Can we improve C IV-based single epoch black hole mass estimations?

J. E. Mejía-Restrepo,1,2* B. Trakhtenbrot,3 † P. Lira1 and H. Netzer4

1 Departamento de Astronomía, Universidad de Chile, Camino el Observatorio 1515, Santiago, Chile
2 European Southern Observatory, Casilla 19001, Santiago 19, Chile
3 Department of Physics, ETH Zurich, Wolfgang-Pauli-Straße 27, CH-8093 Zurich, Switzerland
4 School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel

4 May 2018

ABSTRACT
In large optical surveys at high redshifts (z > 2), the C IV λ1549 broad emission line is the most practical alternative to estimate the mass (MBH) of active super-massive black holes (SMBHs). However, mass determinations obtained with this line are known to be highly uncertain. In this work we use the Sloan Digital Sky Survey Data Release 7 and 12 quasar catalogues to statistically test three alternative methods put forward in the literature to improve C IV-based MBH estimations. These methods are constructed from correlations between the ratio of the C IV λ1549 line-width to the low ionization line-widths (Hα, Hβ and Mg II λ2798) and several other properties of rest-frame UV emission lines. Our analysis suggests that these correction methods are of limited applicability, mostly because all of them depend on correlations that are driven by the linewidth of the C IV profile itself and not by an interconnection between the linewidth of the C IV line with the linewidth of the low ionization lines. Our results show that optical C IV-based mass estimates at high redshift cannot be a proper replacement for estimates based on IR spectroscopy of low ionization lines like Hα, Hβ and Mg II.

Key words: galaxies: active quasars:general quasars:supermassive black holes quasars: emission lines

1 INTRODUCTION
Accurate determinations of super-massive black hole masses (MBH) are essential to fully understand SMBH the physics, demographics, and relations with galaxies. The single epoch (SE) black hole mass estimation method is commonly used on large samples of unobscured, type-I active galactic nuclei (AGN; McLure & Dunlop 2004; Onken & Kollmeier 2008; Shen et al. 2008; Fine et al. 2010; Rafiee & Hall 2011; Trakhtenbrot & Netzer 2012). This method relies on two basic ingredients: (1) the assumption of virialized gas kinematics in the broad line region (BLR) and (2) the empirical relation from reverberation mapping (RM) experiments between the BLR size (RBLR) and the continuum luminosity (Lα ≡ λL(λ)) at a particular wavelength (λ) where RBLR ∝ (Lα)α with α ∼ 0.5 − 0.7 (Kaspi et al. 2000, 2005; Bentz et al. 2009; Park et al. 2012; Bentz et al. 2013).

Under these assumptions the width of the broad emission lines, such as the full width at half maximum (FWHM), is a good proxy for the virial velocity of the BLR clouds. MBH can thus be expressed as:

\[ MBH = fG^{-1}R_{BLR}\alpha^{2}FWHM^2 \]  

(1)

Here G is the gravitational constant, f is a geometrical factor that accounts for the unknown structure and inclination to the line of sight of the BLR. In this paper, we assume f = 1, which is an appropriate median value for MBH estimates using the FWHM (Woo et al. 2015). However, there is a large uncertainty in this value (of at least a factor of 2; e.g. Onken et al. 2004; Woo et al. 2013; Shankar et al. 2016; Batiste et al. 2017) that can be even larger if f depends on luminosity and/or other line properties (e.g. equivalent widths, line offsets, FWHM; Collin et al. 2006; Shen 2013; Mejía-Restrepo et al. 2017).

The most reliable RM-based RBLR − L relation is the RBLR (Hβ) − L5100 relation. This relation is the only one that has been established for a large number of sources and covering a broad luminosity range (10^{43} erg s^{-1} < L_{5100} < 10^{46} erg s^{-1}). Consequently, SE MBH calibrations for other lines are often re-calibrated to match MBH measurements based on Hβ and L_{5100}. Such recalibrations are used to determine MBH values at different redshifts where the Hβ is not available due to observational limitations. In optical surveys, the Hα and Hβ lines can be used up to z ≲ 0.8 (e.g. Greene & Ho 2005; Netzer & Trakhtenbrot 2007; Xiao et al. 2017).
2 J. E. Mejía-Restrepo et al.

2011; Shen & Liu 2012), the Mg II $\lambda 2798$ (hereafter Mg ii) can assist for $M_{BH}$ on sources where $0.6 \lesssim z \lesssim 2.2$ (e.g., McLure & Jarvis 2002; Vestergaard & Osmer 2009; Wang et al. 2009; Trakhtenbrot et al. 2011; Shen & Liu 2012; Trakhtenbrot & Netzer 2012) and the C IV $\lambda 1549$ line (hereafter C IV) is used to estimate black hole masses at even higher redshifts ($2.0 \lesssim z \lesssim 5.0$; Vestergaard & Peterson 2006; Park et al. 2013).

$M_{BH}$ calibrations based on low ionization lines (i.e., H$\alpha$, and Mg ii) generally show good agreement with the H$\beta$ $M_{BH}$ estimator with a typical scatter of $\lesssim 0.2$ dex (Greene & Ho 2005; Xiao et al. 2011; Trakhtenbrot & Netzer 2012). However, the analogous recalibration using the C IV high ionization line is more problematic and shows large scatter (0.4-0.5 dex), possibly driven by several causes. First, the width of C IV is only weakly correlated, if at all, with the width of the low ionization lines and presents large scatter in many AGN samples. Second, the C IV profiles show large blue-shifts (up to several thousand km s$^{-1}$; Richards et al. 2002; Baskin & Lair 2005; Shang et al. 2007; Shen et al. 2008; Fine et al. 2010; Ho et al. 2012; Shen & Liu 2012; Trakhtenbrot & Netzer 2012; Tilton & Shull 2013). In our previous studies, we presented a sample of 39 high-quality, simultaneous (rest-frame) UV-optical spectra of type-1 AGN at $z \sim 1.5$ obtained with X-Shooter (Capellupo et al. 2015, 2016). Using this sample, in Mejía-Restrepo et al. (2016) we were able to reproduce the correlation found in Runnoe et al. (2013) but with a weaker statistical significance.

Given that C IV is the most widely used line for $M_{BH}$ determination at $z \gtrsim 2$ in optical surveys, it is crucial to design practical methodologies to mitigate the issues related to C IV-based $M_{BH}$ determinations. There have been many efforts to improve single-epoch $M_{BH}$ determinations from C IV (e.g., Vestergaard & Peterson 2006; Assef et al. 2011; Denney et al. 2013; Park et al. 2013; Runnoe et al. 2013; Tilton & Shull 2013; Brotherton et al. 2015; Coatman et al. 2016). The studies of Assef et al. (2011), Denney et al. (2013), Park et al. (2013), and Tilton & Shull (2013) claimed that in spectra of limited signal to noise (S/N) and/or spectral resolution, FWHM(C IV) measurements are underestimating the “real” line widths, in objects with strong intrinsic absorption features that cannot be deblended from the emission lines. The method consisted of using a correlation that they found between the Si IV/O IV $\lambda 1400$/C IV line peak intensity ratio and the H$\beta$/C IV FWHM ratio. They claim that using this correlation it is possible to predict FWHM(H$\beta$) from measurements of the Si IV/O IV $\lambda 1400$ (hereafter Si IV/O IV) emission to obtain more accurate C IV based mass measurements. They specifically claim that the scatter between C IV and H$\beta$ estimations is reduced from 0.43 dex to 0.33 dex.

In our previous studies, we presented a sample of 39 high-quality, simultaneous (rest-frame) UV-optical spectra of type-1 AGN at $z \sim 1.5$ obtained with X-Shooter (Capellupo et al. 2015, 2016). Using this sample, in Mejía-Restrepo et al. (2016) we were able to reproduce the correlation found in Runnoe et al. (2013) but with a weaker statistical significance.

The method consisted of using a correlation that they found between the Si IV/O IV $\lambda 1400$/C IV line peak intensity ratio and the H$\beta$/C IV FWHM ratio. They claim that using this correlation it is possible to predict FWHM(H$\beta$) from measurements of the Si IV/O IV $\lambda 1400$ (hereafter Si IV/O IV) emission to obtain more accurate C IV based mass measurements. They specifically claim that the scatter between C IV and H$\beta$ estimations is reduced from 0.43 dex to 0.33 dex.

In our previous studies, we presented a sample of 39 high-quality, simultaneous (rest-frame) UV-optical spectra of type-1 AGN at $z \sim 1.5$ obtained with X-Shooter (Capellupo et al. 2015, 2016). Using this sample, in Mejía-Restrepo et al. (2016) we were able to reproduce the correlation found in Runnoe et al. (2013) but with a weaker statistical significance. Mejía-Restrepo et al. (2016) also found a similar but alternative correlation between the C IV $\lambda 1909$/C IV line peak intensity ratio and the H$\beta$/C IV FWHM ratio. In general, we found that the ratios of FWHM(C IV) to the FWHM of the H$\alpha$, H$\beta$ and Mg II low ionization lines are correlated with both, the Si IV/O IV/C IV and the C IV $\lambda 1909$/C IV line peak ratios. In spite of these correlations, we found that none of them are able to reduce the scatter between C IV-based $M_{BH}$ estimations and the low ionization line $M_{BH}$ estimations.

It is important to point out that the findings of Coatman et al. (2017), Mejía-Restrepo et al. (2016) and Runnoe et al. (2013) are all obtained from relatively small samples (230, 69 and 39 objects respectively) that map different regions in the parameter space of the AGN population (see §2). Thus, the significance of their findings may not be applicable to the overall population of non-obscure type-I AGN population.

The purpose of this work is to test the validity of these empirical alternatives to improve C IV-based $M_{BH}$ estimations on large AGN samples with survey-grade spectroscopic data. To accomplish this goal, in this paper we use data from the Sloan Digital Sky Survey (SDSS York et al. 2000), specifically from the SDSS-III data release 7 and the SDSS-III data release 12 quasar spectroscopic catalogues (DR7Q and DR12Q respectively, Schneider et al. 2010; Päris et al. 2017). All the alternatives that we are testing here stand on correlations that relate FWHM (C IV)/FWHM (H$\beta$) with the C IV line itself or with the properties of emission lines or continuum windows that are close to the C IV line. Due to the lack of simultaneous coverage of C IV and H$\beta$ lines in the optical SDSS survey, we will carry our analysis in terms of FWHM (C IV)/FWHM (Mg ii) ≡ FWHM (C IV)/FWHM (Mg ii) instead of FWHM (C IV)/FWHM (H$\beta$). This is justified as it is well known that FWHM(Mg ii) is tightly correlated with FWHM(H$\beta$) and that $M_{BH}$ estimations from these two emission lines are known to agree within 0.2 dex of accuracy (e.g Wang et al. 2009; Shen & Liu 2012; Trakhtenbrot & Netzer 2012; Mejía-Restrepo et al. 2016). Because

Recently, Coatman et al. (2017) found a strong correlation between the blue-shift of the C IV line centroid and the C IV/H$\alpha$ FWHM ratio for a sample of 66 high luminosity ($10^{46.5}$ erg s$^{-1} < L_{Bol} < 10^{47.5}$ erg s$^{-1}$) and high redshift quasars ($z > 2.1$). They suggested that this correlation can assist to improve C IV-based black-hole masses reducing the scatter between C IV and H$\beta$ based $M_{BH}$ determinations from 0.40 dex to 0.24 dex. However, this procedure is not applicable to large optical surveys because of the difficulty to accurately determine the AGN redshift, necessary to compute the C IV blueshift, without information from low ionization lines. Runnoe et al. (2013) and Brotherton et al. (2015) used a sample of 85 low-redshift (0.03 < $z < 1.4$) and low-to moderate luminosity ($10^{45.4}$ erg s$^{-1} < L_{Bol} < 10^{46.5}$ erg s$^{-1}$) AGN with quasi-simultaneous UV and optical rest-frame spectra to propose a method to calibrate C IV for $M_{BH}$ determination.
of the limitation in S/N of the SDSS data and the difficulties in measuring the \( \sigma_{\text{mea}} \) of CIV, in this paper we do not thoroughly explore the usage of this quantity for C IV measurements, we however briefly analyse the feasibility of its usage in a high-quality spectra subsample of the SDSS DR12Q catalogue.

This paper is structured as follows. In section §2 we present the samples and introduce the most relevant parameters that we measured for our analysis. In §3 we present and discuss our main results and in §4 we highlight our most important findings. Throughout this paper we assume a flat \( \Lambda \)CDM cosmology with the following values for the cosmological parameters: \( \Omega_M = 0.7, \Omega_b = 0.3 \) and \( H_0 = 70 \text{km s}^{-1} \text{Mpc}^{-1} \).

2 SAMPLES, DATA AND ANALYSIS

In this section we describe in detail two large samples, namely, the SDSS DR7Q and the DR12Q samples, as well as three small samples taken from Mejía-Restrepo et al. (2016), Runnoe et al. (2013) and Coatman et al. (2017). We also describe the spectral fitting procedure and the the emission line and continuum properties that were obtained for the analysis presented here.

2.1 Large Samples

To accomplish our goal, we need to guarantee the simultaneous coverage of the Si IV+O IV, C IV, C III], and Mg II emission lines. According to the spectroscopic coverage of the DR7Q (3800-9200Å) and the DR12Q (3600-10400Å) samples, we selected objects with \( 1.8 < z < 2.0 \) and \( 1.7 < z < 2.3 \) respectively. These redshift constraints translate into a total of 4817 objects for the DR7Q catalogue and 69092 objects for the DR12Q catalogue. Although the objects from the SDSS DR7 sample are also included in the DR12Q sample, to construct the DR12Q catalogue, the objects from the DR7Q catalogue were re-observed. The time interval between observations is at least 4 years.

For the DR7Q sample we used the redshifts estimations from Hewett & Wild (2010) which provides important improvements to the SDSS redshifts estimations with a reduction of a factor of 6 of the systematic uncertainties with respect to SDSS redshift estimations. For the DR12Q sample, Hewett & Wild (2010) redshift calculations are not available. We therefore adopt the visually inspected SDSS redshifts estimations described in Páris et al. (2017). Consequently, line shift estimations in the SDSS DR12Q sample are less reliable than in the DR7Q sample.

It is also important to note that because the survey was designed to map the large scale structure of the universe at high redshift, the DR12Q catalogue is primarily biased towards \( z > 2 \) sources (Schlegel et al. 2009). In particular, in our sub-sample of the DR12Q catalogue 75% of the objects are at \( z > 2.0 \).

2.2 Small Samples

We complement our analysis with three additional smaller samples with considerably higher-quality spectroscopic data. These samples correspond to the original samples used to propose the different methodologies to improve C IV-based \( \Lambda_{\text{HHT}} \) estimations that we described in the introduction.

The first sample is described in Capellupo et al. (2016, hereafter the X-Shooter sample) consisting of 39 RQ quasars observed by the X-Shooter spectrograph that guaranteed simultaneous observations of the rest-frame UV and optical. The sample comprises objects with \( 1.45 < z < 1.69 \) and \( 10^{44.8} \text{erg s}^{-1} < L_{1450} < 10^{46.8} \text{erg s}^{-1} \).

The second of these samples is described in Runnoe et al. (2013, hereafter the R13 sample) consisting of 69 objects including 37 radio-loud (RL) and 32 radio-quiet (RQ) quasars with nearly simultaneous observations of the (rest-frame) X-ray, Ultraviolet (UV) and optical. This sample is a subset of the Tang et al. (2012) sample and comprises objects with \( 0.03 < z < 1.4 \) and \( 10^{43.9} \text{erg s}^{-1} < L_{1450} < 10^{46.7} \text{erg s}^{-1} \).

Finally, the sample described in Coatman et al. (2017, hereafter the C17 sample) consists of a compilation of 230 RQ quasars with \( 10^{42.7} \text{erg s}^{-1} < L_{1450} < 10^{47.7} \text{erg s}^{-1} \). This sample comprises sources from Shen & Liu (2012), Coatman et al. (2016) and Shen et al. (2016). All the sources have non-simultaneous optical observations (from SDSS) and ground based near-infra-red observations which at the redshift range of the sample \( 1.5 < z < 4.0 \) correspond to the rest-frame UV and optical range, respectively. This sample has not reported Mg II emission line measurements but includes \( H_0 \) emission line measurements that can be used as a proxy for Mg II line measurements (see e.g., Shen & Liu 2012; Mejía-Restrepo et al. 2016).

2.3 Line and continuum measurements

For each object in the SDSS DR7Q and DR12Q samples we fitted the line profiles of the Si IV+O IV, C IV, C III], and Mg II emission lines as described in Appendix A. From the best fit model of the emission lines of each object we measured the line FWHM, the velocity dispersion \( \sigma_{\text{mea}} \) (following Peterson et al. 2004), the rest-frame equivalent width \( (EW) \), the integrated line luminosity \( (L, \text{line}) \) and the luminosity at the peak of the fitted profile \( (L_{\text{peak}}, \text{line}) \). As line blue-shift indicators we measured two different quantities: (1) the shift of the emission line peak \( (\Delta v_{\text{peak}}) \) and (2) the line centroid shift defined as shift in the flux-weighted central wavelength \( (\Delta \lambda_{\text{line}}, \text{following Peterson et al. 2004}) \). We also computed the monochromatic luminosities at different wavelengths \( (L_\lambda \equiv \lambda \cdot \lambda (\lambda)) \). We particularly measured \( L_{1350}, L_{1450}, L_{2000} \) and \( L_{3000} \) that correspond to continuum bands adjacent to the Si IV+O IV, C IV, C III] and the Mg II emission lines, respectively. Finally, from the large DR7Q and DR12Q samples we excluded broad absorption line quasars (BALQSOs) and objects with unreliable fits following the strategy described in Appendix A. We ended up with 3267 objects from the DR7Q catalogue (out of 4817) and 35674 from the DR12Q catalogue (out of 69062 objects).

In the case of the X-Shooter, R13 and C17 samples we also extracted the measurements of the aforementioned quantities whenever available from the published data in Mejía-Restrepo et al. (2016), Runnoe et al. (2013) and Coatman et al. (2017), respectively. Although the fitting approaches in each of these papers are not identical, they follow similar procedures and then provide comparable measurements.

Mejía-Restrepo et al. (2016) showed that \( \sigma_{\text{mea}} \) and \( L (\text{line}) \) are very sensitive to the continuum placement because of their strong dependence on the line wings. Analogously, \( \Delta \lambda_{\text{line}} \) (C IV), one of the most widely used blue-shift indicators, is also affected by the continuum placement. This fact motivates us to use the alternative blue-shift estimators \( \Delta v_{\text{peak}} \) (see definition above). Similarly, \( EW (\text{line}) \) is also sensitive to continuum placement. Therefore, in addition to \( EW (\text{line}) \), we also use \( L_{\text{peak}}(\text{line}) / L_\lambda \) because of its weaker dependency on continuum placement.

We thus have a set of quantities that are weakly sensitive to...
For our analysis are the following:

- \( L_{1450} \)
- \( L_{3000} \)
- FWHM(C IV)
- FWHM(Mg II)
- FWHM(C IV) / FWHM(Mg II)
- \( L_{\text{peak}} \) [C IV/SiOIV] \( \equiv L_{\text{peak}} \) (C IV) / \( L_{\text{peak}} \) (Si IV + O IV)
- \( L_{\text{peak}} \) [C IV/C III] \( \equiv L_{\text{peak}} \) (C IV) / \( L_{\text{peak}} \) (C III)
- \( L_{\text{peak}} \) [C IV/1450Å] \( \equiv L_{\text{peak}} \) (C IV) / \( L \) (1450Å)
- \( \Delta \nu_{\text{line}} \) (C IV), blue-shift of the C IV line centroid.
- \( \Delta \nu_{\text{peak}} \) (C IV), blue-shift of the C IV line peak.

From all the quantities considered here, the most relevant parameters for our analysis are the following:

- \( L_{1450} \)
- \( L_{3000} \)
- FWHM(C IV)
- FWHM(Mg II)

In Figures 1, 2, 3, 4 and 5 we present relevant information associated with these quantities. First, in Fig. 1 we show the bi-dimensional distribution of \( \log \text{FWHM(C IV)} \) versus \( \log L_{1450} \) (left column) and \( \log \text{FWHM(Mg II)} \) versus \( \log L_{3000} \) (right column) for the DR7Q (top panels) and the DR12Q (bottom panels) samples. We continue with Fig. 2 where we show the bi-dimensional distribution of \( \log \text{FWHM(C IV)} \) versus...
log FWHM (Mg II) for the DR7Q (left) and the DR12Q (right) samples. We also show in Figures 3 and 4 the bi-dimensional distributions of log FWHM (C IV) and log FWHM (C IV/Mg II) versus log $L_{\text{peak}}$ [C IV/SiOIV] (left), log $L_{\text{peak}}$ [C IV/C III] (centre) and log $L_{\text{peak}}$ [C IV/1450Å] (right) for the DR7Q and the DR12Q samples, respectively. Finally, in Figure 5 we show the bi-dimensional distributions of log FWHM (C IV/Mg II) versus $\Delta$V$_{\text{peak}}$ (C IV) and $\Delta$V$_{\text{line}}$ (C IV) for the DR7Q (columns 1 and 2 from left to right) and the DR12Q (columns 3 and 4) samples, respectively. We also show the cumulative distribution function (CDF) of all the quantities and superimpose the relevant information from the X-Shooter, R13 and C17 samples whenever available. In all these figures we show the Pearson correlation coefficient ($r_P$) for the DR7Q and DR12Q bi-dimensional distribution.

As can be seen in all these figures, all samples used for this paper are subject to different limitations and, potentially, different selection effects and biases. On the one hand, large samples have the advantage of better sampling the overall quasar population. However, they not only have limited data quality but are also incomplete at low luminosities (because of flux limits) and high luminosities (because of the upper redshift cuts; Labita et al. 2009). On the other hand, our small samples have very good data quality but cannot statistically represent the overall quasar population. For further details, in Appendix B we discuss the particular advantages and limitations related to the large and small samples used for this work.

### 3 RESULTS AND DISCUSSION

In this section we explore in detail the different methods suggested by the aforementioned authors to improve C IV-based $M_{\text{BH}}$ estimations. First we will analyse our results from the largest SDSS DR7Q and DR12Q samples to subsequently contrast them with those obtained from the X-Shooter, R13 and C17 samples and discuss the possible problems in the analysis done with such small samples.

#### 3.1 SDSS DR7Q and DR12Q samples

In Table A3 we present the correlation matrix associated with the most relevant measurements relating the C IV and Mg II lines, and the continuum emission from the accretion disk in both SDSS samples. One important result shown in this table, as well as in Figure 2, is the very weak (or absent) correlation between FWHM(C IV) and FWHM(Mg II) ($0 < r_P < 0.13$, $P_P < 2 \times 10^{-17}$) that inhibits the possibility to derive reliable C IV-based $M_{\text{BH}}$ estimations by only comparing the C IV with the Mg II line widths. One alternative to overcome this issue is by means of a correlations between the ratio of FWHM(C IV) to the FWHM of the low ionization lines, and other emission lines and/or continuum property. This would provide a simple procedure to predict the width of low ionization lines in terms of FWHM(C IV) and other observed properties as already proposed by Runnoe et al. (2013), Mejía-Restrepo et al. (2016) and Coatman et al. (2017).
3.1.1 Line Peak Ratios

We first explore the statistical significance of the anti-correlations that link FWHM (C IV/Mg II) with $L_{\text{peak}}$ (C IV/SiO IV), $L_{\text{peak}}$ (C IV/C III], and $L_{\text{peak}}$ [C IV/1450Å] and which are used to improve C IV-based $M_{\text{BH}}$ estimations. The reason to include $L_{\text{peak}}$ [C IV/1450Å] in this analysis, which has not been considered in the literature, is its independence on other emission lines. Hereafter we will refer to these three quantities as the line peak ratio quantities.

Figures 3 and 4 show that FWHM (C IV/Mg II) as well as FWHM(C IV) are anti-correlated with $L_{\text{peak}}$ [C IV/1450Å], $L_{\text{peak}}$ (C IV/SiO IV) and $L_{\text{peak}}$ (C IV/C III] in both SDSS quasar samples. Additionally, the corresponding values of $r_p$ suggests

1 We also considered the possibility of using the EW(C IV) for our analysis. However, it shows weaker correlations with FWHM (C IV/Mg II) and FWHM(C IV) than $L_{\text{peak}}$ (C IV/SiO IV), $L_{\text{peak}}$ (C IV/C III], and $L_{\text{peak}}$ [C IV/1450Å].

2 Notice that Figures 3 and 4 map the same dynamical range for log FWHM (C IV) and log FWHM (C IV/Mg II) (1.6 dex in both cases) as well as for log $L_{\text{peak}}$ (C IV/SiO IV), log $L_{\text{peak}}$ (C IV/C III], and log $L_{\text{peak}}$ [C IV/1450Å] (a total of 2.5 dex in all of them).

Figure 3. Bidimensional distributions of FWHM [C IV/Mg II] (top-row) and FWHM(C IV) (bottom row) vs $L_{\text{peak}}$ [C IV/SiO IV] (left-column), $L_{\text{peak}}$ [C IV/C III], and $L_{\text{peak}}$ [C IV/1450Å] (right-column) in the SDSS DR7Q sample. The intensity of the colour represents the relative density of points as shown in the colour bar on the right. The black thin lines represent the 25%, 50%, 75% and 99% contours centred at the maximum probability point. The projected CDFs of each of the quantities are also shown in the right and top side diagrams. We superimpose to each panel analogue data of the X-Shooter and R13 small samples as indicated in the legends. Coloured trend lines represent the median values of FWHM [C IV/Mg II] (middle panels) and FWHM(C IV) (bottom panels) as a function of the different line peak ratios for objects with FWHM (Mg II) < 3000 km s$^{-1}$ (light-turquoise) and FWHM (Mg II) > 4500 km s$^{-1}$ (red). The error bars represent the 1-$\sigma$ dispersion of the points around these trends. Note that the dynamic range that is shown for FWHM(C IV) and FWHM(Mg II) coincides (1.6dex). The same situation occurs with the dynamic range that is shown for $L_{\text{peak}}$ [C IV/SiO IV], $L_{\text{peak}}$ [C IV/C III], and $L_{\text{peak}}$ [C IV/1450Å] (2.5dex). We also show the correlation coefficient $r_p$. In all these cases $r_p$ << 10$^{-3}$ and are not shown in the panels.

Table 1. Scatter found in correlations between the listed quantities in the DR7Q and DR12Q samples

|                   | DR7Q | DR12Q | DR7Q | DR12Q |
|-------------------|------|-------|------|-------|
| $L_{\text{peak}}$ [C IV/SiO IV] | 0.21 | 0.27 | 0.17 | 0.21 |
| $L_{\text{peak}}$ [C IV/C III] | 0.22 | 0.29 | 0.19 | 0.23 |
| $L_{\text{peak}}$ [C IV/1450Å] | 0.20 | 0.25 | 0.14 | 0.19 |
| $\Delta L_{\text{peak}}$ (C IV) | 0.19 | 0.28 | 0.16 | 0.22 |
| $\Delta L_{\text{line}}$ (C IV) | 0.21 | 0.29 | 0.19 | 0.24 |

that in most cases the anti-correlations of the three line peak ratio quantities with FWHM(C IV) are tighter than those with FWHM (C IV/Mg II) with the exception of $L_{\text{peak}}$ [C IV/C III] in the DR7 sample where the anti-correlations are of comparable strength (Fig 3 middle column). In addition to this, the data presented in Table 1 shows that the scatter of the correlations associated with FWHM(C IV) are smaller than those associated with FWHM (C IV/Mg II) in both SDSS quasar samples.

One possibility to explain this behaviour is that the correlations related to FWHM (C IV/Mg II) are driven by the more fundamental FWHM(C IV) correlations. This interpretation is
supported by the tight correlation between FWHM(CIV) and FWHM [CIV/MgII] that we find in both SDSS samples ($r_p = 0.71$ in both cases). Thus, FWHM [CIV/MgII] is just increasing the scatter of the original correlations with FWHM(CIV).

To test this idea we first divided our DR7Q and DR12Q samples into two sub-groups: Objects with FWHM (Mg II) < 3000 km s$^{-1}$ (narrow-group) and objects with FWHM (Mg II) > 4500 km s$^{-1}$ (broad-group). Then, we binned each group by the line peak ratio quantities with a bin size of 0.2 dex. For each bin we computed the median value of FWHM [CIV/MgII] and FWHM(CIV) and the corresponding 16 and 84 percentiles to quantify the dispersion in each bin. The light-turquoise and red solid lines in Figs. 3 and 4 represent the median values of FWHM(CIV) (bottom panels). In those panels the median red lines are just slightly above the light-turquoise lines (roughly 0.07 dex) in all diagrams. However, in those diagrams associated with FWHM [CIV/MgII] (middle panels) we can see a clearer separation between light-turquoise and red lines. Particularly red lines (FWHM (Mg II) > 4500 km s$^{-1}$) in all diagrams. This indicates that FWHM(Mg II) is driving the dispersion in the correlation between FWHM [CIV/MgII] and the line peak ratio quantities.

To obtain further support for the previous finding, we looked at the residuals of the line peak ratios when expressed as a function of FWHM [CIV/MgII]. In the case that FWHM(Mg II) is driving the dispersion in the FWHM [CIV/MgII] correlations, we would find significant anti-correlation between these residuals and FWHM(Mg II). To address this, we fit the line peak ratios in terms of FWHM(CIV) and FWHM [CIV/MgII] using bisector linear regressions. We find that for the peak ratios as functions of FWHM [CIV/MgII], all the line-peak-ratio-residuals are significantly anti-correlated with FWHM(MgII) ($|r_p| > 0.41$ in both samples) as expected. Moreover, for the line peak ratios versus FWHM(CIV) we do not find any significant correlations between any of the residuals with FWHM(MgII) ($|r_p| < 0.23$ in both samples).

An additional test consists of estimating the statistical significance of the difference between the correlation coefficients associated with FWHM(CIV) and those associated with FWHM [CIV/MgII] in both SDSS quasar samples. The William’s test, using Fisher-z transformations, provides a procedure to test the relative significance of the difference between two Pearson correlation coefficients obtained from the same sample and sharing one common variable (Dunn & Clark 1969). By applying this method to the correlations of FWHM(CIV) and FWHM [CIV/MgII] with the common variable $L_{peak}$ [CIV/SiOIV] and the FWHM [CIV/MgII]-$L_{peak}$ [CIV/SiOIV] correlations we find an associated probability of $P_{William} < 10^{-5}$ for upholding the null hypothesis that both correlation coefficients are equal. This result discards the equivalence of both the FWHM(CIV)-$L_{peak}$ [CIV/SiOIV] and the FWHM [CIV/MgII]-$L_{peak}$ [CIV/SiOIV] correlations. We find similar behaviours for the case of the FWHM(CIV)-$L_{peak}$ [CIV/CIII] and FWHM [CIV/MgII]-$L_{peak}$ [CIV/CIII] correlations where we find $P_{William} < 10^{-11}$ in both samples. Finally, for the case of the FWHM(CIV)-$L_{peak}$ [CIV/CIII] and FWHM [CIV/MgII]-$L_{peak}$ [CIV/CIII] correlations we find $P_{William} = 10^{-9}$ in the...
From all the evidence that we have collected, we can conclude that the prescriptions proposed by Runnoe et al. (2013) and Mejía-Restrepo et al. (2016) are of limited applicability for correcting C IV-based estimates of \( M_{\text{HII}} \) because the correlations between the line peak ratios and FWHM(C IV) are statistically stronger and very likely driving the weaker correlations associated with FWHM [C IV/Mg II].

### 3.1.2 C IV blueshifts

We continue to test whether or not the use of \( \Delta v_{\text{line}} \) (C IV) proposed by Coatman et al. (2017) can be used to improve C IV-based measurements. In addition to \( \Delta v_{\text{line}} \) (C IV) we will also include \( \Delta v_{\text{peak}} \) (C IV) in our analysis. The reason for this choice is the better stability of \( \Delta v_{\text{peak}} \) (C IV) to continuum placement as we discuss in § 2.

In Fig. 5 we show the bi-dimensional distribution of FWHM [C IV/Mg II] and FWHM(C IV) versus the C IV blue-shift indicators \( \Delta v_{\text{peak}} \) (C IV) and \( \Delta v_{\text{line}} \) (C IV) in both SDSS samples. In each panel we map the same dynamic range for FWHM(C IV) and FWHM[C IV/Mg II]. We also present the Pearson correlation coefficients for each diagram.

Fig. 5 demonstrates that FWHM [C IV/Mg II] and FWHM(C IV) are both correlated with \( \Delta v_{\text{peak}} \) (C IV) and \( \Delta v_{\text{line}} \) (C IV) in both SDSS samples. It is also noticeable that in most cases, the correlations between both blue-shift estimators and FWHM(C IV) are tighter than with FWHM [C IV/Mg II]. The only exception is with \( \Delta v_{\text{line}} \) (C IV) in the DR7Q sample where both correlations show similar significance. We can also notice in Table 1 that the scatter of the FWHM(C IV) correlations is smaller than the scatter in the corresponding FWHM [C IV/Mg II] correlations in both SDSS samples. These results would indicate that the correlations associated with FWHM(C IV) are driving...
the correlations associated with FWHM [C\textsc{iv}/Mg\textsc{ii}], similarly to what we found in §3.1.1.

We repeated the same three tests described in §3.1.1 to further check the reliability of these results. First, when dividing the samples into two subsets according to their FWHM(Mg\textsc{ii}) and binning by the blue-shift indicators in bins of 700 km s$^{-1}$, we find that the separation of the median trends of the narrow-group from the median trends of the broad-group (light-turquoise and red lines in Fig. 5) is increased from roughly -0.08 dex in the FWHM(CIV) diagrams to roughly 0.25 dex in the FWHM [C\textsc{iv}/Mg\textsc{ii}] diagrams. Second, the residuals of the blue-shift indicators expressed as a function of FWHM [C\textsc{iv}/Mg\textsc{ii}] show significant anti-correlations with FWHM(Mg\textsc{ii}) ($|r_s| > 0.36$ in both samples). In contrast, when the blue-shift indicators are expressed as a function of FWHM(CIV) we find no correlations with FWHM(Mg\textsc{ii}) ($|r_s| < 0.10$ in both samples). Finally, the relative significance test shows that FWHM(CIV) correlations are indeed stronger than the FWHM [C\textsc{iv}/Mg\textsc{ii}] correlations ($P_{\text{William}} < 0.006$) for $\Delta v_{\text{peak}}$(CIV) and $\Delta v_{\text{line}}$(CIV) in the DR12Q sample and for $\Delta v_{\text{peak}}$(CIV) in the DR7Q sample. In the case of $\Delta v_{\text{line}}$(CIV) for the DR7 sample we find that its Pearson correlation coefficients with FWHM(CIV) and FWHM [C\textsc{iv}/Mg\textsc{ii}] (0.48 and 0.50, respectively) are not statistically different to each other ($P_{\text{William}} = 0.1$, smaller than two-sigma significance). All these results support the idea that the correlations between the CIV blue-shifts and FWHM(CIV) are the main drivers for the correlations with FWHM [C\textsc{iv}/Mg\textsc{ii}]. This, in turn, suggests that the prescription introduced by Coatman et al. (2017) may have limited applicability to improve C\textsc{iv} mass measurements.

3.2 Small Samples

We continue our analysis exploring the small samples described in §2. Below we analyse the behaviour of the line peak ratios and the blue-shift relations with FWHM(CIV) and FWHM [C\textsc{iv}/Mg\textsc{ii}] in those samples and discuss the similarities and differences with respect to our findings in the large SDSS samples.

3.2.1 Line Peak Ratios

Given that line peak information is only available for the X-Shooter and R13 samples we limit the analysis of the line peak ratios to these two samples. In addition to the SDSS data, in Figures 3 and 4 we also show the data points and distribution functions associated with the X-Shooter (light-blue squares) and R13 samples (lime open dots and lime filled dots for RL and RQ objects, respectively).

In Table 2 we show the correlation coefficients of the line peak quantities versus (1) FWHM(CIV) and (2) FWHM [C\textsc{iv}/Mg\textsc{ii}] in the following configurations:

- The individual X-Shooter and R13 samples (subsamples $a$ and $b$).
- The combination of the X-Shooter and the R13 samples including RL objects (subsample $c$).
- The combination of the X-Shooter and the R13 samples excluding RL objects (subsample $d$).

We remark that both the X-Shooter and the R13 samples are not complete. Indeed, as discussed in Appendix B, the two samples are mapping totally different regions in the parameter spaces determined by (1) the line peak quantities versus FWHM [C\textsc{iv}/Mg\textsc{ii}] and by (2) the line peak quantities versus FWHM(CIV) (see also Figures 3 and 4). Consequently, after the exclusion of the RL objects from the R13 sample, the combination of the X-Shooter and the R13 samples (i.e. subsample $d$) maps the parameter space of RQ type-1 AGN over wider ranges in $L_{1450}$, FWHM(CIV), FWHM [C\textsc{iv}/Mg\textsc{ii}] and the line peak quantities.

The correlation test presented in Table 2 suggests that for the individual samples ($a$ and $b$) in most cases the correlations of FWHM [C\textsc{iv}/Mg\textsc{ii}] with the line peak quantities are tighter than those associated with FWHM(CIV), in contrast to what we find for the large SDSS samples. The same behaviour is found for the combination of both samples including the RL objects (subsample $c$). However, when the RL objects are excluded from the analysis (subsample $d$), the FWHM [C\textsc{iv}/Mg\textsc{ii}] and FWHM(CIV) correlations coefficients are statically indistinguishable. Thus, the results from subsample $d$, that better maps our parameter space, are in agreement with our results from the large SDSS samples. This may indicate that the large fraction of RL objects in the R13 sample (37/69) are probably artificially strengthening the correlations associated with FWHM [C\textsc{iv}/Mg\textsc{ii}]. This is probably caused by relatively broad Mg\textsc{ii} profiles shown by RL objects (log FWHM (Mg\textsc{ii}) [km s$^{-1}$] $\gtrsim$ 3.5, see right panel of Fig. 1).

3.2.2 CIV blueshifts

Before reporting the results of our comparative analysis for the C17 sample, we note that this sample leans towards high-luminosity sources as can be seen in Fig. 1. Nonetheless, its $\Delta v_{\text{line}}$(CIV) and FWHM(CIV) distribution are in very good agreement with the SDSS-DR7Q sample (see Appendix B and Figures 1, 5 for details).

Using the results reported in Coatman et al. (2017), we find that in their sample $\Delta v_{\text{line}}$(CIV) is very tightly correlated with FWHM(CIV) ($r_p = 0.82$). However, we also find that $\Delta v_{\text{line}}$(CIV)-FWHM [C\textsc{iv}/H\alpha] Pearson correlation coefficient is essentially equal ($r_p = 0.83$). It is also remarkable that Fig. 9 in Coatman et al. (2017) shows that the scatter in the FWHM [C\textsc{iv}/H\alpha] vs $\Delta v_{\text{line}}$(CIV) correlation is clearly dominated by FWHM(H\alpha). These results support our hypothesis that the FWHM(CIV)-$\Delta v_{\text{line}}$(CIV) correlation is the driver of the FWHM [C\textsc{iv}/H\alpha]-$\Delta v_{\text{line}}$(CIV) correlation.

3.3 Resampling tests

Here we present different tests designed to check the validity of the findings presented above. They consist of re-sampling our SDSS DR7Q and DR12Q samples in four different ways:

- Flat distribution in log $L_{1450}$.
- Flat distribution in log FWHM.
- Flat distribution in log FWHM [C\textsc{iv}/Mg\textsc{ii}].
- Flat distribution in both log $L_{1450}$ and log FWHM simultaneously.

The motivation for these tests is to check whether our findings are biased by the concentrated distribution in $L_{1450}$, FWHM(CIV) and FWHM [C\textsc{iv}/Mg\textsc{ii}] and/or the known correlation between $L_{1450}$ and FWHM(CIV) that we observe in Fig. 1 (see also Appendix B). To this end, we first divided our SDSS samples in bins of 0.5dex in $L_{1450}$ starting at log $L_{1450}$ = 45.0 erg s$^{-1}$ in the DR7Q sample and at log $L_{1450}$ = 44.5 erg s$^{-1}$ in the DR12Q sample. For FWHM(CIV) and FWHM [C\textsc{iv}/Mg\textsc{ii}] we divided our sample in bins of 0.4dex. To guarantee an equal number of objects in each bin, we selected 23 objects from the DR7Q sample and 100 objects from
the DR12Q sample, in each realization of the re-sampling simulation. We finally subdivided our SDSS samples in bi-dimensional bins of $L_{1450}$ and FWHM(CIV) of 0.5 and 0.4 dex respectively. For bin we selected 13 and 30 objects in the DR7Q and DR12Q samples. In this case the total number of sources in each re-sampling test is comparable with the size of the small X-Shooter, R13 and C17 samples. To account for statistical variance because of the limited sampling, we repeated these procedures 100 times. We find the FWHM(CIV) associated correlations show larger or equivalent statistical significance than the FWHM [C IV/Mg ii] correlations as suggested by the Williams’s method (See Table 3 for details) which is consistent to what we found for the large SDSS samples.

### 3.4 Signal to noise analysis

We also considered the possibility that our results may be affected by the limited quality of the SDSS spectroscopic data. To this end, we selected a high-quality sub-samples of the SDSS DR12Q catalogue consisting of objects with S/N > 10 at 1700Å and at 3000Å with a binning of 0.75Å/pixel, following Denney et al. (2013). We found a total of 2230 objects meeting these criteria.

As can be seen in Table A2, our analysis on this high-quality sub-sample is consistent with our final results on the entire SDSS DR12Q sample. In particular, we find that the correlations connecting the line peak quantities and the C IV blueshifts with FWHM(CIV) are stronger than those with FWHM [C IV/Mg ii]. The only exception is with $\Delta v_{\text{line}}$ (C IV), where both correlations are of comparable strength. Similarly, in Table A2 we also show that when we further limit our analysis to the 483 objects with $S/N > 20$, the correlations related to FWHM(CIV) are always stronger than those related to FWHM [C IV/Mg ii].

The usage of these high-$S/N$ sub-samples also allows us to test the results of several previous studies that suggested that, in high-quality spectra, the $\sigma_{\text{line}}$ of C IV provides more accurate $M_{\text{HII}}$ estimates than the FWHM of C IV. Because of the lack of $H\beta$ measurements in our sample, we used the FWHM and the $\sigma_{\text{line}}$ of Mg ii as proxies for the $H\beta$ measurements. In contrast to the results of Denney et al. (2013), we found weak or even no correlations between the $\sigma_{\text{line}}$ of C IV and the $\sigma_{\text{line}}$ and FWHMof Mg ii in both of the high-quality sub-samples (i.e., those with $S/N > 10$ and/or > 20; correlation coefficients in the range 0.04 < $r_p < 0.19$). This indicates that the $\sigma_{\text{line}}$ of C IV cannot be reliably used to provide accurate estimates of $M_{\text{HII}}$ even in high quality data, mainly because of its instability to the continuum placement.

### 3.5 Principal Component analysis

We conducted a principal component analysis on this correlation matrixes presented in Table A3 to find different groups of inter-
connected variables and obtain the amount of variance driven by
each group. In Table 4 we show the correlation coefficients be-
tween the first three proper vectors and the quantities that de-
fine them. We can observe that the first proper vector (PV1) is
responsible for 38 and 32 percent of the variance in the DR7Q
and DR12Q samples respectively. In both cases, FWHM(CIV)
and Lpeak [CIV/1450Å] show the strongest correlations with
PV1 indicating that the FWHM(CIV)-Lpeak [CIV/1450Å] anti-
correlation drives PV1 and consequently a large percentage
of the variance in the SDSS samples. FWHM(CIV) and Lpeak
[CIV/1450Å] are basically driven by the strong relations of
these quantities with the properties of the Mg II and C IV respec-
tively. In both cases, FWHM(CIV) is strongly correlated with
PV1. However, these correlations are basically caused by the
strong relations of these quantities with FWHM(CIV) and Lpeak
[CIV/1450Å].

The second proper vector (PV2) is responsible for 16% and
15% of the variance in the DR7Q and DR12Q samples,
respectively, and is strongly correlated with FWHM(Mg II)
in both samples. It also shows a strong correlation with
FWHM(Mg II)/σ(Mg II) and a strong anti-correlation with
FWHM(C IV)/Mg II, which is basically inherited from their cor-
relations with FWHM(Mg II). Given that by definition PV2 is lin-
early independent of the other proper vectors, this result reveals
that FWHM(Mg II) is basically independent of any C IV related
quantity and may indicate that C IV and Mg II profiles show com-
pletely independent behaviours.

Finally, the third proper vector (PV3) drives 13% and 14% of
the variance of the SDSS samples, respectively, and is strongly
correlated with EW(C IV) and Lpeak (C IV)/L (C IV) which are
both strongly correlated with each other because of their depen-
dence on L (C IV). It also shows an important correlation with
FWHM [C IV/Mg II] which is not correlated with any of these
quantities. Thus, PV3 does not provide a link between C IV and
Mg II properties.

4 SUMMARY AND CONCLUSIONS
C IV-based M_BH estimations are known to be problematic. In
the past few years Runnoe et al. (2013), Mejia-Restrepo et al. (2016)
and Coatman et al. (2017) provided alternative methods attempting
to improve C IV-based masses. All these methods were based on
correlations between different observables associated with the C IV
emission and the ratio of FWHM(C IV) and the FWHM of low-
ionization lines (i.e. Hα, Hβ and Mg II). Despite the good quality
of the data used in these works, all these methods were derived
using small samples with limited coverage of the parameter space
of the observables involved in each method.

Using SDSS DR7Q and DR12Q samples (which are more rep-
resentative of the quasar population) we showed that all these meth-
ods are of limited applicability to improve C IV-based M_BH esti-
mations. In fact, we find that the aforementioned methods depend
on correlations that are actually driven by the FWHM of the C IV
profile itself and not by an interconnection between FWHM(C IV)
and the FWHMs of the low ionization lines. Additionally, our
analysis suggests that from all the correlations that we consid-
ered with FWHM(C IV), those that involve Lpeak [C IV/1450Å]
are the tightest ones. We also find that other quantities con-
sidered in this work (Lpeak [C IV/SIOIV], Lpeak [C IV/C III],
Δvpeak (C IV) and Δvline (C IV)) are all tightly correlated with
Lpeak [C IV/1450Å] (see Table. A3).

Further support for these conclusions comes from principal
component analysis which reveals that the first proper vector is
mostly driven by the anti-correlation between FWHM(C IV)
and Lpeak [CIV/1450Å]. This occurs in such a way that the
relations between these quantities and FWHM [C IV/Mg II],
L1450Å, EW(C IV), Lpeak [C IV/SIOIV], Lpeak [C IV/C III],
Δvpeak (C IV) and Δvline (C IV) are basically driven by the
FWHM(C IV)-Lpeak [CIV/1450Å] anti-correlation. Notably, the
second proper vector is mostly driven by FWHM(Mg II) and shows
no correlation with any C IV related quantity. This suggests that
the properties of the Mg II and C IV profiles are independent from
each other. In other words, there is no possibility to relate the
non-virialized C IV emission with the virialized Mg II emission.

A possible explanation for this could be associated with the fact
that the more luminous a quasar is, the lower its EW(C IV).
This is the well-known C IV Baldwin Effect (Baldwin 1977; Baskin
& Laor 2004, 2005; Richards et al. 2011; Ge et al. 2016). Both
the quasar luminosity and EW(C IV) are known to be related with
the C IV blue-shift, the C IV asymmetry, and the relative strength
of the X-ray emission (e.g. Richards et al. 2011; Shen et al. 2016).
Indeed, if we take Lpeak [CIV/1450Å] as a proxy for the EW
of C IV and consider the anti-correlation between FWHM(C IV)
and L1450Å, we can conclude that the very tight anti-correlation
between FWHM(C IV) and Lpeak [CIV/1450Å] can be seen as
inherited from the Baldwin Effect.

Our analysis implies that the well-characterized M_BH estima-
tions from the low ionization lines cannot be accurately predicted
from the emission line properties of the C IV line. Consequently,
 systematic infra-red spectroscopic observations of large samples
of quasars are required to guarantee the coverage of low ionization
lines and the proper determination of the SMBH masses. Achieving
accurate C IV mass estimations requires, apart from a robust
determination of the R bluff (C IV)-L1450Å relation, an exten-
sive analysis of the C IV emission line itself to further understand
the virialized component of the C IV line.

ACKNOWLEDGMENTS
JM acknowledges “CONICYT-CHA doctorado nacional para
extranjeros/2013-63130316” for their PhD scholarship and Univer-
sidad de Chile grant “Ayudas para estadías cortas de investigación
destinadas a estudiantes de doctorado y magister” for their finan-
cial support to visit ETH-Zürich, where most of this work was
done. JM also acknowledges the financial support provided by the
ETH-Zürich during his stay. PL acknowledges support by Fonde-
cyt Project #1161184 and H.N acknowledges support by the Israel
Science Foundation grant 234/13.

REFERENCES
Assef R. J., et al., 2011, ApJ, 742, 93
Baldwin J. A., 1977, ApJ, 214, 679
Baskin A., Laor A., 2004, MNRAS, 350, L31
Baskin A., Laor A., 2005, MNRAS, 356, 1029
Batiste M., Bentz M. C., Raimundo S. I., Vestergaard M., Onken C. A.,
2017, ApJ, 838, L10
Bentz M. C., Peterson B. M., Netzer H., Pogge R. W., Vestergaard M., 2009,
ApJ, 697, 160
Bentz M. C., et al., 2013, ApJ, 767, 149
Brotherton M. S., Runnoe J. C., Shang Z., DiPompeo M. A., 2015, preprint,
(arXiv:1504.03427)
Capellupo D. M., Netzer H., Lira P., Trakhtenbrot B., Mejía-Restrepo J.,
2015, MNRAS, 446, 3427
APPENDIX A: FITTING PROCEDURE, MEASUREMENTS AND BALQSO EXCLUSION

Our broad emission line modelling follows the procedure presented in Mejía-Restrepo et al. (2016) and Trakhtenbrot & Netzer (2012). Very briefly, the most prominent lines (Si Ⅳ+O Ⅳ, C Ⅳ, C Ⅲ and Mg Ⅱ) are modelled using two Gaussian components while other weak emission lines are modelled with a single Gaussian (including He 11640, N Ⅳ1718, Si Ⅲ1892). The central wavelength of each Gaussian component is restricted to move within 1000 km s\(^{-1}\) around the laboratory central wavelength. The C Ⅳ and He 11640 are allowed to be blue shifted up to 5000 km s\(^{-1}\).

We automated the procedure by introducing some additional steps to the line and continuum fitting. We first proceed to fit and subtract the continuum emission within a pair of continuum windows around each line. These continuum windows are set at the wavelengths that we list in Table A1. We subsequently fit the emission line following the “local” approach described in Mejía-Restrepo et al. (2016). After this we obtain the residuals of the fitting and remove the pixels with the 3% most negative fluxes within the continuum windows. The purpose of this step is to exclude from the fitting strong absorption features. We repeat the entire procedure three times to guarantee convergence. We also exclude from our sample objects with final reduced \(\chi^2\) larger than 3.

To avoid C Ⅳ BALQSOs we excluded from the sample objects with more than 7% of the pixels with negative C Ⅳ residuals. To test the performance of this automatic selection method we compare the objects that are flagged as BALQSOs using our method with the sample of 562 manually classified BALQSOs from the SDSS-DR2 quasar database that is described in Ganguly et al. (2007). With our criterion we flagged as BALQSO a total of 560/562 objects from the SDSS-DR2 quasar database that is described in Gan-

### Table A1. Spectral pseudo-continuum windows used for our line fitting procedure under the local continuum approach. 1For each object, we manually adjusted the continuum bands, using the listed wavelength ranges as a reference.

| Line Complex | Continuum windows |
|---------------|-------------------|
| Si Ⅳ+O Ⅳ | 1340-1360Å 1420-1460Å |
| C Ⅳ | 1430-1460Å 1680-1720Å |
| C Ⅲ | 1680-1720Å 1960-2020Å |
| Mg Ⅱ | 2650-2670Å 3020-3040Å |

Trakhtenbrot H., Netzer H., Lira P., Shemmer O., 2011, ApJ, 730, 7
Trevese D., Perna M., Vagnetti F., Saturni F. G., Dadina M., 2014, ApJ, 795, 164
Vestergaard M., Osmer P. S., 2009, ApJ, 699, 880
Vestergaard M., Peterson B. M., 2006, ApJ, 641, 689
Wang J.-G., et al., 2007, ApJ, 707, 1334
Woo J.-H., Schulze A., Park D., Kang W.-R., Kim S. C., Riechers D. A., 2013, ApJ, 772, 49
Woo J.-H., Yoon Y., Park S., Park D., Kim S. C., 2015, ApJ, 801, 38
Xiao T., Barth A. J., Greene J. E., Ho L. C., Bentz M. C., Ludwig R. R., Jiang Y., 2011, ApJ, 739, 28
York D. G., et al., 2000, AJ, 120, 1579

---

1 If we end up with 3267 from the DR7Q catalogue (out of the originally selected 4817 objects) and with 35674 objects unreliably fitted we end up with 3267 from the DR7Q catalogue (out of the originally selected 4817 objects) and with 35674 objects
from the DR12Q catalogue (out of the originally selected 69092 objects).

APPENDIX B: SAMPLE COMPARISON

Here we describe in detail the parameter space of the most relevant physical quantities derived for the samples and summarize the most relevant issues associated with each of the small and large samples used in this paper.

B1 Comments on large samples

- In both SDSS samples we can observe that FWHM(C IV) and $L_{\lambda 1450}$ correlate with each other ($r_p \equiv r_{\text{Pearson}} \sim 0.35$). This indicates that, on average, more luminous quasars typically show broader C IV line profiles. However, the FWHM(Mg II) is completely independent of the quasar luminosity ($r_p < 0.05$ in both SDSS samples).

- The DR12Q sample probes considerably fainter sources, compared with the DR7Q sample (by $\sim 0.5 \text{dex}$), and extends to $L_{\lambda 1450} \gtrsim 10^{44.5} \text{ erg s}^{-1}$. This difference between both samples allows us to directly test the impact of luminosity limited samples as well as data quality in our analysis.

- In the case of log FWHM (C IV) and log FWHM (Mg II) both SDSS samples span similar ranges, from $\sim 3$ to $\sim 4.2$ in log FWHM (C IV), from $\sim 3$ to $\sim 3.8$ in log FWHM (Mg II). However, the DR12Q sample has a larger fraction of object with low log FWHM (C IV) and log FWHM (Mg II). Explicitly, 5% (10%) of the objects in the DR12Q sample have FWHM (C IV) $\lesssim 3.3$ (FWHM (Mg II) $\lesssim 3.3$) versus 2% (6%) in the DR7Q sample. Additionally, the DR12Q sample has a larger fraction of objects with large log FWHM (Mg II). The sharp cut at log FWHM (C IV) = log FWHM (Mg II) = 3 is imposed by the fitting criterion.

The log FWHM (C IV/Mg II) distribution in both samples span over similar ranges, from $\sim 0.6$ to $\sim 0.8$. However, the DR12Q sample shows a larger fraction (28%) of objects with log FWHM (C IV/Mg II) $< 0$ than the DR7Q sample (20%).

- We can observe that the DR12Q sample shows a larger fraction (roughly 10%) of objects with log $L_{\text{peak}}$ (C IV/SiO IV) and log $L_{\text{peak}}$ (C IV/C III]) $\gtrsim 1$ than the DR7Q sample (roughly $\sim 5$%). We need however to be cautious about the reliability of such measurements because those objects show $L_{\text{peak}}$ (Si IV + O IV]) and $L_{\text{peak}}$ (C III]) weaker than one tenth of $L_{\text{peak}}$ (C IV). Thus, the signal to noise of the C III] and Si IV+O IV] line profiles is probably very low in many of those objects. We can also appreciate that the DR12Q and DR7Q samples show a similar distribution in log $L_{\text{peak}}$ (C IV/SiO IV]).

- As we already explained, DR7Q blue-shift estimations are more accurate that in DR12Q. Additionally, we can observe in Figure 5 that the $\Delta v_{\text{peak}}$ (C IV) and the $\Delta v_{\text{line}}$ (C IV) distributions show a larger fraction of objects with small blue-shifts in the DR12Q sample than in the DR7Q sample (6% in DR7Q vs 23% DR12Q and 12% in DR7Q vs 28% in DR12Q for $\Delta v_{\text{peak}}$ (C IV) and $\Delta v_{\text{line}}$ (C IV) $< 200 \text{ km s}^{-1}$ respectively). This behaviour is probably caused by objects in the DR12Q sample whose cosmological redshift has been estimated using the C IV profile. This effect artificially biases the C IV blue-shifts towards values close to 0. Because of these problems with the DR12Q redshift determinations we will mainly focus our blue-shift analysis on the DR7Q sample.

B2 Comments on small samples

- The R13 sample is mostly described by uniform distributions in $L_{\lambda 1450}$, FWHM(C IV) and FWHM(Mg II) that are fairly spread around the SDSS data. However, RL AGN are mostly high luminosity and objects and show large FWHM(Mg II) values. We can also observe that the R13 FWHM (C IV/Mg II) distribution is clearly shifted towards larger values than the peak of the SDSS distributions. In terms of $\Delta v_{\text{peak}}$ (C IV), the sample is shifted towards low values (75% with $< 1000 \text{ km s}^{-1}$). Finally, in terms of log $L_{\text{peak}}$ (C IV) / $L_{\text{peak}}$ (Si IV + O IV]) and log $L_{\text{peak}}$ (C IV) / $L_{\text{peak}}$ (C III]), the sample is shifted towards large values (75% with $\geq 0.5$).

- The X-Shooter Sample also shows mostly flat distributions in log $L_{\lambda 1450}$, log FWHM (C IV) and log FWHM (Mg II) that are also fairly spread around the SDSS data. Its log FWHM (C IV/Mg II) is clearly distributed towards values lower than the peak of the SDSS distribution. Line peak ratios ($\sim 75\%$ with log $L_{\text{peak}}$ (C IV) / $L_{\text{peak}}$ (Si IV + O IV]) $\lesssim 0.5$ and log $L_{\text{peak}}$ (C IV) / $L_{\text{peak}}$ (C III]) $\lesssim 0.5$) and blue-shifts (75% with $< 1000 \text{ km s}^{-1}$) are both distributed towards low values with respect to the SDSS distribution peaks.

- The C17 sample is clearly dominated by objects with very large $L_{\lambda 1450} \gtrsim 10^{46} \text{ erg s}^{-1}$ compared to the other samples. However, its FWHM(C IV) and $\Delta v_{\text{line}}$ (C IV) distributions very closely follow the SDSS DR7Q distributions.

Table A2. Pearson correlation coefficients for the quantities in the first column versus (1) log FWHM (C IV) and (2) log FWHM (C IV/Mg II). In all cases it yields $P_r < 1 \times 10^{-13}$.

|                  | All objects | S/N>10 | S/N>20 |
|------------------|-------------|--------|--------|
| log $L_{\text{peak}}$ (C IV/1450Å) | -0.53 | -0.41 | -0.60 | -0.48 | -0.62 | -0.47 |
| log $L_{\text{peak}}$ (C IV/SiO IV) | -0.46 | -0.42 | -0.52 | -0.48 | -0.59 | -0.49 |
| log $L_{\text{peak}}$ (C IV/C III]) | -0.33 | -0.29 | -0.34 | -0.33 | -0.41 | -0.35 |
| $\Delta v_{\text{peak}}$ (C IV) | 0.37 | 0.29 | 0.55 | 0.46 | 0.62 | 0.45 |
| $\Delta v_{\text{line}}$ (C IV) | 0.39 | 0.37 | 0.54 | 0.56 | 0.57 | 0.55 |

C IV-based Black Hole Mass estimation
Table A3. Pearson correlation coefficients between the listed quantities for the DR7Q and DR12Q samples. We note that in both samples, whenever $|r_p| > 0.1$ it yields $P_r < 1 \times 10^{-10}$.

| Property | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|----------|---|---|---|---|---|---|---|---|---|----|----|----|----|
| DR7Q correlations | | | | | | | | | | | | | |
| $4 \log$ FWHM (C IV) | 1 | 0.17 | 0.71 | 0.34 | 0.51 | 0.44 | -0.63 | -0.51 | -0.36 | -0.11 | -0.83 | 0.22 | -0.19 |
| $2 \log$ FWHM (Mg II) | 0.17 | 1 | -0.58 | 0.10 | -0.11 | -0.19 | -0.07 | 0.03 | 0.09 | 0.07 | -0.20 | 0.60 | -0.10 |
| $3 \log$ FWHM [C IV/Mg II] | 0.71 | -0.58 | 1 | 0.21 | 0.50 | 0.50 | -0.47 | -0.45 | -0.36 | -0.15 | -0.55 | -0.24 | -0.09 |
| $4 \log L_{4500}$ | 0.34 | 0.10 | 0.21 | 1 | 0.28 | 0.37 | -0.36 | -0.36 | -0.07 | -0.09 | -0.44 | 0.08 | -0.16 |
| $5 \Delta V_{peak}$ (C IV) | 0.51 | -0.11 | 0.50 | 0.28 | 1 | 0.68 | -0.49 | -0.50 | -0.39 | -0.25 | -0.45 | 0.05 | -0.07 |
| $6 \Delta b_{line}$ (C IV) | 0.44 | -0.19 | 0.50 | 0.37 | 0.68 | 1 | -0.51 | -0.53 | -0.34 | -0.25 | -0.48 | -0.03 | -0.09 |
| $7 \log L_{peak}$ [C IV/1450Å] | -0.63 | -0.07 | -0.47 | -0.36 | -0.49 | -0.51 | 1 | 0.65 | 0.60 | 0.77 | 0.58 | -0.20 | 0.07 |
| $8 \log L_{peak}$ [C IV/SiOIV] | -0.51 | 0.03 | -0.45 | -0.36 | -0.50 | -0.53 | 0.65 | 1 | 0.47 | 0.45 | 0.43 | -0.08 | 0.03 |
| $9 \log L_{peak}$ [C IV/C III] | -0.36 | 0.09 | -0.36 | -0.07 | -0.39 | -0.34 | 0.60 | 0.47 | 1 | -0.55 | 0.23 | -0.03 | -0.15 |
| $10 \log$ EW (C IV) | -0.11 | 0.07 | -0.15 | -0.09 | -0.25 | -0.25 | 0.77 | 0.45 | 0.45 | -0.55 | 1 | -0.08 | -0.06 | -0.13 |
| $11 \log \left( L_{peak}$ (C IV) $/ L$ (C IV) $\right)$ | -0.83 | -0.20 | -0.55 | -0.44 | -0.45 | -0.48 | 0.58 | 0.43 | 0.23 | -0.08 | 1 | -0.23 | 0.28 |
| $12 \log \left( \frac{FWHM (Mg II)}{FWHM (C IV)} \right)$ | 0.22 | 0.60 | -0.24 | 0.08 | 0.05 | -0.03 | -0.20 | -0.08 | -0.03 | -0.06 | -0.23 | 1 | -0.19 |
| $13 \log \left( \frac{L_{3000}}{L_{1450}} \right)$ | -0.19 | -0.10 | -0.09 | -0.16 | 0.07 | -0.09 | -0.07 | 0.03 | -0.15 | -0.13 | 0.28 | -0.19 | 1 |

| DR12Q correlations | | | | | | | | | | | | | |
| $2 \log$ FWHM (C IV) | 1 | 0.14 | 0.71 | 0.39 | 0.37 | 0.39 | -0.53 | -0.46 | -0.33 | -0.01 | -0.50 | 0.16 | -0.01 |
| $2 \log$ FWHM (Mg II) | 0.14 | 1 | -0.60 | 0.08 | 0.01 | -0.08 | -0.01 | 0.07 | 0.04 | 0.08 | -0.11 | 0.58 | 0.02 |
| $3 \log$ FWHM [C IV/Mg II] | 0.71 | -0.60 | 1 | 0.25 | 0.29 | 0.37 | -0.41 | -0.42 | -0.29 | -0.07 | -0.32 | -0.29 | -0.03 |
| $4 \log L_{1450}$ | 0.39 | 0.08 | 0.25 | 1 | 0.31 | 0.43 | -0.37 | -0.53 | -0.27 | -0.06 | -0.29 | 0.11 | 0.14 |
| $5 \Delta V_{peak}$ (C IV) | 0.37 | 0.01 | 0.29 | 0.31 | 1 | 0.66 | -0.39 | -0.37 | -0.29 | -0.13 | -0.22 | 0.01 | 0.08 |
| $6 \Delta b_{line}$ (C IV) | 0.39 | -0.08 | 0.37 | 0.43 | 0.66 | 1 | -0.45 | -0.46 | -0.29 | -0.14 | -0.27 | -0.02 | 0.03 |
| $7 \log L_{peak}$ [C IV/1450Å] | -0.53 | -0.01 | -0.41 | -0.37 | -0.39 | -0.45 | 1 | 0.59 | 0.53 | 0.58 | 0.28 | -0.11 | -0.04 |
| $8 \log L_{peak}$ [C IV/SiOIV] | -0.46 | 0.07 | -0.42 | -0.53 | -0.37 | -0.46 | 0.59 | 1 | 0.47 | 0.27 | 0.26 | -0.08 | -0.09 |
| $9 \log L_{peak}$ [C IV/C III] | -0.33 | 0.04 | -0.29 | -0.27 | -0.29 | -0.29 | 0.53 | 0.47 | 1 | -0.30 | 0.16 | -0.07 | -0.28 |
| $10 \log$ EW (C IV) | -0.01 | 0.08 | -0.07 | -0.06 | -0.13 | -0.14 | 0.58 | 0.27 | -0.30 | 1 | -0.61 | 0.00 | -0.04 |
| $11 \log \left( L_{peak}$ (C IV) $/ L$ (C IV) $\right)$ | -0.50 | -0.11 | -0.32 | -0.29 | -0.22 | -0.27 | 0.28 | 0.26 | 0.16 | -0.61 | 1 | -0.10 | 0.01 |
| $12 \log \left( \frac{FWHM (Mg II)}{FWHM (C IV)} \right)$ | 0.16 | 0.58 | -0.29 | 0.11 | 0.01 | -0.02 | -0.11 | -0.08 | -0.07 | 0.00 | -0.10 | 1 | -0.07 |
| $13 \log \left( \frac{L_{3000}}{L_{1450}} \right)$ | -0.01 | 0.02 | -0.03 | 0.14 | 0.08 | 0.03 | -0.04 | -0.09 | -0.28 | -0.04 | 0.01 | -0.07 | 1 |