High Eddington accreting quasar spectra as discovery tools: current state and challenges

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Abstract

Broad emitting line regions (BLR) in the active galaxies are primarily emitted by photoionization processes that are driven by the incident continuum arising from the underlying, complex geometrical structure, i.e. accretion disk and corona around a supermassive black hole. Modelling the broad-band spectral energy distribution (SED) effective in ionizing the gas-rich BLR is key to understanding the various radiative processes at play and their importance that eventually leads to the emission of emission lines from diverse physical conditions. Photoionization codes are a useful tool to investigate the two aspects - the importance of the shape of the SED, and the physical conditions in the BLR. In this work, we provide the first results focusing on a long-standing issue pertaining to the anisotropic continuum radiation from the very centres (few 10-100 gravitational radii) of these active galaxies. The anisotropic emission is a direct consequence of the development of a geometrically and optically thick structure at regions very close to the black hole due to a marked increase in the accretion rates. Incorporating the radiation emerging from such a structure in our photoionization modelling, we are successful in replicating the observed emission line intensities, in addition to the remarkable agreement on the location of the BLR with current reverberation mapping estimates. This study took advantage of the look at the diversity of the Type-1 active galactic nuclei (AGNs) provided by the main sequence of quasars. The main sequence permitted to locate the super Eddington
sources in an observational parameter space and to constrain the distinctive physical conditions of their line-emitting BLR. This feat will eventually allow us to use the fascinating super Eddington quasars as probes to understand better the cosmological state of our Universe.

**Keywords:** galaxies: active, quasars: emission lines; quasars: supermassive black holes; quasars: accretion, accretion disks; quasars: reverberation mapping; cosmology

1 Active galactic nuclei - a brief introduction

Active galactic nuclei (AGNs) are among the brightest cosmic objects known to us \[1, 2\]. They harbor a supermassive black hole (SMBH) at their very centers which due to its immense gravitational potential allows for the infalling of matter. This in-falling matter loses angular momentum while being accreted onto the black hole. This accreted matter manifests in the form of a multi-color accretion disk which gets heated up and radiates \[3–6\]. The photon energy of the dissipated radiation spans a wide range in energies (from sub-eV to 100s of eVs) which then illuminates the material surrounding the accretion disk. This then leads to the formation and emission of strong, broad emission lines \[7–11\].

AGNs show variations in their continuum and emission line intensities that can range in the order of minutes/days for the continuum to days/weeks/months timescales for the BLR region. This crucial feature led to the estimation of black hole masses of hundreds of nearby AGNs and relatively distant quasars\(^1\) using the technique of reverberation mapping \[12–15\]. The estimation of black hole masses is perhaps the most sought-after analysis when it comes to AGN studies \[16, 17\]. With the knowledge of the location of the line emitting region from the central SMBH\(^2\), coupled with the information of the velocity profiles from single/multi-epoch spectroscopy \[18–20\] and with a basic knowledge of the geometry of the emitting region \[21, 22\], we are well poised to derive the black hole masses using the virial relation. There are various other ways to estimate the black hole masses discussed in the literature \[23, 24\].

1.1 Spectral Energy Distribution (SED) of AGNs

AGN are observed over the entire range of the electromagnetic spectrum from radio regime up to MeV-GeV-TeV energy emitting gamma-rays \[25–27\]. Different components of the spectral energy distribution (SED) arise due to different radiation mechanisms and at different distances, notably among them: (1) The X-ray emission is produced when the UV photons from the disk undergo inverse

\(^1\)quasars, or QSOs, are brighter AGNs discovered at larger redshifts

\(^2\)In actuality, the difference in the light travel time is estimated by making a cross correlation between the continuum light directly reaching us and the light that bounces of first at the BLR region and then comes to us. The continuum light is produced very close to the SMBH - at the accretion disk [see e.g., 3, 5].
Compton scattering by hot electrons in a corona close to the SMBH [e.g., 28] which manifests in the form of a coronal power-law; and (2) The characteristic ‘Big Blue Bump’ [4, 5] that is formed by the optical and ultraviolet radiation produced due to thermal emission from the accretion disk. In addition to these two components of the broad-band SED of an AGN, the observed AGN spectra usually contain (3) another spectral component, observationally described as a “soft X-ray excess” [e.g., 29]. This component helps bridge the absorption gap between the UV downturn and the soft X-ray upturn [e.g., 25, 30, 31], and changes the far-UV and soft X-ray parts of the spectrum. Thus, it can affect the line production in the BLR. The “intrinsic” AGN continuum at photon energies high enough to ionize Hydrogen is therefore made of the thermal emission from the accretion disk, the coronal power-law, and soft X-ray excess [32–35].

Intrinsic to the AGN is also (4) synchrotron radiation from relativistic jets that accounts for most of the radio emission in the AGN. In the NIR domain, as the low energy tail of the AD emission fades, extrinsic emission is (4) reprocessed emission from the dusty torus which surrounds the accretion disk becomes the dominant emission, along with the polar dust in the direction of SMBH spin axis [11, 36]. In the FIR, the SED might be dominated by dust heated by host galaxy star formation, more than by the AGN itself [37]. This is occurring in systems with high accretion rate [38].

1.2 What an AGN multi-frequency spectrum can reveal to us?

Going back to the AGN spectrum, and looking at it from an observer’s point of view, we can largely quantify the spectrum into two primary components: (1) the emission lines originating from the BLR/NLR clouds; and (2) the AGN continuum, prominent beyond the Lyman limit, that can photoionize the surrounding gas leading to line emission. The ionizing photon flux can be estimated by a careful analysis of the AGN SED, which then gives us a rough idea of the expected line fluxes for the multitude of ionic species (in their various ionization states) that we see in an AGN spectrum. A careful assessment of the density of these ionized clouds and their locations, in addition to the incident photon flux received by them, allows us to estimate the strengths of these lines. Important information about density, ionization conditions, and dynamics in the broad line emitting region of AGN can be inferred from UV spectroscopic observations which are crucial to understanding these line-emitting regions. Past studies have illustrated the use of certain line diagnostic ratios from observed spectra of quasars in order to estimate these (density, ionization condition and metallicity) parameters [39–42, and references therein]. Hence, the combined information obtained from the spectrum can provide us insight on the dynamics (velocity profiles and FWHMs), energetics (emission line intensities) and composition of the immediate surroundings around the SMBH.
1.3 Dichotomy in ionization in emission lines

Historically, the BLR clouds were modelled as single clouds where the different lines arise from different parts of the same cloud - a picture that is still widely accepted. In the mid-1980s, propositions were made to explain the BLR as two distinct components [43, 44]. The broad emission spectrum in AGNs can be divided into two parts: the first set of lines that include Lyα, C iii, C iv, He i, He ii, and N v emitted by a highly ionized region that has a relatively low density (≲10^{10} \text{ cm}^{-3}). These are known as High Ionization Lines (HILs). The upper limit to the density of the media emitting these HILs is set by the semi-forbidden CIII] in order not to be collisionally de-excited. The second set of lines include the bulk of the Balmer lines, Mg ii, Fe ii, O i and Ca ii, emitted by a mildly ionized medium having a much higher density (≳10^{10} \text{ cm}^{-3}). The real scenario is more convoluted and the search for a global unified picture is still ongoing. Although, this representation - dichotomy into LILs and HILs of the line emission, originating from the vicinity of the SMBH due to the inherent radiation of the accretion disk, has been instrumental to identify a low-ionization virialized component and the contribution of a high ionization wind [45, 46].

2 Imminent challenges and opportunities

A better understanding of the inner workings of AGN can pave the road to far reaching applications. One of them is the standardization of quasars (or QSOs) for measuring the cosmological parameters. Two methods that involve quasar intrinsic properties resort to the radius-luminosity scaling laws (Section 2.1), and to a law analogous to that of Faber-Jackson, connecting velocity dispersion and luminosity (Section 3.1). Both methods face challenges.

2.1 Scatter in the R-L relation, standardizing QSOs for cosmological studies:

An important aspect of the reverberation mapping studies comes from the empirical relation - the power-law radius -luminosity relation, R_{BLR} \propto L_{5100}^{\alpha} between the BLR radius (or time delay) and the AGN monochromatic luminosity\(^3\). [18] found a best-fit for a sample of 41 AGNs covering four orders of magnitude in luminosity with a power-law slope value, \(\alpha=0.533^{+0.035}_{-0.033}\), very close to the adopted theoretical value [10, 48, 49]. This function is shown using a dashed line in Figure 1. One can then combine the R_{BLR}-L_{5100} relation with the line widths for the broad emission lines estimated from single/multi-epoch spectroscopy to estimate the black hole masses which makes it especially useful for large statistical surveys of sources throughout cosmic history [16, 17].

Looking at the bigger picture, the R_{BLR}-L_{5100} relation, can allow us to infer the luminosity distances:

\(^3\)here, the relation assumes the BLR radius for the H\textbeta and the nearest continuum luminosity at 5100Å
Fig. 1 BLR radius (of Hβ emitting region) versus the AGN monochromatic luminosity at 5100Å. The sources are colored with respect to their Eddington ratios \( \frac{L_{\text{bol}}}{L_{\text{Edd}}} \). The dashed line shows the classical relation from [18]. The linear best-fit relation (black solid line) for the sources has the form: \( \log R_{\text{H}\beta} = 0.387 \times \log L_{5100} - 15.702 \), with a Spearman’s correlation coefficient \( \rho = 0.733 \) and \( p \)-value \( 2.733 \times 10^{-21} \). The shaded region in light blue marks the 99% confidence interval about the linear best-fit relation. The shaded ellipse highlights the sources with relatively high Eddington ratio values that also deviate away from the classical relation, i.e., towards shorter BLR radii. Data are from [47].

\[
D_L = \sqrt{\frac{L_{5100}}{4\pi F}}
\]  

(1)

where, the \( L_{5100} \) is the AGN monochromatic luminosity that can be estimated using the \( R_{\text{BLR}}-L_{5100} \) relation, and the flux \( F \) can be independently estimated from the observed AGN spectrum for a given source. This way we can avoid the circularity and can have a robust estimate of the luminosity distance \( D_L \). Thereafter, we can construct the Hubble diagram with the luminosity distances and the corresponding redshifts for each source. Hence, reverberation-mapped AGNs can be used as cosmological candles [50–54]. This further allows us to study the evolution of the cosmological parameters as a function of the redshift allowing for the reconciliation of the Hubble-tension - the disparity between the measured value of the Hubble constant in the local and the early Universe (see Figure 2).

Recent observations have led to populate the \( R_{\text{BLR}}-L_{5100} \) observational space and taken the total count over 100, especially the sources monitored under the SEAMBH project (Super-Eddington Accreting Massive Black Holes, [19, 55–59]), and from the SDSS-RM campaigns [60, 61]. But this has introduced us to a new challenge - the inherent dispersion in the \( R_{\text{BLR}}-L_{5100} \) relation after the introduction of these new sources. Figure 1 is an abridged version...
Fig. 2 This graphic lists the variety of techniques that have been used to measure the expansion rate of the universe, known as the Hubble constant (H\(_0\)). One set of observations looked at the very early universe (or the early route, shown in the bottom half of the graphic) and the second set of observation strategies analyzed the universe’s expansion in the local universe (or the late route, shown in the upper half of the graphic). The letters corresponding to each technique are plotted on the bridge on the right. The location of each dot on the bridge road represents the measured value of the H\(_0\), while the length of the associated bar shows the estimated amount of uncertainty in the measurements. The combined average from the seven methods from the late route yield a H\(_0\) value of 73 km s\(^{-1}\) Mpc\(^{-1}\). This number is at odds with the combined value of the techniques used to calculate the universe’s expansion rate from the early route. Their combined value for the H\(_0\) is 67.4 km s\(^{-1}\) Mpc\(^{-1}\).

Abridged version. Original graphic credit: NASA, ESA, and A. James (STScI).

from [47, 62] where the R\(_{\text{BLR-L}5100}\) observational space for 117 reverberation mapped AGNs is shown. The sources are colored with respect to their Eddington ratios (L\(_{\text{bol}}\)/L\(_{\text{Edd}}\)). The best-fit relation for this sample is, log R\(_{H\beta}\) = 0.387×(log L\(_{5100}\)) - 15.702, with a Spearman’s correlation coefficient (\(\rho\)) = 0.733 and p-value = 2.733×10\(^{-21}\), thus making the overall slope of the relation much shallower than obtained from the previous studies by [18] and bringing the validity of the empirical R\(_{\text{BLR-L}5100}\) relation into question. But interestingly, the sources that eventually led to the increase in the scatter in the relation, show an interesting trend with Eddington ratio - larger the dispersion of a source from the empirical R\(_{\text{BLR-L}5100}\) relation, higher is its Eddington ratio! In [47], we found that this dispersion can be accounted for in the standard R\(_{\text{BLR-L}5100}\) relation with an added dependence on the Eddington ratio (L\(_{\text{bol}}\)/L\(_{\text{Edd}}\)). [63] exploited this further in their work and realized that with an
additional correction term, the relation can be reverted back to the original relation with a slope \( \sim 0.5 \). This additional correction term is an observational parameter - the relative strength between the optical Fe\( \text{II} \) emission and the corresponding H\( \beta \) emission (or R\( \text{FeII} \)), which has been shown in earlier studies to be reliable observational proxy for the Eddington ratio [34, 63–67] which we touched upon in earlier sections. The form of the relation as shown in [63], takes the form:

\[
\log \left( \frac{R_{\text{BLR}}}{1 \text{ light-day}} \right) = \kappa + \alpha \log \left( \frac{L_{5100}}{10^{44}} \right) + \gamma R_{\text{FeII}}
\]  

where, \( \kappa = 1.65 \pm 0.06 \), \( \alpha = 0.45 \pm 0.03 \), and \( \gamma = -0.35 \pm 0.08 \). Clearly, the introduction of the R\( \text{FeII} \) term and for sources with strong Fe\( \text{II} \) emission, is able to account for their shorter time-lags and hence, smaller R\( \text{BLR} \) sizes.

2.2 Quasar Main Sequence, division of Type-1 AGNs into Population A and Population B

2.2.1 Narrow-line Seyfert 1s - a special class of AGNs?

Narrow Line Seyfert Type-1 galaxies (or NLS1s)\(^4\) are a special class of Type-1 AGNs that are characterized with “narrower” broad emission lines - especially having FWHM(H\( \beta \text{broad} \)) \( \leq 2,000 \text{ km s}^{-1} \), and the ratio of [OIII]\( \lambda 5007 \) to the H\( \beta \) less than 3 [71, 72]. In addition to these, the NLS1s exhibit strong Fe\( \text{II} \) emission and the relative strength of the optical Fe\( \text{II} \) (within 4434-4684 \( \AA \)) to the H\( \beta \), or R\( \text{FeII} \), \( \gtrsim 1 \) [34, 64, 66]. NLS1s have been used to analyze the Fe\( \text{II} \) emission since the late 1970s (Phillips 1978) and has been regarded among the most noticeable cooling agents of the BLR, emitting about \( \sim 25\% \) of the total energy in the BLR [48]. The Fe\( \text{II} \) is a strong contaminant owing to a large number of emission lines and without proper modelling and subtraction, it may lead to a wrong description of the physical conditions in the BLR [73–77]. More prominently, the parameter R\( \text{FeII} \) is central to the Eigenvector 1 schema which consists of the dominant variable in the principal component analysis presented by [78]. This is now well understood to be associated with important parameters of the accretion process in the AGNs [34, 63–67]. We will return to this issue in the next section.

NLS1s also show stronger blueshifts (blueward asymmetries) especially in the HILs [e.g., 64, 79, 80] and tend to be more variable than their “broader” counterparts in the X-ray regime [81–83], although the scales of their variability is not as pronounced in the optical and infrared regime [84, 85]. NLS1s, typically host black holes with lower masses (\( \lesssim 10^7 \text{ M}_\odot \)), tend to be less luminous and have low radio jet power - which has led many authors [86, 87] to link them to an evolutionary scheme of BHs. These authors have suggested that

\(^4\)Type 1/Type 2 classification is based on the observation of the broad emission line features in an AGN spectrum. According to unified model [11, 68–70], the presence of the dusty, obscuring torus impedes/allows the direct view to the central engine of the SMBH and the BLR region - that is located closer to the SMBH. This then manifests in the AGN spectrum - where the broad emission lines originating from the BLR are either seen (Type-1) or not (Type-2).
the NLS1s are the younger versions of more evolved, more massive SMBHs that are constitute the bulk of the population of AGNs. This is a summary of the conventional view of NLSy1s. A more exhaustive view is reached by the contextualization offered by the Eigenvector 1 Main Sequence.

2.2.2 The Eigenvector 1 / Main Sequence

The study of [78] brought together the spectral diversity of Type-1 AGNs under a single framework. Their paper is fundamental for two reasons: (A) It provides one of the first template for fitting the Fe\textsuperscript{II} pseudo-continuum. The Fe\textsuperscript{II} emission manifests itself as a pseudo-continuum owing to the many, blended multiplets over a wide wavelength range, extracted from the spectrum of a prototypical Narrow Line Seyfert Type-1 (NLS1) source, I ZW 1; and more importantly, (B) for introducing the Quasar Main Sequence to unify the diverse group of AGNs. They used principal component analysis - a conventional dimensionality reduction technique on observed properties of a sample of optically bright quasars to obtain this main sequence, specifically the optical plane which showed the connection between the FWHM of the broad H\textbeta and the strength of the Fe\textsuperscript{II} blend between 4434-4684 Å to the H\textbeta (or R\textsubscript{FeII}). We now are familiar that this optical plane of the main sequence of quasars is primarily driven by the Eddington ratio [e.g., 64–66] among other physical properties of the BH and the BLR [6, 34, 62, 88].

In addition, a classification based on the narrowness or broadness of the H\textbeta emission line profile in an AGN spectrum was introduced, i.e., into Population A and Population B classes. Population A sources contain local NLS1s as well as more massive high accretors which are mostly classified as radio-quiet [e.g., 89] and that have FWHM(H\textbeta) ≤ 4000 km s\textsuperscript{-1}. While Population B sources are those with broader H\textbeta (≥ 4000 km s\textsuperscript{-1}), and are predominantly “jetted” sources [e.g., 36]. The cut off in the FWHM of H\textbeta at 4000 km s\textsuperscript{-1} was suggested by [64, 66] who found that AGN properties appear to change more significantly at this broader line-width cutoff. The usefulness of a fixed FWHM limit – let it 2000 km s\textsuperscript{-1} or 4000 km s\textsuperscript{-1} is questionable, as the FWHM is dependent on \( M_{\text{BH}} \) (or luminosity), viewing angle, and Eddington ratio [66]. It makes sense if the limit is applied to samples in a narrow range of luminosity or \( M_{\text{BH}} \).

Reiterating the question posed by a few years ago [90]:

*Are population A and B simply two extreme ends of the main sequence or do they represent two distinct quasar populations? Or are they tied via a smooth transition in the accretion mode?*

This question is very relevant to our quest to use quasars as standard, or standardizable candles, since the shape of the emission line profiles and continuum strength is directly connected to the central engine, especially to the black hole mass, and, the accretion rate, in addition to the black hole spin and the angle at which the central engine is viewed by a distant observer [34, 66, 77, 91, 92].
2.3 Coming back to the AGN SED problem

Another equally important aspect in this regard is the ionizing continuum produced by the central engine. This is primary radiation that is incident on the BLR and as a result, and is ultimately responsible for line emission. The study and analysis of the spectral energy distribution (SED) is a key element in understanding how the BLR responds to the continuum - hence essential to our understanding how these ionized media respond to the continuum and its temporal variations which is key to the reverberation mapping technique. Through the study and modelling of the emission lines originating from these dense, ionized media can help us answer how much of this incoming radiation is intercepted by the BLR and how much of this intercepted radiation leads to the line-formation and emission [77, 93–97]. The characterization of the ionizing SED, the part of it that comes from regions closer than the BLR, is important for our study of the emission lines\(^5\). From the photoionization point of view, this fraction of the broad-band SED is closely related to the number of ionizing photons that eventually lead to the line production that has led to many authors to estimate the photoionization radius of the line-emitting region of the BLR [40, 77, 97–99].

We tested the variation in the low-ionization emitting regions of the BLR, by accounting for the changes in the shape of the ionizing continuum (the SED) and the location of the H\(\beta\)-emitting BLR from the central ionizing source (or R\(_{\text{BLR}}\)) from the reverberation mapping, in the context of Main Sequence of Quasars [97]. In this and previous work [77], we have found that in order to estimate the correct physical conditions for these low-ionization line emitting regions in the BLR, it is not sufficient to only retrieve the flux ratios (e.g., R\(_{\text{FeII}}\)) but to also have agreement with the corresponding modelled and observed line strengths (or line equivalent widths, EWs). Compared to the results that are directly obtained from the photoionization theory, these new results highlight the shift in the overall location of the line-emitting R\(_{\text{BLR}}\) - in terms of the ionization parameter (\(U\)) and the local cloud density (\(n_{\text{H}}\)) recovered from the analyses towards lower values (by up to 2 dex) compared to the R\(_{\text{BLR}}\) values estimated from the photoionization theory. This brings the modelled location in agreement to the reverberation mapping results, especially for the high-accreting NLS1s which show shorter time-lags/smaller emitting regions. A corollary result that is obtained is that to retrieve such physical conditions, the BLR should “see” a different, filtered SED with only a very small fraction (~1-10%) of the total ionizing photon flux. This analysis was performed on selective sources where their broad-band SEDs were readily available, and had archival spectroscopic measurements. In addition, we had assumed source-specific metallicities that were derived using the UV diagnostic lines from earlier studies [see e.g., 100]. There is a need to extend this analysis to larger number of reverberation mapped sources. We therefore need synchronous multi-wavelength observations to build robust SEDs that can be

\(^5\)especially that carry photon energy at or above 1 Rydberg. This threshold marks the minimum energy required to ionize neutral hydrogen.
used to confirm this scenario. Also, there is a need to bring together a global picture where a combined analysis of the UV and optical emitting regions can be put together - this would allow us to gauge the salient differences in the low- and high-ionization line emitting regions.

![Fig. 3](image)

**Fig. 3** Schematic view of the inner sub-parsec region around the SMBH for a high accreting AGN. Abridged version from [101]; not drawn to scale.

### 3 Possible avenues

NLS1s with high accretion rates are typically shown to have a soft-X-ray excess [29] in their broadband SED [33, 35, 102, 103]. The interstellar medium blocks our view of this spectral region, thus requiring the use of indirect (modelling) methods to predict the emission from this part of the radiation field [33, and references therein]. This component helps to bridge the absorption gap between the UV downturn and the soft-X-ray upturn [25, 30, 31] and changes the far-UV and soft-X-ray part of the spectrum, affecting the Fe $\text{II}$ line production [88].

Wang et al. [101] derived the analytical solutions (steady-state) for the structure of “slim” accretion discs from sub-Eddington accretion rates to extremely high, super-Eddington rates. They notice the appearance of a funnel-like structure very close - few gravitational radii from the SMBH, and attribute this change in the accretion disk structure to the high accretion rates that are realized from the solutions of the slim accretion disks wherein the structure of the geometrically thin, optically thick accretion disk as per the [3] prescription does not hold [101, 104, 105]. We show an illustration of this scenario in the right panel of Figure 3. Such modifications to the disk structure strongly affect the overall anisotropic emission of ionizing photons from the disk in addition to just inclination effects - that arises due to the axisymmetric nature of these
systems. Therefore, with a rise in the accretion rates a viewing-angle dependent anisotropy needs to be accounted for in the modelling, one which then leads to the shrinking in the position of the line emitting BLR and brings the modelled location in agreement to the observed estimates from the reverberation mapping campaigns [see 77, for more details].

![Figure 4](image_url)  
**Fig. 4** Spectral energy distributions (SEDs) obtained for slim accretion disks for a representative black hole mass, $M_{BH} = 10^8 M_\odot$. LEFT: SEDs are shown for a range of viewing angle cases for a representative dimensionless accretion rate, $\dot{\mathcal{M}} = 100$. RIGHT: SEDs are shown for a range of $\dot{\mathcal{M}}$ for a representative viewing angle, $i = 40^\circ$. In both panels, the vertical dash-dotted line marks the 1 Rydberg threshold.

| $i$  | ratio (%) |
|------|-----------|
| $10^\circ$ | 100.00   |
| $30^\circ$ | 87.91    |
| $40^\circ$ | 77.92    |
| $50^\circ$ | 26.11    |
| $60^\circ$ | 7.95     |
| $70^\circ$ | 1.91     |
| $75^\circ$ | 0.78     |
| $80^\circ$ | 0.23     |

The left panel in Figure 4 shows the slim-disk SEDs (Jian-Min Wang, priv. comm.) for a representative BH mass of $10^8 M_\odot$, accreting at $\dot{\mathcal{M}} = 100$ for a range of viewing angles$^6$. The right panel shows the distribution of slim-disk SEDs as a function of $\dot{\mathcal{M}}$ for a representative BH mass of $10^8 M_\odot$ observed at a viewing angle ($i = 40^\circ$). We also report the relative area under the SEDs

$^6$this is the dimensionless accretion rate introduced by [55]. In [97] we provide a analytical form to convert $\dot{\mathcal{M}}$ to Eddington ratio ($L_{bol}/L_{Edd}$, see equation 13 in their paper). This relation additionally depends on the BH mass and the bolometric correction. For a BH mass of $10^8 M_\odot$ with $\dot{\mathcal{M}} = 100$, for a $L_{5100} = 10^{45} \text{ erg s}^{-1}$, the Eddington ratio is $\sim 0.1$
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Table 2 Relative area (in %) under the slim disk SEDs shown in the right panel of Figure 4 (wrt the case with $\dot{M} = 1000$)

| $\dot{M}$ | ratio (%) | $\dot{M}_i / \dot{M}_{i-1}$ |
|-----------|-----------|----------------------------|
| 1         | 0.44      | ...                       |
| 10        | 5.71      | 12.98                     |
| 50        | 32.40     | 5.67                      |
| 100       | 51.49     | 1.59                      |
| 500       | 89.48     | 1.74                      |
| 1000      | 100.00    | 1.12                      |

shown in Figure 4. These values are tabulated in Tables 1 and 2 corresponding to the left and right panels of Figure 4, respectively. We estimate the area under the SEDs accounting only for the fluxes corresponding to a frequency $\geq 1$ Rydberg. We then compute the relative area (a) with respect to the SED case with the viewing angle, $i = 10^\circ$ (Table 1 and left panel of Figure 4); and (b) with respect to the SED case with the dimensionless accretion rate, $\dot{M} = 1000$ (Table 2 and right panel of Figure 4). From the left panel of Figure 4, we can notice that going from the SED viewed at $i = 10^\circ$ to $80^\circ$, keeping the BH mass and accretion rate constant, the extended region receives only a very small fraction of the actual photon flux (only 0.23%), meaning almost all of the ionizing photons (99.77%) never make it to the BLR. This $\sim 2$ dex reduction in the photon flux results in an equal reduction in the ionization parameter (U) which was confirmed already in Panda (2021). On the other hand, changing the accretion rate, going from $\dot{M} = 1$ to 1000 and keeping the BH mass and viewing angle constant (right panel of Figure 4), we find that an accretion rate $\dot{M} = 1$ relates to only a 0.44% of the total photon flux.

This, indirectly confirms the results previous works have been pointing to, that, the main sequence of the quasars is driven by the Eddington ratio and the orientation [34, 65, 66, 106]. The shape of the SED thus plays an important role in explaining the trends in the quasar main sequence wherein the information of the fundamental BH parameters - BH mass, Eddington ratio, orientation and the BH spin, are embedded [see 62, for more details]. In a subsequent work, we will incorporate these slim disk SEDs into our photoionization modelling setup and recover the trends for the low- and high-ionization emission lines, their relative strengths (e.g., $R_{FeII}$) and the EWs, with respect to these fundamental BH parameters.

3.1 An avenue for cosmological studies?

The application of quasars radiating at or above the Eddington limit has been proposed since several years although the method not yet been exploited to its full potential [38, 107, and references therein]. The method is conceptually simple: the accretion luminosity of a quasar is proportional to the line width to the 4th power i.e., $L \propto \text{FWHM}^4$.\(^8\) The value of the exponent comes from the

\(^7\) Rydberg $\approx 3.29 \times 10^{15}$ Hz

\(^8\) The equation is equivalent to the original formulation of the Faber-Jackson law [108], and is equivalent to other relations linking virialized systems to the amount of radiation emitted.
virial relation for the black hole mass, the assumptions of constant Eddington ratio ($L/M_{\text{BH}} \approx \text{const.}$), and of radius scaling rigorously with luminosity as $r \propto L^{0.5}$. The last assumption is likely to be verified for sources radiating close to the Eddington limit: they are identified by spectral similarity ($R_{\text{FeII}}>1$), and so the physical properties of the emitting regions need to be similar.

More in detail, the equation connecting luminosity and line width can be written as:

$$L = \frac{\mathcal{L}_*}{4} \left( \frac{L}{L_{\text{Edd}}} \right)^2 \frac{\kappa_{i,0.5}}{h\nu_{i,100eV}} \frac{1}{(n_HU)_{10^9 \text{ cm}^{-3}}} \left[ \frac{1}{3} \left( \frac{\delta v_{\text{iso}}}{\delta v_K} \right)^2 + \sin^2 \theta \right] \text{erg s}^{-1} (3)$$

where $\mathcal{L}_* = 7.88 \cdot 10^{44}\text{erg s}^{-1}$, the energy value has been normalized to 100 eV ($\nu_{i,100eV} \approx 2.42 \cdot 10^{16} \text{ Hz}$), $\kappa_{i,0.5}$ is the fraction of bolometric luminosity belonging to the ionizing continuum scaled to 0.5, the product density times ionization parameters ($n_HU$) has been scaled to the typical value $10^{9.6} \text{ cm}^{-3}$ [39, 109, 110], and the FWHM of the $\text{H}\beta$ broad component is expressed in units of 1000 km s$^{-1}$. Here the effect of orientation can be quantified by assuming that the line broadening is due to an isotropic component + a flattened component whose velocity field projection along the line of sight is $\propto 1/\sin \theta$:

$$\delta v_{\text{obs}}^2 = \frac{\text{FWHM}^2}{4} = \frac{\delta v_{\text{iso}}^2}{3} + \delta v_K^2 \sin^2 \theta. \quad (4)$$

Deviations between the virial estimates and luminosity estimated from redshift and assumed concordance cosmology can be fully explained by the effect of orientation [111]. The distributions of the viewing angles from the Negrete et al. sample based on $\text{H}\beta$ at low $z$ peaks at about 17 degrees, with only a very small fraction of quasars observed at $\theta \gtrsim 30$. This means that the effect of anisotropy on the computation of the luminosity should introduce a small dispersion. Table 2 shows that the fraction of ionizing photons at very high accretion rate tends to saturate, with only a 10% increasing from the doubling of the accretion rate, from $\dot{M} = 500$ to 1000. At such $\dot{M}$ the Eddington ratio should converge toward a limiting value of $\mathcal{O}(1)$. The product ($n_HU$) is also little affected by changes in SED in the cases shown in Fig. 5. Therefore even if anisotropy effects in line widths are strong, anisotropy in continuum emission and differences in SEDs might not be so strong as to compromise an application to cosmology of Eq. 3 that is – we stress it – generally valid for all AGNs but in practice exploitable for high accretors only.

4 Concluding remarks

There will be an immense potential of the ideas and results presented in this work in the near future, serving as test-beds for the vast number of AGNs that will be explored with the ongoing and upcoming ground-based 10-metre-class
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Fig. 5  SEDs appropriate for high accretors. Upper left panel: comparison between SEDs of Marziani & Sulentic [89], Ferland et al. [35], high and highest Eddington ratio SEDs. The Mathews & Ferland [112] is also shown for comparison. Upper right panel: composite spectrum for xA from Marziani et al. [113], with the Wang et al. SED superimposed for $\dot{M} = 500$. The inset shows the same spectrum as a function of wavelength. Bottom left panel: simplified model for the "high" SED of Ferland et al. using the $\dot{M} = 500$ SED and an X-ray emitting corona (power law with exponential breaks). Bottom right: same, with an additional component (blue dashed) to improve the fit accuracy. Note that the high-energy turnover at $\log \nu \sim 20$ [Hz] is actually poorly known, and in the most extreme case the hard X-ray SED may show no flattening and no break ("highest" case (magenta line) in the upper left panel).

[e.g. Maunakea Spectroscopic Explorer, 114] and 40 metre-class [e.g. The European Extremely Large Telescope, 115] telescopes; and space-based missions such as the JWST [116, 117] and the Nancy Grace Roman Space Telescope [118]. Increased availability of high-quality, multi-wavelength photometric, spectroscopic and interferometric measurements extending to higher redshifts is a necessity to help develop our ever-growing theoretical understanding of how these massive, energetic cosmic sources work and evolve.

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