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# The most luminous blue quasars at $3.0 < z < 3.3$

## II. C IV/X-ray emission and accretion disc physics

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### ABSTRACT

We analyse the properties of the high-ionisation C IV  $\lambda 1549$  broad emission line in connection with the X-ray emission of 30 bright, optically selected quasars at  $z \approx 3.0\text{--}3.3$  with pointed *XMM-Newton* observations, which were selected to test the suitability of active galactic nuclei as cosmological tools. In our previous work, we found that a large fraction ( $\approx 25\%$ ) of the quasars in this sample are X-ray under-luminous by factors of  $>3\text{--}10$ . As absorbing columns of  $\gtrsim 10^{23} \text{ cm}^{-2}$  can be safely ruled out, their weakness is most likely intrinsic. Here we explore possible correlations between the UV and X-ray features of these sources to investigate the origin of X-ray weakness with respect to X-ray-normal quasars at similar redshifts. We fit the UV spectra from the Sloan Digital Sky Survey of the quasars in our sample and analyse their C IV properties – for example equivalent width (EW) and line peak velocity ( $v_{\text{peak}}$ ) – as a function of the X-ray photon index and 2–10 keV flux. We confirm the statistically significant trends of C IV  $v_{\text{peak}}$  and EW with UV luminosity at 2500 Å for both X-ray-weak and X-ray-normal quasars, as well as the correlation between X-ray weakness (parametrised through  $\Delta\alpha_{\text{ox}}$ ) and C IV EW. In contrast to some recent work, we do not observe any clear relation between the 2–10 keV luminosity and  $v_{\text{peak}}$ . We find a statistically significant correlation between the hard X-ray flux and the integrated C IV flux for X-ray-normal quasars, which extends across more than three (two) decades in C IV (X-ray) luminosity, whilst X-ray-weak quasars deviate from the main trend by more than 0.5 dex. We argue that X-ray weakness might be interpreted in a starved X-ray corona picture associated with an ongoing disc-wind phase. If the wind is ejected in the vicinity of the black hole, the extreme-UV radiation that reaches the corona will be depleted, depriving the corona of seed photons and generating an X-ray-weak quasar. Nonetheless, at the largest UV luminosities ( $>10^{47} \text{ erg s}^{-1}$ ) there will still be an ample reservoir of ionising photons that can explain the ‘excess’ C IV emission observed in the X-ray-weak quasars with respect to normal sources of similar X-ray luminosities.

**Key words.** galaxies: active – quasars: general – quasars: supermassive black holes – methods: statistical

## 1. Introduction

Active galactic nuclei (AGN) represent a phase that almost all galaxies will undergo in their lifetime, where the supermassive black hole (SMBH) located in the galaxy centre starts to efficiently accrete matter in the form of a disc (e.g. Soltan 1982). The flow of matter towards the SMBH dissipates angular momentum through viscous friction, heating the disc that will shine at ultraviolet (UV) wavelengths (e.g. Salpeter 1964; Lynden-Bell 1969). The spectral energy distribution (SED) of AGN also presents significant emission ( $\sim 10\text{--}30\%$  of their total luminosity) at high energies ( $>0.1 \text{ keV}$ ), which cannot be produced directly from the accretion disc but is rather interpreted as Comptonised radiation originating in a plasma of hot relativistic electrons in the vicinity of the SMBH, the so-called X-ray corona. The intrinsic nature of this corona is still uncertain, but the existence of a non-linear correlation between the continuum UV (at 2500 Å,  $L_{\text{UV}}$ ) and X-ray (at 2 keV,

$L_{\text{X}}$ ) emission implies a physical connection between the disc and the corona (e.g. Tananbaum et al. 1979; Zamorani et al. 1981; Vignali et al. 2003; Steffen et al. 2006; Just et al. 2007; Lusso et al. 2010; Martocchia et al. 2017). The observation that this non-linear correlation is very tight ( $\leq 0.2$  dex of scatter; Lusso & Risaliti 2016), with a slope independent of redshift, indicates that a strong synergy between disc and corona must subsist in AGN across cosmic time (e.g. Nicastro 2000; Merloni 2003; Lusso & Risaliti 2017; Arcodia et al. 2019).

The tight  $L_{\text{X}}\text{--}L_{\text{UV}}$  relation also allows us to accurately estimate the X-ray luminosity of a quasar for any given UV luminosity in order to define a standard range of soft X-ray emission for typical (i.e. non-broad absorption line, non-jetted, with minimal deviation due to absorption) quasars, or vice versa, to easily identify peculiar objects (e.g. intrinsically X-ray weak, with strong radio jets, or extremely red). The former case is important in designing clean quasar samples with cosmological value, where systematics and biases are minimised (Lusso et al. 2020,

L20 hereafter). In our recent analysis of a sample of 30 quasars at  $z \approx 3.0\text{--}3.3$ , we found that a significant fraction of these high-redshift quasars depart from the  $L_X\text{--}L_{UV}$  relation towards lower X-ray fluxes when compared to quasars with similar UV emission (Nardini et al. 2019, Paper I). This quasar sample was selected from the Sloan Digital Sky Survey (SDSS) to be representative of the most luminous, intrinsically blue quasar population at  $z \approx 3$ , for which we have obtained good-quality X-ray spectra from a dedicated *XMM-Newton* campaign. The main aim of this observational campaign was to investigate the evolution of the quasar Hubble diagram at high redshift, making use of a highly homogeneous sample in terms of UV properties (for details on its cosmological application, see Risaliti & Lusso 2019, RL19 hereafter). We thus presumed that all 30 quasars would follow the  $L_X\text{--}L_{UV}$  relation. Nonetheless, we discovered that  $\approx 25\%$  of the targets present an X-ray emission much weaker than expected, by factors of  $>3$ . This fraction is significantly larger than those previously reported for radio-quiet, non-broad absorption line (BAL) quasars at lower redshift and luminosity ( $\approx 10\%$ ; e.g. Gibson et al. 2008; see also Brandt et al. 2000).

In this paper, the second of a series dedicated to the study of the physical properties of these 30 high-redshift quasars, we focus on the connection between their UV (i.e. CIV and continuum) and X-ray emission to better understand the origin X-ray weakness for the sub-sample of objects that depart from the  $L_X\text{--}L_{UV}$  relation. The paper is organised as follows: In Sect. 2 we describe the dataset and its selection, whilst Sect. 3 is dedicated to the UV observations and spectral analysis. Results and a relative discussion are presented in Sects. 4 and 5, respectively. Conclusions are drawn in Sect. 6.

## 2. The data set

The sample analysed here consists of 30 luminous ( $L_{bol} > 10^{47}$  erg s $^{-1}$ ) quasars in a narrow redshift interval,  $z = 3.0\text{--}3.3$ , for which X-ray observations were obtained through an extensive campaign performed with *XMM-Newton* (cycle 16, proposal ID: 080395, PI: Risaliti), for a total exposure of 1.13 Ms. This sample, selected in the optical from the SDSS Data Release 7 to be representative of the most luminous, intrinsically blue radio-quiet quasars, boasts by construction a remarkable degree of homogeneity in terms of optical/UV properties. Figure 1 shows the distribution of redshift<sup>1</sup>, rest-frame monochromatic luminosity at 2500 Å (derived from the fit of the SDSS spectra, as described in Sect. 3 and Appendix B) and bolometric luminosity (computed from the UV luminosity at 1350 Å, as listed in Shen et al. 2011) for the 30 quasars. All the sources were selected to be radio-quiet (with radio loudness parameter  $R = L_{2500\text{Å}}/L_{1.4\text{GHz}} < 10$ ). The only quasar in the sample that was conservatively flagged as radio-bright is SDSS J090033.50+421547.0 ( $R \approx 2\text{--}2.5$ ; more details on the sample selection in the Supplementary Material of RL19). We thus exclude J0900+42 from any general consideration regarding the sample.

### 2.1. A sample of bright blue quasars

The  $z \approx 3$  quasar sample was filtered to retain minimum levels of both dust reddening and host-galaxy contamination. To select the targets, we followed a similar approach to the one presented in our previous works (Risaliti & Lusso 2015; Lusso & Risaliti

<sup>1</sup> We considered the improved redshifts for SDSS quasars computed by Hewett & Wild (2010).

2016; RL19). We briefly summarise below the main points. We built the rest-frame photometric SEDs to compute, for each object, the slopes  $\Gamma_1$  and  $\Gamma_2$  of a  $\log(\nu)\text{--}\log(\nu L_\nu)$  power law in the rest-frame ranges  $0.3\text{--}1\text{ }\mu\text{m}$  and  $1450\text{--}3000\text{ Å}$ , respectively (see also Hao et al. 2013). We discuss how we constructed the SEDs in Appendix A, whilst Fig. A.1 presents the full SEDs of the  $z \approx 3$  quasars from the near-infrared to the X-rays.

The wavelength intervals for  $\Gamma_1$  and  $\Gamma_2$  were chosen based on the fact that the SED of an ‘intrinsically’ blue quasar displays a different shape from the one of an inactive galaxy or a dust-reddened AGN. On the one hand, the intrinsic quasar SED is characterised by a dip around  $1\text{ }\mu\text{m}$ , where the galaxy has the peak of the emission from the passive/old stellar population (e.g. Elvis et al. 1994, 2012; Richards et al. 2006; Shang et al. 2011; Krawczyk et al. 2013). On the other hand, as dust reddening is wavelength dependent, the UV part of the quasar SED will be attenuated differentially. These two concurrent factors impact on the quasar SED shape, so we can define a set of slopes that single out quasars with minimum levels of both host-galaxy emission and dust reddening (see also Fig. 1 in Hao et al. 2013).

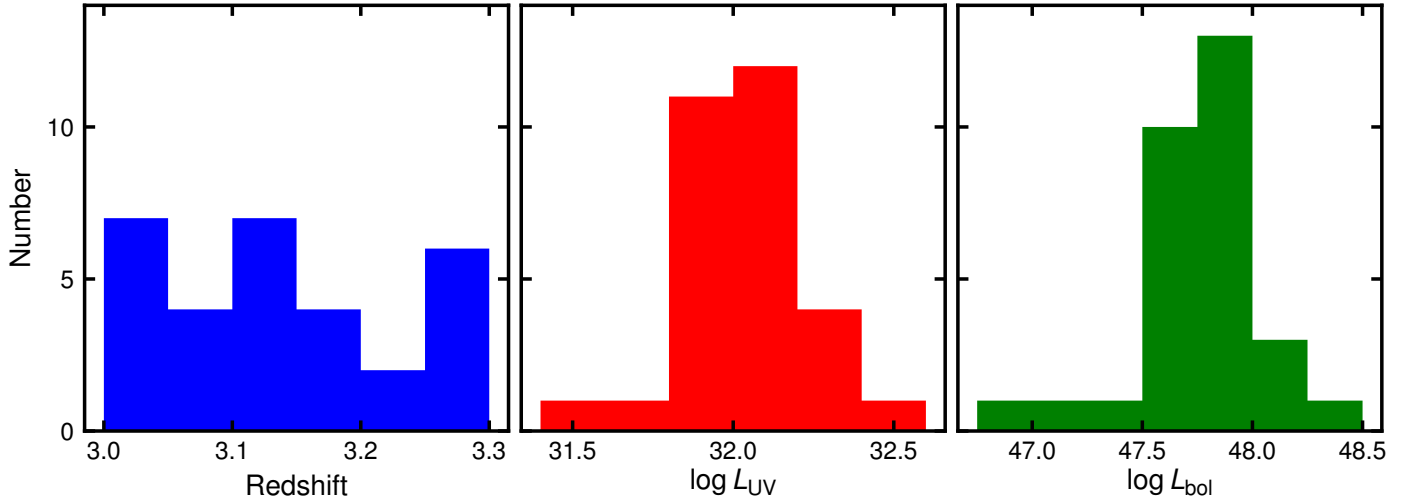
The  $\Gamma_1\text{--}\Gamma_2$  distribution for the  $z \approx 3$  quasars is shown in Fig. 2. We assumed a standard SMC extinction law  $k(\lambda)$  after Prevot et al. (1984), with  $R_V = A(V)/E(B\text{--}V) = 3.1$  (as appropriate for unobscured AGN; Hopkins et al. 2004; Salvato et al. 2009), to estimate the  $\Gamma_1\text{--}\Gamma_2$  correlation as a function of extinction, parametrised by the colour excess  $E(B\text{--}V)$ . The red dashed line in Fig. 2 shows how  $E(B\text{--}V)$  varies in the  $\Gamma_1\text{--}\Gamma_2$  plane, where the green circle (with a radius corresponding to a reddening  $E(B\text{--}V) \approx 0.1$ ) is centred at the reference values for a standard quasar SED of Richards et al. (2006, i.e.  $\Gamma_1 = 0.82$ ,  $\Gamma_2 = 0.40$ ) with zero extinction. The distribution of  $\Gamma_1\text{--}\Gamma_2$  values along the red dashed line is indicative of possible dust reddening, growing in the outward direction, whilst sources with markedly smaller (i.e. negative)  $\Gamma_1$  values are objects with possible host-galaxy contamination (see Risaliti & Lusso 2015; Lusso & Risaliti 2016; RL19 for further details). It is clear from Fig. 2 that the majority of the  $z \approx 3$  quasars are blue with negligible absorption by dust, with  $E(B\text{--}V) < 0.08$ . Only one quasar, J1459+00, has  $E(B\text{--}V) \approx 0.1$ , and it was selected to test our threshold value in the  $\Gamma_1\text{--}\Gamma_2$  plane.

### 2.2. The X-ray data

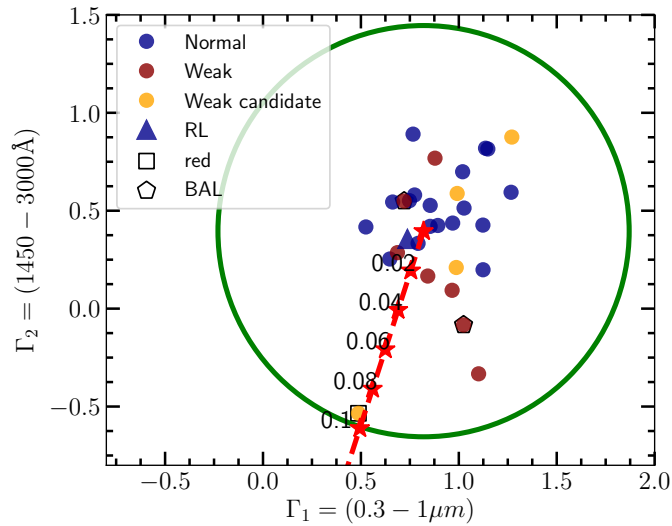
The X-ray spectroscopic data have been extensively analysed in the first paper on this sample; the interested reader should refer to Paper I for details. Here we briefly summarise the main results we obtained from our X-ray analysis.

Twenty-five quasars in the sample are found to be extremely X-ray luminous, with rest-frame 2–10 keV luminosities of  $0.5\text{--}7 \times 10^{45}$  erg s $^{-1}$ . Their continuum photon index distribution shows an average  $\Gamma_X \sim 1.85$ , in excellent agreement with objects at lower redshift, luminosity, and black-hole mass (e.g. Just et al. 2007; Bianchi et al. 2009). Three sources turned out to be very faint (J1159+31, J1425+54, and J1507+24), but we can at least rely on a marginal detection with the EPIC/pn (see Table 1 in Paper I). Only one target (J0945+23) can be formally considered as undetected, given a spurious detection level of 4%. In the following, we consider for the latter four quasars the more conservative flux value computed by assuming a fixed  $\Gamma_X = 1.8$  and free  $N_H$ , thus taking into account intrinsic absorption (see Sect. 4.3 in Paper I for more details; the resulting upper limits are listed in their Table 2).

Yet, our quasars show an unexpectedly diverse behaviour when we plot them in the  $\log L_X\text{--}\log L_{UV}$  plane. In Fig. 3 we



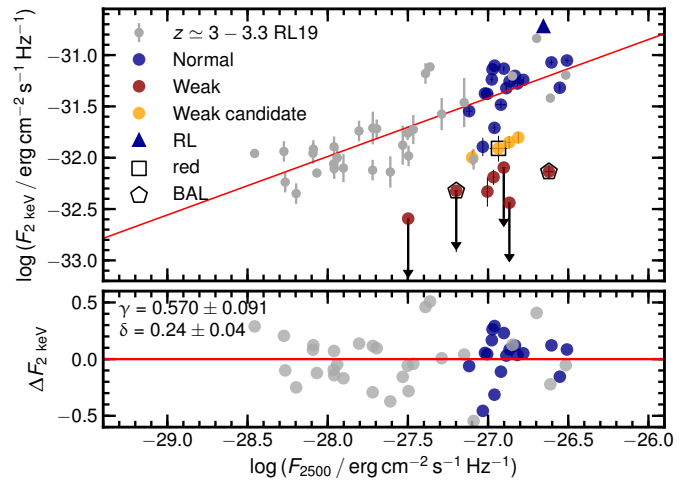
**Fig. 1.** From left to right: distribution of redshift, rest-frame monochromatic luminosity at  $2500 \text{ \AA}$ , and bolometric luminosity (as listed in Shen et al. 2011) for the 30 sources in our  $z \approx 3$  quasar sample.



**Fig. 2.** Distribution of the  $z \approx 3$  quasar sample in the  $\Gamma_1$ – $\Gamma_2$  plot, where  $\Gamma_1$  and  $\Gamma_2$  are the slopes of a power law in the  $\log(\nu)$ – $\log(\nu F_\nu)$  plane in the  $0.3$ – $1 \mu\text{m}$  and  $1450$ – $3000 \text{ \AA}$  intervals (see Sect. 2.1), respectively. The red stars represent the  $\Gamma_1$ – $\Gamma_2$  values of the quasar SED by Richards et al. (2006) with increasing dust reddening (following the extinction law of Prevot et al. 1984), with  $E(B-V)$  in the range  $0$ – $0.1$ . All quasars are within  $E(B-V) = 0.1$ , as marked by the green circle. Blue, brown, and orange symbols represent X-ray-normal quasars, X-ray-weak quasars, and X-ray-weak candidates, respectively, following the definition in Sect. 2.3. The triangle, pentagon, and square symbols mark the radio-bright (J0900+42), BALs (J1148+23, J0945+23), and reddest (J1459+00) quasars in the sample.

illustrate the relation between the rest-frame monochromatic fluxes in the X-rays at  $2 \text{ keV}$  and in the UV at  $2500 \text{ \AA}$  for quasars at  $z = 3.0$ – $3.3$ <sup>2</sup>, where the grey points represent the remaining quasars in the redshift range of interest from the cleaned sample of RL19 (30 objects; see their supplementary figure 4). We refer the reader to RL19 (see also L20) for a detailed discussion of their selection criteria.

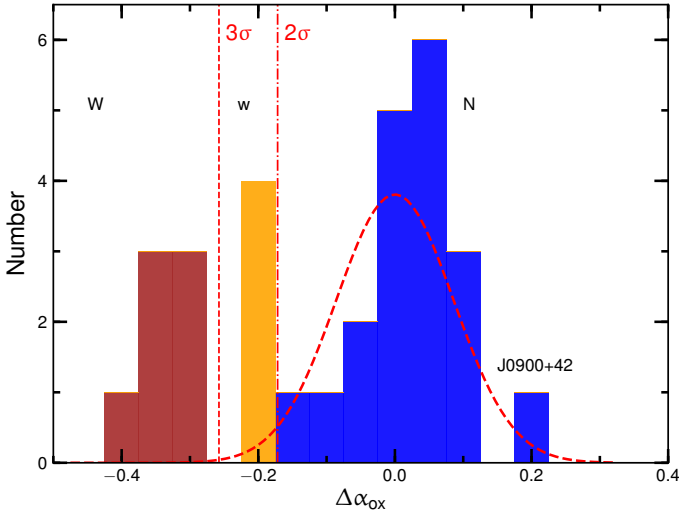
<sup>2</sup> Given the narrow redshift range, we can equivalently deal with fluxes or luminosities.



**Fig. 3.** Relation between the rest-frame monochromatic X-ray ( $2 \text{ keV}$ ) and UV ( $2500 \text{ \AA}$ ) fluxes for quasars in the redshift range  $z = 3.0$ – $3.3$ . The colour code is the same as that adopted in Fig. 2 for the different sub-samples defined in Sect. 2.3. Grey points represent the other sources in the same redshift range from the cleaned quasar sample of RL19 (30 objects). The red line is the regression best fit for the  $z = 3.0$ – $3.3$  RL19 sources only. Slope and dispersion values are reported with the residuals from the best fit in the bottom panel (from which X-ray weak, in brown, and weak candidates, in orange, are omitted for clarity).

The red line in Fig. 3 is the regression best fit of the  $z = 3.0$ – $3.3$  RL19 quasars (grey points only). The observed slope is  $\gamma = 0.570 \pm 0.090$ , and the intercept is  $\beta = -0.318 \pm 0.048$ <sup>3</sup>, with a dispersion  $\delta = 0.24 \pm 0.03$ . While most of the  $z \approx 3$  sources analysed here are clustered around the best-fit relation, a significant fraction ( $\approx 25\%$ ) of them appear to be X-ray under-luminous by factors of  $>3$ – $10$ . Interestingly, the reddest quasar in our sample is not amongst the most deviating objects, suggesting that our selection in the  $\Gamma_1$ – $\Gamma_2$  plane does not play a major role in driving this deviation.

<sup>3</sup> The  $\beta$  value incorporates a normalisation (in logarithm) of  $-27.7$  and  $-31.5$  on the monochromatic UV and X-ray fluxes, respectively.

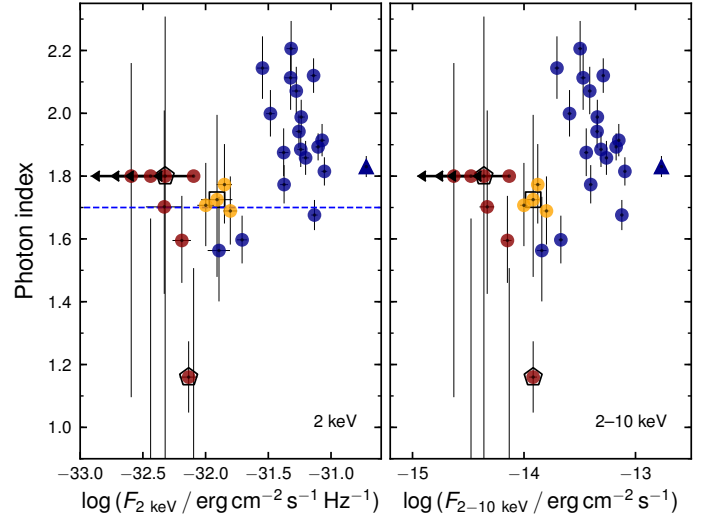


**Fig. 4.** Distribution of  $\Delta\alpha_{\text{ox}}$  in the  $z \approx 3$  sample (see Sect. 2.3 for details). The dashed curve is the best fitting normal distribution for the 25 radio-quiet sources with unquestionable X-ray detection (we also neglected the radio-bright quasar J0900+42), where the peak position is forced to be at  $\Delta\alpha_{\text{ox}} = 0$ . We define as X-ray-weak (*W*) and X-ray-weak candidates (*w*) all the sources at more than  $3\sigma$  (seven objects, brown histogram) and  $2\sigma$  (four objects, orange histogram) from the peak, respectively. All the other quasars are considered as X-ray normal (*N*, blue histogram).

### 2.3. The X-ray-weak quasar fraction

In Paper I we reported on the surprisingly high fraction ( $\approx 25\%$ ) of X-ray-weak sources among our  $z \approx 3$  blue quasars, much larger than previously found for radio-quiet, non-BAL quasars at lower redshift and luminosity. The definition of X-ray weakness is discussed at length in Sect. 5.6 of Paper I, and it is based on the non-linearity of the X-ray to UV correlation. This produces the well-known anti-correlation between  $\alpha_{\text{ox}}$ , defined as  $\alpha_{\text{ox}} = 0.384 \log(F_X/F_{\text{UV}})$ , and  $L_{\text{UV}}$  (e.g. Lusso & Risaliti 2016, 2017, and references therein), as the UV-to-X-ray part of the quasar SED becomes steeper with higher UV luminosities. The  $L_X-L_{\text{UV}}$  relation is thus utilised as a natural benchmark to determine the extent of any intrinsic X-ray weakness.

We distinguish X-ray-normal from X-ray-weak quasars in our sample by computing the differences ( $\Delta\alpha_{\text{ox}}$ ) between the observed and predicted values of  $\alpha_{\text{ox}}$ . To obtain the expected  $\alpha_{\text{ox}}$  to be compared to the observed values, we assumed as the reference  $F_X-F_{\text{UV}}$  relation the one shown in Fig. 3, determined from the 30 objects in the clean sample of RL19 in the same redshift range as the  $z \approx 3$  quasars. Figure 4 presents the distribution of the differences ( $\Delta\alpha_{\text{ox}}$ ) between the observed and predicted values of  $\alpha_{\text{ox}}$  for all the 30  $z \approx 3$  quasars. The dashed curve is the best-fitting normal distribution, with the peak position forced at  $\Delta\alpha_{\text{ox}} = 0$ , for the 25 radio-quiet sources with solid X-ray detection (the radio-bright quasar J0900+42 is conservatively excluded from the fit). We define as X-ray weak (*W*) and X-ray-weak candidates (*w*) all the sources that fall at more than  $3\sigma$  (seven objects) and  $2\sigma$  (four objects) from the peak of the distribution, respectively. The remaining 18 quasars are then labelled as X-ray normal (*N*). Figure 5 reproduces the continuum photon index against the intrinsic flux density at rest-frame 2 keV and integrated 2–10 keV flux, as presented in Paper I. The dashed line in the left panel indicates the minimum  $\Gamma_X$  value adopted by RL19 to define the clean quasar sample for cosmology. Eighteen sources (15 *N* and 3 *w*) are located above this limit.



**Fig. 5.** X-ray properties of the  $z \approx 3$  quasars. *Left panel:* continuum photon index against intrinsic flux density at rest-frame 2 keV, as measured in Paper I. The colour code is the same as that adopted in the previous figures. The dashed line represents the minimum photon index value ( $\Gamma_X = 1.7$ ) adopted by RL19 to select the clean quasar sample for cosmology. *Right panel:* same for the intrinsic rest-frame flux integrated in the 2–10 keV band.

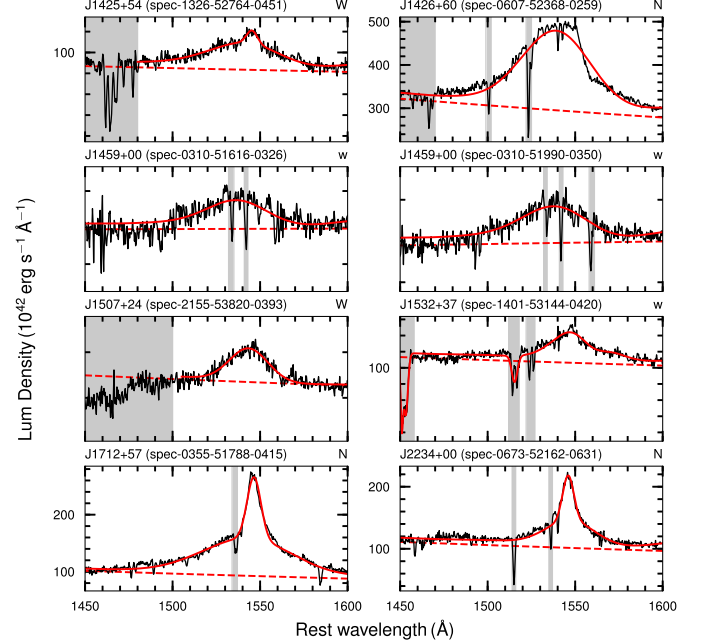
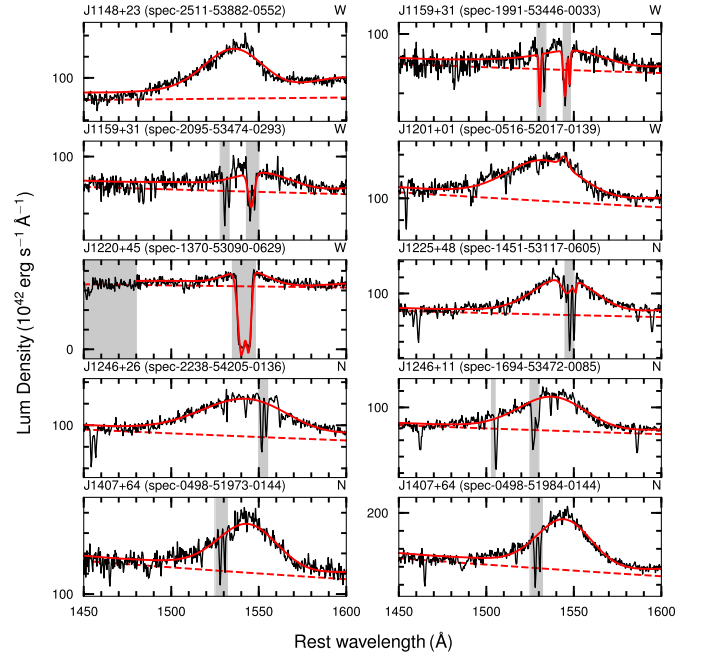
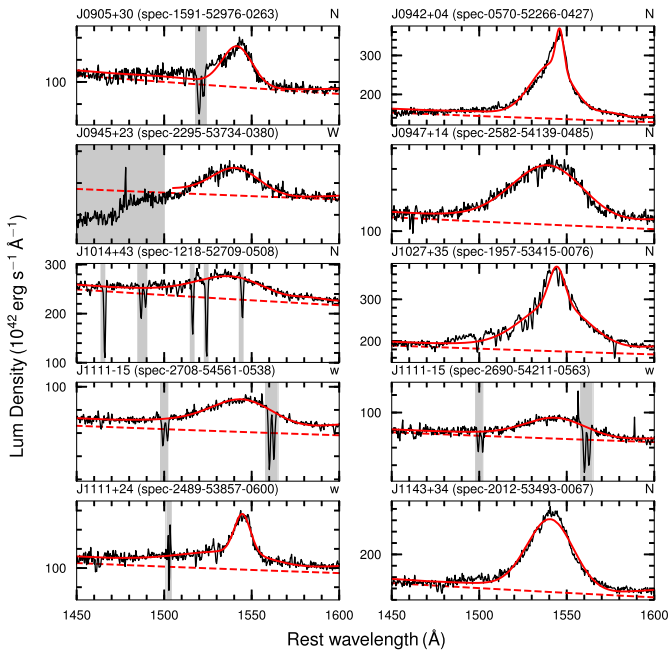
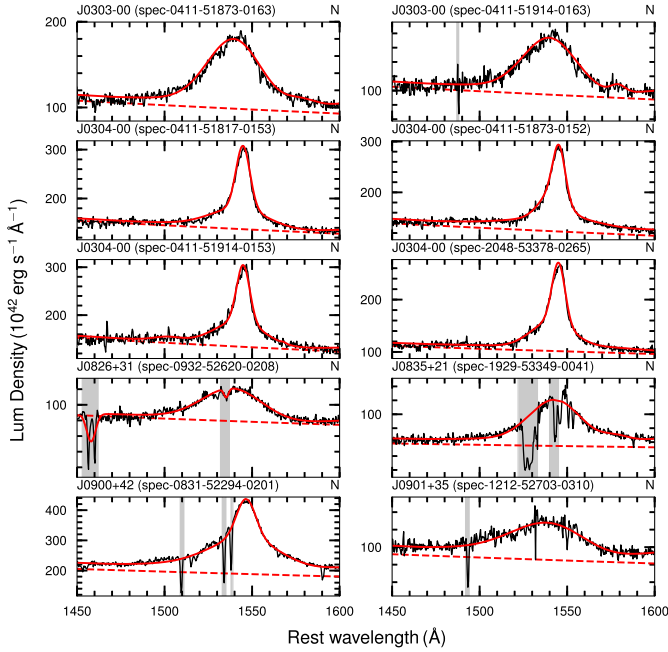
The majority of the  $z \approx 3$  quasars have a photon index consistent with (within the uncertainties) or higher than 1.7, with only 4 objects (all classified as *W*) displaying a much flatter ( $\Gamma_X \lesssim 1.4$ ) continuum.

### 3. Ultraviolet spectral fit

The main aim of this paper is to connect the X-ray properties of the  $z \approx 3$  sample with the UV ones (e.g. emission-line strength, continuum luminosity) to provide an interpretation of the observed X-ray weakness. We thus carried out a detailed spectral fitting of all the SDSS spectra, also considering multiple observations, using both a custom-made code and the publicly available package for spectral fitting QSFIT (Calderone et al. 2017). The spectral fitting was performed independently with each tool, and the relative results were then compared.

Our custom-made code is based on a procedure that uses the IDL MPFIT package (Markwardt 2009), written with the purpose of a simultaneous fitting of continuum, Fe II complex (both optical and UV), and several emission lines. The spectra were corrected for Galactic extinction using the  $E(B-V)$  values from Schlafly & Finkbeiner (2011) and the Fitzpatrick (1999) reddening law with  $R_V = 3.1$ . Broad lines were fitted with a broken power law, convolved with a Gaussian function to avoid the presence of a cusp at the peak (Nagao et al. 2006). This profile is particularly useful when dealing with emission-line complexes, and it helps in limiting the degeneracy in the fits. Narrow lines were fitted with a Gaussian profile, as well as blue/red asymmetries if required by the data. For more details, the interested reader should refer to Bisogni et al. (2017a, see their Sect. 3).

We also independently fitted the SDSS data making use of QSFIT. We modelled each spectrum as follows: the C IV emission line was reproduced by a broad ( $FWHM > 2000 \text{ km s}^{-1}$ ) profile and, whenever required, an additional narrow component ( $FWHM < 2000 \text{ km s}^{-1}$ ), whilst the continuum includes the contributions from the iron UV complex and the AGN continuum. The spectra were corrected for Galactic extinction using the



**Fig. 6.** Fits to the C IV emission line of the 38 SDSS quasar spectra. The data are shown in black, the best fitting model in red, and the continuum with the dashed red line. The source ID, the name of the SDSS spectrum FITS file, and a flag for the X-ray normal (*N*), X-ray weak (*W*), and X-ray-weak candidates (*w*) are shown at the top of each panel. Grey shaded areas highlight bad pixels and/or strong absorption features that are either masked in the fit or considered in the fit to improve the least  $\chi^2$ .

$E(B-V)$  values from Schlegel et al. (1998) and the parametrisation by Cardelli et al. (1989) and O’Donnell (1994), with a total to selective extinction  $R_V = 3.1$  (Calderone et al. 2017).

Making use of different parametrisations for the Fe II complex, reddening values, extinction laws, and line profiles allows us to check their effect on the output parameters.

We searched for all the spectroscopic data in the SDSS archive finding 38 observations, with six quasars having two

**Fig. 6.** continued.

or more spectra. In our analysis we excluded additional BOSS spectroscopy, as its flux calibration may be uncertain<sup>4</sup>. We then started a systematic analysis of the SDSS spectroscopic data of these 38 spectra, focusing mainly on the C IV emission line and the nuclear continuum. Figure 6 shows the best-fit models of the C IV emission line (in red), whilst the continuum is plotted with the red dashed line. The full UV spectra are shown in Fig. B.1. All the output parameters – namely, C IV FWHM and equivalent width (EW), continuum slope, and luminosity – are in good agreement (within a factor of two) between the two different codes. Table B.1 summarises the UV properties, output of the spectral analysis.

<sup>4</sup> See [http://www.sdss3.org/dr9/spectro/caveats.php#qso\\_flux](http://www.sdss3.org/dr9/spectro/caveats.php#qso_flux) for a list of issues in the BOSS flux calibration.

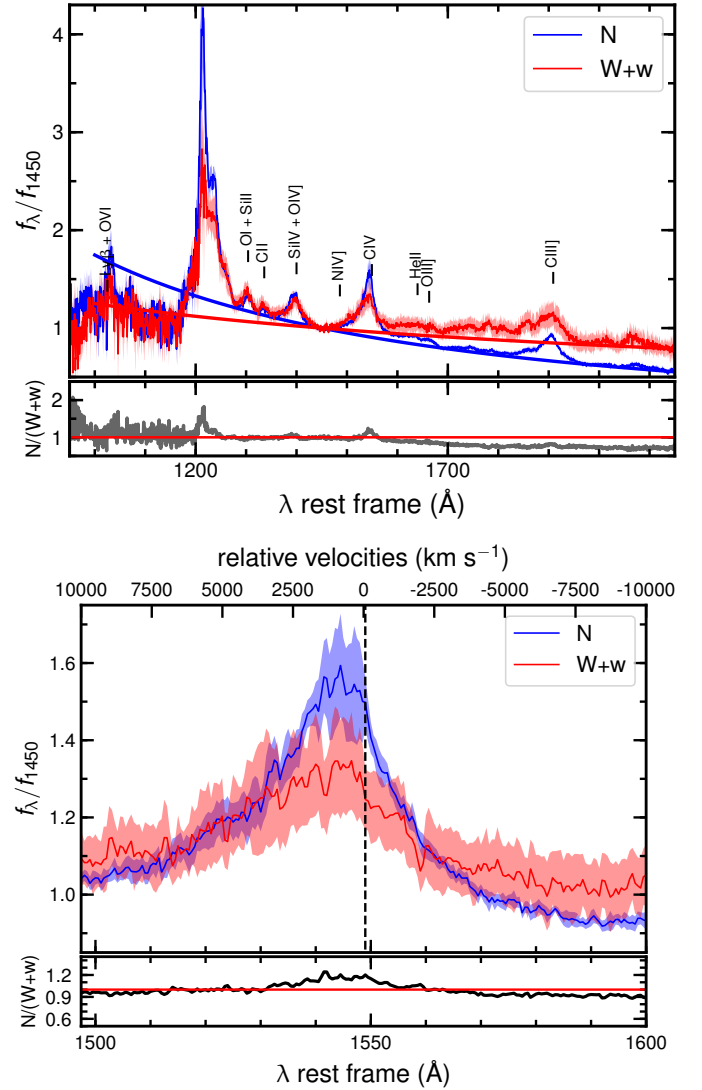
## 4. Results

### 4.1. UV composite of X-ray-normal versus X-ray-weak quasars

The quasars in the  $z \approx 3$  sample are characterised by highly homogeneous UV spectra by construction, with an intrinsically blue continuum. This homogeneity is clearly shown in Paper I (see their Fig. 2), where the  $z \approx 3$  spectral composite is compared with the composite of SDSS AGN of Vanden Berk et al. (2001), and with the one of Lusso et al. (2015), based on 53 quasars at  $z \sim 2.4$  and corrected for intervening absorption by neutral hydrogen in the intergalactic medium. A mild decrease in the emission-line strength due to the Baldwin effect (Baldwin 1977) is observed, but it is clear that both the UV continuum and the overall spectral properties of our sources are in good agreement with the expected intrinsic quasar spectrum.

Following the same methodology for the composite construction as in Paper I (see also Lusso et al. 2015), we also built two separate stacks for the  $N$  and the  $W+w$  sub-samples. Figure 7 (top panel) shows the resulting mean quasar spectra. These stacks are obtained from a mean of the SDSS spectra, each normalised to unit flux at 1450 Å, with uncertainties estimated from bootstrap (shaded areas). The spectral ratio between the  $N$  and  $W+w$  sub-samples is also shown with a black line. The radio-bright (J0900+42), the two BALs (J1148+23, J0945+23), and the reddest quasar (J1459+00) are excluded when building the stacks, since we want to compare possible different spectral features between  $N$  and  $W+w$  sources that may not be connected to their BAL or red (e.g. flatter UV slope) nature. The stack of the  $N$  sub-sample is thus composed by 23 spectra, whilst the  $W+w$  one contains 10 spectra.

There are two main differences between the quasar composites, although the statistics are such that uncertainties are significant. First, the  $W+w$  stack displays a slightly redder (flatter) UV continuum slope ( $\alpha_\lambda \approx -0.6$ )<sup>5</sup> with respect to the  $N$  one ( $\alpha_\lambda \approx -1.5$ ). Second, emission lines in the  $W+w$  stack are broader and fainter than in the  $N$  one. The latter property is also evident in the bottom panel of Fig. 7, where we show the velocity shift from the rest-frame wavelength of the CIV emission-line transition (1549 Å) for the  $N$  and  $W+w$  composites. The emission line presents a mild blueshift<sup>6</sup> of  $\approx 1000 \text{ km s}^{-1}$  with respect to the reference wavelength<sup>7</sup>, and an asymmetric profile towards the blue side in both stacks. Yet, the CIV emission line is broader ( $FWHM \approx 10\,000 \text{ km s}^{-1}$ ) in the  $W+w$  than in the  $N$  composite ( $\approx 7000 \text{ km s}^{-1}$ ). Within the uncertainties, however, these features are consistent with quasars at similar redshifts (e.g. Richards et al. 2002; Shen et al. 2011) and luminosities (e.g. Vietri et al. 2018) for both the  $N$  and  $W+w$  stacks<sup>8</sup>. We stress that the  $z \approx 3$  sample was selected to be ‘blue’, with minimal levels of UV absorption (as shown in Fig. 2), and to span a narrow range of UV fluxes (see Figs. 1 and 3); therefore, any



**Fig. 7.** Spectral stacks of the  $z \approx 3$  quasars. *Top panel:* mean observed quasar spectra for the X-ray normal ( $N$ , blue) and X-ray weak plus X-ray-weak candidates ( $W+w$ , red). These composites are estimated from a stack of the SDSS spectra (23  $N$  and 10  $W+w$  spectra), each normalised to unit flux at 1450 Å with uncertainties from bootstrap analysis (shaded area). The UV continuum slopes for the  $N$  and  $W+w$  composites are shown with the blue and red lines, respectively. *Bottom panel:* zoom-in of the CIV emission line for the  $N$  and  $W+w$  composites. The velocity shift from the rest-frame transition wavelength (1549 Å) is shown on the top x axis. In both panels, the ratio of the  $N$  over the  $W+w$  mean spectra is also shown at the bottom with a black line.

difference between the  $N$  and  $W+w$  sub-samples in the UV is minimised by construction.

Even if the difference in the  $N$  and  $W+w$  spectral properties is not statistically significant, the mild variation between these two sub-samples may hint at a higher incidence of outflowing gas in the  $W+w$  sub-sample with respect to the  $N$  one (the former displaying a higher blueshift and a broader profile of the CIV emission line). To confirm this interpretation, we have embarked upon a near-IR observational campaign (covering the rest-frame optical) with the Large Binocular Telescope (LBT) located in Mount Graham, Arizona, which will provide a better estimate of the systemic redshift from narrow emission lines (e.g. [O III]). Moreover, broad emission components in the rest-frame optical

<sup>5</sup> The relation between the flux densities in wavelength ( $f_\lambda \propto \lambda^{\alpha_\lambda}$ ) and frequency ( $f_\nu \propto \nu^{\alpha_\nu}$ ) space is given by  $\alpha_\nu = -(2 + \alpha_\lambda)$ .

<sup>6</sup> In the general sign convention, blueshifts correspond to ‘negative’ velocity shifts. Here, for simplicity, we assign to blueshift a positive velocity value, which is equivalent to adopting the natural quasar frame (see Richards et al. 2002).

<sup>7</sup> The average CIV emission-line shift for radio-quiet quasars in the SDSS is  $\sim 810 \text{ km s}^{-1}$  (Richards et al. 2011).

<sup>8</sup> We also note that the redshifts for the  $z \approx 3$  sample could still be uncertain by about  $600\text{--}800 \text{ km s}^{-1}$ , since they are based on UV lines (Hewett & Wild 2010).

with blueward asymmetry, such as that observed in the [O III] forbidden line (e.g. [Bischetti et al. 2017](#); [Vietri et al. 2018](#), and references therein), also probe ionised gas that may be in an out-flowing phase at much larger (kpc) scales. We discuss this point further in Sect. 5.

#### 4.2. X-ray parameters as a function of the UV spectral properties

Evidence of correlations involving the C IV and X-ray spectral properties has been reported and widely discussed in the context of the Eigenvector 1 formalism (e.g. [Sulentic et al. 2000, 2007](#); [Marziani & Sulentic 2014](#), and references therein). Recent studies have found that the connection between C IV and X-ray parameters also apply to extremely luminous ( $L_{\text{bol}} > 10^{47}$  erg s $^{-1}$ ), high-redshift ( $z \sim 2-4$ ) quasars ([Martocchia et al. 2017](#); [Vietri et al. 2018](#); [Zappacosta et al. 2020](#)). Nonetheless, previously analysed samples are characterised by a rather high level of inhomogeneity regarding their classification, often comprising a mixed bag of various different types such as BALs, radio-loud and UV-red quasars. By contrast, here we can leverage on the uniform selection of the  $z \approx 3$  sample.

Figure 8 presents the key X-ray properties (i.e. continuum slope and intensity) as a function of C IV emission-line characteristics computed for the 38 SDSS spectra. In the first two rows from top, the X-ray photon index and the 2–10 keV flux values are plotted against the FWHM, the rest-frame EW, the UV continuum slope ( $\alpha_{\nu}$ ) and the total C IV flux. The distribution of each UV parameter is shown in the third row. The red dot-dashed line in the  $\alpha_{\nu}$  panel marks an UV continuum slope of  $-0.5$ , typical for  $z > 2$  quasars ([Lusso et al. 2015](#)), while the red solid line is the  $\Gamma_{\text{X}}$  threshold adopted by [RL19](#) to select the clean quasar sample for cosmology. The cut at  $\Gamma_{\text{X}} = 1.7$  clearly singles out quasars with a typical blue SED in the UV. The fourth and fifth rows show how  $\Gamma_{\text{X}}$  and  $F_{2-10\text{keV}}$  are distributed as a function of the velocity of the C IV line peak ( $v_{\text{peak}}$ , computed with respect to the nominal wavelength), the velocity shift of the centroid of the C IV line (first momentum of the flux distribution), the second momentum of the flux distribution ( $\sigma$ ), and the asymmetry index (AS $^9$ ). Following the definition in [Shen & Liu \(2012\)](#), redward and blueward asymmetries correspond to AS values  $> 1$  and  $< 1$ , respectively. The dot-dashed line marks AS = 1, which is usual for sources of lower UV luminosities and redshifts, while the red shaded area is the typical dispersion on this parameter of 0.22 dex.

The only statistically significant correlation is revealed between  $F_{2-10\text{keV}}$  and  $F_{\text{CIV}}$ , with the blue solid and red dotted lines representing the best-fit regression solutions considering the  $N$  and  $N+W+w$  objects, where radio-bright, BALs and the reddest quasar in our sample are excluded. Figure 9 illustrates the same correlation in luminosities. We performed a regression analysis finding a statistically significant correlation at the  $\sim 3\sigma$  level in the case of the  $z \approx 3$   $N$  quasars, for which

$$\log(L_{2-10\text{keV}} - 45) = (0.50 \pm 0.18)(\log L_{\text{CIV}} - 45) + 0.30 \pm 0.10, \quad (1)$$

with an estimated dispersion of  $0.17 \pm 0.04$  dex. If we perform the regression analysis on the entire  $z \approx 3$  sample, but excluding

the radio-bright quasar, the correlation becomes

$$\log(L_{2-10\text{keV}} - 45) = (1.14 \pm 0.18)(\log L_{\text{CIV}} - 45) - 0.12 \pm 0.08. \quad (2)$$

The observed  $L_{2-10\text{keV}}-L_{\text{CIV}}$  correlation is more significant in the latter case ( $\approx 9\sigma$ ), when the  $W$  and  $w$  quasars are also included. However, the dispersion is much larger ( $0.28 \pm 0.05$  dex) with respect to the same relation for the  $N$  objects only. All the sources at  $L_{2-10\text{keV}} < 10^{45}$  erg s $^{-1}$  are either  $W$  or  $w$ , and also show lower emission-line luminosities, consistent with what we observe in their UV spectral composite in Fig. 7.

Figure 9 also includes 11 sources from the WISE/SDSS-selected hyper-luminous quasar (WISSH) survey analysed by [Martocchia et al. \(2017\)](#), for which both  $L_{\text{CIV}}$  and  $L_{2-10\text{keV}}$  are available $^{10}$ . The WISSH quasars include 3 radio emitting objects and one BAL, which are marked accordingly in Fig. 9. The WISSH subset follows the  $L_{\text{CIV}}-L_{2-10\text{keV}}$  relation, and its inclusion does not significantly change our results when all the quasars are considered.

Summarising, we have explored the hard X-ray band flux and the X-ray photon index as a function of several UV spectral features, finding no significant correlation apart from the one we observe between the X-ray flux and the integrated flux of the C IV emission line.

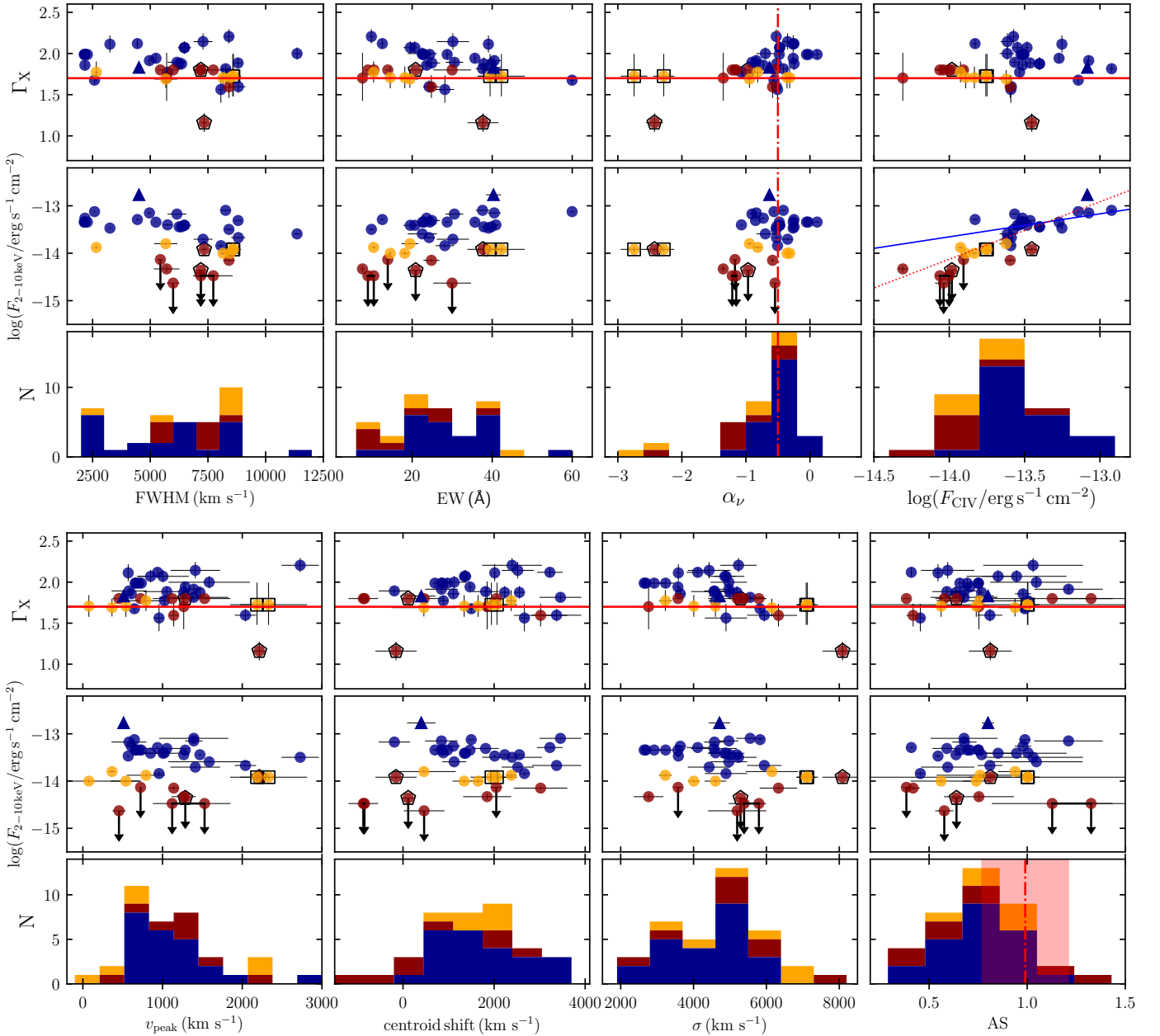
#### 4.3. Comparison with other samples: On the relations with the C IV EW

As already pointed out by [Gibson et al. \(2008\)](#), there is a possible correlation between  $\Delta\alpha_{\text{ox}}$  and  $\log(\text{CIV EW})$ , significant at the  $>99.99\%$  level. We observe the same correlation in the  $z \approx 3$  sample, significant at the  $\sim 98.5\%$  despite the lower statistics, according to both Pearson's  $\rho$  and Kendall's  $\tau$  tests. Such a correlation is interpreted in the context of the quasar disc-wind scenario (e.g. [Elvis 2000](#)), where high-ionisation lines are associated with the presence of a wind component exposed to the quasar UV continuum. Since the  $z \approx 3$  quasars are probing the bright end of the quasar luminosity function, we want to compare their properties with those of a lower redshift/luminosity sample selected in a similar way. The work of [Gibson et al. \(2008\)](#) was recently expanded by [Timlin et al. \(2020, T20 hereafter\)](#), who examined 2106 quasars selected from the SDSS-DR14 in the redshift range  $1.7 \leq z \leq 2.7$ , with archival *Chandra* serendipitous observations. We singled out quasars with blue colours (i.e.  $\Delta(g-i) \leq 0.45$ ; see their Sect. 3), flagged as non-BAL, and with a radio-loudness value (estimated from the ratio of the 2500-Å and the 6-cm flux densities) lower than 10. These criteria to a sample of 1106 'typical' quasars, of which 637 have a measurement of the rest-frame EW for the C IV emission line.

To visualise possible differences between the lower- and higher-redshift (and luminosity) samples, we compare their rest-frame monochromatic luminosities  $\log L_{\text{X}}$  against  $\log L_{\text{UV}}$  in Fig. 10. Sources with an available C IV measurement (T20/C IV) are highlighted with an open circle and span about 2 decades in both UV and X-ray luminosities, and they are preferentially located at lower values than the  $z \approx 3$  quasars, as expected. There is no significant difference in either the UV or X-ray luminosity distributions of the sub-sample with C IV measurements with respect to typical quasars. In the following we

$^9$  The AS parameter is defined as  $\ln(\lambda_{\text{red}}/\lambda_{\text{peak}})/\ln(\lambda_{\text{peak}}/\lambda_{\text{blue}})$ , where  $\lambda_{\text{red}}$  e  $\lambda_{\text{blue}}$  are the wavelengths at half-width of the line profile in the red and blue part, respectively.

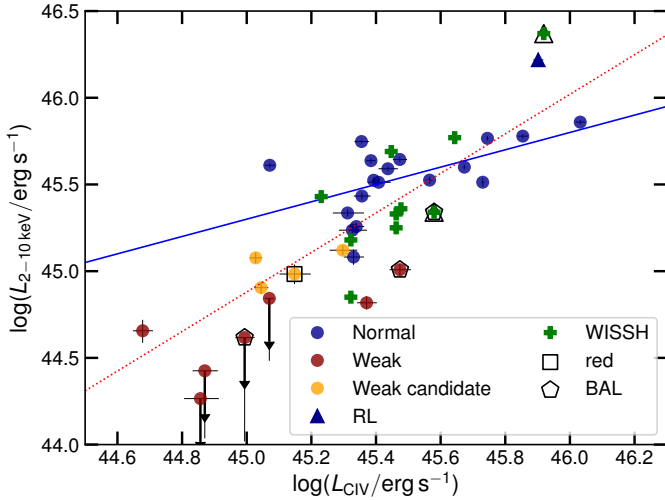
$^{10}$  We excluded two quasars with a  $L_{\text{CIV}}$  measurement but an upper limit in the hard X-ray band. Amongst the 11 WISSH sources, the radio-bright quasar is in common with our sample.



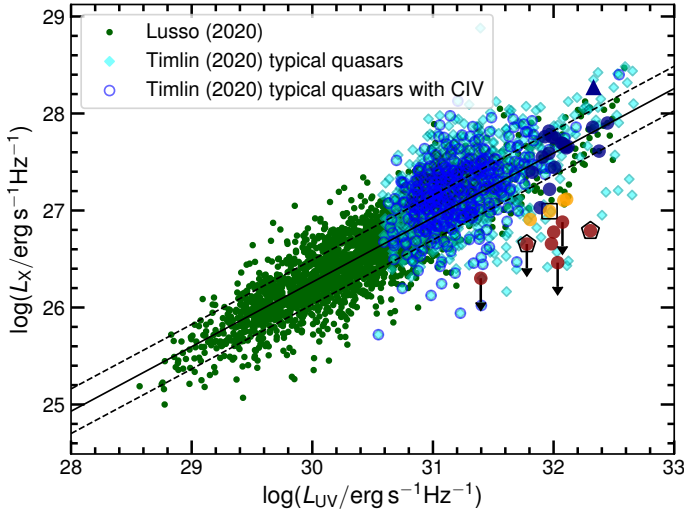
**Fig. 8.** X-ray versus CIV emission-line properties for the 38 SDSS spectra. In the *first two rows from the top*, the continuum photon index and the 2–10 keV flux (in  $\text{erg s}^{-1} \text{cm}^{-2}$ ) are plotted against the CIV FWHM (in  $\text{km s}^{-1}$ ), EW (in  $\text{\AA}$ ), the UV continuum slope ( $\alpha_\nu$ ), and the total CIV emission-line flux (in  $\text{erg s}^{-1} \text{cm}^{-2}$ ), the distributions of which are shown in the *third row*. The solid red line at  $\Gamma_X = 1.7$  represents the minimum value adopted by RL19 to select the clean quasar sample for cosmology. The dot-dashed red line in the  $\alpha_\nu$  panel marks a UV continuum slope of  $-0.5$ , typical for  $z > 2$  quasars (Lusso et al. 2015). Only  $F_{2-10\text{keV}}$  shows a significant correlation with  $F_{\text{CIV}}$ , where the solid blue and dotted red lines represent the best-fit regression solutions for  $N$  and  $N+W+w$  sources (radio-bright, BALs, and red quasars are excluded; see Sect. 2.1). In the *fourth and fifth rows*,  $\Gamma_X$  and  $F_{2-10\text{keV}}$  are plotted as a function of the CIV peak velocity  $v_{\text{peak}}$  (with respect to the nominal wavelength), the velocity shift of the line centroid, the velocity dispersion  $\sigma$ , and the asymmetry index (AS). Redward (blueward) asymmetries correspond to AS values  $>1$  ( $<1$ ), where the dot-dashed line marks  $\text{AS} = 1$  (as generally found at lower UV luminosity and redshift) and the red shaded area the typical dispersion on this parameter of 0.22 dex.

thus focus on the sample with the CIV emission-line properties available. Figure 10 also shows the sample of  $\sim 2400$  quasars from L20, with the relative regression line (with a slope  $\gamma = 0.665 \pm 0.007$ ) for comparison. The dashed lines trace the  $1\sigma$  dispersion, 0.23 dex. The L20 sample is composed by 2421 optically selected quasars (mostly from SDSS) with X-ray data from *XMM-Newton* and *Chandra*, and it spans a redshift interval  $0.009 \leq z \leq 7.541$ , with a mean (median) redshift of 1.442 (1.295). These sources were selected to have minimal contami-

nation from the host galaxy emission (this is especially important for the  $z < 0.7$  AGN) and minimal dust/gas absorption. The Eddington bias is also taken into account. Details about the sample selection are provided in their Sect. 5. Most of the  $z \approx 3$   $N$  quasars are included in the L20 sample. As a whole, the T20/CIV quasar sample is located at relatively bright X-ray and UV luminosities, and is characterised by a much higher dispersion in the  $\log L_X - \log L_{\text{UV}}$  relation (0.32 dex). The slope  $\gamma = 0.540 \pm 0.060$  is flatter with respect to L20, but consistent within a



**Fig. 9.** X-ray luminosity at 2–10 keV ( $\text{erg s}^{-1}$ ) as a function of the total integrated C IV line luminosity ( $\text{erg s}^{-1}$ ). Green plus symbols represent ten quasars from the WISSH sample (Martocchia et al. 2017).



**Fig. 10.** Rest-frame monochromatic luminosities  $\log L_X$  against  $\log L_{UV}$  for the 30 quasars in our  $z \approx 3$  sample. The colour coding is the same as in the previous figures. The green dots represent the sample of  $\sim 2400$  quasars from L20, with the relative regression line. The dashed lines trace the  $1\sigma$  dispersion, 0.23 dex. We overplotted the sample of typical quasars from Timlin et al. (2020), where sources with an available C IV measurement are highlighted with a blue circle.

$2\sigma$  statistical level. The L20 sample was built by applying more stringent constraints than the one considered in T20 (e.g. possibly X-ray absorbed AGN with  $\Gamma_X < 1.7$  were excluded). However, since our focus here is to verify the presence of possible correlations between the X-ray and UV properties of quasars at high redshift, we do not need to reduce the dispersion in the T20 sample further.

Figures 11 and 12 show the comparison of the X-ray weakness parameter  $\Delta\alpha_{\text{ox}}$ , photon index  $\Gamma_X$ ,  $L_{2-10\text{keV}}$ , and  $\log L_{UV}$ , as a function of the rest-frame C IV EW between the  $z \approx 3$  and T20/C IV samples. Since the  $\Delta\alpha_{\text{ox}}$  values for the  $z \approx 3$  sample were computed assuming a different relation (see Sect. 2.3) with respect to the one employed by T20 (i.e.  $\alpha_{\text{ox}} = -0.199 \log L_{UV} + 4.573$ ; see their Eq. (3) and related discussion in their Sect. 4.1), we decided to modify our  $\Delta\alpha_{\text{ox}}$  by assuming for consistency their

$\alpha_{\text{ox}} - \log L_{UV}$  relation as a benchmark. The difference between our original  $\Delta\alpha_{\text{ox}}$  values for the  $z \approx 3$  sample and the new ones is about  $-0.08$ , thus the applied correction shifts all the data points to slightly higher values.

The  $z \approx 3$  sample follows a similar trend to the one published by T20, namely,  $\Delta\alpha_{\text{ox}} = 0.185 \log(\text{C IV EW}) - 0.315$  (with a reported dispersion of 0.10 dex), which is plotted in Fig. 11 with the solid line. Even with the modified  $\Delta\alpha_{\text{ox}}$  values, the W quasars will be still considered as such ( $\Delta\alpha_{\text{ox}} \leq -0.2$ ). The T20 sample extends to larger C IV EW than the  $z \approx 3$  quasars, which is expected given the relative ranges of UV luminosities and the Baldwin effect. The  $z \approx 3$  quasars are selected in a very narrow  $L_{UV}$  range, as shown in Fig. 12, whilst the T20 sample is located at much lower UV luminosities. For this reason, the  $z \approx 3$  N quasars also have higher hard X-ray luminosities than the T20 sample, but do not show any statistical trend with C IV EW. The  $\Gamma_X$  values of our high-redshift N quasars are consistent with the lower-redshift and lower-luminosity T20 sample, and again no statistical trend with C IV EW is present.

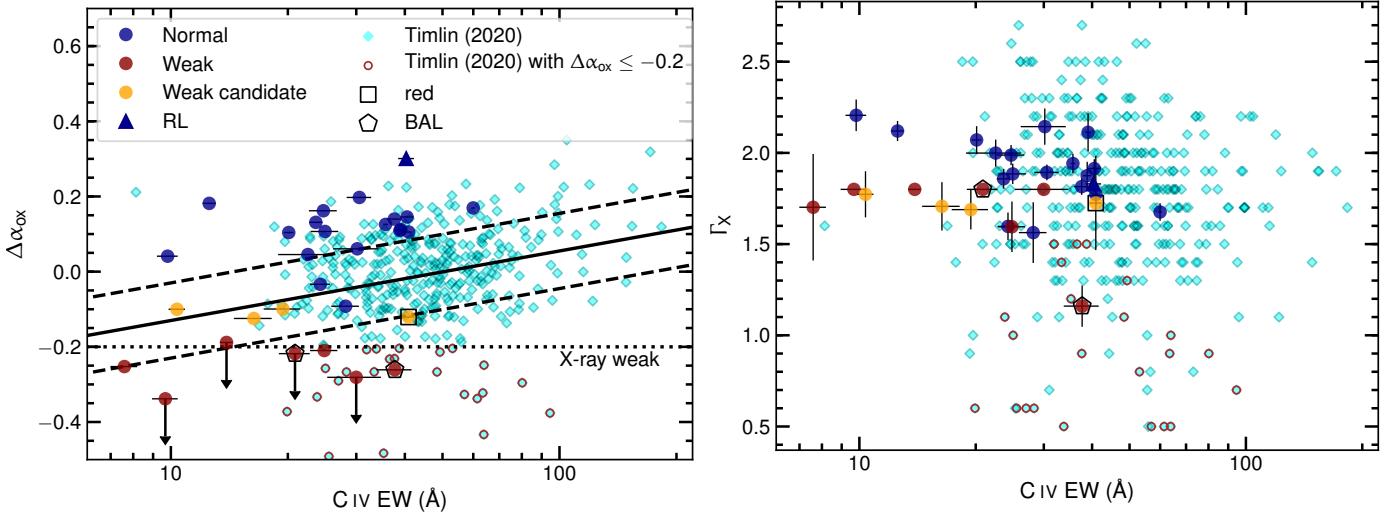
We also report the best-fit regression line published by T20 between C IV EW and  $L_{UV}$  (their Eq. (8); see also Green et al. 2001). The  $z \approx 3$  quasars follow the same relation as observed for the T20 AGN sample. This negative trend is due to the well-known Baldwin effect of the C IV line: the brighter the ionising source, the fainter (in terms of EW) the emission line (e.g. Green 1996; Dietrich et al. 2002). Together, these two samples cover almost three decades in UV luminosity, and the brightest quasars tend to be located at low C IV EW values. However, X-ray-weak quasars show no preference of C IV EW values, covering a range in both UV luminosity and C IV EW similar to that of X-ray-normal quasars.

#### 4.4. Comparison with other samples: On the relations with the C IV velocity shift

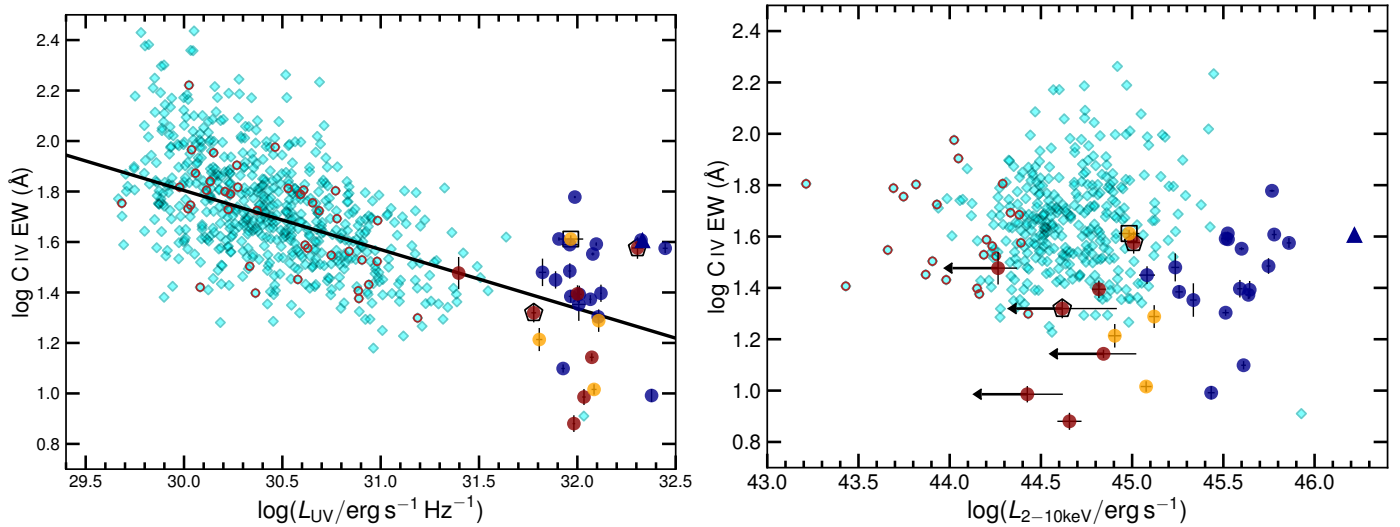
The C IV emission line centroid usually shows a blueshift (up to about  $10\,000 \text{ km s}^{-1}$ ) with respect to the laboratory wavelength or the systemic redshift measured from the narrow emission lines (e.g. Gaskell 1982; Wilkes 1984). Such a property is often observed in bright quasars and it is usually ascribed to the presence of strong winds (e.g. Richards et al. 2002, 2011; Baskin & Laor 2005).

Recently, Zappacosta et al. (2020) reported on a strong correlation between  $v_{\text{peak}}$  and the unabsorbed 2–10 keV luminosity  $L_{2-10\text{keV}}$  for a sample of 13 WISSH quasars at  $2.075 \leq z \leq 3.490$ , with X-ray observations from *XMM-Newton* and/or *Chandra* and C IV emission-line properties available (Vietri et al. 2018). Figure 13 (right) shows such a correlation and the relative dispersion, where we have included our  $z \approx 3$  sample. The N quasars occupy the top right corner of the  $L_{2-10\text{keV}} - v_{\text{peak}}$  plane and are in very good agreement with the observed trend, whilst the W and X objects have  $v_{\text{peak}}$  values consistent with the N quasars in spite of their fainter  $L_{2-10\text{keV}}$ .

Figure 13 also shows the location in the  $L_{2-10\text{keV}} - v_{\text{peak}}$  plane of the lower-redshift and lower-luminosity T20 sample. Given their  $v_{\text{peak}}$  in the range  $\sim 500 - 2000 \text{ km s}^{-1}$  and fainter  $L_{2-10\text{keV}}$  values, the T20 quasars extend the coverage to low  $L_{2-10\text{keV}}$  values, with no observed trend of an decreasing  $v_{\text{peak}}$  (or blueshift) with increasing  $L_{2-10\text{keV}}$ . The absence of a relation between  $L_{2-10\text{keV}}$  and  $v_{\text{peak}}$  in the T20 sample could be due to the lack of strong outflows in these sources, since also their UV luminosity is much lower than that observed in the higher-redshift samples, as shown in the left panel of Fig. 13. There is, however, a strong correlation between  $v_{\text{peak}}$  and  $L_{UV}$  for the T20 sample, and our



**Fig. 11.**  $\Delta\alpha_{\text{ox}}$  (*left*) and photon index  $\Gamma_X$  (*right*) as a function of the rest frame C IV EW for the  $z \approx 3$  and T20/C IV samples. The  $\Delta\alpha_{\text{ox}}$  values for the  $z \approx 3$  sample have been adjusted to be consistent with T20 (see text for details). The solid line in the *left panel* is the  $\Delta\alpha_{\text{ox}}$ -C IV EW relation reported by T20 (see their Eq. (4)). X-ray-weak quasars in T20 ( $\Delta\alpha_{\text{ox}} \leq -0.2$ ) are marked with brown open circles.



**Fig. 12.**  $L_{\text{UV}}$  (*left*) and  $L_{2-10\text{keV}}$  (*right*) as a function of the rest frame C IV EW for the  $z \approx 3$  and T20/C IV samples. The solid line in the *left panel* is the C IV EW- $L_{\text{UV}}$  relation reported by T20 (see their Eq. (8)). X-ray-weak quasars in T20 ( $\Delta\alpha_{\text{ox}} \leq -0.2$ ) are marked with brown open circles.

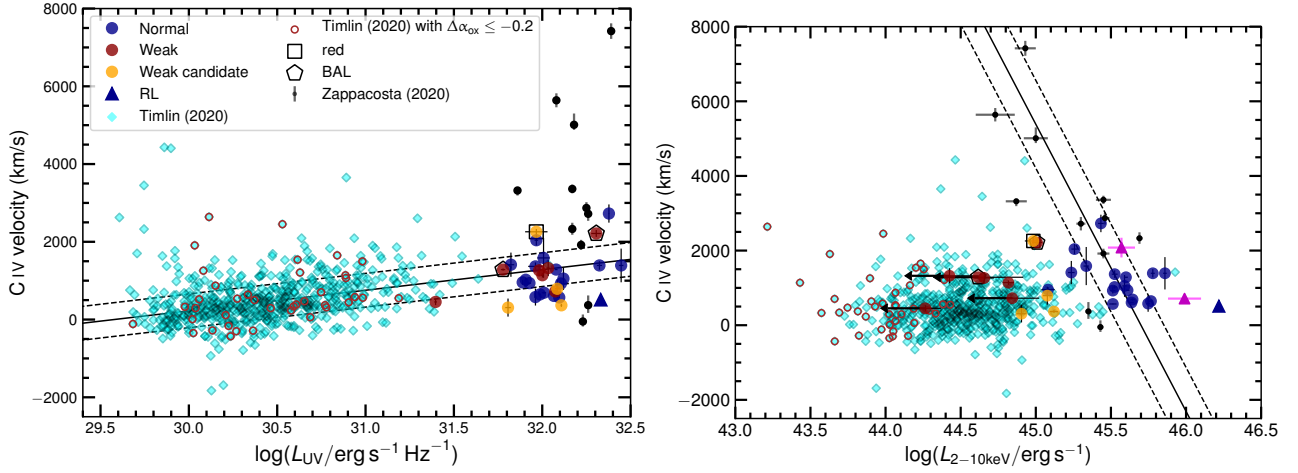
$z \approx 3$  quasars are located at the high end of this  $v_{\text{peak}}-L_{\text{UV}}$  relation. Zappacosta et al. (2020), instead, observed no statistically significant correlation between  $v_{\text{peak}}$  and  $L_{\text{UV}}$ , which can be due to the combination of low sample statistics and the fact that the WISSH quasars (likewise ours) probe too narrow a range of  $L_{\text{UV}}$  values. Since the T20 data are covering a much wider range of  $L_{\text{UV}}$ , we believe that such a correlation is real, and both our  $z \approx 3$  and the WISSH sources are sampling its brighter end. Given the scatter of the relation, and the presence of a few outliers (with  $v_{\text{peak}}$  higher than a few thousand  $\text{km s}^{-1}$ ) also in the T20 sample, we argue that the WISSH data alone are not sufficient to determine if a relation between  $L_{2-10\text{keV}}$  and  $v_{\text{peak}}$  exists, since it can be simply driven by a few peculiar objects<sup>11</sup>.

<sup>11</sup> The three most deviating objects with high blueshifts ( $v_{\text{peak}} > 5000 \text{ km s}^{-1}$ ) in the  $v_{\text{peak}}-L_{\text{UV}}$  plane, which are the main drivers of the  $L_{2-10\text{keV}}-v_{\text{peak}}$  correlation seen in the WISSH sample, are J0958+2827 ( $z = 3.434$ ,  $\Gamma_X = 1.87^{+0.79}_{-0.64}$ ), J1421+4633 ( $z = 3.454$ ,  $\Gamma_X = 1.30^{+0.39}_{-0.36}$ ) and J1521+5202 ( $z = 2.218$ ,  $\Gamma_X = 1.71^{+0.41}_{-0.39}$ ). The  $\Delta\alpha_{\text{ox}}$

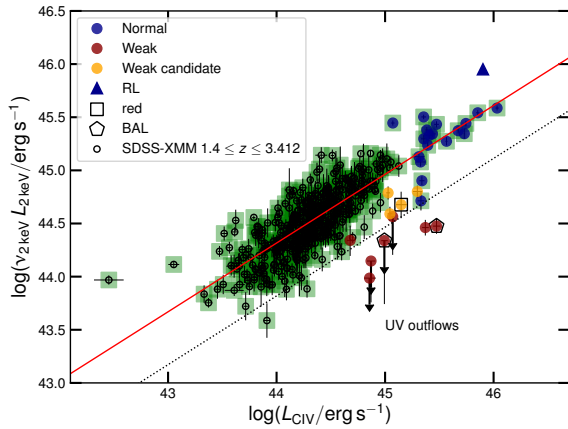
It is worth noting that different investigations use slightly different definitions of  $v_{\text{peak}}$ . T20 defines the C IV blueshift (in units of  $\text{km s}^{-1}$ ) as  $c(1549.06 - \lambda_{\text{peak}})/1549.06$ , where  $\lambda_{\text{peak}}$  is the measured peak of the modelled C IV emission line (in  $\text{\AA}$ ),  $1549.06 \text{ \AA}$  is the C IV laboratory wavelength and  $c$  is the speed of light. Also, the C IV velocity shifts in Zappacosta et al. (2020) are measured from the modelling of the emission line, but they refer to the line centroid offset with respect to the systemic redshift (see Fig. 2 in Vietri et al. 2018 and relative discussion). Our velocity shifts are computed with respect to the C IV vacuum wavelength as in T20. Nonetheless, we note that differences of even several hundreds of  $\text{km s}^{-1}$  amongst the different analyses would not change our conclusions.

Summarising, we confirm a relation between  $v_{\text{peak}}$  and  $L_{\text{UV}}$  across three decades in  $L_{\text{UV}}$  from  $z \approx 1.7$  up to  $z \approx 3.5$ , whilst

parameter reported by Zappacosta et al. (2020) for these objects would place them at the boundary between *W* and *w* (they all have  $\Delta\alpha_{\text{ox}} \approx -0.25$ ).



**Fig. 13.**  $L_{UV}$  (left) and  $L_{2-10\text{keV}}$  (right), as a function of the rest frame C IV peak velocity shift for the  $z \approx 3$ , T20/C IV, and WISSH (Zappacosta et al. 2020) samples (we excluded two quasars that overlap with our  $z \approx 3$  sample), and five additional  $z \approx 3.2-3.7$  quasars with available  $v_{\text{peak}}$  (published by Coatman et al. 2017, magenta triangles, we neglected three overlaps with our  $z \approx 3$  sample). The solid line in the left panel is the C IV  $v_{\text{peak}}-L_{UV}$  best-fit relation by T20, whilst the one in the right panel is the  $L_{2-10\text{keV}}-C\text{ IV } v_{\text{peak}}$  best-fit relation reported by Zappacosta et al. (2020, see their Table 1). X-ray-weak quasars in T20 ( $\Delta\alpha_{\text{ox}} \leq -0.2$ ) are marked with brown open circles.



**Fig. 14.** X-ray luminosity at 2 keV as a function of the total integrated C IV line luminosity. Green squares highlight the sources used in the MCMC regression line analysis. Black circles describe a lower-redshift and lower-luminosity SDSS-XMM sample with a robust measurement of the integrated C IV line luminosity (Signorini et al., in prep.). The dotted line represents three times the intrinsic dispersion on the relation,  $\sim 0.5$  dex.

we do not observe a statistically significant correlation between  $v_{\text{peak}}$  and  $L_{2-10\text{keV}}$ , in contrast to Zappacosta et al. (2020). We argue that the  $v_{\text{peak}}-L_{2-10\text{keV}}$  correlation reported in the latter study is driven by the small sample statistics, as it is not confirmed when including the lower luminosity T20 sample.

#### 4.5. On the relation between X-ray and C IV fluxes

We also checked whether the relation we observe between  $L_{2-10\text{keV}}$  and  $L_{CIV}$  (Fig. 9) is still present when including lower-redshift and lower-luminosity data. We cannot consider at this stage the T20 and WISSH samples as their integrated C IV fluxes are not publicly available. We thus examined a sample of SDSS quasars with the C IV emission line covered by their spectra and an X-ray observation in the latest 4XMM catalogue. The sample is composed by 1761 quasars in the redshift range  $1.703 \leq z \leq 2.697$ , selected to fulfil all the quality criteria dis-

cussed by L20. All the spectra were fitted with QSFIT, and here we consider the quasars with a robust measurement of the C IV spectral properties, leading to 444 sources. All the details will be provided in a forthcoming publication (Signorini et al., in prep.).

We performed a Markov chain Monte Carlo (MCMC) regression analysis of the low-redshift and luminosity sample, where we included the  $z \approx 3$   $N$  quasars (462 sources in total). We considered the relation between the luminosity at 2 keV and  $L_{CIV}$ , but the results do not change when considering  $L_{2-10\text{keV}}$  instead. The choice of using  $L_X$  instead of  $L_{2-10\text{keV}}$  allows us to directly interpret this relation in the context of the  $L_X-L_{UV}$  correlation. We find

$$\log L_X = (0.647 \pm 0.001) \log L_{CIV} + (15.850 \pm 0.001), \quad (3)$$

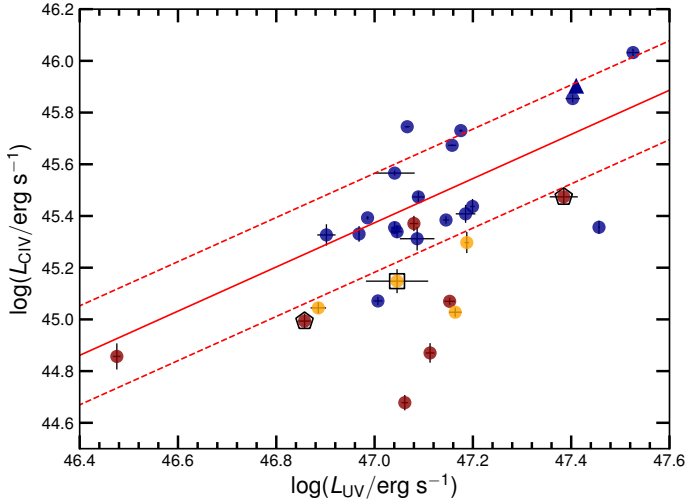
with an estimated intrinsic dispersion of  $0.17 \pm 0.01$  dex (observed dispersion 0.19 dex). Figure 14 presents the X-ray luminosity at 2 keV as a function of the total integrated C IV line luminosity. We overplotted the  $w$ ,  $W$  and the radio-bright quasars, not considered in the fit.  $W$  quasars deviate from the observed relation, being located at faint X-fluxes at a given  $L_{CIV}$ . The slope is similar (slightly steeper<sup>12</sup>) to the one characterising the  $L_X-L_{UV}$  relation, whilst the dispersion of  $\approx 0.17$  dex is akin, if not tighter, with respect to that observed in the  $L_X-L_{UV}$  relation.

## 5. Discussion

We report on a tight relation between X-ray and C IV emission-line fluxes in a homogeneously selected sample of blue quasars at redshift  $z \approx 3$ . The predicted dependence between  $L_{CIV}$  and  $L_{UV}$  can be derived directly from the observed Baldwin effect of the C IV emission line, that is,  $\log(\text{C IV EW}) \propto -0.2 L_{1450}$ , where  $L_{1450}$  is the continuum luminosity at the rest-frame 1450 Å (see Table 1 in Dietrich et al. 2002), which implies a slope of roughly 0.8 between  $L_{CIV}$  and  $L_{UV}$ <sup>13</sup>. We observe a relation

<sup>12</sup> The slope of the  $L_X-L_{UV}$  relation on the C IV sample is  $0.510 \pm 0.018$ .

<sup>13</sup> The rest-frame EW can be written as the ratio between the integrated luminosity of the C IV line and the continuum luminosity at 1549 Å, i.e.  $\text{C IV EW} \approx L_{CIV}/L_{1549}$ . We then assume that  $L_{UV} \propto L_{1549} \propto L_{1450}$ .



**Fig. 15.** Integrated C IV emission line luminosities as a function of the UV luminosities. The regression line (solid red line) is estimated by considering the  $N$  quasars only. We observed a slope of  $0.855 \pm 0.095$  with a standard deviation of 0.19 dex (dashed red lines).

between  $L_{CIV}$  and  $L_{UV}$  for the  $N$  quasars with a slope of  $0.855 \pm 0.095$  (see Fig. 15), in agreement with the expectations. The  $L_X-L_{CIV}$  correlation suggests a strong connection between the relative strength of the X-rays with respect to the UV continuum and the C IV line emission. Specifically, bright high-redshift quasars that appear weaker in the X-rays with respect to the expected emission (if they were to follow the  $L_X-L_{UV}$  relation), also show a weaker C IV line flux compared to objects at similar redshifts. Whilst it is well-known that the C IV emission line is subject to an anti-correlation between its equivalent width and the UV luminosity (i.e. the Baldwin effect), which is more generally associated with the Eigenvector 1 analysis (e.g. Boroson & Green 1992), it is less clear how to connect the C IV properties to the X-ray emission in the X-ray-weak quasars. The  $\alpha_{ox}-L_{UV}$  relationship, thus in turn the  $L_X-L_{UV}$  one, as observed in X-ray-normal, bright blue quasars, is most likely the main driver for the C IV (and overall) Baldwin effect, since the steepening of  $\alpha_{ox}$  with respect to the values observed in quasars of lower UV luminosity leads to a deficit of ionising photons in the far-UV/soft X-rays (e.g. Wu et al. 2009). The  $L_X-L_{CIV}$  correlation could just be a by-product of the  $\alpha_{ox}-L_{UV}$  relationship, yet this does not entirely explain the excess of C IV line flux in the X-ray-weak quasar subset compared to the X-ray-normal quasars of similar X-ray luminosity (see Fig. 14). Kruczek et al. (2011, see also e.g. Richards et al. 2011) found that radio-quiet quasars with both strong C IV line emission and small C IV blueshifts have a flatter  $\alpha_{ox}$  and present significant X-ray emission as compared to the UV, whilst quasars with both weak C IV emission and large C IV blueshifts have a steeper  $\alpha_{ox}$  and weaker X-rays as compared to the UV. Moreover, the former (latter) preferentially exhibit harder (softer) X-ray spectra, with  $\Gamma_X < 2$  ( $\Gamma_X > 2$ ). This is interpreted in the Eigenvector 1 context, which was developed after the study by Boroson & Green (1992, see also Wilkes et al. 1987), who discussed the correlations between the optical, radio, and X-ray continuum (i.e. radio-loudness and  $\alpha_{ox}$ ) and the rest-frame optical emission-line properties (e.g. He II, H $\beta$ , [O III], Fe II complex) through a principal components analysis. A similar approach, with the inclusion of X-ray spectral information and UV lines such as C IV, was then widely utilised to identify the main fac-

tors that explain the variance in the AGN spectra (e.g. Wang et al. 1996; Sulentic et al. 2000, 2007; Richards et al. 2011; Marziani & Sulentic 2014; Rivera et al. 2020). In particular, steep soft X-ray ( $E < 2$  keV) spectra and large C IV blueshifts have been connected to the original Eigenvector 1 ingredients (i.e. H $\beta$  FWHM and Fe II strength), and are considered as diagnostics of high accretion rates (Wang et al. 1996; Sulentic et al. 2007; Shen & Ho 2014). These trends, however, do not explain the flatter  $\Gamma_X$  observed in the  $W+w$  quasars, which do not seem to show much different blueshifts with respect to the ‘normal’ sources (at a similar UV emission). The mild contrast between the emission-line properties of the  $W+w$  and  $N$  subsets could be due to intrinsic differences in their SED in the region where the photons that affect the C IV line are emitted, that is, above the ionisation potential of  $\approx 48$  eV (corresponding to a wavelength of  $258 \text{ \AA}^{14}$ ).

A deficit of continuum photons that ionise elements like C IV could be interpreted in the context of the shielding gas scenario (e.g. Leighly 2004; Wu et al. 2011; Luo et al. 2015; Ni et al. 2018). As the Eddington ratio increases ( $L_{bol}/L_{Edd} \geq 0.3$ ), the inner disc is expected to become geometrically thick (i.e. a slim disc; Abramowicz et al. 1988; Mineshige et al. 2000; Ohsuga & Mineshige 2011; Netzer & Trakhtenbrot 2013; Wang et al. 2014; Castelló-Mor et al. 2016). This puffed up disc could partly prevent ionising photons from reaching the broad line region. Moreover, also X-ray weakness would take place when the line of sight of the observer intercepts the thick disc, leading to an apparently X-ray-weak quasar where broad, high-ionisation emission lines are also faint. Conversely, when the line of sight to the innermost regions is not obstructed by the disc, the quasar would still present weak high-ionisation lines, but the X-ray emission is consistent with the one from a standard X-ray corona.

As mentioned, substantial C IV blueshifts (with  $v_{peak} \gtrsim 1000 \text{ km s}^{-1}$ ) and large broadening ( $FWHM > 5000 \text{ km s}^{-1}$ ) are often observed in weak-line AGN, implying that C IV mostly (if not only) originates in a wind. Also, radiation-driven winds (e.g. Murray et al. 1995) could affect the strength of the emission lines through self-shielding, and depend upon X-ray illumination, as the latter can over-ionise the surrounding gas preventing the establishment of UV-line driving (Proga et al. 1998, 2000; Nomura et al. 2020). Simulations of such radiation-driven winds from bright accretion discs are consistent with the observed anti-correlation between the relative strength of the soft X-ray emission and the C IV absorption equivalent width (see e.g. Brandt et al. 2000), or the X-ray weakness of BALs in general (Gibson et al. 2009). The wind material should have high column densities ( $N_H \sim 10^{23-24} \text{ cm}^{-2}$ ) for an efficient shield, especially the slow part of the wind closer to the disc, which can prevent any other radiation (both UV and X-ray) from reaching the broad line region. The gas flow geometry strongly depends upon the geometry of the radiation field, where a bright disc-corona produces dense, warm, and fast equatorial outflows in which the C IV emission line originates (Proga et al. 2000). Also in this case, orientation would play a role in explaining the UV/X-ray properties of X-ray-weak quasars when the observer’s line of sight passes through the dense outflow, but a standard quasar will be perceived at more polar viewing angles.

<sup>14</sup> The continuum photons principally responsible for C IV line emission likely cover a wider energy range, also including the Lyman continuum (13.6–24.5 eV) and the soft (300–400 eV) X-rays (Krolik & Kallman 1988).

In both disc and wind shielding, we should then expect to observe hard and weak X-ray spectra in a fraction of sources, suggesting high levels of X-ray absorption, with  $N_{\text{H}} \geq 10^{23} \text{ cm}^{-2}$  or higher. Since the X-ray spectra of our quasars exclude such a strong gas absorption and their bolometric luminosities are in excess of  $10^{47} \text{ erg s}^{-1}$  (see Fig. 1), in most of the  $z \approx 3$  sample the disc should be seen almost face-on (see below), as larger disc inclinations would imply that these luminosities, already very high, are underestimated. Gas shielding could still be a viable interpretation of the X-ray weakness for the two BALs in the  $W+w$  subset (J1148+23, J0945+23), whilst for another couple of objects (J1201+01, J1459+0024) the data quality is not sufficient to rule out some degree of X-ray absorption. In Paper I, we investigated through both a detailed spectral analysis and a hardness ratio analysis whether the  $W+w$  quasars could suffer from high levels (i.e.  $N_{\text{H}} > 10^{23} \text{ cm}^{-2}$ ) of X-ray absorption. Since soft emission is detected in the majority of the  $W+w$  quasars, significant X-ray absorption appears unlikely. Indeed, the  $W+w$  quasars show lower emission by a median (mean) factor of  $\sim 6$  (8) in the soft X-ray band (0.5–2 keV, observed frame) compared to  $N$  quasars, which would require a (nearly) neutral shielding column of the order of  $\sim 5 \times 10^{23} \text{ cm}^{-2}$ . We point out that column densities of the order of  $10^{23} \text{ cm}^{-2}$  would produce a clear cut-off around 1 keV, which is not seen even though it would also be easily detectable in the spectra of lower quality. Absorption due to shielding would completely obliterate the observed flux density at rest-frame 2 keV, whilst no evidence of such a spectral turnover is found. Even with a slightly steeper intrinsic photon index, moving from an unabsorbed  $\Gamma_{\text{X}} = 1.8$  to a moderately absorbed  $\Gamma_{\text{X}} = 2.0$ , the difference in terms of the 2 keV flux density would be 40% only. As the average intrinsic photon index is likely intermediate ( $\langle \Gamma_{\text{X}} \rangle \approx 1.91$  for the  $N$  quasars), such a correction should be taken as an upper limit, and none of our results are substantially affected. Therefore, the current data do not favour the shielding scenario to explain the X-ray weakness observed in the  $W+w$  sources. Nonetheless, X-ray absorption could be variable, so multiple X-ray observations of the  $W+w$   $z \approx 3$  quasars can provide deeper insights into the origin of X-ray weakness. Summarising, in the absence of additional data, the low observed gas absorption (i.e.  $N_{\text{H}} < 10^{23} \text{ cm}^{-2}$ ) suggests that the observed X-ray weakness is intrinsic to the source.

In this framework, most of the possible explanations provided by Leighly et al. (2007b, see the discussion in their Sect. 5.1) for the prototypical intrinsically X-ray-weak quasar PHL 1811 remain valid. In particular, in high-Eddington sources a significant fraction of photons can be trapped in the accretion flow towards the SMBH and accreted before they can actually escape, so starving both the corona and the broad line region from photons (Begelman 1978). Here, we want to elaborate in some more depth on the possible connection between X-ray weakness and disc winds.

In a slab or patchy geometry for the accretion-disc corona (see the top and bottom panels of Fig. 6 in Reynolds & Nowak 2003), the radiation pressure due to the UV photons from the disc can push a dense flow into the corona, thus intertwining the processes that give rise to the UV and X-ray emission. This coupling may lead to a quenching of the corona, as the region above the disc will become too dense, opaque, hence too cold to produce sufficient X-rays, as noticed by Proga (2005). Intrinsic quenching (rather than obscuration) of the corona by a failed wind that stalls because of over-ionisation could control the wind duty cycle, and act as a self-regulating mechanism of the accretion and ejection process. Moreover, it can also explain a variety of observations, such as the spectral properties of several

emission and absorption features (Leighly et al. 2007a,b; Wu et al. 2011). This scenario can also account for the flat (hard)  $\Gamma_{\text{X}}$  observed in the  $W+w$  quasars, as an increase in the optical depth naturally leads to a flatter photon index in the Comptonisation process (Zdziarski et al. 1996; Beloborodov 1999), and for the fact that we do not observe strong C IV blueshifts.

We argue that X-ray weakness might also be interpreted in a starved X-ray corona picture, associated with an ongoing disc-wind phase. Although we do not observe significant C IV blueshifts, a wind could still be present given the low disc inclination (i.e. mostly face-on) of our sources and the prevalent equatorial nature of line-driven disc winds (Proga et al. 2000, but see also Rivera et al. 2020 for the relation between the C IV properties and orientation). These winds can significantly change the local accretion rate, and should alter the SED shape and the overall disc emission (as well as the SMBH growth rate; e.g. Slone & Netzer 2012; Laor & Davis 2014; Nomura et al. 2020). The consequences on the corona have not been theoretically explored, but are likely to be important. High accretion rates, such as the ones characterising the  $z \approx 3$  sample, generate large bolometric luminosities and shift the peak of the disc emission towards higher frequencies ( $> 10^{15.5} \text{ Hz}$ ; see e.g. Slone & Netzer 2012). The closer the high accretion rate reaches in with respect to the inner disc radius, the stronger is the emitted ionising UV radiation<sup>15</sup>. Yet, if an outflow is ejected in the vicinity of the SMBH, the extreme-UV radiation that ‘feeds’ the corona will be depleted, starving the corona from the needed seed photons and generating an X-ray-weak quasar. Nonetheless, at large UV luminosities ( $> 10^{47} \text{ erg s}^{-1}$ ; Fig. 1), there could still be a reservoir of ionising photons that can explain the ‘excess’ C IV line emission observed in the  $W+w$  quasars with respect to the sources at similar X-ray luminosities that follow the  $L_{\text{X}}-L_{\text{UV}}$  relation. The strength of the C IV line, in fact, does not simply depend on the amount of ionising photons in the high energy tail of the disc spectrum. The excited level (lying only 8 eV above the ground state) is primarily populated via electron-ion collisions, and X-ray photons are key contributors to the gas heating. In X-ray-weak sources, the integrated C IV flux presumably suffers from the inefficient line excitation due to the scarcity of hot electrons, rather than the limited production of C IV due to the lack of ionising photons (see also Timlin et al. 2021). In normal quasars of comparable X-ray luminosity, but lower  $L_{\text{UV}}$ , the flux of ionising photons is smaller, hence the C IV emission line is fainter.

For the above reasons, the C IV line is not a good indicator of the total budget of ionising photons and of the extreme-UV SED shape. A more suitable line in this sense is the He II  $\lambda 1640$  line. The He II EW values of the  $z \approx 3$  quasars are in the range  $\sim 0.04-0.90 \text{ \AA}$ , consistent with the expectations from the Baldwin effect of the He II line at the UV luminosities of our sample (see the recent analysis by Timlin et al. 2021; Rankine et al. 2020). We were not able to achieve a good fit to the He II line for 7 quasars (4  $N$ , 2  $W$  and 1  $w$ ) as the line is significantly blended with the C IV red wing and the Fe II UV complex. Given the intrinsic faintness of the He II line and the moderate spectral resolution and S/N of the SDSS spectra, the uncertainties in the measure of the He II EW do not allow us to reveal any statistically significant difference between the  $N$  and  $W+w$  sub-samples. A more detailed investigation of He II emission is beyond the scope of the present paper, and requires spectra with higher S/N than the SDSS ones.

<sup>15</sup> Here we refer to the ionising photons that arise in the extreme-UV part of the quasar SED, which we cannot observe.

Other emission lines could be affected by the presence of a wind and by a shortage of extreme-UV photons, in the first place the [O III]  $\lambda 5007$  line, which has an ionisation potential of  $\approx 35$  eV (corresponding to  $\approx 354$  Å) and is produced at larger distances from the SMBH (where the gas density is lower). To explore the [O III] properties, we are currently analysing the near-IR spectra (probing both emission lines and continuum at  $1 \mu\text{m}$ ) of our  $z \approx 3$  quasars obtained with LUCI, the near-IR spectrograph and imager at the LBT. Whilst we have continuum observations for all the sources, medium resolution spectroscopy ( $R_\lambda \approx 1100$  in the  $K_s$  band for 1 arcsec slit) was obtained only for the 9 (4  $N$ , 4  $W$  and 1  $w$ ) quasars with redshift between  $z \approx 3.2$ – $3.3$ <sup>16</sup>. Besides probing the [O III] line emission, the LBT/LUCI spectra will also allow us to measure with better accuracy the rest-frame 2500 Å fluxes without relying on the continuum extrapolation of the SDSS spectra, and to estimate more reliable black-hole masses from the  $H\beta$  and/or Mg II lines. Better estimates of black-hole mass will also allow us to check for possible differences in the accretion disc temperature (e.g. Laor & Davis 2011). The details on the data reduction and spectral analysis will be the subject of a forthcoming publication. It is worth anticipating, however, that by using the [O III] EW as an orientation indicator (e.g. Bisogni et al. 2017b), the data suggest that the accretion disc is preferentially seen at low inclination (i.e. likely to be face-on) in a large fraction of the  $z \approx 3$  quasars (all but one have [O III] EW  $< 25$  Å), which is not surprising given their huge UV luminosity. Moreover, all the  $W+w$  quasars observed with LUCI (5 sources) show weak [O III] ( $< 10$  Å), which is also expected in objects with high Eddington ratios (e.g. Boroson 2002). All this, together with the lack of clear evidence of X-ray absorption in the *XMM-Newton* spectra, argues against the coronal shielding interpretation, irrespective of its origin (either failed wind or inflated inner disc).

Summarising, several scenarios may explain the origin of intrinsic X-ray weakness in connection with the C IV emission-line properties in the  $z \approx 3$  sample. Following Krolik & Kallman (1988, see also Casebeer et al. 2006), intrinsic X-ray weakness can affect C IV emission in two ways, through a deficit of ionising photons produced in the high energy tail of the disc and/or of X-ray photons that contribute to gas heating, since collisional excitation of the line is critical. The latter could affect C IV emission in X-ray-weak quasars, but since we still observe significant C IV emission in the  $W+w$  subset (see Fig. 6), there must be a sufficient amount of ionising photons with energies  $> 48$  eV that can produce C IV emission in excess with respect to what is expected from X-rays only.

## 6. Conclusions

We have presented the UV analysis of 30 quasars at  $3.0 < z < 3.3$  observed as part of an *XMM-Newton* Large Programme in 2017–2018. This sample was selected in the optical/UV from the SDSS-DR7 to be representative of the most luminous, intrinsically blue quasars at high redshift to further test the potential of quasars as cosmological standard candles. Despite the UV homogeneity of the whole sample, the study of the  $L_X$ – $L_{UV}$  relation in Paper I revealed two distinct X-ray populations. About two-thirds of our quasars (X-ray normal,  $N$ ) cluster around the relation, with a minimal dispersion of  $\sim 0.1$  dex. The remaining one-third (X-ray weak and X-ray-weak candidates,  $W+w$ ) appear

<sup>16</sup> For the other quasars in the sample, the redshift is such that the  $H\beta$ –[O III] spectral range is not entirely observable, as it falls in an atmospheric window with poor or no transmission.

to be X-ray under-luminous by factors of  $> 3$ – $10$ . Moreover, the X-ray weakness fraction among our  $z \approx 3$  quasars ( $\approx 25\%$ ) is larger than previously reported for radio-quiet, non-BAL quasars at lower redshift and luminosity. While the  $W+w$  quasars are a miscellaneous subset, we speculated in Paper I that, in some cases, the X-ray corona might be in a radiatively inefficient state owing to the presence of an accretion-disc wind.

In the second paper of this series we have focused on the analysis of the rest-frame UV spectra, in particular on the C IV emission line properties (proxy of winds or outflow) and on the UV continuum (proxy of the accretion disc), in connection with the X-ray emission (proxy of the corona). Our main results are summarised as follows:

1. The analysis of the spectral composites (see Fig. 7) for the  $N$  and the  $W+w$  subsets shows that the UV continuum slope is slightly redder ( $\alpha_\lambda \approx -0.6$ ) for the  $W+w$  stack compared to the  $N$  one ( $\alpha_\lambda \approx -1.5$ ). Emission lines in the  $W+w$  stack are broader and fainter than in the  $N$  one. The C IV emission line presents only a mild blueshift of  $\approx 600$ – $800$  km s<sup>−1</sup> with respect to the reference emission-line wavelength (1549 Å). The line profile, asymmetric towards the blue side, is broader ( $\approx 10\,000$  km s<sup>−1</sup>) than that observed in the  $N$  composite ( $\approx 7\,000$  km s<sup>−1</sup>). Yet, uncertainties on the stacks are such that these features are consistent with quasars at similar redshifts and luminosities for both the  $N$  and  $W+w$  composites, further confirming the homogeneity of the sample by construction.
2. We recover a relation between  $v_{\text{peak}}$  and  $L_{UV}$  across three decades in  $L_{UV}$  in the redshift range  $z \approx 1.7$ – $3.5$  (Fig. 13, left panel), whilst we do not observe a statistically significant correlation between  $v_{\text{peak}}$  and  $L_{2-10\text{keV}}$  (Fig. 13, right panel), differently from previous claims. We argue that the  $v_{\text{peak}}-L_{2-10\text{keV}}$  correlation recently reported in high-redshift quasars is mostly driven by the relatively small sample statistics.
3. We report on a tight ( $\approx 0.17$  dex) log-linear relation between  $L_X$  and the integrated C IV line emission  $L_{CIV}$  across about four orders of magnitude in luminosity (Fig. 14). The slope value is similar to the one already observed in the  $L_X-L_{UV}$  relation ( $\gamma \sim 0.6$ ), albeit slightly steeper, thus preserving the C IV Baldwin effect. Consequently, the observed  $L_X-L_{CIV}$  correlation could be in part a by-product of the  $L_X-L_{UV}$  relationship. X-ray-weak quasars deviate from the main  $L_X-L_{CIV}$  relation, occupying the low X-ray/C IV luminosity part of the plane, thus displaying an ‘excess’ of C IV line emission with respect to normal sources of similar X-ray luminosities.
4. We interpret the X-ray-weak quasars deviating from the  $L_X-L_{CIV}$  relation in the context of the disc-wind quasar scenarios. Whilst the shielding model may explain X-ray weakness for a couple of X-ray-weak quasars in our sample, for the other X-ray-weak objects we consider absorption unlikely. We thus argue that their X-ray weakness might be interpreted in terms of a starved (or quenched) corona associated with an ongoing disc-wind phase. Although collisional excitation of the line might be less efficient, the observed UV luminosities ( $> 10^{47}$  erg s<sup>−1</sup>) characterising the  $z \approx 3$  quasars ensure a significantly large reservoir of ionising photons that can explain the ‘excess’ C IV emission observed in the X-ray-weak sources with respect to normal quasars at similar X-ray luminosities.

Our work on the  $z \approx 3$  blue quasar sample demonstrates that a systematic study of X-ray spectra, optical to X-ray SEDs, and optical/UV emission-line properties in the context of accretion-disc models is mandatory to better understand the observable

effects of disc winds. In the future, it would be interesting to extend this kind of analysis to quasars that deviate from the  $L_X-L_{CIV}$  relation at different redshifts and luminosities.

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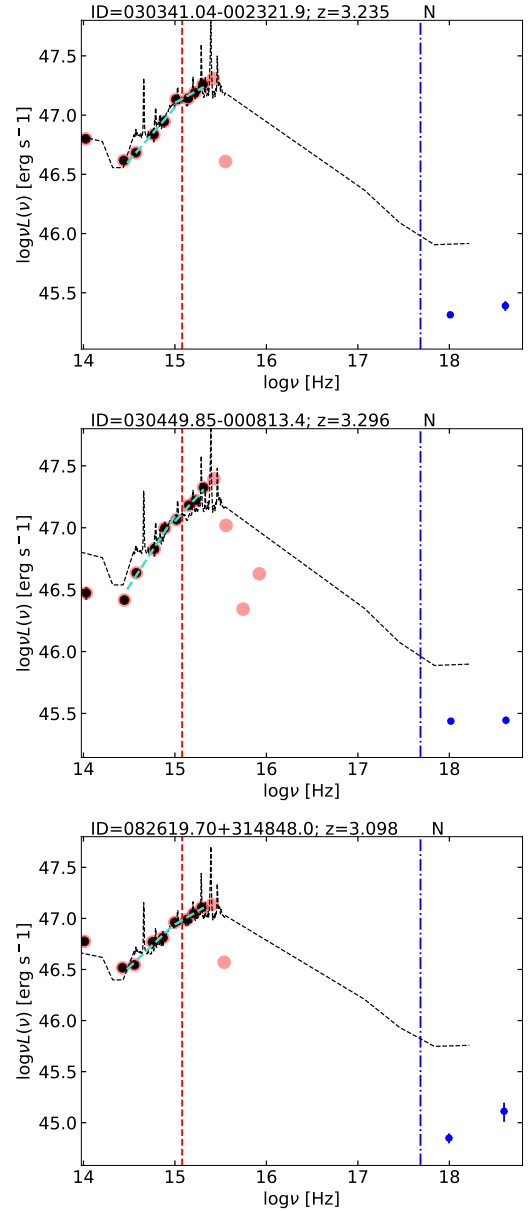
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## Appendix A: Photometric spectral energy distributions of the $z \approx 3$ quasar sample

Figure A.1 presents the full SEDs of the  $z \approx 3$  quasars from near-IR to the X-rays. Photometry from the near-IR to the UV is drawn from SDSS-DR14 quasar catalogue (Pâris et al. 2018, see their Sect. 2.1); the FIRST survey in the radio (Becker et al. 1995), the Wide-Field Infrared Survey (WISE, Wright et al. 2010) in the mid-IR, the Two Micron All Sky Survey (2MASS; Cutri et al. 2003; Skrutskie et al. 2006) and the UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007) in the near-IR, and the Galaxy Evolution Explorer (GALEX; Martin et al. 2005) survey in the UV. To construct the SEDs, we followed the same approach as in L20 (see their Sect. 3). Briefly, after collecting all the photometry available in the SDSS catalogue for each quasar in the sample, we corrected it for Galactic reddening by utilising the selective attenuation of the stellar continuum  $k(\lambda)$  from Fitzpatrick (1999). Galactic extinction is estimated from Schlegel et al. (1998) for each object in the sample. We expect significant absorption by the intergalactic medium (IGM) in the continuum ( $\sim 10\%$  between the Ly $\alpha$  and C IV emission lines; see Lusso et al. 2015 for details) at wavelengths bluer than about 1400 Å. Hence, when computing the relevant parameters, we excluded from the SED all the rest-frame data at  $\lambda < 1500$  Å. The red circles in Fig. A.1 mark all the available photometry from the SDSS-DR14 catalogue, whilst the ones used to construct the SEDs are highlighted with black circles. The cyan dashed lines represent the two near-IR/optical slopes  $\Gamma_1$  and  $\Gamma_2$  in the 0.3–1  $\mu\text{m}$  and 1450–3000 Å range (rest frame), respectively. The blue points at high energies represent the flux at the rest-frame 1 keV and 4 keV derived from the *XMM-Newton* data obtained in our campaign. We computed these flux values following the same approach as in Lusso et al. (2010, see also Lusso et al. 2013). Briefly, we first computed the integrated unabsorbed (considering only the Galactic column density at the source location) fluxes in the observed 0.5–2 keV and 2–8 keV bands from our *XMM-Newton* data. These fluxes are then converted into monochromatic X-ray fluxes in the observed frame at 1 keV and 4 keV for the soft and hard band, respectively, assuming a power-law spectrum with the observed photon index slope. These X-ray fluxes are converted into luminosities and finally redshifted. We also show for reference the composite SDSS quasar spectrum from Shang et al. (2011) with the black-dashed line, which is built from a sample of 27 low-redshift ( $z < 0.5$ ) optical/UV bright radio-quiet quasars. On average, the X-ray part of the Shang et al. (2011) SED shows relatively high X-ray emission compared to our data and previous composites as well, indicating that their sample is not representative of the SDSS quasars at high energies and probably does not follow the  $L_X$ – $L_{UV}$  relationship (see discussion in their Sect. 5.3.3). Nonetheless, the SED shape of the  $z \approx 3$  quasars at UV frequencies is in excellent agreement with the one obtained in the literature for quasars of lower-redshift and lower-luminosity and, thus, lower black-hole mass. This corroborates the notion that the physical mechanism responsible for the intrinsic X-ray emission (tightly connected with the disc emission) of quasars does not evolve with cosmic time and is scale-invariant.

We have compared the 2500 Å fluxes obtained as described above from the broadband photometry to the ones computed from the spectral fits, as presented in Sect. 3 and Appendix B. The top panel of Fig. A.2 shows such a comparison, whilst the distribution of the differences between



**Fig. A.1.** SEDs of the  $z \approx 3$  quasars in the rest-frame  $\nu$ – $\nu L(\nu)$  logarithmic plane. The red circles mark all the available photometry from the SDSS-DR14 catalogue, but only the ones highlighted with black circles were used to construct the SEDs. The dashed cyan lines represent the slopes  $\Gamma_1$  and  $\Gamma_2$  in the 0.3–1  $\mu\text{m}$  and 1450–3000 Å range (rest frame), respectively. The composite SDSS radio-quiet quasar spectrum from Shang et al. (2011) is also shown for reference with the dashed black line, normalised at 2500 Å (indicated by the dashed red line). We included the X-ray data with blue points for the soft and the hard band. The dot-dashed blue line locates the 2 keV point.

photometric and spectroscopic UV fluxes,  $\Delta \log F_{UV}$  (photo–spectro), is shown in the bottom panel. The photometric  $F_{UV}$  is in very good agreement with the spectroscopic one, with a mean (median)  $\Delta \log F_{UV}$  (photo–spectro) =  $-0.002$  ( $0.010$ ), with a standard deviation of 0.05. Even the photometric UV flux of the most deviating object in the  $\Delta \log F_{UV}$  (photo–spectro) distribution, J1148+23, is consistent within a factor of 1.6 with the continuum UV flux from spectral fitting.

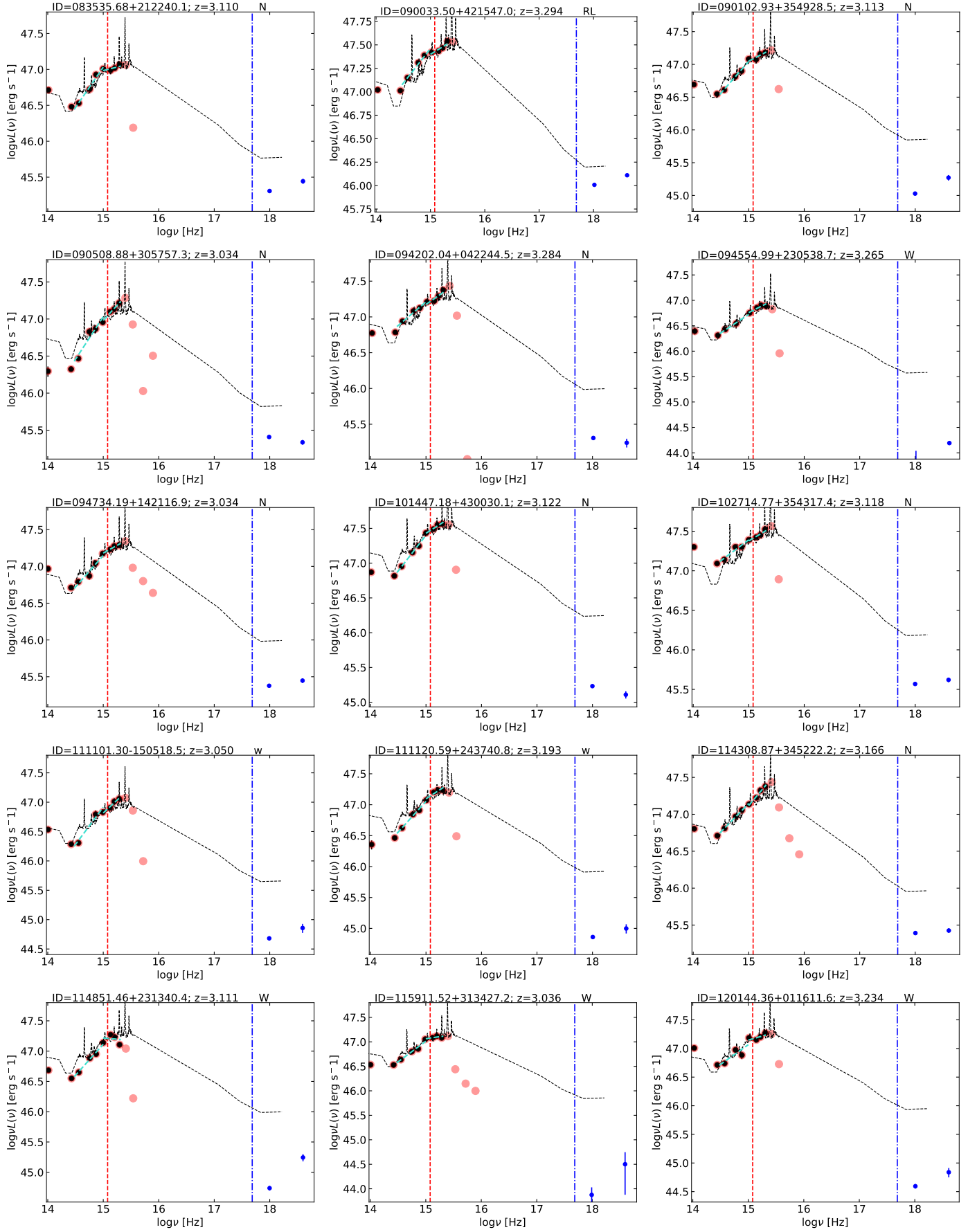


Fig. A.1. continued.

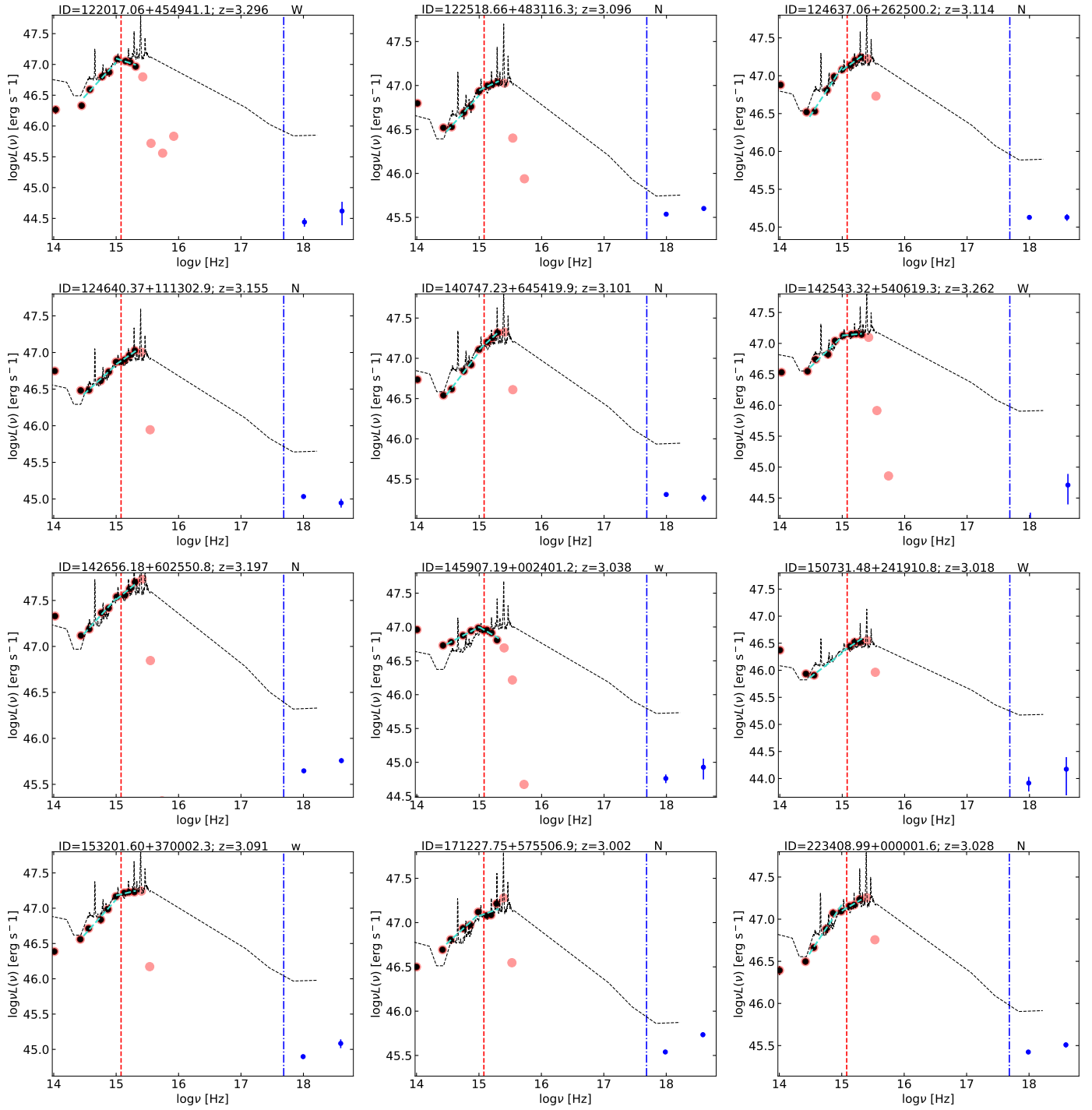
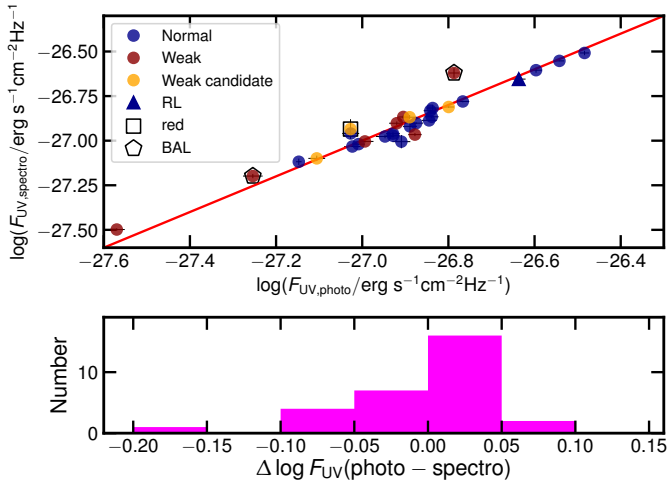


Fig. A.1. continued.



**Fig. A.2.** Comparison between the  $2500 \text{ \AA}$  monochromatic fluxes obtained from the broadband SEDs (Appendix A) and the ones from spectral fitting (Sect. 3 and Appendix B). The red represent the 1:1 relation. The distribution of the differences between photometric and spectroscopic UV fluxes,  $\Delta \log F_{UV}(\text{photo} - \text{spectro})$ , is shown in the bottom panel.

## Appendix B: Ultraviolet SDSS spectra of the $z \approx 3$ quasar sample

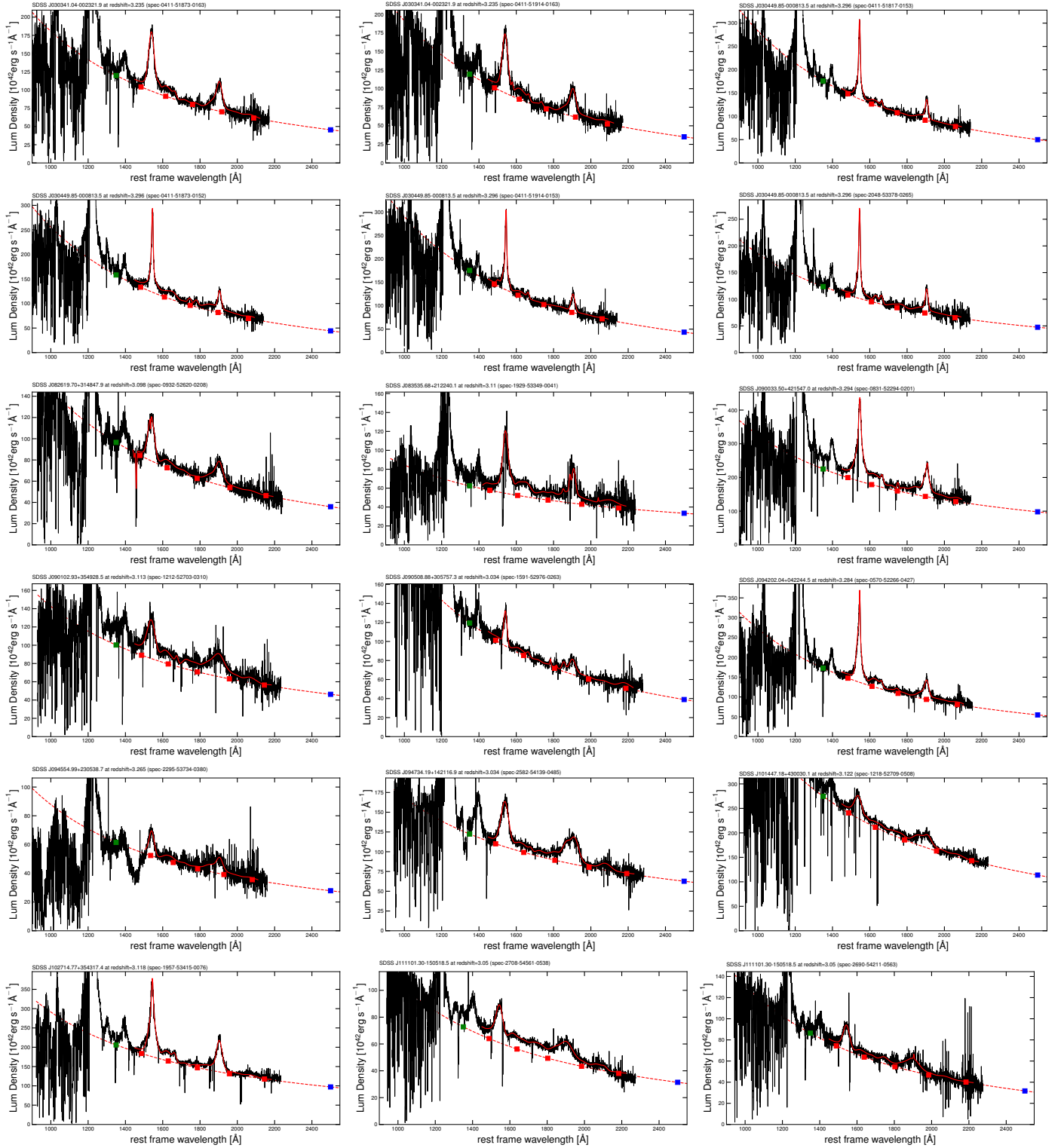
Figure B.1 shows all the UV SDSS spectra used in this analysis (see Table B.1). The red line represents the best-fit model of the data using QSFit. The red square symbols are the continuum luminosities estimated by QSFit, whilst the green and blue squares at  $1350 \text{ \AA}$  and  $2500 \text{ \AA}$ , respectively, represent the location where the nuclear continuum luminosities are extrapolated

from the best-fit of the continuum (red dotted line). For both the fitting procedure (QSFit or our custom fitting code) we follow the strategy below.

We performed the least- $\chi^2$  fits to the SDSS spectra for each object, where the spectrum was de-reddened for Galactic extinction using the Cardelli et al. (1989) Galactic reddening law, assuming a total to selective extinction  $R_V = 3.1$ , where  $E(B-V)$  are derived from the Schlegel et al. (1998) dust map. The spectrum was then shifted to rest frame using the improved redshifts provided by Hewett & Wild (2010) for SDSS quasars. We masked out narrow absorption line features imprinted on the spectrum, which could bias both the continuum and emission line fits (intrinsic reddening is neglected). For a few spectra, absorption features are considered in the fit to improve the least- $\chi^2$ . The C IV and C III] are fitted with one and two Gaussian profiles for the broad component, respectively (in the case of our custom-made code, all the broad lines are fitted with a broken power-law convolved with a Gaussian function in order to avoid a singularity at the peak; see Bisogni et al. 2017a for details). A Lorentzian profile is also used in the cases where the peak of the line is not well modelled by a single Gaussian profile (e.g. J0304–0008). We also fit the He II feature at  $1640 \text{ \AA}$  and the excess emission at  $1600\text{--}1650 \text{ \AA}$  with a pseudo-continuum that is attributed with Fe II emission. We do not impose any constrain between the broad and narrow-line component. We measure line widths for C IV both with and without an additional narrow-line subtraction to test whether it is required to improve the fit. For the majority of the cases, a single Gaussian or Lorentzian profile (or a single broken power-law profile for the custom-made code) is enough to model the entire line. Uncertainties on the relevant parameters (e.g. FWHM, EW,  $\sigma$ ,  $\nu_{\text{peak}}$ ) are computed from the standard deviation of 10 fits where different spectral channels are masked to increase the noise with respect to the original data.

Table B.1. UV spectral properties of the  $z \approx 3$  sample.

| Name               | X-ray class | SDSS spectrum        | $\alpha_\lambda$ | FWHM<br>km s <sup>-1</sup> | $v_{\text{peak}}$<br>km s <sup>-1</sup> | $\sigma$<br>km s <sup>-1</sup> | Centroid shift<br>km s <sup>-1</sup> | AS          | $F_{\text{CIV}}/10^{-17}$<br>erg s <sup>-1</sup> cm <sup>-2</sup> | EW<br>Å     |
|--------------------|-------------|----------------------|------------------|----------------------------|---|--------------------------------|--------------------------------------|-------------|---|-------------|
| 030341.04-002321.9 | N           | spec-0411-51873-0163 | -1.48 ± 0.03     | 6358 ± 16                  | 1469 ± 13                               | 4997 ± 68                      | 2232 ± 93                            | 0.76 ± 0.01 | 3970 ± 42   | 37.9 ± 0.81 |
| 030341.04-002321.9 | N           | spec-0411-51914-0163 | -1.75 ± 0.04     | 6252 ± 23                  | 1266 ± 21                               | 5189 ± 135                     | 2556 ± 111                           | 0.63 ± 0.01 | 3970 ± 78   | 39.7 ± 1.15 |
| 030449.85-000813.4 | N           | spec-0411-51817-0153 | -1.95 ± 0.03     | 2138 ± 22                  | 704 ± 14                                | 2920 ± 316                     | 848 ± 117                            | 0.75 ± 0.01 | 3117 ± 122  | 22.9 ± 0.89 |
| 030449.85-000813.4 | N           | spec-0411-51873-0152 | -1.97 ± 0.04     | 2274 ± 18                  | 734 ± 6                                 | 3232 ± 234                     | 700 ± 45                             | 0.75 ± 0.01 | 3127 ± 81   | 24.3 ± 0.57 |
| 030449.85-000813.4 | N           | spec-0411-51914-0153 | -2.11 ± 0.04     | 2167 ± 8                   | 656 ± 6                                 | 2644 ± 72                      | 858 ± 46                             | 0.65 ± 0.01 | 3049 ± 34   | 22.6 ± 0.37 |
| 030449.85-000813.4 | N           | spec-2048-53378-0265 | -1.52 ± 0.06     | 2167 ± 10                  | 666 ± 12                                | 2691 ± 49                      | 975 ± 37                             | 0.69 ± 0.02 | 2988 ± 40   | 28.7 ± 0.62 |
| 082619.70+314848.0 | N           | spec-0932-52620-0208 | -1.50 ± 0.03     | 8061 ± 120                 | 956 ± 63                                | 4890 ± 579                     | 2665 ± 110                           | 0.45 ± 0.02 | 2562 ± 183  | 28.1 ± 2.31 |
| 083355.69+212240.1 | N           | spec-1929-53349-0041 | -0.93 ± 0.01     | 5748 ± 181                 | 1024 ± 41                               | 4603 ± 188                     | 885 ± 98                             | 1.00 ± 0.02 | 2930 ± 44   | 40.9 ± 0.66 |
| 090033.50+421547.0 | -           | spec-0831-52294-0201 | -1.37 ± 0.02     | 4509 ± 52                  | 511 ± 24                                | 4711 ± 292                     | 400 ± 311                            | 0.80 ± 0.03 | 8242 ± 292  | 40.3 ± 1.88 |
| 090102.93+354928.5 | N           | spec-1212-52703-0310 | -1.48 ± 0.04     | 8816 ± 307                 | 2040 ± 134                              | 5942 ± 471                     | 3372 ± 540                           | 0.80 ± 0.06 | 2582 ± 141  | 24.2 ± 1.42 |
| 090508.88+305757.3 | N           | spec-1591-52976-0263 | -1.75 ± 0.05     | 4442 ± 64                  | 937 ± 4                                 | 4114 ± 304                     | 3225 ± 282                           | 0.40 ± 0.01 | 1483 ± 53   | 12.5 ± 0.47 |
| 094202.04+042244.5 | N           | spec-0570-52266-0427 | -1.74 ± 0.02     | 3251 ± 13                  | 569 ± 10                                | 3583 ± 64                      | 2013 ± 29                            | 0.54 ± 0.01 | 5591 ± 66   | 39.0 ± 0.62 |
| 094554.99+230538.7 | W           | spec-2295-53734-0380 | -1.03 ± 0.05     | 7190 ± 201                 | 1285 ± 28                               | 5289 ± 130                     | 114 ± 129                            | 0.63 ± 0.02 | 1039 ± 71   | 20.8 ± 1.90 |
| 094734.19+142116.9 | N           | spec-2582-54139-0485 | -1.15 ± 0.01     | 8806 ± 153                 | 1053 ± 292                              | 4559 ± 626                     | 1813 ± 288                           | 0.59 ± 0.07 | 3440 ± 236  | 24.9 ± 2.03 |
| 101447.18+430030.1 | N           | spec-1218-52709-0508 | -1.47 ± 0.01     | 8409 ± 180                 | 2727 ± 234                              | 5234 ± 499                     | 2394 ± 655                           | 1.03 ± 0.25 | 2669 ± 160  | 9.8 ± 0.60  |
| 102714.77+354317.4 | N           | spec-1957-53415-0076 | -1.16 ± 0.07     | 4964 ± 83                  | 1392 ± 109                              | 4969 ± 257                     | 843 ± 358                            | 1.21 ± 0.17 | 8423 ± 305  | 40.5 ± 1.61 |
| 111101.30-150518.5 | w           | spec-2708-54561-0538 | -1.64 ± 0.02     | 8458 ± 431                 | 75 ± 636                                | 4600 ± 297                     | 1342 ± 252                           | 0.56 ± 0.15 | 1467 ± 67   | 18.1 ± 0.93 |
| 111101.30-150518.5 | w           | spec-2690-54211-0563 | -1.68 ± 0.02     | 8148 ± 118                 | 540 ± 192                               | 4006 ± 159                     | 1648 ± 95                            | 0.74 ± 0.06 | 1285 ± 25   | 14.5 ± 0.33 |
| 111120.59+243740.8 | w           | spec-2489-53857-0600 | -1.18 ± 0.06     | 2661 ± 75                  | 792 ± 240                               | 3224 ± 172                     | 2374 ± 115                           | 0.75 ± 0.22 | 1186 ± 49   | 10.3 ± 0.50 |
| 114308.87+345222.2 | N           | spec-2012-53493-0067 | -1.74 ± 0.02     | 5245 ± 11                  | 1285 ± 8                                | 3571 ± 75                      | 1471 ± 45                            | 0.70 ± 0.01 | 5355 ± 41   | 35.6 ± 0.49 |
| 114851.46+231340.4 | W           | spec-2511-53882-0552 | 0.43 ± 0.13      | 7335 ± 130                 | 2214 ± 88                               | 8088 ± 549                     | -154 ± 452                           | 0.81 ± 0.10 | 3529 ± 267  | 37.6 ± 3.91 |
| 115911.52+313427.2 | W           | spec-1991-53446-0033 | -0.85 ± 0.02     | 7732 ± 837                 | 1527 ± 324                              | 5793 ± 196                     | -846 ± 90                            | 1.32 ± 0.19 | 997 ± 62  | 10.4 ± 0.68 |
| 115911.52+313427.2 | W           | spec-2095-53474-0293 | -0.79 ± 0.01     | 7190 ± 336                 | 1121 ± 243                              | 5386 ± 424                     | -871 ± 325                           | 1.12 ± 0.30 | 866 ± 55  | 8.9 ± 0.59  |
| 120144.36+011611.6 | W           | spec-0516-52017-0139 | -1.42 ± 0.02     | 8409 ± 241                 | 1140 ± 58                               | 6329 ± 514                     | 3021 ± 586                           | 0.41 ± 0.03 | 2536 ± 178  | 24.8 ± 2.00 |
| 122017.06+454941.1 | W           | spec-1370-53090-0629 | -0.65 ± 0.04     | 5709 ± 550                 | 1266 ± 150                              | 2765 ± 407                     | 1847 ± 528                           | 0.75 ± 0.17 | 491 ± 34  | 7.5 ± 0.60  |
| 122518.66+483116.3 | N           | spec-1451-53117-0605 | -1.09 ± 0.05     | 6154 ± 404                 | 579 ± 218                               | 4573 ± 284                     | -189 ± 344                           | 0.67 ± 0.06 | 2715 ± 138  | 30.5 ± 2.21 |
| 124637.06+262500.2 | N           | spec-2238-54205-0136 | -1.30 ± 0.14     | 1136 ± 143                 | 1585 ± 511                              | 4967 ± 500                     | 1123 ± 263                           | 1.04 ± 0.23 | 2424 ± 266  | 22.5 ± 3.64 |
| 124640.37+111302.9 | N           | spec-1694-53472-0085 | -1.65 ± 0.09     | 7287 ± 413                 | 1411 ± 311                              | 4427 ± 583                     | 2520 ± 354                           | 0.59 ± 0.13 | 2430 ± 242  | 30.1 ± 4.02 |
| 140747.23+645419.9 | N           | spec-0498-51973-0144 | -1.53 ± 0.01     | 6474 ± 76                  | 1005 ± 323                              | 4894 ± 501                     | 1348 ± 80                            | 0.94 ± 0.25 | 2832 ± 212  | 19.5 ± 1.70 |
| 140747.23+645419.9 | N           | spec-0498-51984-0144 | -1.53 ± 0.01     | 6483 ± 283                 | 850 ± 163                               | 4857 ± 295                     | 1374 ± 125                           | 0.85 ± 0.08 | 3281 ± 112  | 20.6 ± 0.66 |
| 142543.32+540619.3 | W           | spec-1326-52764-0451 | -0.83 ± 0.04     | 5438 ± 123                 | 724 ± 15                                | 3574 ± 113                     | 2047 ± 124                           | 0.38 ± 0.01 | 1242 ± 39   | 13.9 ± 0.51 |
| 142656.18+602550.8 | N           | spec-0607-52368-0259 | -1.59 ± 0.04     | 8264 ± 192                 | 1392 ± 433                              | 5554 ± 381                     | 3457 ± 458                           | 0.67 ± 0.17 | 11946 ± 413   | 37.5 ± 1.69 |
| 145907.19+002401.2 | w           | spec-0310-51616-0326 | 0.28 ± 0.16      | 8574 ± 357                 | 2330 ± 483                              | 7124 ± 296                     | 2063 ± 438                           | 1.00 ± 0.83 | 1779 ± 159  | 42.3 ± 5.82 |
| 145907.19+002401.2 | w           | spec-0310-51990-0350 | 0.75 ± 0.21      | 8603 ± 186                 | 2185 ± 214                              | 7090 ± 266                     | 1941 ± 460                           | 1.00 ± 0.06 | 1747 ± 114  | 39.4 ± 3.11 |
| 150731.48+241910.8 | W           | spec-2155-53820-0393 | -1.46 ± 0.05     | 5990 ± 272                 | 453 ± 81                                | 5196 ± 800                     | 463 ± 446                            | 0.57 ± 0.04 | 916 ± 113   | 29.9 ± 4.73 |
| 153201.60+370002.3 | W           | spec-1401-53144-0420 | -1.06 ± 0.04     | 5671 ± 503                 | 364 ± 39                                | 6149 ± 719                     | 459 ± 698                            | 0.93 ± 0.08 | 2385 ± 234  | 19.4 ± 2.09 |
| 171227.75+575506.9 | N           | spec-0355-51788-0415 | -1.44 ± 0.02     | 2583 ± 30                  | 647 ± 4                                 | 5825 ± 40                      | 1498 ± 74                            | 0.98 ± 0.02 | 7180 ± 51   | 59.9 ± 0.61 |
| 223408.99+000001.6 | N           | spec-0673-52162-0631 | -1.27 ± 0.02     | 2167 ± 26                  | 608 ± 14                                | 3637 ± 129                     | 1104 ± 144                           | 0.97 ± 0.04 | 3064 ± 102  | 23.6 ± 0.92 |



**Fig. B.1.** UV SDSS spectra of the  $z \approx 3$  quasar sample (black line). The red line represents the best-fit model of the data using QSFIT. The red squares are the continuum luminosities estimated by QSFIT, whilst the green ( $1350 \text{ \AA}$ ) and blue ( $2500 \text{ \AA}$ ) squares represent the nuclear continuum luminosities extrapolated from the best fit of the continuum (dotted red line).

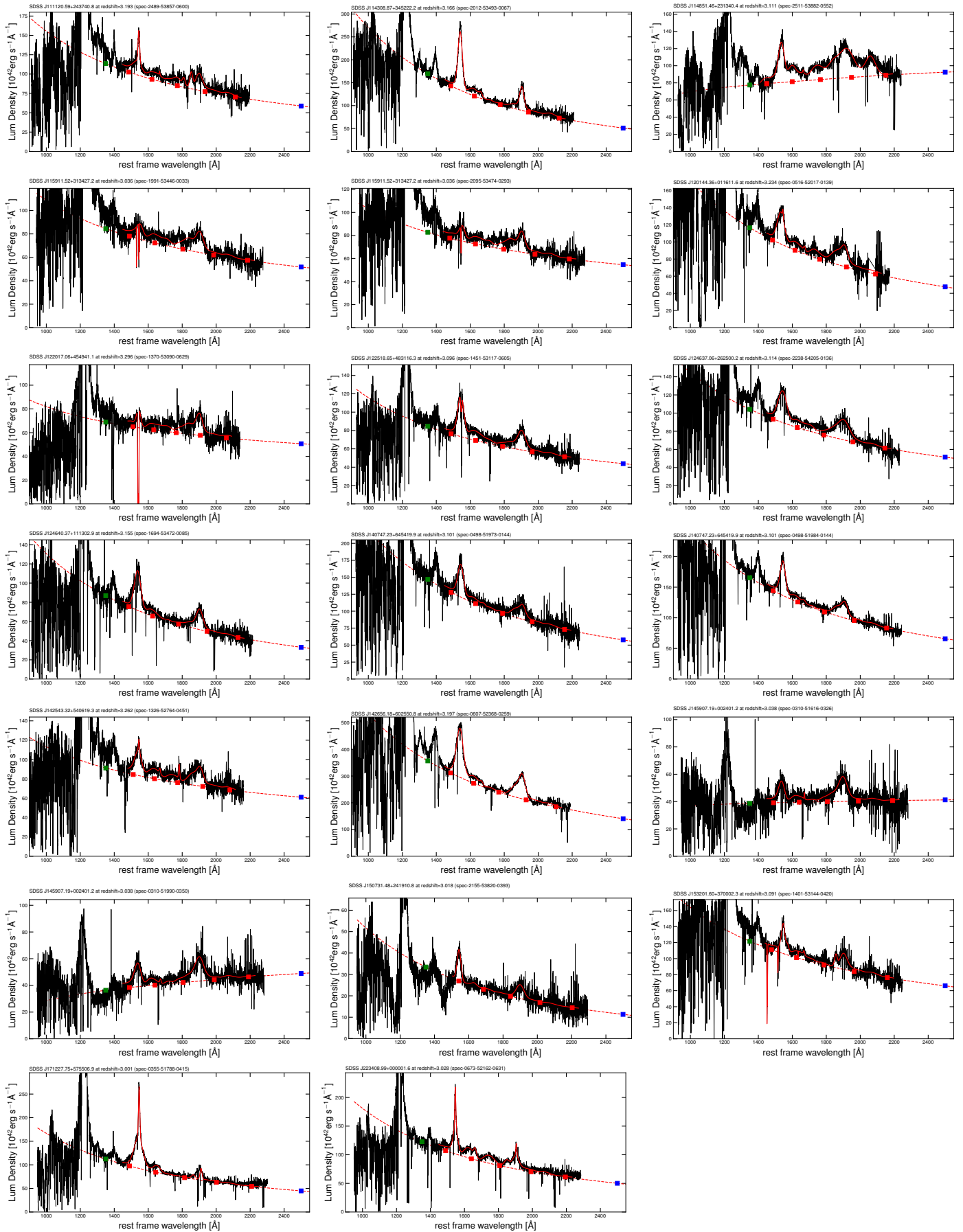


Fig. B.1. continued.