Article

Where to search for supermassive binary black holes

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Abstract: Supermassive binary black holes (SMBBHs) are the anticipated byproducts of galaxy mergers and play a pivotal role in shaping galaxy evolution, gravitational wave emissions, and accretion physics. Despite their theoretical prevalence, direct observational evidence for SMBBHs remains elusive, with only a handful of candidates identified to date. This paper explores optimal strategies and key environments for locating SMBBHs, focusing on observational signatures in the broad Balmer lines. We present a preliminary analysis on a flux-limited sample of sources belonging to an evolved spectral type along the quasar main sequence, and we discuss the spectroscopic clues indicative of binary activity and highlight the critical role of time-domain spectroscopic surveys in uncovering periodic variability linked to binary systems.

Keywords: galaxies: active – quasars: emission lines – galaxies: evolution – black hole physics – accretion – line: formation – ISM: abundances

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1. Introduction

Supermassive black hole binaries (SMBBHs) are an expected consequence of hierarchical galaxy formation. As galaxies merge, their central supermassive black holes (SMBHs), with masses ranging from $10^6 - 10^9\ M_\odot$, are brought together by dynamical friction and may eventually form a bound binary system [1,2]. SMBBHs are relevant for understanding a wide range of astrophysical processes [3], including galaxy evolution, the fueling of active galactic nuclei (AGN), and the generation of low-frequency gravitational waves detectable by pulsar timing arrays (PTAs, [4,5]) and future space-based observatories like LISA [6–8]. Despite their theoretical significance, the observational evidence for SMBBHs remains sparse, with only a handful of candidates identified through periodicity in AGN light curves, dual-AGN systems, or distinct velocity offsets in emission lines [9–11]. Several claims of periodic behavior were nullified by monitoring on a large temporal basis [12–14]. Current estimates of the population of SMBBHs vary depending on the assumptions about galaxy merger rates, SMBH masses, and the efficiency of binary coalescence [15]. Models predict that thousands of SMBBHs could exist within the detectable range of PTAs, assuming typical binary separations of 0.1–10 parsecs and orbital periods ranging from months to decades [4,16]. However, the true population remains highly uncertain due to the complex interplay of gas dynamics, stellar interactions, and gravitational wave emission in the binary evolution [17]. Future surveys and gravitational wave observations are expected to provide a more robust census.

The electromagnetic phenomenology of SMBBHs is all but clear. Previous attempts to identify SMBBHs have resorted to the detection of periodic phenomena involving photometric and spectroscopic properties. Photometric periodicities can arise from several mechanisms, including the modulation of accretion rates due to the gravitational interaction between the binary components, relativistic Doppler boosting of emission from the mini-disk around one of the black holes, or periodic disruptions of gas streams. Examples include the AGN PG 1302-102, which exhibits quasi-periodic oscillations with a period of approximately 5 years, interpreted as evidence of a binary with a sub-parsec separation [18]. Additional candidates have been identified in large surveys such as the Palomar Transient Factory (PTF) and Zwicky Transient Facility (ZTF) [19–22], where systematic searches for

periodic variability in AGN light curves have revealed populations consistent with binary models [23,24]. Furthermore, irregular photometric dips or flares, potentially linked to gas dynamics in the circum-binary disk or mini-disks, provide complementary evidence for the presence of SMBBHs [10].

The interpretation of quasi-periodic variability as evidence for supermassive black hole binaries (SMBBHs) faces significant challenges, particularly from red noise in AGN light curves. AGNs exhibit stochastic variability across a broad range of timescales, which can produce apparent periodic signals through random fluctuations. This variability is characterized by a power-law power spectral density (PSD), where lower-frequency (longer timescale) variations dominate, often described as red noise. Simulated light curves with red noise properties have been shown to produce spurious periodicities that mimic the signals expected from SMBBHs [25,26]. Criticism of candidates like PG 1302-102, originally proposed as a binary due to its periodic variability [18], highlights the difficulty of distinguishing true periodic signals from statistical artifacts [14]. Rigorous tests, such as the Lomb-Scargle periodogram and wavelet analysis, must account for the PSD of AGN variability to avoid false positives [27]. Long monitoring timescales are essential to verify periodicity over multiple cycles and rule out red noise as the source of variability. Systematic studies, such as those using Pan-STARRS and ZTF, increasingly incorporate red noise models to refine binary candidates and improve the reliability of photometric searches for SMBBHs [28]. Applying the same criterion customarily applied for binary stars (at least three full orbits monitoring [29]), would imply a monitoring time of several decades, and suitable data are not yet available for SMBBHs.

Broad emission line profile variability offers a promising avenue for detecting SMBBHs. In a binary system, the orbital motion of the black holes, coupled with their interaction with surrounding gas, can produce periodic changes in the broad-line profiles, such as centroid shifts, line asymmetries, or double peaks. Variability in the broad-line profiles of AGN such as NGC 4151 suggests that gravitational interactions between binary components might influence the emission region [30]. Shen *et al.* [31] conducted a systematic search for binary SMBHs by examining velocity shifts in broad-line centroids using multi-epoch spectroscopy from the Sloan Digital Sky Survey (SDSS), providing statistical evidence for potential binaries. Simulations further demonstrated that periodic line profile changes [e.g., 32], including double peaks and shifts, can arise from mini-disks around individual SMBHs in a binary system. However, explored long-term variability of quasars with double-peaked and peculiar profiles disfavored the idea that periodic changes in the broad Hβ line could be attributed to a SMBBH system [13].

Additional evidence for SMBBHs is arguably based on peculiar broad line profiles. The broad line region (BLR) of 1E 1821+643 exhibits significant velocity offsets of its broad emission line profiles, with the Hβ line centroid shifted by thousands of kilometers per second relative to the host galaxy's systemic velocity [33]. Such offsets could be interpreted as evidence of a gravitationally bound binary system, where the orbital motion of one black hole contributes to the Doppler shift of the observed emission lines. Alternatively, the velocity shifts could indicate a recoiling black hole, where a gravitational wave "kick" following a binary black hole merger ejects the remnant black hole at high velocity from the center of the galaxy [33,34]. Both scenarios are considered compelling but remain speculative due to the complex dynamics of the BLR and alternative explanations involving anisotropic gas motion or asymmetric accretion flows. Future multi-wavelength monitoring, including precision radial velocity measurements and time-domain studies, may help distinguish between these interpretations and provide deeper insight into the nature of 1E 1821+643.

While observational evidence remains sparse due to the complexity of BLR dynamics and the long orbital timescales of SMBBHs, high-resolution spectroscopic monitoring and advanced time-domain surveys are paving the way for more robust detections. However, interpretation is made more complex by the lack of consensus over the expected phenomenology of emission line profiles. Also, in the case of extreme mass ratio inspi-

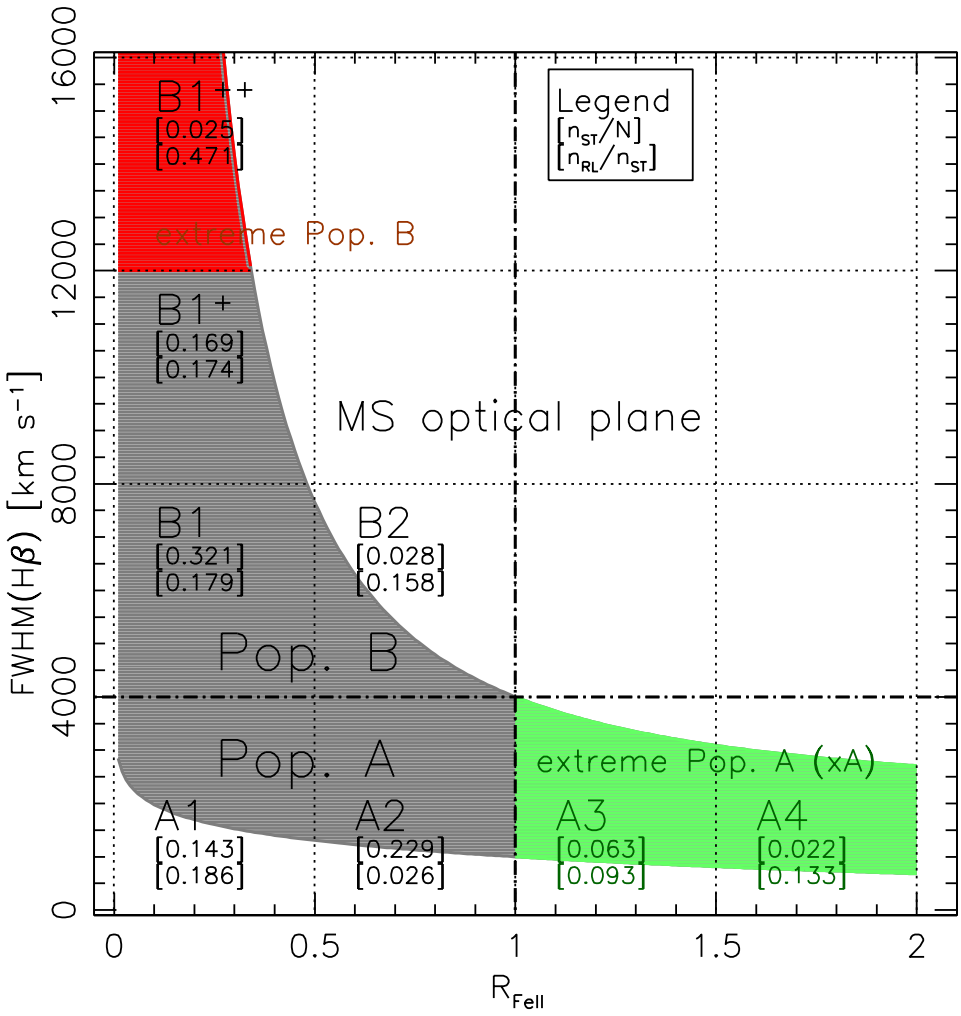

Figure 1. A schematic representation of the optical plane of the quasar main sequence, with the subdivisions into spectral bins clearly marked. The numbers in square brackets beneath each spectral type label indicate the prevalence of the spectral type (number $n_{\rm ST}$ of sources in each spectral type normalized by the number of sources in the full sample), and the fraction of RL (jetted) sources $n_{\rm RL}/n_{\rm ST}$ within each type. The data are from the sample of Marziani *et al.* [35].

rals, a second black hole may not provide a detectable electromagnetic signal, while still perturbing line emission or circum-primary accretion disk.

The previous considerations are meant to stress that an efficient search for SMBBHs should be highly focused. A blind search over the full AGN population will be probably overwhelmed by the red noise characteristics of the light curves and by the lack of contextualization of emission line profile properties. The aim of this note is to point out that there is a well defined segment of the quasar main sequence where SMBBHs can be more easily detected. We begin by summarizing the concept of the quasar main sequence (MS), a framework that has proven to be an effective tool for organizing the diversity of type-1 AGN (§2). From the MS, we focus on a specific spectral type and conduct a detailed analysis of the emission line profiles of the Balmer HI line Hβ and the UV resonance line MgIIλ2800 (§2.1). This particular spectral type exhibits several sources with emission line profiles that can be interpreted as being perturbed by the presence of a secondary compact object. Based on this interpretation, we identify a set of promising candidates for further monitoring (§3 and §4) and outline the fundamental multi-messenger characteristics expected of such binary systems (§5).

2. The quasar main sequence: a brief synopsis

The concept of the main sequence in quasar studies originated from a Principal Component Analysis (PCA) applied to the spectra of Palomar Green quasars, which identified a dominant trend known as Eigenvector 1 (E1; [36]). The E1 revealed an anti-correlation between the strength of the singly ionized iron emission blend centered at λ4570, and the full width at half maximum (FWHM) of Hβ, or alternatively, the peak intensity of [OIII]λ5007. The MS can be represented in a plane where FWHM(Hβ) is plotted against the parameter $R_{\rm FeII}$, defined as the flux ratio F(FeIIλ4570)/F(H$\beta_{\rm BC}$). Figure 1 illustrates the quasar MS in this parameter space. Over time, the MS has been validated and extended from the original sample of 80 objects [36], encompassing now hundreds [37] and tens of thousands sources [38]. The trends identified in the MS have been linked to physical properties of the accretion process and outflows, confirmed by multi-frequency data [39–41] and advanced techniques like locally linear embedding in manifold learning [42,43]. The MS captures fundamental correlations related to quasar dynamics, orientation, and the accretion structure.

The MS encompasses only type-1 AGN, where broad emission lines are visible, and orientation constraints (angle between the line of sight and the AGN symmetry axis $\theta \lesssim 45$) affect the observed line widths. The parameters FWHM(Hβ) and $R_{\rm FeII}$ are particularly revealing. FeII emission, which spans from the UV to the IR, is largely self-similar in type-1 AGN but varies in relative strength to Hβ, with $R_{\rm FeII}$ values ranging from undetectable to $\gtrsim$2 [39,44] which can be directly linked to Eddington ratio [37,45–47]. The FWHM of Hβ reflects the virialized velocity field of the low-ionization BLR and is influenced by orientation, with the angle θ playing a key role [48–50].

A defining feature of the MS is its "elbow" shape, dividing sources into Population A (Pop. A) and Population B (Pop. B) [39]. Pop. A quasars, characterized by FWHM(Hβ) $\lesssim$4000 km/s, exhibit sharp Hβ profiles, prominent FeII emission, and weak [OIII], while Pop. B quasars, with broader Hβ profiles, display weaker FeII and stronger [OIII] [39]. Additionally, high-ionization lines such as CIV λ1549 show systematic blueshifts relative to narrow low-ionization lines like [OII] λ3727 or Hβ narrow component [51]. These distinctions suggest a heuristic subdivision of the BLR into a virialized low-ionization region, likely associated with the accretion disk, and a wind-dominated high-ionization region, particularly pronounced in extreme Population A (xA) sources where $R_{\rm FeII} > 1$ [52–54].

2.1. A special section of the main sequence

Extreme Population B sources are characterized by extremely broad Balmer line profiles, with conventional FWHM limits of $\gtrsim 12,000$ km s^{-1} or even $\gtrsim 16,000$ km s^{-1}. They include only the most extreme cases, and occupy the spectral type B1^{++} in Figure 1). A visual inspection shows symmetric very broad profiles (the red wing of Hβ is invariably extended beyond the [OIII]$\lambda\lambda$4959,5007 emission). These sources also exhibit very low, often undetectable $R_{\rm FeII}$, in contrast to Population A, where the majority of sources have measurable $R_{\rm FeII}$. A hallmark of Population B is the most-pronounced redward asymmetry in low-ionization lines, such as Hβ, a feature well-documented in the literature [37,55–60]. However, the situation for spectral type B1^{++} is less clear: the MgIIλ2800 and Hβ median spectra show an asymmetry index consistent with a symmetric profile (AI $\approx 0.02 \pm 0.06$ and $\approx 0.04 \pm 0.06$ for the two lines, [35]).

The $R_{\rm FeII}$ parameter, central to the definition of the MS, depends not only on the gas physical conditions but also on chemical abundances. This makes it crucial to understand how metallicity (Z) influences a source location in the optical MS plane [41,61,62]. Another key insight from MS studies is the distinct differences in the prevalence of radio-loud (RL) sources across populations. Extreme Population B hosts the largest fraction of "jetted" sources ($\approx$ 50% as reported in Fig. 1), distinguished from radio-quiet (RQ) ones by their distribution of blueshifts in high-ionization lines. Interestingly, this radio-loudness has a minor effect on the low-ionization lines [63,64]. While extreme Population A also includes

powerful radio emitters, these objects are likely fundamentally different in nature from the powerful, jetted sources in Population B. The radio-emitting sources of extreme Population A might be dominated by star formation, with the possible contribution of other mechanisms [65–68].

3. Candidate SMBBHs along the quasar main sequence

3.1. Samples and measurements

The sample of Marziani *et al.* [35,69] is flux-limited and encompasses 680 objects from the DR7 of the SDSS, in the redshift range $0.4 \leq z \leq 0.7$ to make it possible to simultaneously cover the Hβ and the MgIIλ2800 line. The flux limit ensures that the S/N is high enough for a reliable analysis of the Hβ and MgIIλ2800 profiles that are contaminated especially by extended FeII emission [70,71]. The sample is large enough to ensure that all spectral bins identified in Fig. 1 are sufficiently populated. In addition, even if MgIIλ2800 lines are known to be narrower than Hβ in Population B [35,72–74], suggesting a larger emissivity-weighted distance from the continuum source for the MgIIλ2800 line [75–77], Hβ and MgIIλ2800 are both low-ionization lines expected to be predominantly emitted in a low-ionization, virialized part of the BLR [53,78,79], and therefore to show consistent profiles.

Our selection criterion is based on the presence of peculiarities in the emission line profiles. The correlations along the main sequence MS provide a robust framework to identify what is peculiar or, at the very least, rare. For example, the prominent red wing observed in the Hβ profile is a characteristic feature encompassing most of Population B, which constitutes approximately half of optically selected quasar samples [37,80]. While the origin of this feature remains unclear, it is not considered a peculiarity. In contrast, double- or multi-peaked profiles, as well as strongly shifted emission lines, are rare. A systematic line profile analysis along the MS reveals that they tend to be concentrated among quasars with the broadest Hβ profiles [39]. These cases also frequently exhibit rapid profile variability, occasionally leading to the “changing look" phenomenon [81,82]. In Population A, large inter-line shifts are easily understood in the framework of a system accretion disk + wind [53].

Seventeen sources belong to the spectral type B1^{++}, about 2.5 % of the full sample. Their identification is reported in Table 1, along with the SDSS redshift, radio classification, qualitative Hβ profile classification following Sulentic [83], centroid shift at 0.9 fractional intensity. Measurements were obtained through non-linear, multi-components fits of the SDSS spectra within `IRAF v.2.18` [84–86], using the task `specfit` [87]. The same multi-component decomposition has an heuristic base and has been applied in tens of works in the past 25 years [79]. For a previous application on median spectra of the same sample considered here, see Marziani *et al.* [35].

The classification of Sulentic [83] assigns an asymmetry code to the broad line profile (asymmetric to the red (AR) or to the blue (AB), or symmetric) and a code for the line peak shift (R or B). The centroid at different fractional intensity are as originally defined by Marziani *et al.* [53] and applied in several more recent works [for example, 88].

4. Results

The benchmark classification for non-peculiar sources in Population B is AR,R or AR,0, where peak shifts at peak are usually modest, $\lesssim$ a few hundreds km s^{-1} [37,70,90]. Large shifts ($\gtrsim$ 1000 km s^{-1}) are rare and should be considered peculiar. Table 1 reports the amplitude of the centroid at 0.9 fractional intensity $c(0.9)$ that is considered a proxy of the line peak shift. Only three sources in Table 1 show an Hβ profile consistent with the reference AR,R profile for Population B. All the remaining sources show some peculiarities, with 8 sources showing large shifts with absolute amplitude $\gtrsim$ 1000 km s^{-1}, suggesting that the origin of the perturbation is located in correspondence of the BLR. In one case (J130704) the actual peak is even displaced to the blue while the $c(0.9)$ is shifted to the red. This case highlights the large prevalence discordant asymmetries and peak shifts.

Table 1. Basic properties of the B1^{++} sample.

Identification (1)	Jcode (2)	z_{SDSS} (3)	Radio (4)	Hβ (5)	$c(0.9)$ Hβ (6)	Bin.? (7)
WISEA J093642.95+551119.2	J093642	0.4971	RQ	AR,R	1309	Y
SDSS J101230.78+182021.1	J101230	0.4623	RL	AR,B	−480	Y
FBQS J110001.0+231412	J110001	0.5567	RL	AR,R	490	–
3C 254	J111438	0.7359	RL	AR,R	2225	Y
FBQS J111903.2+385852	J111903	0.7344	RL	AR,B	−2149	Y
HB89 1156+631	J115839	0.5924	RQ	AR,B	−349	Y
PG 1201+436	J120424	0.6617	RQ	AR,B	-1374	Y[a]
FBQS J1300+2830	J130028	0.6467	RL	AB,R	1781	Y
WISEA J130704.39+091004.1	J130704	0.5247	RQ	AR,B	3086[b]	Y
SDSS J133051.90+184932.9	J133051	0.5141	RL	AR,B	−885	Y
WISE J133655.49+654115.9	J133655	0.4378	RQ	AR,R	172	Y[a]
FBQS J140012.6+353930	J140012	0.5184	RQ	AR,R	2341	Y
WISEA J141312.59+564113.3	J141312	0.6686	RL	AR,0	53	—
WISEA J150249.02+081305.9	J150249	0.5186	RQ	AR,B	7	Y
FBQS J153159.1+242047	J153159	0.6321	RL	AR,R	597	—
WISEA J155330.23+223010.3	J155330	0.6404	RQ	AR,B	−1809	Y
WISEA J163206.04+441659.5	J163206	0.5304	RQ	AB,B	−411	Y

Notes: Col. (1): common name recognizable by the NASA extragalactic ddatabase (NED); (2) code in the form Jhhmmss; (3) redshift reported in the header of the original SDSS spectra; (4) radio classification following Zamfir *et al.* [89]; (6) centroid at 0.9 fractional intensity of Hβ, in km s^{-1}; (7) answer to the question: is the target a potential SMBBH candidate? [a]: boxy [b]: Peak shifted to the blue $v \sim -3550$ km s^{-1}.

Fig. 2 shows three cases two of which depict the profiles of a binary system with a perturber with different, extreme projections of its velocity along the line of sight. The profile of MgIIλ2800 is narrower and more symmetric, as found in previous studies [72,73, 75] and shown in the third column of Fig. 2. The classifications reported in Table 1 suggest that most sources have a peak shift that might be associated with excess emission over an AR profile. This is confirmed by the distribution of centroids for Hβ and MgIIλ2800. Fig. 3 shows the distribution of the centroids at $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$ and 0.9 fractional intensity. The $c(0.9)$ of Hβ (bottom rightmost panel of Fig. 3) shows a uniform distribution over a range $\sim -2000 - +3000$ km s^{-1}. A consistent distribution is observed also for $c(\frac{3}{4})$. At lower fractional intensity, the shifts to the red associated with the prominent Hβ red wing typical of population B dominates. In other words, apart from a few cases, the impression is the one of a perturbation affecting the top of the profile.

Fig. 2 and Fig. 3 suggest two possibilities. The first is that the profile is affected by an outflow. The second is that there is a perturbation yielding a shifted peak. In the case of B1^{++} the outflow cannot be ruled out, but is not favored by the large shift of the profiles. An outflow component is present in the Hβ profile of Pop. B; however, it is typically associated with the semi-broad component of [OIII]$\lambda\lambda$4959,5007 [91] and with shifts of a few hundred km s^{-1}. The centroid at $\frac{3}{4}$ measurements are available only for the sample of Zamfir *et al.* [80]. Out of 169 B1 sources, only 3 show $|c(\frac{3}{4})| \gtrsim 1000$ km s^{-1}. The distribution of B1 is much more centrally concentrated with a modest dispersion (gray box in Fig. 3). A Kolmogorov-Sminrnov test carried out on the 169 B1 and on the 13 B1^{++} confirms that the two distributions are significantly different at a confidence level $\gtrsim 4\sigma$.

Prominent outflows affecting the profiles up to $\gtrsim 1000$ km s^{-1} are seen only in Population A and extreme Population A at the opposite end of the sequence, where the ratio radiative to gravitational forces is highest [63,64,92].

The interpretation of the red wing is not fully clear. However, the consensus is that it is a M_{BH} effect, either because of infall [56] or because of gravitational and transverse

redshift [55,59,93–96]. The very broad, red wing becomes more prominent for very massive black holes powering the most luminous quasars [57,90], supporting the idea that the Hβ line profile is mostly broadened in the velocity field of a very massive black hole (as are the ones of extreme Population B). Fig. 4 presents the luminosity-to-mass diagram for a sample of type-1 AGN, with the distribution of quasars from the considered sample overlaid for comparison. The data points cluster in correspondence of a fairly well defined limit in Eddington ratio [37], below which the black holes are expected to enter in an inefficient radiative domain [e.g., 97–100]. They involve very massive sources, if black hole mass is estimated using standard relations [101]. This property is consistent with the prominent redward asymmetry and large shifts to the red toward the Hβ line base that are observed in the B1^{++} sample, if they are due to gravitational and transverse redshift. The main body of the line profiles is attributed to the velocity field of virialized gas within the gravitational field of a supermassive black hole, with gravitational redshift becoming increasingly significant as the emitting gas approaches the center of gravity. In contrast, the peaks of the profiles appear to be influenced by perturbations that account for only a small fraction of the line flux. The last column of Table 1 identifies the profiles that can be interpreted along this framework i.e., the sources that could be considered candidates for eventual monitoring.

5. Discussion

5.1. A SMBBH system

The simplest interpretation in terms of a SMBBH system is of a very massive primary (leading to the Hβ profile with redshift increasing toward the line base) with a secondary of small mass ratio $q \sim 0.1$, capable of inducing a measurable effect on the BLR region velocity field and accretion disk, and even jet precession [e.g., 109,110]. There are several factors that may increase the detectability of SMBBHs in the spectral type B1^{++}. The first one is due to orientation. The current interpretation of the BLR of Pop. B is the one of a highly flattened system, coplanar with the accretion disk [91,111,112]. The extreme line width, and the high prevalence of radio sources whose radio axis is seen at a large angle [66,113,114], indicates that the velocity field projection along the line of sight is maximized for B1^{++} sources. B1^{++} can be connected to blazars (sources of low Eddington ratio and minimal FeII emission [115] by an exclusive orientation effect, as blazars are oriented with the jet closely aligned to the line-of-sight (Fig. 3 by Marziani *et al.* [116]), but are otherwise believed to be low accretors. However, orientation alone cannot explain the properties of the B1^{++}.

The low FeII emission, and the extreme line width with extreme redward asymmetries point toward very extremely high $M_{\rm BH}$ and extremely low $L/L_{\rm Edd}$. Indeed, the B1^{++} sources show similar $M_{\rm BH} \sim 10^{10}$ solar masses, and moderate luminosity due to low Eddington ratio $\sim 10^{-2}$. In other words, they are evolved system close to (but not yet in) the condition of "spent" quasars [117]. The presence of a second black hole with $q \gtrsim 0.04$ may induce a truncation in the BLR emission, as the mass flow in circum-binary Keplerian disk is perturbed by tidal forces which carve annular gaps in the second black hole orbital path [118,119], hampering to various extent the accretion process [120]. This might be the case of the classical double "peakers" with broad line profile consistent with the emission from an accretion disk truncated at ~ 1000 gravitational radii [121–124].

The average optical luminosity of the B1^{++} quasars $\sim 5 \cdot 10^{45}$ erg s^{-1}, implies a BLR radius $\sim 5 \cdot 10^{17}$cm $\lesssim 1$ pc, identifying these systems as bona-fide sub-parsec binary candidates. The time to coalescence because of gravitational wave emission is provided by the relation $T_{\rm c} = \frac{15}{304} \frac{c^5 a_0^4}{G^3 M_1 M_2 (M_1+M_2)} \cdot (1-e_0^2)^{7/2} \cdot \frac{1}{g(e_0)}$, where $g(e_0) = 1 + \frac{73}{24} e_0^2 + \frac{37}{96} e_0^4$ [125,126], where e_0 is the initial eccentricity. In our case, assuming that $M_2 = 0.1 M_1$, with $M_1 = 10^{10}$ solar masses, we obtain a coalescence time $\sim 10^7$ yr for a circular orbit for $e_0 = 0$. The $T_{\rm c}$ can be significantly shortened only if the eccentricity is rather high: by a factor 10 if $e_0 = 0.6$, and by a factor 100 if $e_0 = 0.8$. With an orbital period $P \gtrsim 10^2$ yr, the immediate prediction is that the peculiar, displaced peaks should not show any short term variation

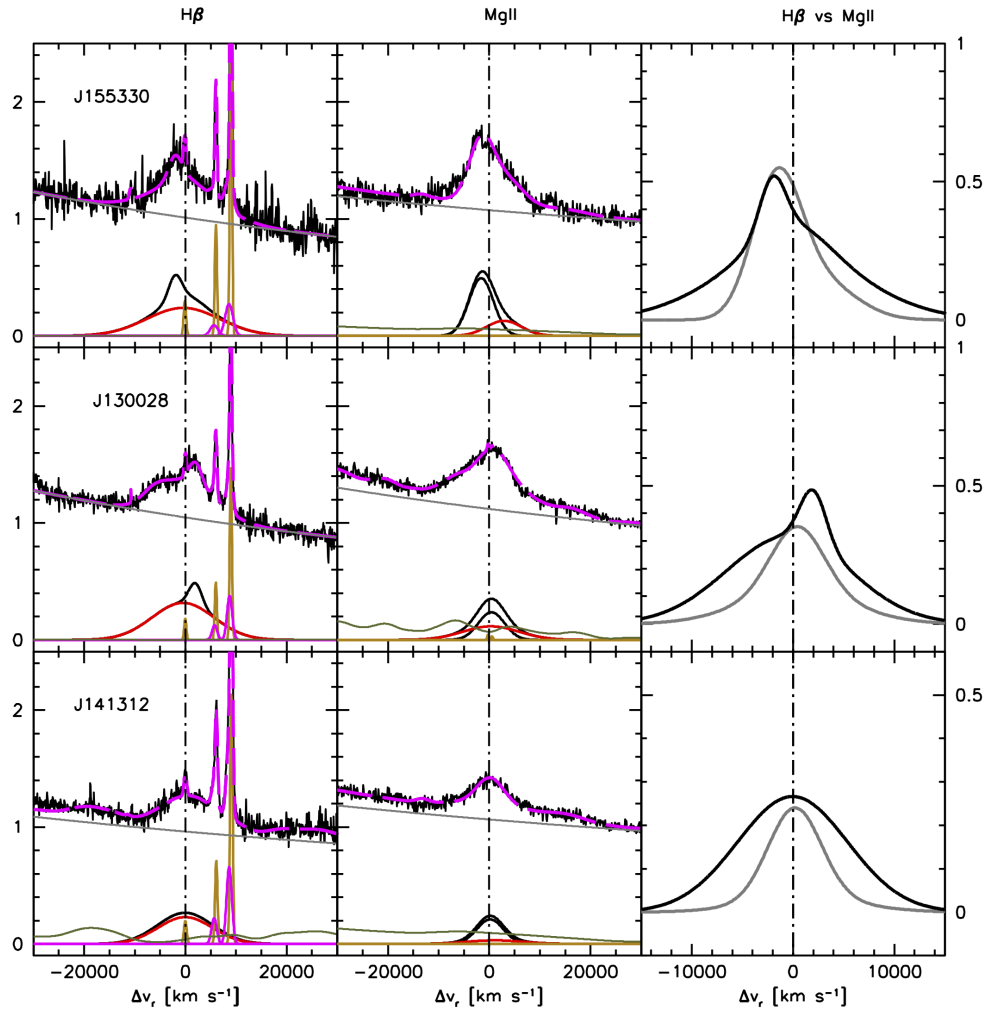

Figure 2. Examples of emission line profile analysis for Hβ (left column) and MgIIλ2800 (middle column). The top plot of each panel shows the original spectrum (thin black line) and the full model (dashed magenta line) along with the adopted continuum (gray) The bottom plots show the multiple components employed in the non-linear fit: broad and very broad Hβ component (black and red Gaussians) [102,103], Hβ and [OIII]$\lambda\lambda$4959,5007 narrow line emission (gold), semi-broad emission of [OIII]$\lambda\lambda$4959,5007 (magenta) and FeII (dark green). FeII emission is very weak in most of the sample, both in the optical and in the UV. The right column shows a comparison between the Hβ and MgIIλ2800 (gray) broad profiles.

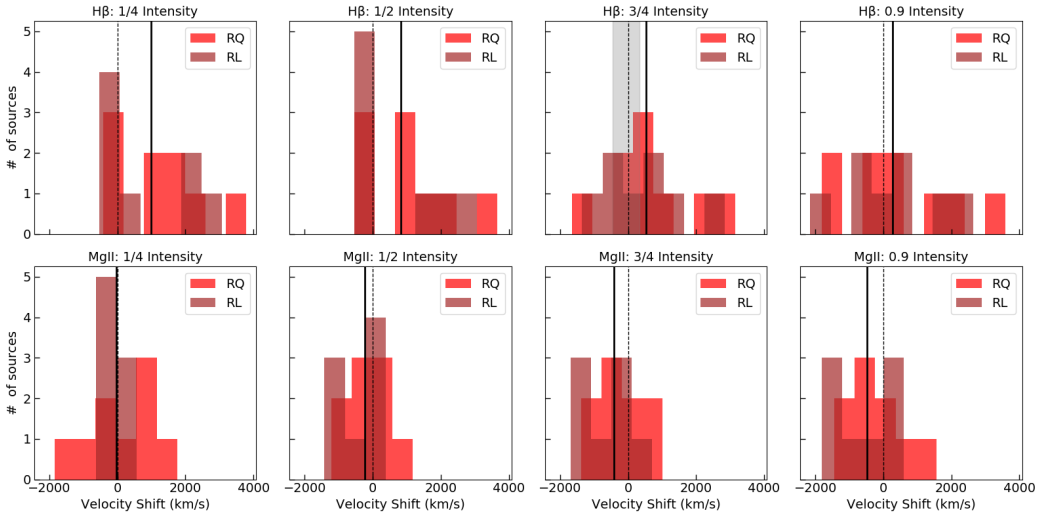

Figure 3. Distribution of centroids at four different fractional intensity levels, from left to right $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$ and 0.9. Top: Hβ, bottom: Mg IIλ2800. Radio-loud sources are shaded brown. The rest frame radial velocity is represented by the dashed line, while the thick black line is the average of the sample. The shaded gray box shows the $\pm 1\sigma$ range for the $c(\frac{3}{4})$ measurement of the B1 spectral type from the sample of Zamfir *et al.* [80].

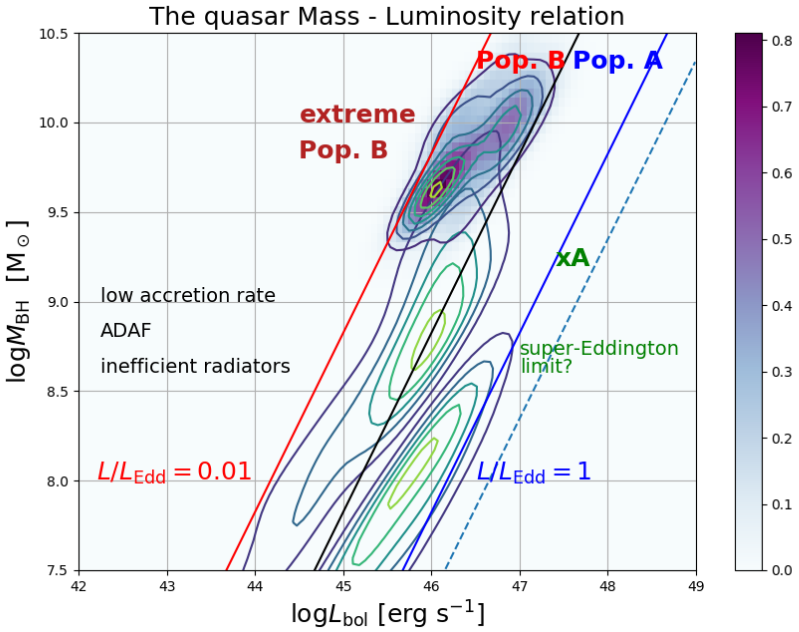

Figure 4. The black hole mass – luminosity diagram for a low-z type quasar sample. The quasar location in the $M_{\rm BH}-L$ diagram corresponds to the contour in the middle upper part of the diagram. The wide majority are located close to the limit $L/L_{\rm Edd}\sim 10^{-2}$, close to the domain expected for inefficient radiators. The black diagonal line at $L/L_{\rm Edd}= 0.1$ separates Population A and B. On the high Eddington ratio side, the possible super-Eddington accretors are labeled as xA (extreme Population A), with Eddington ratios not exceeding 1 by a large factor, as found observationally [104] and as derived from theory of super-Eddington accretion disks as well [105–108].

($\lesssim$ 1 yr), while a systematic shift over 10 – 20 yr might occur. At least, the B1^{++} spectral type can be considered an appropriate testbed for the SMBBH model [see also 127].

The inspiral motion of a less massive black hole in the gravitational field of a supermassive black hole produces a distinctive gravitational wave signal characterized by long-duration, low-frequency waveforms. These signals result from the gradual inspiral of a compact object toward the SMBH. For the sample considered in this study, the black hole masses are extremely large and inspiral motions may produces waves of frequencies in the domain of the Pulsar Timing Array ([128,129], $\nu \sim 10^{-9}$).

5.2. The latest phases of the evolution along the quasar main sequence

We might expect a rich phenomenology in the frequency domains covered by planned space- and ground-based detectors due to the remnants of a nuclear stellar system [130]. Nuclear (i.e., *within the molecular torus*) and circumnuclear star formation occurs in most AGN with moderate or high accretion rates [131–134]. The outer self-gravitating disk and torus provide gas for nuclear fueling, with star formation naturally associated with high or super-Eddington accretion [135–141]. As quasars evolve, feedback processes deplete surrounding material, leading to lower $L/L_{\rm Edd}$ ratios and a transition into Population B, characterized by weaker outflows and stronger core [OIII]$\lambda\lambda$4959,5007 emission [39]. Fraix-Burnet *et al.* [142] list several multi-frequency parameters that are systematically different between Population A and B. Extreme population B sources can be thought as simply reaching the most extreme values in most observational parameters of Population B. The torus may be absent in such low-luminosity AGN [143], leaving the black hole without a large reservoir of accreting matter. The point here is what may happen in the nuclear regions of such evolved stellar system.

The fate of such a system remains unclear. The best prospect for detecting it lies in gravitational radiation, since the electromagnetic signal is overwhelmed by the luminosity of the AGN. The scenario envisaged for super-Eddington accretors will ultimately lead to a population of stellar mass compact objects, and to intermediate mass black holes (IMBHs) [136,144–147].

5.3. GW from IMBH and stellar mass black hole coalescence

Observed nuclear star clusters have extremely high stellar density, in excess of 10^6 $M_\odot$ [148,149], and runaway collisions of massive stars [144,145] could be a pathway to generate IMBHs of $10^4 - 10^5$ $M_\odot$. A second pathway is via the enhancement of stellar black hole merger rates in the dense environment of the accretion disk due to the increased probability of BH–BH encounters, binary formation via orbital migration and migration traps [150]. An IMBH could in turn become a seed black hole in a binary system, and lead to an extreme mass ratio inspirals (EMRI) phenomenology. The gravitational wave frequencies from EMRIs typically fall in the millihertz range, which makes them ideal targets for future space-based gravitational wave detectors like the Laser Interferometer Space Antenna [LISA, 7,8]. LISA will be sensitive to the low-frequency gravitational waves emitted by EMRIs with primary masses covering the domain of IMBHs up to moderately SMBBH ($\sim 10^8$ $M_\odot$, [7,151]), which cannot be detected by ground-based observatories due to their low frequency range.

The first IMBH gravitational-wave detections, such as GW150914, involved black holes of about 29 and 36 solar masses [152] which are thought to form by direct collapse of massive stars in low-metallicity environments [153,154]. If the progenitor of the remnant black holes were high metallicity stars, it might difficult that the initial mass after collapse could be as large as 30 $M_\odot$ [155,156]. In AGN disks, stellar-mass black hole mergers are expected to occur at a higher rate than in isolated environments [157], and produce gravitational wave bursts [158]. The high frequency of mergers is expected in turn to produce a post-AGN population of $\sim$ 10 $M_\odot$ black holes [159], along with a population of IMBHs [147,159]. The signal amplitude of gravitational waves from a binary BH merger is typically expressed in terms of the strain amplitude h, which depends on the masses

of the black holes, the distance to the merger, and the orientation of the system relative to the observer. For a stellar-mass black hole merger, let's assume both black holes have masses of $5M_{\odot}$, typical of a general population of remnant black holes [160]. The chirp mass is $M_{\rm c} = \frac{(M_1 M_2)^{3/5}}{(M_1+M_2)^{1/5}} \approx 4.35M_{\odot}$. The GW strain amplitude h for a circular binary inspiral of two masses M_1 and M_2 is approximated by $h \approx \frac{4(GM_c)^{5/3}}{c^4 D_L}(\pi f)^{2/3}$, where G is the gravitational constant, f is the gravitational wave frequency, D_L is the luminosity distance to the source, and c is the speed of light. Frequencies in the range of 10 Hz to 1000 Hz are typically considered in a binary black hole inspiral. Ground-based interferometers like the Laser Interferometer Gravitational-Wave Observatory [LIGO 161] and Virgo [162] are optimized for detecting the mergers of stellar-mass black holes. A frequency $f = 100\,\mathrm{Hz}$ is in the sensitivity range for both LIGO and the Einstein Telescope [ET, 163,164]. The strain h for a merger at $z \approx 0.55$ is $h \sim 10^{-23}$. The strain sensitivity of LIGO's O3 run is about $h \sim 10^{-23}$ to 10^{-24} at its peak sensitivity. This means that LIGO detects BBH mergers up to typical redshift of the B1^{++} sample. The ET will be 10 to 100 times more sensitive than LIGO, extending the detection horizon to much higher redshifts. The ET will be capable of detecting strain amplitudes as low as $h \sim 10^{-25}$ or even smaller, and sample comfortably the stellar-mass BH remnant population expected in evolved AGN.

6. Conclusions

This study has highlighted the potential of the quasar main sequence as a framework to identify promising candidates for supermassive binary black holes (SMBBHs). By focusing on a specific spectral type along the quasar main sequence, B1^{++}, we identified emission line peculiarities, such as large centroid shifts, which may indicate the presence of secondary compact objects perturbing the accretion dynamics. These findings suggest that high-mass black holes with low Eddington ratios, typical of B1^{++} sources, are favorable environments for detecting SMBBHs.

Future multi-wavelength campaigns and gravitational wave observations will be essential to confirm these systems. Sub-parsec binaries within this spectral class may also provide crucial insights into the role of tidal forces and binary-induced disk perturbations in shaping AGN emission profiles and evolutionary pathways.

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Abbreviations

The following abbreviations are used in this manuscript:

AGN	Active Galactic Nucleus/i
BH	Black Hole
BLR	Broad Line Region
E1	Eigenvector 1
ET	Einstein Telescope
EMRI	Extreme mass ratio inspiral
FWHM	Full Width Half Maximum
GW	Gravitational Wave
LIGO	Laser Interferometer Gravitational-Wave Observatory
LISA	Laser Interferometer Space Antenna
LIL	Low Ionization Line
MDPI	Multidisciplinary Digital Publishing Institute
MS	Main Sequence
NLSy1	Narrow Line Seyfert 1
PCA	Principal Component Analysis
PTF	Palomar Transient Factory
RL	Radio-Loud
RQ	Radio-Quiet
SDSS	Sloan Digital Sky Survey
SMBH	Super-Massive Black Hole
SMBBH	Super-Massive Binary Black Hole
xA	extreme (Population) A
ZTF	Zwicky Transient Facility

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