









The Structure and Evolution of LRDs: Insights from JWST NIRSpec Medium and High Resolution Spectroscopy at $z \sim 4$

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ABSTRACT

We present an analysis of medium/high-resolution JWST/NIRSpec spectra for 11 LRDs at $z \sim 4$. By decomposing the broad and narrow components of the Balmer emission lines, we investigate the connection between line emission and UV/optical continua for the LRD population. We find that the broad H α luminosity strongly correlates with the optical continuum (but not with the UV), indicating a common AGN origin for both. In contrast, the [O III] line strength is correlated with the UV continuum rather than the optical. Using the width and luminosity of the broad H α line, we estimate central black hole masses of 10^6 – $10^8 M_{\odot}$ accreting at high Eddington ratios ($\lambda_{\text{Edd}} \sim 0.6$), consistent with an early, rapid-growth phase of AGN evolution. Assuming a constant mass accretion rate in the framework of slim-disk models, we infer growth timescales of $\sim 10^5$ – 10^7 yr, and suggest LRDs may evolve into narrow-line Seyfert 1 galaxies. Upper limits from our spectra indicate that LRDs exhibit intrinsically weak optical Fe II emission compared to typical AGN. To simultaneously account for the inferred broad-line region size and observed luminosity, we propose a “Clumpy Envelope” model in which the optical emission arises from an extended, clumpy gas with a characteristic radius of tens of light-days. The diversity in observed optical continuum shapes can be explained by radial temperature gradients and self-absorption effects within this structure. Our results demonstrate the power of JWST high-resolution spectroscopy in probing the central engines and physical nature of the LRD population.

Keywords: Active galactic nuclei(16) — Supermassive black holes(1663) — Galaxy evolution(594) — James Webb Space Telescope (2291)

1. INTRODUCTION

Little Red Dots (LRDs) are a class of luminous, high-redshift objects and represent one of the most significant discoveries of the early years of JWST operations. Their high number density, particularly in the high-redshift

universe (e.g. Matthee et al. 2024; Kocevski et al. 2025), suggests potential effects on supermassive black hole and galaxy co-evolution. Furthermore, statistical analysis of LRDs may help to refine our understanding of the black hole seed formation process (Taylor et al. 2025a; Jiang et al. 2026).

Observationally, LRDs exhibit distinctive characteristics in the optical to near-infrared bands. Their defining properties include: 1) a distinctive “V-shaped” continuum, characterized by a blue UV slope and an apparent change in slope near the Balmer break (Setton et al. 2025a; Akins et al. 2025a); 2) a compact morphol-

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ogy, unresolved by JWST at least by NIRCcam long-wavelength channels, implying sizes of $\lesssim 100$ pc (Kokorev et al. 2024a; Yanagisawa et al. 2026); 3) broad hydrogen and helium emission lines with widths of larger than several thousand km s^{-1} (Greene et al. 2024; Matthee et al. 2024; Juodžbalis et al. 2026); and 4) a high incidence of red- and blue-shifted Balmer and He I absorption features (Juodžbalis et al. 2024a; Lin et al. 2024; Kocevski et al. 2025).

The intrinsic physical origin of the LRD spectral energy distribution (SED) has been extensively debated due to the high degeneracy between active galactic nuclei (AGN) and stellar components. Initial interpretations proposed LRDs as either dust-reddened AGN (e.g., Matthee et al. 2024; Labbe et al. 2025; Kocevski et al. 2025) motivated by the discovery of broad Balmer lines in a high fraction of LRDs (e.g., Greene et al. 2024; Hviding et al. 2025), or massive post-starburst or dusty star-forming galaxies (e.g., Labbé et al. 2023; Pérez-González et al. 2024; Wang et al. 2024; Baggen et al. 2024), due to the frequent detection of Balmer breaks (Setton et al. 2025a). However, with expanding LRD samples and multi-wavelength follow-up observations, both models face significant challenges. The dusty AGN model fails to explain the general lack of mid- to far-infrared emission from cold and hot dust (e.g., Casey et al. 2024, 2025; Akins et al. 2025a; Setton et al. 2025b; Xiao et al. 2025), as well as the weakness of X-ray and radio emission expected from typical AGN (e.g., Yue et al. 2024a; Ananna et al. 2024; Maiolino et al. 2025; Mazzolari et al. 2024; Gloude-mans et al. 2025). Conversely, purely stellar models struggle to reproduce the SEDs of the most extreme LRDs discovered to date (de Graaff et al. 2025a; Naidu et al. 2025).

A promising alternative model interprets LRDs as rapidly accreting SMBHs embedded within dense, ionized gaseous envelopes (Rusakov et al. 2025; Inayoshi & Maiolino 2025; Naidu et al. 2025). This “gas shell” framework can simultaneously account for several puzzling features, including the Balmer absorption lines, unusually large Balmer decrements, deep Balmer breaks, the large equivalent widths (EW) of $\text{H}\alpha$ emission, and the possible exponential profiles of broad-line components (e.g., Juodžbalis et al. 2024a; Lin et al. 2024; Ji et al. 2025; de Graaff et al. 2025a). While the existence of the dense gas component is now widely accepted, the functions of that component are different among models. The model of Liu et al. (2025) explained the observed continuum SEDs by super-Eddington accreting black holes within massive envelopes. Theoretical work leveraging the “quasistar” concept posits that LRDs may represent a stable evolutionary phase last-

ing tens of millions of years when radiation pressure could support the gas around the black hole (Begelman & Dexter 2026; Inayoshi et al. 2025), with their red optical spectra arising from an optically thick photosphere with temperatures of 5000–7000 K and radius of $\sim 10^3$ AU, analogous to stars near the Hayashi limit (Kido et al. 2025). Recently, updated non-spherical “cocoon” models have been proposed to explain both the continuum and emission-line shapes through detailed radiative transfer (Sneppen et al. 2026).

Although the models above could explain most of the observation features, key open questions remain on the structure of the gas (e.g., the location of broad-line regions (BLRs), the total size of the structure) and the properties of the central engines (e.g., normal AGN accretion or quasistars). To address these questions, recent studies have begun mapping the parameter space, including emission-line and continuum properties (e.g., de Graaff et al. 2025b; Barro et al. 2025; Asada et al. 2026). de Graaff et al. (2025b) suggest a correlation between Balmer decrement, total luminosity of $\text{H}\alpha$ emission line, and continuum luminosity of 5100 Å. High [O III] EWs and the relations between [O III] and UV magnitude are also reported. Moreover, the modified blackbody fitting shows the diversity of the LRD optical continuum. Barro et al. (2025) focuses more on the continuum correlations between UV and optical bands and proposed evolution progresses of LRDs on the schematic diagram. However, these analyses only used low-resolution NIRSpec/prism spectra, which limit the ability to decompose broad and narrow emission-line components accurately. Besides, while LRDs are increasingly viewed as a new class of AGN, their precise relationship to classical AGN remains an open and challenging topic.

In this paper, we advance the understanding of LRDs by analyzing JWST NIRSpec medium/high-resolution spectra. We decompose the broad and narrow components of Balmer lines to investigate the correlations between line luminosity and the UV/optical continuum. This allows us to place new observational constraints on LRD models. Furthermore, we examine the location and potential evolutionary trajectories of LRDs on traditional AGN diagnostic diagrams, using physical properties derived from the broad $\text{H}\alpha$ component. The paper is structured as follows: Section 2 describes the sample and data. Section 3 details the spectral fitting methodology. Section 4 presents the main results of our work. Section 5 discusses the systematic uncertainties in black hole mass estimation, examines the black hole mass to stellar mass relation, and proposes a thicker gas envelope model to explain the diversity of optical continuum shapes. Section 6 summarizes our conclusions.

Throughout this work, we assume a Λ CDM cosmology with parameters $\Omega_m = 0.30$, $\Omega_\Lambda = 0.7$ and $h_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. DATA AND SAMPLE

2.1. Data

We utilize all publicly available NIRSpec MSA spectra from version 4.4 of the DAWN JWST Archive (DJA; Brammer & Valentino 2023). The spectra were reduced using `msaexp` (Brammer 2023), largely following the methodology outlined in Heintz et al. (2025) and de Graaff et al. (2025c), with local background subtraction performed on nodded exposures where possible.

To further decompose the broad and narrow emission-line components, we carry out a detailed analysis using medium- and high-resolution NIRSpec spectra. These include data obtained with the G140M, G235M/H, and G395M/H gratings/filters from the RUBIES (de Graaff et al. 2025a), JADES (Eisenstein et al. 2023; Curtis-Lake et al. 2025; Scholtz et al. 2025), and NIRSpec GTO-Wide (Maseda et al. 2024).

2.2. Sample

We adopt the LRD catalog from de Graaff et al. (2025b) for further analysis of related properties which contains 116 LRDs. Briefly, de Graaff et al. (2025b) conducted a comprehensive selection of LRD sources using prism spectra from multiple programs and performed careful analysis of spectral line and continuum properties through fitting of UV/optical continua and emission lines. To ensure that each source has a well-defined optical continuum shape and to obtain a more robust constraint on its optical luminosity, we require that the peak flux density in the rest-frame optical band is clearly detected in the prism spectra from the de Graaff et al. (2025b) catalog, which is related to a $z \lesssim 4$ for a blackbody with 5000 K. To further separate the broad and narrow emission-line components, we cross-match their sample with all DJA datasets that contain medium or high-resolution observations of $\text{H}\alpha$ emission line with peak signal-to-noise ratio (SNR) larger than 3. This yields 13 individual sources, among which 2 show no significant broad component (full width at half maximum, $\text{FWHM} > 600 \text{ km/s}$) in their $\text{H}\alpha$ emission lines (See details of the fitting method in the Section 3). Of the remaining 11 sources, four also have medium-resolution observations covering the spectral region around $\text{H}\beta$ and [O III], three of which have a broad component in the $\text{H}\beta$ emission line. Compared to the parent sample of 116 LRDs from de Graaff et al. (2025b), our final sample of 11 sources has a lower redshift but similar distributions in optical luminosity, UV magnitude, and $\text{H}\alpha$ flux.

For the continuum properties, we adopt the results from de Graaff et al. (2025b)¹. Briefly, de Graaff et al. (2025b) gives the continuum fitting of the prism spectra in two parts separated by the Balmer limit. The rest-frame UV continuum was fitted with a power law, and the fitting profile was extrapolated to a rest-frame wavelength of 1500 Å to compute the UV magnitude (M_{UV}). For the optical band, a modified blackbody spectrum was used for fitting, and its integration yielded the optical luminosity (L_{opt}).

3. SPECTRA FITTING PROCESS

After downloading the NIRSpec 1D spectra from the DJA, we began the emission line fitting process with continuum subtraction. The continuum was fitted in nearby wavelength windows on both sides of each emission line: for $\text{H}\alpha$ we used 6264–6414 Å and 6714–6864 Å; for $\text{H}\beta$ and [O III] we used 4561–4711 Å and 5157–5307 Å. Within these windows, the continuum was modeled with a quadratic polynomial. A quadratic function was chosen because the rest-frame optical continua of LRDs exhibit a convex blackbody-like shape, which is better approximated locally by a second-order polynomial; however, switching to a linear or power-law function does not significantly affect the final line-fitting results.

After subtracting the continuum, we used the LMFIT package² to perform multi-component Gaussian fitting of $\text{H}\alpha$, $\text{H}\beta$, and [O III] within specified wavelength ranges: 6414–6714 Å for $\text{H}\alpha$ and 4711–5157 Å for $\text{H}\beta$ and [O III]. Following Zhuang et al. (2025), our selection criterion for the broad component is $\text{FWHM} \geq 600 \text{ km/s}$. This criterion is more lenient than the often adopted criterion of $\geq 1000 \text{ km/s}$ (e.g., Greene et al. 2024; Matthee et al. 2024), and similar with several works adopting an even smaller FWHM threshold (e.g., Maiolino et al. 2024; Taylor et al. 2025b; Juodžbalis et al. 2026). For $\text{H}\alpha$, which has relatively high SNR, we adopted a model consisting of two broad components and one narrow component. For $\text{H}\beta$, whose broad component is often fainter, we used one broad and one narrow Gaussian and suggest that three out of four spectra have $\text{H}\beta$ broad component with $\text{SNR} > 3$. For [O III], we fixed the relative velocities of the $\lambda 4959$ and $\lambda 5007$ lines and fitted them with a single narrow component each. The fitted [O III] line ratio falls between 2.8 and 3.2 with a typical error of 0.15, consistent with the theoretical value of 2.98, indicating that fixing the ratio does not significantly influence the fitting results. It’s worth noticing

¹ 10.5281/zenodo.17665942

² 10.5281/zenodo.16175987

that no [O III] broad components or significant blue-shift of the broad Balmer lines are detected in our LRD samples.

For emission lines with absorption features (e.g., scrid=28074 in Figure 1), we first masked the absorption regions and fitted the emission lines with multiple Gaussian components. Then we compared the fitted emission profile to the observed data, and fitted the absorption component with a single Gaussian profile. This process was iterated three times; during each iteration, the absorption profile obtained from the previous step was added to the observed data when fitting the emission lines. The resulting fits for H α and for H β /[O III] are shown in Figures 1 and 2, respectively, together with the individual broad and narrow Gaussian components. Finally, the instrumental broadening correction was applied using the wavelength-dependent resolution of NIR-Spec, with revisions on the resolution of medium/high-resolution spectra ($R \sim 1000$ for medium-resolution & $R \sim 3000$ for high-resolution) (Shajib et al. 2025). For each spectrum, we also performed a Monte Carlo simulation based on the error array to estimate uncertainties in the fitted parameters. All derived total H α luminosities ($L_{\text{H}\alpha, \text{total}}$) and [O III] $\lambda 5007$ luminosities ($L_{[\text{O III}], 5007}$) agree within 10% with the results from prism spectra in de Graaff et al. (2025b), as expected given differences in continuum model and spectral resolution between prism and medium/high-resolution data.

Notably, none of the four medium-resolution spectra covering H β and [O III] show any detectable Fe II features. We therefore derived 3σ upper limits for the Fe II flux by fitting an empirical Fe II template by Véron-Cetty et al. (2004) to the 1D error spectrum. Following the Fe II strength ($R_{\text{FeII}} = F_{\text{Fe}}/F_{\text{H}\beta}$) definition used in Wu & Shen (2022) and Pan et al. (2025), we computed the upper limit for the Fe II flux integrated over the rest-frame wavelength range 4434–4684Å. The information on emission line fitting results is listed in Table 1 and Table 2.

4. RESULTS

In this section, we present the correlations between different emission-line components and continuum luminosities, estimate the black hole properties of our LRD sample, and compare these properties with those of normal AGNs.

4.1. Relation Between Emission Line and Continuum Luminosity

Figure 3 illustrates the relationship between the broad and narrow H α component fluxes, as well as the [O III] $\lambda 5007$ flux, and the absolute UV magnitude

(M_{UV}) at 1500 Å and the optical continuum luminosity. Spearman correlation coefficients and corresponding p-values are indicated in the upper right corner of each panel. As shown in the first column, the flux of the broad H α component exhibits a strong correlation with the optical luminosity but shows virtually no correlation with the UV magnitude. A natural explanation for this result is that the broad H α emission and the optical continuum share a common origin, both likely powered by the central black hole accretion process. In comparison, de Graaff et al. (2025b) also reports a tight correlation between the total H α luminosity and the rest-frame optical continuum, which is partly consistent with our findings, given that the broad component dominates the H α flux in most of our LRD sample (The median flux fraction of broad component is 74%). A more detailed analysis of the H α emission-line components was recently presented by Asada et al. (2026), who inferred that both the broad and narrow Gaussian components of H α correlate with UV luminosity. However, their study primarily used lower-resolution prism spectra, and therefore their definitions for decomposing broad and narrow components differ from ours. They also noted that the correlation for the broad H α components shows slightly larger scatter compared to that of the narrow components.

The second column of Figure 3 presents the results for the narrow component of H α . Unlike the broad component, the narrow component shows only weak correlations with both UV and optical luminosity. This could be due to the lower SNR of several detections or to a more complex physical origin for the narrow H α emission. Statistically, the narrow H α component appears more likely to correlate with the UV magnitude—a trend similar to that seen for [O III], described below. Nevertheless, a portion of the narrow H α emission may still be linked to the optical continuum, which could originate from the thinner gas outside the gas shell structures in LRDs, an analogy of the narrow-line region (NLR) in AGN.

The last column of Figure 3 shows that the [O III] flux strongly correlates with the UV magnitude but shows almost no correlation with the optical luminosity. This suggests that the far-UV photons extended from the UV continuum are the most likely source of ionizing photons for the [O III] lines, which is consistent with de Graaff et al. (2025b) and Asada et al. (2026), although the UV magnitude may have relatively large uncertainty due to the limited fitting wavelength in the rest-frame prism spectra. The origin of both the UV continuum and the [O III] emission still remains difficult to constrain with

Table 1. The properties of LRDs in our sample

SCRID	Redshift	FWHM _{Hα}	log $L_{H\alpha, \text{ broad}}$	log M_{BH}	λ_{Edd}	log M_*
		km s ⁻¹	log(erg s ⁻¹)	log(M_{\odot})		log(M_{\odot})
(1)	(2)	(3)	(4)	(5)	(6)	(7)
13329	3.94	814 ± 33	42.29 ± 0.03	6.41 ± 0.04	0.36 ± 0.04	9.32 ± 0.10
23438	3.69	967 ± 115	42.42 ± 0.02	6.70 ± 0.11	0.35 ± 0.09	9.16 ± 0.13
28074	2.26	1126 ± 17	43.31 ± 0.01	7.29 ± 0.01	0.84 ± 0.03	9.54 ± 0.04
28812	4.22	1009 ± 123	42.85 ± 0.03	6.95 ± 0.13	0.56 ± 0.25	8.70 ± 0.10
31747	4.13	523 ± 16	42.45 ± 0.01	6.23 ± 0.03	1.55 ± 0.11	8.53 ± 0.15
53501	3.43	753 ± 98	42.62 ± 0.03	6.56 ± 0.12	0.73 ± 0.20	9.15 ± 0.07
73488	4.13	681 ± 64	42.76 ± 0.02	6.58 ± 0.09	1.21 ± 0.24	9.44 ± 0.07
119957	4.15	1070 ± 80	42.45 ± 0.03	6.81 ± 0.07	0.30 ± 0.05	8.73 ± 0.08
144195	3.35	1117 ± 81	42.49 ± 0.03	6.90 ± 0.07	0.31 ± 0.06	8.59 ± 0.09
154183	3.55	570 ± 132	42.84 ± 0.03	6.49 ± 0.21	2.08 ± 1.07	8.42 ± 0.10
167741	4.12	1348 ± 146	42.55 ± 0.02	6.99 ± 0.10	0.18 ± 0.05	9.53 ± 0.18

NOTE—Column (1): scrid number, same as [de Graaff et al. \(2025b\)](#) catalog. Columns (2): redshifts derived from the NIRSpect spectra. Column (3)-(4): The FWHM (after the instrumental broadening correction) and luminosity of the broad H α emission line components. Column (5): The log scale blackhole masses derived from the H α emission line. Column (6): The Eddington ratio. Column (7): The stellar mass estimation results under derived from the UV luminosity.

Table 2. The properties of H β and Fe II in our sample

SCRID	FWHM _{Hβ}	log $L_{H\beta, \text{ broad}}$	log L_{Fe}
	km s ⁻¹	log(erg s ⁻¹)	log(erg s ⁻¹)
(1)	(2)	(3)	(4)
28074	1439 ± 112	41.89 ± 0.03	< 42.52
53501	569 ± 120	41.32 ± 0.08	< 42.55
73488	1049 ± 221	41.14 ± 0.08	< 42.42

NOTE—Column (1): scrid number, same as [de Graaff et al. \(2025b\)](#) catalog. Columns Column (2)-(3): The FWHM and luminosity of the broad H β emission line components. Column (4): The upper limit of total luminosity of Fe lines in 4434–4684Å

current observations. In general, three main possibilities are considered:

- 1. Stellar Origin.** One explanation attributes the UV continuum to recently formed stars in the host galaxy. Observationally, this could account for the extended structures seen in the rest-frame UV for some LRDs. Furthermore, extreme starburst galaxies (e.g., the extreme emission-line galaxies in JADES, [Boyett et al. 2024](#)) can produce the high [O III] EWs measured in LRDs ([de Graaff et al. 2025b](#); [Barro et al. 2025](#)). This origin is also sug-

gested by the empirical decomposition process of prism spectra of LRD ([Sun et al. 2026](#)).

- 2. AGN Origin.** Another interpretation is that both the [O III] emission and the UV continuum originate from the narrow-line region and the inner accretion disk of a central AGN. However, compared to the standard AGN unification model ([Antonucci 1993](#); [Netzer 2015](#)), two issues need to be addressed. First is the large EWs of the [O III] line. Even when calculated using the observed (relatively red) LRD continuum (which already overestimates the available ionizing photons), the [O III] EWs are higher than those in most type-I ([Shen et al. 2011](#)) or type-II ([Bongiorno et al. 2010](#); [Caccianiga & Severgnini 2011](#)) AGN. This may require a larger covering factor of the NLR, specific gas-phase metallicity, or lower gas densities. Second is the viewing-angle constraint: if AGN-originated UV photons can escape along certain lines of sight and excite more distant narrow-line gas, we would expect to observe a population of “bluer dots” with UV luminosities significantly exceeding those from star formation and showing shorter UV variability timescales. To date, no such population has been statistically confirmed though several cases have been observed (e.g., [Brazzini et al. 2026](#)).

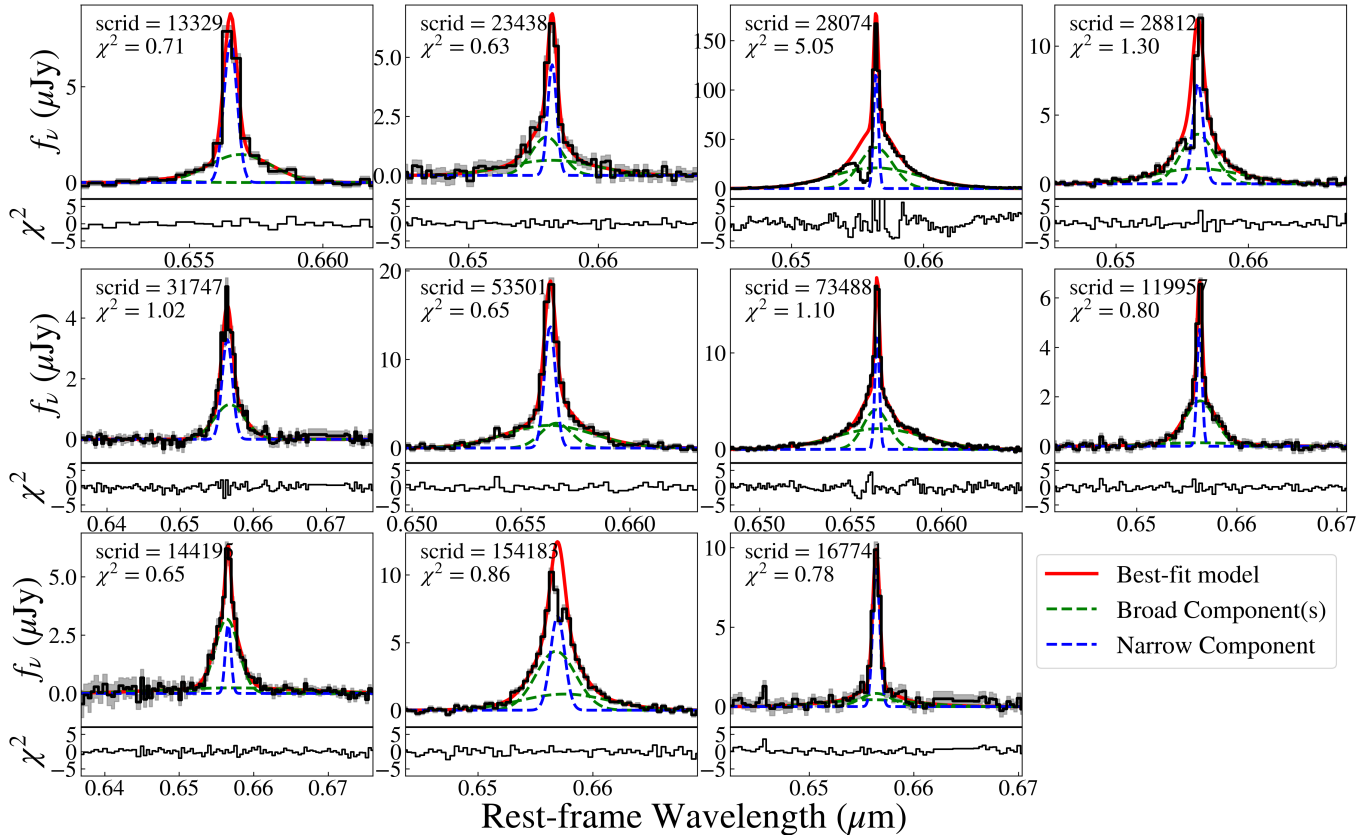


Figure 1. Spectral fitting results for the H α emission lines in our LRD sample. In each panel, the black histogram represents the observed 1D flux density f_ν (in units of μJy), the gray shaded region indicates its 1σ uncertainty, and the best fitting total model is shown as the solid red line. The broad and narrow emission-line components are depicted by the green and blue dashed curves, respectively. The source ID and reduced χ^2 results are indicated in each panel. The lower panels show the residuals of each fitting.

3. Diffuse Ionized Gas Origin. This scenario suggests that the UV photons come from recent star formation in the host galaxy, while the [O III] emission is collisionally excited by more tenuous gas located outside the central black hole’s gas shell. This region more closely resembles the photo-ionization conditions of diffuse ionized gas (DIG) rather than those of classical H II regions in the local universe. This may cause a mild FWHM in [O III] line, which relates to the stellar feedback and gas removal around the central accreting BH (Inayoshi et al. 2025).

4.2. Location and Evolution of LRD in AGN diagram

We estimate the black hole mass (M_{BH}), bolometric luminosity (L_{bol}), and Eddington ratio (λ_{Edd}) for our sample based on the broad H α emission-line features. Systematic uncertainties in the M_{BH} estimation, including contributions from electron scattering, are discussed in Section 5.1. Specifically, The M_{BH} is derived us-

ing the virial mass estimator calibrated by Reines et al. (2013):

$$\log(M_{\text{BH}}/M_\odot) = \log(\epsilon) + 6.57 + 0.47 \log\left(\frac{L_{\text{H}\alpha, \text{ broad}}}{10^{42} \text{ erg s}^{-1}}\right) + 2.06 \log\left(\frac{\text{FWHM}_{\text{H}\alpha}}{10^3 \text{ km s}^{-1}}\right)^2 \quad (1)$$

where $L_{\text{H}\alpha, \text{ broad}}$ is the luminosity of the broad H α component and $\text{FWHM}_{\text{H}\alpha, \text{ broad}}$ is its full width at half maximum after correcting for instrumental broadening. A scaling factor of $\epsilon = 1.075$ is adopted following Reines & Volonteri (2015). The instrumental broadening correction was applied using the wavelength-dependent resolution of NIRSpect, with revisions on the resolution of medium/high-resolution spectra (Shajib et al. 2025). Note that we do not correct $L_{\text{H}\alpha, \text{ broad}}$ for extinction. The bolometric luminosity is estimated using the calibration $L_{\text{bol}} = 130 \times L_{\text{H}\alpha, \text{ broad}}$ from Stern & Laor (2012). The Eddington ratio is then calculated as $\lambda_{\text{Edd}} = L_{\text{bol}}/L_{\text{Edd}}$ with $L_{\text{Edd}} = 1.26 \times$

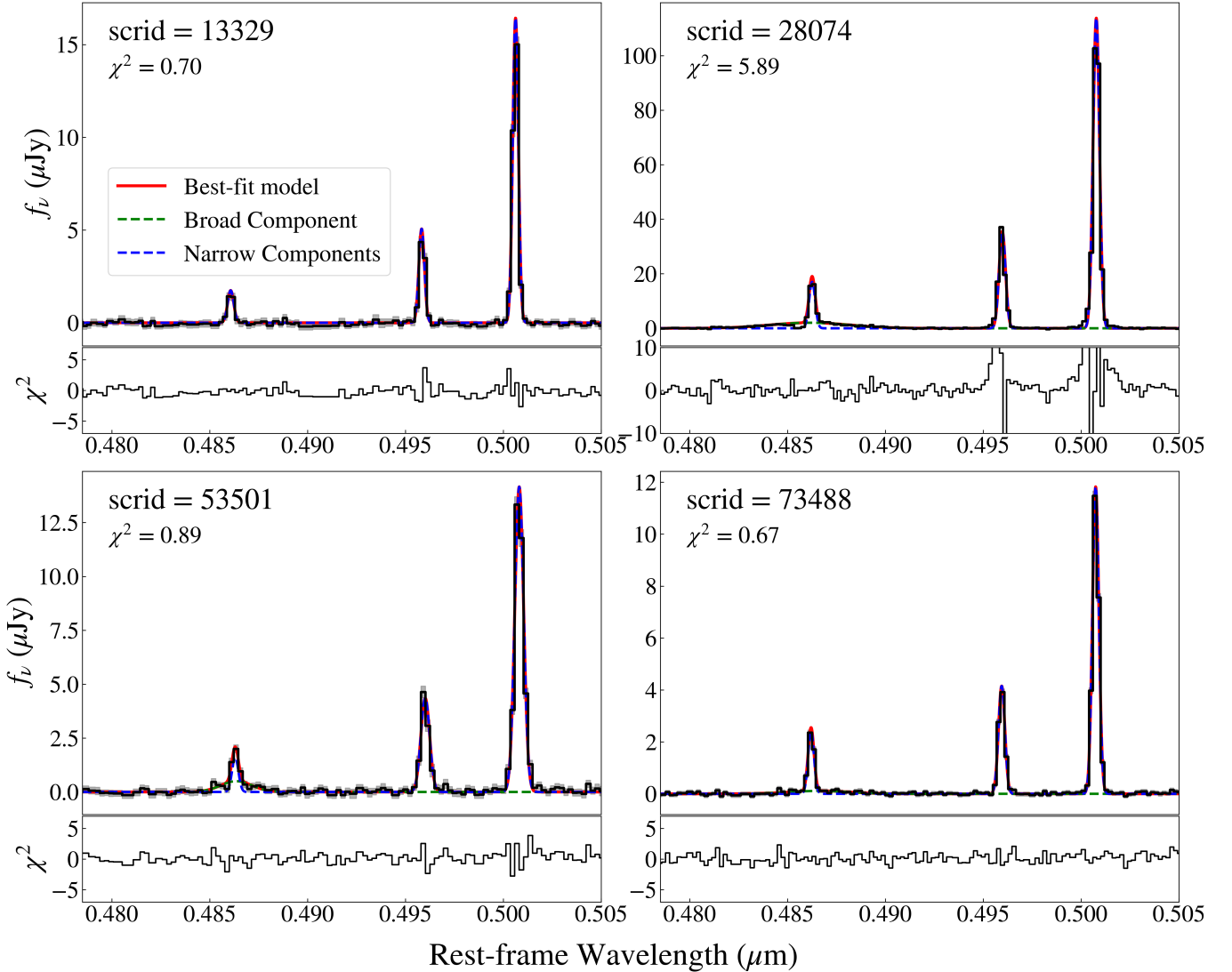


Figure 2. Spectral fitting results for the H β and [O III] emission lines in our LRD sample. The line components, labels, and annotations are the same as Figure 1.

$10^{38}(M_{\text{BH}}/M_{\odot}) \text{ erg s}^{-1}$. The estimated M_{BH} and λ_{Edd} results are compiled in Table 1.

The distribution of LRDs and other AGN populations on the $\text{FWHM}_{\text{H}\alpha}$ – λ_{Edd} plane is shown in Figure 4. Despite potential systematic uncertainties in the mass estimation, the majority of the LRD sample has inferred black hole mass of $10^6 \sim 10^8 M_{\odot}$ and exhibits relatively high Eddington ratios between 0.3 and 2. These properties place them in an extreme early evolutionary phase in the AGN main sequence, characterized by lower black hole masses compare to typical narrow-line Seyfert 1 (NLS1) galaxies (Paliya et al. 2024) and higher accretion rates compare to DESI dwarf AGNs (Pucha et al. 2025). Assuming a slim-disk accretion model (Watarai et al. 2000), the implied current mass accretion rate is $0.03 \sim 1 M_{\odot} \text{ yr}^{-1}$. Following the model by Inayoshi

et al. (2025), which derived a relatively stable mass accretion rate, we can further infer the history and evolutionary pathway of LRDs. If the LRDs are seeded by low-mass black holes ($M_{\text{BH, seed}} \ll 10^6 M_{\odot}$), then the estimated age of the LRD phase is about $10^5 \sim 10^7$ years, consistent with the estimation results of the “quasistar” evolutionary model prediction (Begelman & Dexter 2026; Inayoshi et al. 2025).

The dashed lines in Figure 4 trace the evolution of LRDs over an additional 20 Myr—a typical LRD lifetime in the Inayoshi et al. (2025) model—assuming the current mass accretion rate is maintained. The endpoints of these tracks indicate that all of our LRDs would settle within the parameter space occupied by NLS1 galaxies. This suggests that, even after transitioning into an active AGN phase, these systems would still have an evo-

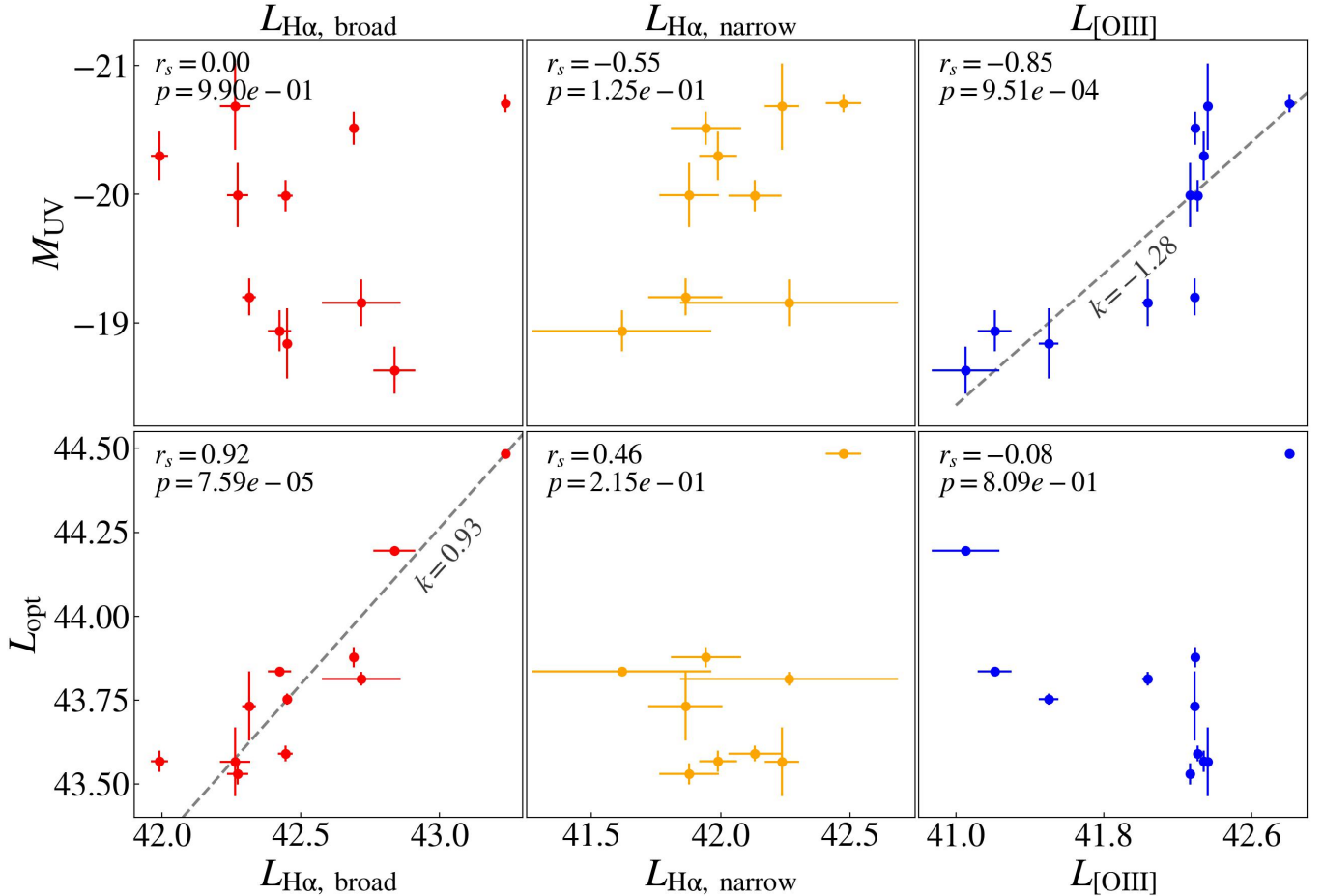


Figure 3. The flux of the broad $H\alpha$ component, the narrow $H\alpha$ component, and the $[O\ III]\lambda 5007$ emission line as a function of rest-frame UV and optical luminosities from de Graaff et al. (2025b) in our LRD sample. Spearman correlation coefficients and p-values are indicated in each panel. The broad $H\alpha$ flux shows a strong correlation with the optical luminosity but exhibits no significant correlation with the UV magnitude. Conversely, the $[O\ III]$ flux correlates with the UV magnitude rather than the optical luminosity. The slopes of significant correlation are noted in the corresponding sub-panels. The narrow $H\alpha$ component displays weak correlations with both the UV and optical bands.

lutionary path ahead before reaching the properties of typical QSOs observed in SDSS (e.g., Wu & Shen 2022). This scenario is also consistent with the recent proposed “transitional phase” of LRDs, characterized by a similar “V-shaped” SED but with clear X-ray detections (Li et al. 2025b; Fu et al. 2025), which are located at the edges of NLS1 samples.

In Figure 4, we also plot the locations of the most extreme LRDs identified to date, although their properties are mainly based on prism spectra (Labbe et al. 2024; de Graaff et al. 2025a; Naidu et al. 2025; Wang et al. 2025; Taylor et al. 2025a; Ji et al. 2025). These extreme LRDs occupy a region distinct from that of our sample, which can be explained by two possibilities. Their emission-line widths could be affected by strong electron scattering, which would place them in a region corresponding to lower black hole masses and higher accretion rates. Alternatively, the formation history and evolution of these

extreme LRDs may be governed by different initial conditions.

4.3. The Strength of Iron Lines of LRDs

The Fe II emission lines are common and diagnostically important features in Type-I AGN spectra (Osterbrock 1977; Wills et al. 1985; Boroson & Green 1992). In the standard AGN model, optical Fe II emission is thought to originate in the outer part of the BLR (Kovačević et al. 2010). Their line shape and EW can reflect the physical conditions of the emitting clouds (Baldwin et al. 2004). Observationally, the optical Fe II lines around $H\beta$ and $[O\ III]$ form the major part of Eigenvector1 (or the quasar main sequence, Yip et al. 2004; Shen & Ho 2014), exhibiting strong correlations between Fe II strength, $[O\ III]$ EW, and other optical spectral properties. The Fe II strength, quantified by the flux ratio $R_{FeII} = F_{Fe}/F_{H\beta}$, is an important di-

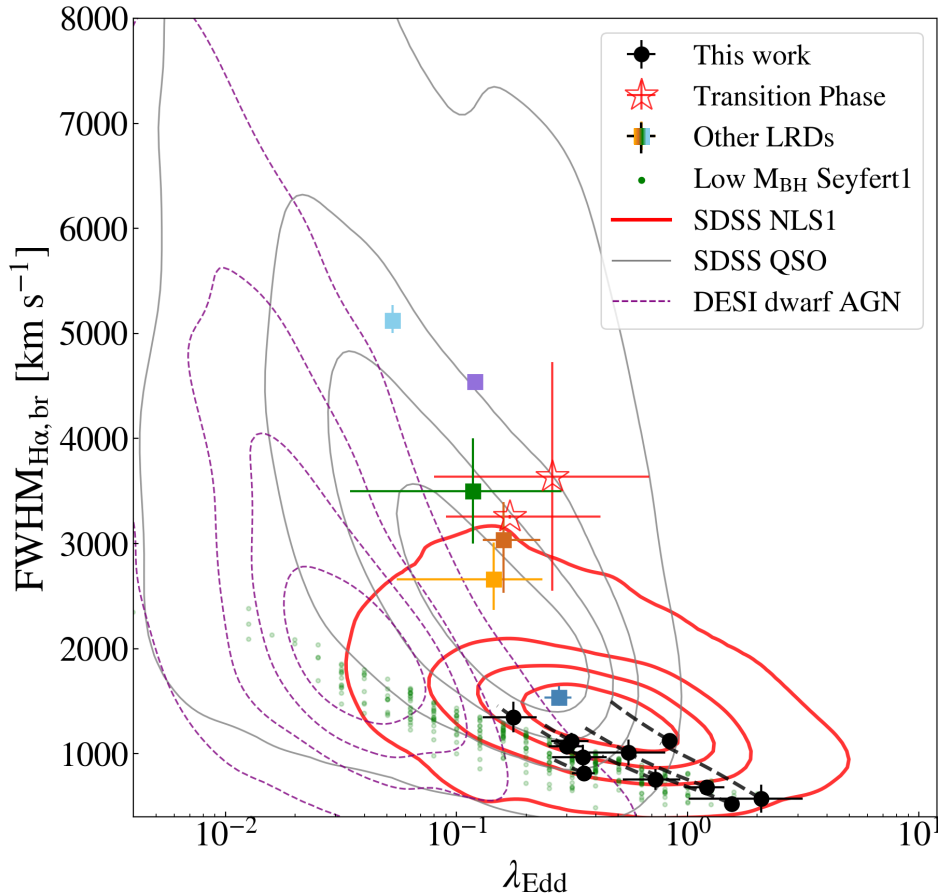


Figure 4. Distribution of LRDs and AGNs on the $\text{FWHM}_{\text{H}\alpha, \text{br}} - \lambda_{\text{Edd}}$ plane. Our LRD sample is shown as black filled circles. Other known LRDs from Labbe et al. (2024); de Graaff et al. (2025a); Naidu et al. (2025); Wang et al. (2025); Taylor et al. (2025a); Ji et al. (2025) are indicated by colored squares (using the same method from $\text{H}\alpha$ line in this work to estimate the λ_{Edd}). Recently identified candidates in a possible transitional phase of LRDs from Li et al. (2025b); Fu et al. (2025) are represented by open red stars. For comparison, the black, purple, and red contours show the distributions of SDSS QSOs from Wu & Shen (2022), DESI dwarf AGNs from Pucha et al. (2025), and narrow-line Seyfert 1 (NLS1) galaxies from Paliya et al. (2024), respectively (the contour lines contains 95%, 71%, 48%, and 23% sources). Seyfert 1 galaxies with low-mass black holes from Dong et al. (2012) are also included as green dots (the vertical pattern is due to the 0.1 dex precision in λ_{Edd} parameter). The black dashed lines trace the projected evolution over the next 20 million years for our LRD sources, assuming the mass accretion rate remains roughly constant.

agnostic for the Eddington ratio and black hole mass scaling relations.

In our sample, three sources have detected broad $\text{H}\beta$ emission, but none show a significant detection of the associated Fe II lines. Adopting the R_{FeII} definition which estimate the Fe flux spanning from 4434 to 4684Å from Wu & Shen (2022) and Pan et al. (2025), we estimate 3σ upper limits for R_{FeII} , shown as black filled circles in Figure 5. For comparison, the open circles represent the predicted R_{FeII} values inferred from the $\lambda_{\text{Edd}} - R_{\text{FeII}}$ relation from the QSO sample from DESI QSOs by Pan et al. (2025). Our upper limits lie systematically below these predictions. We further compile recent observational constraints on Fe lines in LRDs: Labbe et al.

(2024) report detections of broad Fe II lines, with line detection in 4434 to 4684Å, their LRD is unprecedented luminous; Tripodi et al. (2025) detect four broad optical Fe II lines in four sources, though not within the R_{FeII} calculation range; D’Eugenio et al. (2025) and Torralba et al. (2025) detect narrower forbidden [Fe II] lines. Compared to the distribution of SDSS QSOs, the measured (or constrained) Fe II values in LRDs are generally lower than expected given their high Eddington ratios, indicating relatively weak permitted Fe II emission in these systems.

Furthermore, the forbidden [Fe II]/[O I] line ratios presented by D’Eugenio et al. (2025) suggest that the metallicity of the Fe-emitting gas is not particularly low.

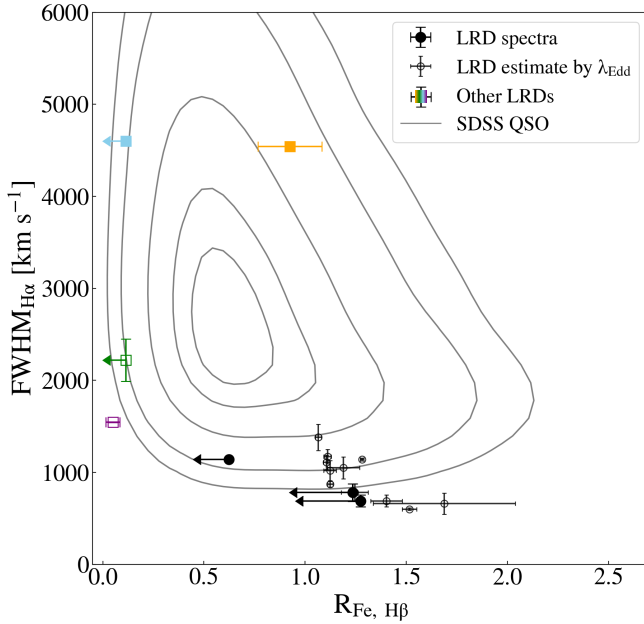


Figure 5. Distribution of LRDs and AGNs on the $\text{FWHM}_{\text{H}\alpha}$ - R_{FeII} plane. Upper limits for our LRD sample are plotted as black filled dots, while predicted R_{FeII} values based on the $\lambda_{\text{Edd}} - R_{\text{FeII}}$ relation from the QSO sample in Pan et al. (2025) are indicated by open black dots. Results from other literature studies with Fe line fitting are summarized as squares (Labbe et al. 2024; Torralba et al. 2025; Tripodi et al. 2025; D’Eugenio et al. 2025). The permitted and forbidden line detection results are represented by solid and open squares, respectively. The background gray contours represent the distribution of SDSS QSOs from Wu & Shen (2022). Here, R_{FeII} is calculated using the Fe flux within the rest-frame wavelength range of 4434–4684Å.

This argues against the possibility that the weakness of the permitted Fe II lines is primarily due to low metallicity, although we note that forbidden and permitted Fe II lines trace different gas phases (Torralba et al. 2025). Another relevant clue from Tripodi et al. (2025) is that the permitted Fe II lines in their LRDs have lower FWHM than the Balmer lines, implying an origin at larger radii. This stratified structure is reminiscent of that observed in normal AGN. We therefore suggest that the weakness of the Fe II emission in LRDs is likely caused by a deficit of ionizing photons in the outer regions of the gas shell. We will discuss more details of this scenario in Section 5.2.

5. DISCUSSION

In this section, we first discuss the systematic uncertainties in the estimates of M_{BH} and L_{bol} , and then examine the $M_{\text{BH}}-M_*$ relation. We next investigate the characteristic size, mass, and structure of the LRD gas shell, and finally propose a model with a thickened pho-

tosphere, analyzing its implications for the observed optical continuum under different physical conditions.

5.1. The uncertainty of M_{BH} & L_{bol} estimation

Recent work by Rusakov et al. (2025) and Sneppen et al. (2026) suggests that electron scattering can significantly broaden the Balmer emission lines. A key piece of evidence is that for high SNR $\text{H}\alpha$ line profiles, models that convolve a single Gaussian with an exponential wing could yield the best fit. Specifically, two sources in our sample overlap with those analyzed by Rusakov et al. (2025): scrid-73488 (our $\log(M_{\text{BH}}/M_{\odot}) = 6.58$ versus their value of 6.1) and scrid-53501 (our $\log(M_{\text{BH}}/M_{\odot}) = 6.55$ versus their upper limit of 5.6). It is worth noting that our use of a double-Gaussian profile to fit the broad component gets reasonable fitting results (double-Gaussian profile also giving similar BIC values for most sources in Rusakov et al. 2025) and yields a black hole mass roughly one order of magnitude lower than that from a single-Gaussian fit in Rusakov et al. (2025) due to a better capture of the line shape. Nevertheless, fully accounting for the electron scattering effect could potentially lower the inferred M_{BH} by an additional ~ 0.7 dex.

A lower black hole mass implies a correspondingly higher Eddington ratio for these LRDs. Even without correcting the optical continuum luminosity for dust extinction, the inferred luminosities are already comparable to L_{Edd} . Given the relatively small values of M_{BH} , this implies black hole growth timescales of $\lesssim 10^4$ – 10^5 yr, as well as short gas-shell depletion timescales of order 10^3 – 10^4 yr (Sneppen et al. 2026). A promising method to distinguish between these models is to study the variability timescale of the $\text{H}\alpha$ line, particularly its wings. The electron scattering scenario predicts a smaller BLR size, and the associated ionization structure would respond more rapidly to changes in the ionizing continuum than the dynamical timescale of the BLR (Laor 2006).

It is important to acknowledge that single-epoch spectroscopic mass estimates carry an intrinsic systematic uncertainty due to uncertainties in the virial factor and other BLR structural parameters (Peterson 2011; Shen & Liu 2012; Du et al. 2018). A dedicated reverberation-mapping campaign for LRD objects is crucial to provide an empirical calibration for black hole mass estimates in this population.

Our estimate of L_{bol} relies on the $\text{H}\alpha$ emission line under the assumption that the broad $\text{H}\alpha$ component is photo-ionized by a SED similar to a standard AGN model. This means that the inferred L_{bol} carries a systematic uncertainty related to the true structure of the LRD’s gas shell (or photosphere) and its interior. We

also compared L_{bol} derived from $\text{H}\alpha$ with that estimated from 5100\AA continuum using the bolometric correction from Richards et al. (2006). The two estimates are consistent within a scatter of 0.2 dex. Regarding the results by Greene et al. (2026) that L_{bol}/L_{5100} may be overestimated by a factor of 2, our sample may overestimate by approximately the same factor.

5.2. The Gas Envelope of LRDs

Within the framework where the optical emission originates from the central black hole accretion, two main models currently seek to explain the origin of the optical continuum and broad emission lines in LRDs. The first posits a supermassive black hole accreting from an asymmetric, dense gas cocoon, where the inner region is ionized and surrounded by a much larger reservoir of cold gas (e.g., Rusakov et al. 2025; Sneppen et al. 2026). In this picture, the broad emission lines could be produced by electron scattering in the inner region, while the continuum is shaped by the outer gas. The second model analogizes the LRD’s core to a “quasistar”, where the continuum arises from a stellar-like photosphere, and the broad-line region (BLR) resides inside or outside this photosphere (e.g., Kido et al. 2025; Inayoshi et al. 2025). In this section, we propose a model revision featuring a thicker, clumpy gas envelope. This structure can produce blackbody-like emission at larger radii while also accommodating the ionized clouds responsible for broad emission lines.

As presented in Section 4, the strong correlation between the broad-line luminosity and the optical continuum luminosity strongly suggests a common origin. Moreover, the large Balmer decrement observed in LRD (> 10 for both broad $\text{H}\alpha$ and $\text{H}\beta$ detected in our sample; see also Brooks et al. 2025) indicates that the broad lines likely form within a dense gas with $n_{\text{H}} \geq 10^8 \text{ cm}^{-3}$ (Yan et al. 2025), which could also account for the Balmer absorption features seen in a proportional of LRDs (e.g. Lin et al. 2024; Juodžbalis et al. 2024a). The most natural interpretation of these observations is that the BLR is embedded within the dense gas shell; equivalently, the outer radius of the shell (i.e., the photosphere) must exceed the characteristic size of the BLR.

We first estimate the BLR size in LRDs to constrain the minimum outer radius of the gas shell. Using the established $R - L$ relation for traditional AGNs, we estimate the radius of the $\text{H}\alpha$ -emitting BLR clouds to be 22–42 light-days for our sample (spanning the 17th to 84th percentiles, hereinafter the same). For normal AGNs, the BLR covering factor is typically 20% (Baldwin et al. 1995; Panda 2022). Assuming LRDs represent a more extreme case with a covering factor of 50%, the

corresponding lower limit for the gas shell radius would be ~ 13 –26 light-days.

On the other hand, we can estimate the photospheric radius by comparing the intrinsic blackbody emission to the observed optical luminosity. Using the continuum fitting results from de Graaff et al. (2025b), we estimate a radius of 6–11 light-days for a single-temperature blackbody with a 100% covering factor. This value is smaller than the BLR size estimated above, presenting a potential contradiction.

To resolve this tension, we propose a model featuring a thicker, clumpy outer gas envelope. To illustrate how this model differs from a simple stellar photosphere, we construct a toy model as follows. Consider a gas shell with an inner radius $R_{\text{in}} = 10$ light-days and an outer radius $R_{\text{out}} = 30$ light-days (2000 – 5000 AU). To prevent the escape of interior photons, we assume the total line-of-sight covering factor through the entire shell is 100%, but the covering factor at any given radial layer is much less than unity. We assume the physical cross-sectional area of optically thick clumps is constant with radius, implying that the local covering factor scales as $f(r) \propto r^{-2}$. Consequently, the luminosity incident on each layer also scales as $L(r) \propto r^{-2}$. Assuming all incident radiation is thermally reprocessed and emitted as a blackbody, with a constant emitting area in each layer, the effective blackbody temperature scales as $T(r) \propto r^{-0.5}$. From the ideal gas law $p = nkT$, where the radiation pressure $p(r) \propto L(r) \propto r^{-2}$ and k is the Boltzmann constant, the gas density then scales as $n(r) \propto r^{-1.5}$. We also account for the effect of gas motion, though its influence on the continuum shape is minor. Specifically, we assume that at a radius of 13 light-days, the gas layer co-rotates with the BLR gas at a velocity of 1000 km s^{-1} (analogous to the case of scrid-23438), while at other radii within the envelope, the velocity follows a profile $v(r) \propto r^{-0.5}$. These velocity profiles are then convolved, as Gaussian broadening kernels, with the intrinsic blackbody emission at each layer.

Under these conditions, the synthesized continuum spectrum is calculated and shown in the upper panel of Figure 7. For an inner boundary temperature $T_{\text{in}} = 6200 \text{ K}$, the overall spectrum is nearly indistinguishable from a single 5000 K blackbody. In terms of total luminosity, this gas envelope with $R_{\text{in}} = 10$ light-days and $R_{\text{out}} = 30$ light-days is equivalent to a 5000 K blackbody photosphere with a radius of ~ 9 light-days. For specific layer of gas in the 4700–5300 K range, the integrated covering factor is roughly 20%. The proposed gas shell is approximately three times larger than pre-

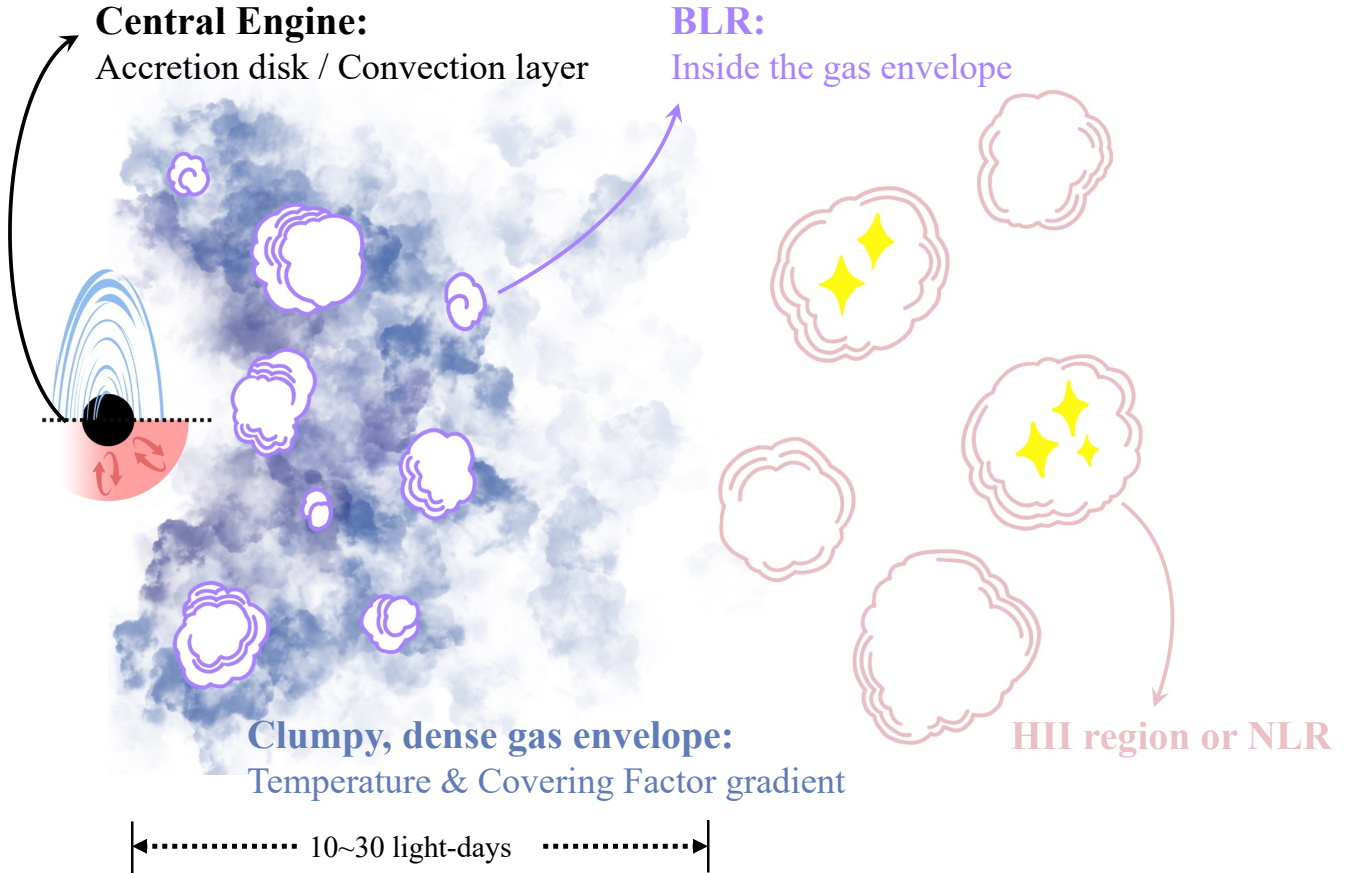


Figure 6. Schematic illustration of our proposed gas shell structure for LRDs. Compared to the cocoon envelope model originally proposed by Naidu et al. (2025), our model suggests a larger physical size and lower covering factor in each layer of the cocoon envelope. Compared to the black hole star model of Inayoshi et al. (2025), our model possesses a thicker photosphere, with a temperature that gradually decreases from the inner to outer regions, resulting in a larger outer radius for the gas shell. Relative to the model presented by Lin et al. (2025), our model is also compatible with an asymmetrical BLR structure.

vious estimates, leaving ample volume for the ionized BLR gas to reside.

This model can also account for the weakness of the Fe II lines in LRDs compared to normal AGN as seen in Section 4. Since the Fe II lines have lower FWHM and originate from the outer part of the gas shell, the integrated covering factor of the inner, optically thick gas layers is higher along their line of sight. This results in a great reduction of the ionizing photons from the central engine before they reach the Fe II-emitting zone. In contrast, classical Type-I AGN lack such an extensive, obscuring gas shell. Consequently, the outer gas in standard AGN receives a much higher flux of ionizing photons, leading to the stronger Fe II emission typically observed.

Recently, Wang et al. (2026) analyzed two LRDs at relatively low redshifts, detecting water absorption features around $1.4 \mu\text{m}$ at the rest-frame. They inferred the presence of a temperature gradient in the outer gas shell, decreasing from about 4000 K to 2000 K. This

finding is broadly consistent with our toy model when a lower central temperature is considered. Our model predicts a variability timescale of several tens of days for both the optical continuum and the broad emission-line profiles at the rest-frame. Because the ionizing photons from the central engine have undergone radiative transfer through the extended outer envelope, we expect little or no correlated variability between the broad H α emission line and the optical continuum.

In summary, by increasing the thickness of the optically emitting layers within the gas shell and introducing a radial temperature gradient, while correspondingly reducing the volume-averaged covering factor, we can reproduce both the spectral shape and total flux expected from a smaller-radius blackbody photosphere with a single effective temperature of 5000 K. This configuration allows the BLR to embed within the gas envelope, which is the main difference from the black hole star model. Our model differs from the dense gas cocoon framework in both scale and physical structure. While the latter

typically assumes a lower black hole mass and a more compact, high-density gas configuration, our model instead favors a gas envelope that is approximately 0.5 dex larger in spatial extent and characterized by a lower effective covering factor. Consequently, a key observable difference between these scenarios lies in the variability timescales of the spectral components. Nevertheless, the broad Balmer lines could still be obscured and scattered by clouds in the outer, blackbody-emitting layers, leading to a large Balmer decrement and additional broadening of its FWHM. Besides, our model remains compatible with an asymmetric BLR geometry proposed by Lin et al. (2025). This aspect could be tested in future studies by examining potential viewing-angle effects within a larger LRD sample. A schematic illustration of our proposed gas shell structure are shown in Figure 6.

5.3. Application to the LRD optical continuum

When observed over a sufficiently broad wavelength range, the real optical continuum of LRDs often reveals systematic deviations from a pure blackbody spectrum. These deviations can be phenomenologically modeled, as in de Graaff et al. (2025b), by introducing a power-law correction term, characterized by:

$$f_\nu \propto B_\nu(T) \left(\frac{\nu}{\nu_0} \right)^\beta$$

where $\nu_0 = c/5500\text{\AA}$. This results in two primary cases: $\beta > 0$, where the observed continuum is narrower than a blackbody when plotted against wavelength, and $\beta < 0$, where it is broader. However, the physical origin of these deviations remains poorly understood.

Applying standard extinction curves to a ~ 5000 K blackbody does not significantly alter its fundamental shape. As illustrated in the upper panel of Figure 7, a 5000 K blackbody subjected to $A_V = 1$ extinction (assuming the law from Fitzpatrick 1999) becomes similar with a cooler 4000 K blackbody. Therefore, the observed deviations in LRD continua are more likely intrinsic to the gas emission process itself.

We propose that the gas envelope model introduced in the previous section can, in principle, account for both types of spectral deviation. As shown in the lower panel of Figure 7:

1. Broader continua ($\beta < 0$): If each layer of the gas envelope emits as a blackbody and the foreground extinction is negligible, the emergent spectrum is a superposition of blackbodies at different temperatures. This can produce a composite spectrum that is broader than a single-temperature blackbody when the covering factor of the outer layers exceeds the value assumed in the toy model in

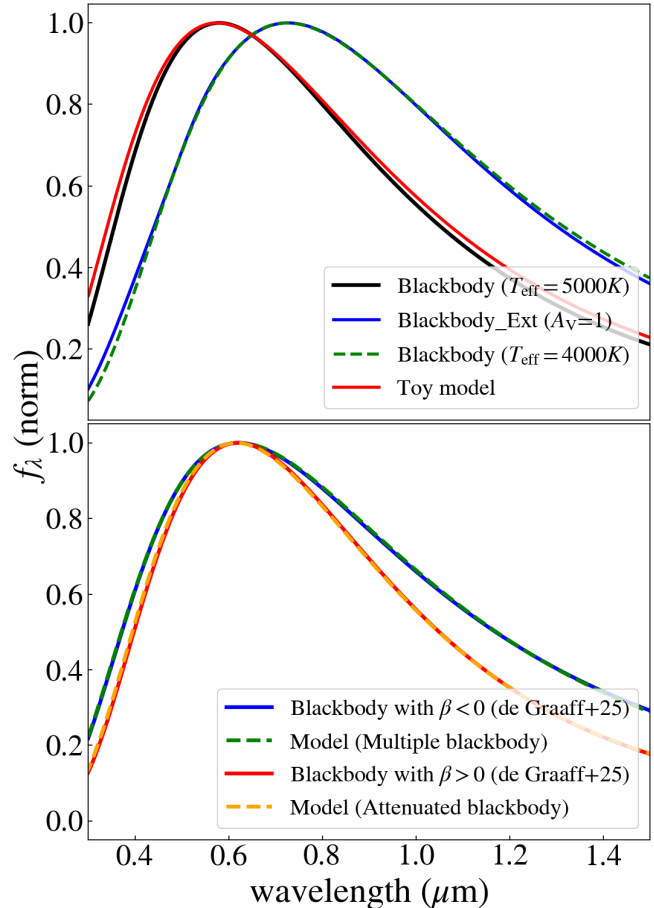


Figure 7. Physical origins and interpretations of the LRD optical continuum shape. **Upper panel:** Influence of extinction and gas shell thickness. The black solid curve represents the standard blackbody emission for $T_{\text{eff}} = 5000\text{K}$. The blue curve shows the same blackbody spectrum after applying an extinction of $A_V = 1$ assuming the extinction law from Fitzpatrick (1999), which does not differ significantly from a cooler 4000K blackbody (green curve). The red curve shows the multicolor blackbody spectrum produced by a photosphere of our toy model described in Section 5.2, which is largely consistent with the standard 5000K blackbody. **Lower panel:** Examples of the actual LRD continuum shape from de Graaff et al. (2025b). The blue spectrum is from NEXUS-20152, which has $\beta < 0$ (broader than a standard blackbody) and can be well fit by a combination of multiple blackbody profiles (green dashed curve) with a higher covering factor of the outer layers compare to the toy model. The red spectrum is from RUBIES-UDS-31747, which has $\beta > 0$ (narrower than a standard blackbody). Its shape can be explained by the blackbody emission of the inner layers undergoes radiative transfer through a tenuous gas in the outer layer, rather than escaping directly in the toy model.

Section 5.2. The example in the figure is NEXUS-20152 ($T_{\text{eff}} = 5119$, $\beta = -0.42$), whose continuum is well-matched by the sum of three blackbodies at 4000, 5000, 6000 K.

2. Narrower continua ($\beta > 0$): If the emergent radiation undergoes radiative transfer through a high-density, low-column-density outer gas layer with a wavelength-dependent optical depth τ , the resulting spectrum can appear narrower than that of a standard blackbody (see also Liu et al. 2025). An example is RUBIES-UDS-31747 ($T_{\text{eff}} = 3827$, $\beta = 1.08$), whose shape is consistent with a 3900 K blackbody spectrum attenuated by a foreground gas with $N_{\text{H}} = 10^{20} \text{ cm}^{-2}$ and $n_{\text{H}} = 10^9 \text{ cm}^{-3}$. This scenario occurs when the blackbody emission from the inner region passes through a tenuous gas in the outer layer, rather than escaping directly as assumed in the simplified toy model of Section 5.2.

In short, the proposed gas envelope framework can reproduce the primary observed deviations of LRD continua from simple blackbody shapes. We are currently employing spectral synthesis codes (MAPPINGS and CLOUDY) within this scenario to fit the full prism continuum shapes of LRDs and derive the corresponding physical parameters of their gaseous structures.

5.4. Upper limit of the Stellar Mass

Accurately estimating the stellar masses (M_*) of LRDs is still challenging. This difficulty stems from the ambiguous origin of their “V-shaped” spectrum and the strong degeneracies in decompose the contributions of stellar light from that of the AGN (e.g., Kokorev et al. 2023; Barro et al. 2024; Furtak et al. 2024; Wang et al. 2024, 2025; Akins et al. 2025a; Labbe et al. 2024).

In this work, we follow the assumption that the rest-frame UV emission is predominantly stellar in origin, while the rest-frame optical is dominated by the AGN (Taylor et al. 2025a; de Graaff et al. 2025b; Barro et al. 2025). Under this assumption, we estimate M_* using the empirical relation between UV luminosity and stellar mass from Song et al. (2016), shown in the last column in Table 1. We note that the derived stellar masses carry a substantial uncertainty of roughly 1 dex. This uncertainty arises because ongoing star formation at the epoch of observation can outshine the integrated light from older stellar populations (Narayanan et al. 2024). Since the AGN light or nebular emission may also contribute to (or even dominate) the UV flux (Chen et al. 2025), our estimates could be regarded as upper limits.

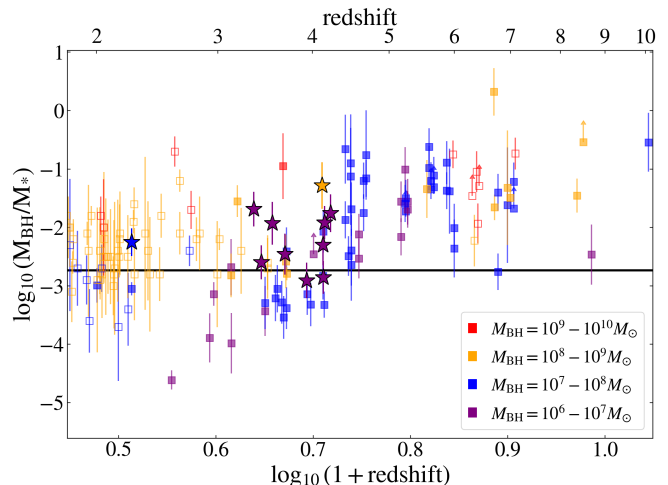


Figure 8. Redshift evolution of the black hole to stellar mass ratio (M_{BH}/M_*). LRD sources from this work are plotted as stars. Filled squares denote recently identified JWST selected normal AGNs and LRDs (Goulding et al. 2023; Larson et al. 2023; Kocevski et al. 2023; Harikane et al. 2023; Bogdán et al. 2024; Wang et al. 2024; Furtak et al. 2024; Kokorev et al. 2024b; Maiolino et al. 2024; Juodžbalis et al. 2024b; Sun et al. 2025; Akins et al. 2025b; Li et al. 2025a). Open squares represent classical QSOs selected from ground-based surveys (Ding et al. 2023; Yue et al. 2024b; Hoshi et al. 2024; Hoshi & Yamada 2025). All symbols are color-coded according to different black hole mass bins. As a benchmark for the local relation, the line $\log_{10}(M_{\text{BH}}/M_*) = -2.73$ (black solid line) is shown, which corresponds to the typical value of the $M_{\text{BH}}/M_{\text{bulge}}$ relation in the local universe for black holes in the mass range $10^6 - 10^{10} M_{\odot}$ (Kormendy & Ho 2013).

Using these stellar mass estimates and M_{BH} , we compute a black hole-to-stellar mass ratio (M_{BH}/M_*) of approximately 0.6% for our sample. We present these results in Figure 8, where our LRDs are plotted alongside AGN samples selected both before the JWST era (Ding et al. 2023; Yue et al. 2024b; Hoshi et al. 2024; Hoshi & Yamada 2025) and from recent JWST surveys (Goulding et al. 2023; Larson et al. 2023; Kocevski et al. 2023; Harikane et al. 2023; Bogdán et al. 2024; Wang et al. 2024; Furtak et al. 2024; Kokorev et al. 2024b; Maiolino et al. 2024; Juodžbalis et al. 2024b; Sun et al. 2025; Akins et al. 2025b; Li et al. 2025a).

Figure 8 shows that our LRD sample appears slightly “overmassive”—i.e., their M_{BH}/M_* ratios are higher—compared to the local $M_{\text{BH}} - M_{\text{bulge}}$ relation. We also find a tentative correlation between the degree of “overmassive” and redshift: lower-redshift sources lie closer to the local relation, and this trend appears to hold within individual black hole mass bins, which is consistent with previous results (e.g., Zhang et al. 2023). Based on these results, we suggest a scenario in which

black holes form and grow rapidly at early times, followed by the gradual buildup of stellar mass in their host galaxies, ultimately establishing the observed $M_{\text{BH}}-M_*$ relation. However, this interpretation remains tentative, given the potential impact of selection biases (e.g., Shen & Kelly 2010; Li et al. 2023) and the intrinsic large scatter from recent simulation results (e.g., Dattathri et al. 2025).

6. SUMMARY

In this work, we investigate the medium/high-resolution spectra of 11 LRDs at redshifts 2–4 from the sample of de Graaff et al. (2025b). By decomposing the broad and narrow components of the Balmer emission lines, we analyze the correlation between the line fluxes and the continuum luminosity and estimate key physical parameters for the LRD sample. Our main conclusions are summarized as follows:

1. The broad component of the $\text{H}\alpha$ emission line ($\text{FWHM} \geq 600\text{km/s}$) shows a strong correlation with the optical luminosity of LRDs but exhibits no correlation with the UV magnitude. This suggests a common origin for the broad $\text{H}\alpha$ component and the optical continuum. In contrast, the [O III] line strength correlates strongly with the UV magnitude but not with the optical luminosity, indicating that the [O III] emission is likely excited by FUV photons from the UV continuum. However, the origin of the UV continuum and the [O III] line remains unclear. The narrow component of $\text{H}\alpha$ ($\text{FWHM} < 600\text{km/s}$) displays only weak correlations with both UV and optical luminosities, implying a more complex origin.
2. Using the FWHM and luminosity of the broad $\text{H}\alpha$ component, we estimate black hole masses in the range $10^6 - 10^8 M_\odot$ for these LRDs, with correspondingly high Eddington ratios ($\lambda_{\text{Edd, med}} = 0.6$). In the plane of the quasar main sequence, they occupy the lower-right region. Assuming a constant mass accretion rate, the growth timescale (or the age) of LRDs in our sample is about $10^5 - 10^7$ year, which is consistent with the estimation results of the “quasistar” evolutionary model. Furthermore, if the current accretion rate is sustained for an additional 20 Myr, the predicted final state of LRDs would lie within the parameter space occupied by local narrow-line Seyfert 1 (NLS1) galaxies.
3. From the four medium-resolution spectra covering the $\text{H}\beta$ region, we do not detect broad Fe II features in the 4434–4684 Å range. Combining these

upper limits with a few Fe II fitting attempts in other LRDs, we suggest that LRDs exhibit intrinsically weaker Fe II emission compared to normal AGN. This may be attributed to structural differences of the gas shell with the AGN unified model.

4. Using the $R - L_{\text{H}\alpha}$ relation, we estimate that the BLR gas is located at distances of 10–26 light-days from the central black hole. To match the size of BLR with the luminosity from the gas shell, we propose an extended, clumpy photosphere with a temperature gradient and a smaller covering factor, rather than a thin, isothermal layer, as the source of the optical continuum. The BLR is located in the inner part of the photosphere. A simple toy model shows that the emission from such an extended gas envelope can be similar to an ideal blackbody spectrum from a much smaller radius.
5. The diversity of the observed optical continuum shapes of LRDs (broader or narrower than a single temperature blackbody) can be explained by the thicker gas envelope as a composite of multiple blackbodies from different layers, or by self-absorption of the blackbody emission in the inner region, respectively. Future high signal-to-noise continuum observations can therefore be used to constrain the physical parameters within the photosphere.

In summary, by combining detailed emission-line information with UV and optical continuum luminosities, we have further constrained the gaseous structure and evolutionary pathway of LRDs. Our results demonstrate the crucial role of JWST NIRSpec medium- and high-resolution spectroscopy in probing the central engines of LRDs. Looking forward, we anticipate using more high SNR spectra to perform detailed analysis of the $\text{H}\beta/[\text{O III}]$ region in LRDs, combining NIRCам and MIRI photometry to study the optical continuum properties of LRDs at higher redshifts, and conducting long-term spectroscopic monitoring to constrain the physical scales of the emission-line and continuum regions. We hope these efforts will lead to a clear understanding of the physical nature of the LRD population and the detailed properties of their gaseous structures in the near future.

ACKNOWLEDGMENTS

We thank Zhiwei Pan for his useful discussions and suggestions. This work is supported by the China Manned Space Program with grant no. CMS-CSST-2025-A06, the National Key R&D Program of China No.2025YFF0510603, the National Natural Science Foundation of China (grant 12373009), the CAS Project for Young Scientists in Basic Research Grant No. YSBR-062, and the Fundamental Research Funds for the Central Universities. XW acknowledges the support by the Xiaomi Young Talents Program, and the work carried out, in part, at the Swinburne University of Technology, sponsored by the ACAMAR visiting fellowship. X.W. acknowledges the National Key R&D Program of China (No. 2025YFA1614100). These observations are associated with programs 1180, 1181, 1210, 1213, 1286, 1287, and 4233. This work is based on observations made with the NASA/ESA/CSA James Webb Space Telescope. The data were obtained from the Mikulski Archive for Space Telescopes at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-03127 for JWST.

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