

# The Growth and Evolution of Massive Black Holes

## 1 Overview

Recent observations have for the first time found a link between supermassive black holes and the galaxies which harbor them. The observed correlation between black hole mass and galactic bulge stellar mass (Figure 1) has thus placed the evolution of supermassive black holes, or quasars, in the broader context of the formation of galaxies and structures. So far, observations are limited by the small aperture of HST to the most nearby galaxies only. GSMT with AO will be the only facility to have the combination of spatial resolution and light-gathering power to measure kinematical masses of the stars surrounding black holes at cosmological distances. Closer to home, the light-gathering power of GSMT will allow us to watch individual stars as they fall into the supermassive black hole in the center of our Galaxy, a process hinted at by the 8m and 10m telescope AO images of the brightest stars circling Sgr A\*.

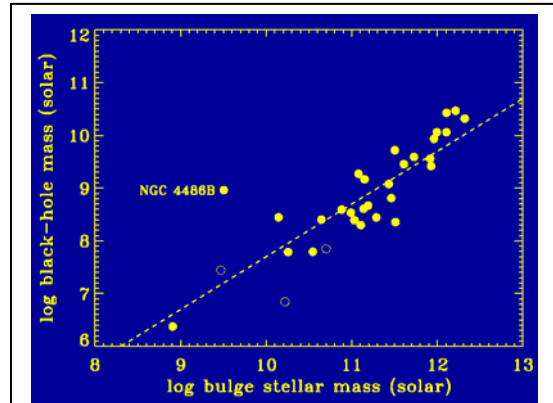


Figure 1. The correlation of central black hole mass with mass of the host galaxy bulge, for nearby galaxies. Adapted from Tremaine et al. (2002).

## 2 Background

Wide field surveys for quasars such as 2DF, the Sloan Digital Sky Survey, 2Mass and First are revealing an ever more complete census of the quasar population from redshifts  $z = 0$  to 7. Quasars turned on around  $z \sim 7$ , and reionized the intergalactic hydrogen, but the peak of quasar activity was at  $z \sim 2$ , when the Universe was only 30% of its present age. At that time, the space density of quasars was 30-40 times what it is today.

After four decades of multiwavelength spectroscopy from the radio through X-ray and gamma-ray, as well as extensive theoretical modeling, a well-tested paradigm for the quasar phenomenon has been developed (Figure 2). At the heart of quasars is a supermassive black hole, surrounded by a disk of accreting gas and dust. In about 10% of all quasars, the accretion results in ejection of collimated relativistic plasma observed as radio and X-ray jets. Quasars invariably are found in the centers of host galaxies, which often host starbursts as well. Yet despite a

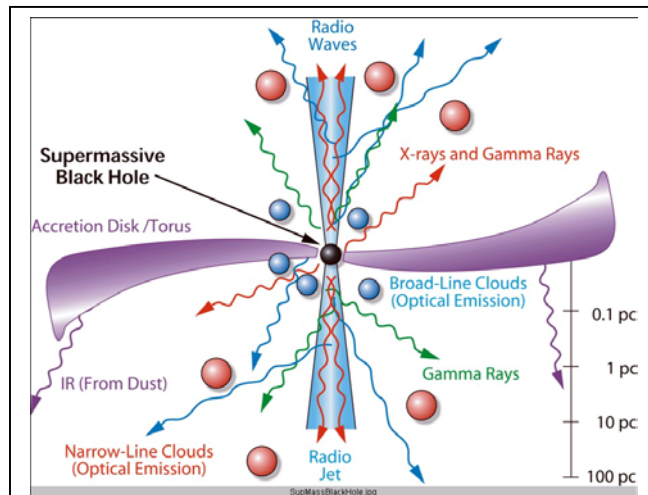


Figure 2. Quasar structure. The structure of the “central engine” of the quasar, inferred from multiwavelength spectroscopy and spectropolarimetry.

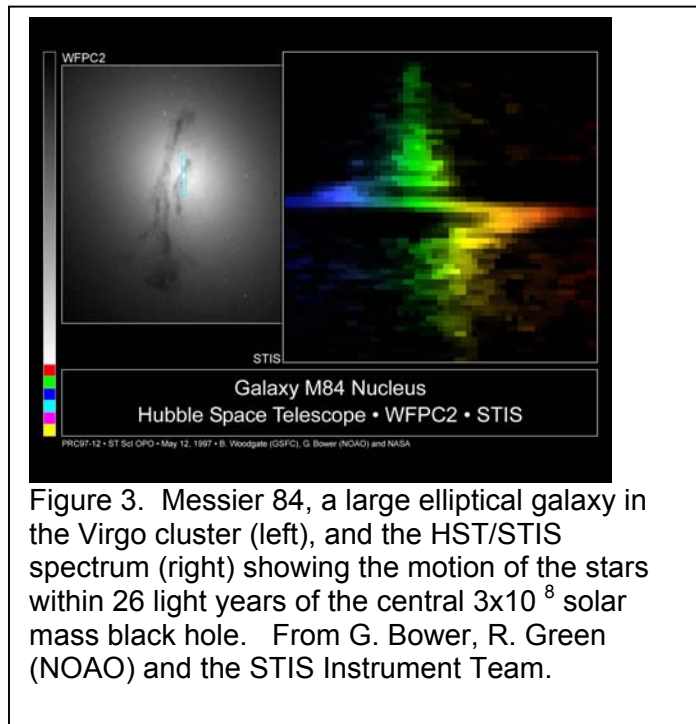
wealth of beautiful observational results and theoretical advances, we do not really understand *why* quasars evolve.

The observation that supermassive black holes exist in local galaxies which are not quasars, and that the black hole masses are correlated with the host galaxy mass (Figure 1) implies that the quasars are not just curiosities, but common phenomena tied to galaxy formation and evolution. The question then is how the quiescent black holes we see today relate to the quasars we see at high redshift. By extending the kinematic measurements of black hole masses to cosmological redshift we can test if the relation seen in Figure 1 is constant with epoch. How important was merging of galaxies and black holes in driving the evolution of quasars? Was every galaxy a luminous quasar at one time? Why aren't all the black holes we see in the local universe accreting gas and stars as prodigiously as the quasars in the early Universe? Why do radio and X-ray jets appear in only 10% of all active quasars? How do galaxies "feed" black holes with gas and stars?

### 3 Kinematic measurements of black hole masses

Spectroscopy of the cores of galaxies with excellent spatial and spectral resolution reveal the systematic motions of stars in the gravitational field of the central black hole. Thus far, HST spatial resolution has been required to carry out this observation (Figure 3), and with a 2m aperture, the resolution is sufficient for only very near-by galaxies. However, the AO corrected images possible with a 30m telescope or 20/20, combined with their huge light-gathering power, will enable the extension of these types of measurements to  $z \sim 1-2$ .

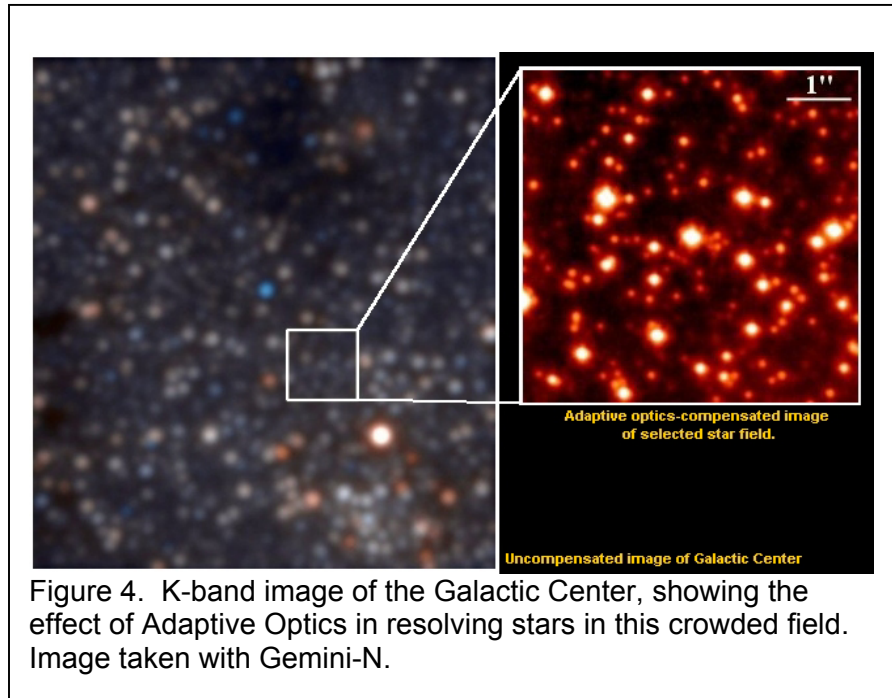
Table 1 compares the diffraction limit of HST with facilities being planned for the next decade and the quasar structures that each facility can probe as a function of redshift. A 20-30m ground based telescope with adaptive optics will have the spatial resolution to probe deep into the stellar kinematics near the central black holes of galaxies at all  $z < 7$ .



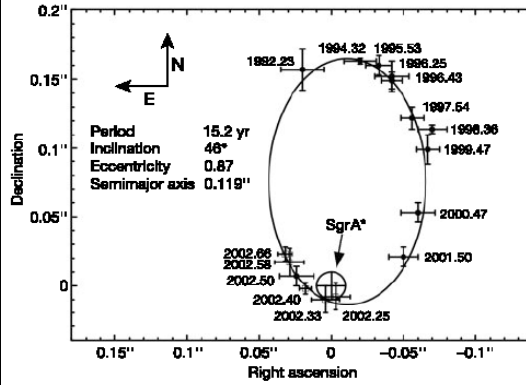
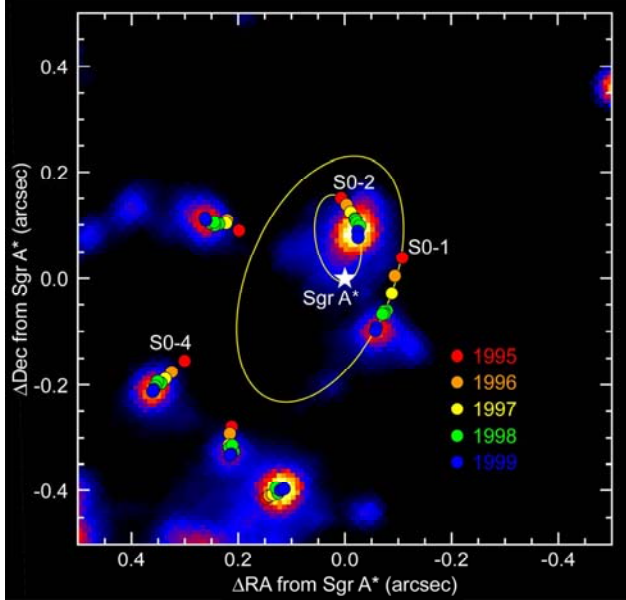
#### 4 The Supermassive Black Hole in our Own Back Yard: Sgr A\* in the Galactic Center

The nearest example of a supermassive black hole is SgrA\*, in our own Galaxy, which is closer by at least a factor of 300 than the next candidate. At radio wavelengths, it is a bright continuum source, which remains unresolved even at millimeter wavelengths. With VLBI techniques, there is only the slightest hint that structures may be detectable at about 70 Schwarzschild radii. At optical and near-infrared wavelengths, SgrA\* is not detected. However, there are a number of stars which have been seen to be in orbit around SgrA\*, with proper motion velocities exceeding 5000 km/s (Figure 4).

Studies over the past ten years have now demonstrated that some of these stellar orbits are bound. In particular, one object known as S2, is in a tight elliptical Keplerian orbit, with a semimajor axis of 5.5 light days, an orbital period of 15.2 years, and the nearest approach to SgrA\* of 17 light hours (124 AU). The orbital motions are direct probes of the gravitational field. The deduced enclosed mass is 3.7 million solar masses. The extremely close approach distance to SgrA\* eliminates the other possible explanations for this enigmatic source, such as a dense cluster of dark stellar matter or degenerate fermions. The observed data constitute the best observational evidence for a supermassive black hole.



The pericenter distance is only 2100 Schwarzschild radii, and only 70 times the tidal radius (16 light minutes). This suggests that with greater sensitivity and greater angular resolutions, there exist the possibility of detecting other stellar objects which might approach even closer to the central point mass. The importance of these proper motion studies is that the stellar objects are like test particles which sample the gravitational field very close in to a massive black holes. We have the sensitivity to follow these test particles, and furthermore we know there are more test particles to be detected.



**Figure 5. Left:** The proper motions of a number of stars in the immediate vicinity of SgrA\*. **Right:** The measurements of the orbit of SO-2 around SgrA\* over the period of 1994 to 2002 (Schodel et al. 2002). Note the extremely fast motions of SO-2 as it swings past SgrA\* over a period of only 5 months. This is due to the extremely close approach to the center of the gravitational potential well.

The GSMT can provide much better sensitivity, and much higher angular resolution, assuming that adaptive optics will work successfully. This will enable detection of fainter sources, better constraints on orbital parameters on a shorter time line, probe deeper hopefully into the potential well, detect acceleration effects, detect possibly tidal effects, detect possibly relativistic motions at 100 Schwarzschild radii. The Galactic Center is an unique opportunity to learn as much as we can about a supermassive black hole.

### 5 Synergy with Alma, JWST and Con-X

In combination with ALMA, Con-X and JWST, GSMT will provide unprecedented insight into the physics of the quasar phenomenon. Constellation-X will probe the inner part of the accretion disk where the iron K-alpha emission line is produced ( $R \ll 1$  pc) and yield unique constraints on general relativity and the accretion process near supermassive black holes. ALMA will be able to map molecular gas as it flows from the host galaxy towards the central engine, yielding a more precise picture of how supermassive black holes are 'fed'. GSMT will enable spectroscopy of the stars in

### Spatial resolution

	arcseconds	R (pc) at Z=1
HST	0.042''	337
JWST (6.5m)	0.032''	257
ALMA	0.010''	80
30m	0.007''	56
20/20	0.0017''	14

**Table 1: Comparison of spatial resolution for present and future facilities. Diffraction limits at 1 micron except for HST (0.5 micron) and ALMA, and the physical scale this correspond to at z=1 (assuming WMAP best cosmology). ALMA, GSMT and 20/20 will be able to probe quasar structures smaller than 100 pc.**

the central cores of the host galaxies and thus kinematic measurement of the black hole mass. HST and JWST lack the spatial resolution to probe the spatial scales required at cosmological distances; however the mid-infrared sensitivity of JWST will allow the spectral energy distribution of the dust in quasars to be mapped. Only 30m class telescopes, and ideally the 20m-20m interferometer, will have sufficient spatial resolution to push the blackhole-stellar bulge relation to high redshift.

## **6. Key Measurements and Baseline Program**

The requirement is to obtain rest-frame optical spectra of the stellar component of at least 100 high redshift galaxies, on spatial scales of 10-50 parsec, at spectral resolution of  $R=6000$  or better. At  $z=1-2$ , the diffraction limit of the GSMT will allow  $\sim 50$  pc spatial resolution, in the near-IR. Scaling from the exposure time calculator of NIRI on Gemini, a  $s/n$  of 6 per pixel can be obtained with a 30m telescope in 8 hours at  $R=6000$ , with diffraction limited spatial resolution for an object with integrated K-magnitude per square arcsec of  $K=19$ . This is sufficient to probe  $L^*$  galaxies at  $z=1-2$ , with observations of intrinsically fainter galaxies possible at lower redshift. To estimate the feasibility of observing  $\sim 100$  objects, comparable to the number of galaxies surveyed locally, one would have to factor in the performance of the AO system (strehl and sky coverage) which is beyond the scope of this report. The read noise of the detector is an important limitation for these long exposures, and the anticipated improvement in the next 10 years would have to be estimated. The spatial resolution of an interferometer like 20/20 would be ideal, but the design of a spectrograph to take advantage of the interferometric spatial resolution at high spectral resolution needs to be made. Nonetheless, the extension of high spatial resolution kinematic studies to cosmological distances would provide enormous advances in our understanding of quasars and the formation and evolution of supermassive black holes.

## **REFERENCES**

**Tremaine, S. et al. 2002 ApJ 574, 740.**