not only will LSST open a whole new vista of AGN discovery space, timely access to its expansive data bases will leverage access to and optimize the use of TMT, JWST, and ALMA. LSST has the potential to revolutionize several areas of astronomy, such as galaxy evolution, and near-Earth objects. Partnership in LSST would benefit much of the Canadian astrophysics community.

3) We recommend seeking partnerships in one or more upcoming X-ray missions, such as ASTRO-H, and perhaps IXO (see WP2010 by Gallo et al. 2010). Canadian partnership may be secured through in-kind contributions in areas of Canadian technological expertise, such as metrology, star-trackers, attitude control systems, optical design, mechanical and thermal design. In the longer term, Canada should remain open to opportunities for collaboration in the Square Kilometer Array, which will revolutionize low frequency astronomy and the study neutral hydrogen at high redshifts.

4) Finally, Canadian astronomers will be unable to reap the full benefits of these remarkable facilities without an increase in research funding. The typical NSERC Discovery Grant (DG) is funded at a level of roughly \$30K per year. This level of funding provides for a couple of graduate students, travel, and miscellaneous expenses. Funding for postdoctoral fellows is beyond the reach of most Canadian astronomers. The DG program is considered a base of support to be leveraged against more lucrative industrial and governmental grants. However, the nature of astronomical research limits the amount of extra funding that is available. Most Canadian astronomers are funded solely by their DGs, and thus are unable to compete with much larger and better funded teams in the U.S. and Europe. We recommend the CSA develop agreements with NASA, JAXA, and ESA to provide funding for Canadian observing programs selected competitively for time on space facilities (e.g., HST, Chandra, Herschel). We encourage the CSA and NSERC to develop funding programs modeled broadly around the CSA's Space Science Enhancement Program to support large scientific endeavors.

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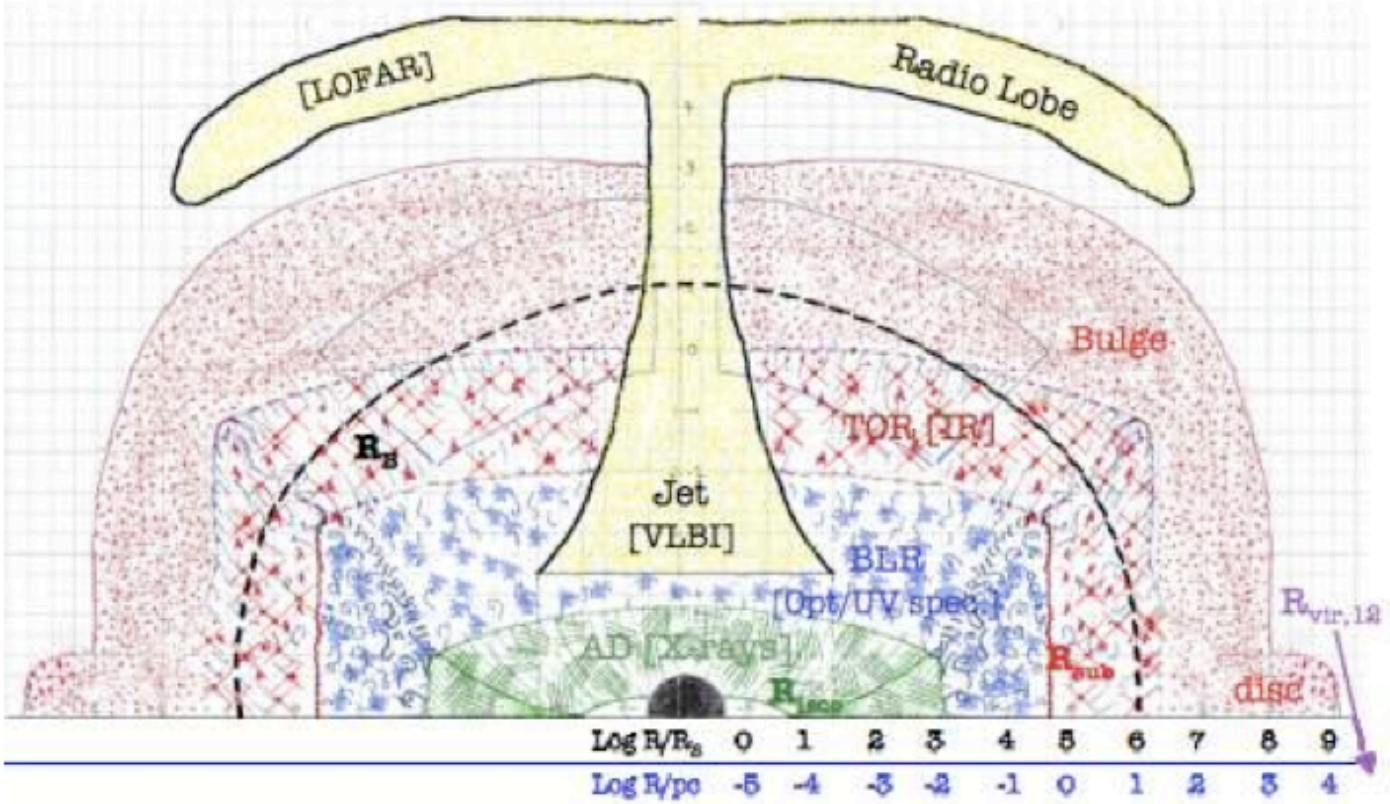

FIG. 1.— A logarithmic cartoon view of an AGN-galaxy system (Taken from Merloni 2009). Scales on the bottom axes are in units of Schwarzschild radii and parsec, and are approximately inferred for a $10^{11}\ M_\odot$ galaxy containing a $10^8\ M_\odot$ black hole. Here, $R_{\rm vir}$ is the virial radius of a $10^{12}\ M_\odot$ dark matter halo, RB stands for the Bondi radius (marked also by a thick dashed line), $R_{\rm sub}$ and RISCO for the dust sublimation radius and the innermost stable circular orbit (inner edge of the accretion disc), respectively. The logarithmic scales at the bottom are in units of Schwarzschild radii (R_S) and parsec, respectively

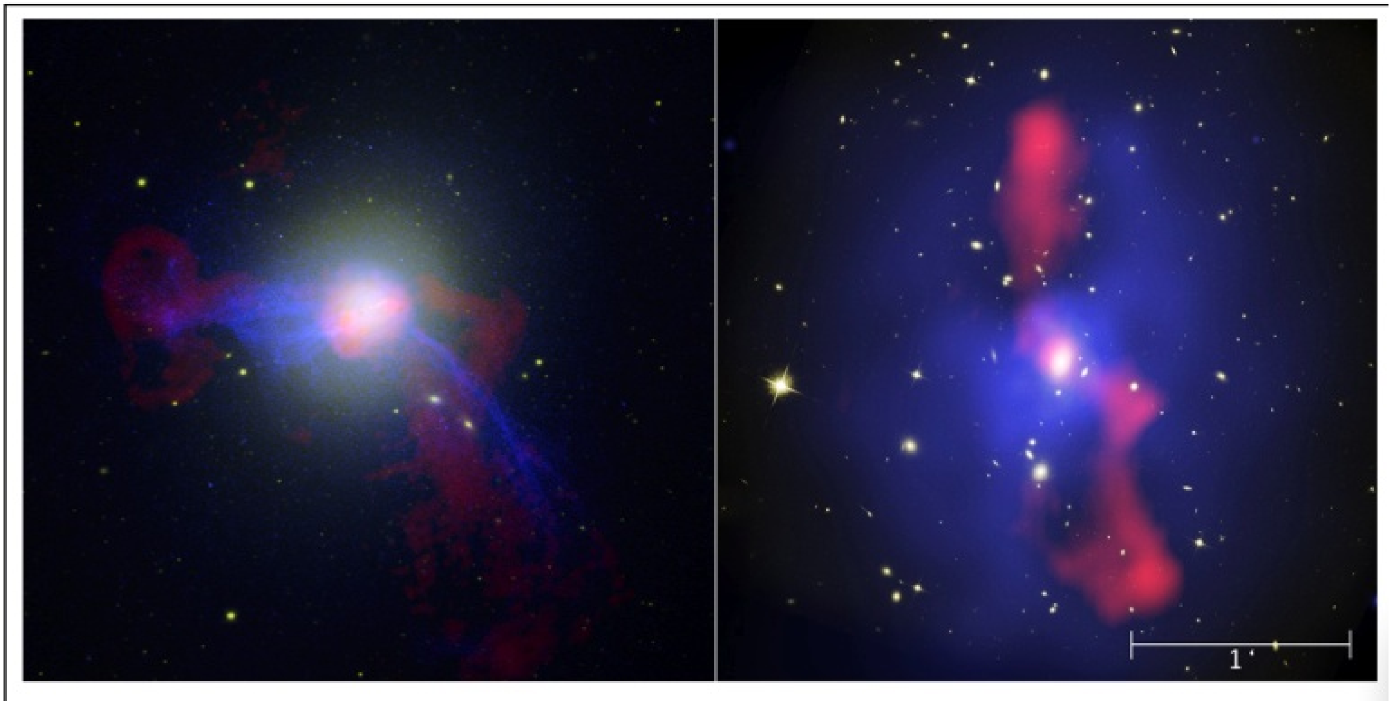

FIG. 2.— Left: X-ray emission (blue), radio emission (red) superposed on an optical image of M87. The X-ray structure (shocks, bubbles) was induced by a 10^{58} erg outburst that began 10 Myr ago (Forman et al. 2005). The image is 50 kpc on a side. Right: X-ray emission (blue), 320 MHz radio emission (red) superposed on an HST image of the z=0.21 cluster MS0735.6+7421 (McNamara et al. 2009). The image is 700 kpc on a side. Giant cavities, each 200 kpc (1 arcmin) in diameter, were excavated by the AGN. The mechanical energy is reliably measured in X-rays by multiplying the gas pressure by the volume of the cavities, and by the properties of the surrounding shock fronts. With a mechanical energy of 10^{62} erg, MS0735 is the most energetic AGN known. This figure shows that AGN can affect structures on galaxy scales of tens of kpc and on cluster-wide scales, spanning hundreds of kpc in MS0735.

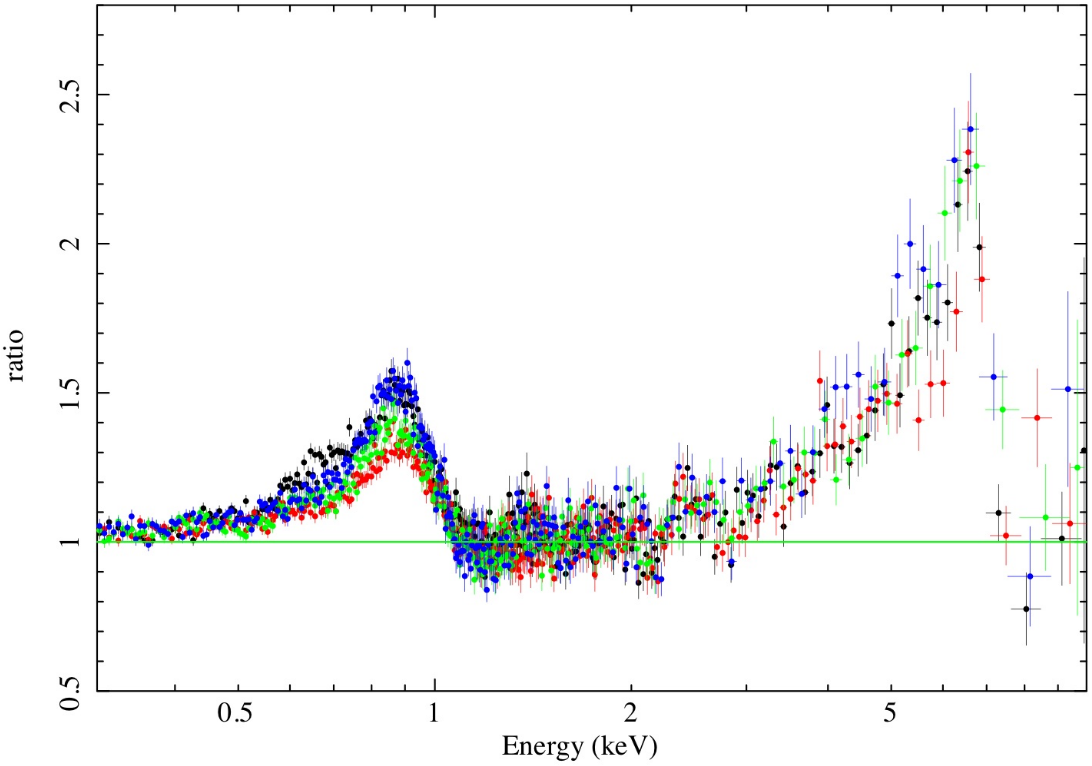

FIG. 3.— Relativistically broadened Fe Kα and Fe Lα detected from a 500 ks *XMM-Newton* observation of the AGN 1H0707-495. Figure taken from Fabian et al. (2009). The continuum emission from the corona illuminates the top layers of the relatively cool accretion disk resulting in scattered emission that is rich in fluorescent emission lines (i.e. a reflection spectrum). The strongest emission line is that of Fe Kα at $\sim$ 6.4 keV. As the reflection spectrum originates in the accretion disk rotating the SMBH, the spectrum is sculpted by Doppler, special, and general relativistic effects that asymmetrically stretch and broaden the line to lower energies as X-ray photons lose their energy escaping the deep gravitational potential well of the SMBH. The effect is a consequence of how close the inner accretion disk radius is to the black hole, and thus the black hole's spin.

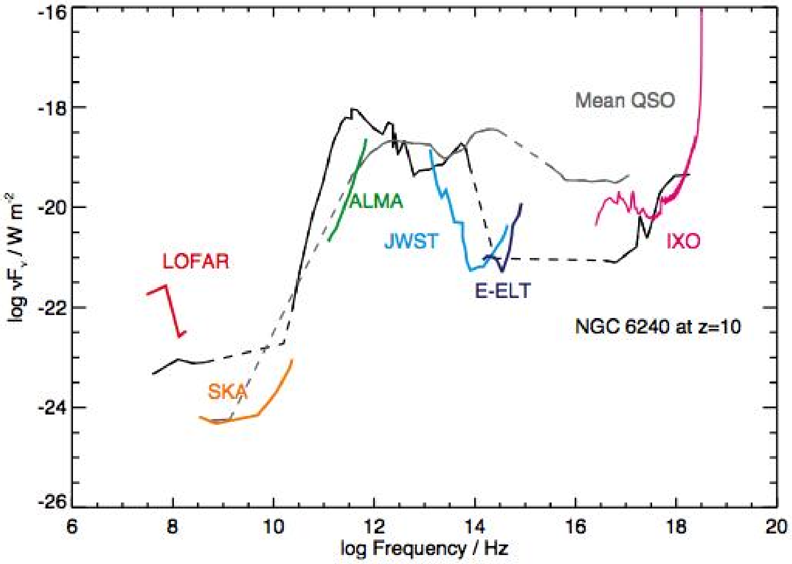

FIG. 4.— Expected spectrum of a average quasar (gray) and star formation in the host galaxy of a heavily obscured quasar redshifted to z = 10, taken from Nandra et al. (2009). The plot shows the range of sensitivity of several telescopes discussed in this WP. Dashed sections indicate currently unobserved portions of the spectrum.