

Wings of little dots: Exponential broad lines from a stratified broad-line region

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ABSTRACT

We investigate the origin of the broad exponential wings seen in the $H\alpha$ profiles of many JWST-discovered little red dots (LRDs) and little blue dots (LBDs). Recent studies show that exponential broad-line profiles are not unique to LRDs, are common in LBDs too, and need not imply that electron scattering is the dominant broadening mechanism in every source. We model the broad Balmer emission with a virialized, radially stratified broad-line region (BLR), motivated by our unification picture, in which LRDs are dust-reddened, high-inclination counterparts of compact blue broad-line active galactic nuclei (AGNs). In this framework, the observed profile is the luminosity-weighted superposition of clouds spanning a range of radii, and hence virial velocities. We show that a stratified BLR reproduces the exponential-like wings observed in three representative LRDs and one LBD, without requiring electron scattering as the dominant broadening mechanism. For the LBD GS-3073, the same BLR – calibrated only to $H\alpha$ – predicts, parameter-free, that $\text{He II } \lambda 4686$ and $H\beta$ should be broader than $H\alpha$, consistent with observations and offering an independent test of BLR ionization stratification. Our results support a picture in which wings and cores encode different physics: the wings arise primarily from virial BLR stratification, while the cores retain imprints of absorption and radiative transfer in dense gas. The fits further suggest that the cloud radial distribution peaks near the dust sublimation radius, with the exponential wings shaped by the inner, line-emitting BLR shells whose higher virial velocities produce the high-velocity tails. This offers a simple physical explanation for the exponential wings of little dots, without invoking exotic new components or scenarios.

Key words. galaxies: active – galaxies: formation – galaxies: high-redshift – galaxies: nuclei – quasars: emission lines

1. Introduction

The *James Webb* Space Telescope (JWST) has uncovered a large population of moderate-luminosity broad-line active galactic nuclei (BLAGNs) at $z \gtrsim 4$, powered by accretion onto early massive black holes with inferred masses of order 10^6 – $10^8 M_\odot$ (e.g., Harikane et al. 2023; Maiolino et al. 2024; Taylor et al. 2025; Juodžbalis et al. 2026), and partitioned by their UV-optical continuum slopes into “little red dots” (LRDs) and “little blue dots” (LBDs) (Brazzini et al. 2026). These sources are distinguished by broad Balmer emission, compact morphologies, weak X-ray emission, and, in the case of LRDs, red or V-shaped UV-optical continua with strong Balmer breaks. Their spectra often lack the prominent high-ionization features typical of classical unobscured active galactic nuclei (AGNs), indicating that the physical conditions of the line-emitting and circumnuclear gas differ substantially from those within standard quasar populations (e.g., Matthee et al. 2024; Greene et al. 2024; Lambrides et al. 2026; Kocevski et al. 2025; Wang et al. 2025; Hainline et al. 2025; Akins et al. 2025; Delvecchio et al. 2025; Barro et al. 2026; Hviding et al. 2025; Maiolino et al. 2025; Tang et al. 2025; Zucchi et al. 2026).

A major focus of recent work has been the origin of the broad $H\alpha$ line profiles in these systems, and more generally of

the broad hydrogen and helium emission lines. Rusakov et al. (2026) argued that, in high-quality LRD spectra, the broad exponential wings are produced primarily by Thomson scattering in compact, Compton-thick ionized cocoons. In this interpretation, the intrinsic line cores are much narrower, implying substantially lower black-hole masses than standard virial estimates. By contrast, Scholtz et al. (2026) showed from a larger sample of 32 JWST AGNs that exponential profiles are not unique to LRDs, are often also present in LBDs, and are not universally preferred over Lorentzian or multicomponent Gaussian descriptions. They further demonstrated that exponential wings can arise naturally from the superposition of virialized BLR clouds spanning a range of radii, without requiring scattering to dominate the line broadening.

At the same time, Matthee et al. (2026) have emphasized that the line cores vary systematically with continuum color and Balmer-break strength: blue sources show relatively narrow central cores, redder systems exhibit P-Cygni-like absorption, and the reddest sources display absorption-dominated cores, while broad exponential wings remain present throughout the sequence. This suggests that the wings and cores may encode different physics, with the former tracing the intrinsic BLR velocity field and the latter the radiative-transfer and absorption effects of dense circumnuclear gas.

In a recent paper, Madau & Maiolino (2026) proposed that LRDs are the dust-reddened, high-inclination counterparts of

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compact blue broad-line AGNs powered by super-Eddington accretion. In that picture, a geometrically thick funnel produces a strongly anisotropic ionizing continuum, while an equatorially concentrated BLR and a modest dusty screen explain the large Balmer equivalent widths, weak high-ionization lines, and red continua of LRDs without invoking a fully enclosing cocoon. Motivated by this framework, here we investigate whether the observed exponential $H\alpha$ wings can be reproduced by a virialized, radially stratified BLR and whether the detailed line cores require additional absorption. We first test the model against three absorbed LRDs and then extend the analysis to the unabsorbed LBD GS-3073, assessing whether BLR stratification provides a common origin for the broad wings of both populations. GS-3073 offers a complementary test because, unlike the three LRDs, its $H\alpha$ profile shows no detected Balmer absorption, allowing both broad wings to be fitted, while its detected broad He II $\lambda 4686$ emission provides an additional probe of ionization-dependent BLR stratification.

2. The stratified BLR of little dots

A natural alternative to dominant electron scattering is that broad Balmer profiles are produced by a radially stratified BLR, in which clouds at different radii contribute different characteristic velocities. This interpretation is motivated by the fact that exponential wings are not unique to LRDs, are also found in LBDs, and can arise naturally from the stratification of virialized BLR clouds rather than from a separate scattering cocoon. Scholtz et al. (2026) explicitly argue that exponential wings can emerge from BLR stratification in virial motion and that stacking or superposing multiple kinematic BLR components tends to produce profiles that are indistinguishable from exponential, even when individual components are not themselves exponential. Exponential or exponential-like broad-line wings are also not unique to JWST-discovered sources. A classic case is the $H\alpha$ profile of the low-luminosity Seyfert NGC 4395, where symmetric exponential wings were identified by Laor (2006); more generally, Kollatschny & Zetzl (2013) discussed exponential profiles as one of the standard phenomenological broad-line shapes in classical AGNs.

The logic of our model is simple. In a super-Eddington funnel geometry, the escaping continuum is highly anisotropic: near-polar observers see a brighter, harder ionizing spectral energy distribution (SED), whereas along equatorial directions self-shadowing suppresses the hardest XUV/soft-X-ray photons and reshapes the continuum (Wang et al. 2014; Lupi et al. 2024; Madau 2026). In addition, efficient Compton cooling of the hot corona by the intense soft-photon field in the inner accretion flow may intrinsically suppress hard X-ray emission, even in the absence of line-of-sight obscuration (Madau & Haardt 2024; Trinca et al. 2026). If the BLR is concentrated toward the equatorial plane, it is illuminated by a softer, more self-shielded continuum than that seen by low-inclination observers, naturally weakening high-ionization lines while preserving strong Balmer emission. A dusty component with a modest covering factor associated with the outer BLR or a compact circumnuclear obscurer then reddens high-inclination sight lines into the V-shaped continua of LRDs, while lower-inclination views appear as LBDs (Madau & Maiolino 2026). In this picture, the observed differences between LRDs and LBDs arise primarily from orientation and line-of-sight processing rather than from intrinsically different engines or evolutionary stages (e.g., Kido et al. 2025; Naidu et al. 2025; Pacucci et al. 2026). The model

predicts broader and more extended high-equivalent-width (EW) tails for the Balmer lines in LRDs than in LBDs, owing to the suppression of the observed continuum along dust-intercepted high-inclination sight lines.

Following Madau & Maiolino (2026), we model the BLR as an equatorially concentrated cloud distribution by specifying the mean number of clouds along a direction of polar angle i as

$$N(i) = N_0 \exp\left[-\frac{\cos^2 i}{2\sigma_{\text{BLR}}^2}\right], \quad (1)$$

where σ_{BLR} sets the angular thickness of the cloud distribution about the equatorial plane. The corresponding escape probability for direct disk photons is

$$P_{\text{esc}}(i) = \exp[-N(i)]. \quad (2)$$

We fix the normalization N_0 by requiring that the angle-averaged probability of intercepting at least one cloud equals the global BLR covering factor,

$$C_{\text{BLR}} = \int_0^{\pi/2} [1 - P_{\text{esc}}(i)] \sin i \, di, \quad (3)$$

where symmetry about the mid-plane has been assumed. For any chosen pair of values $(\sigma_{\text{BLR}}, C_{\text{BLR}})$, equation (3) is solved for N_0 . The corresponding normalized angular weighting of BLR clouds is then

$$p(i) = \frac{[1 - P_{\text{esc}}(i)] \sin i}{\int_0^{\pi/2} [1 - P_{\text{esc}}(i')] \sin i' \, di'}. \quad (4)$$

In our picture, the BLR extends over a range of radii interior to the dust sublimation boundary. This is physically motivated by the fact that, beyond the sublimation radius, surviving dust, rather than gas, dominates the absorption of ionizing photons, so that only a small fraction of the ionizing continuum is available for gas ionization and line emission. Nebular emission is therefore strongly suppressed there, in addition to being affected by dust extinction (Netzer & Laor 1993). We write the shell-integrated radial cloud distribution as

$$\frac{dN}{dr} \propto r^{\alpha-1} \exp\left(-\frac{r}{r_{\text{sub}}}\right), \quad (5)$$

where r_{sub} is the dust sublimation radius (Barvainis 1987),

$$r_{\text{sub}} = 1.4 \left(\frac{L_{\text{UV}}}{10^{45.5} \text{ erg s}^{-1}} \right)^{1/2} \left(\frac{T_{\text{sub}}}{1200 \text{ K}} \right)^{-2.8} \text{ pc}, \quad (6)$$

which we take to define the characteristic outer scale of the BLR, and the slope α controls the relative weighting of the inner and outer BLR clouds. We assume that all clouds have the same physical emitting area, independent of radius. Since the emergent $H\alpha$ line power of a cloud, $P_{\text{H}\alpha}^c(r, i)$, depends on both the radius and the BLR angle, the line profile is written as

$$\frac{dL}{dv}(v) = \int dr \frac{dN}{dr} \int di p(i) P_{\text{H}\alpha}^c(r, i) G[v; \sigma(r)], \quad (7)$$

where $G(v; \sigma)$ is the Gaussian kernel that describes the effective one-dimensional distribution of cloud bulk velocities at a fixed radius r . Here i denotes the polar angle of an individual BLR cloud, and the $p(i)$ -weighted integral accounts for the

anisotropic illumination of clouds at different angles from the disk axis under our assumption of isotropically re-emitted line radiation; it is therefore distinct from the observer's own line-of-sight inclination i_{obs} , which instead enters only through the directly viewed continuum in the equivalent-width calculation of Section 5. Because the incident hydrogen-ionizing photon rate $Q_{\text{HI}}(i)$ is anisotropic, $p(i)$ weights a mixture of angle-dependent radial emissivity distributions. Thus, both σ_{BLR} and, through the nonlinear dependence of $p(i)$ on N_0 , C_{BLR} can influence the predicted wing shape, although the dependence on C_{BLR} becomes weak at small covering factors. Nevertheless, we fix both at representative values (Section 5) and vary only α and f_{vir} when fitting the observed profiles. The same fixed values of C_{BLR} and σ_{BLR} are then reused to predict how the total $\text{H}\alpha$ EW varies with i_{obs} in Section 5.

Assuming gravitationally dominated motion, the characteristic Keplerian velocity is

$$v_K(r) = \left(\frac{GM_{\text{BH}}}{r} \right)^{1/2}. \quad (8)$$

In the phenomenological fits considered here, we parameterize the local line-of-sight velocity distribution as a Gaussian with dispersion

$$\sigma(r) = f_{\text{vir}} v_K(r), \quad (9)$$

where the dimensionless velocity-scale parameter f_{vir} absorbs geometric and kinematic factors, as well as source-to-source differences in black-hole mass relative to the adopted value. Because the profile width scales as $f_{\text{vir}} M_{\text{BH}}^{1/2}$, these effects are degenerate in the present model. Any inclination dependence is also absorbed into f_{vir} ; if an ordered in-plane component were modeled explicitly, its projected velocity would scale as $\sin i_{\text{obs}}$.

The inner BLR therefore contributes the high-velocity tails, while larger radii supply the low-velocity core. In this way, a continuous radial distribution of virialized clouds can generate broad exponential-like wings without requiring scattering to dominate the profile, as detailed in the next section. This interpretation also naturally allows different emission lines to have different profiles. As we shall see, higher-ionization lines are weighted toward smaller radii and, therefore, acquire broader profiles than the Balmer lines. Such line-dependent widths are not naturally expected if a single scattering medium dominates the broadening, but arise straightforwardly in a stratified BLR. More generally, BLR stratification is already a standard ingredient in AGN physics, supported by reverberation-mapping studies showing that higher-ionization lines are emitted closer to the black hole than the Balmer lines (e.g., Peterson 1993; Pancoast et al. 2014; Grier et al. 2017; Fausnaugh et al. 2017; Netzer 2020). Our model therefore does not invoke a new or exotic component, but rather applies a structure already known to be present in AGNs.

3. Line profiles of LRDs

To illustrate the implications of our stratified BLR framework, we construct detailed line-profile models for three representative JWST broad-line AGNs: GN-68797, GN-9771, and GS-13971. All three are LRDs with deep NIRSpec grating spectroscopy and are included in the recent line-profile analysis of Scholtz et al. (2026), where they are classified as absorbed LRDs. Their spectroscopic redshifts are $z = 5.04, 5.53$, and 5.48 , respectively. In the Matthee et al. (2026) sample, the total $\text{H}\alpha$ rest-frame

equivalent widths inferred from the PRISM spectra are $1306 \text{ \AA}$ for GN-68797, $1713 \text{ \AA}$ for GN-9771, and $894 \text{ \AA}$ for GS-13971, confirming that all three are strong Balmer emitters within the broader JWST broad-line population.

We generated grids of photoionization models with the C23 release of CLOUDY (Chatzikos et al. 2023), tailored to typical BLR conditions with hydrogen density $n_{\text{H}} = 10^{10} \text{ cm}^{-3}$ and column density $N_{\text{H}} = 10^{23} \text{ cm}^{-2}$. We adopted a metallicity $Z = 0.1 Z_{\odot}$, representative of galaxies at the redshifts where LRDs (and LBDs) are most commonly found¹, and explored a grid of ionization parameters $-4 \leq \log U \leq +1.5$ in steps of 0.5 dex. For the line-profile calculations, we adopt a fiducial central engine with $M_{\text{BH}} = 10^{7.5} M_{\odot}$ and $\dot{m} = 32$, thereby fixing the angle-dependent ionizing photon rate $Q_{\text{HI}}(i)$ incident on BLR clouds at polar angle i . Each value of U maps to a characteristic BLR radius through

$$r(U, i) = \left[\frac{Q_{\text{HI}}(i)}{4\pi c n_{\text{H}} U} \right]^{1/2}. \quad (10)$$

We use this mapping to assign the Cloudy line intensity calculated at each U to the corresponding radius. The profile integral is then evaluated directly in radial space, with the cloud population weighted by dN/dr .

For the profile fits, we normalize both the observed spectrum and the model to the peak flux density of the observed total $\text{H}\alpha$ profile. The BLR covering factor C_{BLR} and angular thickness σ_{BLR} are fixed to representative values following the equivalent-width analysis of Madau & Maiolino (2026). The radial stratification parameter α and the dimensionless velocity-scale parameter f_{vir} are varied in the fits. Because these parameters are strongly degenerate, unconstrained minimization can drive f_{vir} far from unity for only a marginal reduction in χ^2 . We therefore restrict f_{vir} to within 40% of unity ($0.6 \leq f_{\text{vir}} \leq 1.4$), selecting solutions whose characteristic velocities remain comparable to the Keplerian value adopted in the model. For smooth profile construction, the CLOUDY $\text{H}\alpha$ line powers are log-linearly interpolated across the sampled $\log U$ grid. In GN-68797 and GS-13971, the absorption profile, narrow $\text{H}\alpha$ component, and continuum are fixed to the published line-profile decomposition of Scholtz et al. (2026). For GN-9771, we adopt a two-step procedure: first, we fit the full profile with the stratified BLR multiplied by a free absorption component and a free narrow Gaussian, then fix the resulting narrow and absorption profiles, and refit only the red wing to determine the final BLR parameters. Because in all three objects the blue side of the line is affected by absorption, we fit only the red wing over the velocity interval $300 < v < 4000 \text{ km s}^{-1}$. We exclude the innermost $|v| < 300 \text{ km s}^{-1}$ around the line center because that part of the profile is most sensitive to uncertainties in the systemic velocity, the fixed narrow-line decomposition, and the absorption-related core structure. This allows the fit to focus on the velocity range that most directly traces the stratified BLR responsible for the extended wings. We then add the stratified broad-line component and compare the resulting normalized model profiles directly to the data.

Figure 1 shows the best-fit stratified BLR model for the LRD GN-68797. Despite the simplicity of the model, the agreement with the data is excellent: the broad exponential-like wings, the

¹ While the $\text{H}\alpha$ emissivity is less sensitive to metallicity than metal-line diagnostics, changing Z modifies the thermal balance, ionization structure, and diffuse continuum of the BLR gas, and therefore can affect both the $\text{H}\alpha$ line power and its EW at a moderate level.

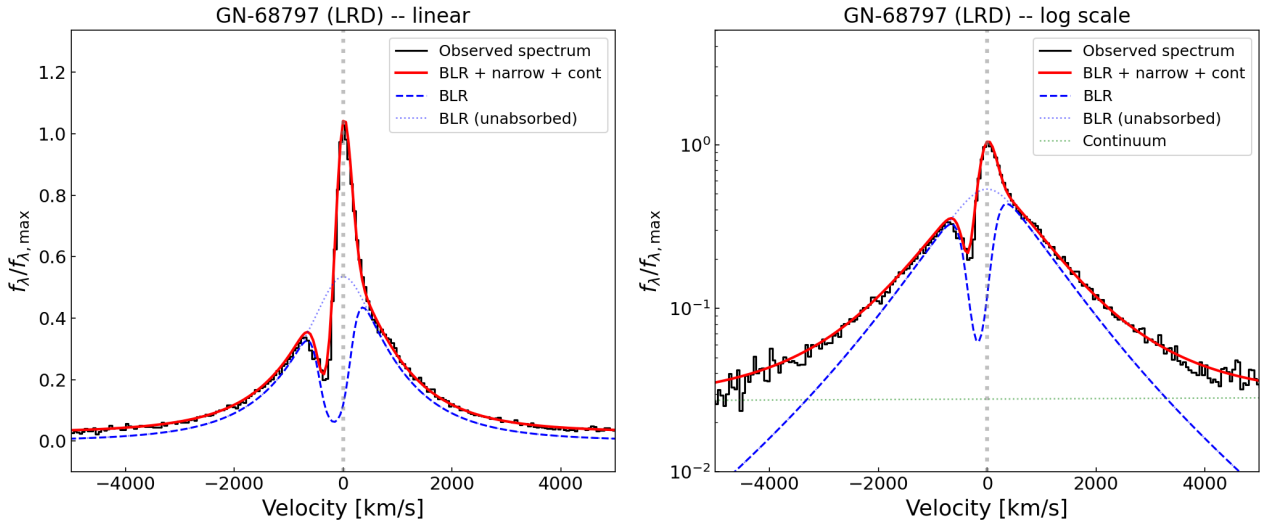


Fig. 1. Best-fit stratified-BLR model for the LRD GN-68797. Left: linear-scale view of the observed H α profile (black) and best-fit model (red), obtained by fitting only the red wing of the line. The blue dashed curve shows the absorbed broad stratified BLR component, while the dotted blue curve shows the corresponding unabsorbed BLR profile; the difference between the two illustrates the effect of the fixed absorption profile adopted from the published line-profile decomposition (Scholtz et al. 2026). Right: the same comparison on a logarithmic scale, highlighting the extended, nearly exponential wings. The fit is obtained for a reduced chi-square of $\chi^2/\text{d.o.f.} = 1.8$, with $\alpha = 1.75$ and $f_{\text{vir}} = 1.2$, assuming $r_{\text{sub}} = 7.2 \times 10^{18}$ cm. The model reproduces the broad wings and the overall profile shape, supporting an interpretation in which the extended wings arise from the superposition of virialized clouds spanning a range of radii, while the suppressed core is shaped by line-of-sight absorption and the fixed narrow H α component.

suppressed core, and the overall shape of the observed profile are all reproduced well. Fitting only the red wing, we obtain a best-fit with a reduced chi-square of $\chi^2/\text{d.o.f.} = 1.8$, radial-slope parameter $\alpha = 1.75$, and effective virial factor $f_{\text{vir}} = 1.2$, adopting a sublimation radius of $r_{\text{sub}} = 7.2 \times 10^{18}$ cm. Since the cloud distribution per logarithmic radial interval peaks at $r = \alpha r_{\text{sub}}$, this places the bulk of the cloud population moderately outside the dust-sublimation radius, rather than at or dominated by the innermost BLR. At the same time, inner clouds still make a disproportionate contribution to the highest-velocity tails, since the local velocity width scales as $v_K \propto r^{-1/2}$. The broad, nearly exponential wings therefore arise naturally from the superposition of virialized clouds spanning a range of radii, rather than from a single characteristic emitting radius.

This interpretation is qualitatively consistent with the stratified BLR picture inferred in low-redshift AGNs from reverberation mapping and velocity-resolved broad-line studies, which indicate that different parts of the line profile probe gas spanning a range of radii and exhibiting distinct kinematic signatures, including virialized motion, inflow, and outflow (e.g., Peterson 1993; Pancoast et al. 2014; Grier et al. 2017; Netzer 2020), and with the idea that the low-ionization BLR is associated with the region where the outer accretion disk merges into the inner edge of the dusty torus (Goad et al. 2012). The parameter $f_{\text{vir}} = 1.2$ indicates that the effective one-dimensional velocity width required by the fit is somewhat larger than the fiducial virial scaling, absorbing both geometric and kinematic effects as well as any mismatch between the adopted fiducial black-hole mass, $M_{\text{BH}} = 10^{7.5} M_{\odot}$, and the true mass of the source.

Similar results are obtained for the LRDs GS-13971 and GN-9771, whose line-profile decompositions are shown in Figures 2 and 3. In both cases, the agreement between the data and the stratified BLR model is excellent. For GS-13971 we obtain a best fit with reduced chi-square $\chi^2/\text{d.o.f.} = 1.0$, $\alpha = 1.75$, and $f_{\text{vir}} = 0.94$, while for GN-9771 we find $\chi^2/\text{d.o.f.} = 1.4$, $\alpha = 1.75$,

and $f_{\text{vir}} = 1.3$. As in GN-68797, the model reproduces the extended, nearly exponential wings of the other sources. The best-fit radial slopes for all three LRDs, while nearly identical, are degenerate: the χ^2 surface is nearly flat over a wide range of α (GS-13971), or exhibits a shallow secondary minimum tied with a lower value (GN-68797, GN-9771). As for GN-68797, most clouds again reside at radii on the order of the dust-sublimation scale, with the innermost clouds still dominating the high-velocity tails. Thus, the comparable broad-line morphologies arise from a similar balance between outer-BLR weighting and inner-BLR kinematic broadening, without requiring a universal radial slope.

4. The LBD GS-3073

We extend our analysis to GS-3073, “Blue Rosetta,” a compact LBD at $z = 5.55$ originally presented by Übler et al. (2023) and subsequently studied in detail by Brazzini et al. (2026) and Scholtz et al. (2026). Unlike the absorbed LRDs considered above, GS-3073 has a blue optical and UV continuum and shows no detected Balmer absorption, but its broad H α line exhibits prominent non-Gaussian wings. Scholtz et al. (2026) identify an exponential profile as the preferred empirical description of H α , making GS-3073 a useful test of whether the same stratified-BLR interpretation extends beyond the LRD population. More importantly, the detection of broad HeII $\lambda 4686$ provides a direct test of ionization stratification: if the higher-ionization line originates closer to the black hole, it should exhibit larger characteristic velocities than H α .

For GS-3073 we adopt the same stratified BLR framework, embedding it in the fuller multicomponent decomposition of the H α complex presented by Scholtz et al. (2026) and Brazzini et al. (2026). Their model resolves H α into a narrow component, the [N II] $\lambda\lambda 6548, 6583$ doublet (fixed to the theoretical

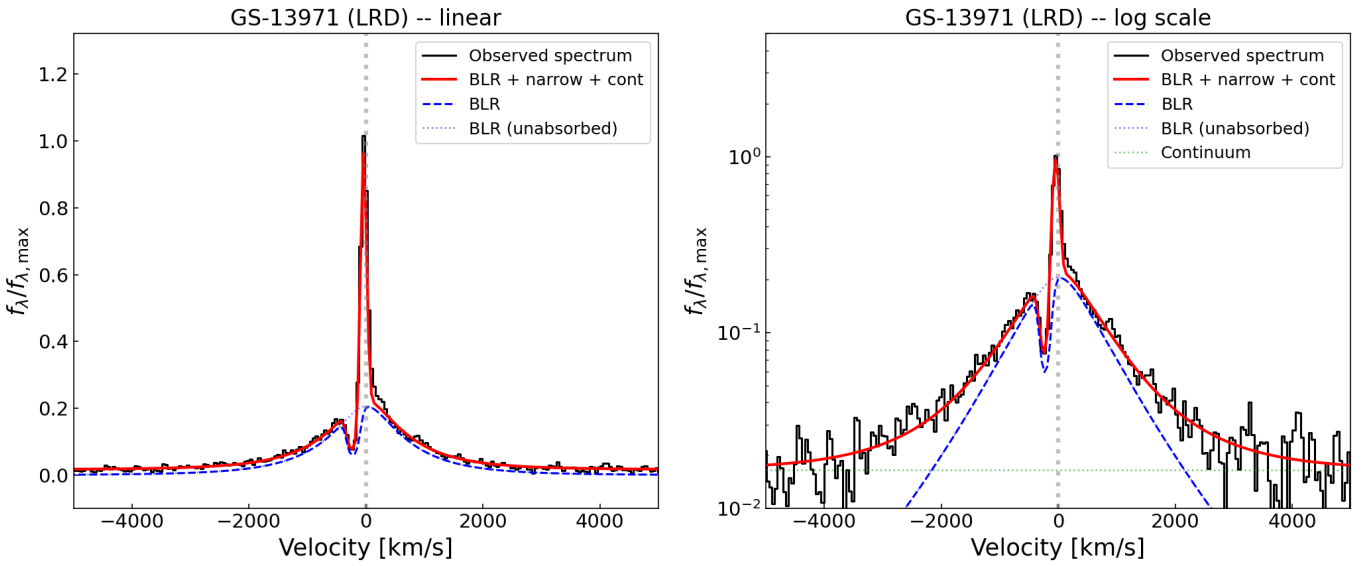


Fig. 2. Best-fit stratified-BLR model for the LRD GS-13971. Left: linear-scale view of the observed H α profile (black) and best-fit model (red), again fitting only the red wing of the line. The dashed blue curve shows the absorbed broad stratified BLR component and the dotted blue curve the corresponding unabsorbed BLR profile, illustrating the effect of the fixed absorption component adopted from the published decomposition. Right: the same comparison on a logarithmic scale, emphasizing the extended wings. The best fit is obtained for a reduced chi-square of $\chi^2/\text{d.o.f.} = 1.0$, with $\alpha = 1.75$ and $f_{\text{vir}} = 0.94$, adopting the same fiducial sublimation radius.

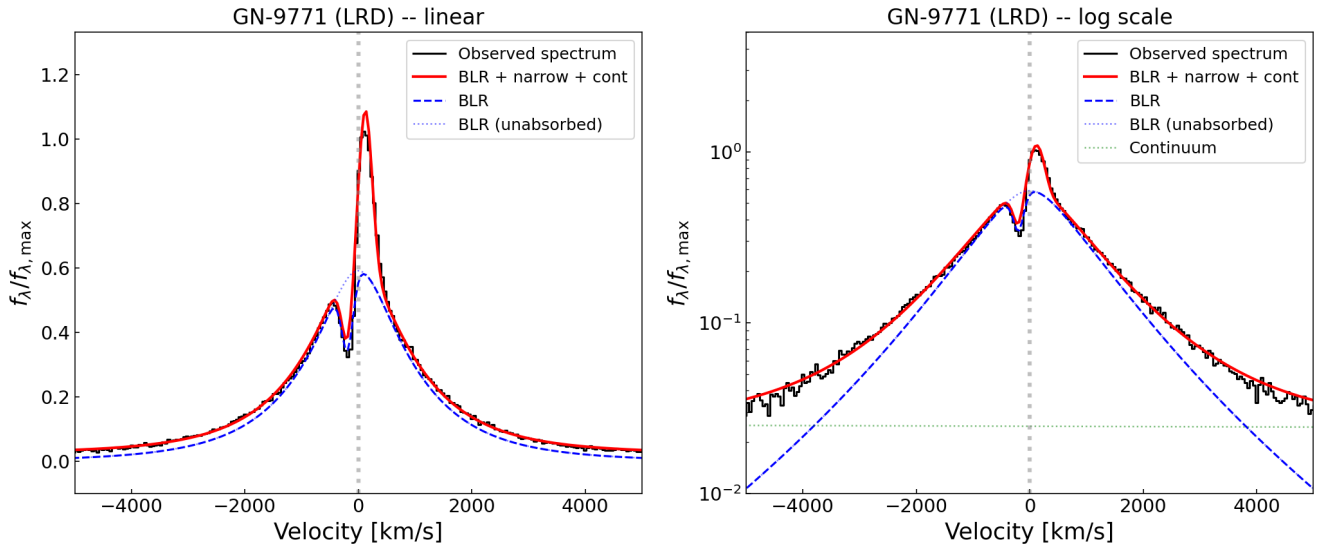


Fig. 3. Best-fit stratified-BLR model for the LRD GN-9771. Left: linear-scale view of the observed H α profile (black) and best-fit model (red), again fitting only the red wing of the line. The dashed blue curve shows the absorbed broad stratified BLR component and the dotted blue curve the corresponding unabsorbed BLR profile, illustrating the effect of the absorption component determined from the full-profile fit (see text). Right: the same comparison on a logarithmic scale, emphasizing the extended wings. The best fit is obtained for a reduced chi-square of $\chi^2/\text{d.o.f.} = 1.4$, with $\alpha = 1.75$ and $f_{\text{vir}} = 1.3$, adopting the same fiducial sublimation radius. As for GN-68797 and GS-13971, the model provides an excellent description of the broad, nearly exponential wings, indicating that a radially stratified BLR weighted toward large radii can account naturally for the observed line profile.

3:1 ratio), a blueshifted outflow component, and a broad component described empirically by an exponential, scattering-wing profile; every component except the broad one is a simple Gaussian. Rather than adopt the published narrow, [N II], and outflow amplitudes as fixed, we retain their centroids and widths but refit their amplitudes as free linear scale factors simultaneously with the stratified BLR component, so that any mismatch between our flux calibration and the published decomposition is absorbed

by these nuisance parameters rather than propagating into the wing residuals that constrain the BLR fit. The empirical broad-H α exponential is replaced entirely by our stratified BLR profile, built from the same Cloudy photoionization grid and Keplerian velocity field used above (Figure 4).

Because the extended red and blue wings constrain the BLR shape parameters here, and because α and f_{vir} are, as before, degenerate, we calibrate $f_{\text{vir}}(\alpha)$ analytically rather than fitting it

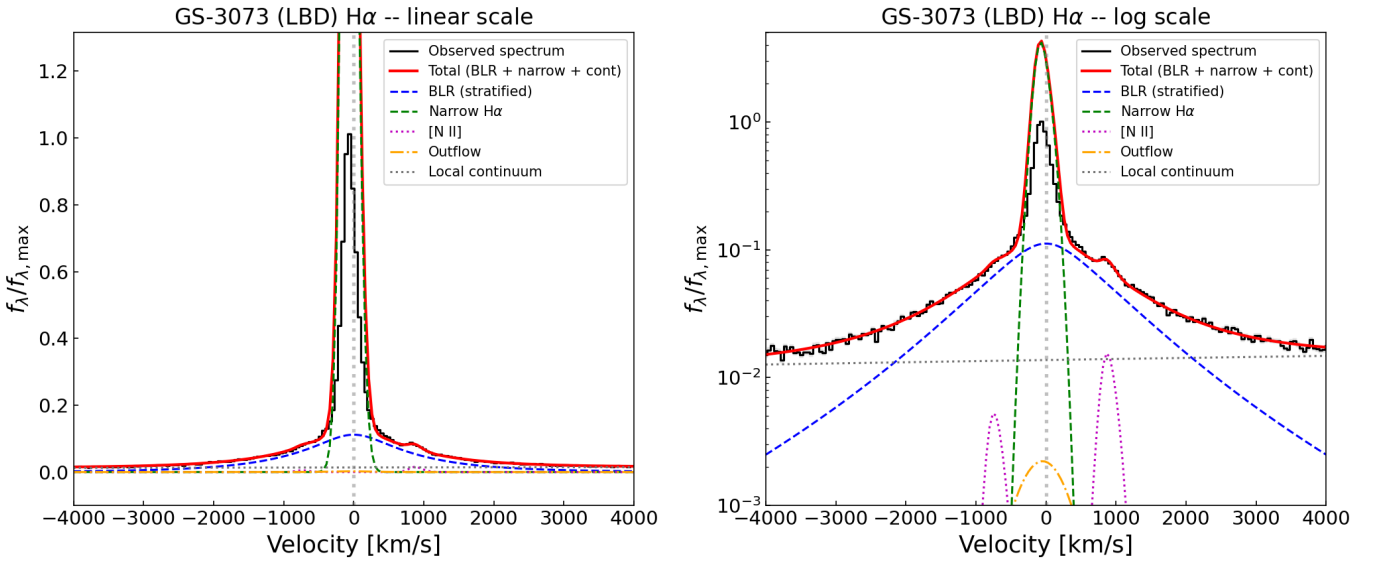


Fig. 4. Best-fit stratified-BLR model for the LBD GS-3073. Left: linear-scale view of the observed H α profile (black) and best-fit model (red), fitting both wings of the line. The stratified-BLR component is shown together with the refitted narrow H α , [N II], and outflow components; their sum gives the total model. Right: the same comparison on a logarithmic scale, emphasizing the extended wings. For the adopted solution, obtained using the prior on α motivated by the three LRDs, we find $\chi^2/\text{d.o.f.} = 4.1$, $\alpha = 1.75$, and $f_{\text{vir}} = 1.1$, adopting the same fiducial sublimation radius. The model captures the broad-wing morphology, although statistically significant residuals remain, likely associated with the complex narrow-line and outflow components.

freely: for each trial α , f_{vir} is set so that the velocity dispersion of model H α matches the observed value, $\sigma_{\text{H}\alpha} = 1550 \text{ km s}^{-1}$, exactly. We use the line dispersion σ rather than the full width at half maximum (FWHM) for this calibration, since FWHM is not a well-defined, comparable quantity for a profile built from the superposition of several differently-weighted Gaussian components, whereas the flux-weighted variance σ^2 remains additive and physically meaningful for the composite. With f_{vir} calibrated this way, α is the only remaining H α shape parameter. The H β and He II line widths can then be predicted conditionally on the adopted value of α , without introducing additional line-specific parameters.

The resulting $\chi^2(\alpha)$ curve is nearly flat, as found for the three LRDs, and therefore the H α profile of GS-3073 alone does not provide an independent constraint on α . We consequently adopt a Gaussian prior centered at $\alpha = 1.75$, with a dispersion of 0.25 corresponding to one grid step, motivated by the solutions obtained for GN-68797, GS-13971, and GN-9771. Including this prior yields an adopted solution with $\alpha = 1.75$ and $f_{\text{vir}} = 1.1$. Thus, the value of α is not independently constrained by GS-3073; rather, the H α profile demonstrates that the radial stratification inferred from the three LRDs is also consistent with this unabsorbed LBD.

For this prior-informed solution, calibrated to reproduce the observed H α line dispersion of $\sigma_{\text{H}\alpha} = 1550 \text{ km s}^{-1}$, the model predicts $\sigma_{\text{HeII}} = 2600 \text{ km s}^{-1}$, corresponding to $\sigma_{\text{HeII}}/\sigma_{\text{H}\alpha} = 1.7$. The predicted H β dispersion is 1880 km s^{-1} , or $\sigma_{\text{H}\beta}/\sigma_{\text{H}\alpha} = 1.2$. These are conditional predictions of the H α -calibrated model and do not require additional line-specific parameters. The model therefore predicts the observed sense of ionization stratification, with higher-ionization emission weighted toward smaller radii and larger characteristic velocities. However, quantitatively, the predicted width ratio of He II to H α remains below the value of $\sim 2.1 \pm 0.2$ implied by the observed dispersions. This shortfall persists across the full α scan: no value of α raises $\sigma_{\text{HeII}}/\sigma_{\text{H}\alpha}$

above ~ 1.7 – 1.8 , because the Cloudy He II emissivity turns over and declines at the highest ionization parameters sampled, while H α emissivity continues to rise. This caps how much additional weight the model can place on the innermost, highest-velocity shells specifically for He II, independent of the adopted radial slope.

Figure 5 shows the H α , H β , and He II profiles predicted by the prior-informed, H α -calibrated solution. The relative H β and He II widths do not require additional line-specific parameters. This is qualitatively consistent with reverberation-mapping studies, which generally find H α lags comparable to or somewhat longer than H β lags, i.e., H α emission weighted toward slightly larger BLR radii than H β , commonly attributed to differential optical depth through the Balmer series (e.g., Grier et al. 2017). A similar excess width of H β relative to H α , of marginal significance ($\sim 1.3\sigma$), has also been reported for the LRD GN-9771 ($\text{FWHM}_{\text{H}\beta} = 2180 \pm 490$ vs. $\text{FWHM}_{\text{H}\alpha} = 1549 \pm 5 \text{ km s}^{-1}$), one of our own comparison sources (Section 3) (Torralba et al. 2026). That work notes that this result sits in tension with a pure electron-scattering origin for the Balmer wings, which predicts equal FWHM for lines scattered within the same layer, but does not propose an alternative explanation for the discrepancy. The stratified-BLR framework adopted here offers one: a broader H β emerges as a natural, parameter-free consequence of the Cloudy emissivity of H β being weighted toward marginally smaller, faster-moving radii than those of H α .

5. Discussion and summary

So far, we have focused on fitting the shape of the broad H α profile. If the BLR is flattened and its kinematics are dominated by ordered in-plane motion, then the large line widths inferred here are naturally suggestive of high observer inclinations, since the projected velocity field increases approximately as $\sin i_{\text{obs}}$ (e.g., Peterson et al. 2004; Pancoast et al. 2014; Netzer 2020). It is then

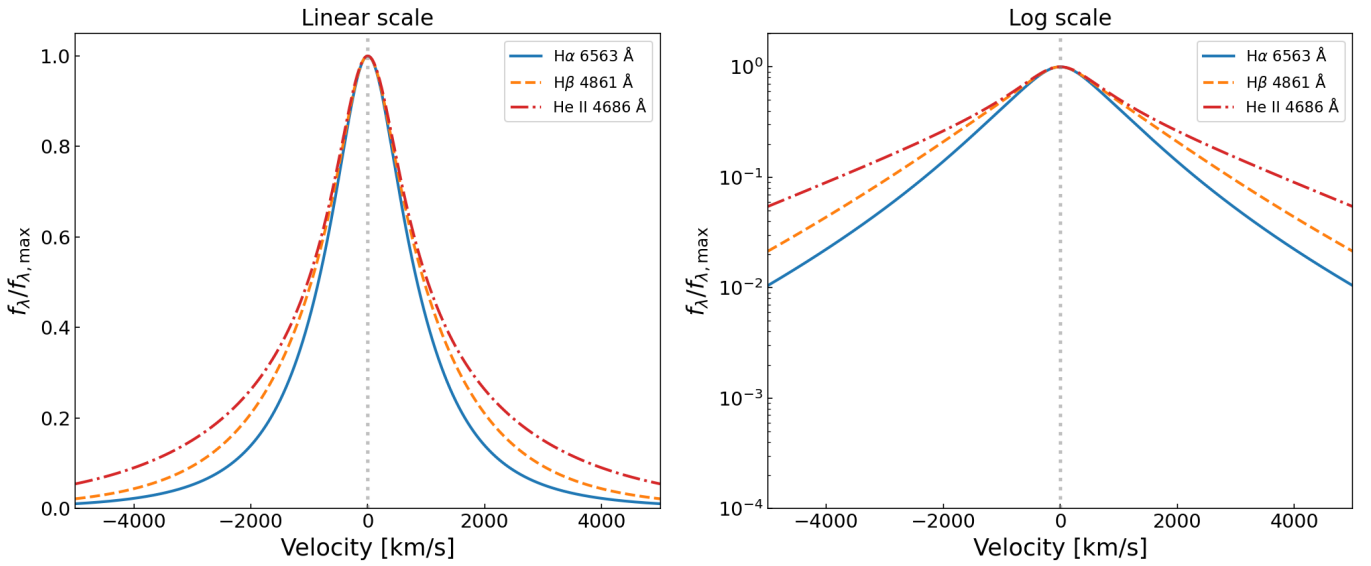


Fig. 5. Predicted broad-line profiles for H α , H β , and He II λ 4686 at the adopted stratified-BLR solution ($\alpha = 1.75$, $f_{\text{vir}} = 1.1$) of GS-3073. Left: linear scale; right: logarithmic scale, emphasizing the extended wings. All three profiles are computed from the same physical model and geometry constrained by the H α wing fit alone – conditional on the adopted α and the H α calibration, the relative widths and wing strengths of H β and He II are predicted without additional line-specific parameters, with progressively broader, more extended profiles reflecting the decreasing Cloudy emissivity-weighted characteristic radius with increasing ionization potential.

Table 1. Predicted H α equivalent widths as a function of observer inclination for the three LRDs.

i_{obs}	GN-68797			GS-13971			GN-9771		
	EW _{BLR} (Å)	EW _{NLR} (Å)	EW _{tot} (Å)	EW _{BLR} (Å)	EW _{NLR} (Å)	EW _{tot} (Å)	EW _{BLR} (Å)	EW _{NLR} (Å)	EW _{tot} (Å)
30°	153	41	194	153	35	188	153	5	158
50°	220	59	279	220	51	271	220	7	227
70°	436	117	553	436	100	537	436	15	451
75°	577	154	732	577	133	710	577	19	597
80°	829	221	1051	829	190	1020	829	28	857
85°	1379	368	1747	1379	317	1695	1379	46	1425
Observed	1306			894			1713		

Notes. The calculations adopt $\alpha = 1.75$, $C_{\text{BLR}} = 0.1$, and $\sigma_{\text{BLR}} = 0.2$. The narrow-to-broad H α flux ratios are fixed to those inferred from the line-profile decompositions. Because the same BLR parameters and fiducial central engine are adopted for all three sources, the predicted broad H α EW is identical across the three columns; the differences in total EW arise solely from the adopted narrow-to-broad flux ratios.

natural to ask whether the same stratified-BLR framework, supplemented by representative choices for the BLR covering factor and angular thickness, can also account for the large observed H α EWs of the three LRDs. To this end, we evaluate the inclination dependence of the broad-line EW within the same model adopted for the profile fitting.

In our model, the BLR is described by an equatorially concentrated cloud distribution with covering factor $C_{\text{BLR}} = 0.1$ and angular thickness $\sigma_{\text{BLR}} = 0.2$. A global covering factor of ≈ 0.1 is consistent with standard estimates for low- z Type 1 AGNs (e.g., Peterson 2006; Pandey et al. 2023, see also Madau & Maiolino 2026). This angular thickness implies a geometrically flattened BLR, in which the probability of intercepting clouds increases strongly toward the equatorial plane. The broad-line profile is produced by a radially stratified distribution of virialized clouds, while the observed EW depends on the inclination-dependent continuum against which the line is seen. We compute $\text{EW}(i_{\text{obs}})$ using the formalism of Madau & Maiolino (2026), in which

the broad-line and nebular continuum emission are treated as isotropic, while the direct and transmitted optical continuum increases toward lower observer inclinations. Because the direct continuum is progressively suppressed toward high inclinations, the model naturally predicts larger H α EWs for more edge-on sight lines (Madau 2026; Madau & Maiolino 2026).

This trend is borne out by the calculations. Table 1 shows the predicted broad, narrow, and total H α equivalent widths for a representative set of observer inclinations. For all three LRDs, the total EW increases steeply toward equatorial sight lines, reaching values comparable to those observed only for $i_{\text{obs}} \gtrsim 80^\circ$. This provides an independent consistency check on the high-inclination interpretation suggested by the profile fitting and by the red continua of these sources. For the best-fit value $\alpha = 1.75$, the broad H α EW rises from only ~ 150 Å for nearly polar sight lines to ~ 580 Å at 75° and ~ 1380 Å at 85° . The observed total EWs of the three LRDs therefore fall naturally within the range expected for highly inclined observers. At

fixed angular thickness, the predicted EW increases with BLR covering factor, so somewhat lower inclinations could in principle reproduce the observed values if C_{BLR} were larger than the representative value adopted here. Nevertheless, for a modest covering factor and a strongly equatorial angular distribution, the observed $\text{H}\alpha$ EWs are naturally matched only at high inclinations, consistent with the interpretation suggested independently by the red continua and absorption features.

The profile fitting leads to a similarly coherent picture. All three LRDs are well reproduced with the same radial slope $\alpha = 1.75$, indicating that the cloud distribution is concentrated near the dust sublimation radius, while the inner BLR still supplies the highest-velocity tails through the virial scaling $v_K \propto r^{-1/2}$. Although in principle α is partially degenerate with the adopted fiducial black-hole mass², in practice the three LRDs all converge to the same best-fit value, $\alpha \approx 1.75$, whereas the source-to-source differences are captured mainly by f_{vir} . This suggests that the preferred radial stratification is a stable feature of the fits. The fitted values of the effective virial parameter provide an additional consistency check. For GN-68797 and GN-9771 we obtain $f_{\text{vir}} = 1.2$ and $f_{\text{vir}} = 1.3$, respectively, while for GS-13971 we find $f_{\text{vir}} \approx 0.94$. Thus, in one source, the fiducial virial scaling is already sufficient, whereas in the other two a modest upward correction is required, plausibly reflecting a combination of geometry, kinematics, and the fact that the true black-hole mass may exceed the reference value adopted in the model.

The LBD GS-3073 extends this picture to a physically distinct regime. Unlike the three absorbed LRDs, GS-3073 shows a blue optical/UV continuum and no detected Balmer absorption, yet its broad $\text{H}\alpha$ wings are equally well described by the same stratified-BLR framework, and the adopted, prior-informed radial slope – based on the $\alpha = 1.75$ solutions for GN-68797, GS-13971, and GN-9771 (Section 3) – is fully consistent with the value preferred by the three LRDs in isolation. Because α and f_{vir} are strongly degenerate – including within GS-3073’s own $\chi^2(\alpha)$ curve – its $\text{H}\alpha$ profile alone cannot independently confirm $\alpha = 1.75$; the value is adopted via the external prior, not derived from GS-3073 in isolation. What its data show is that $\alpha = 1.75$ is not excluded: it falls within the flat, near-degenerate region of the $\chi^2(\alpha)$ curve ($\chi^2/\text{dof} \approx 4$), statistically indistinguishable from the formal minimum. That a single slope is at least consistent with four sources spanning both the absorbed LRD and unabsorbed LBD classes is compatible with the stratification being a property of the BLR itself, though given the degeneracy, this is a consistency argument, not an independent confirmation.

GS-3073 additionally offers a test unavailable for the three LRDs, since it has a detected broad He II $\lambda 4686$ line: the same $\alpha = 1.75$, $f_{\text{vir}} = 1.1$ solution predicts $\sigma_{\text{HeII}}/\sigma_{\text{H}\alpha} = 1.7$ and $\sigma_{\text{H}\beta}/\sigma_{\text{H}\alpha} = 1.2$, both in the sense expected from ionization stratification – higher-ionization, more centrally-weighted lines being kinematically broader – though the He II ratio falls slightly short of the value ($\sim 2.1 \pm 0.2$) implied if the observed dispersions are taken at face value (Section 4). We regard this as a genuine and falsifiable limitation of the single-population, uniform-density radial model rather than a failure of the overall picture, since the same architecture reproduces the $\text{H}\alpha$ wings, the common radial slope, and the correct sense of the He II and $\text{H}\beta$ stratification without additional line-specific parameters. GS-3073’s

blue continuum and the lack of Balmer absorption are also naturally accommodated within the same equatorial-wind geometry invoked below for the three LRDs: if the absorbing and red-denning material is concentrated toward the equatorial plane, a source viewed at lower inclination – away from the densest wind streamlines – would be expected to show both a bluer continuum and weaker or absent Balmer absorption, exactly as observed for GS-3073, without requiring a different underlying BLR or wind structure.

Our results therefore support the following picture. A BLR with moderate covering factor, strong equatorial concentration, and radial stratification can simultaneously account for three otherwise puzzling features of LRDs: very large Balmer equivalent widths, broad exponential wings, and absorption-distorted cores. Within this framework, the large $\text{H}\alpha$ EWs do not require unusually large covering factors but naturally follow super-Eddington SEDs that provide a higher ionizing-to-optical photon budget than standard quasar composites, thereby boosting the intrinsic line-to-continuum ratio. Likewise, the broad wings need not be attributed primarily to Thomson scattering but emerge from the radial superposition of virialized clouds. This does not exclude a minor contribution from electron scattering, which may well operate in the dense inner regions of these systems, but rather shows that it is not required as the dominant mechanism shaping the wings.

The blueshifted absorption troughs detected in all three LRDs are consistent with a P-Cygni interpretation, in which the absorbing gas has a net outflow component along the observer’s line of sight. In super-Eddington accretion flows, radiatively driven material launched from the disk surface (e.g., Murray et al. 1995; Proga & Kallman 2004) could naturally produce such blueshifted absorption. The absorber must lie at radii comparable to or larger than the BLR, since it imprints on the broad $\text{H}\alpha$ profile rather than on the continuum alone. Because the densest wind streamlines are concentrated near the equatorial plane, they are preferentially intercepted by high-inclination LRD sight lines, whereas lower-inclination LBD sight lines – including GS-3073, as noted above – cross a much smaller absorbing column, naturally accounting for the much weaker incidence of Balmer absorption in LBDs.

The fraction of little dots with genuinely exponential wings also merits comment in light of our results. Scholtz et al. (2026) find no statistical preference for an exponential profile in $\sim 60\%$ of their 32-object sample, with Lorentzian or multi-Gaussian models providing equally good or better fits, and note that LRDs specifically favor Lorentzian profiles more often than LBDs do. This is naturally accommodated within our stratified-BLR picture: a superposition of virialized clouds spanning a range of radii generically produces extended, non-Gaussian wings, but the precise functional form – exponential, Lorentzian, or some intermediate shape – depends on the detailed radial weighting of cloud number and emissivity, rather than being a fixed prediction of the model. The absence of a strictly exponential wing in a given source therefore does not argue against BLR stratification as the broadening mechanism; it simply reflects a different realization of the same underlying radial cloud distribution.

Although our stratified-BLR model does not by itself predict a one-to-one relation between the strength of the Balmer break and exponential-wing prominence (Matthee et al. 2026), a qualitative connection is natural: if stronger Balmer breaks trace a larger column of dense circumnuclear gas, they may also correspond to a larger effective BLR covering factor and/or a larger mass of BLR clouds along equatorial sight lines. The resulting increase in the number of virialized kinematic

² For a larger adopted M_{BH} , the virial velocities increase at all radii, which could be partially compensated for by a larger α that shifts more weight toward the lower-velocity outer BLR; conversely, a smaller M_{BH} would favor a flatter radial distribution.

components contributing to the integrated profile would enhance the prominence of the nearly exponential wings. However, this qualitative connection should be viewed in the context of the current observational uncertainty, since the relation between stronger Balmer breaks and more prominent exponential wings reported by Matthee et al. (2026) was not confirmed by Scholtz et al. (2026). The three LRDs studied here, together with the LBD GS-3073, are consistent with a picture in which stratified BLRs viewed at high inclination can account for both the broad exponential wings and the large Balmer equivalent widths, while lower-inclination sight lines through the same underlying structure naturally account for unabsorbed blue-continuum sources like GS-3073, providing a simple and physically plausible explanation for at least part of the LRD phenomenon.

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