

The Discovery of Little Red Dots in the Local Universe: Signatures of Cool Gas Envelopes

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(Received XXX; Revised YYY; Accepted ZZZ)

Submitted to AJ

ABSTRACT

JWST observations have revealed a population of high-redshift “little red dots” (LRDs) that challenge conventional AGN models. We report the discovery of three local LRDs at $z = 0.1\text{--}0.2$, initially selected from the SDSS database, with follow-up optical/near-IR spectroscopy and photometry. They exhibit properties fully consistent with those of high-redshift LRDs, including **broad hydrogen and helium emission lines**, compact morphologies, V-shaped UV-optical SED, declining near-IR continua, and **no significant variability**. Two sources were targeted but not detected in X-rays with statistical significance. All three sources show blue-shifted He I absorption, while two exhibit H α and Na D absorption lines. We detect **full Balmer and Paschen line series** in all three objects, along with abundant narrow [Fe II] emission in two. The emission line analyses suggest narrow lines originate from AGN-powered, metal-poor regions with minimal dust; broad lines come from inner regions with exceptionally high density or atypical dust properties; and [Fe II] emission arises from dense gas between broad and narrow-line regions. One of our objects, J1025+1402 (nicknamed *The Egg*), shows extremely high equivalent width Na D, K I, Fe II, and Ca II triplet absorption lines, suggesting the presence of a cool (~ 5000 K), metal-enriched gas envelope. The optical/near-IR continua of these LRDs are also consistent with theoretical models featuring an atmosphere around black holes. The WISE-detected IR emission is consistent with weak dust emission of $T \sim 10^2 - 10^3$ K. We propose a conceptual model consisting of a largely thermalized cool-gas envelope surrounding the central black hole and an extended emission line region with high-density outflowing gas to explain the observed properties of these local LRDs.

Keywords: high-redshift — active galactic nuclei — black holes

1. INTRODUCTION

The so-called “little red dots” (LRDs) have been among the most significant discoveries of the early years of JWST operations (e.g., I. Labbe et al. 2025; J.

Matthee et al. 2024; X. Lin et al. 2024; H. B. Akins et al. 2024). These sources appear compact even in JWST imaging, and the majority of them (over 70–80%) exhibit broad Balmer emission lines with FWHM $\gtrsim 1000 \text{ km s}^{-1}$, indicative of black holes (BHs) of 10^6 – $10^8 M_{\odot}$ (e.g., J. E. Greene et al. 2024; D. D. Kocevski et al. 2024; J. Zhang et al. 2025). They display V-shaped spectral energy distributions (SEDs), characterized by a blue UV continuum and a red optical continuum (D. D. Kocevski et al. 2024; D. J. Setton et al. 2024; R. E. Hviding et al. 2025). Moreover, a large fraction of these V-shaped objects present Balmer absorption on top of the broad emission line, which is rarely seen in other type-1 AGNs (e.g., J. Matthee et al. 2024; X. Lin et al. 2024; B. Wang et al. 2025a; F. D’Eugenio et al. 2025).

Debates about the nature of LRDs are ongoing, particularly concerning the origin of their V-shaped SEDs, the spectral shape inflection near the Balmer break, and the prevalence of Balmer absorption (e.g., D. J. Setton et al. 2024; X. Lin et al. 2024). Early studies have shown that if the Balmer break arises from massive host galaxies, it would challenge our current understanding of structure formation (e.g., B. Wang et al. 2024; I. Labbe et al. 2024). Alternatively, if these features are attributed to reddened AGNs, it is difficult to account for the lack of strong rest-frame IR detections for most high-redshift LRDs, by JWST/MIRI, Spitzer, or ALMA (e.g., P. G. Pérez-González et al. 2024; C. C. Williams et al. 2024; Y. Ma et al. 2024; D. J. Setton et al. 2025). New models have started to explore the distribution of dust (Z. Li et al. 2025; K. Chen et al. 2025), along with new constraints on the dust content in LRDs from multi-wavelength data (C. M. Casey et al. 2024, 2025).

The unusual continuum shape of LRDs has motivated multiple theoretical models (K. Inayoshi et al. 2025; D. Kido et al. 2025). Recent studies have proposed that BHs embedded in dense gas with a high covering fraction can explain the presence of both the observed Balmer breaks and absorption features (K. Inayoshi & R. Maiolino 2024). Such models have been applied to several high-redshift LRDs and have achieved reasonably good fits to their spectra (X. Ji et al. 2025; A. J. Taylor et al. 2025a; A. de Graaff et al. 2025; R. P. Naidu et al. 2025). However, for sources with rest-frame IR detections, these models struggle to simultaneously reproduce the weak IR photometry and the shape of Balmer breaks. They typically require either an extremely high column density of hydrogen gas (e.g., $N_{\text{H}} = 10^{26} \text{ cm}^{-2}$), exotic modified dust attenuation laws, or intrinsically red AGN SEDs (A. de Graaff et al. 2025). Even with these additional free parameters, challenges still remain for fully explaining the IR broadband photometry (e.g.,

A. de Graaff et al. 2025; R. P. Naidu et al. 2025; A. J. Taylor et al. 2025a).

Currently, only a limited number of high-redshift LRDs have been detected with JWST/MIRI, while the vast majority remain either not covered by or undetected in the mid-IR (e.g., G. C. K. Leung et al. 2024; D. J. Setton et al. 2025; X. Lin et al. 2025; A. J. Taylor et al. 2025a). Most JWST/NIRSpec spectroscopy of LRDs at $z > 4$ has been conducted in the prism mode, and high-resolution grating observations of several objects reveal only their brightest features. In contrast, LRDs at low redshifts can be observed with a variety of facilities/instruments at multiple wavelengths, with high spectral and spatial resolution at relatively low cost, providing deep insights into the nature of LRDs as a population. Rest-frame IR and high-resolution grating spectra have been obtained for a small number of luminous LRDs at cosmic noon (e.g., I. Juodžbalis et al. 2024; B. Wang et al. 2025a; A. de Graaff et al. 2025). Systematic searches for LRDs at $z < 4$ using wide-field sky surveys are now underway and have already demonstrated successful spectroscopic follow-up with ground-based facilities (R. Lin et al. 2025; Y. Ma et al. 2025; Euclid Collaboration et al. 2025). However, photometrically selected LRDs at cosmic noon are still relatively faint ($m_g \sim 24$ – 25 mag), making follow-up observations challenging with current ground-based facilities.

Identifying LRDs in the local Universe opens a valuable window into understanding the nature of this population. Recent observations and theoretical predictions suggest that their number density declines significantly at $z < 4$, dropping by 1–2 dex from $z \sim 4$ to $z \sim 2$ (D. D. Kocevski et al. 2024; Y. Ma et al. 2025; K. Inayoshi 2025). This implies that local LRDs are rare and are linked to physical conditions that may be more common in the early Universe. Their discovery at low redshift would offer critical insights into the evolutionary pathways of LRDs and their connection to BH growth across cosmic time. Moreover, local LRDs may enable spatially resolved observations of themselves, their host galaxies, and their environments, revealing their structure, kinematics, and dust/gas content. These observations would not only be cost-effective but also may unravel details that remain challenging to obtain from their high-redshift counterparts, even with JWST.

In this paper, we present the search and discovery of three local LRDs at $z=0.1$ – 0.2 from the SDSS spectroscopic database, followed by high signal-to-noise radio ground-based spectroscopic observations. The paper is organized as follows. In §2 we introduce the selection criteria we used to search the SDSS spectral database for local LRDs. We present the SDSS data and follow-

up observations on the three selected local LRDs in §3. In §4 we describe their overall properties and spectral features, which are fully consistent with those of JWST-discovered high-redshift LRDs. In §5, we analyze their emission line properties and infer the physical conditions. We then conduct a detailed case study of one object in §6. Finally, in §7 we interpret the observed features to understand their physical nature. Throughout this work, we adopt the AB magnitude system for all photometric measurements. All equivalent widths (EWs) are reported in the rest frame. A flat Λ CDM cosmology is assumed, with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_{\Lambda,0} = 0.7$, and $\Omega_{m,0} = 0.3$.

2. SELECTION AND SAMPLE FROM SDSS

In the literature, a wide range of selection criteria have been used to define the LRD population (e.g., [K. N. Hainline et al. 2025](#); [R. E. Hviding et al. 2025](#)). In this paper, we adopt a narrow definition of LRDs, referring specifically to objects that simultaneously satisfy the following criteria: (1) presence of broad Balmer emission lines; (2) compact morphology in the rest-frame optical, particularly in photometric bands dominated by $H\alpha$ emission; and (3) a V-shaped SED, characterized by a blue UV continuum slope and red optical continuum slope. A detailed description of the selection of local LRDs will be presented in an upcoming paper. Here, we provide a summary of the procedure.

2.1. Selection

We first built a library of high-redshift LRDs with well-characterized UV-to-optical spectra. We adopted the compilation of high-redshift LRDs from [D. J. Setton et al. \(2024\)](#), which exhibit clear V-shaped SEDs with inflection points near the Balmer limit. Their JWST/NIRSpec PRISM spectra were obtained from the DAWN JWST Archive ¹¹.

We then searched for local LRD candidates in the SDSS DR17¹² spectroscopic database ([K. N. Abazajian et al. 2009](#); [Abdurro'uf et al. 2022](#)). We started with the *GUVmatch*¹³ catalog, which cross-matches GALEX far-UV (FUV) and near-UV photometry (NUV) with SDSS DR14 *ugriz* photometry. We shifted the high-redshift LRD PRISM spectra to $z = 0.0\text{--}0.5$ to serve as templates for our local LRD search. This redshift range was chosen to ensure that the $H\alpha$ emission line falls within the SDSS spectroscopic wavelength coverage. We then re-projected the template spectra to GALEX and SDSS

photometry to obtain the expected broadband photometry of local LRDs. Using these synthetic colors, we searched for candidates in *GUVmatch* with similar SED shapes. Specifically, we computed the Euclidean distance in magnitude space between the observed photometry and each individual template. This distance was defined as the root mean square of the magnitude differences across the GALEX and SDSS bands, normalized by the r -band flux. Then, we selected sources with a distance of less than one magnitude from any of the templates. Finally, we imposed a compactness criterion by requiring the SDSS-reported Petrosian radii ([V. Petrosian 1976](#)) in both the g and r bands to be smaller than 1.8 arcsec (physical scale of 3.3 kpc at $z \sim 0.1$). This morphological criterion was relatively permissive, and variations in the threshold do not affect the selection results.

After the photometric selection, we retrieved the SDSS spectra of the selected candidates. We examined their emission line properties using the *SPZLINE* extension, which provides automated emission-line fits from the SDSS pipeline ([A. S. Bolton et al. 2012](#)). We first required the EWs of [O III] $\lambda 5008$ to exceed 10 Å, and the line ratio [O III] $\lambda 5008$ /[O II] $\lambda 3727$ (O32) to be greater than 10. The first criterion effectively excludes stellar objects, quiescent galaxies, and post-starburst galaxies, which could exhibit strong Balmer breaks and are prevalent in the local Universe. The second criterion ensures that the selected galaxies have physical conditions similar to those of high-redshift galaxies.

To further remove contaminants and confirm the presence of red optical continua, we inspected the continuum underlying emission lines in the *SPZLINE* extension. We required the continuum under $H\alpha$ to be redder than that under [O III] $\lambda 5008$, i.e., $\frac{f_{\text{cont},H\alpha}}{f_{\text{cont},[\text{OIII}]}} > 1$ in f_λ space. We also required the [O III] $\lambda 5008$ continuum to be redder than that under [O II] $\lambda 3727$.

Although we define LRDs by the presence of broad $H\alpha$ lines, up to this stage, the broad-line criterion has not yet been explicitly applied during the selection process above. Nonetheless, all targets selected based on the above criteria have already exhibited clear broad $H\alpha$ emission in their SDSS spectra. We therefore obtained a sample of local sources that meet all the criteria defining LRDs from the SDSS DR17 spectroscopic database.

2.2. Sample from SDSS

In this paper, we report the discoveries and follow-up observations of three local LRDs: SDSS J102530.29+140207.3 (J1025+1402 hereafter), SDSS J104755.92+073951.2 (J1047+0739), and SDSS

¹¹ <https://dawn-cph.github.io/dja/>

¹² <https://www.sdss4.org/dr17/>

¹³ <https://archive.stsci.edu/hlsp/guvcat>

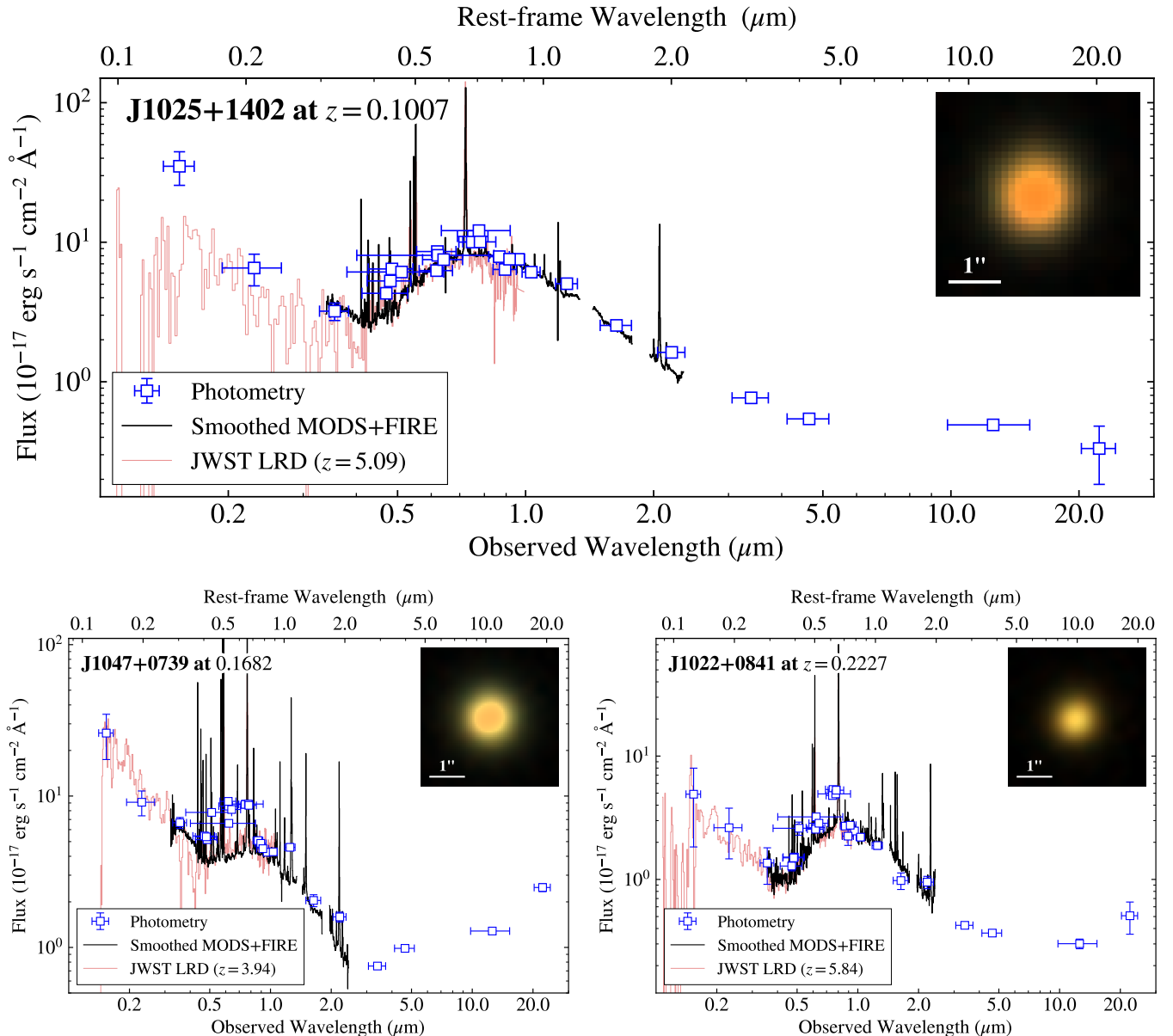


Figure 1. The images, multi-wavelength photometry, and LBT/MODS and Magellan/FIRE spectra of the three local LRDs. The photometric data are shown as the blue squares. The LBT/MODS+ Magellan/FIRE spectra are shown as the black lines. The spectra are smoothed for display purposes only. The RGB thumbnails are composed of the *grz* images from the Legacy Surveys DR10. The red lines show the best-matching LRD templates from the compilation by D. J. Setton et al. (2024). These templates are JWST/NIRSpec PRISM spectra with their original redshifts labeled, but have been shifted to match the redshift of each local LRD.

J102208.52+084156.1 (J1022+0841). The full sample will be presented in a forthcoming paper.

Figure 1 shows the images, photometry, and spectra of the three selected local LRDs. These objects closely match their corresponding LRD templates and exhibit unambiguous V-shaped UV-to-optical SEDs.

In fact, the local LRDs presented in this paper were originally selected as quasar candidates (G. T. Richards et al. 2002). The SDSS target selection flag

for J1025+1402 and J1022+0841 is QSO_HIZ, as their *riz* colors meet the criteria for selecting high-redshift quasars, primarily at $z \gtrsim 3.5$. Both objects show rising flux toward and peaking in the *i* band, followed by a decline toward the *z* bands, resembling the spectral shape of a Lyman break with a blue UV continuum, characteristic of quasars at $z > 3.5$. J1047+0739 is flagged as both QSO_CAP and QSO_HIZ: the former because its *u-g* color meets the selection criteria for quasars at $z < 2.2$,

and the latter because it satisfies a relaxed *griz* criterion for high-redshift quasars. These flags indicate that the three selected objects are outliers in both the *ugri* and *griz* color spaces, making them easily misclassified during color selection.

Our LRD selection is incomplete, since it requires that the object has an existing SDSS spectrum. The SDSS main galaxy survey is biased against LRDs because of their compact morphology, which is one of the reasons that they are labeled as quasar candidates. Therefore, we estimate a conservative lower limit on the number density of local LRDs at $z=0-0.5$, based on the effective SDSS survey area of $9,376 \text{ deg}^2$. The discovery of these three objects yields an estimated lower limit of approximately $5 \times 10^{-10} \text{ Mpc}^{-3}$ within this redshift range. Our estimated number density at $z=0-0.5$ is more than several orders of magnitude higher than the extrapolation of the log-normal distribution fitted to the LRD population at $z \sim 4-7$ (K. Inayoshi 2025). However, this large discrepancy arises in the exponentially damped tail of the assumed distribution, where such divergence is expected due to the steep functional form and limited constraints at low redshifts. We find that a modest increase in the dispersion (by 10–20%) of the log-normal model from K. Inayoshi (2025) yields a redshift evolution of the LRD abundance consistent not only with measurements at $z \approx 2-3$ (Y. Ma et al. 2025), but also with our observations at $z=0-0.5$. Nonetheless, this trend suggests that the BH accretion mode giving rise to LRDs, while rare in the local Universe, is not exclusively unique to the early Universe.

From the SDSS spectra, J1025+1402 shows clear blueshifted $\text{H}\alpha$ absorption, while J1022+0841 exhibits tentative but unresolved $\text{H}\alpha$ absorption. Both features are confirmed by our spectroscopic follow-up with higher spectral resolution (see §4.3). J1025+1402 and J1047+0739 were identified by Y. I. Izotov & T. X. Thuan (2008) as metal-poor AGNs in SDSS DR5, with $12 + \log(\text{O}/\text{H}) = 7.36$ and 7.99 , respectively. C. Simmonds et al. (2016) further noted that they are weak in X-rays, revealed by the non-detection of Chandra. C. J. Burke et al. (2021) found no significant variability in either optical broadband photometry or broad $\text{H}\alpha$ luminosity.

3. DATA AND OBSERVATIONS

3.1. Photometry

The three targets were observed by multiple wide-field sky surveys. We adopt photometric data from the following surveys: FUV and NUV from GALEX DR6 (L. Bianchi & B. Shiao 2020), *ugriz* Petrosian photometry from SDSS DR17 (K. N. Abazajian et al. 2009; Ab-

durro'uf et al. 2022), *grizy* PSF photometry from Pan-STARRS DR2 (H. A. Flewelling et al. 2020), *g, bp, rp* mean photometry from GAIA DR3 (Gaia Collaboration et al. 2023), *griz* photometry from Legacy Surveys DR10 (A. Dey et al. 2019), *YJHK* Petrosian photometry from UKIDSS DR11PLUS (A. Lawrence et al. 2007), and W1, W2, W3, W4 photometry from WISE (E. L. Wright et al. 2010). The GALEX photometry is taken from the GUVmatch catalog. The WISE photometry has been incorporated into the Legacy Survey catalog based on the unWISE images (E. F. Schlafly et al. 2019). All other data are retrieved from Astro Data Lab¹⁴ (M. J. Fitzpatrick et al. 2014; R. Nikutta et al. 2020).

3.2. Spectroscopic Follow-up Observations

We obtained high signal-to-noise-ratio (S/N) LBT/MODS and Magellan/FIRE spectroscopy to characterize the UV-to-NIR spectra of the three local LRDs. We also obtained MMT/Binospec spectra of J1025+1402 and J1022+0841 to measure their high-resolution $\text{H}\alpha$ profiles.

The LBT/MODS (R. W. Pogge et al. 2010) is a pair of dual-channel spectrographs on the $2 \times 8.4\text{m}$ Large Binocular Telescope, with the blue channel covering $3300-6000 \text{ \AA}$ and the red channel $5000-10000 \text{ \AA}$. We observed the three targets on February 24, 2025, using 1.0-arcsec slits in grating mode under an average seeing of ~ 0.8 arcsec. This setup achieved a spectral resolution of $R \approx 800-1500$ in the blue channel and $R \approx 800-1700$ in the red channel. Observations of each target included $3 \times 600\text{s}$ exposures in both the blue and red channels, with the two LBT telescopes observing simultaneously. As a result, each target effectively has $6 \times 600\text{s}$ exposures in both the blue and red channels.

The Magellan/FIRE (R. A. Simcoe et al. 2013) is a near-IR echelle spectrograph covering $0.8-2.5 \mu\text{m}$ on the 6.5m Magellan Baade Telescope. We observed J1025+1402 using a 0.75-arcsec slit on December 21, 2024, reaching $R = 3000-6000$. The observation included $5 \times 900\text{s}$ exposures. We observed J1047+0739 and J1022+0841 using 1-arcsec slits on March 11, 2025, with $7 \times 900\text{s}$ exposures for J1047+0739 and $6 \times 900\text{s}$ exposures for J1022+0841, reaching $R = 2000-4000$. The seeing for these observations was $\sim 0.5-0.7$ arcsec.

The MMT/Binospec observation of J1025+1402 was conducted in the IFU mode (D. Fabricant et al. 2019, 2025) on December 7, 2024, using the 600 line/mm grating. The observation consisted of $3 \times 600\text{s}$ exposures and achieved a spectral resolution of $R \sim 3600$. The see-

¹⁴ <https://datalab.noirlab.edu/>

ing during the observation was approximately 1.6 arcsec. For J1022+0841, the observation was conducted in long-slit mode on January 23, 2024, using a 1-arcsec slit and the 600 line/mm grating, under a seeing of approximately 2.3 arcsec. The observation included 6×600 s exposures, with a spectral resolution of $R \sim 4400$.

The LBT/MODS and Magellan/FIRE data were reduced with `PypeIt` (J. Prochaska et al. 2020). We performed bias subtraction, flat-fielding, wavelength calibration, sky subtraction, spectral extraction, and telluric correction. To correct for slit losses and calibrate the absolute flux of the LBT/MODS spectra, we first matched them to the SDSS spectra using a wavelength-dependent linear function. The spectra in SDSS DR17 have been processed with an updated flux calibration algorithm, yielding significant improvements at wavelengths below 6000 \AA ¹⁵. We confirmed that the SDSS spectra closely follow the shape of the corresponding photometry. Then, we applied a constant scaling factor to align the semi-calibrated spectra with the SDSS *ugriz* photometry. The Magellan/FIRE spectra were scaled to match the UKIDSS *Y*-band photometry using a constant factor. The MMT/Binospec data were reduced using the `Binospec` pipeline (J. Kinsky et al. 2019). The IFU data were extracted with a rectangular aperture matching the seeing disk. Throughout this work, most measurements are based on MODS and FIRE spectra, while Binospec spectra are used exclusively to analyze the $H\alpha$ absorber profiles of J1025+1402 and J1022+0841.

The SDSS spectra have a resolution of $R \sim 1500\text{--}2500$. We convolve the SDSS spectra to match the spectral resolution of the MODS data. These SDSS spectra reach $S/N \approx 2.5$ per \AA at $4000\text{--}5000 \text{ \AA}$ and $S/N \approx 9$ at $7000\text{--}8000 \text{ \AA}$ for J1025+1402. In stark contrast, the MODS-B and MODS-R spectra achieve $S/N \approx 13$ and 81 , respectively, improving the S/N by factors of 5 (blue) and 9 (red). For J1047+0739, the S/N improves from 3.5 to 19 at $4000\text{--}5000 \text{ \AA}$, and from 6 to 60 at $7000\text{--}8000 \text{ \AA}$. For J1022+0841, the S/N increases from 0.6 to 5.5 at $4000\text{--}5000 \text{ \AA}$, and from 2.6 to 29 at $7000\text{--}8000 \text{ \AA}$.

Figure 1 shows the UV-to-NIR spectra, multi-wavelength photometry, and images of the three targets. The LBT/MODS spectra confirm the presence of the V-shape of the UV-to-optical continua. The declining near-IR spectra in f_λ space are consistent with the rest-frame IR photometry of bright high-redshift LRDs detected by MIRI (e.g., B. Wang et al. 2025a; A. de

Graaff et al. 2025; A. J. Taylor et al. 2025a; D. J. Setton et al. 2025).

4. EVIDENCE AS LOCAL LRDs

In this section, we present the observed characteristics of three local objects that closely resemble high-redshift LRDs. The section is organized as follows: morphology and continuum luminosities are discussed in §4.1; broad emission lines and BH masses in §4.2; Balmer and He I absorption features in §4.3; variability properties in §4.4; X-ray and radio properties in §4.5; and a summary of the observational evidence as LRDs is provided in §4.6. We present their zoomed-in spectra in Figures 2, 3, and 4, and summarize the derived properties in Table 1.

4.1. Morphology and Continuum Luminosity

All three objects exhibit very compact morphologies across the optical bands. They are not spatially resolved in LBT/MODS direct imaging with a seeing of $\sim 0.9''$. This implies that the diameter of J1025+1402 is comparable to or smaller than 1.7 pkpc, while those of J1047+0739 and J1022+0841 are constrained to be smaller than 2.5 pkpc and 2.3 pkpc, respectively.

J1047+0739 was observed with the HST/ACS FR782N ramp filter narrow-band imaging that covers both the $H\alpha$ line and the adjacent continuum (GO-15617; PI: F. Bauer), achieving a spatial resolution of 206 pc. The continuum map reveals a bright central point source contributing about 85% of the light, alongside a compact yet clumpy host galaxy with a half-light radius of 530 pc. The $H\alpha$ line map is dominated by the central point source with minimal host contribution. The spatially resolved map shows that, in J1047+0739, AGN emission dominates both the continuum and the $H\alpha$ line, in agreement with our definition of LRDs, although with a non-negligible contribution of the stellar light from the host galaxy to the continuum. The detailed morphological analysis is presented in Appendix A. Future high-resolution imaging with HST, JWST, or ground-based AO will further constrain the properties of the physical sizes of the local LRDs and their host galaxy properties.

All three objects exhibit continuum shapes characterized by pronounced V-shapes and declining IR slopes. The inflections occur near the Balmer limit. The continuum luminosity at rest-frame 5100 \AA (λ_{L5100}) is around $10^{43} \text{ erg s}^{-1}$. J1047+0739 exhibits a potential Balmer jump, presumably due to the presence of a host galaxy. For all three objects, the WISE photometry at rest-frame $3\text{--}20 \mu\text{m}$ reveals the presence of weak dust emission, at a wavelength range beyond what is possible with JWST observations of high-redshift LRDs. We integrate the continua from rest-frame 2000 \AA to $20 \mu\text{m}$

¹⁵ <https://www.sdss4.org/dr17/algorithms/spectrophotometry/>

Basic property

Name	RA	DEC	z	r (mag)	λL_{5100} (10^{42} erg s $^{-1}$)	$L_{2000\text{\AA}-20\mu\text{m}}$ (10^{43} erg s $^{-1}$)	$L_{2-10\text{keV}}$ (10^{41} erg s $^{-1}$)	$12 + \log(\text{O}/\text{H})$
J102530.29+140207.3	156.37622	14.03586	0.1007	19.003	7.47 ± 0.30	$4.95^{+0.03}_{-0.02}$	< 1.1	7.55 ± 0.03
J104755.92+073951.2	161.98302	7.66423	0.1682	18.846	18.5 ± 0.53	29.93 ± 0.01	$2.2^{+2.1}_{-1.2}$	8.00 ± 0.02
J102208.52+084156.1	155.53552	8.69892	0.2227	20.011	17.4 ± 0.31	$17.72^{+0.03}_{-0.04}$	–	7.43 ± 0.03

 $\text{H}\alpha$ emission-line and BH properties

Name	$L_{\text{H}\alpha,\text{broad}}$ (10^{41} erg s $^{-1}$)	$L_{\text{H}\alpha,\text{narrow}}$ (10^{41} erg s $^{-1}$)	$\text{FWHM}_{\text{H}\alpha,\text{broad}}^*$ (km s $^{-1}$)	$\text{FWHM}_{\text{H}\alpha,\text{narrow}}$ (km s $^{-1}$)	$\log(M_{\text{BH}}/M_{\odot})$
J1025+1402	8.68 ± 0.13	1.33 ± 0.02	983 ± 10	unresolved 17 ± 1^a	$6.25^{+0.08}_{-0.07}$
J1047+0739	27.51 ± 0.58	18.86 ± 0.15	949 ± 25	47 ± 3	6.50 ± 0.09
J1022+0841	48.10 ± 0.49	3.43 ± 1.10	1022 ± 18	170 ± 17^b 77 ± 2^a	6.70 ± 0.09

Table 1. Observed and derived properties of the three local LRDs. The first table presents photometric and continuum parameters, along with metallicities derived using the direct T_e method. The systemic redshifts are determined by the center of the narrow $\text{H}\alpha$ emission lines. The r -band magnitude is the observed magnitude from Legacy Survey DR10 (A. Dey et al. 2019). The 2–10 keV luminosity is adopted from C. Simmonds et al. (2016), assuming a $\Gamma = 1.8$ powerlaw spectrum absorbed by Galactic H I. The second table lists the emission-line and BH properties, including luminosities of broad and narrow $\text{H}\alpha$, FWHMs, and BH mass estimates. $\text{FWHM}_{\text{H}\alpha,\text{broad}}^*$ refers to the effective FWHM of the composite broad $\text{H}\alpha$ profile, modeled with multiple Gaussian components spanning intermediate ($\gtrsim 500$ km s $^{-1}$) to very broad (~ 2000 km s $^{-1}$) line widths. For consistency, all these measurements are based on the MODS spectra. ^a measured from Binospec spectra. ^b blended with $\text{H}\alpha$ absorption.

to estimate the total continuum luminosity over this wavelength range, yielding $L_{2000\text{\AA}-20\mu\text{m}} \sim 5 \times 10^{43} - 3 \times 10^{44}$ erg s $^{-1}$ for all three objects.

4.2. Broad Emission Lines and BH masses

The three objects show clear broad profiles in $\text{H}\alpha$, $\text{H}\beta$, $\text{Pa}\alpha$ to $\text{Pa}\delta$, and several He I lines (e.g., He I $\lambda 7065$, $\lambda 10830$). J1025+1402 and J1022+0841 also exhibit broad infrared O I emission lines, consistent with the line broadening originating from gas motions in the BLRs around BHs. The methodology of the line measurements is detailed in Appendix B. Specifically for the $\text{H}\alpha$ lines, we model the narrow component using a single narrow Gaussian. The broad components are fitted with two to three broad Gaussians. The [N II] $\lambda\lambda 6548, 6583$ doublet is modeled with two narrow Gaussians sharing the same FWHM as the narrow $\text{H}\alpha$ component and fixed line ratios of 3. For J1025+1402 and J1022+0841, additional Gaussian absorbers are applied atop the broad emission lines. The measurements from the MODS spectra are summarized in Table 1. We also report the narrow $\text{H}\alpha$ FWHMs of J1025+1402 and J1022+0841 from the Binospec spectra, taking advantage of its higher spectral resolution.

All three objects exhibit broad $\text{H}\alpha$ emission with luminosities around 10^{42} erg s $^{-1}$, and their individual broad

components exhibit FWHMs ranging from > 500 km s $^{-1}$ to 2000 km s $^{-1}$, with the composite FWHMs around ~ 1000 km s $^{-1}$. We estimate their BH masses using the $\text{H}\alpha$ luminosity ($L_{\text{H}\alpha}$), the composite broad-line $\text{H}\alpha$ FWHM, and the empirical relation from J. E. Greene & L. C. Ho (2005). We find BH masses around $10^6 - 10^7 M_{\odot}$. This scaling relation for BH mass estimates is widely used in high-redshift LRD studies (e.g., J. Matthee et al. 2024; X. Lin et al. 2024, 2025; A. J. Taylor et al. 2025b). However, this estimator might not be fully applicable to LRDs, if their physical nature is different from classical AGNs, particularly if their line profiles and continua arise from distinct physical mechanisms (see §7). The measured $L_{\text{H}\alpha,\text{broad}}$ values in these objects are 3–6 times higher than the $L_{\text{H}\alpha}$ predicted by the $L_{5100} - L_{\text{H}\alpha}$ relation in J. E. Greene & L. C. Ho (2005), where $L_{\text{H}\alpha}$ refers to the total (broad + narrow) $\text{H}\alpha$ luminosity from AGNs. It remains unclear whether L_{5100} or $L_{\text{H}\alpha,\text{broad}}$ reliably traces the BLR size in these systems.

4.3. Balmer and He I Absorption

Figure 5 presents the line profiles of $\text{H}\beta$, $\text{H}\alpha$, He I, and $\text{Pa}\alpha$ for the three local LRDs. All three objects exhibit absorption lines in their Balmer series or He I $\lambda 10830$ lines. For $\text{H}\alpha$, we model the absorber as Gaus-

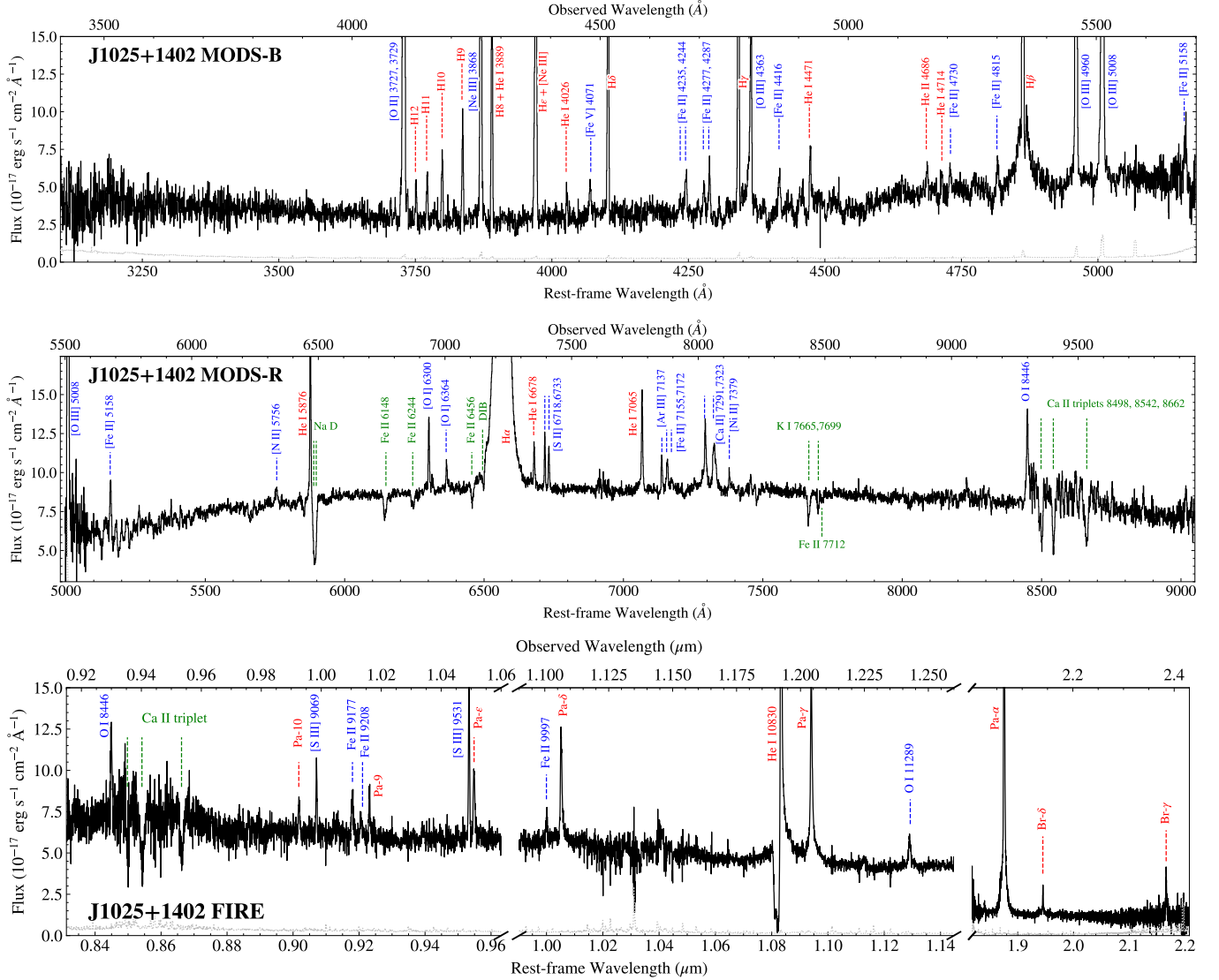


Figure 2. Zoomed-in view of the MODS blue channel (MODS-B), MODS red channel (MODS-R), and Magellan/FIRE spectra of J1025+1402. Hydrogen and helium emission lines are marked with red dashed lines and labels, while metal emission lines are indicated with blue dashed lines and labels. Metal absorption features are labeled as green dashed lines. The gray dotted lines represent the 1σ flux uncertainties. In the MODS-R spectrum, these uncertainties are sufficiently low to fall below the plotted range.

sian components superimposed on the intrinsic broad $H\alpha$ emission. We then simultaneously fit the absorbers, the narrow $H\alpha$, broad $H\alpha$, and the $[\text{N II}] \lambda\lambda 6548, 6583$ doublet. For $H\beta$ and $\text{He I } \lambda 10830$, absorbed regions are masked, and the intrinsic emission line profile is modeled using a narrow Gaussian combined with multiple broad Gaussians. The detailed fitting methodology and complete absorption measurement information are described in Appendix B.

J1025+1402 exhibits a redshifted $H\beta$ absorption feature superimposed on the broad $H\beta$ emission and continuum, with $\Delta v = 73 \text{ km s}^{-1}$ and $\text{EW} = 4.16 \pm 0.43 \text{ \AA}$. A similar redshifted $H\beta$ absorber is also seen in the triply

imaged $z = 7.04$ LRD in the Abell 2744 field (X. Ji et al. 2025). J1025+1402 and J1047+0739 both have $H\alpha$ absorption, superimposed on the broad $H\alpha$ emission. The $H\alpha$ absorber of J1025+1402 has an EW of $2.54 \pm 0.07 \text{ \AA}$, and is blueshifted by $\Delta v = -148 \text{ km s}^{-1}$ relative to the center of the broad $H\alpha$ component. The $H\alpha$ absorber in J1022+0841 can be described with two Gaussian components, one blueshifted by $\Delta v = -96 \text{ km s}^{-1}$ and one redshifted by $\Delta v = 102 \text{ km s}^{-1}$. Their EW s are $0.92 \pm 0.21 \text{ \AA}$ and $2.08 \pm 0.52 \text{ \AA}$, respectively, yielding a total EW of $3.00 \pm 0.56 \text{ \AA}$. An alternative solution is one Gaussian absorber with $\Delta v = 11 \text{ km s}^{-1}$ and EW of $4.16 \pm 0.33 \text{ \AA}$ (see

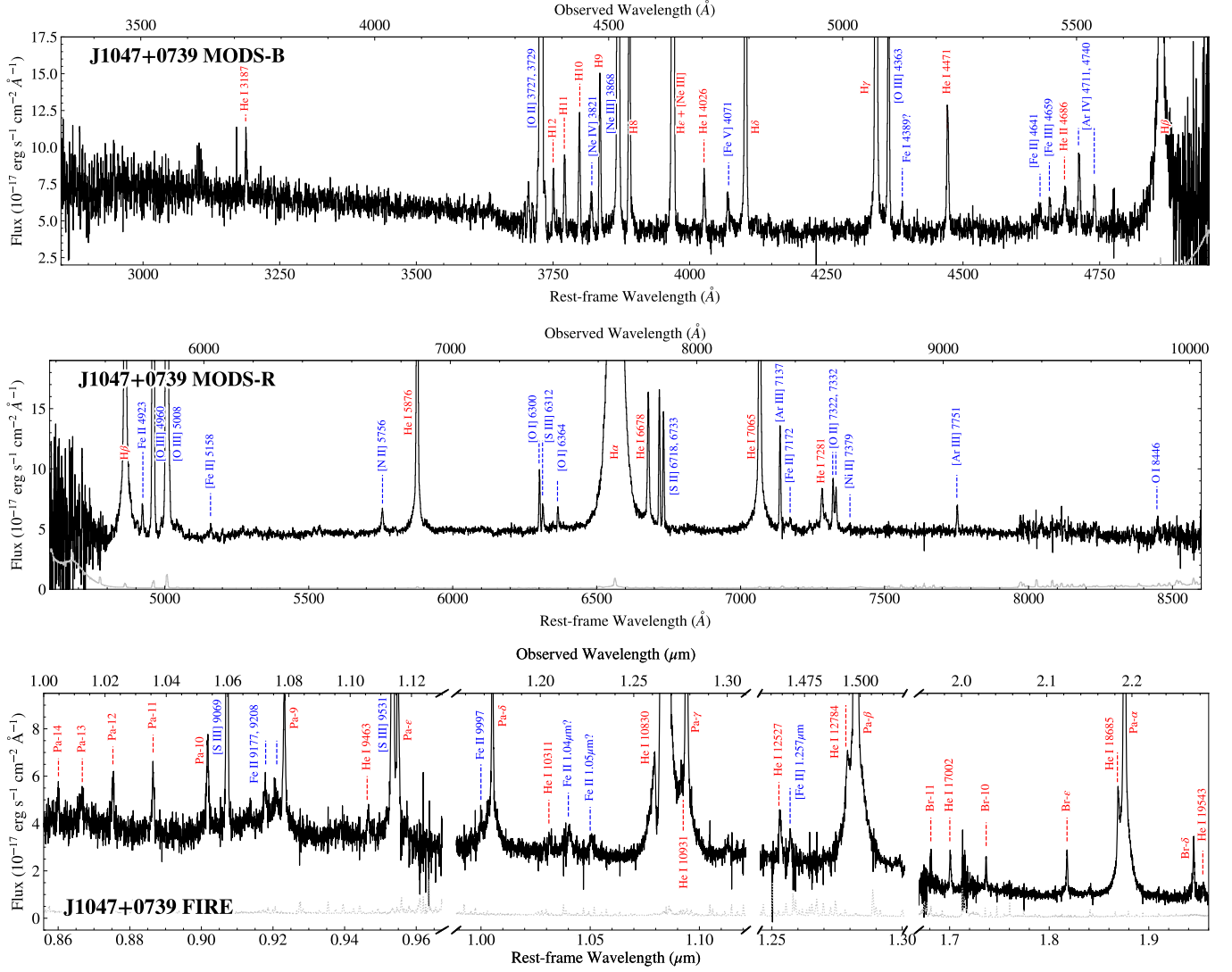


Figure 3. Zoomed-in view of the spectra of J1047+0739, similar to Figure 2

Appendix B). J1047+0739 does not show clear Balmer absorption.

The lack of $H\beta$ absorbers corresponding to $H\alpha$ absorbers in J1025+1402 and J1022+0841 might be attributed to the S/N of the $H\beta$ spectra. However, a puzzling aspect of J1025+1402 is that its redshifted $H\beta$ absorber does not have corresponding $H\alpha$ absorption. This suggests that the two lines might have distinct origins.

All three targets show prominent blueshifted He I $\lambda 10830$ absorption. The He I $\lambda 10830$ absorber of J1025+1402 and J1047+0739 has multiple components with distinct kinematics (Figure 6). The line profile of the J1025+1402 He I $\lambda 10830$ absorber, as shown in Figure 5, can be described using three Gaussian components, blueshifted with $\Delta v = -613, -410,$ and -248 km s^{-1} , respectively. This profile may alternatively result from a mixture of saturated He I absorbers.

The line profile of the J1047+0739 He I $\lambda 10830$ absorber can be described using five Gaussian components with $\Delta v = -1646, -1431, -1088, -889,$ and -801 km s^{-1} , respectively. For J1022+0841, the He I $\lambda 10830$ absorber is well described by a single Gaussian component with $\Delta v = -54 \text{ km s}^{-1}$. They highlight the prevalence of He I absorption in local LRDs. As shown in Figure 6, for J1025+1402 and J1022+0841, the velocities of the He I and $H\alpha$ absorbers are not well aligned, indicating complex outflow kinematics.

For reference, we also show the $\text{Pa}\alpha$ line profile in Figure 5. No absorption features are associated with $\text{Pa}\alpha$. This suggests that the Balmer absorbers originate from hydrogen atoms with a population elevated to the $n = 2$ energy level, but not to the $n = 3$ level.

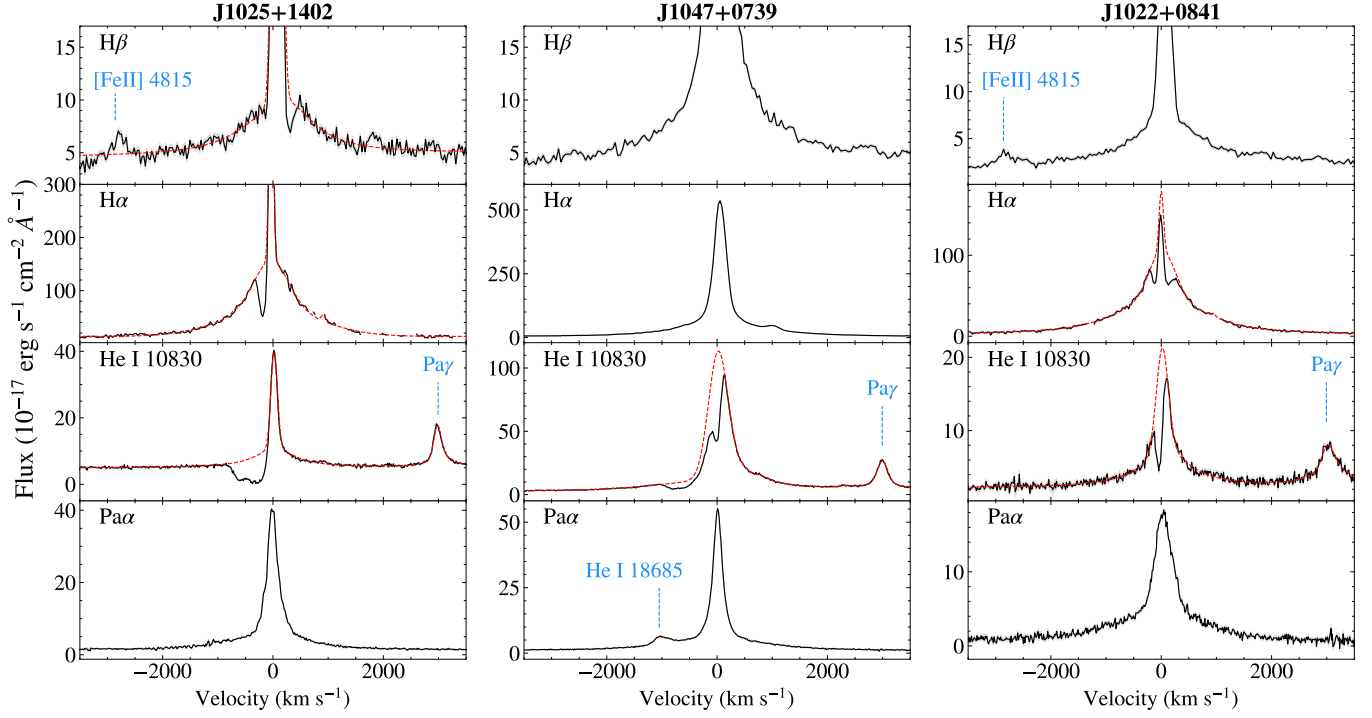


Figure 5. The $H\beta$, $H\alpha$, He I $\lambda 10830$, and $Pa\alpha$ line profiles of the three local LRDs. These line profiles are from the MODS and FIRE observations, except for the $H\alpha$ profile of J1025+1402 and J1022+0841, which are from the Binospec observations. For emission lines with absorption, the red dashed lines depict the intrinsic profiles without absorption.

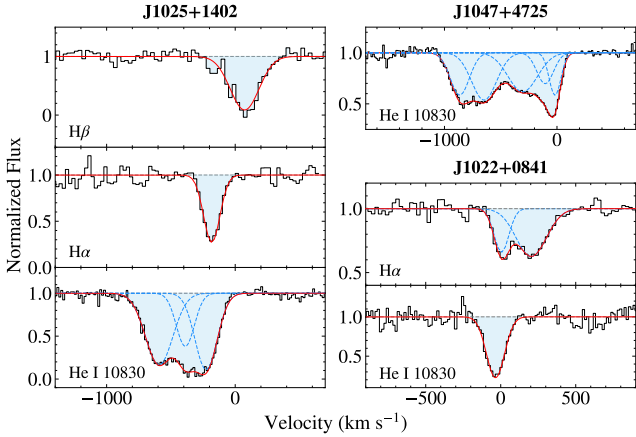


Figure 6. Normalized Balmer and He I $\lambda 10830$ absorption line profiles. For multi-component absorption profiles, the individual components are shown as the blue dashed lines.

model of AGN variability (B. C. Kelly et al. 2009; C. L. MacLeod et al. 2010).

4.5. X-ray and Radio

C. Simmonds et al. (2016) reported < 4.6 net counts of Chandra for J1025+1402 in a net exposure time of

4937 s, placing an upper limit¹⁶ of $L_{2-10\text{ keV}} < 1.1 \times 10^{41} \text{ erg s}^{-1}$. For J1047+0739, they reported $3.0_{-1.6}^{+2.9}$ net counts in 4782 s. We further examined the Chandra Source Catalog Release 2.1 (I. N. Evans et al. 2024), which includes more recent observations of J1047+0739, and found $5.03_{-2.23}^{+3.24}$ net counts in the 0.5–7 keV band over a 53 ks exposure. This corresponds to an X-ray luminosity of $L_{0.5-7\text{ keV}} \approx 5 \times 10^{41} \text{ erg s}^{-1}$, although the detection is only significant at $\lesssim 2\sigma$. For J1022+0841, no Chandra observations are currently available.

The comparison of the X-ray emission of J1025+1402 and J1047+0739 with that of typical type-1 AGNs is detailed in C. Simmonds et al. (2016). The upper limits or $< 2\sigma$ X-ray detections suggest that J1025+1402 and J1047+0739 are X-ray weak, exhibiting $L_{2-10\text{ keV}}/L_{H\alpha}$ ratios at least 1–2 dex below those of typical type-1 AGNs with similar broad $H\alpha$ luminosities (J. E. Greene & L. C. Ho 2004; F. Panessa et al. 2006; L.-B. Desroches et al. 2009). This X-ray weakness is consistent with that seen in high-redshift LRDs (M. Yue et al. 2024; T. T. Ananna et al. 2024).

We examine the radio data from the VLA Sky Survey (M. Lacy et al. 2020), the TIFR GMRT Sky Sur-

¹⁶ Assuming a $\Gamma = 1.8$ power law spectrum absorbed by Galactic N_{H} .

vey (H. T. Intema et al. 2017), and the VLA FIRST Survey (R. H. Becker et al. 1995). We find no radio detections at 153 MHz, 1.4 GHz, and 3 GHz for any of the three sources. The corresponding 5σ upper limits for J1025+1402, J1047+0739, and J1022+0841 are: 13.8, 12.5, and 15.1 mJy at 153 MHz; 0.7, 0.7, and 0.8 mJy at 1.4 GHz; and 0.4, 0.5, and 0.4 mJy at 3 GHz, respectively. The 5σ upper limits of radio-loudness ($\mathcal{R} \equiv L_{3\text{GHz}}/L_{5100}$, M. Sikora et al. 2007) for the three objects are estimated to be 8, 12, and 20, respectively. The current radio data are not deep enough to determine whether these sources are radio-quiet ($\mathcal{R} < 1$).

4.6. Summary of Evidences as LRDs

As discussed above, the three objects at $z = 0.1\text{--}0.2$ satisfy all the defining criteria for LRDs. We summarize the similarity between the observed properties of the three local sources to high-redshift LRDs as follows:

- compact morphology;
- V-shaped continuum (blue UV continuum slope, red optical continuum slope) and decreasing IR continuum at $\lesssim 0.7 - 2 \mu\text{m}$;
- broad Balmer and Paschen emission lines, consistent with $\sim 10^6\text{--}10^7 M_{\odot}$ BHs;
- weak X-ray emission;
- no significant (or low-level) variability;
- high occurrence rate of Balmer and He I $\lambda 10830$ absorption.

Their broad $\text{H}\alpha$ luminosities, $L_{\text{H}\alpha, \text{broad}} \sim 10^{42} \text{ erg s}^{-1}$, fall within the range observed in high-redshift LRDs. If redshifted to $z = 6$, their expected apparent magnitudes in JWST/NIRCam F444W would be 25.7–26.8 mag. These values lie within the magnitude range observed for the diverse LRDs discovered at $z > 5$ (e.g., J. E. Greene et al. 2024; D. D. Kocevski et al. 2024; H. B. Akins et al. 2024; D. D. Kocevski et al. 2025).

5. EMISSION LINE ANALYSIS

In this section, we discuss in detail the properties of the emission lines detected in the local LRDs to constrain their origins, gas density, metallicity, and ionizing sources.

5.1. Balmer Lines and Paschen Line Decrements.

We utilize the rich series of Balmer and Paschen lines to measure the Balmer and Paschen decrements. For high-order hydrogen lines with insufficient S/N to detect reliable broad components, we fit them with a single

Gaussian representing the narrow component, assuming that the broad components are buried in the noise. All measurements are based on the MODS spectra for consistency. As shown in Figure 7, the narrow Balmer lines from $\text{H}\alpha$ to $\text{H}12$ in J1025+1402 and J1022+0841 closely match the intrinsic Case B recombination predictions ($n = 100 \text{ cm}^{-3}$, $T = 10^4 \text{ K}$). The narrow Balmer lines in J1047+0739 are consistent with the SMC dust attenuation law (Y. C. Pei 1992) with modest attenuation of $A_V = 0.8$. The exception is $\text{H}\epsilon$ and $\text{H}8$, which are blended with $[\text{Ne III}]$ and $\text{He I } \lambda 3889$, respectively. The agreement indicates that the narrow hydrogen lines originate from regions with minimal dust attenuation. However, we caution that the decomposition of narrow and broad components is degenerate, and the strength of the potential underlying absorption remains uncertain.

The narrow Paschen lines generally follow the Case B predictions, similar to the Balmer series, although J1022+0841 exhibits significant scatter due to limited S/N. The $\text{P}\alpha$ line in J1025+1402 deviates from the Case B prediction, but its flux measurement may be contaminated by nearby He I emission lines adjacent to the Paschen transitions. This issue may also affect the measurement in J1022+0841. In contrast, the He I emission is particularly strong in J1047+0739, allowing both the He I and Paschen lines to be reliably fitted.

The broad $\text{H}\alpha/\text{H}\beta$ line ratios are $\gtrsim 10$ in all three objects. Such large decrements may be attributed to either radiative transfer effects in high-density gas (e.g., collisional excitation and de-excitation, resonance scattering, etc.) or substantial dust attenuation. Notably, the measured decrements, both in the broad and narrow components, are well consistent with those observed in high-redshift LRDs (M. Brooks et al. 2025). These values are comparable to those expected for the SMC attenuation law with $A_V \approx 5$ under Case B conditions. However, one caveat in attributing the broad-line decrements to dust is the survival of dust grains in the BLRs, which likely lies within the sublimation zone (e.g., P. G. Martin & G. J. Ferland 1980; M. Kishimoto et al. 2007; C. M. Gaskell & P. Z. Harrington 2018; A. Baskin & A. Laor 2018). For comparison, type-1 AGNs in the SDSS typically show broad $\text{H}\alpha/\text{H}\beta$ ratios around 3.7, with the most extreme cases reaching ~ 5 (D. Ilić et al. 2012). The much larger broad Balmer decrements observed in LRDs suggest that their BLRs may have extreme conditions with unusually dense gas or atypical dust properties, which differ substantially from those in typical type-1 AGNs (e.g., K. Inayoshi et al. 2022).

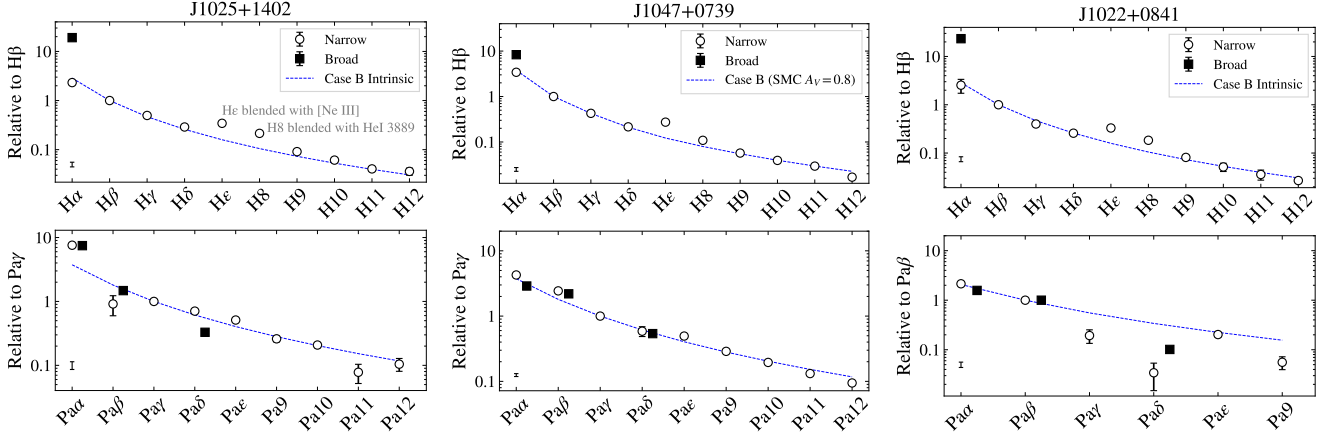


Figure 7. The Balmer and Paschen decrements of the three local LRDs. The decrements of the broad and narrow components are shown as black squares and white circles, respectively. The intrinsic line decrements under Case B conditions ($n_e = 100 \text{ cm}^{-3}$, $T_e = 10^4 \text{ K}$) are indicated by the blue dashed lines for J1025+1402 and J1022+0841. For J1047+0739, the Case B predictions with SMC dust attenuation law of $A_V = 0.8$ are shown. The median error bars are indicated in the lower left corner of each panel. For the Paschen series in J1022+0841, we normalize to Pa β due to the relatively large uncertainty in Pa γ .

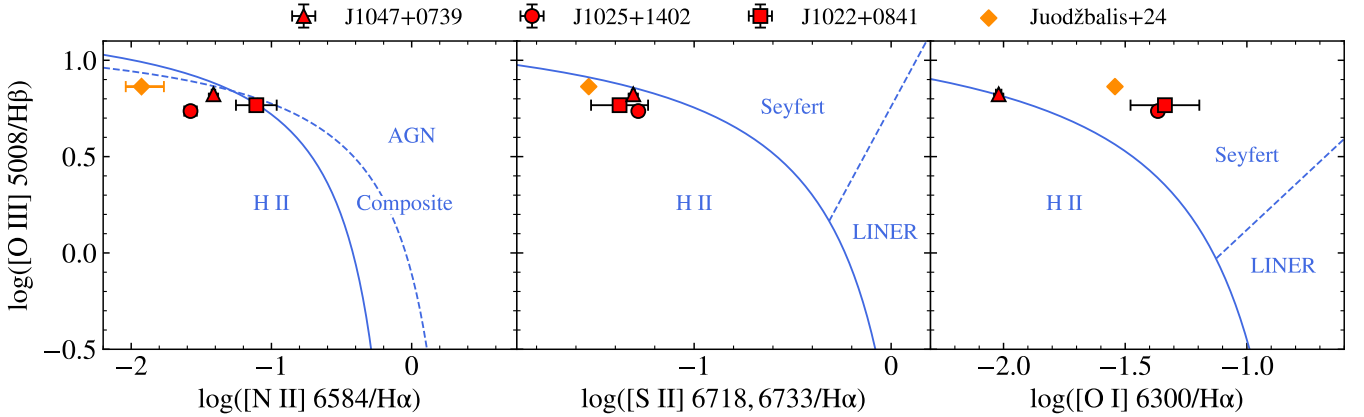


Figure 8. The BPT diagrams for the three local LRDs. The classification boundaries for different ionization mechanisms (L. J. Kewley et al. 2006) are shown as blue solid and dashed lines. The corresponding regions are labeled. We also mark the cosmic-noon LRD in I. Juodžbalis et al. (2024) for reference.

5.2. BPT Diagram and Metallicity

We estimate the BPT diagnostics (J. A. Baldwin et al. 1981) and the gas-phase metallicity of the narrow line regions (NLRs). To measure the fluxes of forbidden lines, we fit Gaussian profiles. Since the [O III] $\lambda 4363$ and $\lambda 5008$ lines are blended with [Fe II] emission, their fluxes are measured from spectra where the [Fe II] contribution has been subtracted using the best-fit models (see §5.3).

We show the positions of the three local LRDs on the [N II], [S II], and [O I] BPT diagrams in Figure 8. In the [N II] and [S II] diagrams, all three LRDs lie near the boundary between H II regions and AGN ionization. In the [O I] diagram, J1025+1402 and J1022+0841 fall within the Seyfert region, while J1047+0739 lies near the

edge of the H II region. Their positions on the [N II] and [S II] diagrams also overlap with those of low-metallicity AGNs (L. J. Kewley et al. 2013; C. Simmonds et al. 2016). Notably, the locations of these local LRDs closely match that of the cosmic-noon LRD in I. Juodžbalis et al. (2024). This suggests that the narrow emission lines in both local and high-redshift LRDs are excited by similar mechanisms associated with AGN activity.

Additionally, we detect [Fe V] $\lambda 4071$ emission lines in all three objects. This high-ionization line further indicates the presence of a hard ionizing radiation field and AGN activity.

We determine the metallicities of the NLRs using the direct electron temperature (T_e) method. The T_e of the O^{++} zone is derived from the ratio between

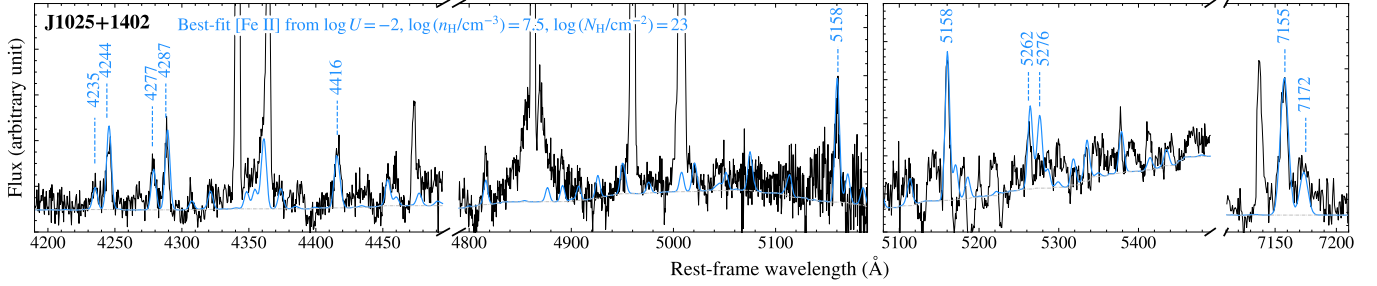


Figure 9. The narrow [Fe II] emission lines in J1025+1402 and the best-fit CLOUDY model. The left panel shows the MODS-B spectrum, and the right panel shows the MODS-R. The observed [Fe II] lines used for the modeling are labeled. The gray dashed line indicates the continuum level. The best-fit [Fe II] spectrum is shown as the blue line.

[O III] λ 4363 and [O III] λ 5008, assuming $n_e = 250 \text{ cm}^{-3}$. The estimated $T_e(\text{O}^{++})$ is 21406^{+570}_{-536} K for J1025+1402, 14095^{+180}_{-171} K for J1047+0739, and 23908^{+827}_{-767} K for J1022+0841. The T_e of the O^+ zone is estimated using the empirical $T_e(\text{O}^+) - T_e(\text{O}^{++})$ relation from Y. I. Izotov et al. (2006). We apply a dust attenuation correction of $A_V = 0.8$ to J1047+0739. As summarized in Table 1, all three objects exhibit metal-poor NLRs with $12 + \log(\text{O}/\text{H})$ ranging from 7.42 to 8.00. The values are broadly consistent with those reported by Y. I. Izotov & T. X. Thuan (2008) for J1025+1402 and J1047+0739.

We note that although the [O II] $\lambda\lambda$ 7322, 7332 lines are detected in J1047+0739, they are significantly affected by recombination excitation enhanced by the hard ionizing radiation field (X. W. Liu et al. 2000; S. Tan et al. 2024). Therefore, we do not use them for $T_e(\text{O}^+)$ diagnostics. The $T_e(\text{O}^+)$ value directly derived from the [O II] $\lambda\lambda$ 7322, 7332 and [O II] $\lambda\lambda$ 3727, 3729 line ratios exceeds $\sim 3 \times 10^4$ K, approximately twice that of $T_e(\text{O}^{++})$. This result further suggests an AGN origin for the narrow emission lines driven by hard ionization.

Based on the Balmer decrements, BPT diagram, and direct T_e -based metallicity, we conclude that the narrow lines in local LRDs originate from metal-poor NLRs powered by AGNs with minimal dust content.

5.3. [Fe II] Emission Analysis

The series of narrow [Fe II] emission lines observed in J1025+1402 and J1022+0841 stands in stark contrast to the broad Fe emission lines typically observed in type-1 AGNs (e.g., I Zw 1, M. P. Véron-Cetty et al. 2004). Though narrow optical [Fe II] lines have been reported in type-1 AGNs, they are blended with broad Fe lines and exhibit transitions and line ratios different from those in our sample; these narrow Fe lines are absent in type-2 AGNs (X.-B. Dong et al. 2010). To constrain the physical conditions such as temperature and density, we employ CLOUDY for photoionization modeling (C23, C. M. Gunasekera et al. 2023), with the latest Fe II atomic database (R. T. Smyth et al. 2019). We consider scenar-

ios in which the gas is photoionized by AGN radiation. The modeling methodology is detailed in Appendix C.

The AGN photoionization models yield best-fit parameters for both J1025+1402 and J1022+0841 of $\log(n_{\text{H}}/\text{cm}^{-3}) = 7.5$, $\log(N_{\text{H}}/\text{cm}^{-2}) = 23$, and $\log U = -2$. The relative [Fe II] line ratios are not strongly sensitive to metallicity, so we adopt a fiducial value of Z_{\odot} without attempting to constrain it. The average temperature of the [Fe II]-emitting gas is approximately 10^4 K, ranging from 4×10^3 K in the inner region to 2×10^4 K on the surface. As shown in Figure 9, the best-fit model reproduces the observed [Fe II] line ratios of J1025+1402 reasonably well, although some lines (e.g., [Fe II] λ 5278) remain imperfectly matched. A similar level of agreement is achieved for J1022+0841 using the same best-fit parameters (Figure C.1).

The inferred density lies between typical values for the BLRs and NLRs. The FWHMs of the [Fe II] lines are also intermediate ($\approx 200 \text{ km s}^{-1}$ for J1025+1402 and $\approx 300 \text{ km s}^{-1}$ for J1022+0841), broader than the narrow H α and [O III] (H $\alpha \sim 20\text{--}70 \text{ km s}^{-1}$ in Binospec, [O III] not resolved in MODS). This suggests that the [Fe II] emission may arise from dense gas located outside the BLRs but inside the NLRs. We emphasize that our models are qualitative. Fe emission lines in AGNs are inherently complex and can be influenced by a variety of physical processes, making comprehensive theoretical modeling challenging (e.g., A. Sarkar et al. 2021; A. Pandey et al. 2025). Further refinement is required to fully understand the origin and nature of [Fe II] emission in the LRD population.

6. CASE STUDY: J1025+1402, “THE EGG”

In this section, we connect the observed spectral characteristics to the underlying physical picture of LRDs, using J1025+1402 as a case study. J1025+1402 is the most extreme object in our sample, distinguished by its prominently V-shaped continuum and high-EW absorption features in the optical spectrum. These characteristics provide important insights into the nature of LRDs.

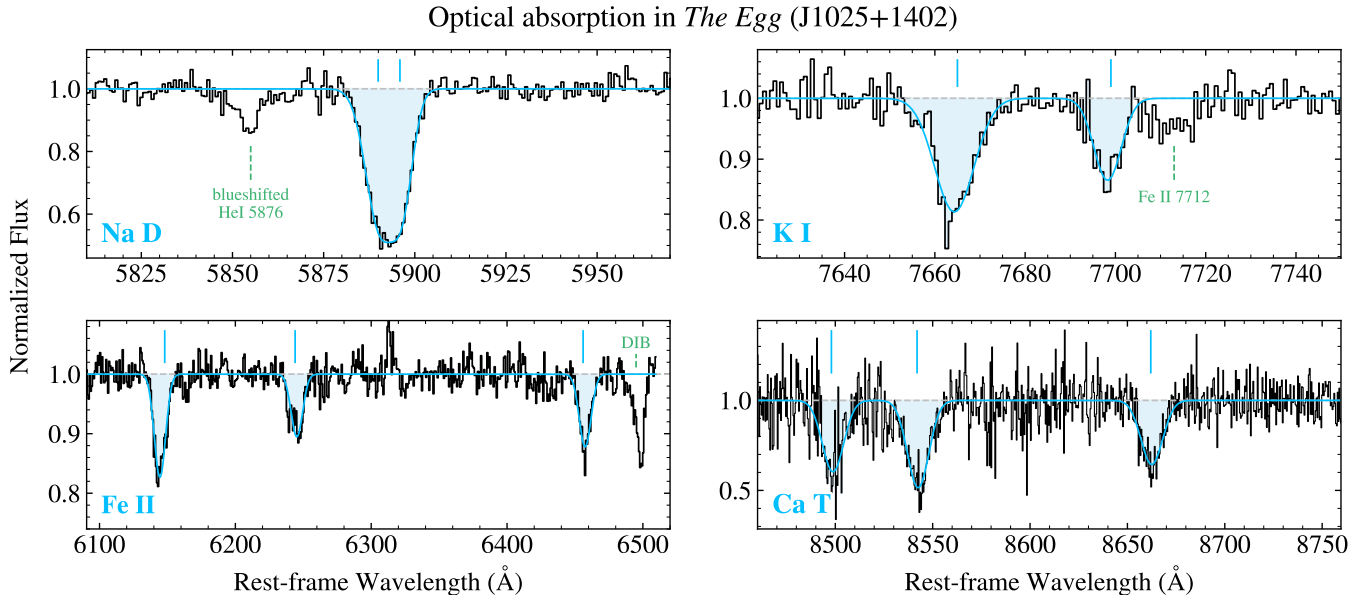


Figure 10. The metal absorption in the optical spectrum of *The Egg* (J1025+1402). The normalized profiles of Na D, K I, and Fe II are from the MODS spectra, and the Ca T is from the FIRE. The Na D profile is fitted with two blended Gaussian components, while each of the remaining absorbers is fitted with a single Gaussian. The blue vertical lines indicate the rest-frame wavelengths of metal absorbers, and other absorbers are marked with green dashed lines and labeled accordingly.

We extend the insights gained from J1025+1402 to the broader LRD population in §7. Although the extreme metal absorbers seen in J1025+1402 are not observed in the other two objects, we attribute this diversity to the effects of geometry, viewing angle and metallicity (see §7).

Hereafter, we nickname J1025+1402 as the *Egg*, inspired by its Ca-rich envelope, a temperature comparable to that of yellow supergiant stars, and its distinctive geometry. These features will be discussed in more detail below. An independent discovery and analysis of this object is also presented in Ji et al. (in prep).

6.1. Strong Metal Absorption: Evidence for a Cool Gas Envelope

The Egg exhibits exceptionally high-EW Na D $\lambda\lambda 5890, 5896$, K I $\lambda\lambda 7665, 7699$, Fe II $\lambda\lambda 6148, \lambda 6244, \lambda 6456$, and Ca triplets ($\lambda\lambda 8498, \lambda 8542, \lambda 8662$; Ca T) absorption features in its optical continuum. We show their profiles in Figure 10 and summarize their properties in Table 2.

6.1.1. Na D and K I Absorption

The Na D absorption in *The Egg* has an EW of $6.6 \pm 0.1 \text{ \AA}$ and K I absorption shows an EW of $3.2 \pm 0.1 \text{ \AA}$. These two neutral alkali metals can be easily ionized by photons with low ionization potentials (5.14 eV for Na and 4.34 eV for K). This implies that the absorbing gas must be both cool and dense to preserve its neutral state. One possible origin for these absorbers is the cold,

Absorber	EW (\AA)	FWHM (km s^{-1})
Na D doublets	6.6 ± 0.1	280 ± 19
K I doublets	3.2 ± 0.1	312 ± 20
Fe II triplets	4.3 ± 0.2	398 ± 26
Ca II triplets	17.1 ± 0.2	452 ± 6

Table 2. The properties of metal absorbers in *The Egg* (J1025+1402). The EWs are rest-frame equivalent widths summed over all absorption lines for each ionic species.

self-shielded intervening gas in the interstellar medium (ISM), with a minor contribution from late-type stars. However, the observed Na D EW in *The Egg* exceeds those typically found in such environments. The Na D EW in *The Egg* is higher than that observed in most galaxies and AGNs (typically $\lesssim 2 \text{ \AA}$; Y.-M. Chen et al. 2010; S. Cazzoli et al. 2016; D. S. N. Rupke et al. 2021; Y. Sun et al. 2024), and is only comparable to a few extreme IR-luminous LINERs (D. S. Rupke et al. 2005). In local galaxies and AGNs, high-EW Na D absorption typically traces gas outflows or inflows with velocities of several hundred km s^{-1} (S. Cazzoli et al. 2016; G. W. Roberts-Borsani & A. Saintonge 2019; D. S. N. Rupke et al. 2021; Y. Sun et al. 2024), whereas in *The Egg* we do not observe significant velocity shifts.

Likewise, the K I EW is orders of magnitude larger than those found in the Galactic interstellar medium or in circumstellar gas clouds around young stellar objects,

where values typically range from a few up to $\sim 200 \text{ m}\text{\AA}$ (L. M. Hobbs 1975; D. E. Welty & L. M. Hobbs 2001; I. Pascucci et al. 2015). All of these lines of evidence point to a non-stellar and non-ISM origin.

6.1.2. Fe II Absorption

The optical Fe II absorption lines at $\lambda 6148$, 6244 , and 6456 are rarely observed in galaxies or AGNs. These features have been reported in a Type Ia supernova (K. Maguire et al. 2023), but with large blueshifts of several thousand km s^{-1} and broad line widths. In contrast, the Fe II absorption seen in *The Egg* shows no significant velocity shift and narrow FWHMs of $\sim 400 \text{ km s}^{-1}$. Although the origin of these Fe II absorption features remains uncertain, their co-occurrence with Na D, K I, and Ca T absorption may suggest a shared origin.

6.1.3. Ca T Absorption

The Ca T absorption at 8498 , 8542 and 8662 \AA in *The Egg* has an EW of $17.1 \pm 0.2 \text{ \AA}$. In Figure 11, we compare this value to typical Ca T EWs observed in stars, star-forming galaxies, and AGNs. The Ca T EW in *The Egg* exceeds those of most stars and all known galaxies and AGNs, where Ca T EWs are generally below 10 \AA .

Only a few individual stars, such as yellow hypergiants or supergiants (S. V. Mallik 1997; A. J. Cenarro et al. 2001), can exhibit comparable Ca T EWs. However, reproducing the observed Ca T EWs in the integrated galaxy light would require an unusually exotic stellar population composed solely of these stars.

6.1.4. The Origin: a Cool Gas Envelope around BHs

The unusually high-EW Na D, K I, Fe II, and Ca T absorption lines of *The Egg* all point to a non-stellar and non-ISM origin. If the optical continuum is AGN-dominated, these absorption lines likely arise from an atmosphere-like gas envelope in the vicinity of the central BHs. Although a stellar population struggles to explain the lines observed in *The Egg*, the microphysics of line formation may apply to both stellar atmospheres and LRDs. Therefore, a comparison to stellar spectra enables us to infer the physical conditions of the absorbing gas.

In the following, we investigate the EW of Ca T absorption as a key tracer. Figure 12 places *The Egg*'s CaT absorption in the context of stellar atmospheres. As shown in the left panel of Figure 12, within the stellar catalog presented here, only two metal-rich stars exhibit Ca T EWs greater than that of *The Egg*. These two stars are classified as an Ia yellow supergiant and a 0-Ia yellow hypergiant, with effective temperature (T_{eff}) of 5500 and 5727 K , surface gravities ($\log g$) of 0.0 and

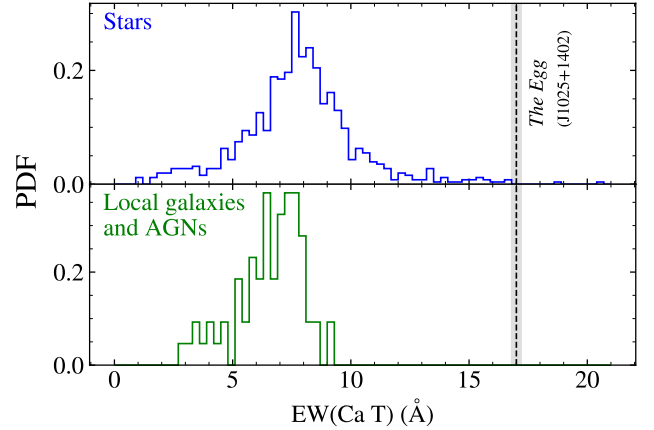


Figure 11. The Ca T absorption EW of *The Egg* (J1025+1402) compared to those typically observed in stars, galaxies, and AGN host galaxies in the local Universe. The stellar Ca T absorption EWs are compiled from S. V. Mallik (1997); A. J. Cenarro et al. (2001), and the Ca T absorption EWs of galaxies and AGNs are compiled from A. Garcia-Rissmann et al. (2005). The Ca T absorption EW and its uncertainty are shown as the black dashed line and gray shaded region.

0.4 , and metallicities $[\text{Fe}/\text{H}]$ of -0.28 and 0.32 , respectively.

The yellow supergiant and hypergiant stars exhibit the strongest Ca T absorption due to their low surface gravity and their effective temperatures of $T_{\text{eff}} \sim 5000 \text{ K}$. This temperature allows Ca in the atmosphere to exist mainly in the singly-ionized state. In stellar atmospheres, the EWs of Ca T absorption strongly anticorrelate with surface gravity (e.g., S. V. Mallik 1997; A. J. Cenarro et al. 2002). This is due to the gas opacity changing with the photosphere density, which generally increases with $\log g$ in stellar atmosphere models. As $\log g$ decreases, the photosphere density decreases, leading to a diminished continuum absorption opacity (the main source being H^- ions at $T \sim 5000 \text{ K}$ and at wavelengths around $8000\text{--}9000 \text{ \AA}$), while the line opacity of Ca II changes only mildly (U. G. Jorgensen et al. 1992). This enhances the contrast between the line and continuum opacities, increasing the EWs of the Ca T absorption. Thus, the Ca T EWs are essentially atmospheric density indicators at a given effective temperature.

We interpret the Ca T absorption in *The Egg* as originating from an atmosphere-like gas envelope surrounding the BH, with a structure and opacity analogous to that of cool stellar atmospheres. We apply stellar Ca T diagnostics to estimate $\log g$ to first order. The right panel of Figure 12 demonstrates the stellar Ca T EWs as a function of $\log g$. The Ca T EW- $\log g$ relation also depends on stellar metallicity. Extrapolating the em-

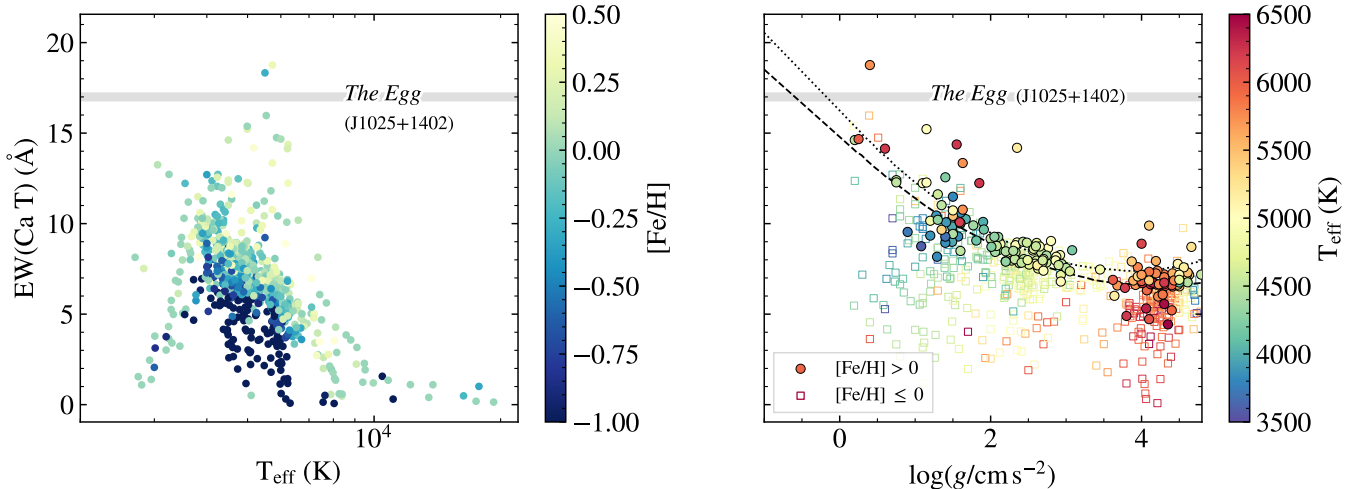


Figure 12. The Ca T absorption of *The Egg* (J1025+1402) in the context of stellar Ca T absorption. *Left:* EWs of stellar Ca T absorption as a function of the effective temperature (T_{eff}). The data points are color-coded by the metallicity of the stellar atmosphere. The range of *The Egg*'s Ca T absorption within $\pm 1\sigma$ is indicated by the gray-shaded region. *Right:* EWs of stellar Ca T absorption as a function of the surface gravity ($\log g$). The data points are color-coded with T_{eff} . Metal-rich stars ($[\text{Fe}/\text{H}] > 0$) are shown as the filled circles, and the metal-poor ones ($[\text{Fe}/\text{H}] \leq 0$) are shown as the open squares. The empirical relations between $\log g$ and Ca T EW from A. J. Cenarro et al. (2002) are shown: the dashed line corresponds to the relation for stars with $-0.25 < [\text{Fe}/\text{H}] < 0.25$, and the dotted line represents that for stars with $[\text{Fe}/\text{H}] > 0.25$.

pirical Ca T EW- $\log g$ relation for metal-rich stars with $[\text{Fe}/\text{H}] > 0.25$ to match the observed Ca T EW of *The Egg* yields an estimated $\log g$ of approximately -0.2 . If we assume a slightly lower metallicity ($[\text{Fe}/\text{H}] \approx -0.25$ to 0.25), the inferred $\log g$ would be about -0.4 . The value may be even lower given the low metallicity we have inferred from the NLR (Section 5.2).

In conclusion, the Ca T absorption in *The Egg* indicates the presence of a metal-rich cool gas envelope with low surface gravity ($\log g < 0$). Comparison with known supergiant and hypergiant stars suggests that the T_{eff} of such an atmosphere is likely around 5000–6000 K. However, we emphasize that this is a first-order approximation with simplified assumptions; the actual physical conditions of the absorbing gas may differ substantially from those in stellar atmospheres. In particular, the mapping between $\log g$ and the stellar atmosphere density (and hence opacity) is based on hydrostatic equilibrium, which is not necessarily true for the envelope of *The Egg*. Nevertheless, as we argue above, the line formation process mainly depends on the atmospheric temperature and density. The inferred value of $\log g$ above may not reflect the dynamical condition of the envelope, but does suggest that its atmosphere density may resemble that of very low-surface gravity stars. Standard stellar photosphere relations imply that $\log g = 0$ at $T_{\text{eff}} = 5000$ K corresponds to a photosphere density of 3×10^{-10} g cm⁻³ (e.g., C. J. Hansen et al. 2004, their Equations (4.56)(4.65)). Thus, we expect the photo-

sphere density of *The Egg* to be on the order of or lower than 10^{-10} g cm⁻³.

We note that the FWHMs of these metal absorbers are about 300–450 km s⁻¹ (Table 2), significantly broader than those typically observed in stellar atmospheres. For instance, Ca T absorption lines in stars are intrinsically narrow, with FWHMs reaching only up to ~ 70 km s⁻¹ in supergiant stars (A. V. Filippenko & L. C. Ho 2003). The broad Ca T absorption in *The Egg* suggests that the cool gas envelope is turbulent or dynamically complex. A more detailed analysis, incorporating tailored modeling of the gas properties, is necessary for a comprehensive understanding.

We have limited our analysis to the Ca T lines; similar atmosphere conditions are presumably responsible for the other absorption lines identified here. However, we do not perform the same analysis on them due to our unawareness of dedicated stellar datasets on these lines. Future characterization of observed stellar spectral lines combined with analysis of theoretical spectral libraries can directly test our scenario.

6.2. Optical to IR Continuum: Evidence of Thermalized Emission

As discussed in §6.1, we find evidence for cool gas envelopes that may be analogous to (supergiant or hypergiant) stellar atmospheres at ~ 5000 K. In this section, we investigate the potential application of atmosphere-like gas envelopes to explain the observed continuum shape of the local LRDS. A similar comparison con-

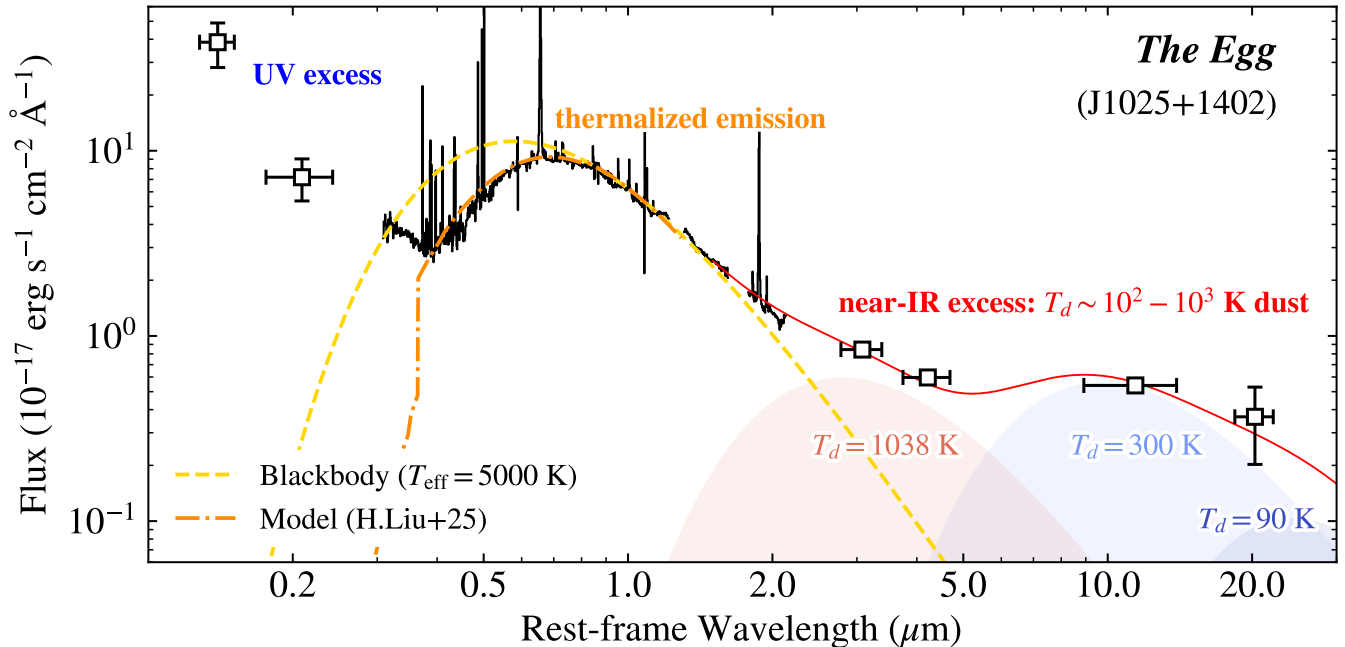


Figure 13. The SED of *The Egg* (J1025+1402) in comparison with a 5000 K blackbody spectrum and the theoretical model from H. Liu et al. (2025). The dust components are indicated by the shaded regions in the near-IR wavelength range.

ducted by A. de Graaff et al. (2025) also noted a resemblance to supergiant stars, though with notable discrepancies. In Figure 13, we compare the spectrum of *The Egg* to a 5000 K blackbody. The $> 8000 \text{ \AA}$ regime of *The Egg*’s spectrum can be reasonably well described by the Rayleigh-Jeans tail of a 5000 K blackbody. However, the $< 8000 \text{ \AA}$ region shows a significant flux deficit relative to the blue side of the blackbody spectrum, even without subtracting the extrapolation from the UV continuum as a separate component. Varying the blackbody temperature does not yield a better match, as the optical-to-near-IR continuum of *The Egg* exhibits stronger curvature than a standard blackbody. Such a pseudo-blackbody continuum shape signifies thermalized emission, but may involve intricate physical mechanisms.

Recent theoretical models propose that envelope-like structures can form around SMBHs under super-Eddington accretion and emit thermal radiation with characteristic temperatures of $\sim 5000 \text{ K}$ (D. Kido et al. 2025; H. Liu et al. 2025). To investigate such scenarios, we compare the observed continuum of *The Egg* with the models from H. Liu et al. (2025), which assume an atmosphere formed by quasi-spherical super-Eddington accretion flows. As shown in Figure 13, one such model from H. Liu et al. (2025) provides a good match to the optical continuum shape of *The Egg*. This model has a total luminosity $L = 2.1 \times 10^{43} \text{ erg s}^{-1}$ and a density

of $\rho_{\text{ph}} = 3.5 \times 10^{-12} \text{ g cm}^{-3}$ at the photosphere¹⁷; a star at $T_{\text{eff}} = 5000 \text{ K}$ would have this photosphere density at $\log(g/\text{cm s}^{-2}) \sim -2.8$ (C. J. Hansen et al. 2004). The photosphere (defined by the Rosseland-mean optical depth) is located at 510 AU with $T_{\text{eff}} = 4761 \text{ K}$. The frequency-dependent gas optical depth effects suppress the UV-to-optical flux, making the predicted continuum deviate from a blackbody¹⁸. Essentially, the optical spectrum is “reddened” by the atmospheric gas; otherwise, we would have to invoke a very steep dust extinction law to explain the optical redness while retaining the declining IR slope (see Appendix D). However, we caution that the model assumes super-Eddington accretion, while current observations do not provide direct evidence of it. The integrated $L_{2000, \text{\AA} - 20, \mu\text{m}}$ corresponds to about 22% of the Eddington luminosity, based on the M_{BH} listed in Table 1. The true Eddington ratio is unconstrained, as both M_{BH} and the intrinsic bolometric luminosity are uncertain. In addition to the theoretical model, we present an alternative empirical parameterization of the pseudo-blackbody continuum shape in Appendix D.

¹⁷ $\rho_{\text{ref}} = 1.2 \times 10^{-12} \text{ g cm}^{-3}$ in their notation.

¹⁸ We invoke no dust reddening to the model curve; we have checked that adding a modest level of dust extinction ($A_V \lesssim 1 \text{ mag}$ using the SMC dust extinction law) would further improve the agreement.

The origin of the blue UV continuum remains uncertain. Several observations suggest a stellar origin from young host galaxies, based on the lack of UV variability, the absence of high-ionization UV lines, and the extended, complex UV morphologies in a number of high-redshift LRDs (P. Rinaldi et al. 2024; H. B. Akins et al. 2025; W. L. Tee et al. 2025; R. P. Naidu et al. 2025). However, these features do not definitively rule out an AGN origin, either directly from the accretion disk or scattered by electrons/dust (E. Lambrides et al. 2024; Z. Li et al. 2025; K. Inayoshi et al. 2025). This is especially the case when considering the recent detection of AGN-powered high-ionization UV lines in a subset of LRDs (M. Tang et al. 2025). Recently, P. Rinaldi et al. (in prep.) found that a V-shaped continuum similar to that of LRDs originates from the nuclei of a cosmic-noon IR-bright galaxy, further suggesting that AGN emission could contribute to the blue UV continua. At present, we lack spectral information at rest-frame wavelengths below 2000 Å to map diagnostic UV lines that could distinguish between AGN and star-forming activity. As such, the origin of this component remains inconclusive given the current data. Deep UV spectroscopy or polarization measurements, both of which could trace AGN light, is needed to clarify its nature.

6.3. The Dust Emission

The WISE photometry of local LRDs suggests that the dust content in these objects, while not as strong as implied by a standard AGN dust torus, is also not negligible. A typical AGN dust torus, when scaled to LRD luminosities, would show rapidly increasing emission beyond 1–2 μm, peaking around 10 μm, which is clearly not the case for LRDs (M. Stalevski et al. 2016; B. Wang et al. 2025b). All three local LRDs show flattening or an increase in flux beyond rest-frame 10 μm (W3 and W4 bands; Figure 1). At $z > 3$, this wavelength range is beyond JWST coverage, and it is either only partially covered by Spitzer and Herschel or falls into gaps between their coverage, leaving it largely unconstrained for high-redshift LRDs (H. B. Akins et al. 2024; C. M. Casey et al. 2024, 2025; D. J. Setton et al. 2025).

Qualitatively, the IR excess from the WISE photometry in these local LRDs (Figure 1) reveals at least dust components with temperatures approximately between 10^2 and 10^3 K. The emission at rest-frame 3 μm corresponds to the peak of a ~ 1000 K blackbody, and the emission at 10 μm matches a ~ 300 K blackbody. As shown in Figure 13, if assuming templates from J. Lyu & G. H. Rieke (2021) that include dust components at $T_d = 2100, 1038, 300,$ and 90 K (see Appendix §D.2),

the IR emission of *The Egg* can be well reproduced by significant dust components at 1038 K and 300 K. However, the derived dust properties depend sensitively on the chosen templates. We discuss alternative dust templates based on Haro 11 (J. Lyu et al. 2016) and the degeneracies in Appendix D.3. In the absence of longer-wavelength data, it is difficult to robustly constrain the dust properties, particularly the cold dust content with temperatures below 100 K.

7. A CONCEPTUAL PICTURE OF LRDs

Based on the observational evidence and physical interpretations discussed above, we construct a conceptual picture of LRDs, as shown in Figure 14. Table 3 summarizes the proposed physical processes, their observational signatures, and the associated caveats in our interpretation.

We first conduct an order-of-magnitude estimate of the characteristic physical scales that support the proposed framework. Assuming that the observed emission line broadening is gravitational in origin, the enclosed mass is given by $M \approx v^2 r / G$. For a broad emission line with FWHM of 1000 km s^{-1} , and adopting a low surface gravity atmosphere with $\log(g/\text{cm s}^{-2}) = 0$ as implied by the strong Ca T absorption, we derive

$$M \approx \frac{v^4}{Gg} \approx 8 \times 10^5 M_\odot, \quad r \approx \frac{v^2}{g} \approx 700 \text{ AU}. \quad (1)$$

In the calculation above, we use the broad emission lines as velocity indicators, rather than the absorption line widths, and place the BLRs near the edge of the photosphere. The kinematics of the BLR clouds are assumed to be primarily governed by gravity, allowing for a reasonably simplified estimate based on Kepler’s laws. In contrast, the broadening of metal absorption lines in the atmosphere is more complex, influenced by intricate processes such as anisotropically distributed turbulence, making their kinematics more difficult to interpret.

The total luminosity of a blackbody radiation with a temperature of 5000 K (Figure 13) and a radius of 700 AU is about $5 \times 10^{43} \text{ erg s}^{-1}$. This estimated luminosity is consistent within an order of magnitude with the observed luminosities ($L_{2000\text{Å}-20\mu\text{m}}$, Table 1) and the luminosities of the theoretical models (Figure 13 and D.1) for the three local LRDs. For comparison, the corresponding Eddington luminosity for a $8 \times 10^5 M_\odot$ BH is $10^{44} \text{ erg s}^{-1}$. The BH mass estimated here is up to an order of magnitude smaller than the H α -based BH masses listed in Table 1. Given the approximate nature of these estimates, the overall agreement between the observed properties and those inferred from this conceptual model supports the feasibility of an atmosphere-

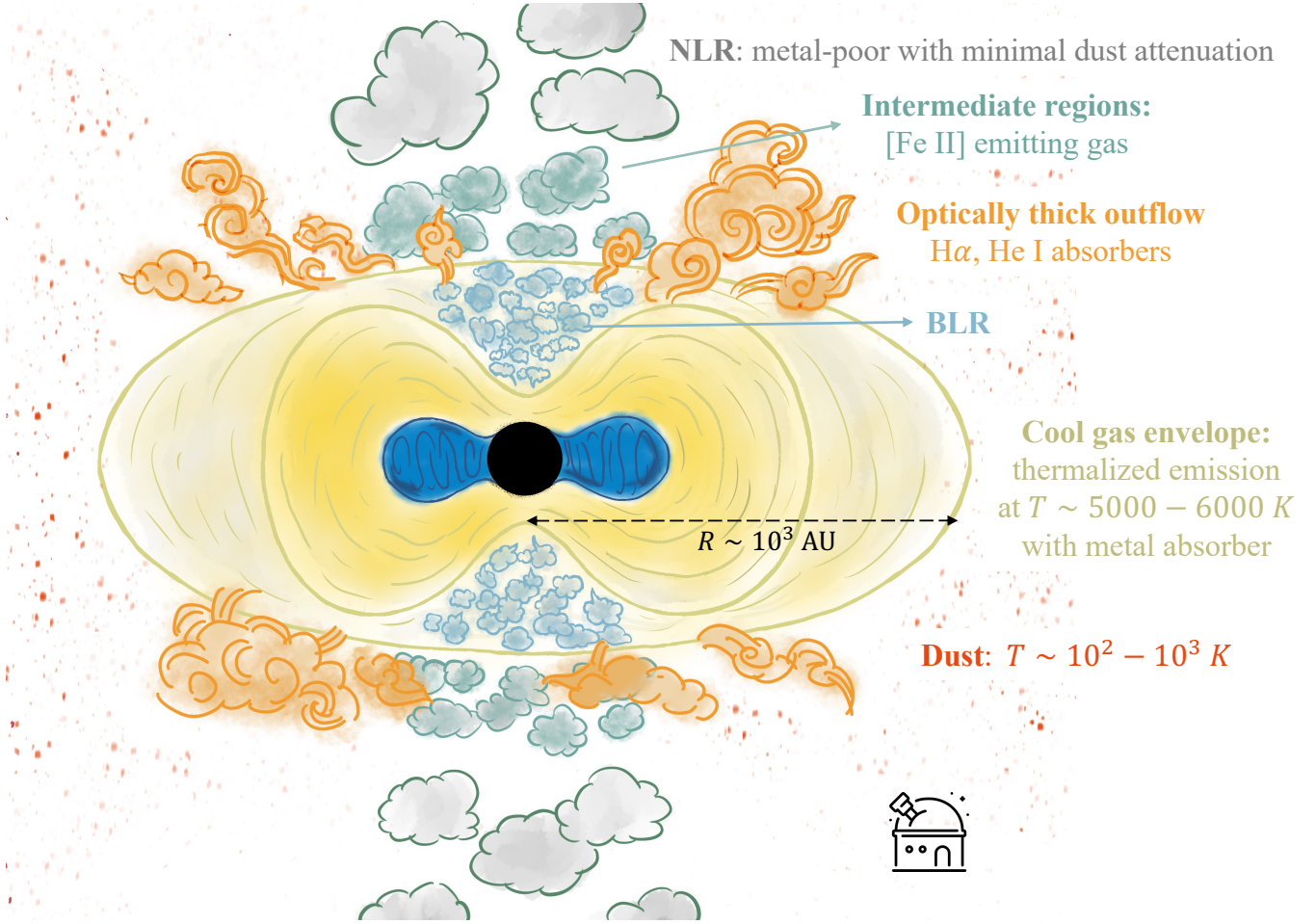


Figure 14. Schematic illustration of the structural components of LRDs. The viewing angle, indicated by the telescope icon, is randomly selected here for illustrative purposes; its impact on observed properties is discussed in the main text.

enshrouded BH model. The individual components of our conceptual framework are described in detail below.

- **BLRs and NLRs.** The broad Balmer and Paschen lines, along with the infrared O I emission lines (in *The Egg*, see Figure 2), indicate that the observed line broadening arises from gas motions within the BLRs surrounding the BHs. Analysis of the Balmer decrements, BPT diagrams, and metallicity suggests that the narrow emission lines originate from AGN-powered NLRs with low metallicity and minimal dust.
- **[Fe II] emitting gas intermediate between the BLRs and NLRs.** The AGN-excited [Fe II] emission lines indicate gas with a density of approximately $n_{\text{H}} \approx 10^{7.5} \text{ cm}^{-3}$, intermediate between the BLRs and NLRs. The FWHM of the [Fe II] lines ($\approx 200 \text{ km s}^{-1}$ for *The Egg* and $\approx 300 \text{ km s}^{-1}$ for J1022+0841 in MODS spectra) is likewise between that of the broad ($\sim 1000 \text{ km s}^{-1}$) and narrow lines (17 km s^{-1} for *The Egg* and

77 km s^{-1} for J1022+0841 in the Binospec spectra). The absence of these [Fe II] lines in J1047+0739 may be attributed to a lower covering fraction of the intermediate emitting regions.

- **A cool gas envelope with $T \sim 5000$ – 6000 K and photosphere density of $\rho_{\text{ph}} \lesssim 10^{-10} \text{ g cm}^{-3}$ ($\log(g/\text{cm s}^{-2}) \lesssim 0$).** The optical–IR continua of the three local LRDs exhibit pseudo-blackbody shapes indicative of thermalized emission and are in good agreement with theoretical atmosphere models (H. Liu et al. 2025). The presence of extremely high-EW metal absorbers (Na D, K I, Fe II, Ca T) in *The Egg* further indicates a cool, optically thick gas envelope surrounding the BH. Analysis of the Ca T EW, by analogy with stellar atmospheres, suggests an atmospheric temperature of approximately 5000–6000 K and surface gravity of $\log(g/\text{cm s}^{-2}) \lesssim 0$ at the photosphere, corresponding to a density of $\rho_{\text{ph}} \lesssim 10^{-10} \text{ g cm}^{-3}$. The size of this envelope is on

Physical Process	Observational Evidence	Caveat and prospects
BH accretion	Broad emission lines (e.g., Balmer and Paschen series, infrared O I, infrared Fe II) with FWHM $\sim 1000 \text{ km s}^{-1}$	Optically thick gas envelope prevents direct observations of BH accretion process.
AGN Emission Line Regions	Narrow and broad line regions consistent with AGN ionization; [Fe II] emission lines with FWHM and inferred density between broad and narrow components	Modeling of [Fe II] is complex and potentially degenerate
Cool gas envelope	Metal absorption lines, especially with extremely high-EW Na D, K I, Fe II, and Ca T absorption features in <i>The Egg</i> ; the thermalized emission in good agreement with theoretical atmosphere models (H. Liu et al. 2025)	Requires detailed modeling of opacity, cooling, and circum-BH environments; must also account for the FWHMs of absorption lines
Non-spherical geometry and viewing angle	Optically thin channels within the envelope are required for AGN ionizing photons to escape and illuminate the BLRs, intermediate [Fe II] regions, and NLRs; may also explain the diversity in continuum shapes and the presence or absence of high-EW metal absorbers.	The impact of viewing angle is difficult to quantify without a statistically large sample.
Outflowing optically-thick gas	Blueshifted Balmer and He I absorption lines	Their correlation with other properties of LRDs (i.e., Balmer break strength) remains uncertain; the origin of He I emission (ionized gas versus dense neutral gas) requires further study.
Dust emission	near-IR excess in WISE photometry (rest-frame 3–20 μm)	Constraints on dust components depend on model assumptions; cannot fully characterize dust properties from the AGN to the ISM due to the lack of longer-wavelength data.

Table 3. Summary of physical processes potentially contributing to the observed features, along with associated limitations and future prospects.

the order of 10^3 AU as inferred from the optical-IR luminosity and the effective temperature. A consequence of an optically thick cool gas envelope is that the BH accretion process, i.e., the emission from the accretion disk itself, is not directly observable.

- **Non-spherical geometry and role of the viewing angle.** The observed AGN-powered emission lines imply that the BLRs, intermediate regions, and NLRs cannot be located entirely outside the gas envelope. Otherwise, the $T \sim 5000\text{--}6000$ K central source would not produce enough ionizing photons responsible for the recombination lines or the photo-ionization conditions required for forbidden lines (e.g., [Fe II], [N II], O I). Therefore, there should be a relatively optically thin channel that allows high-ionization photons to escape from the disk and gas envelope. We attribute such an optically thin channel along the direction of the line-emitting regions. This non-spherical geometry allows emission lines to form while preserving the envelope structure.

The viewing angle in this non-spherical geometry can explain the diversity in continuum shapes and the presence or absence of metal absorption fea-

tures among different objects. Changes in viewing angle can modulate the relative contributions of thermalized emission and AGN photoionized radiation. It also determines whether the line of sight intersects the metal-absorbing layers within the cool gas envelope. For example, the line of sight toward *The Egg* may intersect the optically thick part of the envelope with high metal-line opacity. This orientation results in a significant contribution to the continuum from the thermalized emission, making the metal absorbers observable. J1022+0841 could be oriented closer to the optically thin region, where the optical depth of metal lines is lower. J1047+0739 could lie even closer to the optically thin region, leading to a reduced contribution from the thermalized emission to the total optical continuum. However, we emphasize that this is a speculative scenario, and a larger statistical sample is needed to better understand the roles of geometry and viewing angle. Differences in the metallicities of the cool gas envelope would also contribute to the diversity of observed metal absorption features.

- **Optically thick outflows.** In most high-redshift LRDs, the Balmer absorption lines are blueshifted,

with only a few cases showing redshifted $H\alpha$ absorption with minimal velocity offsets (X. Lin et al. 2024; X. Ji et al. 2025; F. D’Eugenio et al. 2025). Up to now, all detected He I absorbers in LRDs are blueshifted (I. Juodžbalis et al. 2024; B. Wang et al. 2025a; F. Loiacono et al. 2025). The Balmer absorbers are superimposed on broad Balmer emission lines, and the He I absorbers are superimposed on both the broad emission and the underlying continuum. We thus attribute these absorbers to optically thick outflowing gas located either within or outside the BLRs. The rare instances of redshifted Balmer absorption with small velocity shifts may indicate gas cooling and inflowing back toward the nucleus. Although the relationship between the absorption and LRD properties (e.g., Balmer break strength) remains unclear, it is a plausible connection that merits further exploration.

- **Dust at 10^2 – 10^3 K.** The WISE photometry of the three local LRDs is consistent with dust components with temperatures ranging from 10^2 to 10^3 K. These dust components, cooler than typical AGN-heated hot dust but warmer than ISM dust, is likely located outside the ~ 5000 K atmosphere yet still within the AGN vicinity. However, we note that the analysis of the dust components is highly uncertain, model-dependent, and subject to degeneracies.

In the proposed scenario, the BH resides in an environment distinct from that of typical type-1 AGNs. As discussed in §4, it remains unclear whether the empirical BH mass estimators calibrated for type-1 AGNs are valid for LRDs, given their potentially different physical conditions. Assuming a BH mass of $M_{\text{BH}} \sim 10^6$ – $10^7 M_{\odot}$, the corresponding Eddington luminosity is 10^{44} – $10^{45} \text{ erg s}^{-1}$. For the three objects, if we take the total integrated luminosity $L_{2000\text{\AA}-20\ \mu\text{m}}$, assuming that the UV continuum is AGN light, the Eddington ratio would be ~ 0.2 – 0.8 . The current observations do not provide sufficient evidence to determine whether LRDs are in a super-Eddington accretion mode, as proposed by some theoretical scenarios (e.g., K. Inayoshi et al. 2024; F. Pacucci & R. Narayan 2024). The accretion rate of the central BH and its disk can significantly influence the geometry of both the disk and the surrounding gas envelope (e.g., C. Dotan & N. J. Shaviv 2011). We leave a detailed exploration of this to future work.

8. SUMMARY

We searched the SDSS spectroscopic database for local LRDs using high-redshift LRD templates and identified three LRDs at $z = 0.1$ – 0.2 . We followed up these sources with MMT/Binospec, LBT/MODS, and Magellan/FIRE spectroscopy, which reveal detailed spectral features that probe the physical nature of these local LRDs. Our findings are summarized below.

- The three local objects closely resemble the high-redshift LRDs. They display compact morphologies. HST narrow-band imaging of J1047+0739 reveals that both the continuum and the $H\alpha$ line emission are AGN-dominated, with the compact yet clumpy host galaxy (half-light radius about 530 pc) contributing a minor fraction to the continuum. All the three objects exhibit clear V-shaped UV-to-optical continua with inflections around the Balmer break, and a decreasing IR continuum from $\sim 7000 \text{ \AA}$ to $2 \mu\text{m}$. All of them show broad $H\alpha$ emission with $\text{FWHMs} \sim 1000 \text{ km s}^{-1}$, along with broad Paschen and He I lines. All of them exhibit blueshifted He I $\lambda 10830$ absorbers; two of them show $H\alpha$ absorbers, and one even shows a redshifted $H\beta$ absorber without an $H\alpha$ counterpart. None of the objects shows significant optical or IR variability. Two were targeted in hard X-rays but were either not detected or detected with low statistical significance.
- The Balmer and Paschen decrements, covering from $H\alpha$ to $H12$ and from $\text{Pa}\alpha$ to $\text{Pa}12$ (or $\text{Pa}9$ for one object), indicate negligible dust attenuation in the NLRs. The broad $H\alpha/H\beta$ ratios are $\gtrsim 10$ in all three objects, higher than those observed in most local AGNs, indicating either unusually high-density gas or atypical dust properties in the BLRs.
- The BPT diagram shows that the narrow emission lines are photoionized by AGNs and overlap with the region occupied by a known LRD. The NLRs are metal-poor, with $12+\log(\text{O}/\text{H}) \approx 7.43$ – 8.00 .
- Two of the objects exhibit prominent narrow [Fe II] emission lines that are distinct from those typically seen in type-1 AGNs. Photoionization modeling suggests that the [Fe II]-emitting gas is AGN-powered, with physical conditions characterized by $\log(n_{\text{H}}/\text{cm}^{-3}) = 7.5$, $\log(N_{\text{H}}/\text{cm}^{-2}) = 23$, $\log U = -2$, and an average temperature of 10^4 K. Based on the inferred gas density and FWHMs, we propose that the [Fe II]-emitting region lies at an intermediate scale between the BLRs and NLRs.

- One of the local LRDs, J1025+1402 (*The Egg*) exhibits exceptionally high EWs in Na D, K I, Fe II, and Ca T absorption lines, with narrow FWHMs of about 300–400 km s⁻¹ and no significant velocity shifts. Such strong metal absorbers are rarely seen in the ISM, galaxies, AGNs, or stars. Its Ca T EW is matched only by that of two supergiant and hypergiant stars. These extreme properties suggest a non-stellar and non-ISM origin. We interpret the Ca T absorption in *The Egg* as arising from a cool gas envelope around the BH, analogous to stellar atmospheres. We infer $T_{\text{eff}} \approx 5000\text{--}6000\text{ K}$ and $\log(g/\text{cm s}^{-2}) < 0$ at the photosphere, corresponding to a density of $\rho_{\text{ph}} \lesssim 10^{-10}\text{ g cm}^{-3}$.
- The optical-IR continua of these local LRDs exhibit pseudo-blackbody shapes. The shapes are consistent with theoretical models featuring atmospheres surrounding BHs (H. Liu et al. 2025), with characteristic temperatures of $\sim 5000\text{ K}$. The WISE photometry indicates modest dust emission at temperatures of $10^2\text{--}10^3\text{ K}$.
- By combining the observational evidence, we propose a conceptual model for the structure of LRDs. In this scenario, BHs are embedded within a cool gas envelope that emits thermalized radiation, giving rise to the observed pseudo-blackbody continuum and metal absorption features. The Balmer and He I absorbers are attributed to optically thick outflows launched from the envelope. The overall AGN structure consists of BLRs, an intermediate region that contains [Fe II]-emitting gas, and NLRs with minimal dust attenuation. The geometry of these structures, along with the viewing angle, may account for the diverse observed features across different objects.

Local LRDs offer a valuable opportunity to investigate the physical nature of this population. The conceptual framework presented in §7 provides one possible scenario to explain the observed features. However, open questions remain. Do LRDs, and the scenario illustrated in Figure 14, represent a specific evolutionary phase of SMBHs? Are they connected to conventional type-1 and type-2 AGNs? How do the physical conditions that give rise to LRDs evolve with redshift, and why are they so rare in the local Universe? How do the BH and host galaxy properties of LRDs change over cosmic time? While answering these questions is beyond the scope of this paper, they are critical for understanding the broader context of BHs and merit future investigation.

Ongoing wide-field surveys, such as DESI and Euclid, along with upcoming missions like the Roman Space Telescope, will open new windows for identifying LRDs at low redshift. These efforts will enable studies of their cosmic evolution and contributions to the history of SMBH growth. Large statistical samples will be essential for establishing their demographics. Future observations with high-resolution facilities such as HST and JWST will provide critical insights to test the proposed scenarios and directly probe the properties of their host galaxies.

ACKNOWLEDGMENTS

We thank Zuyi Chen, Anna de Graaf, Christina Eilers, Carl Fields, Yifei Jin, Raphael Hviding, Rob Kennicutt, Serena Kim, Rohan Naidu, George Rieke, Pierluigi Rinaldi, Hans-Walter Rix, Jinyi Shanguan, Nathan Smith, and Marianne Vestergaard for valuable discussions and comments. We thank Joe Shields and Joannah Hinz for approving LBT Directory Discretionary Time, Jenny Powers for her expert help with LBT observations, and Olga Kuhn for her help with the data reduction. We thank Ben Weiner and Sean Moran for their assistance with the Binospec data reduction. We thank Cass Fan for help with the illustration. XL, XF and FW acknowledge support from the NSF grant AST-2308258.

Observations reported here were obtained at the MMT Observatory, a joint facility of the University of Arizona and the Smithsonian Institution. The LBT is an international collaboration among institutions in the United States, Italy and Germany. LBT Corporation partners are: The University of Arizona on behalf of the Arizona university system; Istituto Nazionale di Astrofisica, Italy; LBT Beteiligungsgesellschaft, Germany, representing the Max-Planck Society, the Astrophysical Institute Potsdam, and Heidelberg University; The Ohio State University, and The Research Corporation, on behalf of The University of Notre Dame, University of Minnesota and University of Virginia. This paper used data obtained with the MODS spectrographs built with funding from NSF grant AST-9987045 and the NSF Telescope System Instrumentation Program (TSIP), with additional funds from the Ohio Board of Regents and the Ohio State University Office of Research.

This paper includes data gathered with the 6.5 meter Magellan Telescopes located at Las Campanas Observatory, Chile.

This research uses services or data provided by the Astro Data Lab, which is part of the Community Science and Data Center (CSDC) Program of NSF NOIRLab. NOIRLab is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under a cooperative agreement with the U.S. National Science Foundation.

This research is based on observations made with the Galaxy Evolution Explorer, obtained from the MAST data archive at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

This work has made use of data from the European Space Agency (ESA) mission *Gaia* (<https://www.cosmos.esa.int/gaia>), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, [\[cosmos.esa.int/web/gaia/dpac/consortium\]\(https://www.cosmos.esa.int/web/gaia/dpac/consortium\)\). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.](https://www.</p>
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This work is based in part on data obtained as part of the UKIRT Infrared Deep Sky Survey.

The Pan-STARRS1 Surveys (PS1) and the PS1 public science archive have been made possible through contributions by the Institute for Astronomy, the University of Hawaii, the Pan-STARRS Project Office, the Max-Planck Society and its participating institutes, the Max Planck Institute for Astronomy, Heidelberg and the Max Planck Institute for Extraterrestrial Physics, Garching, The Johns Hopkins University, Durham University, the University of Edinburgh, the Queen's University Belfast, the Harvard-Smithsonian Center for Astrophysics, the Las Cumbres Observatory Global Telescope Network Incorporated, the National Central University of Taiwan, the Space Telescope Science Institute, the National Aeronautics and Space Administration under Grant No. NNX08AR22G issued through the Planetary Science Division of the NASA Science Mission Directorate, the National Science Foundation Grant No. AST-1238877, the University of Maryland, Eotvos Lorand University (ELTE), the Los Alamos National Laboratory, and the Gordon and Betty Moore Foundation.

The Legacy Surveys consist of three individual and complementary projects: the Dark Energy Camera Legacy Survey (DECaLS; Proposal ID #2014B-0404; PIs: David Schlegel and Arjun Dey), the Beijing-Arizona Sky Survey (BASS; NOAO Prop. ID #2015A-0801; PIs: Zhou Xu and Xiaohui Fan), and the Mayall *z*-band Legacy Survey (MzLS; Prop. ID #2016A-0453; PI: Arjun Dey). DECaLS, BASS, and MzLS together include data obtained, respectively, at the Blanco telescope, Cerro Tololo Inter-American Observatory, NSF's NOIRLab; the Bok telescope, Steward Observatory, University of Arizona; and the Mayall telescope, Kitt Peak National Observatory, NOIRLab. Pipeline processing and analyses of the data were supported by NOIRLab and the Lawrence Berkeley National Laboratory (LBNL). The Legacy Surveys project is honored to be permitted to conduct astronomical research on Iolkam Du'ag (Kitt Peak), a mountain with particular significance to the Tohono O'odham Nation.

NOIRLab is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation. LBNL is managed by the Regents of the University of California under contract to the U.S. Department of Energy.

This project used data obtained with the Dark Energy Camera (DECam), which was constructed by the Dark Energy Survey (DES) collaboration. Funding for the DES Projects has been provided by the U.S. Department of Energy, the U.S. National Science Foundation, the Ministry of Science and Education of Spain, the Science and Technology Facilities Council of the United Kingdom, the Higher Education Funding Council for England, the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign, the Kavli Institute of Cosmological Physics at the University of Chicago, the Center for Cosmology and Astro-Particle Physics at the Ohio State University, the Mitchell Institute for Fundamental Physics and Astronomy at Texas A&M University, Financiadora de Estudos e Projetos, Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro, Conselho Nacional de Desenvolvimento Científico e Tecnológico, and the Ministério da Ciência, Tecnologia e Inovação, the Deutsche Forschungsgemeinschaft, and the Collaborating Institutions in the Dark Energy Survey. The Collaborating Institutions are Argonne National Laboratory, the University of California at Santa Cruz, the University of Cambridge, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas-Madrid, the University of Chicago, University College London, the DES-Brazil Consortium, the University of Edinburgh, the Eidgenössische Technische Hochschule (ETH) Zürich, Fermi National Accelerator Laboratory, the University of Illinois at Urbana-Champaign, the Institut de Ciències de l'Espai (IEEC/CSIC), the Institut de Física d'Altes Energies, Lawrence Berkeley National Laboratory, the Ludwig-Maximilians-Universität München and the associated Excellence Cluster Universe, the University of Michigan, NSF's NOIRLab, the University of Nottingham, the Ohio State University, the University of Pennsylvania, the University of Portsmouth, SLAC National Accelerator Laboratory, Stanford University, the University of Sussex, and Texas A&M University.

BASS is a key project of the Telescope Access Program (TAP), which has been funded by the National Astronomical Observatories of China, the Chinese Academy of Sciences (the Strategic Priority Research Program “The Emergence of Cosmological Structures”, Grant #XDB09000000), and the Special Fund for Astronomy from the Ministry of Finance. BASS is also supported by the External Cooperation Program of Chinese Academy of Sciences (Grant #114A11KYSB20160057), and the Chinese National Natural Science Foundation (Grant #12120101003, #11433005).

The Legacy Survey team makes use of data products from the Near-Earth Object Wide-field Infrared Survey Explorer (NEOWISE), which is a project of the Jet Propulsion Laboratory/California Institute of Technology. NEOWISE is funded by the National Aeronautics and Space Administration.

The Legacy Surveys imaging of the DESI footprint is supported by the Director, Office of Science, Office of High Energy Physics of the U.S. Department of Energy under Contract No. DE-AC02-05CH1123, by the National Energy Research Scientific Computing Center, a DOE Office of Science User Facility under the same contract, and by the U.S. National Science Foundation, Division of Astronomical Sciences under Contract No. AST-0950945 to NOAO.

Funding for the Sloan Digital Sky Survey IV has been provided by the Alfred P. Sloan Foundation, the U.S. Department of Energy Office of Science, and the Participating Institutions.

SDSS-IV acknowledges support and resources from the Center for High Performance Computing at the University of Utah. The SDSS website is www.sdss4.org.

SDSS-IV is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS Collaboration including the Brazilian Participation Group, the Carnegie Institution for Science, Carnegie Mellon University, Center for Astrophysics — Harvard & Smithsonian, the Chilean Participation Group, the French Participation Group, Instituto de Astrofísica de Canarias, The Johns Hopkins University, Kavli Institute for the Physics and Mathematics of the Universe (IPMU) / University of Tokyo, the Korean Participation Group, Lawrence Berkeley National Laboratory, Leibniz Institut für Astrophysik Potsdam (AIP), Max-Planck-Institut für Astronomie (MPIA Heidelberg), Max-Planck-Institut für Astrophysik (MPA Garching), Max-Planck-Institut für Extraterrestrische Physik (MPE), National Astronomical Observatories of China, New Mexico State University, New York University, University of Notre Dame, Observatório Nacional / MCTI, The Ohio State University, Pennsylvania State University, Shanghai Astronomical Observatory, United Kingdom Participation Group, Universidad Nacional Autónoma de México, University of Arizona, University of Colorado Boulder, University of Oxford, University of Portsmouth, University of Utah, University of Virginia, University of Washington, University of Wisconsin, Vanderbilt University, and Yale University. Collaboration Overview Affiliate Institutions Key People in SDSS Collaboration Council Committee on Inclusiveness Architects SDSS-IV Survey Science Teams and Working Groups Code of Conduct SDSS-IV Publication

APPENDIX

A. HST FR782N IMAGING OF J1047+0739

As described in §4.1, HST program GO-15617 (PI: F. Bauer) obtained high resolution ACS FR782N ramp filter images on J1047+0739. To cover the continuum, broad $H\alpha$, and narrow $H\alpha$ lines, the observations were taken using the FR782N ramp filter with four configurations centered at 7474Å 7583Å 7669Å, and 7755Å, respectively. The total integration time of each configuration is ~ 5000 s. In our analysis, we focus on the narrow-band images centered at 7474Å and 7669Å. The 7474Å narrow-band image serves as the continuum map at rest-frame 6397Å. We subtract it from the 7669Å narrow-band image to obtain the pure $H\alpha$ line map without continuum contribution. The $H\alpha$ line map covers the entire narrow $H\alpha$ component and 91% of the broad component.

We compare the profile of the continuum and $H\alpha$ line map with that of the PSF. The PSF is constructed using a star within the HST field-of-view $16''$ away from the object. As shown in the left panel of Figure A.1, the continuum map has a bright central point source and an extended asymmetric structure, which we assume to be stellar light from the LRD host galaxy. Its radial profile is consistent with a PSF profile within $\lesssim 0.5$ kpc, while showing a deviation at $\gtrsim 0.5$ kpc. The $H\alpha$ line map exhibits a point-source-like morphology with clear diffraction spikes. Its radial profile closely matches that of the PSF. It indicates that the $H\alpha$ line is primarily contributed by the AGN.

We model the morphology of the continuum map using GALFIT (C. Y. Peng et al. 2002). We assume a PSF and four Sérsic components. The right panel of Figure A.1 presents the best-fit model and the PSF-subtracted components, which represent the host galaxy. The host galaxy has compact, yet clumpy morphology, with a half-light radius of 530 pc. The luminosity of the central PSF is 5.5 times that of the host galaxy, indicating that the AGN contributes about 85% of the total continuum light in the optical.

We note that the compact host galaxy of J1047+0739 detected by HST at $z = 0.17$ will be very challenging to resolve and detect for an LRD at high redshift, even at JWST resolution. This highlights the need for spatially resolved studies of local LRDs.

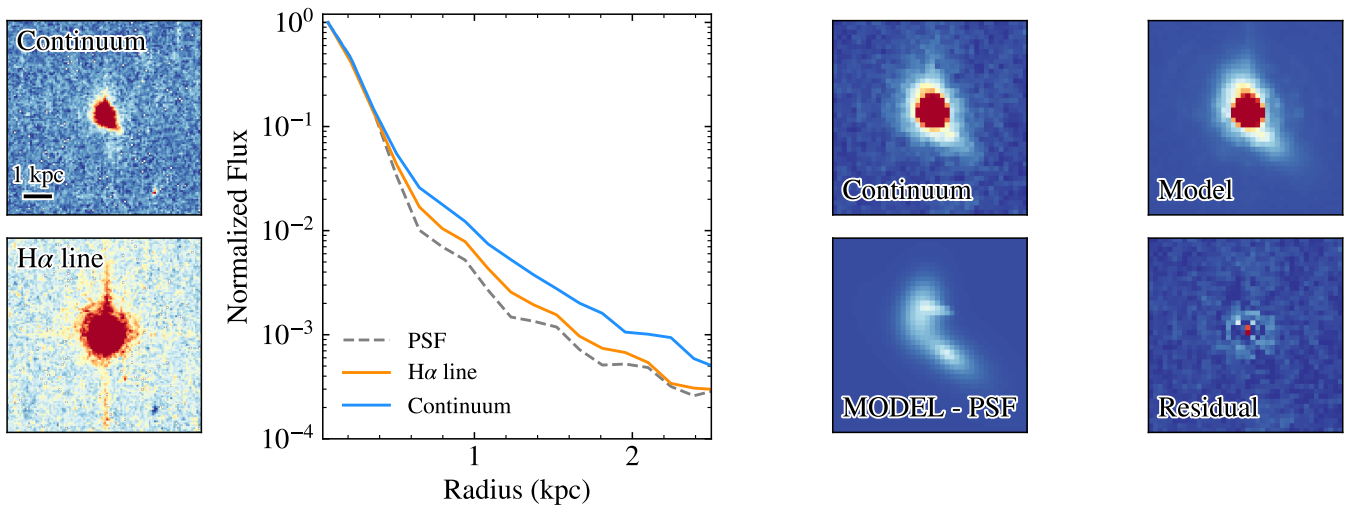


Figure A.1. Morphology of the continuum at rest-frame 6397 Å and $H\alpha$ line maps of J1047+0739. *Left panel:* the continuum map, $H\alpha$ line map, and the radial profiles compared with that of the PSF. *Right panel:* The best-fit model of the continuum, the PSF-subtracted component representing the galaxy light, and the residual. The four figures are shown in the same color scale.

B. EMISSION LINE FITTING

For strong emission lines with visible broad components (e.g., $H\alpha$, $Pa\alpha$), we model each line with a single narrow Gaussian plus one or more broad Gaussian or Lorentzian profiles to capture the composite broad features. A linear polynomial is added to account for the local continuum. Specifically, broad Paschen lines are modeled with Lorentzian profiles, leveraging the high-resolution FIRE spectra to resolve line wings, while broad $H\alpha$ components are depicted by two to three Gaussian profiles. The $[N\ II]\ \lambda\lambda 6548, 6583$ doublet is fit simultaneously with $H\alpha$. We model them with two narrow Gaussians, fixing their FWHMs to match the narrow $H\alpha$ component and setting their flux ratio to 3. In J1047+0739, the Paschen lines and adjacent IR He I lines are modeled simultaneously, with the He I emission represented by broad and narrow Gaussian components. Note that for each line profile fit, the parameters of the narrow Gaussian component are treated independently, as the spectral resolution varies across wavelengths and instruments. For example, $[O\ III]\ \lambda 5007$ in the MODS spectra is unresolved, with its observed FWHM determined by the wavelength-dependent line spread function. Therefore, we do not use its fit to constrain the narrow components of $H\alpha$ or $Pa\alpha$.

For the $H\alpha$ emission lines of *The Egg* and J1022+0841, whether from MODS or Binospec spectra, we simultaneously fit the absorption and emission profiles. Given the higher resolution of the Binospec spectra, we rely on them for more precise absorber measurements. As shown in Figure B.1, a Gaussian absorption component ($EW = 2.54 \pm 0.07\ \text{\AA}$) is applied on top of the composite broad $H\alpha$ profile (i.e., the sum of the two broad Gaussians). For J1022+0841, we test two different fitting models: one assuming a single Gaussian absorber superimposed on the broad emission lines, and the other using two Gaussian absorbers. As shown in Figure B.1, the two-Gaussian model provides a better fit, more accurately capturing the profile wing.

Since the He I $\lambda 10830$ absorption profiles are complex, we model the intrinsic emission by masking the absorption-affected regions. The remaining line profile wings, unaffected by absorption, are used to constrain and recover the symmetric emission line profiles. The emission is modeled with one or two broad Gaussian components plus a narrow component. For $H\beta$ line of *The Egg*, we also mask the absorbed region and fit the intrinsic emission profile.

The normalized $H\alpha$ absorption profiles shown in Figure 6 are derived by dividing the absorbed broad $H\alpha$ emission by the intrinsic broad $H\alpha$ line profile. For $H\beta$ in *The Egg* and He I $\lambda 10830$ in all three objects, the profiles are normalized by the total unabsorbed profiles, including both the broad emission lines and continua. Normalizing $H\beta$ using only the broad emission line is tested but results in an absorption peak below zero. We then model the normalized $H\beta$ absorber with a single Gaussian and the normalized He I $\lambda 10830$ absorber with multiple Gaussians. Table 4 summarizes the best-fit parameters for each absorber.

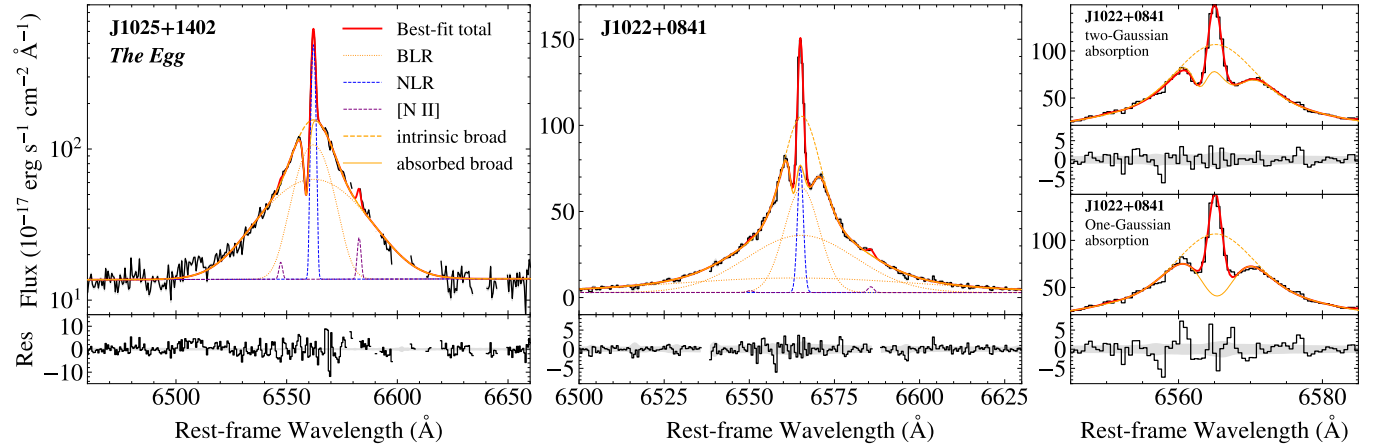


Figure B.1. Best-fit line profiles for *The Egg* and J1022+0841 from Binospec spectra, with absorption components overlaid on the emission profiles. The middle panel shows the two-Gaussian absorption model for J1022+0841, while the right panel compares fits with one and two Gaussians; the single-Gaussian fit does not sufficiently reproduce the profile wings. For each fit, the residuals (i.e., data - model) are shown at the bottom, with the gray shaded region indicating the data uncertainty.

Name	H β			H α			He I λ 10830		
	Δv (km s $^{-1}$)	FWHM (km s $^{-1}$)	EW (\AA)	Δv (km s $^{-1}$)	FWHM (km s $^{-1}$)	EW (\AA)	Δv (km s $^{-1}$)	FWHM (km s $^{-1}$)	EW (\AA)
<i>The Egg</i> (J1025+1402)	73	232 \pm 25	4.16 \pm 0.43	-148	142 \pm 5	2.54 \pm 0.07	-613	249 \pm 17	8.05 \pm 0.71
							-410	163 \pm 31	3.93 \pm 1.67
							-248	195 \pm 20	6.97 \pm 1.23
							total	18.95 \pm 2.19	
J1047+0739	-	-	-	-	-	-	-1646	163 \pm 17	3.15 \pm 0.44
							-1431	237 \pm 41	4.69 \pm 0.80
							-1088	282 \pm 58	4.47 \pm 0.93
							-889	133 \pm 29	2.06 \pm 0.61
							-801	47 \pm 14	1.96 \pm 0.29
							total	16.33 \pm 1.47	
J1022+0841	-	-	-	(two Gaussian)			-54	100 \pm 4	4.25 \pm 0.11
				-96	93 \pm 16	0.92 \pm 0.21			
				102	228 \pm 39	2.08 \pm 0.52			
				total	3.00 \pm 0.56				
				(one Gaussian)					
11	273 \pm 26	4.16 \pm 0.33							

Table 4. Properties of the Balmer and He I absorbers in the three local LRDs. For multi-component profiles, we list the parameters of individual components along with the summed EWs. For the H α absorber in J1022+0841, we present two modeling scenarios.

C. [Fe II] MODELING

To model AGN photoionization scenarios for [Fe II] emission, we adopt AGN SEDs from C. Jin et al. (2012). While the chosen SED corresponds to an Eddington ratio of 0.17, our CLOUDY modeling is intended to be qualitative and is not highly sensitive to this assumed value. How the Eddington ratio impacts the AGN SED, and consequently the resulting [Fe II] spectrum, is beyond the scope of this paper. Our CLOUDY models span a grid of hydrogen densities from $\log(n_{\text{H}}/\text{cm}^{-3}) = 8$ to 13 (0.5 dex step), column densities from $\log(N_{\text{H}}/\text{cm}^{-2}) = 20$ to 25 (0.5 dex step), ionization parameters from $\log U = -4$ to 0 (1 dex step), and metallicities from $Z/Z_{\odot} = -1$ to 2 (1 dex step). We run a suite of CLOUDY models over this parameter space, assuming a plane-parallel geometry, and obtain the predicted [Fe II] line spectra.

To determine the best-fit models, we compare the observed emission line fluxes with those predicted by the modeled [Fe II] spectrum. Specifically, we use the fluxes of [Fe II] λ 4235, λ 4244, λ 4278, λ 4287, λ 4416, λ 5158, λ 5262, λ 7155, and λ 7172. Additionally, since [Fe II] λ 5169 is highly sensitive to the gas conditions but is not detected, we include its 3σ upper limit as an extra constraint. All line fluxes, both observed and modeled, are normalized to that of [Fe II] λ 4244, and we compute the χ^2 value for each model grid.

For comparison, we also explored models using a 5000 K blackbody as the ionizing source. The temperature is chosen based on our analysis in §6 and §7. These models fail to reproduce the observed [Fe II] line ratios, with significant discrepancies particularly in [Fe II] λ 4235, λ 4244, λ 4278, λ 4287, and λ 4416.

In Figure C.1, we present the best-fit [Fe II] model for J1022+0841. Its best-fit parameters are identical to those used for J1025+1402.

D. THE PARAMETERIZATION OF THE CONTINUA

D.1. Theoretical atmosphere model + dust templates

We begin with the best-matched theoretical models from H. Liu et al. (2025) and model the dust emission using the dust templates from J. Lyu & G. H. Rieke (2021). These dust templates, originally developed for type-1 AGNs, include four components: blackbodies at 2100 K, 1038 K, and 300 K, and a graybody at 90 K. We extrapolate the theoretical model spectra by assuming a blackbody tail in the near-IR, consistent with the model’s effective temperature. We

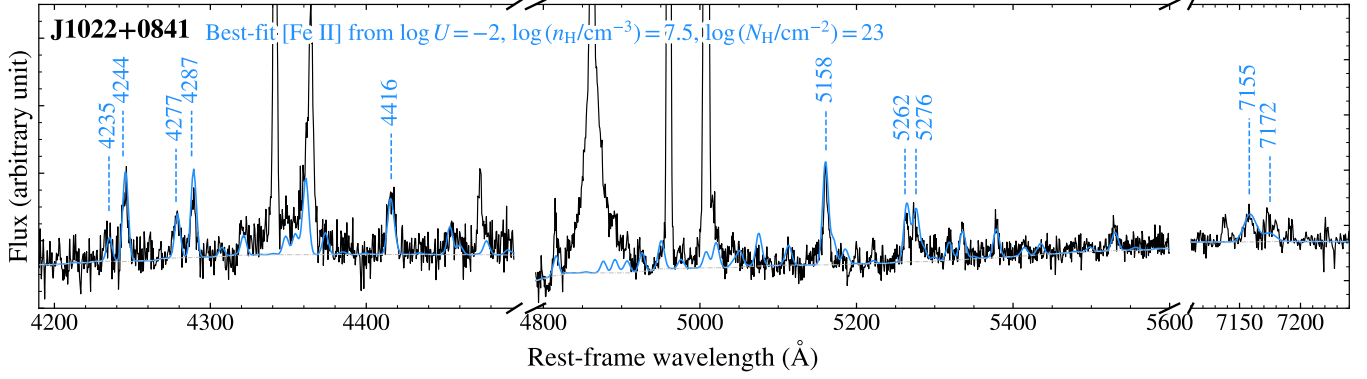


Figure C.1. Same as Figure 9, but for J1022+0841. The best-fit parameters are identical to those for J1025+1402.

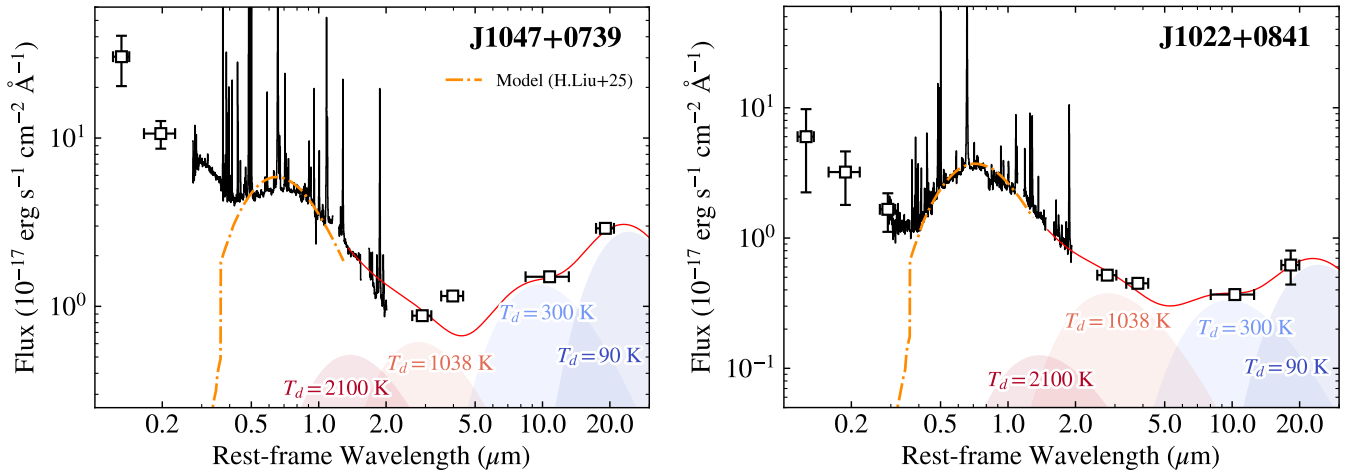


Figure D.1. The SEDs of J1047+0739 and J1022+0841 and their respective best-matched models from H. Liu et al. (2025). The dust components, assuming templates from J. Lyu & G. H. Rieke (2021), are shown as the color-shaded regions.

then fit the amplitudes of the four dust components to reproduce the overall continuum and WISE photometry at wavelengths longer than $1.5 \mu\text{m}$.

Figure 13 demonstrates that this model successfully reproduces the near-infrared photometry of *The Egg*. Figure D.1 shows the SEDs of J1047+0739 and J1022+0841 compared with and the models from H. Liu et al. (2025) that visually match the data. The intrinsic luminosity of the H. Liu et al. (2025) model is $4.1 \times 10^{43} \text{ erg s}^{-1}$ for J1047+0739, with a reference density of $\rho_{\text{ref}} = 1.1 \times 10^{-12} \text{ g cm}^{-3}$ (which is comparable to the photosphere density; see H. Liu et al. (2025) for exact definition). These model parameters give an effective temperature of $T_{\text{eff}} = 4816 \text{ K}$. For J1022+0841, the model luminosity is $5.1 \times 10^{43} \text{ erg s}^{-1}$ with $\rho_{\text{ref}} = 1.9 \times 10^{-12} \text{ g cm}^{-3}$, and the resulting $T_{\text{eff}} = 4614 \text{ K}$. We note that the SED of J1047+0739 is less well reproduced, mainly due to the non-negligible galaxy light. The HST narrow-band imaging (see Appendix A) reveals that, although the AGN dominates the continuum, the host galaxy contributes at least 18% of the continuum light around the $\text{H}\alpha$ wavelengths. The contribution from the host galaxy is likely minor in *The Egg* and J1022+0841, both of which exhibit more prominent V-shaped SEDs with redder optical continua. This suggests stronger AGN dominance in the optical continua. Nevertheless, the comparison between the model and observed spectra aims to demonstrate the plausibility of the theoretical models rather than to constrain the physical properties of these objects.

As shown in Figure D.1, the rest-frame near-IR emission of J1047+0739 and J1022+0841 can be described by dust components with temperatures ranging from 2100 K to 90 K. However, the inferred amplitudes are highly sensitive to the assumed optical-to-IR continuum shape and the choice of dust templates. We discuss alternative approaches and associated degeneracies below.

D.2. *An empirical parameterization of the continuum*

We attempt to empirically parameterize the optical-IR continuum shapes of local LRDs with a pseudo-blackbody spectrum. This parameterization is purely descriptive, intended to capture the observed continuum shape but not to provide a physical interpretation. We adopt the functional form of a modified Calzetti law (S. Noll et al. 2009), but it should not be interpreted as indicating any particular amount of dust attenuation. The parameterization can be expressed as:

$$f_{\text{MB}}(\lambda) = f_{\text{UV}} \left(\frac{\lambda}{3000 \text{ \AA}} \right)^\alpha + f_{\text{BB}} \left[e^{-0.4 \tilde{A}_\lambda(\tilde{A}_V, \delta)} \cdot \text{BB}(\lambda, T) \right] + \sum_i f_{d,i} B_d(\lambda, T_i) \quad (\text{D1})$$

where the free parameters are f_{UV} , α , \tilde{A}_V , δ , f_{BB} , T , and $f_{d,i}$. f_{UV} and α are the amplitude and power-law slope of the UV continuum. It represents a distinct component, which could be either due to the AGN light or the host galaxy. $\tilde{A}_\lambda(\tilde{A}_V, \delta)$ denotes the form of the modified Calzetti law (S. Noll et al. 2009), where \tilde{A}_λ represents a generalized attenuation curve (not necessarily tied to physical dust properties), and δ is the power-law modification parameter, normalized at 5500 Å. For J1047+0739, we introduce an additional free parameter to model the Balmer jump as a discontinuity in the power-law at 3645 Å. $\text{BB}(\lambda, T)$ is the blackbody spectrum at temperature T , and f_{BB} is its amplitude. For the dust emission, we adopt the dust templates from J. Lyu & G. H. Rieke (2021). $f_{d,i}$ and $B_d(\lambda, T_i)$ are the amplitude and blackbody or gray body spectrum of the i -th dust component.

The best-fit continua of the three local LRDs are shown in Figure D.2. The corresponding best-fit parameters and component luminosities are summarized in Table 5. We do not include associated uncertainties given the descriptive nature of this parameterization. All three objects exhibit temperatures around 5000–6000 K and very negative values of δ . The extreme δ produces a very steep modification to the original blackbody. Such a negative δ strongly suppresses the UV-to-optical flux of the blackbody spectrum while leaving the IR spectrum largely unaffected. As discussed in §6.2, physical mechanisms, such as metal cooling and gas opacity, may contribute to this modification. In particular, the contribution of the UV power-law component to the optical continuum in J1047+0739 is non-negligible. At the H α wavelength, the power-law component is only a factor of 2.3 fainter than the pseudo-blackbody. This is broadly consistent with measurements from its HST narrow-band image, which show the AGN luminosity to be 5.5 times that of the host galaxy. In the other two objects, the power-law components at optical wavelengths are orders of magnitude fainter than the pseudo-blackbody components.

Parameter	J1025+1402 (<i>The Egg</i>)	J1047+0739	J1022+0841
α	-1.51	-1.52	-1.76
$f_{\text{UV}} (10^{-17} \text{ erg s}^{-1} \text{ \AA}^{-1})$	4.25	4.92	1.45
\tilde{A}_V	0.58	1.81	0.87
δ	-4.37	-0.11	-1.65
$T_{\text{BB}} (\text{K})$	5019	5013	5558
$L_{\text{pseudo-BB}} (10^{43} \text{ erg s}^{-1})$	1.89	3.58	4.17
$L_{\text{dust},2000\text{K}} (10^{43} \text{ erg s}^{-1})$	–	–	0.98
$L_{\text{dust},1038\text{K}} (10^{43} \text{ erg s}^{-1})$	0.55	0.95	2.07
$L_{\text{dust},300\text{K}} (10^{43} \text{ erg s}^{-1})$	2.21	17.5	76.90
$L_{\text{dust},90\text{K}} (10^{43} \text{ erg s}^{-1})$	0.84	57.9	28.94

Table 5. The best-fit continuum parameters for the three local LRDs are derived using the parametrization in Equation D1. The normalization amplitude in Equation D1 is converted into the luminosity of each component. T_{BB} is the effective temperature of the pseudo-blackbody spectrum, and $L_{\text{pseudo-BB}}$ is the total luminosity of the pseudo-blackbody component. $L_{\text{dust},2000\text{K}}$, $L_{\text{dust},1038\text{K}}$, $L_{\text{dust},300\text{K}}$, and $L_{\text{dust},90\text{K}}$ denote the luminosities of dust emission at 2000 K, 1038 K, 300 K, and 90 K, respectively, based on the templates in J. Lyu & G. H. Rieke (2021).

In *The Egg*, the two most prominent dust components are the 1038 K and 300 K blackbody components, which dominate the SED at wavelengths of 3-10 μm and 10-20 μm , respectively. They drive the rising flux observed in the four WISE bands. The contributions from the remaining two dust components are minor.

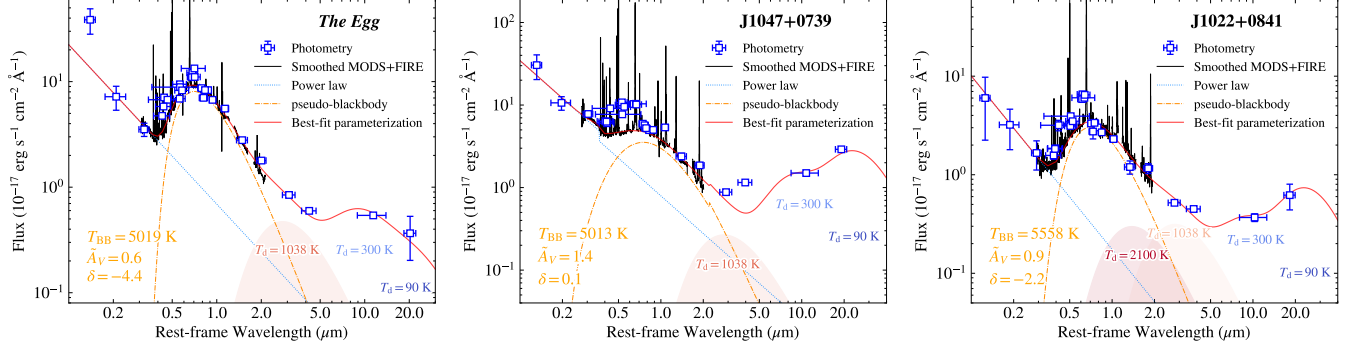


Figure D.2. The best-fit parameterization. The best-fit model (Equation D1) is shown as the red line, which includes a power-law component shown as the blue dotted line, a pseudo-blackbody component shown as the orange dashed-dotted line, and dust components shown as the color-shaded regions. The discontinuity around $2 \mu\text{m}$ in J1047+0739 arises from the range limitation of the modified Calzetti law, but it does not affect the result. The best-fit parameters are labeled; we emphasize that A_V and δ are purely descriptive of the continuum shape and are not intended to represent physical dust attenuation.

D.3. The Haro 11 dust template

The inferred dust components are highly sensitive to the choice of fitting templates. In J1047+0739, the W2 photometry at a rest-frame wavelength of $4 \mu\text{m}$ is not well reproduced, as simple blackbody or graybody models fail to capture features such as PAH emission and silicate absorption. In J1022+0841, a dust component with $T_d \approx 2100 \text{ K}$ appears, but this primarily reflects the influence of the four dust templates adopted from J. Lyu & G. H. Rieke (2021). To explore alternative interpretations, we replace the dust component in Equation D1 with the Haro 11 dust template from J. Lyu et al. (2016) and fit the continua of the three local LRDS, as shown in Figure D.3. Notably, the dust emission in J1022+0841 is well reproduced by the Haro 11 template, suggesting that its dust may reside in the ISM and be heated by AGN-driven feedback or massive star clusters in the host galaxy. This degeneracy highlights the need for mid- to far-infrared observations to robustly constrain the dust content and its origin in these systems.

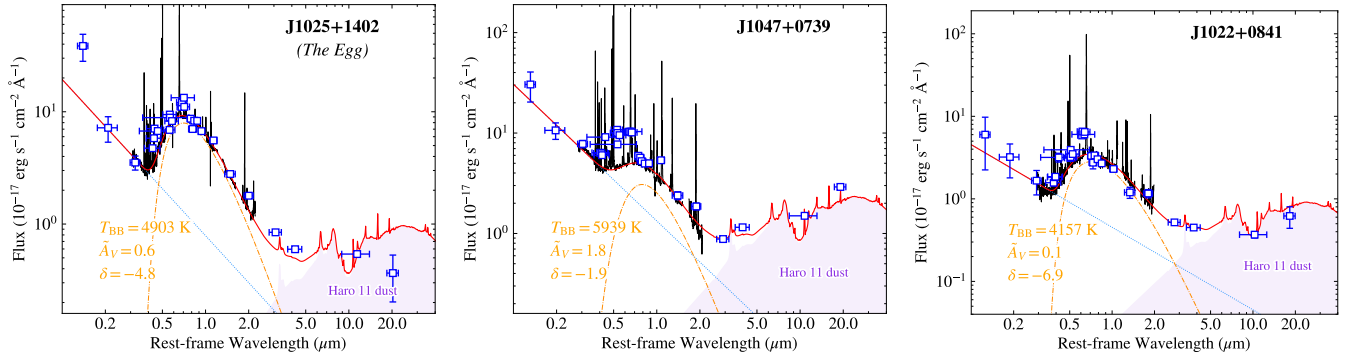


Figure D.3. Similar to Figure D.2, but using the Haro 11 dust template.

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