An FMOS Survey of Moderate-luminosity, Broad-line AGNs in COSMOS, SXDS, and E-CDF-S

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Abstract

We present near-IR spectroscopy in the J- and H-bands for a large sample of 243 X-ray-selected, moderate-luminosity Type 1 active galactic nuclei (AGNs) in the COSMOS, SXDS, and E-CDF-S survey fields using the multi-object spectrograph Subaru/FMOS. Our sample covers the redshift range 0.5 \( \lesssim z \lesssim 3.0 \) and X-ray luminosity range of \( 10^{43} \lesssim L_{2-10keV} \lesssim 10^{45} \) erg s\(^{-1}\). We provide emission-line properties and derived virial black hole mass estimates, bolometric luminosities, and Eddington ratios, based on \( \text{H}\alpha \) (211), \( \text{H}\beta \) (63), and \( \text{Mg}\ II \) (4). We compare line widths, luminosities, and black hole mass estimates from \( \text{H}\alpha \) and \( \text{H}\beta \), and augment these with commensurate measurements of \( \text{Mg}\ II \) and \( \text{C}\ IV \) detected in optical spectra. We demonstrate the robustness of using \( \text{H}\alpha \), \( \text{H}\beta \), and \( \text{Mg}\ II \) as reliable black hole mass estimators for high-z moderate-luminosity AGNs, while the use of \( \text{C}\ IV \) is prone to large uncertainties (\( \gtrsim 0.4 \) dex). We extend a recently proposed correction based on the \( \text{C}\ IV \) blueshift to lower luminosities and black hole masses. While our sample shows an improvement in their \( \text{C}\ IV \) black hole mass estimates, the deficit of high blueshift sources reduces its overall importance for moderate-luminosity AGNs compared to the most luminous quasars. In addition, we revisit luminosity correlations between \( \text{H}\alpha \) and \( \text{Mg}\ II \), and find them to be consistent with a simple empirical model, based on a small number of well-established scaling relations. Finally, we highlight our highest redshift AGN, CID 781, at \( z = 4.6 \), which has the lowest black hole mass (\( \sim 10^8 M_\odot \)) among current near-IR samples at this redshift and is in a state of fast growth.

Key words: galaxies: active – galaxies: nuclei – quasars: general

Supporting material: machine-readable table

1. Introduction

The study of the population of active galactic nuclei (AGNs) and its evolution out to high redshift is closely entangled with the understanding of galaxy evolution and the role supermassive black holes (SMBHs) play therein. Evidence of a link between SMBH growth and galaxy evolution comes from observational results (e.g., Magorrian et al. 1998; Silverman et al. 2008; Alexander & Hickox 2012; Fabian 2012; Kormendy & Ho 2013) and from theoretical arguments (e.g., Silk & Rees 1998). It is also an essential ingredient in numerical simulations and semi-analytical models (e.g., Di Matteo et al. 2005; Somerville et al. 2008; Vogelsberger et al. 2014; Schaye et al. 2015). However, the details and especially the causal connection between the two remain poorly understood. An essential cosmic period for studying the connection between black hole growth and star formation/galaxy evolution is the redshift range 1 \( < z < 3 \), corresponding to the peak epoch of star formation and black hole activity and the beginning of their decrease (Boyle & Terlevich 1998; Silverman et al. 2008; Aird et al. 2015).

Disentangling the black hole growth history requires knowledge of not only the AGN luminosities but also their black hole masses and normalized accretion rates, i.e., their Eddington ratios. Such knowledge allows a more meaningful study of the demographics and cosmic evolution of the AGN population (e.g., McLure & Dunlop 2004; Netzer & Trakhtenbrot 2007; Vestergaard & Osmer 2009; Trakhtenbrot & Netzer 2012; Kelly & Shen 2013; Schulze et al. 2015). These studies revealed an intrinsically broad distribution of Eddington ratios, with an upper boundary around the Eddington limit and with the mean Eddington ratio increasing
with increasing redshift. They also demonstrated the role of black hole mass in the downsizing trends seen in the AGN luminosity function (Schulze & Wisotzki 2010; Schulze et al. 2015). Furthermore, knowledge of the SMBH mass is essential to study the cosmic evolution of the scaling relation between SMBH mass and its host galaxy properties out to high redshifts (e.g., Peng et al. 2006; Salvian et al. 2007; Park et al. 2015).

For broad-line (Type 1) AGNs, SMBH mass estimates can be obtained from single-epoch spectroscopy using the so-called virial method (e.g., McLure & Jarvis 2002; Shen 2013). Under the assumption that the motion of the broad-line region (BLR) gas is virialized, it is possible to infer the central black hole mass. This became feasible thanks to extensive reverberation mapping campaigns (Peterson et al. 2004), which established an empirical scaling of the BLR size with AGN continuum luminosity (Kaspi et al. 2000; Bentz et al. 2009). The velocity of the BLR gas can be inferred from the width of the broad emission lines. The virial method builds on these reverberation mapping results and is directly calibrated to it, at least for the broad Hβ line (Vestergaard & Peterson 2006). Other broad emission lines, like Hα, Mg II, and C IV, are commonly calibrated to Hβ (e.g., Greene & Ho 2005; McGill et al. 2008; Park et al. 2017). More recent reverberation mapping experiments targeting such lines generally confirm the validity of these calibrations (Grier et al. 2017; Lira et al. 2018). At z > 1, Hβ moves out of the optical spectral range, which necessitates either the use of a different broad line to infer the black hole mass or observations in the near-IR.

Since the broad Balmer lines are considered to provide the most reliable black hole mass estimates, observations of high-z broad-line AGNs in the near-IR, covering the rest-frame wavelength range, easily observed at low redshift, provides additional information on the AGN structure and demographics, from probing the outer accretion disk emission, the optical BLR, and the narrow-line region (NLR). A good tracer of the NLR, its size, and its kinematics, largely due to its strength, is the [O III] λλ4959,5007 line doublet (e.g., Mullaney et al. 2013; Stern & Laor 2013; Shen & Ho 2014).

These considerations have provided the motivation for studies of broad-line AGNs in the near-IR using either single-object (Yuan & Wills 2003; Shemmer et al. 2004; Sulentic et al. 2004, 2006; Netzer et al. 2007; Dietrich et al. 2009; Marziani et al. 2009; Greene et al. 2010; Ho et al. 2012; Shen & Liu 2012; Bongiorno et al. 2014; Collinson et al. 2015; Jun et al. 2015; Zuo et al. 2015; Cooray et al. 2016; Mejía-Restrepo et al. 2016; Saito et al. 2016; Trakhtenbrot et al. 2016; Bisogni et al. 2017; Jun et al. 2017; Vietri et al. 2018) or, more recently, multi-object spectroscopy with instruments such as the Fibre Multi-Object Spectrograph (FMOS; Nobuta et al. 2012; Matsuoka et al. 2013; Karouzos et al. 2015; Suh et al. 2015).

Most of such studies, and particularly the earlier ones, focused on extremely luminous sources, powered by SMBHs with high Eddington ratios (0.1–1.0) and/or high SMBH masses, reaching ~10¹⁰ M_☉. Such very luminous systems are intrinsically rare and do not represent the typical AGN population at z > 1 (Richards et al. 2006b; Ross et al. 2013; Aird et al. 2015).

In particular, moderate-luminosity AGNs (10⁴⁴ < L_{bol} < 10⁴⁶) at high redshift (z > 1) are important probes of black hole growth and AGN physics since they trace the bulk of the population and have direct analogs (e.g., similar luminosity) at lower z. Deep X-ray surveys are very effective at detecting this population of unobscured to moderately obscured AGNs (e.g., Brandt & Alexander 2015; Xue 2017). The COSMOS field (Scoville et al. 2007) has been very important in this respect, due to its deep X-ray coverage (Civano et al. 2016) and available multi-wavelength data (e.g., Laigle et al. 2016; Smolčić et al. 2017). Another important X-ray extragalactic survey field is the Subaru/ XMM-Newton Deep Survey (SXDS; Furusawa et al. 2008; Ueda et al. 2008; Akiyama et al. 2015). Both fields constitute the UltraDeep layer of the ongoing Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP) survey on the Subaru telescope (Aihara et al. 2018), where they will be covered in grizy to a depth of i ≈ 28 mag.

Additional information on the AGN population (i.e., black hole masses and Eddington ratios) is important for a broad range of applications, including the investigation of black hole–galaxy coevolution (Jahne et al. 2009; Merloni et al. 2010; Cisternas et al. 2011; Schramm & Silverman 2013; Sun et al. 2015), the connection between AGN activity and host star formation (Rosario et al. 2013), the study of AGN demographics itself (Trump et al. 2009; Nobuta et al. 2012; Schulze et al. 2015), or the dependence of observed AGN properties on black hole mass and Eddington ratio (Brightman et al. 2013).

In this work, we present near-IR spectroscopy, covering the broad Hα, Hβ, and Mg II lines, for an unprecedentedly large sample of 243 moderate-luminosity AGNs at 0.5 ≲ z ≲ 3.0 obtained with FMOS (Kimura et al. 2010) on the Subaru telescope. Our main target fields are COSMOS and SXDS. We augment the sample with additional observations in the Extended Chandra Deep Field South (E-CDF-S; Lehmer et al. 2005). Initial results for a subset of 43 AGNs of our sample in COSMOS and E-CDF-S have been presented in Matsuoka et al. (2013, hereafter M13). For the majority of our sample in SXDS, broad Hα measurements have been presented in Nobuta et al. (2012, hereafter N12), but they did not provide direct black hole mass estimates from that line. Here, we provide those estimates as well as broad Hβ detections for these and additional broad-line AGNs in SXDS. A complete black hole mass catalog of AGNs in COSMOS, including results from optical spectroscopy, will be presented in a future publication.

We present the sample and observations in Section 2. In Section 3, we present our spectral measurements and an assessment of the prominence of reddening in our sample. In Section 4, we present the derived estimates of SMBH mass and Eddington ratio and discuss correlations between different virial SMBH mass estimators. In Section 5, we give a discussion of topics pertaining to our near-IR spectra, including the virial SMBH mass estimators, comparison with low-redshift analogs of similar luminosity, correlations between different bolometric luminosity indicators, and the early growth of the black hole population. We present our conclusions in Section 6. Throughout this paper, we use a Hubble constant of H₀ = 70 km s⁻¹ Mpc⁻¹ and cosmological density parameters Ω_M = 0.3 and Ω₇ = 0.7. Magnitudes are expressed in the AB system.
2. Sample and Observations

FMOS is a near-infrared fiber spectrograph mounted on the Subaru telescope. It allows the placement of 400 fibers (1.2 diameter each) over a circular region of 300 diameter. Spectra for 200 targets can be obtained simultaneously over the field of view in cross-beam switching mode, which dithers targets between close fiber pairs for improved sky subtraction. In addition, an OH-airglow suppression filter (Maihara et al. 1994; Iwamuro et al. 2001) masks out regions of strong atmospheric emission lines in the J-band and H-band. Observations can be carried out in two resolution modes. The low-resolution (LR) mode allows simultaneous coverage of the J-band and H-band over the wavelength range 0.9–1.8 μm at a spectral resolution of λ/Δλ ≈ 600. The high-resolution (HR) mode achieves a spectral resolution of λ/Δλ ≈ 2600, but requires four high-resolution gratings to fully cover the J- and H-bands.

The FMOS survey we are using in this work consists of four observational efforts carried out with different spectral resolutions. In the COSMOS field, we have conducted a survey in the LR mode (J. Kartaltepe et al. 2018, in preparation) and a survey in the HR mode (Silverman et al. 2015). Both surveys cover the full 2 deg2 area of the COSMOS field. In SXDS and E-CDF-S we carried out observations in the LR mode only. We here present and combine results obtained from all four efforts.

2.1. Target Selection

The FMOS survey in COSMOS was primarily designed as a near-IR survey of high-z galaxies, in particular targeting optical-near-IR-selected star-forming galaxies at z ~ 1.6 (Kashino et al. 2013; Zahid et al. 2014; Silverman et al. 2015; Kashino et al. 2017a, 2017b) and far-IR and mid-IR sources using Herschel/PACS or Spitzer/MIPS (Kartaltepe et al. 2015; Puglisi et al. 2017). In addition, the survey targeted X-ray-selected AGNs, which are the focus of the present work. Initial results on the LR AGN sample have been presented in M13 and Brightman et al. (2013).

The AGN selection is based on the X-ray point source catalogs from Chandra (Elvis et al. 2009; Civano et al. 2012, 2016) and XMM-Newton (XMM-COSMOS; Cappelluti et al. 2009; Brusa et al. 2010), with sensitivities of f0.5−2.0keV > 2 × 10−16 erg cm−2 s−1 and f2−10keV > 7.3 × 10−16 erg cm−2 s−1 in the soft and hard bands, respectively, for Chandra and f0.5−2.0keV > 5 × 10−16 erg cm−2 s−1 and f2−10keV > 3 × 10−15 erg cm−2 s−1 for XMM-Newton. From these catalogs, we targeted both Type 1 and Type 2 AGNs with spectroscopic or photometric redshifts, allowing the detection of either Hα, Hβ, or Mgb within the spectral coverage. Over the wavelength range covered by FMOS, Hα can be detected between 0.5 < z < 1.7, Hβ between 1.2 < z < 2.7, and Mgb between 2.8 < z < 5.3, with gaps at z ~ 1.1, ~1.8, and ~4.0, respectively, due to strong atmospheric absorption between the J- and H-bands. The aim of the FMOS NIR campaign was to target the Hα or Hβ lines. The Mgb targets were included as fillers.

For the LR observations, we used the XMM-COSMOS (Brusa et al. 2010) and C-COSMOS (Civano et al. 2012) catalogs as input. For the HR campaign, we used the C-COSMOS catalog for the central square degree observations, augmented with the Chandra COSMOS-Legacy survey (Civano et al. 2016; Marchesi et al. 2016) for the outer area. We purposefully reobserved AGNs that already had LR data in HR mode, since the HR mode has a higher throughput, to investigate the impact of spectral resolution on our results. In addition to AGNs specifically targeted as X-ray sources, some were also targeted by other selection criteria, e.g., as Herschel sources. We include all FMOS spectra of X-ray-detected AGNs, irrespective of their initial selection. Furthermore, we note that all detected broad-line AGNs in our sample are included in the Chandra COSMOS-Legacy survey (Marchesi et al. 2016). We associate each of our FMOS COSMOS AGNs to the respective X-ray source and optical counterpart given in Marchesi et al. (2016). While the full AGN sample contains both Type 1 and Type 2 AGNs, in this paper we only focus on the Type 1, i.e., broad-line, AGN sample. We targeted broad-line AGNs down to a limiting magnitude of JAB = 23, with preference given to those at JAB < 21.5. Multiwavelength photometry is provided in Laigle et al. (2016).

For the SXDS field, the FMOS observations focused on spectroscopic follow-up of X-ray sources detected with XMM-Newton (Ueda et al. 2008). The X-ray observations cover a 1.3 deg2 field with a flux sensitivity of f0.5−2.0keV ~ 1 × 10−15 erg cm−2 s−1 and f2−10keV ~ 3 × 10−15 erg cm−2 s−1. Optical counterparts have been presented in Akiyama et al. (2015) and additional multiwavelength photometry, including Subaru/HSC, for SXDS sources is provided in Mehta et al. (2018).

The AGN sample in E-CDF-S (Lehmer et al. 2005) is similar to that presented in M13. We targeted X-ray AGNs detected in the central 4 Ms area (Luo et al. 2010; Xue et al. 2011). Priority was given to those with RAB < 22. We associate optical/near-IR counterparts based on the multiwavelength catalog of Hsu et al. (2014).

We took advantage of the high multiplex factor of the FMOS spectrograph to target a large number of both Type 1 and Type 2 AGNs in each of the campaigns. For the COSMOS-LR campaign, we observed in total 932 AGNs in the COSMOS Chandra Legacy catalog. In the COSMOS-HR campaigns, 892 targets were observed. In the SXDS field, 851 out of the full sample of 896 unique AGN candidates in SXDS have been targeted with FMOS (Akiyama et al. 2015). We here only consider those AGNs for which we robustly detect a broad emission line in the FMOS spectrum, as listed in Table 1. A study of the Type 2 population will be presented in Kashino et al. (2018, in preparation).

For the fields of COSMOS and E-CDF-S, almost all of the Type 1 AGNs considered here had prior spectroscopic redshifts from optical spectroscopy obtained from several observing programs in COSMOS (Lilly et al. 2007; Trump et al. 2007; Coil et al. 2011; Alam et al. 2015; Hasinger et al. 2018) and E-CDF-S (Szokoly et al. 2004; Popesso et al. 2009; Silverman et al. 2010), as listed in Marchesi et al. (2016) and Xue et al. (2016). Two targets only had a photo-z (Salvato et al. 2011) before the FMOS observations. In SXDS, the FMOS observations have been carried out in parallel to optical spectroscopy for identification and redshift determination, as discussed in Akiyama et al. (2015).

18 The instrument was decommissioned in 2016.
19 We make use of photometric redshifts for part of the Type 2 AGN population and use spectroscopic redshifts whenever available.

20 The deeper 7 Ms data were not available when the survey was conducted.
2.2. Observations and Data Reduction

We provide a brief summary of the observations and data reduction. Further details can be found in Mehta et al. (2015) for the LR survey and in Silverman et al. (2015) for the HR survey. Observations for the LR survey over the full COSMOS field were obtained between 2010 and 2012 (semesters S10B–S12A). Total exposure times are around 2–3.5 hr on-source per pointing. The HR survey in COSMOS was conducted between 2012 and 2016, with observations of the central square degree carried out in 2012–2014 and of the outer area in 2015–2016. Several gratings were used (H-LONG, J-LONG, H-SHORT, H-SHORT-prime), especially to cover both the Hα and Hβ regions for z ∼ 1.6 galaxies and AGNs. Total on-source exposure times are 3–5 hr per observation. Observations in SXDS were carried out between 2009 and 2011 in guaranteed, engineering, and open-use time over 22 pointings. Typical exposure times per pointing range between 1 and 5 hr. Observations in both LR and HR modes were carried out in cross-beam switching mode. We performed data reduction, and wavelength and flux calibration using the publicly available pipeline FIBRE-pac (FMOS Image-Based REduction package; Iwamuro et al. 2012), providing 1D and 2D reduced spectra and their error spectra.

Although an initial flux calibration is performed during the data reduction process using spectra of bright stars, we scale the flux of each spectrum to its H-band or J-band magnitude to account for flux loss due to aperture effects, variable seeing, and other factors. For COSMOS, we are using the deep near-IR photometry from UltraVISTA (McCracken et al. 2012), taken from the COSMOS2015 catalog (Laigle et al. 2016). The near-IR photometry for the SXDS field is taken from the VISTA Deep Extragalactic Observations (VIDEO) survey (Jarvis et al. 2013) as provided in the recent SPLASH-SXDF catalog (Mehta et al. 2018). For both surveys, we use VISTA J or H magnitudes measured within a 3″ aperture. For E-CDF-S, we use the near-IR photometry taken from VIDEO DR3 (Jarvis et al. 2013), with the VISTA J or H magnitudes corrected to an aperture of 2″ diameter. This approach to absolute flux calibration ignores the effect of AGN variability (e.g., Vanden Berk et al. 2004; Caplar et al. 2017), which is expected to be of the order of 0.2 mag for our sample, based on a comparison of near-IR photometry between VIDEO and the Ultra Deep Survey (UDS) in the SPLASH-SXDF catalog.

2.3. Sample Properties

Of all targets observed with FMOS, we include those that have a detected broad emission line with an FWHM > 1000 km s⁻¹ in either Hα, Hβ, or Mg II. We initially fit a parent sample of FMOS AGN spectra with sufficient signal-to-noise ratio (S/N) as described in Section 3.1 using both a spectral model which only includes narrow emission lines and one with the addition of a broad line. We classify the spectrum as a broad-line AGN based on the FMOS spectra if the addition of a broad component leads to a significant improvement of the best fit in terms of reduced χ².

We provide sample statistics for the three surveys in Table 1. In total, we include 243 objects, with 145 in COSMOS, 87 in SXDS, and 11 in E-CDF-S. Broad Hα is detected for most of them (211), while Mg II is only detected in four cases at z > 2.8. Our highest redshift AGN is CID 781 at z = 4.6. Our sample provides Hα measurements for spectroscopically confirmed Type 1 AGNs over the respective redshift range for ~53% of the objects in the COSMOS-Legacy survey down to J < 21.5 mag.

We show the redshift and X-ray luminosity L[2–10keV] distribution for our sample in Figure 1. The X-ray luminosities are absorption-corrected assuming an X-ray spectral index Γ = 1.8, taken from Marchesi et al. (2016) for COSMOS and Akiyama et al. (2015) for SXDS. For E-CDF-S, we adopt the absorption-corrected L[0.5–7.0keV] luminosity from either the 7 Ms CDFS catalog of Luo et al. (2017) or the E-CDF-S catalog of Xue et al. (2016), where we use L[2–10keV] = 0.721L[0.5–7.0keV] (Xue et al. 2016). The majority of our sources are located at 0.7 < z < 1.7, where Hα is within the spectral range. Both Hβ and Mg II are significantly weaker and thus more challenging to detect. Within the redshift range 1.2 < z < 1.7, where we are able to simultaneously cover both Hα and Hβ, we only detect Hβ reliably in ~26% (35/135) of the cases.

For four of our AGNs, we found previous near-IR spectroscopic observations in the literature. CID 87 (XID 18) and LID 1646 (XID 5321) have been observed with VLT/XSHOOTER (Bongiorno et al. 2014; Brusa et al. 2015) as a result of a selection based on their red optical colors (R – K > 4.5). While the S/N and spectral resolution of the XSHOOTER spectra are higher, our results for these two objects are consistent with their work. We note, however, that our measurement for CID 87 has large uncertainties.

For CID 352, our FMOS spectrum covers Hβ, while Trakhtenbrot et al. (2016) observed the Hα line region in the

| Sample | Total | Hα | Hβ | Mg II |
|--------|-------|----|----|-------|
| COSMOS | 145   | 121| 39 | 4     |
| SXDS   | 87    | 79 | 24 | 0     |
| E-CDF-S| 11    | 11 | 0  | 0     |
| Total  | 243   | 211| 63 | 4     |

Figure 1. Distribution of redshift vs. 2–10 keV X-ray luminosity for the X-ray-selected broad-line AGN FMOS sample. Green squares denote AGNs in COSMOS, orange squares are for AGNs in SXDS, and blue diamonds mark AGNs in E-CDF-S. We use the same color scheme to distinguish the three survey fields throughout this paper. We have omitted CID 781 at z = 4.6 from the plot.
K-band with MOSFIRE at Keck. Finally, for CID 113 at $z = 3.3$, we detect the Mg II line in the $J$-band, while Trakhtenbrot et al. (2016) present MOSFIRE observations of the H$\beta$ line in the $K$-band. We note that our SMBH mass estimates are higher by 0.5 and 0.3 dex than those reported in their work for CID 352 and CID 113, respectively. For CID 352, this difference is mainly due to the use of a different virial mass formula, while for CID 113, it is caused by a broader Mg II line in our observations compared to the expectation based on the H$\beta$ line in Trakhtenbrot et al. (2016). Two of the COSMOS AGNs in our sample at $z > 2$ (CID 166 and CID 346) are also part of the ESO Large Programme SUPER (PI: V. Mainieri; see Circosta et al. 2018). SUPER will provide high-S/N and spatially resolved observations in the $H$- and $K$-bands using VLT/SINFONI.

In Figure 2, we show the S/Ns of our sample, for each emission line and the continuum, as a function of H-band magnitude. We define the line S/N (S/N$_{\text{line}}$) as the signal-to-noise ratio per pixel measured at the peak of the respective broad emission line, while the continuum S/N (S/N$_{\text{cont}}$) is given by the median S/N per wavelength pixel over two 40 Å wide regions redward and blueward of the respective emission line (16 resolution elements). For the HR spectra, we rebinned the spectra to the same resolution as the LR spectra before computing the S/N. The majority of our sample has S/N$_{\text{Cont}} < 10$; some of them have S/N$_{\text{Cont}} < 1$. At least for the broad H$\alpha$ line, S/N$_{\text{Line}} > 3$ for the majority of our objects, allowing reliable measurements in most cases. Measurements for the considerably weaker H$\beta$ line are overall much less reliable and should be taken with caution, especially for fainter objects ($H > 20$ mag). Thus, we emphasize that the large size of our sample comes at the cost of typically larger uncertainties for individual objects. We investigate and discuss the typical uncertainty of our measurements in Sections 4.1 and 4.3.

3. Analysis

3.1. Spectral Measurements

Our measurements of H$\alpha$, H$\beta$, and Mg II; the continuum fluxes; and the narrow [O III] lines are based on spectral model fits to the respective wavelength regions. Our procedure for continuum fitting and emission-line modeling is similar to several previous studies (e.g., Schulze et al. 2010; Shen et al. 2011; Shen & Liu 2012; Schulze et al. 2017, M13).

We correct the spectra for galactic extinction using the extinction map from Schlegel et al. (1998) and the reddening curve from Cardelli et al. (1989) and shift them to their rest frame using their spectroscopic redshift from either the X-ray catalog (Hsu et al. 2014; Akiyama et al. 2015; Marchesi et al. 2016) or the FMOS catalog (Silverman et al. 2015). For the spectral fit, we mask out regions in the near-IR that are strongly affected by OH emission. We initially fit every FMOS spectrum by both a narrow-line and a broad-line AGN model, based on a Levenberg–Marquardt least-squares minimization as implemented in MPFIT (Markwardt 2009). We classify the AGN as Type 1 if the broad-line AGN model leads to a significant improvement in the reduced $\chi^2$, i.e., a decrease in the reduced $\chi^2$ by at least 25%. Otherwise, we classify the object as a Type 2 AGN. We visually inspect each spectral fit and manually adjust the model fit if appropriate. For the purpose of this paper, we only further consider those AGNs for which our analysis of the FMOS spectrum results in a Type 1 classification. For AGNs with FWHM < 2000 km s$^{-1}$, there exist the possibility of confusion with an intrinsically Type 2 AGN or with an AGN-driven wind (Fürster Schreiber et al. 2018), especially for the LR mode data. However, the inclusion of ancillary data from optical spectroscopy and the SED minimizes this possibility.

We here provide details on the spectral models for the individual line complexes (see also Schulze et al. 2017). For H$\alpha$, we first fit a local power-law continuum to wavelength regions free of emission lines. An emission-line model is fit to the continuum-subtracted spectrum within 6200–7000 Å. In the case of the narrow-line model, only the narrow emission lines are included, composed of single Gaussians each for H$\alpha$, [N II] $\lambda\lambda 6548,6584$ and [S II] $\lambda\lambda 6717,6731$. The line widths and offsets of all narrow lines are constrained to the same value (in velocity space). Their flux ratios are free to vary, apart from the flux ratio of the [N II] lines, which is fixed to 2.96. For the broad-line model, in addition, the broad H$\alpha$ line is fit by up to three Gaussians, which is flexible enough to capture the often non-Gaussian broad-line profile. If a broad-line model is preferred, we test both a model with only a broad line and one with the inclusion of narrow lines. We use the latter model if it leads to a decrease of the reduced $\chi^2$ by at least 25%, and a broad line only model otherwise.

For H$\beta$, the narrow-line model is composed of a local power-law continuum, a single narrow Gaussian for H$\beta$, and a single Gaussian each to model the narrow [O III] $\lambda\lambda 4959,5007$ lines with their line ratio fixed to 3.0. The velocity offset of all narrow lines is tied together, and their line widths are constrained to the same value. For the broad-line H$\beta$ model, we fit a local pseudo-continuum, consisting of a power-law continuum and an optical iron template (Boroson & Green 1992), broadened by a Gaussian, whose width is a free parameter. A line model is fit to the pseudo-continuum-subtracted spectrum over the range 4700–5100 Å. We fit up to
three Gaussians for the broad Hβ line and include the narrow Hβ and [O III] lines as above.

We detect broad Mg II in four cases in our FMOS sample. To model their spectrum, we again first fit and subtract a local pseudo-continuum, consisting of a power law and iron contribution. For the latter, we use a broadened Fe II template from Mejía-Restrepo et al. (2016). We then fit the emission-line model over the range 2700–2900 Å. A single broad Gaussian is sufficient to model the line profile in all cases.

In Section 4.3, we include optical spectra covering the Mg II line at z < 1.7 from the optical spectra of SDSS and zCOSMOS (bright and deep component; Lilly et al. 2007). The Mg II line fitting procedure for these optical spectra in COSMOS is outlined in Schramm & Silverman (2013) and M13. A detailed discussion of SMBH masses obtained from optical spectroscopy in COSMOS and their corresponding SMBH mass catalog will be presented in a future publication.

For the SXDS sample, the Mg II measurements are taken from N12 and for the E-CDF-S sources from M13. These measurements are based on a similar spectral fitting method, which warrants combining them in our analysis.

For every emission line, we use the best-fit model to measure the FWHM (corrected for the instrumental resolution) of the broad and/or narrow component, the line flux, and the velocity offset. In addition, we measure the continuum flux from the power-law continuum fit and use these to compute the monochromatic continuum luminosities at rest frame 5100 Å and 3000 Å. We derive uncertainties on these parameters based on 100 Monte Carlo realizations for each spectrum (e.g., Shen et al. 2011; Mejía-Restrepo et al. 2016; Schulze et al. 2017). For each realization, we modify the spectrum by adding Gaussian random noise, with the standard deviation at each pixel drawn from the flux density error spectrum, and re-fit this modified spectrum. The uncertainties for each measured parameter are taken as the 68% range from the distribution of this parameter measured on the best fit to the set of mock spectra. This approach generally provides more realistic uncertainties than the formal errors of the fitting procedure.

We have re-measured the systemic redshifts of the AGN from the best-fit spectral models. In cases where our spectroscopy covers the [O III] lines and [O III] λ5007 is detected at S/N > 5 we use the model peak of that line as our systemic redshift estimate. Otherwise, we use the model peak of the total Hα profile or, if Hα is not covered, that of the total Hβ profile as the systemic redshift. These lines have average offsets from the systemic redshift of less than 120 km s⁻¹ (Shen et al. 2016). Our near-IR redshift measurements are given in Table 2, together with the catalog redshift, which is largely based on optical spectroscopy (Xue et al. 2011; Akiyama et al. 2015; Marchesi et al. 2016). We generally find a good agreement between the catalog redshift and the near-IR redshift. We define the difference in the redshift measurements as ε(z_{cat} − z_{NIR})/(1 + z_{NIR}). For the combined sample, find a median of 28 and a median absolute deviation (MAD) of 228 km s⁻¹.

The continuum and line measurements are given in Table 2. Example line fits for all three surveys, as well as for COSMOS LR and HR spectra, are shown in Figures 3 and 4. The spectra and best fits for the Mg II line regions for the four objects detected are shown in Figure 5.

We note that our new measurements for Hα are consistent with those presented before in M13 and N12. Comparing with the sample in M13, we find for the difference in log FWHM and log L_{Hα}, a mean and standard deviation of (0.000, 0.168) and (−0.012, 0.173), respectively. Compared to the Hα measurements in N12, we find a mean and standard deviation in log FWHM of (0.011, 0.082). N12 do not provide measurements of L_{Hα} but rather couple their Hα measurements to the virial mass estimator for Mg II.

3.2. Spectral Energy Distribution and Reddening

To investigate the amount of dust reddening affecting our AGN sample, we construct the spectral energy distribution (SED) for the AGN sample in COSMOS and SXDS. For COSMOS, we utilize the multiwavelength catalog COSMOS2015 (Laigle et al. 2016), where we include homogenized photometry in u*, B, V, g, r, i, z+ from the Canada–France–Hawaii Telescope (CFHT) and Subaru Suprime-Cam, in YJHKs from VINCAM/VISTA (UltraVISTA DR2) and in 3.6 μm, 4.5 μm, 5.8 μm, and 8.0 μm from Spitzer-IRAC (S-COSMOS and SPLASH). For SXDS, we use the homogenized multiwavelength catalog of Mehta et al. (2018). We include data only from the CFHT u-band program MUSUBI, Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP; grizY), the VISTA Deep Extragalactic Observations (VIDEO) survey (YJHKs), and Spitzer-IRAC. We use photometry within a 3″ aperture.

We show the SEDs for the individual broad-line AGNs in the FMOS sample in COSMOS and SXDS in the upper panels of Figure 6. We normalize each SED to λF_λ = 1 at 2.5 μm. Although the host galaxy can make a significant contribution at ~1 μm, the emission at this wavelength is expected to be dominated by the AGN emission and to be unaffected by dust reddening. In addition, we plot the median SED for the FMOS sample (black solid line) and the unobscured quasar SED template from Richards et al. (2006a), based on SDSS quasars with 45 < log L < 46.02 (the fainter half of their sample; magenta dashed line). This SED template overall agrees well with the typical SEDs of our AGNs, although some differences are present. Comparing our median SED to the Richards et al. (2006a) quasar SED, there is enhanced flux around 1–2 μm, which we attribute to host galaxy emission (see, e.g., Bongiorno et al. 2012). Furthermore, at shorter wavelengths, the spectral slope is redder. There is a significant population with much redder slopes than both the median SED of the FMOS sample and the Richards et al. (2006a) SED. A plausible explanation for this population is dust reddening within the host galaxy.

We define the reddened AGN population in the FMOS sample as deviating by more than 0.5 dex in their rest-frame UV to near-IR flux ratio from the Richards et al. (2006a) quasar SED, the typical dispersion observed in Richards et al. (2006a). Specifically, we use log(λF_λ(2500 Å)/λF_λ(2.5 μm)) < −0.3. We indicate this separation into normal blue AGNs and red AGNs in the lower panels of Figure 6 in blue and red, respectively. In SXDS, 27 of 87 AGNs are classified as red, while in COSMOS we identify 27 of 141 AGNs to have a red SED. In the small E-CDF-S sample, none of the objects are identified as a red AGN. The blue AGN population is consistent with a standard unreddened AGN SED within their typical dispersion, while the red AGN population is consistent with dust reddening by E(B − V) ≥ 0.1. We estimate the amount of reddening for each object by de-reddening their observed SEDs with an SMC-like dust extinction curve.
(Gordon et al. 2003)\textsuperscript{21} to match the median SED of the blue AGN population in the respective field, using $\chi^2$ minimization. We derive dust extinction values in the range $E(B - V) = 0.1-0.65$, which are listed in Table 2.

\textsuperscript{21} We also note that a steeper extinction curve has been suggested for a few luminous red QSOs (Zafar et al. 2015). Our results do not significantly depend on the specific choice of extinction law, thus we here adopt the most commonly used SMC extinction curve. A more detailed study of the extinction curve for AGNs is beyond the scope of this paper.

For the red AGN population, we correct the continuum and broad emission-line luminosities obtained from the spectral fits for dust reddening using the obtained $E(B - V)$ estimates. We verified that correcting the entire spectrum of each of the red AGNs does not affect the best-fit spectral parameters in a significant way. For H$\alpha$, the reddening correction has a moderate effect ($<0.5$ dex) on the line luminosity, but it can be up to more than 1 dex for $L_{3000}$. We note that the default black hole mass estimates and bolometric luminosities for the

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**Table 2**

Spectral Measurements for the FMOS H$\alpha$ and H$\beta$ Sample

| Column name | Format | Units | Description |
|-------------|--------|-------|-------------|
| Field       | String |       | Survey field |
| XID         | String |       | X-ray identifier in the format “survey_id” with survey in (CID,LID,SXDS,E-CDF-S) |
| XMM         | Int    |       | ID from XMM-COSMOS for COSMOS objects, X-ray ID otherwise |
| RAdeg       | Float  | deg   | Optical Right Ascension (J2000) |
| DeDeg       | Float  | deg   | Optical Declination (J2000) |
| z           | Float  |       | catalog redshift |
| zsys        | Float  |       | redshift measured from peak of lines in near-IR spectra |
| f_zsys      | String |       | line used for near-IR redshift measurement |
| imag        | Float  | mag   | $i$-band AB magnitude |
| Jmag        | Float  | mag   | $J$-band 3" aperture AB magnitude |
| Hmag        | Float  | mag   | $H$-band 3" aperture AB magnitude |
| E(B-V)      | Float  |       | $E(B-V)$ measured from peak of lines in near-IR spectra |
| logLx       | Float  | erg s$^{-1}$ | 2–10 keV rest-frame luminosity |
| E(B-V)ii    | Float  |       | estimated $E(B-V)$ due to intrinsic dust reddening |
| HaMode      | String |       | FMOS mode for H$\alpha$ |
| HaSN        | Float  |       | median continuum S/N per pixel around H$\alpha$ |
| HaLSN       | Float  |       | peak S/N of the H$\alpha$ line |
| logLHa      | Float  | erg s$^{-1}$ | broad H$\alpha$ line luminosity |
| logLHaDr    | Float  | erg s$^{-1}$ | reddening-corrected broad H$\alpha$ line luminosity |
| e_logLHa    | Float  | erg s$^{-1}$ | measurement error for broad H$\alpha$ line luminosity |
| FWHMHa      | Float  | km s$^{-1}$ | broad H$\alpha$ FWHM |
| e_FWHMHa    | Float  | km s$^{-1}$ | measurement error for broad H$\alpha$ FWHM |
| logMHa      | Float  | $M_\odot$ | SMBH mass estimated from H$\alpha$ |
| e_logMHa    | Float  | $M_\odot$ | measurement error for SMBH mass estimated from H$\alpha$ |
| logLbolHa   | Float  | erg s$^{-1}$ | bolometric luminosity estimated from H$\alpha$ |
| e_logLbolHa | Float  | erg s$^{-1}$ | measurement error for bolometric luminosity estimated from H$\alpha$ |
| logEddRHa   | Float  |       | Eddington ratio estimated from H$\alpha$ |
| e_logEddRHa | Float  |       | measurement error for Eddington ratio estimated from H$\alpha$ |
| HbMode      | String |       | FMOS mode for H$\beta$ |
| HbSN        | Float  |       | median continuum S/N per pixel around H$\beta$ |
| HbLSN       | Float  |       | peak S/N of the H$\beta$ line |
| logLO3      | Float  | erg s$^{-1}$ | [O III] line luminosity |
| e_logLO3    | Float  | erg s$^{-1}$ | measurement error for [O III] line luminosity |
| logLHb      | Float  | erg s$^{-1}$ | broad H$\beta$ line luminosity |
| logLHbdrl   | Float  | erg s$^{-1}$ | reddening-corrected broad H$\beta$ line luminosity |
| e_logLHb    | Float  | erg s$^{-1}$ | measurement error for broad H$\beta$ line luminosity |
| logL5100    | Float  | erg s$^{-1}$ | continuum luminosity at 5100 Angstrom |
| logL5100dr  | Float  | erg s$^{-1}$ | reddening-corrected continuum luminosity at 5100 Angstrom |
| logL5100cr  | Float  | erg s$^{-1}$ | continuum luminosity at 5100 Angstrom with average host correction and reddening correction |
| e_logL5100  | Float  | erg s$^{-1}$ | measurement error for continuum luminosity at 5100 Angstrom |
| FWHMHb      | Float  | km s$^{-1}$ | broad H$\beta$ FWHM |
| e_FWHMHb    | Float  | km s$^{-1}$ | measurement error for broad H$\beta$ FWHM |
| logMBhb     | Float  | $M_\odot$ | SMBH mass estimated from H$\beta$ |
| e_logMBhb   | Float  | $M_\odot$ | measurement error for SMBH mass estimated from H$\beta$ |
| logLbolHb   | Float  | erg s$^{-1}$ | bolometric luminosity estimated from H$\beta$ |
| e_logLbolHb | Float  | erg s$^{-1}$ | measurement error for bolometric luminosity estimated from H$\beta$ |
| logEddRHB   | Float  |       | Eddington ratio estimated from H$\beta$ |
| e_logEddRHB | Float  |       | measurement error for Eddington ratio estimated from H$\beta$ |

Note. Format for the sample properties and spectral measurements for the FMOS sample with either broad H$\alpha$ or H$\beta$ detection. In addition, we also make it available at the following link: http://member.ipmu.jp/fmos-cosmos/fmosBL.fits.

This table is available in its entirety in machine-readable form.
majority of our sample are based on Hα. For those AGNs where we measure a broad Hβ line, only three are classified as red AGNs. For these three objects, we do not apply a reddening correction for the narrow [O III] emission lines.

4. Results

4.1. Comparison of the Low- and High-resolution Modes of FMOS

For the COSMOS sample, we have obtained spectroscopy in both the LR and HR modes of FMOS. Although we will combine the samples from both campaigns further below, we carried out the spectral fitting independently on both subsamples. There are in total 39 AGNs in our COSMOS sample with observations in both modes. We are thus able to compare the emission-line and continuum measurements from these two independent observations with their different spectral resolutions. This provides an independent assessment of the measurement uncertainty of broad-line widths and luminosities.

In Figure 7, we show the comparison of the Hα and Hβ FWHMs, Hα luminosity $L_{\text{H}\alpha}$, continuum luminosity at 5100 Å $L_{5100}$, and the derived SMBH masses $M_{\text{BH}}$ obtained from the LR and HR spectra. For the $M_{\text{BH}}$ estimates, we use the relations as defined below, which are based on previous quantities, in Section 4.2. We indicate objects whose spectral fit is affected by poor data quality in one of the two spectra by open symbols. We see that the poor quality cases tend to be outliers in their broad-line FWHM and to a lesser extent also in $L_{\text{H}\alpha}$. For the higher quality cases, we find a generally good correlation between the LR and HR results. The continuum luminosity $L_{5100}$ naturally shows the best agreement, while the line fits have larger dispersion. For the FWHM, we find a standard deviation of 0.14 dex and 0.17 dex for Hα and Hβ, respectively. In particular for Hβ, the FWHM from the LR mode tends to be overestimated compared to the HR spectra, with a mean offset of $-0.08$ dex. These trends propagate to the SMBH mass estimates, which show an uncertainty of $\sim 0.35$ dex.

The scatter in the measured line properties originates in the ambiguities in the line fit for low-S/N data, including the contribution of a narrow component or choice of parametric model for the broad component, e.g., number of Gaussian components (Denney et al. 2009; Shen et al. 2011; Karouzos et al. 2015; Denney et al. 2016). We note that for the vast majority of our sources, the continuum S/N for at least one of the spectra is $< 5$. The dispersion we see in our sample is consistent with the expectation from previous studies for data of those S/N (Denney et al. 2009; Shen et al. 2011), which demonstrated that both the measurement scatter and systematic biases in the measurement will typically increase for spectra with continuum S/N $\lesssim 5$. Another inherent source of scatter for these moderate-luminosity AGNs is spectral variability (Woo et al. 2007; Denney et al. 2009). The work by Sánchez et al. (2017) studied the near-IR variability in the COSMOS field, finding $\sim 32\%$ of their broad-line AGNs to show variability in the J-band. For these, they report a structure function with a mean magnitude difference on a 1 yr timescale of $A = 0.13$ and power-law index $\gamma = 0.62$. For a typical time between the LR and HR observations of two to five years, this corresponds to an average variability of $0.08$–$0.14$ dex in luminosity and $0.02$–$0.03$ dex in FWHM. Thus, spectral variability is subdominant compared to the scatter due to data quality.

We conclude that we expect an average uncertainty on the black hole mass estimates from our sample of $\sim 0.3$–$0.35$ dex, due to data quality. This uncertainty adds in quadrature to the systemic uncertainty of $\sim 0.3$ dex for the virial method itself.

We combine the measurements from the LR and HR subsamples to build a merged COSMOS sample. In case both LR and HR spectra are available, we choose the best case based...
on the S/N of the spectrum and visual inspection of the two best-fit models.

4.2. Bolometric Luminosities, Black Hole Masses, and Eddington Ratios

We estimate black hole masses for our sample based on the virial method for broad-line AGNs (e.g., McLure & Dunlop 2004; Greene & Ho 2005; Vestergaard & Peterson 2006). While the virial method is only calibrated based on reverberation mapping campaigns for the broad H\(\beta\) line (Collin et al. 2006; Vestergaard & Peterson 2006), the broad Mg\(\text{II}\) and H\(\alpha\) lines are known to provide reliable black hole mass estimates, when calibrated using AGNs having H\(\beta\)-based black hole mass estimates (Greene & Ho 2005; Shen & Liu 2012; Trakhtenbrot & Netzer 2012; Mejía-Restrepo et al. 2016). Broad Mg\(\text{II}\) has the advantage that it can be observed in optical spectra out to higher redshift \(z \sim 2.3\) than H\(\beta\) and with near-IR spectroscopy out to \(z \sim 6\) (e.g., Kurk et al. 2007; Willott et al. 2010; De Rosa et al. 2011; Mazzucchelli et al. 2017). For our sample, the use of Mg\(\text{II}\) enables us to obtain black hole mass estimates for four AGNs at \(z > 2.8\), including our highest redshift source CID 781 at \(z = 4.64\).
A major advantage of broad Hα compared to Hβ is that it is considerably stronger, which makes it a powerful alternative not only for low-luminosity AGNs (Greene & Ho 2007; Dong et al. 2012; Reines et al. 2013), but also for low-S/N spectra, which is usually the case for near-IR spectroscopy. The latter is also realized for our FMOS sample, where the Hβ line is generally detected at low to moderate quality, making Hα the preferred MBH estimator for our sample. Furthermore, the Hα luminosity L_{Hα} is free of host galaxy contamination, contrary to the continuum luminosity L_{5100}. For some cases, an explicit comparison of both virial estimators is presented in Section 4.3.

We use Hβ to anchor our virial mass estimators, i.e., to ensure that the virial mass estimators for the other broad lines are consistently calibrated to this Hβ relation. We base our virial mass estimation on the relation for Hβ by Vestergaard & Peterson (2006), which is directly calibrated to reverberation mapping studies:

$$M_{\text{BH}}(H\beta) = 10^{6.91} \left( \frac{L_{5100}}{10^{44} \text{ erg s}^{-1}} \right)^{0.5} \left( \frac{\text{FWHM}}{1000 \text{ km s}^{-1}} \right)^2 M_\odot \quad (1)$$

At the moderate luminosities of our AGN sample, the host galaxy contamination in the continuum luminosity L_{5100} is not negligible. Shen et al. (2011) showed that host galaxy contamination becomes significant at log L_{5100} < 45 erg s^{-1}. We account for the host contribution in an average sense by applying the formula for the average host contamination given by Shen et al. (2011) in their Equation (1).

For Hα, we use the formula presented in Schulze et al. (2017).

$$M_{\text{BH}}(H\alpha) = 10^{6.71} \left( \frac{L_{H\alpha}}{10^{42} \text{ erg s}^{-1}} \right)^{0.48} \left( \frac{\text{FWHM}}{1000 \text{ km s}^{-1}} \right)^{2.12} M_\odot \quad (2)$$

This black hole mass relation is based on Equation (1) and uses empirical scaling relationships between Hα and Hβ FWHM, as well as between L_{H\alpha} and L_{5100} from Jun et al. (2015). Their work updates the commonly used relations from Greene & Ho (2005) and extends them over a wider luminosity range.

For Mg II, we use the relation from Shen et al. (2011), which is also tied to the virial estimator from Vestergaard & Peterson (2006; see also Trakhtenbrot & Netzer 2012):

$$M_{\text{BH}}(Mg\text{II}) = 10^{6.74} \left( \frac{L_{3000}}{10^{44} \text{ erg s}^{-1}} \right)^{0.62} \left( \frac{\text{FWHM}}{1000 \text{ km s}^{-1}} \right)^2 M_\odot \quad (3)$$

We base our estimate of the bolometric luminosity either on the continuum luminosities L_{5100} and L_{3000}, or on the luminosity of the broad Hα line L_{H\alpha}. The intrinsic bolometric luminosity is given by the integration over the X-ray, UV, and optical luminosities, i.e., by the contribution of the accretion disk and hot corona. The mid-IR emission should be excluded since it constitutes reprocessed UV-optical emission and would therefore lead to double-counting (e.g., Marconi et al. 2004).

For L_{5100}, we use a constant bolometric correction factor BC_{5100} = 7.0 (Netzer & Trakhtenbrot 2007), which is on average consistent with the luminosity-dependent bolometric correction of Marconi et al. (2004) and excludes reprocessed emission. For L_{3000}, we use the luminosity-dependent relation presented in Trakhtenbrot & Netzer (2012), inferred from the Marconi et al. (2004) bolometric correction (BC_{3000} = 4.12 at L_{3000} = 10^{45} \text{ erg s}^{-1}, the typical luminosity of our sample). To obtain a bolometric luminosity estimate from broad Hα, we combine the scaling relation to L_{5100} from Jun et al. (2015) and BC_{5100}, which gives

$$\log L_{\text{bol}} = 0.96(\log L_{H\alpha} - 42) + 44.23 \quad (4)$$

We explicitly test the validity of these bolometric luminosity indicators in Section 5.3.

The Eddington ratio is given by $\lambda_{\text{Edd}} = L_{\text{bol}}/L_{\text{Edd}}$, where $L_{\text{Edd}} \simeq 3 \times 10^{38}(M_{\text{BH}}/M_\odot)$ erg s^{-1} is the Eddington luminosity for the object, given its black hole mass. We show the distribution of our sample in the $M_{\text{BH}}$–$\lambda_{\text{Edd}}$ plane in Figure 8 for SMBH masses based on Hα, Hβ, and Mg II. In total for our sample, 211 objects have robust black hole masses based on Hα, 63 based on Hβ, and 4 based on Mg II. In particular, for Hα, we find a broad distribution in both black hole mass ($\log M_{\text{BH}} = [7.5, 9.5]$) and Eddington ratio ($\log \lambda_{\text{Edd}} = [-2.5, 0]$) with median values of $\log M_{\text{BH}} = 8.54$ and $\log \lambda_{\text{Edd}} = -1.11$ and a dispersion of 0.54 dex and 0.51 dex, respectively. This is consistent with previous results on moderate-luminosity AGNs in small-area deep fields (Gavignaud et al. 2008; Trump et al. 2009; Merloni et al. 2010; Schulze et al. 2015; Suh et al. 2015) and qualitatively agrees with the expectation from the underlying active black hole mass function (BHMF) and Eddington ratio distribution function.
(ERDF; N12, Schulze et al. 2015). Our Hβ SMBH mass sample is shifted toward higher luminosities and therefore on average higher \( M_{\text{BH}} \) and \( \lambda_{\text{Edd}} \). For this sample, we find median values of \( \log M_{\text{BH}} = 8.91 \) and \( \log \lambda_{\text{Edd}} = -0.90 \). This is because the Hβ mass sample extends to higher redshift \( z > 2 \), and furthermore, the detection of the weaker H3 line is only possible in the brighter subset of our sample at \( z > 1.2 \). The few MgII detections are of AGNs at even higher redshift \( z > 2.7 \) and, given the common flux limit, preferentially target the more massive black holes at higher accretion rates than the lower \( z \) samples, with median \( \log M_{\text{BH}} = 8.72 \) and \( \log \lambda_{\text{Edd}} = -0.50 \).

We see the consequence of the flux limit on our sample in the apparent lack of objects in the lower-left corner of the \( M_{\text{BH}} - \lambda_{\text{Edd}} \) plane, at low \( M_{\text{BH}} \) and low \( \lambda_{\text{Edd}} \). The absence of AGNs in our sample at high \( M_{\text{BH}} \) and high \( \lambda_{\text{Edd}} \) (upper-right corner) is caused by the rarity of these objects (Richards et al. 2006a; Kelly & Shen 2013; Schulze et al. 2015), which makes them effectively absent in the limited volume covered by COSMOS, SDSS, and E-CDF-S. They will be found in large area surveys like SDSS (e.g., McLure & Dunlop 2004; Vestergaard & Osmer 2009; Shen et al. 2011). We show, in addition, in Figure 8 a sample of such luminous broad-line AGNs at about the same redshift range with near-IR spectroscopy from Shen & Liu (2012, for Hα and Hβ) and Zuo et al. (2015, for MgII), targeted based on the SDSS quasar catalog (Schneider et al. 2010). They indeed fill in the area in the upper-right corner not populated by our relatively small area survey. Combining such samples of luminous quasars with our sample of moderate-luminosity broad-line AGNs provides a fairly complete coverage of the \( M_{\text{BH}} - \lambda_{\text{Edd}} \) plane, which enables us to study the properties of a representative sample of Type 1 AGNs. The addition of the moderate-luminosity AGN regime, located at the same redshift, is of special importance since it represents the bulk of the population.

### 4.3. Line Correlations

In this section, we investigate the correlations of FWHM and luminosity and a comparison of virial black hole mass estimators. A significant amount of work has been put into the empirical establishment of these correlations and the cross-calibration of the virial method for different broad lines (McGill et al. 2008; Wang et al. 2009; Assef et al. 2011; Ho et al. 2012; Shen & Liu 2012; Trakhtenbrot & Netzer 2012; Park et al. 2013; Jun et al. 2015; Mejía-Restrepo et al. 2016; Woo et al. 2018, M13). Our goal here is less to provide a new calibration, but rather to test the validity of current calibrations for our sample. Specifically, the lines we compare with each other are Hα, Hβ, and MgII. We will discuss correlations with the broad CIV line separately in Section 4.4, since the use of this line as a virial black hole mass estimator is still under debate.

In Figure 9, we show the relation between the Hα and Hβ FWHMs, luminosities, and \( M_{\text{BH}} \), and the \( L_{\text{Hα}} - L_{\text{Hβ}} \) relation. In addition to our FMOS sample, we show the sample of luminous quasistellar objects (QSOs) from Shen & Liu (2012), to cover a wide luminosity range. We compare these to established relations from the literature. For FWHM and \( L_{\text{Hα}} \), we use the empirical relation from Jun et al. (2015). These are based on a large compilation of measurements from the literature, augmented by their own measurements at the highest luminosities. They establish these relationships over a wide range in luminosity and are consistent with previous studies over their common luminosity range (Greene & Ho 2005; Shen & Liu 2012). Specifically, these are:

\[
\log \text{FWHM}_{\text{Hα},3} = 1.061 \log \text{FWHM}_{\text{Hα},3} + 0.055, \tag{5}
\]

\[
\log L_{\text{Hα},42} = 1.044 \log L_{5100,44} + 0.646. \tag{6}
\]

For the relationship between \( L_{\text{Hα}} \) and \( L_{\text{Hβ}} \) we assume as default relation a Balmer decrement of 3.1, as expected for Case B recombination. For the relation \( M_{\text{BH}}(\text{Hα} - \text{Hβ}) \) we assume a one-to-one relation. These default relations are shown by the black dashed line in Figure 9. We provide the mean and the standard deviation of our data around these relations in Table 3. Our data are fully consistent with the reference relationships, with a mean offset of less than 0.04 dex. We find for the FMOS sample that Hβ is on average broader than Hα by a factor of 1.34. This is consistent with previous studies, which focused on low-\( z \) AGNs (Osterbrock & Shuder 1982; Greene & Ho 2005; Shen et al. 2008; 22 We denote here the units FWHMH = \( 10^3 \) km s\(^{-1} \), \( L_{\text{Hα},42} = L_{\text{Hα}} / 10^{42} \) erg s\(^{-1} \), and so forth.)
are shown. In each panel, the black dashed line is for a reference relation as discussed in the text. The red dashed line is the best FMOS sample, and the blue solid line is the best relation.

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Figure 9. Comparison of the spectral measurements and derived black hole masses between Hα and Hβ for those AGNs with both lines detected in COSMOS (green squares) and SXDS (orange circles), supplemented by the luminous quasar sample of Shen & Liu (2012, gray circles). The correlations for FWHM, L_{Hα}–L_{5100}, L_{Hα}–L_{Hβ}, and M_{BH} are shown. In each panel, the black dashed line is for a reference relation as discussed in the text. The red dashed line is the best fit to the FMOS sample, and the blue solid line is the best fit to the combined sample from FMOS and Shen & Liu (2012). The black dotted line in the FWHM panel is the one-to-one relation.

Schulze & Wisotzki (2010). This indicates a slightly larger virial velocity for Hβ, which is emitted closer to the black hole. Since Hβ is emitted preferentially in regions of higher density and/or higher ionization parameter (Osterbrock & Ferland 2006), this is expected for an increasing density or ionization parameter in the BLR with decreasing radius.

In addition, we perform a linear regression on the line correlations. For consistency with the adopted reference relations by Jun et al. (2015), we here use the BCES method (Akritas & Bershady 1996; see also Nemmen et al. 2012), which accounts for measurement errors in both variables and for intrinsic scatter. We also tested the linmix.err method (Kelly 2007), finding consistent results. We use orthogonal regression, i.e., we do not specify a unique response variable but treat both symmetrically and derive errors via bootstrapping. We consider two cases: (1) only including our FMOS sample and (2) adding the luminous QSO sample from Shen & Liu (2012). The results are listed in Table 3 and shown in Figure 9 by the red dashed line and blue solid line, respectively. As previously mentioned, we find generally very good agreement between relations based on our data and those reported in the literature over the parameter range covered by our sample. For the L_{Hα}–L_{5100} correlation based only on the FMOS sample, we find a deviation at the luminous end where our best fit is extrapolated beyond the luminosity regime of our sample. Including the luminous SDSS QSO sample into the regression brings our best fit in good agreement with the reference relation over the full luminosity range (10^{43} < L_{Hα} < 10^{46} \text{ erg s}^{-1}). We conclude that in their Hα and Hβ properties, our AGNs are fully consistent with the general broad-line AGN population.

In Figure 10, we show the correlations of the FWHM, luminosity, and black hole mass for Hα and Hβ with Mg II for those that have Mg II measurements from optical spectroscopy. We base our reference relation for FWHM and luminosity again on the study by Jun et al. (2015), which reports

\[
\log \text{FWHM}_{Hβ,3} = 1.226 \log \text{FWHM}_{MgII,3} + 0.078, \quad (7)
\]

\[
\log L_{3000,44} = 0.973 \log L_{5100,44} + 0.287. \quad (8)
\]

The reference relation for Hα against Mg II is obtained by combining these with Equations (5) and (6). For M_{BH}, we again assume a one-to-one relation. Our FMOS sample is fully consistent with those reference relationships. We give their mean and dispersion around the reference relations in Table 3. Additionally, we provide the best-fit linear regression result based on a fit to the FMOS sample only, as well as to the combination of the FMOS sample with the high-luminosity QSO samples from Shen & Liu (2012) and Zuo et al. (2015). We find an excellent agreement with the reference relations.

Our sample of moderate-luminosity AGNs at high redshift is fully consistent with previous works, which mainly combined luminous high-z QSOs with moderate-luminosity low-z AGNs. We conclude that the relationship of Mg II with Balmer lines is fully consistent with the broad-line AGN population, typically observed at lower redshift.

\[
23 \text{ The sample by Zuo et al. (2015) is only used for Hβ versus Mg II as they do not observe Hα.}
\]
and Mg II. We also list the scatter around the best-fit relation as \( \sigma \) and the parameters for a reference relation as discussed in the text, and provide the mean and the standard deviation of our sample around this reference relation as \( \Delta X_{\text{ref}} \) and \( \sigma_{\text{ref}} \) respectively.

### 4.4. C IV Line Correlations

The broad C IV line is sometimes used as a virial black hole mass estimator, enabling black hole mass estimates at \( 2 < z < 5 \) from optical spectroscopy (e.g., Vestergaard 2004; Vestergaard & Osmer 2009; Shen et al. 2011; Kelly & Shen 2013). However, its reliability is questionable, since it is often severely affected by a non-virial component of the BLR gas (Baskin & Laor 2005a; Denney 2012; Trakhtenbrot & Netzer 2012; Coatman et al. 2017, and references therein). This potentially outflowing component is especially significant for the most luminous quasars observed at high redshift. However, the C IV line appears to be a more robust black hole mass estimator for local low-luminosity AGNs (Vestergaard & Peterson 2006; Tilton & Shull 2013). Therefore, it is worth reexamining the reliability of C IV as a virial black hole mass estimator especially for moderate-luminosity AGNs at high-\( z \).

For our FMOS sample in the COSMOS and SXDS fields, we obtain optical spectra from SDSS (Abazajian et al. 2009), BOSS (Alam et al. 2015), and zCOSMOS-Deep (Lilly et al. 2007). We measure the C IV line for 43 AGNs (25 in COSMOS and 18 in SXDS). We have excluded CID 346 here due to the presence of a strong C IV BAL, preventing a robust measurement of the intrinsic line profile. We tied the absolute flux calibration to the optical photometry from Subaru (Laigle et al. 2016; Mehta et al. 2018).

We fit the C IV spectral region following previous studies (e.g., Shen et al. 2011). For each spectrum, we first fit the local continuum by a power law. The broad C IV line is fit using up to three Gaussian components over the interval 1450–1700 Å. In addition, we allow for the inclusion of the He II \( \lambda 1640 \), O III] \( \lambda 1663 \), and N IV] \( \lambda 1486 \) lines, each modeled by a single broad Gaussian component, with a common line width and velocity shift (Fine et al. 2010; Trakhtenbrot & Netzer 2012). We manually mask out spectral regions affected by narrow absorption features, which can affect the line fit. We obtained the C IV FWHM and the continuum luminosity at 1350 Å, \( L_{1350} \), from the best-fit model and their uncertainties from Monte Carlo simulations, as we did for the other emission-line measurements (see Section 3.1). To estimate \( M_{\text{BH}} \), we use the virial relation for C IV of Vestergaard & Peterson (2006).

In Figure 11, we compare the FWHM and luminosity measurements and the \( M_{\text{BH}} \) estimates from C IV to those from the Balmer lines measured from the FMOS spectra. We again compare these with the relations given by Jun et al. (2015),

\[
\log \text{FWHM}_{\text{H}/\text{3}, \text{3}} = 1.054 \log \text{FWHM}_{\text{CIV}, \text{3}} + 0.024.
\]  

\[
\log L_{1350, \text{44}} = 0.974 \log L_{5100, \text{44}} + 0.391.
\]
Combining sample of FMOS and the two luminous quasar samples. The black dotted line in the FWHM panel is the one-to-one relation.

Circles spectra in COSMOS (green squares), SXDS (orange circles), and E-CDF-S (blue diamonds), augmented by the luminous quasar samples by Shen & Liu (2012, gray circles) and Zuo et al. (2015, pink diamonds). The black, red, and blue lines are for the reference relation, the best fit to the FMOS sample, and the best fit to the combined sample of FMOS and the two luminous quasar samples. The black dotted line in the FWHM panel is the one-to-one relation.

Figure 10. Comparison of spectral measurements and derived black hole masses between H$\alpha$/H$\beta$ and Mg II for those AGNs with Mg II measurements from optical spectra in COSMOS (green squares), SXDS (orange circles), and E-CDF-S (blue diamonds), augmented by the luminous quasar samples by Shen & Liu (2012, gray circles) and Zuo et al. (2015, pink diamonds). The black, red, and blue lines are for the reference relation, the best fit to the FMOS sample, and the best fit to the combined sample of FMOS and the two luminous quasar samples. The black dotted line in the FWHM panel is the one-to-one relation.

shown as the black dashed lines. Furthermore, we show the best-fit relation to the FMOS sample, combined with the luminous QSOs from Shen & Liu (2012) and Zuo et al. (2015), by the blue solid line. Their best-fit values are given in Table 3. The luminosity $L_{1350}$ shows a good correlation with both $L_{5100}$ and $L_{H\alpha}$, consistent with the reference relation given in Equation (10). The FWHM measurements show a large scatter between C IV and the Balmer lines, with $\sigma \sim 0.3$ dex. A Spearman rank-order test does not find a statistically significant correlation between the FWHM of C IV and the Balmer lines for our sample. Although measurement uncertainties due to the data quality of both the optical and near-IR spectra will have a significant contribution to this scatter, it is, however, clear that the C IV FWHM has a significantly weaker correlation with the FWHM of the Balmer lines than that of Mg II.

Under the assumption of virialized motion, we would expect FWHM(C IV) > FWHM(H$\alpha$ or H$\beta$). However, this is not seen in our sample, consistent with several previous studies (Trakhtenbrot & Netzer 2012 and references therein) and with the reference relation given by Equation (9). We find FWHM(C IV) < FWHM(H$\alpha$) for 50% (14/28) and FWHM (C IV) < FWHM(H$\beta$) for 60% (18/30) of our sources. As discussed in Trakhtenbrot & Netzer (2012), this suggest that C IV is not virialized, as is required for the application of the virial method. Thus, our results support the notion of C IV as a less reliable black hole mass estimator, differing from large uncertainties. This is confirmed by the direct comparison of the $M_{BH}$ estimates in the right panels of Figure 11. However, while there is a significant scatter of 0.43–0.48 dex in the $M_{BH}$ estimates, the combined sample from FMOS and the luminous QSOs on average is fully consistent with the one-to-one relation between $M_{BH}$(C IV) and the $M_{BH}$ estimate from the Balmer lines.

There have been several attempts to improve the reliability of C IV-based SMBH masses (Denney 2012; Park et al. 2013; Runnoe et al. 2013; Coatman et al. 2017). The study by Coatman et al. (2017) demonstrated a correlation between the FWHM ratio of C IV to the Balmer lines and the C IV blueshift for very luminous QSOs. They propose an improved C IV virial $M_{BH}$ estimator, including knowledge of the C IV blueshift (but see Mejía-Restrepo et al. 2018b for a contradictory argument). We here test if (1) our moderate-luminosity AGN sample follows the same correlation, and (2) if their improved $M_{BH}$ estimator also provides a significant improvement for these moderate-luminosity AGNs. The C IV blueshift for our FMOS sample is defined as the velocity offset of the peak of the C IV line, measured from the best fit, with respect to the near-IR redshift, as discussed in Section 3.1.

In the left panel of Figure 12, we plot the ratio $M_{BH}$(C IV)/$M_{BH}$(H$\alpha$ or H$\beta$) against the C IV blueshift. For comparison, we also show the luminous QSO sample from Coatman et al. (2017) as gray circles and their best-fit relation as the solid blue line. While our sample shows a larger scatter, it is consistent with the relation found by Coatman et al. (2017). However, we note that our moderate-luminosity AGN sample shows a narrower distribution of C IV blueshifts, largely lacking very strong blueshifts, with a median velocity shift of 820 km s$^{-1}$ compared to 1290 km s$^{-1}$. This can be understood as a consequence of the lower luminosities of the FMOS sample. Less luminous AGNs have on average higher C IV equivalent width (the well-known Baldwin effect; Baldwin 1977) and high C IV EW AGNs tend to show a lack of large blueshifts (Richards et al. 2011).
In the central and right panels of Figure 12, we show the comparison of the Balmer line $M_{\text{BH}}$ estimates to the C IV line $M_{\text{BH}}$ estimates based on Vestergaard & Peterson (2006) and based on the blueshift-based correction prescription from Coatman et al. (2017), respectively. We find that the Coatman et al. (2017) prescription provides an improvement on the C IV masses, with the dispersion around the one-to-one relation decreasing from 0.53 to 0.43 dex for the FMOS sample (while the mean offset changes from −0.09 to 0.06). However, this is less than the improvement from 0.4 to 0.2 dex found for the luminous QSOs in Coatman et al. (2017). We attribute at least part of this reduced effectiveness to the lack of large-blueshift AGNs ($>3000\,\text{km}\,\text{s}^{-1}$) in our moderate-luminosity AGN sample. For these objects, the improvement is most significant as illustrated in the left panel of Figure 12. However, we caution that the spectra for our sample are typically of lower quality in both the optical and NIR than those used in Coatman et al. (2017).

We conclude that moderate-luminosity AGNs follow a similar relation between their C IV and Balmer FWHM ratio and the C IV blueshift as luminous AGNs, but are lacking the highest blueshift objects as a consequence of the Baldwin effect. When we apply a correction to the virial formula using the C IV blueshift, this leads to an improvement of the $M_{\text{BH}}$ estimates. However, the deficit of high blueshift sources somewhat reduces the overall importance and effectiveness of such a correction for moderate-luminosity AGNs like those studied here, compared to the most luminous QSOs.

5. Discussion

5.1. The Virial Black Hole Mass Estimators

In the previous sections, we presented a comparison of broad-line and continuum measurements as well as the resulting black hole mass estimates for different AGN broad emission lines, commonly used for the virial method. Our FMOS study is unique in that it robustly tests these relationships and the reliability of current calibrations of the virial method for an unprecedentedly large sample of moderate-luminosity AGNs at high redshift, which is probing the bulk of the (unobscured) AGN population at the epoch of peak SMBH mass assembly. As shown in Section 4.3, the empirical relationships in FWHM and luminosity between H$\alpha$, H$\beta$, and Mg II hold for moderate-luminosity AGNs at $z \gtrsim 1$, consistent with previous works based on smaller samples (M13; Karouzos et al. 2015; Suh et al. 2015). Furthermore, the virial $M_{\text{BH}}$ estimators presented in Section 4.2 provide consistent results.

For the correlation between the H$\alpha$ and H$\beta$ $M_{\text{BH}}$, we find a scatter of $\sim0.3$ dex, which is similar to our estimate of the measurement uncertainty in Section 4.1 due to data quality. This confirms the good agreement between these two black hole mass estimators. Both lines provide statistically equivalent black hole mass estimates.

The $M_{\text{BH}}$ estimates based on Mg II show a larger scatter to the Balmer-line-based $M_{\text{BH}}$ of $\sim0.4$–$0.5$ dex, but no statistically significant offset when consistently calibrated virial relationships are used. Part of the increased scatter is caused by the non-simultaneous nature of the optical and near-IR spectra, i.e., the effect of AGN variability, and the typical rather low S/N in both of them. However, it has been shown in several studies that Mg II-based $M_{\text{BH}}$ show a larger scatter for Balmer line-based $M_{\text{BH}}$ than those among the Balmer line calibrations itself (e.g., Shen & Liu 2012; Mejia-Restrepo et al. 2016), which is qualitatively consistent with our results.

The $M_{\text{BH}}$ estimates based on C IV show a larger scatter than those based on Mg II, but also no statistically significant offset when using consistent local virial calibrations. This is
consistent with the common understanding that C IV-based $M_{BH}$ estimates bear large uncertainties. Correcting these $M_{BH}$ estimates by using C IV blueshifts, as suggested by Coatman et al. (2017), improves the agreement with the Balmer-line-based $M_{BH}$, leading to a comparable scatter as what we find for the Mg II-based $M_{BH}$. While higher S/N data would be needed to draw more robust conclusions, this seems to support the notion that it is possible to rehabilitate the use of C IV as a virial SMBH mass estimator (Runnoe et al. 2013; Mejía-Restrepo et al. 2016; Coatman et al. 2017).

Our results provide validation for the use of H$\alpha$, H$\beta$, and Mg II for moderate-luminosity AGNs out to high-z. However, we caution that the relative precision of these three black hole mass estimators does not inform us about their overall accuracy. The single-epoch method to estimate black hole masses is most likely prone to systematics, which are unaccounted for and are often hard to quantify (e.g., Shen 2013), including the inclination of the BLR toward our line of sight (Collin et al. 2006; Decarli et al. 2008; Mejía-Restrepo et al. 2018a), radiation pressure effects (Marconi et al. 2008; Netzer & Marziani 2010), etc. Larger samples of AGNs with $M_{BH}$ measurements complementary to virial $M_{BH}$ estimates are crucial to improve on the accuracy of the virial method as an effective means to infer the mass of an SMBH. This can include direct dynamical measurements (Onken et al. 2007), large-scale reverberation mapping campaigns (Peterson et al. 2004; Shen et al. 2015; Kollmeier et al. 2017), or accretion disk modeling (Capellupo et al. 2016).

5.2. Redshift and Luminosity Dependence of Rest-frame Optical Spectral Properties

Our sample enables us to disentangle redshift evolution and luminosity effects in the rest-frame optical spectra of broad-line AGNs. While moderate-luminosity AGNs are easily probed at low z, the space density of luminous quasars is too low to enclose a sizable sample of luminous quasars in the local volume. On the other hand, at z $>$ 1, luminous quasars are much more common and can easily be detected by large area surveys (Richards et al. 2006b), and their near-IR follow-up can be carried out at moderate-size telescopes. Observations of the rest-frame optical spectra of moderate-luminosity AGNs are more demanding and require 8 m class telescopes. This makes a one-to-one comparison of luminosity-matched samples at different redshifts often challenging.

Here, we compare the composite spectra for our moderate-luminosity AGN sample with a luminous AGN sample at comparable redshift and with a low-z AGN sample at matched luminosity. We stack the spectra of our FMOS sample with H$\alpha$ (211 AGNs) and H$\beta$ detection (63 AGNs) separately. For the luminous AGN comparison sample, we use the study by Shen & Liu (2012),$^{24}$ consisting of 60 quasars with H$\alpha$ and H$\beta$ coverage. For the low-z sample, we construct a luminosity-matched sample at z $<$ 0.84 (for H$\beta$) or z $<$ 0.35 (for H$\alpha$) from the SDSS DR7 quasar catalog (Schneider et al. 2010; Shen et al. 2011). For every FMOS AGN, we find the three closest luminosity matches in $L_{5100}$ (for H$\beta$) or in $L_{H\alpha}$ (for H$\alpha$). Each spectrum is shifted into rest frame (based on the near-IR redshift), rebinned to a common wavelength scale, and normalized at 5100 Å for the H$\beta$ stack and at 6400 Å for the H$\alpha$ stack. Stacked spectra are then generated using the median. Uncertainties are derived from bootstrapping the sample where we applied the Monte Carlo approach discussed in Section 3.1 to every bootstrapped object. In addition to generating a composite spectrum for the full FMOS sample, we also only use the HR spectra, in which case we maintain the higher resolution during the stacking process.

In the left panel of Figure 13, we show the composite spectra for the FMOS sample, compared to the luminous quasar sample from Shen & Liu (2012). For the H$\alpha$ line, the most prominent difference is the narrower width of the broad line. This is consistent with the FWHM$\alpha$ distribution of the two samples, with a median FWHM$\alpha$ of 3550 km s$^{-1}$ for the FMOS sample and 4233 km s$^{-1}$ for the luminous quasar sample. The latter value is mainly driven by the lack of FWHM$\alpha$ $<$ 2500 km s$^{-1}$ in the luminous quasar sample. This is a physical consequence of the Eddington limit, which is largely obeyed in both samples. A maximum $\lambda_{Edd}$ set by the Eddington limit translates into a minimum FWHM at a given luminosity, which, particularly for the most luminous quasars, restricts the possible range in FWHM. The broad H$\beta$ line does not show as pronounced a difference with median FWHM$\beta$ $\sim$ 5000 km s$^{-1}$ in both samples. This can be understood since the H$\beta$ FMOS sample has a higher average luminosity than the H$\alpha$ sample and thus the luminosity difference with the high-L comparison sample is smaller, as, for example, shown in Figure 8. We do see a

$^{24}$ The reduced spectra have been kindly made publicly available in Shen (2016).
stronger prominence of the narrow lines in the FMOS sample in both Hα and Hβ. The most prominent difference in the Hβ region is the strength and profile of [O III]. The moderate-luminosity sample from FMOS has a significantly larger [O III] equivalent width (EW) than the luminous quasar sample. This Baldwin-effect-type behavior of the [O III] EW is well known, especially at $z < 1$ (Stern & Laor 2013; Zhang et al. 2013; Shen & Ho 2014) and for luminous quasars at $z > 2$ (Netzer et al. 2004). Here, we extend the trend to significantly lower luminosities at $z > 1$. We also find evidence for a more prominent blue wing component of the [O III] line in the high-L composite, indicative of a higher strength and/or ubiquity of ionized outflows in luminous quasars, consistent with previous work (Shen & Ho 2014; Bischetti et al. 2017).

In the right panel of Figure 13, we show the comparison of our high-$z$ sample with the lower-$z$ match from the SDSS quasar catalog. For the Hβ region, we find the higher-$z$ sample to be fully consistent with the lower-$z$ matched sample. This indicates a significant redshift evolution in the average rest-frame optical properties of luminosity-matched AGNs, including broad Hβ, [O III], and Fe II. In the Hα region, we find a generally good agreement in the broad Hα shape, but when normalized in continuum luminosity, the FMOS sample shows weaker broad Hα. This corresponds to a lower broad Hα EW, consistent with the measurements from the individual fits, where we find median values of $EW_{\text{H}α} = 257$ and $374$ km s$^{-1}$ for the high-$z$ and low-$z$ samples, respectively. Potential reasons for this deviation are differences in the host galaxy contribution, sample selection effects (e.g., optical versus X-ray selection), or intrinsic redshift evolution effects.

5.3. Correlation of Bolometric and X-Ray Luminosity with Optical Luminosity Indicators

Knowledge of the bolometric luminosity of an AGN is fundamental to understand its current accretion and growth phase, energy output, and impact on its environment. However, in most cases, observations are only available at particular wavelengths, and the full SED is often difficult to assess. Thus, one typically has to rely on either optical emission-line or continuum luminosities or X-ray luminosities as bolometric luminosity indicators. In principle, the optical continuum luminosity traces the accretion disk emission most directly with scatter mainly caused by the variation of intrinsic SED shapes. However, the optical continuum luminosity can suffer from severe contamination by the host galaxy or extinction, or will be completely absorbed in the case of obscured AGNs. Alternative common bolometric luminosity indicators (especially for obscured AGNs) involve hard X-ray luminosity (e.g., Marconi et al. 2004; Vasudevan & Fabian 2009; Lusso et al. 2012) or [O III] luminosity (e.g, Heckman et al. 2004; Kauffmann & Heckman 2009; LaMassa et al. 2009; Pennell et al. 2017). Here, we compare several bolometric luminosity indicators for our sample. In addition, for part of the COSMOS sample, we incorporate bolometric luminosities presented in Lusso et al. (2012). They derived bolometric luminosities for AGNs detected within XMM-COSMOS by integrating the observed SED for Type 1 AGNs from 1 $\mu$m to 200 keV. In total, 95/141 FMOS AGNs in COSMOS with Hα or Hβ detection have an $L_{\text{bol}}$ measurement from Lusso et al. (2012). Our sample provides a unique opportunity to study several different bolometric luminosity indicators in relation to directly integrated $L_{\text{bol}}$ measurements for a homogeneous sample of AGNs at high-$z$.

In Figure 14, we compare measurements of $L_{\text{bol}}$, $L_{(2-10\text{keV})}$, $L_{(0.1-10\text{keV})}$, $L_{(\text{F}1000)}$, and $L_{\text{H}α}$ for our FMOS sample with each other. The latter three luminosities are obtained from the FMOS spectra as discussed above, the $L_{\text{bol}}$ for COSMOS AGNs is taken from Lusso et al. (2012), and $L_{(2-10\text{keV})}$ has been presented in Civano et al. (2016), Akiyama et al. (2015), and Xue et al. (2011) for COSMOS, SXDS, and E-CDF-S, respectively. We perform a linear regression using the BCES method for each luminosity comparison, shown by the blue dashed line and listed in Table 4. In addition, we show a relation taken from the literature for the specific luminosity comparison as a black solid line. We also inspected the flux–flux relation for each of the $L–L$ relations we consider here and performed a BCES regression for these. We confirmed that
none of the trends discussed here is seriously affected or driven by the $d_T^2$ term that goes into both axes in an $L-L$ plot.

The first row in Figure 14 provides the comparison between $L_{\text{bol}}$ and four common bolometric luminosity indicators. As expected, $L_{\text{bol}}$ has the best correlation, with a scatter of 0.19 dex. $L_{\text{H} \alpha}$ is also a good bolometric luminosity indicator for our sample, with a scatter of 0.27 dex. The black solid line in both panels shows the bolometric correction factors adopted in Section 4.2, i.e., based on BC5100 $\sim 7$. Our best fit is in good agreement with this assumption, verifying the average robustness of our derived $L_{\text{bol}}$ and $\lambda_{\text{edd}}$ for the remainder of the sample without a direct $L_{\text{bol}}$ measurement.

Both $L_{\text{O} III]$ and $L_{[2-10keV]}$ show a clear correlation with $L_{\text{bol}}$, but with considerably larger scatter (0.43 and 0.34 dex, respectively). However, we note that for the $L_{\text{O} III]$–$L_{\text{bol}}$ correlation, the sample size is small. The [O III] $\lambda 5007$ line is ionized by the extreme-UV part of the accretion disk emission and therefore can serve as an average bolometric luminosity indicator. However, the line strength is also strongly affected by the size and physical conditions in the narrow-line region (NLR) where it is emitted from, including its density, clumpiness, and the NLR covering factor (Baskin & Laor 2005b; Stern & Laor 2012). Furthermore, the emission line is sensitive to extinction by dust along the line of sight. A further source of scatter is the extended spatial scales of the NLR on which [O III] is emitted, compared to the central engine. Given the time variability of AGNs, $L_{\text{O} III]$ traces the time-averaged AGN luminosity over $>100$ years rather than the instantaneous luminosity. Furthermore, $L_{\text{O} III]}$ can suffer from contamination by star formation. All of these factors will contribute to the large scatter in the $L_{\text{O} III}$–$L_{\text{bol}}$ relation and make $L_{\text{O} III]}$

only an approximate bolometric luminosity indicator for individual objects.

We note that our best-fit $L_{\text{O} III]}$–$L_{\text{bol}}$ relation is consistent with a slope of unity and a bolometric correction of $L_{\text{bol}}/L_{\text{O} III]} = 2200$ (median value). This is somewhat lower than the commonly adopted value for the observed [O III] luminosity of $\sim 3500$ (Heckman et al. 2004) derived for local Type 1 AGNs via the correlation with $L_{\text{5000}}$ and the bolometric correction by Marconi et al. (2004). We show this value as the reference relation by the black solid line in the $L_{\text{O} III]}$–$L_{\text{bol}}$ panel. Pennell et al. (2017) found a similar average value of 3400 for their sample of Type 1 AGNs at $0.03 < z < 1.0$, based on directly integrated SEDs. But they also report a much

Figure 14. Correlation of various AGN luminosities against each other, namely $L_{\text{bol}}$, $L_{[2-10keV]}$, $L_{\text{O} III]}$, $L_{\text{5100}}$, and $L_{\text{H} \alpha}$. The color-coding for the FMOS subsamples is as in the previous figures. The best-fit relation to our data is shown as a blue dashed line, while the black solid line shows a reference relation, as discussed in the text. In the bottom row, we show the luminous quasar sample by Shen & Liu (2012) as gray circles and the local sample of SDSS DR7 quasars (Shen et al. 2011) by the gray contours. In the $L_{\text{O} III]}$–$L_{\text{bol}}$ panel, the black dotted line shows the expected relation assuming $L_{\text{bol}}/L_{\text{5100}} = 7$ and $L_{\text{5100}}/L_{\text{O} III]} = 320$. In the $L_{\text{O} III]}$–$L_{[2-10keV]}$ panel, the dotted magenta line indicates the relation from Ueda et al. (2015), and the magenta stars show the Type 1 AGNs in their sample.

Table 4

| Y       | X       | N | a        | b        | $\sigma$ |
|---------|---------|---|----------|----------|----------|
| $L_{\text{bol}}$ | $L_X$  | 95 | 1.22 ± 0.10 | 1.47 ± 0.04 | 0.34 |
| $L_{\text{bol}}$ | $L_{\text{O} III]}$ | 25 | 1.14 ± 0.20 | 3.41 ± 0.23 | 0.43 |
| $L_{\text{bol}}$ | $L_{\text{5100}}$ | 27 | 1.04 ± 0.08 | 0.83 ± 0.12 | 0.18 |
| $L_{\text{bol}}$ | $L_{\text{H} \alpha}$ | 82 | 0.96 ± 0.07 | 2.23 ± 0.05 | 0.26 |
| $L_X$  | $L_{\text{O} III]}$ | 60 | 0.81 ± 0.16 | 1.35 ± 0.20 | 0.32 |
| $L_X$  | $L_{\text{5100}}$ | 63 | 0.66 ± 0.17 | −0.41 ± 0.21 | 0.32 |
| $L_X$  | $L_{\text{H} \alpha}$ | 204 | 0.96 ± 0.08 | 0.71 ± 0.06 | 0.35 |
| $L_{\text{O} III]}$ | $L_{\text{5100}}$ | 119 | 0.96 ± 0.08 | −2.45 ± 0.15 | 0.44 |
| $L_{\text{O} III]}$ | $L_{\text{H} \alpha}$ | 93 | 0.88 ± 0.07 | −1.27 ± 0.06 | 0.41 |
| $L_{\text{5100}}$ | $L_{\text{H} \alpha}$ | 93 | 0.93 ± 0.03 | 1.26 ± 0.02 | 0.13 |

Note. BCES orthogonal best fit to the relation $\log Y = a(\log X - 44) + b + 44$. The correlations between $L_{\text{H} \alpha}$, $L_{\text{5100}}$, and $L_{\text{O} III]}$ include the sample of luminous quasars by Shen & Liu (2012).
flatter slope of 0.56, derived over a similar luminosity range to that in our study. On the other hand, we find that the value \( L_{5100}/L_{\text{O III}} \approx 320 \) given in Heckman et al. (2004), shown as a black solid line in the \( L_{5100}^{-}\) panel in Figure 14, is in perfect agreement with our best-fit relation to the combined FMOS and Shen & Liu (2012) sample. We thus suspect that the difference stems from their assumed bolometric correction \( BC_{5100} = 10.9 \) compared to the \( BC_{5000} = 7 \) adopted in this work. Using the latter value would lead to \( L_{\text{bol}}/L_{\text{O III}} = 2240 \) (shown as dotted line in Figure 14), in good agreement with our result. Given the good agreement of our adopted value for \( BC_{5000} \) with the bolometric luminosities from Lusso et al. (2012), we recommend a value of \( L_{\text{bol}}/L_{\text{O III}} \approx 2200 \) or the relation given in Table 4 for the bolometric correction of \( L_{\text{O III}} \) if these luminosities are not corrected for intrinsic extinction. We note that while we find a clear correlation of \( L_{\text{O III}} \) with both \( L_{5100} \) and \( L_{\text{H}\alpha} \), the scatter is increased compared to the correlation with \( L_{\text{bol}} \) (see Table 4). While the samples and sample sizes are different, this might indicate that the \( L_{\text{O III}}^{-}\) relation is in fact the most fundamental of these, and the latter two arise as secondary correlations via \( L_{\text{bol}} \). Interestingly, the \( L_{5100}^{-}\) relation shows the largest scatter among our correlations, even though both quantities are measured from the same observation, i.e., they suffer the least from potential systematics.

We now move our discussion to the correlations with the hard X-ray luminosity \( L_{[2-10\text{keV}]} \). The X-ray emission is emitted much closer to the central black hole than the narrow emission lines. The UV photons emitted from the accretion disk are inverse Compton scattered in a plasma of hot electrons known as the corona to X-ray energies. Assuming a universal physical relation between the disk emission and the reprocessed X-ray emission from the hot corona, a tight correlation between bolometric luminosity (or UV luminosity) and X-ray luminosity would be expected. Indeed, such a correlation has been observed and is well studied both for the bolometric luminosity (e.g., Vasudevan & Fabian 2009; Lusso et al. 2012) and for the UV luminosity (e.g., Steffen et al. 2006; Young et al. 2010; Lusso & Risaliti 2016), although with a typical dispersion of 0.35–0.4 dex. We confirm the correlation of \( L_{\text{bol}} \) with the intrinsic \( L_{[2-10\text{keV}]} \) for our sample, at a dispersion of 0.34 dex. Our data are in good agreement with the commonly adopted luminosity-dependent bolometric correlation by Marconi et al. (2004), shown as a black solid line in the \( L_{[2-10\text{keV}]}^{-}\) panel in Figure 14. Our best-fit relation is in perfect agreement with Marconi et al. (2004) at lower luminosities (\( L_{[2-10\text{keV}]} \approx 10^{48} \)), but slightly deviates at the higher luminosity range (\( L_{[2-10\text{keV}]} \approx 10^{49} \)).

The second row in Figure 14 shows the correlation of \( L_{[2-10\text{keV}]} \) with the optical luminosity indicators. While a significant correlation is present in each case, all of the correlations of the optical luminosity indicators with \( L_{[2-10\text{keV}]} \) show significant scatter. For the reference relations shown as black lines in each panel, we adopt the Marconi et al. (2004) bolometric correction and \( BC_{5100} = 7 \). For \( L_{\text{H}\alpha} \), we fold in Equation (6) and for \( L_{\text{O III}} \), we use \( L_{5100}/L_{\text{O III}} = 320 \). For \( L_{5100} \), we find our best-fit relation in good agreement with the reference relation over the luminosity range covered, but slightly steeper when extrapolated beyond that. For \( L_{\text{H}\alpha} \), our best-fit relation is also in fair agreement with the reference over the luminosity range for the bulk of our sample, but in general it is considerably steeper. It is consistent with unity, rather than the flatter relation predicted by propagating through the luminosity correlations discussed above. Robustly testing the validity of the reference relation requires extending the dynamical range in the luminosity of the sample, but is beyond of the scope of the current work.

For \( L_{[2-10\text{keV}]}^{-}\), our best fit is in excellent agreement with the adopted reference relation. In addition, we show the empirical relation by Ueda et al. (2015) as the magenta dotted line (their best-fit relation for Type 1 AGNs, i.e., \( N_{\text{H}} = 10^{22} \text{cm}^{-2} \), and uncorrected \( L_{\text{O III}} \) and their Type 1 AGN subsample as magenta stars. This relation has been established for low-redshift hard X-ray (\( >10\text{keV} \)) selected AGNs from the Swift BAT All-Sky survey (see also Berney et al. 2015). While their best-fit relation is in excellent agreement with both our best-fit and our adopted reference relation at low luminosities, it significantly deviates at high luminosities. However, the average log \( L_{[2-10\text{keV}]} \) of their Type 1 subsample is 43.36, significantly fainter than our FMOS sample. Thus, the apparent disagreement at high luminosities is caused by the extrapolation of their best fit beyond the main luminosity range of their sample. Indeed, the data points of the Swift BAT Type 1 subsample are fully consistent with our sample. We therefore advocate the use of our best fit for the \( L_{[2-10\text{keV}]}^{-}\) relation for Type 1 AGNs with uncorrected \( L_{\text{O III}} \), especially at high luminosities, and caution against extrapolating the regression lines by Ueda et al. (2015) to high luminosities.

We confirm the presence of a nonlinear correlation between \( L_{[2-10\text{keV}]} \) and \( L_{\text{O III}} \) suggested by Ueda et al. (2015) for Swift BAT also for the FMOS sample studied here, though with an even flatter slope than found in their study. We argue that the observed nonlinearity is fully consistent with the luminosity dependence of the \( L_{[2-10\text{keV}]} \) bolometric correction, and thus with the luminosity dependence of the number of X-ray photons to the number of ionizing UV photons emitted by the AGNs, as demonstrated by the good agreement with the reference relation that only assumes the luminosity-dependent bolometric correction by Marconi et al. (2004) and constant scale factors to \( L_{5100} \) and then to \( L_{\text{O III}} \).

For our sample, we find the scatter in the \( L_{[2-10\text{keV}]}^{-}\) relation to be comparable to or even smaller than that in the relation of \( L_{[2-10\text{keV}]} \) with \( L_{5100} \) and \( L_{\text{H}\alpha} \) and even smaller than that in the correlation with \( L_{\text{bol}} \). Given the much larger scatter of \( \sim 0.5–0.6 \text{dex} \) found for local AGNs (Heckman et al. 2005; Berney et al. 2015; Ueda et al. 2015), it is not clear if this indicates a tighter physical correlation or is due to sample selection effects. Given the considerable scatter of both \( L_{[2-10\text{keV}]} \) and \( L_{\text{O III}} \) with \( L_{\text{bol}} \) and the assumption that the physical origin of the scatter for both luminosities are uncorrelated, given the very different spatial scales and physical conditions of their respective emission regions, the comparatively small scatter we find in the \( L_{[2-10\text{keV}]}^{-}\) relation is at least somewhat surprising.

We conclude that we find a consistent set of correlations for various bolometric luminosity indicators for our data set when tied to the bolometric corrections given by Marconi et al. (2004), folding in optical luminosity correlations established at lower redshift. We emphasize that we find this good agreement with a few simple assumptions, established independently from our data set at low redshift, namely the bolometric correction from \( L_{[2-10\text{keV}]} \) to \( L_{\text{bol}} \) from Marconi et al. (2004), a bolometric correction to optical continuum luminosity \( L_{\text{bol}}/L_{5100} = 7 \), a
ratio $L_{3100}/L_{[O~III]} = 320$, and a correlation between $L_{5100}$ and $L_{[O~III]}$, given by Equation (6). This indicates that the basic physics that govern these relationships did not drastically change between $z \sim 2$ and $z \sim 0$.

5.4. Black Hole Growth at $z \gtrsim 3$

In this section, we focus on the small but interesting subsample of moderate-luminosity AGNs at $z \gtrsim 3$ for which we detect a broad Mg II line. In total, we obtained Mg II-based $M_{BH}$ for four AGNs, including our highest-$z$ source CID 781 at $z = 4.64$. We list their properties and spectral measurements in Table 5. In Figure 15, we show their distribution in $L_{bol}$, $M_{BH}$, and $E_{edd}$, as a function of redshift, together with samples from the literature at $z > 2.5$ with reliable black hole mass estimates from either Mg II or H/β. These include samples of luminous QSOs at $z \sim 3.5$ (Shemmer et al. 2004; Netzer et al. 2007; Zuo et al. 2015), $z \sim 4.8$ (Iwamuro et al. 2002; Trakhtenbrot et al. 2011), and $z \sim 6.2$ (Willott et al. 2010; De Rosa et al. 2011; Wu et al. 2015; Mazzucchelli et al. 2017), as well as of moderate-luminosity AGNs at $z \sim 3.5$ in COSMOS from Trakhtenbrot et al. (2016). We note that one AGN in our sample (CID 113) is also included in the latter study. While we observe Mg II in the J-band, Trakhtenbrot et al. (2016) measured $M_{BH}$ from the broad H/β observed in the K-band. Our $M_{BH}$ estimate of $10^{8.1} M_\odot$ is consistent with their H/β-based $M_{BH}$ estimate of $10^{8.78} M_\odot$ within the uncertainties of the virial method.

Our three AGNs at $z \sim 3$ fall in a parameter space similar to that in previous studies (Netzer et al. 2007; Trakhtenbrot et al. 2016). CID 781, on the other hand, occupies a luminosity regime that has not yet been probed at $z \sim 4.7$, being >0.5 dex fainter than previous near-IR studies (Trakhtenbrot et al. 2011). Its black hole mass, of about $10^8 M_\odot$, is at the low end of the currently probed $M_{BH}$ distribution and about 1 dex below the

Figure 15. Overview of the distribution of $L_{bol}$ (upper panel), $M_{BH}$ (middle panel), and $E_{edd}$ (lower panel) for near-IR observations of broad-line AGN samples at $2.7 < z < 7.1$. The four FOSM AGNs are marked as large red circles. The red dashed line shows their potential growth path predicted for the toy model discussed in the text. The other symbols represent samples from the literature with reliable $M_{BH}$ estimates based on either H/β or Mg II. At $z \sim 3.5$, these are the AGNs from Shemmer et al. (2004), Netzer et al. (2007, blue squares), Zuo et al. (2015, pink diamonds), and Trakhtenbrot et al. (2016, olive triangles). At $z \sim 4.8$, these are the AGN samples from Trakhtenbrot et al. (2011, cyan squares) and De Rosa et al. (2011, gold triangles), based on Iwamuro et al. (2002), and at $z \sim 6$, again from De Rosa et al. (2011, gold triangles), Willott et al. (2010, green downward triangles), Wu et al. (2015, magenta circle), and Mazzucchelli et al. (2017, brown squares). The horizontal dashed line in the lower panel indicates the Eddington limit.

Table 5
Spectral Measurements for the FOSM Mg II Sample

| Name      | CID 113     | CID 343     | CID 3576    | CID 781    |
|-----------|-------------|-------------|-------------|------------|
| ID I09    | 1463661     | 797841      | 632431      | 1226535    |
| ID XMM    | 180         | 146         | 5023        |            |
| RA (J2000) | 150.209     | 149.910     | 149.650     | 150.101    |
| DEC (J2000)| 2.482       | 2.081       | 1.866       | 2.419      |
| $z_{cut}$ | 3.333       | 2.802       | 2.935       | 4.660      |
| $z_{SNR}$ | 3.358       | 2.809       | 2.936       | 4.643      |
| i mag     | 20.220      | 20.280      | 19.730      | 22.600     |
| H mag     | 19.592      | 19.458      | 19.069      | 21.236     |
| J mag     | 19.484      | 19.545      | 19.142      | 21.892     |
| log $L_{bol}$ | 44.374   | 44.307      | 44.330      | 44.345     |
| S/NMgII   | 11.582      | 3.237       | 6.082       | 0.789      |
| S/NMgII,t  | 7.889       | 3.732       | 4.980       | 3.768      |
| log $L_{bol}$ | 44.031±0.020 | 44.048±0.056 | 43.981±0.042 | 43.857±0.068 |
| $FWHM_{MgII}$ | 3437±011 | 3422±568    | 1745±249    | 1929±295   |
| log $L_{[O~III]}$ | 46.061±011 | 46.011±032 | 45.919±036 | 45.377±0138 |
| log $M_{BH}$ | 9.090±056  | 9.055±0150  | 8.413±0134  | 8.164±0157  |
| log $L_{bol}$ | 46.565±012 | 46.517±032 | 46.428±036 | 45.926±0138 |
| log $E_{edd}$ | -0.635±055 | -0.648±0146 | -0.095±0134 | -0.348±0149 |
| $t_{growth}$ [Myr] | 224.6 | 230.2 | 56.3 | 95.0 |
| $t_{growth}/t_{lim}$ | 1.97 | 1.011 | 0.260 | 0.754 |

Note. Sample properties and spectral measurements for the four AGNs at $z > 2.7$ with a broad Mg II detection. All of them have been observed in COSMOS in the LR mode. ID I09 is the optical counterpart ID in the catalog of Ilbert et al. (2009), ID XMM is the ID in XMM-COSMOS, and $z_{cut}$ and $z_{SNR}$ denote the redshift reported in Marchesi et al. (2016) and as measured from the Mg II.
typical masses of more luminous quasars at the same redshift. The Eddington ratio, however, is similar to more luminous quasars at high-$z$. It can serve as an interesting analog to low-luminosity quasars recently discovered in large numbers at $z \gtrsim 6$ by HSC-SSP (Matsuoka et al. 2016, 2018a, 2018b).

We note that all of our high-$z$ AGNs have fairly high $\lambda_{\text{Edd}}$ ($\log \lambda_{\text{Edd}} > -0.7$), while our survey would be sensitive to detect lower $\lambda_{\text{Edd}}$ objects with $M_{\text{BH}} > 10^5 M_\odot$. This is consistent with the results from Trakhtenbrot et al. (2016) and with observations for $z \gtrsim 6$ quasars (e.g., Willott et al. 2010), although rare cases with low $\lambda_{\text{Edd}}$ have also been discovered at these redshifts (Trakhtenbrot et al. 2015; Kim et al. 2018). This might indicate on average higher $\lambda_{\text{Edd}}$ for the $z \gtrsim 3$ AGN population than what is found at lower redshift (Schulze et al. 2015), i.e., a redshift evolution in the shape of the ERDF. Robustly confirming this suggestion requires a full determination of the underlying active BHMF and ERDF at $z \gtrsim 3$, based on black hole mass estimates for a well-defined AGN sample (Schulze et al. 2018, in preparation).

We next use our $z \gtrsim 3$ AGN sample to evaluate their constraints on the black hole growth in the early universe. While black hole growth is most likely a stochastic process with significant variation in their accretion rates over timescales of $>10^5$ yr (e.g., Novak et al. 2011; Schawinski et al. 2015), we here explore a simplified growth model in which we assume accretion at a constant Eddington ratio and with constant radiative efficiency (e.g., Salpeter 1964; Trakhtenbrot et al. 2011). This case corresponds to an exponential growth with an $e$-folding time of

$$\tau = 4 \times 10^8 \frac{\eta}{\lambda_{\text{Edd}}(1 - \eta)} \text{yr},$$

and a growth time of $t_{\text{growth}} = \tau \ln \left( \frac{M_{\text{BH}}}{M_{\text{seed}}} \right)$. For simplicity, we here assume $\eta = 0.1$, $M_{\text{seed}} = 10^4 M_\odot$, and constant accretion at the measured $\lambda_{\text{Edd}}$, consistent with previous studies (Netzer & Trakhtenbrot 2007; Trakhtenbrot et al. 2011). We show the growth path for our $z \gtrsim 3$ AGNs under this simplified scenario as red dashed lines in Figure 15 and provide the growth times in Gyr and normalized by the age of the universe at the respective $z$ in Table 5. Their currently high $\lambda_{\text{Edd}}$ correspond to $e$-folding timescales of 56–230 Myr. For the two higher $\lambda_{\text{Edd}}$ sources, CID 781 and CID 3576, these timescales are fast enough to allow the SMBHs to grow to their current masses under our simplistic scenario. For the other two, CID 113 and CID 343, their inferred growth times are around or slightly exceed the age of the universe at their redshift. This suggests that they most likely have been growing at a higher rate at least for some fraction of the time, since we made the optimistic assumption of continuous growth, i.e., a duty cycle of unity. Alternative solutions involve a higher seed black hole mass or a lower radiative efficiency as assumed here. We conclude that with our sample we are probing a more typical $M_{\text{BH}}$ regime, $10^8 - 10^9 M_\odot$, in an evolutionary phase of fast growth at $z \gtrsim 3$.

6. Conclusions

We present near-IR spectroscopy in the J- and H-bands for a large sample of 243 X-ray-selected moderate-luminosity Type 1 AGNs in the extragalactic survey fields of COSMOS, SXDS, and E-CDF-S using the multi-object spectrograph Subaru/FMOS. Our sample covers the redshift range $0.5 < z < 4.7$ (with the vast majority at $z < 2.6$) over an X-ray luminosity range of $10^{43} \lesssim L_{2-10\text{keV}} \lesssim 10^{45}$ erg s$^{-1}$. Broad H$\alpha$ is detected in 211 AGNs, broad H$\beta$ in 63, and Mg II is covered in the FMOS spectra in four AGNs at $z > 2.7$. We fit parametric models to the near-IR spectra, measure line widths and line and continuum luminosities, and estimate black hole masses for our targets. We supplement these with Mg II and C IV measurements from optical spectra and compare line widths, luminosities, and black hole mass estimates using different broad emission lines. In addition, we generate composite spectra for our FMOS sample and compare them with composite spectra of more luminous AGNs at similar redshift and with low-$z$ AGNs at matched luminosity. Our main results are the following.

1. We provide a catalog of estimates of $M_{\text{BH}}$, $L_{\text{bol}}$, and $\lambda_{\text{Edd}}$ for a sample of 243 AGNs in the deep fields COSMOS, SXDS, and E-CDF-S, with their rich multwavelength coverage. Our results enhance the legacy value of AGN studies in these fields and enable future studies on SMBH–galaxy coevolution, AGN physics, and others. We make the catalog available online.\textsuperscript{25}

2. We confirm the validity of several correlations from the literature between broad-line FWHM, broad-line luminosity, and continuum luminosity between H$\alpha$, H$\beta$, Mg II, and C IV for our data set.

3. We show that black hole mass estimates from H$\alpha$, H$\beta$, and Mg II are unbiased and consistent with each other on average for our moderate-luminosity AGN sample when consistently calibrated virial mass formulas are used. There is a non-negligible amount of scatter between our $M_{\text{BH}}$ estimates from different lines, due to a combination of limited data quality and intrinsic effects.

4. For the C IV line, we find a considerable scatter in the comparison of their FWHMs to those from H$\alpha$ and H$\beta$ and consequently also in the C IV-based $M_{\text{BH}}$ estimates, confirming the large uncertainties associated with using C IV as a virial $M_{\text{BH}}$ estimator. Using a correction based on the C IV blueshift leads to an improvement in the $M_{\text{BH}}$ estimates, but for our moderate-luminosity AGN sample, such a correction is less important than for more luminous AGNs.

5. We find differences in the composite spectra between our moderate-luminosity sample and a high-luminosity sample, in line with expectations given their different bolometric luminosities, $M_{\text{BH}}$, and $\lambda_{\text{Edd}}$. We also directly confirm the presence of a Baldwin-effect-like trend in the [O III] line at $z > 1$ and an enhanced prominence of ionized outflow indications in luminous AGNs compared to our moderate-luminosity AGN sample. Comparison with a lower redshift, luminosity-matched sample shows good agreement for the H$\beta$ region, but we find on average lower H$\alpha$ EW in the higher-$z$ FMOS sample.

6. The observed luminosity correlations between $L_{\text{bol}}$, $L_{2-10\text{keV}}$, $L_{\text{O III} \lambda 5007}$, $L_{\text{5100}}$, and $L_{\text{H}$ all with each other are consistent with a simple empirical model based on the $L_{\text{bol}} - L_{2-10\text{keV}}$ bolometric correction by Marconi et al. (2004), $L_{\text{bol}}/L_{\text{5100}} = 7$, $L_{\text{5100}}/L_{\text{O III} \lambda 5007} = 320$, and a correlation between $L_{\text{5100}}$ and $L_{\text{H}_\alpha}$ given by Equation (6).

7. We have detected broad Mg II in CID 781, a moderate-luminosity AGN at $z \sim 4.6$, and three additional AGNs at

\textsuperscript{25} http://member.ipmu.jp/fmos-cosmos/fmosBL_fits
z ∼ 3. CID 781 occupies a luminosity regime not yet probed before at z > 4 with near-IR spectroscopy. Its current growth rate is fast enough to allow growth to its current mass from a $10^4 M_\odot$ seed black hole. For the z ∼ 3 objects, two-thirds require growth at a faster rate than suggested by their current accretion rate at least over some periods in their past.

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Software: NumPy, SciPy, AstroPy (The Astropy Collaboration et al. 2018), Matplotlib (Hunter 2007), pymsphot (STScI Development Team 2013), TOPCAT (Taylor 2005), MPFIT (Markwardt 2009).

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