On the Relation between the Hard X-Ray Photon Index and Accretion Rate for Super-Eddington Accreting Quasars

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Abstract

We investigate whether the correlation between the hard X-ray photon index ($\Gamma$) and accretion rate for super-Eddington accreting quasars is different from that for sub-Eddington accreting quasars. We construct a sample of 113 bright quasars from the Sloan Digital Sky Survey Data Release 14 quasar catalog, with 38 quasars as the super-Eddington subsample and 75 quasars as the sub-Eddington subsample. We derive black hole masses using a simple-epoch virial mass formula based on the H/β lines, and we use the standard thin disk model to derive the dimensionless accretion rates ($\dot{\mathcal{M}}_{\text{Edd}}$) for our sample. The X-ray data for these quasars are collected from the Chandra and XMM-Newton archives. We fit the hard X-ray spectra using a single power-law model to obtain $\Gamma$ values. We find a statistically significant ($R_S = 0.43, p = 7.75 \times 10^{-3}$) correlation between $\Gamma$ and $\dot{\mathcal{M}}_{\text{Edd}}$ for the super-Eddington subsample. The $\Gamma-\dot{\mathcal{M}}_{\text{Edd}}$ correlation for the sub-Eddington subsample is also significant, but weaker ($R_S = 0.30, p = 9.98 \times 10^{-3}$). Linear regression analysis shows that $\Gamma = (0.34 \pm 0.11)\log\dot{\mathcal{M}}_{\text{Edd}} + (1.71 \pm 0.17)$ and $\Gamma = (0.09 \pm 0.04)\log\dot{\mathcal{M}}_{\text{Edd}} + (1.93 \pm 0.04)$ for the super- and sub-Eddington subsamples, respectively. The $\Gamma-\dot{\mathcal{M}}_{\text{Edd}}$ correlations of the two subsamples are different, suggesting different disk–corona connections in these two types of systems. We propose one qualitative explanation of the steeper $\Gamma-\dot{\mathcal{M}}_{\text{Edd}}$ correlation in the super-Eddington regime that involves larger seed photon fluxes received by the compact corona from the thick disks in super-Eddington accreting quasars.

Unified Astronomy Thesaurus concepts: Accretion (14); X-ray quasars (1821); Supermassive black holes (1663)

Supporting material: machine-readable tables

1. Introduction

Active galactic nuclei (AGNs) produce a considerable amount of X-ray emission ubiquitously (Tananbaum et al. 1979), which is considered to be produced by a corona of hot electrons located close to the inner accretion disk of the supermassive black hole. The optical/UV photons from the thermal accretion disk emission are inverse-Compton scattered into X-ray energies by the hot electrons in the corona (e.g., Liang & Price 1977; Haardt & Maraschi 1993; Done 2010; Gilfanov & Merloni 2014; Fabian et al. 2017). Such a mechanism implies a connection between the X-ray corona and the accretion disks for AGNs.

Previous studies have found a significant positive correlation between the hard (rest-frame $\gtrsim 2$ keV) X-ray photon index ($\Gamma$) and the accretion rate parameterized as the Eddington ratio ($\lambda_{\text{Edd}}$) for typical AGNs (e.g., Lu & Yu 1999; Wang et al. 2004; Shenmer et al. 2008; Risaliti et al. 2009; Brightman et al. 2013; Trakhtenbrot et al. 2017), where $\lambda_{\text{Edd}} = L_{\text{bol}}/L_{\text{Edd}}$, with $L_{\text{bol}}$ being the bolometric luminosity and $L_{\text{Edd}}$ the Eddington luminosity. This $\Gamma-\lambda_{\text{Edd}}$ correlation is indicative of the connection between the accretion disk and X-ray corona. The physics behind this correlation is not clear. One possible explanation is that when the accretion rate is higher, the cooling of the corona becomes more efficient, which decreases the temperature and/or the optical depth of the corona (e.g., Fabian et al. 2015; Yang et al. 2015; Kara et al. 2017; Ricci et al. 2018; Barua et al. 2020). The X-ray spectrum is thus softer because the cooler corona produces relatively fewer hard X-ray photons (e.g., Vasudevan & Fabian 2007; Davis & Laor 2011).

Previous studies typically found substantial scatter for the $\Gamma-\lambda_{\text{Edd}}$ correlation, which may be partially due to the complications in deriving the $\lambda_{\text{Edd}}$ and $\Gamma$ parameters. For example, there are substantial uncertainties for single-epoch virial black hole masses, including systematic errors ($\approx 0.4-0.5$ dex; e.g., Shen 2013) and measurement errors ($\approx 0.15$ dex; Shen et al. 2011). There may even be a bias when using the C IV line emission to estimate black hole masses, due to the possible blueshift component of C IV which may be produced by outflowing wind (e.g., Baskin & Laor 2005; Richards et al. 2011; Shen 2013; Plotkin et al. 2015). The different methods and energy bands used for fitting the X-ray spectra may in addition lead to systematically different $\Gamma$ values (e.g., Trakhtenbrot et al. 2017; Ricci et al. 2018).

The different physics of accretion disks with different accretion rates may also affect the observed $\Gamma-\lambda_{\text{Edd}}$ correlation. The accretion disk of sub-Eddington accreting AGNs with normal accretion rates ($0.001 \lesssim \lambda_{\text{Edd}} \lesssim 0.1$; e.g., Netzer 2019) is generally described as a geometrically thin, optically thick accretion disk (Shakura & Sunyaev 1973). For super-
Eddington accreting AGNs with high accretion rates ($\dot{\lambda}_{\text{Edd}} \geq 0.1$), geometrically thick inner accretion disks are generally expected from either analytical solutions (e.g., Abramowicz et al. 1988; Wang & Zhou 1999; Mineshige et al. 2000) or numerical simulations (e.g., Jiang et al. 2014, 2019; Sadowski & Narayan 2016). In analytical solutions, the geometrically thick accretion disk in the super-Eddington regime has the "photon trapping" effect (e.g., Abramowicz et al. 1988; Wang & Zhou 1999; Ohsuga et al. 2002). The diffuse timescale for photons to escape from the thick disk surface may be longer than the timescale for photons to be advected into the central black hole. Therefore, the bolometric luminosity of a super-Eddington accreting AGN may be saturated and depend weakly on its accretion rate, which can be expressed as $L_{\text{bol}} \approx 2L_{\text{Edd}}[1 + \ln(\dot{\lambda}/50)]$ (e.g., Mineshige et al. 2000; Wang et al. 2014). In the equation above, the dimensionless accretion rate ($\dot{\lambda}$) is defined as $\dot{\lambda} = \dot{M}c^2/L_{\text{Edd}}$, where $\dot{M}$ is the mass accretion rate; $\dot{\lambda}$ is related to $\dot{\lambda}_{\text{Edd}}$ as $\dot{\lambda} = \dot{\lambda}_{\text{Edd}}/\eta$, where $\eta$ is the radiative efficiency parameter. However, recent simulation results suggest that photons may escape from the thick disk surface more efficiently via vertical advection from effects such as magnetic buoyancy (e.g., Jiang et al. 2014; Sadowski et al. 2014). These suggest that the photon trapping effect may not dominate the cooling of accretion disks in the super-Eddington regime. The differences in the disk structure and physics between sub- and super-Eddington accreting AGNs suggest that the connections between the accretion disk and the X-ray corona may be different in these two types of systems. Observationally, we may expect different correlations between the X-ray photon index and Eddington ratio, which contribute partially to the strong scatter of the overall $\Gamma - \dot{\lambda}_{\text{Edd}}$ correlation. Previous studies on the $\Gamma - \dot{\lambda}_{\text{Edd}}$ correlation did not separate these two populations of AGNs into respective samples, probably because of the limited sample sizes and the difficulty in selecting super-Eddington accreting AGNs. For super-Eddington accreting AGNs, the Eddington ratio may not be a good indicator of the accretion rate due to the possible photon trapping effect. Therefore, it is valuable to check the $\Gamma - \dot{\lambda}$ correlations when investigating the connections between the accretion disks and coronae for super-Eddington accreting AGNs.

The black hole mass is the key parameter for computing the dimensionless accretion rate or the Eddington ratio. For distant AGNs, the black hole masses are usually estimated using single-epoch virial mass estimation that is based on the empirical broad-line region (BLR) size versus luminosity ($R-L$) relation (e.g., Kaspi et al. 2000, 2005; Netzer & Trakhtenbrot 2007). Recently, it has been proposed that the conventional $R-L$ relation may overestimate the BLR sizes for super-Eddington accreting AGNs (e.g., Wang et al. 2014; Du et al. 2016) and the virial black hole masses are thus overestimated. Based on the analysis of a sample of AGNs with reverberation mapping data including a sample of super-Eddington accreting AGNs, Du & Wang (2019) take into account the Fe II emission strength ($R_{\text{Fe}}$)\(^9\) and propose an updated $R-L$ relation to provide more accurate estimations of black hole masses, especially for super-Eddington accreting AGNs.

In this study, we aim to investigate if there is any difference between the disk–corona connections in super- and sub-Eddington accreting AGNs, by comparing the correlations between the hard X-ray photon index and the accretion rates for these two types of systems. Due to the additional uncertainties on the estimations of bolometric luminosities, especially in the super-Eddington regime, we prioritize our investigation in the $\Gamma - \dot{\lambda}$ correlation. Statistically significant samples of super- and sub-Eddington accreting AGNs are thus needed. The Sloan Digital Sky Survey (SDSS) Data Release 14 (DR14) quasar catalog (Pâris et al. 2018) provides a large sample of quasars with optical spectra. The X-ray data of these SDSS quasars can be searched from the Chandra and XMM-Newton archives. We use broad Hβ emission-line profiles and the updated $R-L$ relation of Du & Wang (2019) for relatively reliable black hole mass estimation and super-Eddington accreting quasar selection. We organize our work as follows. In Section 2, we present our sample selection using the SDSS DR14 quasar catalog and the Chandra and XMM-Newton archives. Basic quasar properties including black hole masses, dimensionless accretion rates, and Eddington ratios are derived for our final sample. In Section 3, we describe the procedure for X-ray data reduction, and we measure the $\Gamma$ values for our final sample. In Section 4, we investigate the correlation between the hard X-ray photon index and dimensionless accretion rates for the super-Eddington subsample, and we compare it to that for the sub-Eddington subsample. In Section 5, we discuss the implication of our results. In Section 6, we summarize our work and discuss some future prospects.

Throughout this paper, we use a cosmology with $H_0 = 67.4$ km s\(^{-1}\) Mpc\(^{-1}\), $\Omega_M = 0.315$, and $\Omega_{\Lambda} = 0.685$ (Planck Collaboration et al. 2018).

2. Sample Selection

2.1. Initial SDSS Quasar Selection

We use the SDSS DR14 quasar catalog (Pâris et al. 2018), which contains 526,356 quasars, to select an initial quasar sample. We first select 36,697 quasars with $z < 0.7$. Within this redshift range, the SDSS spectra cover the rest-frame 5100 Å continuum, the optical Fe II line emission, and the broad Hβ emission line, so that we can measure the rest-frame 5100 Å continuum luminosities, the $R_{\text{Fe}}$ values, and the FWHM of the broad Hβ emission line. These parameters are used to derive the bolometric luminosities and black hole masses.

Then, we select bright quasars by requiring the i-band magnitude ($m_i$) to be less than 19, because the probability of finding useful X-ray archival data for bright quasars is relatively high. There are 12,638 quasars satisfying both the redshift and $m_i$ criteria. Before fitting the SDSS spectra of these quasars, we search for X-ray archival coverage to reduce significantly the sample size and our workload.

2.2. Chandra Archival Coverage

We search for public Chandra Advanced CCD Imaging Spectrometer (ACIS) nongrating observations of all the 12,638...
initial sample objects in the Chandra archive as of 2019 July 9. For each quasar, we use a 14′ matching radius to search for available X-ray observations. We find 903 quasars that have matched Chandra observations, including 205 quasars with multiple Chandra observations.

To select observations that yield large numbers of source counts for spectral fitting, we further filter the 903 quasars using the following criteria:

1. The quasar is the target of the matched observation with an off-axis angle smaller than 1′. We obtain 163 quasars after using this criterion.
2. The quasar is not the target of the matched observation, but it has an off-axis angle smaller than 10′, and the exposure time of the observation is longer than 5 ks. We obtain 305 quasars using this criterion.
3. The quasar has an off-axis angle larger than 10′ but smaller than 14′, and the exposure time of the matched observation is longer than 20 ks. We obtain 83 quasars using this criterion.

If a quasar still has multiple Chandra observations after the above selection, we only use the observation with the longest exposure time. Using the criteria above, we select 551 (163 + 305 + 83) quasars with good archival ACIS data. We analyze the Chandra data of these quasars to obtain their X-ray properties (see Section 3.1 below). In order to obtain reliable spectral fitting results, we select only 120 of these 551 quasars with numbers of net counts more than 200 in the observed-frame 2/(1 + z)−7 keV band, excluding the Fe K complex that is adopted to be between rest-frame 5.5 and 7.5 keV. We require signal-to-noise ratio per pixel to be $>10$ in the rest-frame 4430−5550 Å spectrum. This wavelength range covers the Hβ, [O III], and optical Fe II line emission. After applying this criterion, we select 179 quasars.

2.4. Selection by SDSS Spectral Quality

Among the 120 quasars with Chandra observations and 118 quasars with XMM-Newton observations, there are 26 quasars in common. For each of these 26 quasars, we choose the Chandra or XMM-Newton observation with a larger number of net source counts. Thus, we obtain a sample of 212 (120 + 118 − 26) quasars. We fit the SDSS spectra of these quasars following the same procedure described in Hu et al. (2008, 2015). The sample is further filtered with the following additional criteria based on the spectral quality and shapes.

1. We require signal-to-noise ratio per pixel to be $>10$ in the rest-frame 4430−5550 Å spectrum. This wavelength range covers the Hβ, [O III], and optical Fe II line emission. After applying this criterion, we select 179 quasars.

2. We require the power-law spectral slope of the decomposed optical continuum ($\alpha_\text{O}$) to be $<0$. This criterion is to exclude quasars with SDSS spectra that may have strong host galaxy contamination or be affected by heavy absorption. We select 161 quasars after using this criterion. The emission-line and continuum properties for our final sample are listed in Table 1.

2.5. Exclusion of Radio-loud Quasars

Because radio-loud quasars may produce a significant amount of X-ray emission associated with jets (e.g., Miller et al. 2011), we need to remove radio-loud quasars from our sample. Following Shen et al. (2011), we first match our sample of 161 quasars to the 14Dec17 version of the Faint Images of the Radio Sky at Twenty-Centimeters (FIRST) source catalog (White et al. 1997) using a 3″ matching radius. For a quasar with two or more FIRST counterparts within the 30″ radius circular region, we use the summed peak flux densities at 20 cm of all the FIRST counterparts to compute the rest-frame 6 cm flux density, $f_{6\text{ cm}}$, adopting a power-law spectral slope of $\alpha_r = -0.8$ (e.g., Falcke et al. 1996; Barvainis et al. 2005). There are 20 such quasars; we visually inspect the FIRST and Digital Sky Survey images of these sources, and we find no apparent additional optical counterparts associated with the FIRST counterparts, suggesting that these FIRST counterparts are radio components of the quasars. For a quasar with only one FIRST counterpart within the matching radius, we rematch it to the FIRST catalog using a 5″ matching radius to determine if the one FIRST source is the correct radio counterpart. We then use the peak flux density at 20 cm of the FIRST counterpart to compute the rest-frame 6 cm flux density. For a quasar with no FIRST counterpart, we set $\sigma_{\text{rms}} = 0.25$ mJy as the upper limit on the 20 cm flux density, where $\sigma_{\text{rms}}$ is the rms noise at the source position and 0.25 mJy is used to account for the CLEAN bias (Gibson et al. 2009). The upper limit on $f_{6\text{ cm}}$ is then calculated from the upper limit on the 20 cm flux density.

There are six quasars not in the coverage of the FIRST catalog. We match the six quasars to the NRAO VLA Sky Survey (NVSS) source catalog (Condon et al. 1998) using the same method described above. Only one quasar has a radio counterpart within a 5″ matching radius. For the other five quasars with no NVSS counterparts, we use 2.5 mJy (the threshold of NVSS source detection) as the upper limit on the flux densities at 20 cm. We calculate $f_{6\text{ cm}}$ or its upper limit

2.3. XMM-Newton Archival Coverage

We use the 3XMM-DR8 source catalog11 (Watson et al. 2009; Rosen et al. 2016), which contains 775,153 X-ray sources drawn from 10,242 European Photon Imaging Camera (EPIC) observations between 2000 February 3 and 2017 November 30, to search for XMM-Newton observations for the initial sample. We match the 12,638 quasars to the 3XMM-DR8 source catalog using a 3″ matching radius, and we obtain 487 matches.

Among these quasars, we further select 188 quasars that have more than 1100 total pn camera counts in the observed-frame 0.2−12 keV band adopted from the 3XMM-DR8 source catalog. This source count criterion is chosen to yield \( \gtrsim 160 \) net source counts in the observed-frame $2/(1 + z)−10$ keV band excluding the Fe K complex, adopting a single power-law spectrum with $\Gamma = 1.9$, $z = 0.4$ (the mean redshift of the 487 quasars), and typical pn response files. For a quasar with multiple XMM-Newton observations, we select the observation with the highest number of source counts in the observed-frame 0.2−12 keV band from the 3XMM-DR8 source catalog.

We analyze the corresponding XMM-Newton data to obtain X-ray properties of these 188 quasars (see Section 3.2 below). We keep 118 of these quasars with more than 200 net source counts in the observed-frame $2/(1 + z)−10$ keV band excluding the Fe K complex to obtain reliable spectral fitting results.

10 https://cda.harvard.edu/chaser/
11 https://heasarc.gsfc.nasa.gov/w3browse/xmm-newton/xmmssc.html
Table 1
Optical and Radio Properties for the Final Sample

| Object Name   | Redshift | $M_\star [z=2] | \log \text{FWHM}_{1}\beta | \log l_{\beta} | \log l_{\beta,1000} | \log l_{\beta,5100} | \log l_{\beta,51,000} | \log M_{\star} | \log \lambda_{\text{bol}} | \log R |
|---------------|----------|----------------|--------------------------|--------------|-------------------|-------------------|-------------------|-------------|----------------|-------|
| (J2000)       | (1)      | (2)            | (3)                      | (4)          | (5)               | (6)               | (7)               | (8)         | (9)            | (10)  |
| 002233.27-003448.4 | 0.504 | –23.78 | 3.26 | 42.81 | 42.67 | 44.51 | 45.64 | 7.42 | 0.12 | 1.42 | <0.99 |
| 004319.74+005115.4 | 0.309 | –23.79 | 3.97 | 42.63 | 41.96 | 44.43 | 45.63 | 9.00 | –1.47 | –1.86 | 3.30 |
| 005709.94+144610.1 | 0.172 | –24.47 | 4.00 | 43.09 | –1.00 | 44.94 | 45.71 | 9.35 | –1.74 | –1.79 | 2.18 |
| 012549.97+020332.2 | 0.500 | –23.77 | 3.78 | 42.93 | –1.00 | 44.78 | 45.73 | 8.85 | –1.22 | –1.03 | <2.46 |
| 013418.19+001536.7 | 0.401 | –25.34 | 3.72 | 43.37 | 42.95 | 45.18 | 46.10 | 8.77 | –0.77 | –0.29 | <0.76 |
| 014959.27+125658.0 | 0.432 | –24.33 | 3.54 | 43.00 | 42.63 | 44.74 | 45.84 | 8.19 | –0.45 | 0.23 | <4.17 |
| 015950.24+002340.8 | 0.163 | –24.04 | 3.45 | 42.78 | 42.77 | 44.77 | 45.77 | 7.83 | –0.16 | 0.99 | 6.10 |
| 020011.52-093126.2 | 0.360 | –23.81 | 3.90 | 43.35 | 42.70 | 45.06 | 45.70 | 9.13 | –1.53 | –1.19 | <0.95 |
| 020039.15-084554.9 | 0.432 | –24.54 | 3.25 | 42.81 | 42.78 | 44.81 | 45.81 | 7.46 | 0.25 | 1.78 | <1.04 |
| 020354.68-060844.0 | 0.464 | –24.25 | 3.80 | 43.18 | 42.24 | 44.95 | 45.69 | 8.92 | –1.33 | –0.93 | <2.28 |
| 020840.66-062716.7 | 0.092 | –20.73 | 3.62 | 41.32 | 41.14 | 43.49 | 44.19 | 7.71 | –1.62 | –0.69 | <2.04 |

Note. Column (1): name of the object, in order of increasing R.A.; column (2): redshift; column (3): the absolute magnitude in the $i$ band at $z = 2$; column (4): logarithm of the FWHM of the broad H$\beta$ emission line in units of km s$^{-1}$; column (5): logarithm of the luminosity of the H$\beta$ broad emission line in units of erg s$^{-1}$; column (6): logarithm of the luminosity of the optical FeII line emission in units of erg s$^{-1}$, which is labeled as "−1.00" when there is no FeII component measured from the optical spectrum; column (7): logarithm of the continuum luminosity at rest-frame 5100 Å in units of erg s$^{-1}$; column (8): logarithm of the bolometric luminosity derived from integrating the SED in units of erg s$^{-1}$; column (9): logarithm of the black hole mass derived from Equation (2), in units of solar mass; column (10): logarithm of the Eddington ratio; column (11): logarithm of the dimensionless accretion rate; column (12): the radio-loudness parameter or its upper limit.

This table is available in its entirety in machine-readable form.

using the same method as that for quasars with FIRST coverage.

The sample of 161 quasars contains 56 quasars with FIRST or NVSS counterparts and 105 quasars without radio counterparts. We convert the flux density at rest-frame 5100 Å measured from the SDSS spectra (see Section 2.4) to the flux density at rest-frame 4400 Å ($f_{\lambda_{4400}}$) for each quasar using the optical power-law spectral slope we obtain from the spectral fitting. We compute the radio-loudness parameter or its upper limit using $R = f_{\text{rest}} / f_{\lambda_{4400}}$ (e.g., Kellermann et al. 1989). We consider a quasar to be radio-quiet (RQ) if its $R$ value is less than 10 or its upper limit on $R$ is less than 100. We remove 37 quasars with $R$ values more than 10 from our sample, and there is no quasar that has an upper limit on $R$ more than 100. The remaining 124 quasars are considered to be RQ. Only three quasars in these 124 quasars have upper limits on $R$ larger than 10, and the largest upper limit is only 13.6, suggesting that our sample is a reliable RQ quasar sample. The radio properties for our final sample (see Section 2.6) are listed in Table 1.

2.6. Exclusion of X-Ray Absorbed Quasars

Because we are studying the correlation between the corona and accretion disk, we need to obtain the intrinsic hard X-ray photon index for our quasars. The X-ray emission from a small fraction of quasars may be affected by absorption, and the main population of these quasars is broad absorption-line (BAL) quasars (e.g., Gallagher et al. 2002, 2006; Fan et al. 2009; Gibson et al. 2009). It is difficult to derive the intrinsic $\Gamma$ values for X-ray absorbed quasars without very good X-ray spectra. Therefore, we need to remove X-ray absorbed quasars from our sample.

We remove 11 X-ray absorbed quasars which are probably BAL quasars from our sample after fitting the X-ray spectra (see Section 3.3 below). We check the SDSS spectra of these 11 quasars for BAL features. Five quasars have no Mg II coverage, and the other six quasars do not have apparent Mg II absorption. Mg II BAL quasars are much rarer than C IV BAL quasars, but for the redshift range of our sample, the SDSS DR14 spectra do not cover the C IV line. We note that the fraction of X-ray absorbed quasars in this sample (11/124) is smaller than the fraction of BAL quasars ($\approx 15\%$; e.g., Hewett & Foltz 2003; Trump et al. 2006; Gibson et al. 2009; Allen et al. 2011). We consider that this is a natural consequence of selecting X-ray bright quasars (see Sections 2.2 and 2.3), which generally guards against X-ray absorbed quasars.

After excluding the 11 X-ray absorbed quasars, the remaining 113 quasars constitute our final sample. We show the distribution of the absolute $i$-band magnitude ($M_i$) versus redshift for our final sample. The $M_i$ values are adopted from the SDSS DR14 quasar catalog. The red filled circles and blue open circles represent our super- and sub-Eddington subsamples, respectively. The gray dots represent the SDSS DR14 quasars with $z < 0.7$.

Figure 1. Distribution of the absolute $i$-band magnitude ($M_i$) vs. redshift for our final sample. The $M_i$ values are adopted from the SDSS DR14 quasar catalog. The red filled circles and blue open circles represent our super- and sub-Eddington subsamples, respectively. The gray dots represent the SDSS DR14 quasars with $z < 0.7$. 

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We estimate the black hole masses by adopting the virial mass formula \( M_{BH} = f V_{\text{FWHM}}^2 \frac{R_{H\beta}}{G} \), where \( f \) is the virial factor, \( V_{\text{FWHM}} \) is the FWHM of the broad H\( \beta \) emission line, \( G \) is the gravitational constant, and \( R_{H\beta} \) is the H\( \beta \) BLR size (e.g., Kaspi et al. 2000, 2005; Bentz et al. 2013). We adopt \( f = 1 \) following Du & Wang (2019).

The updated \( R-L \) relation from (Du & Wang 2019) can be expressed as

\[
\log R_{H\beta} = 1.64 \pm 0.06 + 0.45 \pm 0.04 \log l_{44} + -0.35 \pm 0.09 R_{Fe},
\]

where \( R_{Fe} \) is the relative strength of the optical Fe II line emission (see footnote 10) and \( l_{44} \) is the 5100 Å luminosity in units of \( 10^{44} \) erg s\(^{-1}\). This relation indicates that the BLR sizes for super-Eddington accreting AGNs are relatively smaller than those of sub-Eddington accreting AGNs, as super-Eddington accreting AGNs usually have larger \( R_{Fe} \) values (Boroson & Green 1992; Hu et al. 2008; Dong et al. 2011). With the updated \( R-L \) relation, the single-epoch virial mass formula can be expressed as

\[
\log \left( \frac{M_{BH}}{M_\odot} \right) = 7.83 + 2 \log (V_{H\beta}) + 0.45 \log (l_{46}) - 0.35 R_{Fe},
\]

where \( V_{H\beta} \) is FWHM\( H\beta/10^3 \) km s\(^{-1}\) and \( l_{46} \) is the 5100 Å luminosity in units of \( 10^{46} \) erg s\(^{-1}\). We list the \( M_{BH} \) values and other optical properties for the 113 quasars in our final sample in Table 1. Our final sample has \( M_{BH} \) values ranging from \( 10^{6.7} \) to \( 10^{9.9} \) \( M_\odot \), with a median value of \( 10^{8.2} \) \( M_\odot \). The \( M_{BH} \) values are used to derive the \( \dot{M} \) and \( \lambda_{Edd} \) values for our final sample (see Section 2.8 below).

For comparison, we also use the conventional \( R-L \) relation calibrated by Kaspi et al. (2005) to estimate the black hole masses. Netzer & Trakhtenbrot (2007) used the \( R-L \) relation calibrated by Kaspi et al. (2005) and obtained a virial mass formula expressed as

\[
\log \left( \frac{M_{BH,NT}}{M_\odot} \right) = 8.02 + 2 \log (V_{H\beta}) + 0.65 \log (l_{46}).
\]

We use this formula to obtain \( M_{BH,NT} \) values and then use the \( M_{BH,NT} \) values to derive \( \lambda_{Edd,NT} \) and \( \dot{M}_{\text{NT}} \) values. A comparison of the black hole masses estimated using the two \( R-L \) relations is shown in Figure 2(a). The \( M_{BH,NT}/M_{BH} \) ratios have a mean value of 1.87 for the super-Eddington subsample, and a mean value of 1.09 for the sub-Eddington subsample. The comparison shows that the two sets of black hole masses differ mainly for super-Eddington accreting quasars, where the black hole masses estimated from Equation (2) are generally smaller.

2.8. Dimensionless Accretion Rates and Eddington Ratios

We estimate the dimensionless accretion rates and Eddington ratios for our final sample. For each quasar in our sample, the \( \dot{\mathcal{M}} \) value is estimated based on the standard thin disk accretion model (e.g., Wang et al. 2014; Du et al. 2016) and can be expressed as

\[
\dot{\mathcal{M}} = 20.1 (l_{44}/\cos i)^{3/2} m_7^{-2},
\]

where \( m_7 = M_{BH}/10^7 M_\odot \). We adopt \( \cos i = 0.75 \) in this study (see Du et al. 2016 for discussions).

We note that the above formula is likely also valid for estimating the dimensionless accretion rates for super-Eddington accreting AGNs where thick accretion disks are generally expected, and it has been frequently adopted in recent reverberation mapping studies of super-Eddington accreting AGNs (e.g., Du et al. 2014, 2016; Hu et al. 2015; Wang et al. 2016; Li et al. 2018). Theoretically, the slim disk model (Wang et al. 1999; Wang & Zhou 1999) indicates that the 5100 Å disk emission region is beyond the photon trapping radius provided that \( \dot{\mathcal{M}} \lesssim 3 \times 10^3 m_7^{-1/2} \) (see footnote 8 of Du et al. 2016), and thus a standard thin disk solution still applies when adopting the 5100 Å luminosity to estimate the dimensionless accretion rate. Among the 113 quasars in our final sample, none has the dimensionless accretion rate exceeding the above limit. Observationally, studies on the spectral energy distributions (SEDs) of super-Eddington accreting AGNs often found that
their optical/UV SEDs are well fit by the standard thin disk model, and any thick disk emission signature likely only exists in the extreme UV (EUV) where few observational data are available (e.g., Castellón-Mor et al. 2016; Kubota & Done 2019). In addition, from a recent Swift accretion disk reverberation mapping campaign on the super-Eddington accreting AGN Mrk 142 (Cackett et al. 2020), multiwavelength time lags in the optical/UV were found to follow in general the $\tau(\lambda) \propto \lambda^{1/3}$ relation that is consistent with the thin disk model, suggesting that the optical/UV emission is likely still from a thin disk. Therefore, we use Equation (4) to estimate the dimensionless accretion rates for all our sample quasars, and the obtained $\dot{\mathcal{M}}$ values are listed in Table 1. The dimensionless accretion rates for the final sample range from $7.9 \times 10^{-4}$ to $280$, with a median value of 0.54.

We adopt a criterion of $\dot{\mathcal{M}} > 3$ to select super-Eddington accreting quasars (e.g., Wang et al. 2014; Du et al. 2016). Based on this criterion, 38 (34%) of the 113 quasars in our final sample are considered super-Eddington accreting quasars, and we refer to these quasars as “the super-Eddington subsample.” The other 75 quasars constitute the sub-Eddington subsample. We show the $R_{\text{Fe}}$ versus $M_{\text{BH}}$ distributions for the super- and sub-Eddington subsamples in Figure 2(b). The super-Eddington subsample has larger $R_{\text{Fe}}$ values on average, which is consistent with previous findings (e.g., Boroson & Green 1992; Hu et al. 2008; Dong et al. 2011).

We estimate the bolometric luminosities for our sample quasars by integrating their SEDs. We collect their near-infrared (NIR), optical, and UV photometric data from the public catalogs of the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006), SDSS, and Galaxy Evolution Explorer (GALEX; Martin et al. 2005). We correct the SED data of each quasar for the Galactic extinction at its source position. Among the 113 quasars in our final sample, 24 quasars do not have 2MASS photometric data, and 13 quasars do not have GALEX photometric data. We construct the SEDs following mainly the procedure described in Section 3.1 of Davis & Laor (2011). The SEDs between 1 $\mu$m and 1549 Å are simple linear interpolations from the NIR-to-UV photometric data; for the 24 quasars without 2MASS data, the NIR SEDs are linear extrapolations from the SDSS data adopting a power-law spectral slope ($F_\nu \propto \nu^b$) of $-0.3$ (Davis & Laor 2011), and for the 13 quasars without GALEX data, the UV SEDs are linear extrapolations from the SDSS data adopting a spectral slope of $-0.5$ (Vanden Berk et al. 2001). The 1–30 $\mu$m SEDs are set to power laws with a spectral slope of 1/3 (Davis & Laor 2011). We then add the EUV-to-X-ray SEDs. We assume a spectral slope of $-1$ between 1549 and 1000 Å. The 2–10 keV power-law spectra are obtained from our spectral fitting in Section 3.3 below, with spectral slopes of 1–$\Gamma$. We estimate the 0.2–2 keV spectral slopes from the Hβ FWHM using the relation in Brandt et al. (2000). The spectra between 1000 Å and 0.2 keV are then simple power laws connecting the two end points. We integrate the 30 $\mu$m–10 keV SEDs to obtain the bolometric luminosities ($L_{\text{bol}}$), and the derived values are listed in Table 1. For our sample, the $L_{\text{bol}}$ values range from $1.5 \times 10^{44}$ to $5.2 \times 10^{46}$ erg s$^{-1}$, with a median value of $4.1 \times 10^{45}$ erg s$^{-1}$.

We caution that there may be considerable uncertainties associated with the bolometric luminosities derived from the multiband SEDs above, especially for the super-Eddington accreting quasars. Besides potential host-galaxy contaminations in the NIR–optical SEDs that are usually small for luminous quasars and potential variability effects due to the nonsimultaneous SED data, super-Eddington accreting quasars might have significantly enhanced EUV emission compared to typical quasars (e.g., Davis & Laor 2011; Jin et al. 2012; Castellón-Mor et al. 2016; Kubota & Done 2019). There is no clear observational constraint on the EUV emission from super-Eddington accreting quasars due to the lack of data, and thus we cannot evaluate the scale of such a potential bias on the $L_{\text{bol}}$ values for the super-Eddington subsample.

Another common approach of obtaining bolometric luminosities is through the use of bolometric corrections to the optical luminosities (e.g., $L_{\text{bol,BC}} \approx k_{\text{bol}}L_{5100}$). We also estimate the bolometric luminosities for our sample quasars using bolometric corrections. We first adopt the bolometric correction factors in Netzer (2019), which are expressed as

$$k_{\text{bol}} = 40(L_{5100}/10^{42} \text{ erg s}^{-1})^{-0.2}. \tag{5}$$

The derived $L_{\text{bol,BC}}$ values are comparable to our SED-derived $L_{\text{bol}}$ values, and the $L_{\text{bol,BC}} / L_{\text{bol}}$ ratios range from 0.53 to 4.04, with a median value of 1.17. It appears that the agreement between the two sets of estimates is slightly better for the super-Eddington subsample, with the median value of $L_{\text{bol,BC}} / L_{\text{bol}}$ ratios being 1.05, while it is 1.23 for the sub-Eddington subsample. Next, we adopt a constant bolometric factor, often found from observations on large AGN samples (e.g., Richards et al. 2006; Duras et al. 2020), to obtain another set of $L_{\text{bol,BC}}$ estimates. We set $k_{\text{bol}}$ to be 10 following Kaspi et al. (2000). The derived $L_{\text{bol,BC}}$ values are again comparable to our SED-derived $L_{\text{bol}}$ values. The $L_{\text{bol,BC}} / L_{\text{bol}}$ ratios range from 0.34 to 2.28, with a median value of 1.01; the median values are 0.95 for the super-Eddington subsample and 1.08 for the sub-Eddington subsample. We caution that the above bolometric corrections were derived from thin disk models or from typical AGN SEDs, and they are probably still not applicable in the super-Eddington regime, where larger correction factors are likely expected (e.g., Castellón-Mor et al. 2016; Netzer 2019).

We consider that the differences between the two sets of $L_{\text{bol,BC}}$ values and the SED-derived $L_{\text{bol}}$ values simply reflect the systematic offsets between the different methods used to estimate the bolometric luminosities, and they do not provide useful insight into the accuracy of the SED-derived $L_{\text{bol}}$ values in the super-Eddington regime. In our following analysis, we adopt the SED-derived $L_{\text{bol}}$ values; using either set of the $L_{\text{bol,BC}}$ values above instead would not change the results significantly.

With the Eddington luminosities computed as $L_{\text{Edd}} = 1.26 \times 10^{38}(M_{\text{BH}}/M_\odot) \text{ erg s}^{-1}$, the Eddington ratios for our sample quasars are derived. We list the Eddington ratios for our final sample in Table 1, which range from $5.2 \times 10^{-3}$ to 3.3, with a median value of 0.16. Compared to the dimensionless accretion rates, the Eddington ratios have additional uncertainties associated with the bolometric luminosities that are especially uncertain for the super-Eddington subsample. Therefore, we focus our study on the $\Gamma - \dot{\mathcal{M}}$ correlation below. We still keep the analysis of the $\Gamma - \dot{\mathcal{M}}$ correlation, mainly for the comparisons of this correlation to those found in previous studies.
2.9. The Connection between $\dot{M}$ and $\lambda_{\text{Edd}}$

Analytical solutions indicate that for a black hole with a given black hole mass and spin, there is a connection between the dimensionless accretion rate and the Eddington ratio (e.g., Mineshige et al. 2000; Watarai et al. 2000). When the black hole is sub-Eddington accreting, the Eddington ratio should change linearly with the dimensionless accretion rate because the radiative efficiency is a constant for a standard thin disk. When the accretion is in the super-Eddington regime, the radiative efficiency decreases significantly due to the photon trapping effect, which indicates that the linear correlation between $\lambda_{\text{Edd}}$ and $\dot{M}$ disappears.

In this study, we investigate the correlation between $\lambda_{\text{Edd}}$ and $\dot{M}$ for our sample objects. The distribution of the $\lambda_{\text{Edd}}$ versus $\dot{M}$ values for our sample is shown in Figure 3(a). For the full sample, there is a significant power-law correlation between $\lambda_{\text{Edd}}$ and $\dot{M}$, with a power-law slope of 0.52. The $\lambda_{\text{Edd}}$-$\dot{M}$ correlation from a semianalytical model (Mineshige et al. 2000; Watarai et al. 2000; $\eta = 0.04$ in the radiatively efficient case) is shown in Figure 3(a) for comparison, where $\lambda_{\text{Edd}}$ changes linearly with $\dot{M}$ (with a power-law slope of 1) when $\dot{M} < 50$, and it saturates above $\dot{M} = 50$. The strong $\lambda_{\text{Edd}}$-$\dot{M}$ correlation and its deviation from the analytical expectation can be understood from Equation (4), which indicates $\dot{M} \propto L_{5100}^{1.5} M_{\text{BH}}^{-2}$. The $\lambda_{\text{Edd}}$ parameter is related to $L_{5100}$ and $M_{\text{BH}}$ in the form $\lambda_{\text{Edd}} \propto L_{5100} M_{\text{BH}}^{-1} \propto L_{5100}^{0.5} M_{\text{BH}}^{-0.5}$, considering that the bolometric luminosity is generally linearly scaled to the optical luminosity with some scatter. Therefore, $\lambda_{\text{Edd}}$ is correlated to $\dot{M}$ with a power-law form: $\lambda_{\text{Edd}} \propto L_{5100}^{0.52}$. The dependence on $L_{5100}$ is small and the range of $L_{5100}$ for our sample quasars is also limited. This explains the $\lambda_{\text{Edd}} \propto \dot{M}^{0.52}$ power-law correlation we observe in Figure 3(a).

This $\lambda_{\text{Edd}}$-$\dot{M}$ relation also indicates that the radiative efficiency $\eta$ is correlated with black hole mass in the form of $\eta = \lambda_{\text{Edd}} / \dot{M} \propto L_{5100}^{0.5} M_{\text{BH}}$. The $\eta$ parameter is roughly linearly correlated with $M_{\text{BH}}$. In Figure 3(b), we plot the best-fit $\eta-M_{\text{BH}}$ correlation for our final sample. The best-fit $\eta-M_{\text{BH}}$ correlation is $\eta \propto M_{\text{BH}}^{0.81}$. Previous studies also found similar correlations between $\eta$ and $M_{\text{BH}}$ (Davis & Laor 2011; Chelouche 2013). For example, Davis & Laor (2011) used a sample of Palomar–Green quasars and found that $\eta \propto M_{\text{BH}}^{0.53}$. We compare the $\dot{M}$ values derived from Equation (4) to those derived from Equation (7) in Davis & Laor (2011), and they are consistent.

We explore several possible factors that may explain the unusual $\lambda_{\text{Edd}}$-$\dot{M}$ correlation and the deviation from the analytical expectation:

1. The standard thin disk model needs to be modified, and thus the computation of $\dot{M}$ using Equation (4) is not appropriate (e.g., see Section 4.3 of Davis & Laor 2011).
2. The bolometric luminosities for the super-Eddington accreting quasars are highly uncertain and may even be biased. However, we note that if considering only the sub-Eddington subsample, the strong nonlinear $\lambda_{\text{Edd}}$-$\dot{M}$ correlation still exists and deviates from the theoretical expectation (Figure 3(a)). Therefore, we consider that the uncertainties on the bolometric luminosities are not the main cause for the unusual $\lambda_{\text{Edd}}$-$\dot{M}$ correlation.
3. There is a real connection between the radiative efficiency and the black hole masses (Figure 3(b)). If $\eta$ increases as $M_{\text{BH}}$ increases, the $\lambda_{\text{Edd}}$-$\dot{M}$ correlation ($\eta = \lambda_{\text{Edd}} / \dot{M}$) would be flatter than the power law with a unity slope, as smaller $\dot{M}$ values should correspond to larger $M_{\text{BH}}$ and thus larger $\eta$ values. Such an $\eta-M_{\text{BH}}$ correlation would suggest that the black hole spin increases as the black hole gains its mass via accretion (e.g., Davis & Laor 2011).

In addition, the uncertainties on the $M_{\text{BH}}$ and $L_{\text{bol}}$ parameters may also contribute partially to the $\eta-M_{\text{BH}}$ correlation in Figure 3(b) (see Sections 4.1 and 4.2 of Davis & Laor 2011) and thus the $\lambda_{\text{Edd}}$-$\dot{M}$ correlation in Figure 3(a). Nevertheless, it is possible that some of the above points are working together to create the observed $\lambda_{\text{Edd}}$-$\dot{M}$ correlation, and it appears inevitable to obtain such a correlation if the standard thin disk model is adopted. In the current study, we focus on the relation between the hard X-ray photon index and the accretion rate for super-Eddington accreting quasars. Considering the additional uncertainties associated with the bolometric luminosities, we prioritize the use of the $\dot{M}$ to represent the accretion rates for our sample objects.
3. Data Analysis

3.1. Chandra Data Analysis

For each Chandra observation, we analyze the data using the Chandra Interactive Analysis of Observation (CIAO; v4.10) tools. We first use the CHANDRA_REPRO script to generate a new level 2 event file and then filter background flares by running the DEFLARE script using an iterative 3σ clipping algorithm to obtain the cleaned event file. We create an X-ray image in the 0.5–7 keV band from the cleaned event file by running the DMCOPY tool.

To search for X-ray sources in the X-ray image, we use the WAVDETECT tool (Freeman et al. 2002) with a false-positive probability threshold of 10⁻⁶ and scale sizes of 1, 1.414, 2, 2.828, 4, 5.656, and 8 pixels. We then match the optical position of the quasar to the X-ray source positions to search for the X-ray counterpart, using a 3″ matching radius. For the quasars in our final sample, the offsets between the optical positions and the X-ray counterpart positions have a mean value of 0″99. To extract the source spectrum for each source, we choose a circular source region centered on the X-ray counterpart, with a radius of the 90% PSF size plus 3″; we use the PSFSIZE_SRC script to obtain the size of the PSF with 90% enclosed counts at 1.5 keV. To extract the background spectrum, we choose an annulus region with radii of three times and five times the source extraction radius. The background region is also centered on the X-ray position of the quasar. For three sources that are in crowded areas or near the chip edges, we make the source or background regions smaller to avoid contamination from other detected X-ray sources or bias from the chip edges. We use the SPECEXTRACT tool to extract the X-ray source spectrum.

In order to measure the hard X-ray photon index for each Chandra source in our sample, we fit the X-ray spectra in the observed-frame 2/(1 + z)–7 keV band. To exclude the Fe K complex, we exclude the spectrum in the rest-frame 5.5–7.5 keV band (Brightman et al. 2013). We obtain the number of net source counts in the observed-frame 2/(1 + z)–7 keV band (excluding the Fe K complex) by subtracting the estimated number of background counts in the source aperture from the number of source counts. The number of background counts is scaled using the area scaling factor, which is the ratio between the areas of the background and source extraction regions. The number of the net source counts is then used to select X-ray bright quasars (see Section 2.2).

3.2. XMM-Newton Data Analysis

We use the Science Analysis System (SAS; v1.2) for the XMM-Newton data reduction. We follow the standard procedure in the SAS Data Analysis Threads (SAS; v3.05 Kaastra et al. 1996) to process the data. For all sources, we only use the data from the pn camera. We use the EPPROC tool to get calibrated and concatenated event lists. We use a count rate threshold of 0.4 cts/s to filter background flares, and we use the TABGTIGEN script to create good-time-intervals files. We then use the EVSELECT tool to obtain the cleaned event files.

Based on the flare-filtered event files, we use the EVSELECT tool to construct images in the 0.3–10 keV band. Then, we use the EDETECT_CHAIN tool to detect point sources in the images.

For each quasar, we select a circular source region with a radius of 30″ and a circular background region with a radius of 40″. The source region is centered on the optical position of each quasar. The background region is chosen to be on the same CCD chip as the source region and is free of other X-ray sources. For six sources that are in crowded areas or near the chip edges, we make the source region smaller to avoid contamination from other detected X-ray sources or bias from the chip edges. Then we use the EVSELECT tool to extract the X-ray spectra in the observed-frame 0.1–10 keV band.

To measure the hard X-ray photon index Γ for each XMM-Newton source in our sample, we fit the spectrum in the observed-frame 2/(1 + z)–10 keV band. We also ignore the spectrum in the rest-frame 5.5–7.5 keV band to exclude the Fe K complex. We obtain the number of net source counts in the observed-frame 2/(1 + z)–10 keV band (excluding the Fe K complex) by subtracting from the number of source counts the estimated number of background counts in the source aperture. Then, we use the number of net source counts to select X-ray bright quasars (see Section 2.3).

Among the 113 quasars in our final sample, there are six quasars that have both Chandra and XMM-Newton observations. We choose the observation that yields a larger number of net source counts (see Section 2.4). We adopt Chandra observations for 43 quasars (Chandra group) and XMM-Newton observations for the other 70 quasars (XMM-Newton group). We show the histograms of the cleaned exposure times of the X-ray observations for our final sample in Figure 4. The X-ray properties for each quasar in our final sample, such as the cleaned exposure times and net source counts, are listed in Table 2. For our final sample, the cleaned exposure times have a median value of 21.8 ks, and the numbers of net source counts have a median value of 465.9.

3.3. X-Ray Spectral Fitting

To obtain the Γ value for each source, we fit the X-ray spectrum. We analyze the spectra of the 124 radio-quiet quasars (see Section 2.5) using SPEX (v.3.05 Kaastra et al. 1996). Following the guide of the SPEX cookbook (SPEX; v3.05 Kaastra et al. 1996), we use the TRAFO tool in SPEX to convert the OGIP spectra into the

Figure 4. Distributions of the cleaned exposure times of the X-ray observations for our final sample, including 43 Chandra observations (blue solid line) and 70 XMM-Newton observations (red dashed line).

For each quasar, we select a circular source region with a radius of 30″ and a circular background region with a radius of 40″. The source region is centered on the optical position of each quasar. The background region is chosen to be on the same CCD chip as the source region and is free of other X-ray sources. For six sources that are in crowded areas or near the chip edges, we make the source region smaller to avoid contamination from other detected X-ray sources or bias from the chip edges. Then we use the EVSELECT tool to extract the X-ray spectra in the observed-frame 0.1–10 keV band.

To measure the hard X-ray photon index Γ for each XMM-Newton source in our sample, we fit the spectrum in the observed-frame 2/(1 + z)–10 keV band. We also ignore the spectrum in the rest-frame 5.5–7.5 keV band to exclude the Fe K complex. We obtain the number of net source counts in the observed-frame 2/(1 + z)–10 keV band (excluding the Fe K complex) by subtracting from the number of source counts the estimated number of background counts in the source aperture. Then, we use the number of net source counts to select X-ray bright quasars (see Section 2.3).

Among the 113 quasars in our final sample, there are six quasars that have both Chandra and XMM-Newton observations. We choose the observation that yields a larger number of net source counts (see Section 2.4). We adopt Chandra observations for 43 quasars (Chandra group) and XMM-Newton observations for the other 70 quasars (XMM-Newton group). We show the histograms of the cleaned exposure times of the X-ray observations for our final sample in Figure 4. The X-ray properties for each quasar in our final sample, such as the cleaned exposure times and net source counts, are listed in Table 2. For our final sample, the cleaned exposure times have a median value of 21.8 ks, and the numbers of net source counts have a median value of 465.9.
SPEX format. We group each X-ray spectrum into at least one count per bin for spectral fitting, and we use the W statistic for parameter estimation.

We use a redshifted (REDS) single power-law model (POW) to fit the spectrum for each quasar. We consider the galactic-absorption correction for each source by adding a neutral hydrogen gas absorption component (ABSM). As mentioned in the Section 2.6, we aim to exclude X-ray absorbed quasars in our sample via X-ray spectral fitting. Thus, we add another redshifted absorption component to fit for any intrinsic absorption. We use the FTEST tool in XSPEC (v.12.10.1; Arnaud 1996) to evaluate whether the intrinsic absorption component is appropriate. We identify five XMM-Newton sources and six Chandra sources that have intrinsic absorption at a 95% confidence level, with $N_H$ values in the range of $6.4 \times 10^{21}$ to $6.6 \times 10^{22}$ cm$^{-2}$. We thus exclude these 11 quasars from our sample (see Section 2.6). The spectra for the 113 quasars in our final sample are all fitted with a power-law model modified by Galactic absorption.

The C statistic (Cash 1979; Kaasstra 2017) in SPEX can provide us with the confidence level of the spectral fitting results, while the W statistic is not able to do so. Thus, we also use the C statistic in the spectral fitting and group the data using the optimal data bin size (Kaasstra & Bleeker 2016), which can be achieved via the OBIN command in SPEX. We compare the fitting results from the two different statistics. We find that for the Chandra spectra, the $\Gamma$ values measured from the W statistic + “one count per bin” is consistent with that from the C statistic + “obin.” But for the XMM-Newton spectra, especially those XMM-Newton spectra with relatively smaller numbers of net source counts, the $\Gamma$ values are not consistent. The XMM-Newton observations generally have more background counts than Chandra observations. When the numbers of net source counts are relatively small compared to the number of background counts, the C statistic in SPEX may give biased results (see the SPEX Reference Manual15 for details). Thus, it is not suitable yet to use the C statistic in SPEX to fit the XMM-Newton spectra with small numbers of net counts. We still use the W statistic + “one count per bin” results in this study. The W/d.o.f. values for our final sample range from 0.51 to 1.08, and have a median value of 0.86.

The distributions of the $\Gamma$ values for our final sample is shown in Figure 5(a). The $\Gamma$ values of the Chandra group have a median value of 1.92, while the $\Gamma$ values of the XMM-Newton group have a median value of 1.99. We perform the Kolmogorov–Smirnov test using the KSTWO tool in IDL. The result shows that $D = 0.21$ and $P = 0.175$, which indicate that the $\Gamma$ values of these two groups of sources are not statistically different.

We list the X-ray properties from the spectral fitting for our final sample in Table 2. We show the $\Gamma$ values versus the net counts for the super- and sub-Eddington subsamples in Figure 5(b). The uncertainties of the $\Gamma$ values for our sample are generally smaller than 0.2, because we only select quasars with numbers of X-ray net source counts larger than 200 (see Sections 2.2 and 2.3).

### 4. Results

The aim of our study is to investigate if there is any difference between the disk–corona connections in super- and sub-Eddington accreting quasars, by comparing the correlations between $\Gamma$ and $\dot{m}$ for these two types of accretion systems. In this section, we examine the correlations between $\Gamma$ and $\dot{m}$, and the correlations between $\Gamma$ and $\lambda_{\text{Edd}}$ for the super- and sub-Eddington subsamples, respectively. When performing linear regression analysis, we consider the 1σ uncertainties of the $\Gamma$ and log $\dot{m}$ (log $\lambda_{\text{Edd}}$) values. We adopt the typical uncertainty of $\dot{m}$ ($\lambda_{\text{Edd}}$) to be 0.4 dex (0.2 dex) from Du & Wang (2019), which is dominated by the systematic uncertainty of deriving the black hole mass from the updated $R$–$L$ relation and the virial mass formula. We also investigate whether there is a correlation between $\Gamma$ and $M_{\text{BH}}$.

15 https://var.sron.nl/SPEX-doc/manualv3.05/manual.html
Figure 5. (a) Distributions of the $\Gamma$ values for quasars in our final sample. The blue solid line represents the distribution for the Chandra group and the red dashed line for the XMM-Newton group. (b) The hard X-ray photon index vs. net spectral counts for the super- and sub-Eddington subsamples.

Table 3
Results of Spearman Rank Correlation Tests and Linear Regression Analyses

| Relation (1) | Sample (2)   | $R_S$ (3) | $p$ (4)     | $S$ (5) | $C$ (6) |
|--------------|--------------|-----------|-------------|---------|---------|
| $\Gamma$ versus $\dot{M}$ | Super-Eddington | 0.43  | $7.75 \times 10^{-3}$ | 0.34 ± 0.11 | 1.71 ± 0.17 |
|               | Sub-Eddington | 0.30  | $9.98 \times 10^{-3}$ | 0.09 ± 0.04  | 1.93 ± 0.04 |
|               | Full         | 0.56  | $1.10 \times 10^{-10}$ | 0.13 ± 0.02  | 1.97 ± 0.02 |
| $\Gamma$ versus $\dot{M}_\text{NT}$ | Super-Eddington | 0.32  | $4.75 \times 10^{-2}$ | 0.44 ± 0.25  | 1.81 ± 0.30 |
|               | Sub-Eddington | 0.23  | $4.78 \times 10^{-2}$ | 0.07 ± 0.05  | 1.93 ± 0.04 |
|               | Full         | 0.52  | $2.69 \times 10^{-9}$ | 0.15 ± 0.02  | 2.00 ± 0.02 |
| $\Gamma$ versus $\lambda_{Edd}$ | Super-Eddington | 0.56  | $2.76 \times 10^{-4}$ | 0.59 ± 0.16  | 2.13 ± 0.03 |
|               | Sub-Eddington | 0.21  | $7.10 \times 10^{-2}$ | 0.12 ± 0.07  | 2.03 ± 0.09 |
|               | Full         | 0.53  | $1.32 \times 10^{-9}$ | 0.23 ± 0.03  | 2.13 ± 0.03 |
| $\Gamma$ versus $\lambda_{Edd,NT}$ | Super-Eddington | 0.49  | $1.92 \times 10^{-3}$ | 0.73 ± 0.27  | 2.34 ± 0.09 |
|               | Sub-Eddington | 0.15  | $2.07 \times 10^{-1}$ | 0.09 ± 0.08  | 1.97 ± 0.09 |
|               | Full         | 0.50  | $2.49 \times 10^{-8}$ | 0.26 ± 0.04  | 2.18 ± 0.04 |
| $\Gamma$ versus $M_{BH}$ | Super-Eddington | −0.25 | $1.35 \times 10^{-1}$ |          |         |
|               | Sub-Eddington | −0.30 | $6.92 \times 10^{-3}$ |          |         |
|               | Full         | −0.53 | $1.20 \times 10^{-9}$ |          |         |
| $\Gamma$ versus $M_{BH,NT}$ | Super-Eddington | −0.17 | $4.16 \times 10^{-1}$ |          |         |
|               | Sub-Eddington | −0.20 | $8.62 \times 10^{-2}$ |          |         |
|               | Full         | −0.43 | $2.67 \times 10^{-6}$ |          |         |

Note. Column (1): the parameter used for testing the correlation with $\Gamma$; $\dot{M}$ ($\dot{M}_{Edd}$) is derived from the mass estimated using the Equation (2), while $\dot{M}_\text{NT}$ ($\dot{M}_{Edd,NT}$) is derived from the mass estimated using Equation (3); column (2): the subsamples and full sample; column (3): the Spearman rank coefficient; column (4): the null hypothesis probability; column (5): the slope of the best-fit relation; column (6): the constant of the best-fit relation.

4.1. The Correlation between $\Gamma$ and $\dot{M}$

For our super-Eddington subsample, we perform the Spearman rank correlation test using the $R_S$ CORRELATE tool in IDL to investigate if there is a correlation between $\Gamma$ and $\dot{M}$. The result of the test is presented in Table 3, which shows that the correlation between $\Gamma$ and $\dot{M}$ is statistically significant, with the null hypothesis probability $p = 7.75 \times 10^{-3}$ and the Spearman rank coefficient $R_S = 0.43$.

Then, we use the LINMIX_ERR tool (Kelly 2007) in the IDL Astronomy User’s Library to perform linear regression analysis. The best-fit relation is

$$\Gamma = (0.34 \pm 0.11) \log \dot{M} + (1.71 \pm 0.17).$$

We list the parameters of the best-fit correlation in Table 3, and we plot the $\Gamma$–$\dot{M}$ correlation for the super-Eddington subsample in Figure 6.

We also perform the Spearman rank correlation test on the sub-Eddington subsample. The $\Gamma$–$\dot{M}$ correlation is statistically significant with the null hypothesis probability $p = 9.98 \times 10^{-3}$. However, the Spearman coefficient $R_S$ value (0.30) is smaller than that of the super-Eddington subsample (0.43), suggesting that the $\Gamma$–$\dot{M}$ correlation for the sub-Eddington subsample is weaker than that for the super-Eddington subsample. We perform linear regression analysis for the sub-Eddington subsample; the best-fit relation is

$$\Gamma = (0.09 \pm 0.04) \log \dot{M} + (1.93 \pm 0.04).$$
The slope of this correlation differs from that for the super-Eddington subsample (Equation (6)) at the \( \approx 2.1 \sigma \) level.

We also investigate the \( \Gamma-\dot{M} \) correlation for all the 113 quasars in our final sample. Using the same approaches above, we find that the \( \Gamma-\dot{M} \) correlation for the full sample is statistically significant, with \( p = 1.10 \times 10^{-10} \) and \( R_S = 0.56 \). The best-fit relation is

\[
\Gamma = (0.13 \pm 0.02) \log \dot{M} + (1.97 \pm 0.02). \tag{8}
\]

We show the best-fit correlations between \( \Gamma \) and \( \dot{M} \) for the sub-Eddington subsample and full sample in Figure 6, and we list the best-fit parameters in Table 3.

As mentioned in Section 2.8, we also use the \( M_{BH,NT} \) values to derive the \( \dot{M}_{NT} \). We also investigate the correlation between \( \Gamma \) and \( \dot{M}_{NT} \) for our two subsamples and the full sample. The \( \Gamma-\dot{M}_{NT} \) correlation (with \( p = 4.75 \times 10^{-2} \) and \( R_S = 0.32 \)) for the super-Eddington subsample is also stronger than that for the sub-Eddington subsample (with \( p = 4.78 \times 10^{-2} \) and \( R_S = 0.23 \)).

Generally, the \( \Gamma-\dot{M} \) correlations are slightly stronger than the \( \Gamma-\dot{M}_{NT} \) correlations, which may suggest that the black hole masses estimated by the updated \( R-L \) relation are more reliable.

4.2. The Correlation between \( \Gamma \) and \( \lambda_{\text{Edd}} \)

We also perform the Spearman rank correlation tests on the two subsamples and the full sample to investigate the correlations between \( \Gamma \) and \( \lambda_{\text{Edd}} \). The results of the tests are presented in Table 3. We find a significant correlation between \( \Gamma \) and \( \lambda_{\text{Edd}} \) for the super-Eddington subsample (with \( p = 2.76 \times 10^{-4} \) and \( R_S = 0.56 \)). A weak correlation is found for the sub-Eddington subsample (with \( p = 7.10 \times 10^{-2} \) and \( R_S = 0.21 \)). We find a strong and statistically significant correlation between \( \Gamma \) and \( \lambda_{\text{Edd}} \) for the full sample, with \( p = 1.32 \times 10^{-9} \) and \( R_S = 0.53 \).

We use the LINMIX_ERR tool to perform linear regression analysis. The results are shown in Table 3. The best-fit correlation for the super-Eddington subsample is

\[
\Gamma = (0.59 \pm 0.16) \log \lambda_{\text{Edd}} + (2.16 \pm 0.03), \tag{9}
\]

while the best-fit correlations for the sub-Eddington subsample and the full sample are

\[
\Gamma = (0.12 \pm 0.07) \log \lambda_{\text{Edd}} + (2.00 \pm 0.08) \tag{10}
\]

and

\[
\Gamma = (0.23 \pm 0.03) \log \lambda_{\text{Edd}} + (2.13 \pm 0.03). \tag{11}
\]

We plot the \( \Gamma-\lambda_{\text{Edd}} \) correlation for the two subsamples and the full sample in Figure 7. The results also show that the \( \Gamma-\log \lambda_{\text{Edd}} \) correlation slope for the super-Eddington subsample is steeper than that for the sub-Eddington subsample, which is consistent with the \( \Gamma-\log \dot{M} \) correlation. Due to the significant power-law correlation between \( \dot{M} \) and \( \lambda_{\text{Edd}} \) (see Section 2.9), the slopes of the \( \Gamma-\log \dot{M} \) and the \( \Gamma-\log \lambda_{\text{Edd}} \) correlations are actually tightly connected. For example, the slope of the \( \Gamma-\log \lambda_{\text{Edd}} \) correlation for the full sample is about twice the slope of the corresponding \( \Gamma-\log \dot{M} \) correlation.

We compare our \( \Gamma-\lambda_{\text{Edd}} \) correlation for the full sample to those in previous studies (e.g., Wang et al. 2004; Shemmer et al. 2008; Brightman et al. 2013). Wang et al. (2004) found a correlation slope of \( (0.26 \pm 0.05) \), Shemmer et al. (2008) found a correlation slope of \( (0.31 \pm 0.01) \), and Brightman et al. (2013) found a correlation slope of \( (0.32 \pm 0.05) \). The \( \Gamma-\log \lambda_{\text{Edd}} \) correlation slope is \( (0.23 \pm 0.03) \) for our full sample. Considering the uncertainties, our correlation is generally consistent with those in previous studies; small differences might be caused by the different samples and methodologies utilized in these studies.

We also investigate the correlations between \( \Gamma \) and \( \lambda_{\text{Edd,NT}} \). The results are listed in Table 3. We still find that the \( \Gamma-\lambda_{\text{Edd}} \) correlations are slightly stronger than the \( \Gamma-\lambda_{\text{Edd,NT}} \) correlations, and the \( \Gamma-\log \lambda_{\text{Edd,NT}} \) correlation slope for our super-Eddington subsample is steeper than that for our sub-Eddington subsample. We notice that if we use \( \lambda_{\text{Edd,NT}} \) as the Eddington ratio for the linear regression, we can obtain a more consistent correlation with the previous studies, with the correlation slope of \( (0.26 \pm 0.04) \) for the full sample. The slope gets steeper because when we use the conventional \( R-L \) relation, the black hole masses of super-Eddington accreting quasars are larger.
which lead to smaller Eddington ratios and thus a steeper slope of the correlation.

4.3. The Correlation between $\Gamma$ and Other Parameters

The correlation between $\Gamma$ and $\dot{M}$ might be instead driven by potential correlations between $\Gamma$ and other parameters. The two parameters, $L_{5100}$ and $M_{BH}$, are used for calculating the dimensionless accretion rates and Eddington ratios. We thus investigate whether there are any correlations between $\Gamma$ and these two parameters.

For the full sample, we perform the Spearman rank correlation test on the $\Gamma$ and $L_{5100}$ values, and we find no correlation between these two parameters, with $R_S = 3.63 \times 10^{-3}$ and $p = 0.97$. This also indicates that the $\Gamma$ parameter has no apparent correlation with $L_{bol}$, which was derived from $L_{5100}$ (see Section 2.8). This result is consistent with the results of previous studies (e.g., Shemmer et al. 2008; Risaliti et al. 2009; Brightman et al. 2013). We also find no correlations between $\Gamma$ and $L_{5100}$ for the super- and sub-Eddington subsamples.

We also investigate the correlation between $\Gamma$ and $M_{BH}$, and we show our results in Table 3. We find statistically significant, negative correlations between $\Gamma$ and $M_{BH}$ (and $M_{BH,NT}$) for the full sample. The $\Gamma$–$M_{BH}$ correlation is stronger than the $\Gamma$–$M_{BH,NT}$ correlation. For our sub-Eddington subsample, we also find a significant correlation between $\Gamma$ and $M_{BH}$. However, we find no correlation between $\Gamma$ and $M_{BH}$ for our super-Eddington subsample.

Previous studies also found correlations between $\Gamma$ and $M_{BH}$. For example, Risaliti et al. (2009) found that for their SDSS quasar sample, there is a negative correlation between $\Gamma$ and $M_{BH}$. They argued that due to the connection between $\lambda_{Edd}$ and $M_{BH}$, the partial degeneracy between the $\Gamma$–$\lambda_{Edd}$ and $\Gamma$–$M_{BH}$ correlation cannot be removed. Similarly, for our full sample here, it is difficult to determine whether the $\Gamma$–$\dot{M}$ or the $\Gamma$–$M_{BH}$ correlation is the more fundamental correlation. Nevertheless, we find a significant correlation between $\Gamma$ and $\dot{M}$, and no correlation between $\Gamma$ and $M_{BH}$ for our super-Eddington subsample, suggesting that the correlation between $\Gamma$ and $\dot{M}$ is more fundamental in the super-Eddington regime.

5. Discussion

5.1. The $\Gamma$–$\lambda_{Edd}$ Correlation

Previous studies did not separate super- and sub-Eddington accreting AGNs in their samples, and thus the observed $\Gamma$–$\lambda_{Edd}$ correlation is probably a mixture of the different correlations of the two types of accretion systems. In this study, we do find a strong and statistically significant $\Gamma$–$\lambda_{Edd}$ correlation for our full sample, and the slope of our correlation is consistent with those of previous studies (see Section 4.2).

The difference between the slopes of the $\Gamma$–$\log \lambda_{Edd}$ correlations for the two subsamples is large, with a slope of $(0.59 \pm 0.16)$ for the super-Eddington subsample and a slope of $(0.12 \pm 0.07)$ for the sub-Eddington subsample. The slope is steeper for the super-Eddington subsample, suggesting that cooling of the corona (steepening of the X-ray spectrum) is more efficient as $\lambda_{Edd}$ increases in the super-Eddington regime. One natural explanation of such a phenomenon is that $\lambda_{Edd}$ is not a good representative of the accretion rate, due to the photon trapping effect; for a given amount of change in $\lambda_{Edd}$, the accretion rate actually changes by a larger amount. In this scenario, the correlation between $\Gamma$ and the accretion rate would be flatter for super-Eddington accreting quasars. Such flattening is indeed observed in the $\Gamma$–$\dot{M}$ correlation. However, due to the complications of the $\lambda_{Edd}$–$\dot{M}$ correlation discussed in Section 2.9 and the uncertainties in deriving $L_{bol}$, we focus our discussion on the $\Gamma$–$\dot{M}$ correlations below.

5.2. The $\Gamma$–$\dot{M}$ Correlation

We investigate the differences of the $\Gamma$–$\dot{M}$ correlations in super- and sub-Eddington accreting quasars. For our super-Eddington subsample, we find a statistically significant positive correlation between $\Gamma$ and $\dot{M}$, for our sub-Eddington subsample, we find a weaker positive $\Gamma$–$\dot{M}$ correlation with a smaller $R_S$ value and a larger $p$ value, though the sample size of the sub-Eddington subsample is nearly twice that of the super-Eddington subsample and its dynamical range in $\lambda_{Edd}$ is also larger. The correlation slope $(0.34 \pm 0.11)$ for the super-Eddington subsample is steeper than that $(0.09 \pm 0.04)$ for the sub-Eddington subsample, providing suggestive evidence that the disk–corona connections are different in these two types of accretion systems.

The steeper $\Gamma$–$\dot{M}$ correlation in the super-Eddington regime might be an artificial effect caused by the soft X-ray excess components in quasars spectra, which are usually quite strong in super-Eddington accreting quasars (e.g., Boller et al. 1996; Kubota & Done 2019; Gliozzi & Williams 2020). We fit the X-ray spectra in the rest-frame >2 keV band to reduce the contamination from possible soft X-ray excess components. But they may still contribute to the rest-frame >2 keV spectra, leading to an overestimation of $\Gamma$ values and a steeper $\Gamma$–$\dot{M}$ correlation in the super-Eddington regime. We examine such a possibility by fitting the spectra in the rest-frame >3 keV band. In this case, the number of our sample objects satisfying the criterion of >200 net counts reduces to 59, and only 19 of these are super-Eddington accreting quasars. The updated $\Gamma$ values for these 19 quasars differ slightly, with a median offset of $-0.06$. After replacing these 19 $\Gamma$ values, we perform the Spearman rank correlation test on the super-Eddington subsample to check whether the $\Gamma$–$\dot{M}$ correlation still exists. We find a weaker correlation with $R_S = 0.36$ and $p = 0.025$, but this correlation is still stronger than that for the sub-Eddington subsample. The new best-fit $\Gamma$–$\log \dot{M}$ correlation for the super-Eddington subsample has a slope of 0.34, consistent with the previous slope. Therefore, we consider that the soft X-ray excess does not contribute significantly to the steeper $\Gamma$–$\dot{M}$ correlation for the super-Eddington subsample.

We note that a few recent studies have similar findings, suggesting that the $\Gamma$ versus accretion rate correlation is steeper in the super-Eddington regime (Gliozzi & Williams 2020; H. Liu et al. 2020, in preparation). If such a trend is indeed physical, it would suggest that cooling of the corona (steepening of the X-ray spectrum) is more efficient as accretion rate increases in super-Eddington accreting AGNs. The cooling of the corona is dominated by optical/UV seed photons from the accretion disk, and an increase of the photon flux received by the corona could enhance its cooling. Considering that one main difference between a super-Eddington accreting disk and a sub-Eddington one is the thickness of the disk, one possible scenario is that disk photons are more easily able to escape from the inner part of a thick disk because of the stronger vertical advection in the inner region from
effects such as magnetic buoyancy (e.g., Jiang et al. 2014). The corona that is considered to be located in the immediate vicinity of the black hole (e.g., Dai et al. 2010; Morgan et al. 2012; Luo et al. 2015; Kubota & Done 2018) thus receives a larger photon flux from a thick disk. This qualitatively explains the steeper \( \Gamma \sim \dot{m} \) correlation in the super-Eddington regime.

Nevertheless, the \( \Gamma \sim \dot{m} \) correlations found in our study show large scatter. A larger statistical sample is required to better constrain the correlations and confirm the difference between the disk–corona connections in super- and sub-Eddington accreting AGNs. Such observational constraints will help us understand better the super-Eddington accreting systems that are still largely uncertain.

6. Summary and Future Work

6.1. Summary

In this study, we investigate the \( \Gamma \sim \dot{m} \) correlation for a sample of super-Eddington accreting quasars, and we compare it to that for a sample of sub-Eddington accreting quasars. The key points are as follows.

1. We construct a final sample of 113 broad-line, radio-quiet quasars from the SDSS DR 14 quasar catalog. We fit their optical spectra to obtain the continuum and the emission-line properties, and we use these properties to estimate the black hole masses and dimensionless accretion rates. The X-ray data of our sample are gathered from the Chandra and XMM-Newton archives, and the \( \Gamma \) values are estimated from the X-ray spectral fitting. See Sections 2 and 3.

2. We identify a super-Eddington subsample with 38 quasars from our final sample, and we find a statistically significant correlation between \( \Gamma \) and \( \dot{m} \). We find a significant, but weaker, \( \Gamma \sim \dot{m} \) correlation for the sub-Eddington subsample that includes 75 quasars. The correlation slope \((0.34 \pm 0.11)\) for the super-Eddington subsample is steeper than that \((0.09 \pm 0.04)\) for the sub-Eddington subsample. See Section 4.1.

3. We also find statistically significant correlations between \( \Gamma \) and \( \log \lambda_{\text{Edd}} \) for the full sample and super-Eddington subsample. The slope of our \( \Gamma \sim \log \lambda_{\text{Edd}} \) correlation for the full sample is consistent with those of previous studies. The \( \Gamma \sim \lambda_{\text{Edd}} \) correlation for the super-Eddington subsample is stronger than that for the sub-Eddington subsample. See Section 4.2.

4. We find no apparent correlation between \( \Gamma \) and \( L_{\text{2100}} \). We find that the correlation between \( \Gamma \) and \( M_{\text{BH}} \) is significant for the full sample and the sub-Eddington subsample. We find no correlation between \( \Gamma \) and \( M_{\text{BH}} \) for the super-Eddington subsample. See Section 4.3.

5. Our findings on the \( \Gamma \sim \dot{m} \) correlations provide suggestive evidence that the disk–corona connections are different in super- and sub-Eddington accreting quasars. We propose one qualitative explanation of the steeper \( \Gamma \sim \dot{m} \) correlation in the super-Eddington regime that involves larger seed photon fluxes received by compact coronae from the thick disks in super-Eddington accreting quasars. See Section 5.2.

6.2. Future Work

Larger statistical samples of quasars are required to extend our current study, so that we can confirm our finding of the different \( \Gamma \sim \dot{m} \) correlations in super- and sub-Eddington accreting quasars and also explore the underlying physics. It is important to select super- and sub-Eddington samples and analyze data in an unbiased and systematic manner. One possibility is to also include higher-redshift SDSS quasars, if we can control or understand the uncertainties on the estimated black hole masses derived utilizing Mg II and C IV emission-line properties; obtaining NIR spectroscopy for these high-redshift quasars would also provide a viable way to derive relatively reliable black hole masses using the H\( \beta \) emission lines.

Our limited sample size is mainly caused by the lack of sensitive X-ray coverage for the SDSS quasars, as Chandra and XMM-Newton only cover a small portion of the whole sky. The eROSITA telescope (e.g., Merloni et al. 2012; Comparat et al. 2019) has the potential for providing good X-ray observations for the SDSS quasars. We estimate the number of SDSS DR14 quasars at \( z < 0.7 \) that will have more than 200–10 keV net counts from the eROSITA 4 yr all sky survey. There are 36,697 SDSS quasars, and we estimate their expected X-ray fluxes from the X-ray–UV correlation of Steffen et al. (2006), adopting an optical spectral slope of \(-0.5\) and an X-ray photon index of \(1.8\). Given the expected limiting flux \((10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1})\) in the 2–10 keV band) from the eROSITA 4 yr survey (Merloni et al. 2012), approximately 675 quasars will be sufficiently bright to be detected by eROSITA with more than 200 net counts. This will substantially increase the sample size for our study presented here.

In the near future, optical spectroscopic surveys such as the SDSS-V\(^{16}\) (Kollmeier et al. 2017) and the Dark Energy Spectroscopic Instrument (DESI)\(^{17}\) surveys will provide much larger samples of quasars with optical spectra. Combining these with the Chandra and XMM-Newton archives and the eROSITA data, we will be able to constrain the disk–corona connection in super-Eddington accreting AGNs with greater certainty.

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\(^{16}\) https://www.sdss.org/future

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