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LISTINGS

ACRONYMS

AGN Active Galactic Nuclei

NLR Narrow Line Region

BLR Broad Line Region

EV1 Eigenvector 1

ICA Independent Component Analysis

PCA Principal Component Analysis

SDSS Sloan Digital Sky Survey

BOSS Baryon Oscillation Spectroscopic Survey

UV Ultra-Violet

EQW Equivalent Qidth

S/N Signal-to-noise

BH Black Hole

SED	Spectral Energy Distribution
IR	Infrared
NIR	Near-infrared
FWHM	Full-Width-at-Half-Maximum

1 INTRODUCTION

1.1 DISCOVERY

The first quasar was discovered when it was found that the star-like, thirteenth magnitude objected associated with the radio source 3C 273 was at a cosmological distance ($z = 0.158$; Schmidt, 1963). This implied an enormous luminosity ($4 \times 10^{12} L_{\odot}$) for such a compact object and it was quickly realised that energy source was the release of gravitational potential energy as mass is accreted onto a super-massive black hole (BH) at the centre of a galaxy (e.g. Hoyle and Fowler, 1963; Salpeter, 1964; Lynden-Bell, 1969; Lynden-Bell and Rees, 1971).

Super-massive: $10^{6-9}\ M_{\odot}$

1.2 BASIC STRUCTURE

An Active Galactic Nucleus[1] (AGN) is significantly more compact than a cubic parsec, and yet can outshine the starlight from an entire galaxy. The basic features of the current paradigm explaining this phenomenon are essentially unchanged from Salpeter, (1964), although many of the details remain unclear. Material is pulled towards a super-massive BH and sheds angular momentum through viscous and turbulent processes in a hot accretion disc (e.g. Begelman, 1985). The accretion disc reaches temperatures of $\sim 10^{6}$K, and radiates primarily at ultraviolet (UV) to soft-X-ray wavelengths. Hard X-ray originate in a hot corona near the BH, emission lines are produced in rapidly moving clouds of ionised gas and infrared emission is dominated by thermal emission from a dusty, obscuring structure. Collimated jets of relativistic plasma and/or associated lobes are also seen in the 10 per cent of quasars that are radio-loud (e.g. Peterson, 1997).

1.2.1 *The broad line region*

One of the pre-eminent features of many AGN spectra are broad optical and UV emission lines produced in the *broad line region (BLR)*. The BLR consists of gas clouds at distances from several light-days to several light-months that are photo-ionised by the ultraviolet continuum emission emanating from the accretion disc. Because of the

1 Throughout this thesis we use the terms 'quasar' and 'Active Galactic Nucleus (AGN)' interchangeably to describe active supermassive black holes, although the term quasar is generally reserved for the luminous ($L_{Bol} > 10^{12} L_{\odot}$) subset of AGNs.

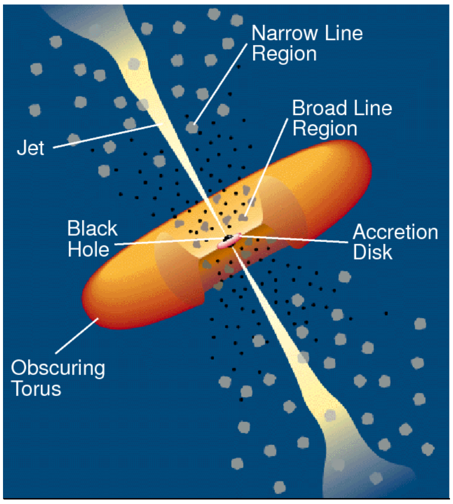

Figure 1.1: Illustration of the physical structure of an AGN in a simple orientation-based unification model. Figure taken from Urry and Padovani, (1995).

close proximity to the central super-massive BH, bulk motions are dominated by gravity and radiation pressure. The very broad emission line widths are assumed to Doppler-broadened, and imply line-of-sight velocities of FWHM~$5000 \mathrm{km\,s^{-1}}$.

1.2.2 *The dusty torus*

Further out, beyond the dust sublimation radius ($\gtrsim 10^{17}$cm), are dusty, molecular clouds which are co-planar with the accretion disc. These dusty component are generally referred to as the 'torus'. In a Type II AGN, the accretion disc is observed in an edge-on configuration. As a result, emission from the accretion and BLR is obscured by the dusty torus (e.g. Antonucci, 1993). Although the simple picture shown in Figure 1.1 is a useful staring point, the idea of a torus as a static, doughnut-like structure is almost certainly incorrect. For example, the problem of maintaining the thickness of such a structure has long been recognized. In one alternative scenario, the torus is the dusty part of an accretion disc wind that provides the required toroidal obscuration (e.g. Konigl and Kartje, 1994; Everett, Gallagher, and Keating, 2009; Gallagher et al., 2012; Everett, 2005; Keating et al., 2012; Elitzur and Shlosman, 2006).

1.2.3 *The narrow line region*

Further away from the central BH and beyond the dusty torus is the narrow emission line region (NLR). Like the BLR, the NLR is ionised by radiation from the central source. Unlike the BLR, densities in the NLR are low enough that forbidden transitions are not collisionally suppressed. Emission line widths are typically hundreds of km s^{-1}. The NLR is sufficiently extended to be spatially resolved. Observations reveal the illumination to be bi-conical, most likely due to the torus. Outflowing gas is also common.

1.3 WINDS AND OUTFLOWS IN AGN

Quasars are very powerful sources of radiation, and are embedded in matter-rich environments at the centres of galaxies. Strong winds, driven by some combination of gas pressure, radiation pressure due to dust or lines, and magnetic forces, are to be expected under these conditions (e.g. Blandford and Payne, 1982; Proga, Stone, and Kallman, 2000; Everett, 2005). In line with these expectations, outflows are very commonly observed around quasars.

Perhaps the most dramatic evidence of outflows in quasars are broad absorption features in the ultra-violet resonance lines of highly ionised N V, C IV and Si IV which are observed in broad absorption line quasars (BALQSOs; Weymann et al., 1991). BALs are always blueshifted, and are evidence for fast outflows with velocities as large as 60 000 km s^{-1}(e.g. Turnshek, 1988). The observed C IV BALQSO fraction in radio-quiet quasars is ~ 15 per cent (e.g. Hewett and Foltz, 2003; Reichard et al., 2003) and the intrinsic fraction has been estimated at 40 per cent (Allen et al., 2011). The blueshifting of high-ionisation lines in the BLR (including C IV) also appears to be nearly ubiquitous in the quasar population (e.g. Richards et al., 2002; Richards et al., 2011), suggesting winds are even more common. Outflows are also used to explain narrow UV and X-ray absorption lines (NALs) which are seen in ~ 60 per cent of Seyfert 1 galaxies (Crenshaw et al., 1999) and some quasars (e.g. Hamann et al., 1997). The wide range of emission and absorption line phenomena can be explained in disc wind models (e.g. Murray et al., 1995; Elvis, 2000; Proga, Stone, and Kallman, 2000; Everett, 2005)

Models of galaxy evolution that invoke AGN feedback require these outflows to reach galactic scales and quench star formation in the AGN host galaxies. In recent years, a huge amount of resources have been devoted to searching for observational evidence of these galaxy-wide, AGN-driven outflows. This has resulted in recent detections of outflows in AGN-host galaxies using tracers of atomic, molecular, and ionised gas (e.g. Nesvadba et al., 2006; Arav et al., 2008; Nesvadba et al., 2008; Moe et al., 2009; Dunn et al., 2010; Alexander et al., 2010; Harrison et al., 2012; Harrison et al., 2014; Nesvadba et al., 2010; Rupke and Veilleux, 2013; Veilleux et al., 2013; Nardini et al., 2015; Feruglio et al., 2010; Alatalo et al., 2011; Cimatti et al., 2013; Cicone et al., 2014).

Broad absorption line quasars (BALQSOs) are a sub-population of quasars exhibiting blue-shifted absorption troughs broader than 2000

$\mathrm{km\,s^{-1}}$(Weymann et al., 1991) which are unambiguously associated with AGN-driven out-flowing gas. As well as showing high rates of mergers, an anomalously large fraction of heavily reddened objects exhibit broad blue-shifted absorption troughs in their spectra (Urrutia et al., 2009; Glikman et al., 2012). This observation suggests that the BAL phenomenon may be related to a 'blow-out' phase of a quasars lifetime as it transitions from a dusty, obscured objected to a luminous blue quasar, at the same time quenching star formation. Since outflows are believed to be fundamental to AGN feedback, a better understanding of their properties could shed light on the outflow phenomenon.

1.4 OUTFLOWS

One particularly successful technique has been observing forbidden emission lines, which trace warm ($T{\sim}10^4$K) ionised gas in the AGN NLR. Because of its high equivalent width, [O III]λ5008 is the most studied of the narrow AGN emission lines. In general, the [O III] emission consists of two distinct components: a narrow, 'core' component, with a velocity close to the systemic redshift of the host galaxy, and a broader 'wing' component, which is normally blueshifted. The general consensus is that the core component traces the gravitational potential of the host galaxy, as the width correlates well with the stellar velocity dispersion. On the other hand, the broad, blueshifted wing is tracing outflowing gas. This emission appears blueshifted because the far-side of the outflow - that is, the side which is moving away from the line of sight - is obscured (e.g. Heckman et al., 1981; Vrtilek, 1985).

Observations of broad velocity-widths and blueshifts in narrow emission lines stretch back several decades (e.g. Weedman, 1970; Stockton, 1976; Heckman et al., 1981; Veron, 1981; Feldman et al., 1982; Heckman, Miley, and Green, 1984; Vrtilek, 1985; Whittle, 1985; Boroson and Green, 1992). However, these studies rely on small samples, which are often unrepresentative of the properties of the population. More recently, the advent of large optical spectroscopic surveys (e.g. SDSS) have facilitated studies of the NLR in tens of thousands of AGN (e.g. Boroson, 2005; Greene and Ho, 2005a; Zhang et al., 2011; Mullaney et al., 2013; Zakamska and Greene, 2014; Shen and Ho, 2014). This has provided constraints on the prevalence and drivers of ionised outflows. At the same time, there is strong evidence from spatially resolved spectroscopic observations that these outflows are extended over galaxy scales (e.g. Greene et al., 2009; Greene et al., 2011; Hainline et al., 2013; Harrison et al., 2012; Harrison et al., 2014).

However, these studies do not cover the redshift range when star formation and BH accretion peaked, and consequently when feedback is predicted to be strongest. At these redshifts the bright optical emission lines are redshifted to near-infrared wavelengths, where observations are much more challenging. As a consequence, studies at high redshifts have typically relied on relatively small numbers of objects (e.g. Netzer et al., 2004; Sulentic et al., 2004; Shen, 2016). These studies find [O III] to be broader in more luminous AGN, suggesting that AGN efficiency in driving galaxy-wide outflows increases with luminosity (e.g. Netzer et al., 2004; Nesvadba et al., 2008; Kim et al., 2013; Brusa et al., 2015; Carniani et al., 2015; Perna et al., 2015; Bischetti et al., 2016). The fraction of objects with very weak [O III] emission alsp appears to increase with redshift and/or luminosity (e.g. Netzer et al., 2004).

Other recent studies have looked at the [O III] emission properties of extreme objects - e.g. heavily obscured quasars (Zakamska et al., 2016) and the most luminous quasars (Bischetti et al., 2016) - at redshifts $z \sim 2$. The [O III] emission in these objects is extremely broad and strongly blueshifted. These observations are consistent with galaxy formation models that predict AGN feedback to be strongest in luminous, dust-obscured quasars.

1.5 THE AGN-HOST GALAXY CONNECTION

Super-massive BHs are found at the centres of most nearby massive galaxies (e.g. Kormendy and Richstone, 1995; Ferrarese and Ford, 2005; Kormendy and Ho, 2013). Remarkably, given their spatial scales differ by many orders of magnitude, the BH mass and mass of the host galaxy spheroid are strongly correlated (Ferrarese and Merritt, 2000; Gebhardt et al., 2000; Graham et al., 2001; Tremaine et al., 2002; Marconi and Hunt, 2003; Aller and Richstone, 2007; Gültekin et al., 2009). Although any underlying causal mechanism(s) responsible for the correlation is yet to be conclusively identified, there is considerable observational and theoretical support for a 'feedback' relationship in which the energy output from rapidly accreting BHs (in a quasar phase) couples with the gas in the host galaxy and quenches star formation (e.g. Silk and Rees, 1998; King, 2003; Di Matteo, Springel, and Hernquist, 2005; King and Pounds, 2015).

Quasar feedback has also been invoked to explain the similarity of the cosmic BH accretion and star formation histories. The number density of quasars, which evolves strongly with redshift, peaks at redshifts $2 \lesssim z \lesssim 3$ (e.g. Brandt and Hasinger, 2005; Richards et al., 2006b) and the most massive ($M_{\bullet} \gtrsim 10^{9} M_{\odot}$) present-day BHs experienced much of their growth during this epoch. The star formation rate, which closely follows the cosmological evolution of the quasar luminosity function, also peaks during this epoch (e.g. Boyle and Terlevich, 1998). Quantifying the growth-rate of massive BHs at $2 \lesssim z \lesssim 3$ would therefore help significantly in understanding the role quasars play in galaxy evolution.

1.6 MEASURING BLACK HOLE MASSES

As one of just two fundamental quantities describing a BH on astrophysical scales, the mass is of crucial importance to virtually all areas of quasar science, including the evolution and phenomenology of quasars, and accretion physics. The power output of quasars is directly proportional to the BH mass. There is much debate regarding what effect the energy output by quasars has on evolution and structure of the host galaxy.

The masses of BHs in many local, inactive galaxies have been measured by dynamical modelling spatially resolved kinematics. However, this requires the sphere-of-influence of the BH, R_{BH}, to be resolved. With masses only ~0.1 per cent of the stellar masses of the host galaxies, $R_{BH} \sim 1 - 100$ pc. With current instrumentation, resolving this region is only possible in very close by, inactive galaxies.

$R_{BH} = \frac{2GM_{BH}}{\sigma *}$

The reverberation mapping method, first proposed by Blandford and McKee, (1982), uses the time delay between continuum variations and emission-line variations to estimate the size of the BLR. Because it depends on time resolution rather than spatial resolution, it can applied out to much greater distances. This means that

1.6.1 *Reverberation mapping*

Continuum variability is a common characteristic of quasars. Because the BLR is photo-ionized by the continuum, the broad emission lines also vary with some characteristic lag, which is related to the light travel time across the BLR. The reverberation mapping technique uses the time lag between variations in the continuum emission and correlated variations in the broad line emission to measure the typical size of the BLR. Today RM has become a practical and powerful tool to study BLRs (see reviews by, e.g., Peterson 1993; Netzer & Peterson 1997; Horne et al. 2004).

Under the assumptions that the BLR dynamics are virialised and the gravitational potential is dominated by the BH, the BH mass is simply given by the product of the typical BLR radius and the square of the virial velocity of the BLR clouds. In practice, reverberation mapping relies on dense spectrophotometric monitoring campaigns which span many years. The typical velocity in he BLR is measured from the width of he broad Hβ lines in the RMS spectra, ensuring that only the variable part of the line contributes to the line width calculation. Since the structure and geometry of the BLR is unknown, a virial coefficient f is introduced to transform the observed line-of-sight velocity inferred from the line width in to a virial velocity. In practice, the value of is empirically determined by requiring that the derived masses are consistent with those predicted from the M-σ relation for local inactive galaxies. Although this technique has proved to be effective, because it relies on resource-intensive spectro-photometric monitoring campaigns, masses have been derived for only ~ 50 AGN, all at low redshifts $z \lesssim 0.3$. There are now several dozens of AGNs and quasars (most are at redshifts $z < 0.3$) with average lag measurements (e.g. Kaspi et al., 2000; Peterson et al., 2004; Bentz et al., 2009; Denney et al., 2010; Barth et al., 2011; Grier et al., 2012). The current sample is strongly biased toward relatively low-luminosity AGNs, mostly nearby Seyfert 1 galaxies. A number of Palomar-Green (Schmidt & Green 1983) quasars are included, but the highest-redshift source studied is only at z = 0.29 (PG 1700+518). The uncertainty in the reverberation-mapping masses is $\sim 0.4 - 0.5$ dex (e.g. Peterson, 2010).

If the line-emitting clouds in the broad line region (BLR) are assumed to be virialised and moving in a potential dominated by the central BH, then the BH mass is simply a product of the BLR size and the square of the virial velocity (give equation) The reverberation-mapping technique uses the time lag between variations in the continuum emission and correlated variations in the broad line emission to measure the typical size of the BLR (Peterson, 1993; Peterson, 2014). The full width at half maximum (FWHM) or dispersion (σ; derived from the second moment) velocity of the prominent broad emission line of Hβ (4862.7Å)[2] is used as an indicator of the virial velocity, with extensions to other low-ionization emission lines such as Hα (6564.6Å) and Mg IIλλ2796.4,2803.5 (e.g. Vestergaard, 2002; McLure and Jarvis, 2002; Wu et al., 2004; Kollmeier et al., 2006; Onken and Kollmeier, 2008; Wang et al., 2009; Rafiee and Hall, 2011). Extensive reverberation mapping campaigns have provided accurate BH masses for ~50 active galactic nuclei (AGN) at relatively low redshifts and of modest luminosity (e.g. Kaspi et al., 2000; Kaspi et al., 2007; Peterson et al., 2004; Bentz et al., 2009; Denney et al., 2010).

FWHM: Full width of the line profile at half of maximum intensity

1.6.2 *Single-epoch virial estimates*

Single-epoch virial BH mass estimates normally take the form

$$M_{BH} = 10^{a} \left(\frac{\Delta V}{1000 \text{ km s}^{-1}} \right)^{b} \left[\frac{L_{\lambda}}{10^{44} \text{ erg s}^{-1}} \right]^{c} \tag{1.1}$$

where ΔV is a measure of the line width (from either the FWHM or dispersion), L_λ is the monochromatic continuum luminosity at wavelength λ, and a, b, and c are coefficients, determined via calibration against a sample of AGN with reverberation-mapping BH mass estimates. Several calibrations have been derived using different lines (e.g. Hβ, Mg II, C IV) and different measures of the line width (FWHM

2 Vacuum wavelengths are employed throughout the thesis.

or dispersion) (e.g. Vestergaard, 2002; McLure and Jarvis, 2002; Vestergaard and Peterson, 2006; McGill et al., 2008; Wang et al., 2009; Rafiee and Hall, 2011; Park et al., 2013).

Reverberation mapping campaigns have also revealed a tight relationship between the radius of the BLR and the quasar optical (or ultraviolet) luminosity (the $R-L$ relation; e.g. Kaspi et al., 2000; Kaspi et al., 2007). The emission-line spectrum from an ionized gas, setting aside elemental abundances, is largely controlled by the particle density n and an ionization parameter

$$U = \frac{Q(H)}{4\pi R^2 nc} \tag{1.2}$$

where Q(H) is the number of hydrogen-ionizing photons emitted per second by the central object. To some low order of approximation (principally ignoring the Baldwin Effect), all AGN spectra have similar emission-line flux ratios and similar emission-line equivalent widths, suggesting that U and n do not vary much from one source to another. If we further assume that $Q(H) \propto L$ where L is the luminosity of the central source in some arbitrary band, we are led to the naive prediction that $R \propto L1/2$.

An advantage of the technique is that it is inexpensive in telescope time. A single spectrum yields a mass measurement. This relation provides a much less expensive method of measuring the BLR radius, and large-scale studies of AGN and quasar demographics have thus become possible through the calibration of single-epoch virial-mass estimators using the reverberation-derived BH masses (e.g. Greene and Ho, 2005b; Vestergaard and Peterson, 2006; Vestergaard and Osmer, 2009; Shen et al., 2011; Shen and Liu, 2012; Trakhtenbrot and Netzer, 2012). The uncertainties in reverberation mapped BH masses are estimated to be ~ 0.4 dex (e.g. Peterson, 2010), and the uncertainties in virial masses are similar (e.g. Vestergaard and Peterson, 2006). Since the structure and geometry of the BLR is unknown, a virial coefficient f is introduced to transform the observed line-of-sight velocity inferred from the line width in to a virial velocity. This simplification accounts for a significant part of the uncertainty in virial BH masses (in addition to, for example, describing the BLR with a single radius R and scatter in the $R-L$ relation; Shen, 2013). By far the biggest uncertainty is the virial coefficient f . It is unknown, and it probably varies from source to source. A spherical distribution of clouds on random, isotropic orbits has $f = 3/4$ for ΔV = FWHM and $f = 3$ for $\Delta V = \sigma$ (Netzer 1990). Furthermore, if the BLR is anisotropic (for example, in a flattened disk; e.g. Jarvis and McLure, 2006) then the line width will be orientation-dependent (e.g. Runnoe et al., 2013; Shen and Ho, 2014; Brotherton et al., 2015).

For example, single epoch estimates have been used to calculate black hole masses in the highest redshift quasars to study the growth of SMBHs. This figure shows a compilation of SE mass estimates for quasars over a wide redshift range from different studies. These studies show that massive, 10^9 BHs are probably already in place by $z \sim 7$, when the age of the Universe is less than 1 Gyr. The fact that a SMBH exists in a quasar at such high redshift is of great importance in physics. The high redshift means that it was already there when our universe was very young, only about 800 million years old. And the fact that a SMBH was able to grow up in such a short time put some very tight constraints upon both the cosmological parameters and the accretion history of the SMBH itself (Willott et al. 2003).

Single epoch masses have also been used to study the distribution of quasars in the BH mass-luminosity plane, which conveys important information about the accretion process of these active black holes (e.g. Kollmeier et al. 2016). Redshift evolution of BH-bulge scaling relations (e.g. Bennert et al. 2011). Clustering (Shen & Ho 2014; Timins et al.?). With the R–L relationship, we are able to explore the black hole mass function, not only locally but at high redshift, enabling us to trace the history of black hole growth. Some exploratory work has been done on this and in fact there are claims that the M-sigma relation evolves over time. Estimates of such masses are important with respect to the relation between the MBH in the center of a stellar spheroid and the velocity dispersion.

We emphasize that application of single-epoch spectroscopy to quasars rests on the untested assumption that machinery which is calibrated for sub-Eddington BHs with $M \sim 10^7$ still works for BHs with masses up to 10^{10} that radiate near the Eddington limit. Refer forward to problems with C IV (Chapter 3)

Throughout this thesis we adopt a ΛCDM cosmology with $h_0 = 0.71$, $\Omega_M = 0.27$, and $\Omega_\Lambda = 0.73$. All wavelengths and equivalent width measurements are given in the quasar rest-frame, and all emission line wavelengths are given as measured in vacuum.

1.7 SEDS

AGN! (**AGN!**) emit strongly over many decades in frequency. At different frequencies, the emission originates from processes occurring in different regions of the **AGN!**. Hard X-ray emission is dominated by Compton up-scattering of accretion disk photons by electrons in a hot corona (e.g. Sunyaev and Titarchuk, 1980), **UV!** (**UV!**)/optical by thermal accretion disc emission, **IR!** (**IR!**) by dust at a wide range of temperatures, and radio by synchrotron emission in relativistic jets.

Significant diversity is observed in the **SED!** (**SED!**)s of individual objects. However, the systematic study of the dependence of the **SED!** shape on physical parameters has, until very recently, been limited by the difficulty in obtaining a large sample of quasars with good multi-wavelength coverage and large dynamic range in luminosity and redshift. However, we are able to take advantage of a number of recent, sensitive, wide-field photometric surveys, including SDSS (in the UV/optical), UKIDSS (in the **NIR!** (**NIR!**)) and WISE (in the mid-infrared). We will combine this information with the **BH!** (**BH!**) mass and mass-normalised accretion rate estimates and outflow diagnostics which we developed in Chapters **??** and **??**. We will determine whether there are **SED!**-related systematics as a function of outflow signatures and **BH!** mass or Eddington ratio.

Since the physical processes that power **AGN!** are generally understood only qualitatively, almost all **AGN!** **SED!** templates are empirical. The empirical template of Elvis et al., (1994) is still the most commonly cited, despite many additions and updates (e.g. Polletta et al., 2000; Kuraszkiewicz et al., 2003; Risaliti and Elvis, 2004; Richards et al., 2006a; Polletta et al., 2007; Lusso et al., 2010; Shang et al., 2011; Marchese et al., 2012; Trichas et al., 2012). However, these composite spectra are often constructed from quasars with a huge range in luminosity as a function of wavelength. In addition, the presence of significant host galaxy at optical wavelengths in low-redshift objects is an additional complication which has not always been taken care of adequately. There is therefore a strong rationale for taking a parametric approach to modelling quasar **SED!**s. This is the approach we take in this chapter.

1.8 SUMMARY / WHAT I NEED TO GET ACROSS

It's a data rich time. SDSS has been revolutionary - shown the power of large surveys. We have wide-field photometry in a number of bands - important because AGN emit strongly over many decades in frequency. With spectra from SDSS we can derive BH masses and outflow properties from optical lines. But these are shifted to infrared wavelengths at redshifts > 1, when things get interesting. Increasing availability of infrared-spectra. Looking to the future, huge spectroscopic surveys - WEAVE, 4MOST.

Quasar black hole masses: Shen, (2013), Peterson, (2010), Peterson, (2011), Vestergaard et al., (2011), Marziani and Sulentic, (2012). This has motivated a considerable amount of observational work searching for feedback signatures (for recent reviews, see Alexander and Hickox, 2012; Fabian, 2012; Heckman and Best, 2014).

Get across:

Quasars are not all the same! orientation/evolution false dichotomy really a dynamic thing