

Compact Core, Extended Reach: A Bipolar kpc-Scale Elongation in a Little Red Dot at $z \approx 5.5$ ZHIYUAN JI ¹, YANG SUN ¹, MAURO GIAVALISCO ², YONGDA ZHU ¹, GEORGE H. RIEKE ¹,
CHRISTINA C. WILLIAMS ^{3,1}, MICHAEL V. MASEDA ⁴, JIANWEI LYU ¹, MARCIA RIEKE ¹ AND
SANDRO TACCHELLA ^{5,6}¹*Steward Observatory, University of Arizona, 933 N. Cherry Avenue, Tucson, AZ 85721, USA*²*University of Massachusetts Amherst, 710 North Pleasant Street, Amherst, MA 01003-9305, USA*³*NSF–DOE Vera C. Rubin Observatory/NSF NOIRLab, 950 N. Cherry Ave., Tucson, AZ 85719, USA*⁴*Department of Astronomy, University of Wisconsin-Madison, 475 N. Charter St., Madison, WI 53706 USA*⁵*Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge, CB3 0HA, UK*⁶*Cavendish Laboratory, University of Cambridge, 19 JJ Thomson Avenue, Cambridge, CB3 0HE, UK***ABSTRACT**

Little Red Dots (LRDs) appear extremely compact at rest-frame optical wavelengths, yet many show extended rest-frame UV morphology revealing more complex internal structure. We present a combined analysis of VLT/MUSE rest-frame UV integral-field spectroscopy and continuum-subtracted [O III], H β , and H α + [N II] emission-line maps from JWST/NIRCam imaging at sub-kpc resolution for LRD-204851 at $z = 5.482$ in GOODS-S. We find that LRD-204851 hosts a remarkably thin, bipolar, elongated structure passing through the optical continuum centroid and extending several kpc on either side, traced by both the UV continuum and the rest-frame optical emission lines, with a bright [O III] clump-like structure ~ 2 kpc to the south-east of the centroid. The MUSE observations reveal a double-peaked Ly α profile, with a broad and bright near-systemic red peak and a relatively faint peak blueshifted by ~ 430 km s⁻¹, accompanied by a tentative N v $\lambda 1238$ detection at similar velocity. In narrow-band imaging extracted from the MUSE IFU cube, both the blue Ly α peak and the tentative N v emission lean toward this same south-eastern direction. Independently, radiative-transfer modeling of the integrated Ly α profile favors a biconical low-column-density cavity in a dense, slowly expanding neutral envelope, in support of the bipolar geometry traced by the line maps. Together, these results suggest that the elongated emission of LRD-204851 is connected to radiation and/or gas flow from its central engine through a low-column-density channel with a small opening angle that may trace either a slow outflow or a quasi-static ionization cone. LRD-204851 is one of the first LRDs where the central engine’s impact on its host galaxy is potentially directly observable on kpc scales.

1. INTRODUCTION

Little Red Dots (LRDs) are a population of compact, optically red sources discovered in JWST observations (I. Labbé et al. 2023; G. Barro et al. 2024; D. D. Kocevski et al. 2025; J. Matthee et al. 2024; J. E. Greene et al. 2024; L. J. Furtak et al. 2024; P. G. Pérez-González et al. 2024; C. C. Williams et al. 2024; H. B. Akins et al. 2025). They are characterized by a distinctive “V-shaped” continuum, blue in the rest-frame UV and red in the rest-frame optical (I. Labbé et al. 2023; P. G. Pérez-González et al. 2024; B. Wang et al. 2025; A. de Graaff et al. 2025a), and a substantial fraction exhibit broad (FWHM $\gtrsim 1000$ km s⁻¹) H α emission, often ac-

companied by Balmer absorption features (V. Kokorev et al. 2023; J. Matthee et al. 2024; R. Maiolino et al. 2024; J. E. Greene et al. 2024; L. J. Furtak et al. 2024; I. Juodžbalis et al. 2024, 2026; A. de Graaff et al. 2025b; B. Wang et al. 2025; X. Ji et al. 2025; D. D. Kocevski et al. 2025; A. de Graaff et al. 2025a).

Despite a rapidly growing observational record, the physical nature of LRDs remains debated. The broad H α emission has been interpreted as classical Type-1 AGN broad line region (BLR) emission viewed through a partially obscuring neutral medium (e.g., J. Matthee et al. 2024; J. E. Greene et al. 2024; R. Maiolino et al. 2024; I. Juodžbalis et al. 2026), but recent work has also proposed that the broadening is dominated by electron scattering in a dense ionized cocoon surrounding a young supermassive black hole, a “quasi-star”- or “black-hole-star”-like configuration (e.g., K. Inayoshi & R. Maiolino

2025; A. de Graaff et al. 2025b; R. P. Naidu et al. 2025; A. de Graaff et al. 2025a). Empirical evidence in support of this picture includes exponential Balmer line wings, ubiquitous Balmer absorbers, and bright broad $H\alpha$ accompanied by $H\beta$ profiles dominated by their narrow component, all of which are difficult to reproduce with classical Keplerian BLR broadening (V. Rusakov et al. 2026; J. Matthee et al. 2026). The nature of the V-shaped continuum is similarly debated, with proposed origins ranging from a dust-reddened AGN (J. E. Greene et al. 2024; M. Killi et al. 2024; B. Wang et al. 2025) to a super-Eddington intermediate-mass black hole (e.g., F. Pacucci & R. Narayan 2024; H. Liu et al. 2025) to a dust-obscured starburst (P. G. Pérez-González et al. 2024; C. C. Williams et al. 2024; H. B. Akins et al. 2025). Distinguishing among these scenarios requires diagnostics that probe the kinematics, geometry, and ionization state of the gas around the central source.

Emission lines provide a particularly powerful tool for this task. UV emission lines such as $Ly\alpha$ and high-ionization $N\,V$ are sensitive to the column density and geometry of the neutral gas around the central source through their characteristic line profiles (e.g., A. Verhamme et al. 2006, 2008; M. Hansen & S. P. Oh 2006; M. Dijkstra et al. 2006; Z. Ji et al. 2026), and to the hardness of the ionizing radiation field through their relative strengths (e.g., F. Hamann & G. Ferland 1999; D. E. Vanden Berk et al. 2001; K. N. Hainline et al. 2011; H. Treiber et al. 2025). The rest-frame optical Balmer lines and forbidden lines such as $[O\,III]\,\lambda 4959, 5007$ ($[O\,III]$ hereafter) and $[N\,II]\,\lambda 6548, 6584$ ($[N\,II]$ hereafter), in turn, probe the photoionization conditions, dust attenuation, and the presence of dense neutral absorbers in front of the broad-line region (e.g., J. A. Baldwin et al. 1981; S. Veilleux & D. E. Osterbrock 1987; L. J. Kewley et al. 2019). Combining the integrated UV and optical emission-line measurements on the same source therefore yields an internally consistent constraint on the gas content, kinematics, ionization state, and dust geometry that neither set of diagnostics provides alone.

Beyond the integrated line measurements, the spatial distribution of emission lines provides a critical, complementary constraint, distinguishing scenarios in which the line emission is co-spatial with the central LRD continuum from those in which it extends to circumnuclear or galactic scales. JWST/NIRCam imaging is particularly well suited for this purpose at high redshift: the rest-frame optical lines $[O\,III]$, $H\beta$, $H\alpha$, and $[N\,II]$ redshift into the NIRCam wavelength range. The growing number of programs with NIRCam medium-band imaging coverage, such as JEMS (C. C. Williams et al. 2023), JOF (D. J. Eisenstein et al. 2025), MegaScience (K. A.

Suess et al. 2024) and MINERVA (A. Muzzin et al. 2025), now provide deep coverage in dozens of broad and medium bands across legacy extragalactic fields. This opens a unique opportunity to construct sub-kpc-resolution maps of the optical emission lines around individual LRDs, complementing ancillary ground-based integral-field rest-frame UV spectroscopy from MUSE (e.g., R. Bacon et al. 2023) and Keck (e.g., D. K. Erb et al. 2023).

LRD-204851 (J033233.26-274724.89) is one such source where this combined analysis can be carried out in unprecedented depth. Spectroscopically confirmed at $z_{\text{sys}} = 5.482$ based on the $[O\,III]$ emission line from NIRSpec high-resolution grating observations (J. Matthee et al. 2026), the source was first identified as an LRD by J. Matthee et al. (2024) based on a broad $H\alpha$ emission line detected in a NIRCam/WFSS grism spectrum from the FRESCO survey (P. A. Oesch et al. 2023). The broad $H\alpha$ line was subsequently confirmed at higher resolution by NIRSpec R1000 grating observations from the JADES program (I. Juodžbalis et al. 2026), and the source was further classified as an LRD by A. de Graaff et al. (2025a) on the basis of its V-shaped UV-to-optical continuum and compact F444W morphology (also see Figure 1). Recent NIRSpec/G395H observations further reveal that the broad $H\alpha$ profile is well described by exponential wings with $\text{FWHM} \approx 1080\text{ km s}^{-1}$ and a blueshifted Balmer absorber at $\Delta v \approx -80\text{ km s}^{-1}$ (J. Matthee et al. 2026).

Located close to the Hubble Ultra Deep Field (HUDF; S. V. W. Beckwith et al. 2006) in GOODS-S (M. Giavalisco et al. 2004), LRD-204851 benefits from one of the most comprehensive multiwavelength datasets available for an LRD, spanning deep JWST NIRCam imaging in 14 broad and medium bands from JADES (D. J. Eisenstein et al. 2025) and JEMS (C. C. Williams et al. 2023), as well as VLT/MUSE spectroscopy from the MUSE Hubble Ultra Deep Field surveys (R. Bacon et al. 2023). As Figure 1 shows, while LRD-204851 appears as a compact red point source in the rest-frame optical continuum, the rest-frame UV continuum reveals a remarkably elongated extension from southeast to northwest, and the rest-frame optical emission lines display complex morphologies, features that hint at a rich and structured gas environment around this LRD.

In this Letter, we present a combined analysis of MUSE UV spectroscopy and optical emission-line maps, constructed from JWST/NIRCam imaging, of LRD-204851. We characterize the gas geometry, kinematics, and ionization state around this source. The combination of integrated and spatially resolved UV resonance-line spectroscopy with rest-frame optical emission-

line imaging on a single LRD offers a unique multi-wavelength view that sheds light on the competing physical scenarios outlined above, and offers a direct glimpse of a possible central-engine impact on the host galaxy at kpc scales.

Throughout this paper, we adopt the AB magnitude system and a Λ CDM cosmology with [Planck Collaboration et al. \(2020\)](#) parameters, i.e., $\Omega_m = 0.315$ and $h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1}) = 0.673$.

2. OBSERVATIONS

In this study, we use VLT/MUSE integral-field data from the final official data release of the MUSE Hubble Deep Field South surveys ([R. Bacon et al. 2017, 2023](#)). The source lies in the MOSAIC portion of the survey (see [R. Bacon et al. 2023](#)), which reaches a depth of 10 hr exposure time. The science-ready products, including the full data cube, extracted 1D spectrum, and emission-line maps, were obtained through the **AMUSED** web interface⁷. As detailed in Appendix A, an astrometric correction was applied to align the MUSE World Coordinate System (WCS) with the NIRCам imaging mosaics; after this correction, the relative astrometric precision reaches a median of zero and a standard deviation of $\approx 0.07''$.

We also use NIRCам imaging data obtained from the JADES survey ([M. J. Rieke et al. 2023](#); [D. J. Eisenstein et al. 2026](#)), together with NIRCам medium-band imaging from the JEMS survey ([C. C. Williams et al. 2023](#)). All NIRCам mosaics used in this study are taken from the latest JADES data release, DR5 ([B. D. Johnson et al. 2026](#); [B. E. Robertson et al. 2026](#)). The images have a drizzle scale of $0.03'' \text{ pix}^{-1}$ and are registered to the Gaia DR3 WCS reference frame ([Gaia Collaboration et al. 2021](#)). We adopt JADES PSF models constructed for the region containing the source. These models are based on WEBBPSF ([M. D. Perrin et al. 2014](#)), while carefully accounting for data-reduction effects, and have been validated against point sources observed in JADES ([Z. Ji et al. 2024](#)). They are consistent with the observed point sources at the $\lesssim 3\%$ level in the inner core, while retaining the high S/N that would otherwise be difficult to achieve with conventional empirical PSF models because of the limited number of bright, isolated stars in GOODS-S.

3. UV EMISSION-LINE PROPERTIES FROM MUSE

3.1. The double-peaked Ly α profile and tentative Nv detection

As Figure 2 shows, the MUSE observations reveal a multi-component Ly α emission line and a tentative detection of Nv $\lambda 1238$ in LRD-204851. In the official catalog from the MUSE HUDF team ([R. Bacon et al. 2023](#)), the Ly α line is decomposed into two Gaussian components: a narrow blue peak at $\lambda_{\text{obs}} = 7868.6 \text{ \AA}$ and a broader red peak at $\lambda_{\text{obs}} = 7880.9 \text{ \AA}$. The combined Ly α blend has total flux $F_{\text{Ly}\alpha} = (4.1 \pm 0.1) \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$ (rest-frame EW $\simeq 144 \text{ \AA}$, $L_{\text{Ly}\alpha} \simeq 1.5 \times 10^{43} \text{ erg s}^{-1}$), of which $\sim 6\%$ sits in the blue component ($F_{\text{Ly}\alpha, \text{blue}} = (2.4 \pm 0.5) \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$). The tentative Nv $\lambda 1238$ line is reported at $\lambda_{\text{obs}} = 8015.3 \text{ \AA}$ with S/N = 2.1. We note that Nv is a resonance doublet, with the redder $\lambda 1242$ component intrinsically a factor of ~ 2 weaker than the $\lambda 1238$ one in the optically thin limit, set by the 2:1 ratio of oscillator strengths ([D. C. Morton 2003](#)). Given the modest S/N $\simeq 2.1$ of the $\lambda 1238$ line, the $\lambda 1242$ component is therefore expected to be undetected. As a consistency check, we also independently re-extract the 1D spectrum from the WCS-corrected cube in the AMUSED Ly α and Nv emission-line segmentation apertures (with local-sky subtraction) and integrate the line fluxes over the AMUSED bandpasses. Our measurements and the [R. Bacon et al. \(2023\)](#) catalog Ly α and Nv fluxes, as well as the blue/red peak velocities, agree with each other at the $\lesssim 10\%$ level. We adopt the published [R. Bacon et al. \(2023\)](#) values throughout.

Relative to the systemic redshift $z_{\text{sys}} = 5.482$ (based on the [O III] emission line from a NIRSpect high-resolution spectrum presented in [J. Matthee et al. 2026](#)), the red Ly α peak sits at $\Delta v = -38 \text{ km s}^{-1}$, while the blue Ly α peak and the tentative Nv $\lambda 1238$ line are blueshifted by $\Delta v_{\text{Ly}\alpha, \text{blue}} = -431 \pm 9 \text{ km s}^{-1}$ and $\Delta v_{\text{Nv}} = -467 \pm 241 \text{ km s}^{-1}$, respectively (Figure 2). The blue Ly α peak and Nv are therefore consistent with being at the same velocity within uncertainties, providing additional support for the otherwise tentative Nv detection.

The detection of a blueshifted Ly α peak at $z \approx 5.5$ is itself notable: at this redshift, the IGM neutral H I fraction typically extinguishes such peaks along an average sightline ([P. Madau 1995](#); [A. K. Inoue et al. 2014](#); [P. Laursen et al. 2011](#); [S. E. I. Bosman et al. 2022](#)). Confirmed blue-peak detections at such high redshift have been attributed to large local “proximity zones” around the source, where the source’s own ionizing flux, e.g. from a quasar, exceeds the UV background and lowers

⁷ <https://amused.univ-lyon1.fr/project/UDF/>

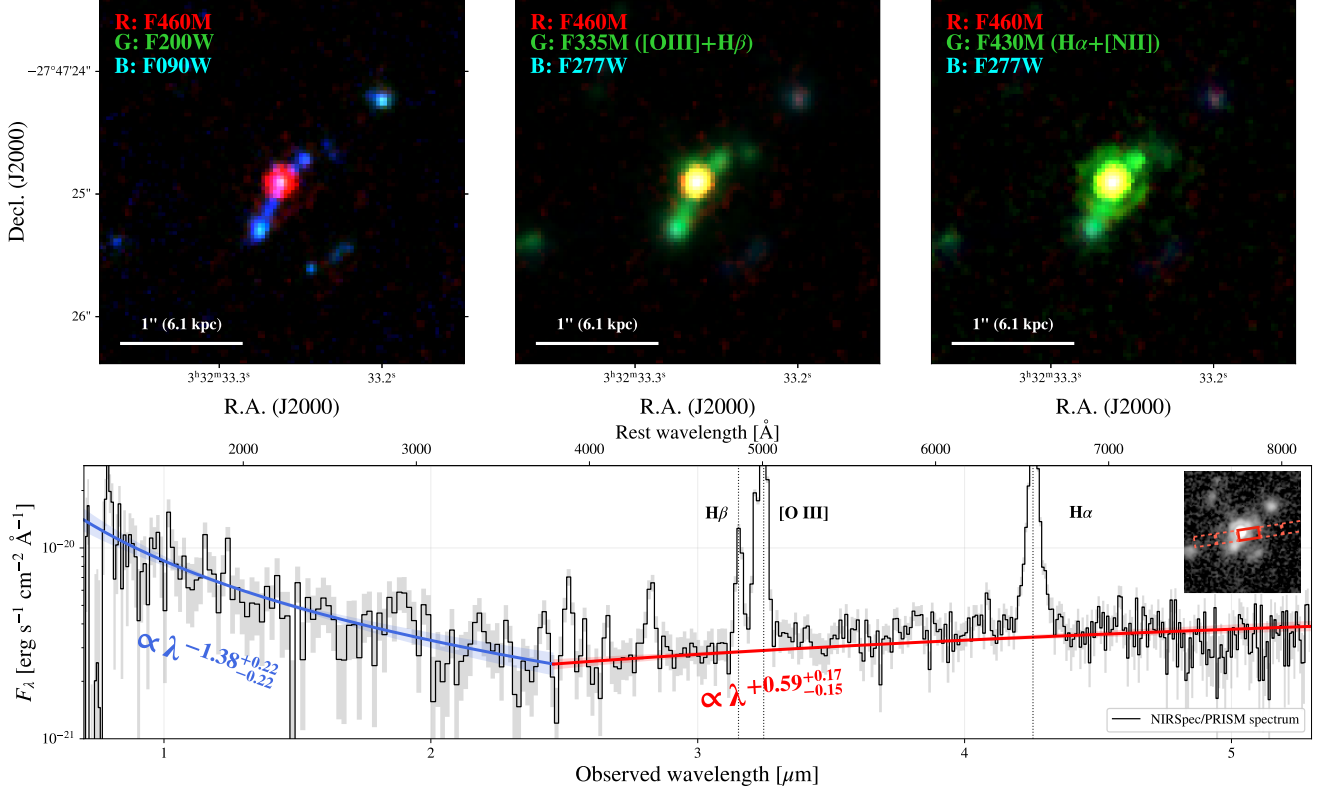


Figure 1. NIRCcam imaging and NIRSpect/PRISM spectrum of LRD-204851 at $z_{\text{sys}} = 5.482$. **Top row:** Three NIRCcam RGB cutouts at the native resolution, all shown with a common linear stretch. The left panel uses three continuum filters; the middle panel highlights [O III]+H β ; and the right panel highlights H α + [N II] in green. The target is a compact red point source in F460M, but shows a remarkably elongated blue continuum extension from southeast to northwest, as well as complex structures in optical emission lines. **Bottom:** NIRSpect/PRISM spectrum (MSA shuttle is shown in the inset). The blue and red solid lines show the rest-UV and rest-optical continuum power laws, respectively. The characteristic “V-shaped” continuum identifies LRD-204851 as a Little Red Dot, and higher-resolution spectra confirm that its H α emission includes a broad component with FWHM $> 1000 \text{ km s}^{-1}$ (J. Matthee et al. 2024; I. Juodžbalis et al. 2026; J. Matthee et al. 2026); these spectra are not shown here.

the local IGM neutral fraction. The most notably example is COLA1 at $z = 6.59$, whose blue peak is consistent with a $\sim 0.7 \text{ Mpc}$ ionized bubble carved by its own high Lyman continuum (LyC) escape fraction (e.g., E. M. Hu et al. 2016; J. Matthee et al. 2018; A. Torralba et al. 2024). Local IGM underdensities have also been proposed as a theoretical alternative (e.g., H. Park et al. 2026).

We assess the proximity-zone possibility for the blue Ly α peak observed in LRD-204851. Using the measured UV continuum magnitude ($M_{1500} = -18.82$) and UV slope ($\beta = -1.38$) from Z. Ji et al. (2026), we infer a LyC luminosity of $L_{912} \simeq 1.1 \times 10^{28} \text{ erg s}^{-1} \text{ Hz}^{-1}$. We then estimate R_{eq} , which denotes the distance from the source where the photoionization rates of the source $\Gamma_{\text{source}}(r)$ and of the cosmic UV background Γ_{bg} would be equal for purely geometric dilution in the absence of attenuation. Following the R_{eq} formalism of Y. Zhu et al. (2023), and adopting an ionizing-spectrum slope $\alpha_{\nu}^{\text{ion}} = 1.5$ and a $\Gamma_{\text{bg}} = 5 \times 10^{-13} \text{ s}^{-1}$ representative of

$z \sim 5.5$ (e.g., G. D. Becker & J. S. Bolton 2013; S. E. I. Bosman et al. 2022), this corresponds to a proximity-zone radius $R_{\text{eq}} \simeq 0.2 \text{ Mpc}$. This is substantially smaller than the $\simeq 0.7 \text{ Mpc}$ Hubble-flow distance corresponding to a $\Delta v_{\text{Ly}\alpha, \text{blue}} \simeq -430 \text{ km s}^{-1}$ photon, so a proximity zone alone cannot account for the observed blue Ly α peak.

3.2. Ly α profile modeling

Our calculation above indicates that the proximity zone can only provide a supporting transmission channel that allows blue Ly α photons in LRD-204851 to remain visible through the surrounding CGM and nearby IGM. The observed blue Ly α emission should therefore arise primarily from local radiative-transfer processes. This interpretation is further motivated by the Ly α profile itself: a broad red peak near systemic accompanied by a blueshifted component is characteristic of Ly α escape through a partially ionized, kinematically struc-

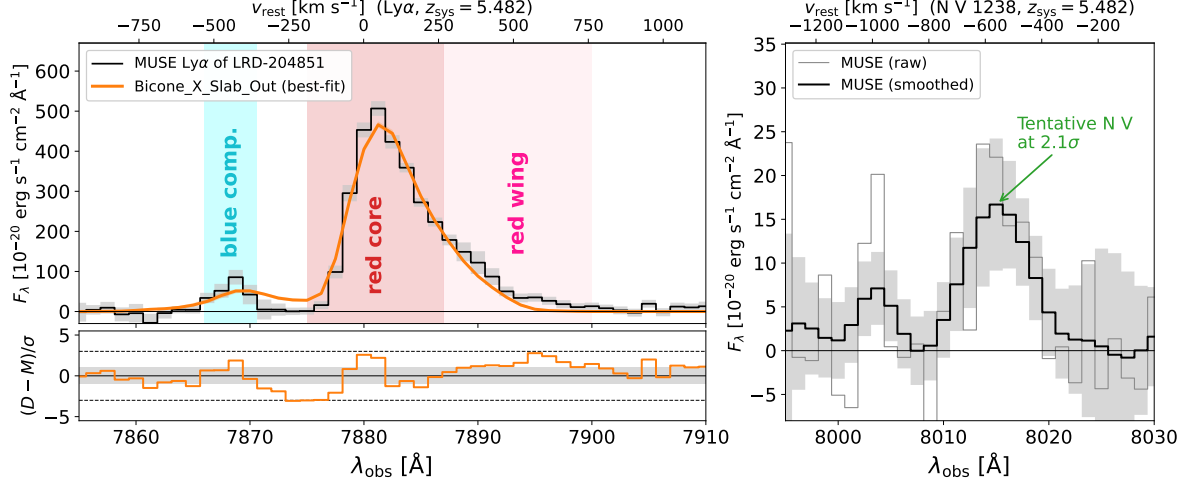


Figure 2. **Left:** MUSE spectrum (black) of the Ly α region with the `Bicone_X_Slab_Out` best-fit model (orange) overlaid. The cyan, red, and pink bands mark the disjoint windows used to build the blue-component, red-core, and red-wing narrow-band maps (see Section 3.3). The lower sub-panel shows the fit residuals with $\pm 1\sigma$ (grey band) and $\pm 3\sigma$ (dashed) reference levels. The full posterior is shown in Appendix B. **Right:** MUSE spectrum around N V $\lambda 1238$, with the raw flux (light grey) overlaid by a 1.5-pixel (i.e., $\approx 1.8\text{\AA}$) Gaussian-smoothed version (black) and its propagated $\pm 1\sigma$ band. The arrow marks the tentative 2.1σ N V $\lambda 1238$ detection.

tured neutral medium (e.g., A. Verhamme et al. 2006; M. Hansen & S. P. Oh 2006; M. Dijkstra et al. 2006).

We therefore model the Ly α profile with `zELDA` (S. Gurung-López et al. 2019, 2022), which provides pre-computed Ly α profiles from the Monte Carlo radiative-transfer code `LyaRT` (A. Orsi et al. 2012). We consider four available outflow geometries: (1) `Thin_Shell`, a uniformly expanding spherical thin shell of neutral hydrogen surrounding the source; (2) `Galactic_Wind`, a homologous ($v \propto r$) wind in which the density decreases with radius; (3) `Bicone_X_Slab_Out`, a thick neutral slab pierced by a biconical low-column-density cavity and viewed from outside the cone, approximately edge-on; and (4) `Bicone_X_Slab_In`, the same slab-plus-cone geometry viewed down the cone axis, approximately face-on. The fit includes four parameters: the Ly α redshift $z_{\text{Ly}\alpha}$, the bulk outflow expansion velocity V_{exp} , the neutral hydrogen column density N_{HI} , and the dust optical depth τ_a . We fit the data using the nested-sampling code `dynesty` (J. S. Speagle 2020).

Among the four gas geometries available in `zELDA`, the `Bicone_X_Slab_Out` geometry is strongly preferred. It is the only model that simultaneously reproduces the near-systemic red peak and the blueshifted blue companion of LRD-204851 (Figure 2), and it is favored over each of the other three geometries by the Bayesian evidence at the “decisive” level ($\Delta \ln Z \geq 8$ for all alternatives; see Appendix B for the detailed four-geometry comparison). The marginalized parameters from its full posterior are $z_{\text{Ly}\alpha} = 5.4792$ ($\Delta v \simeq -143 \text{ km s}^{-1}$ relative to z_{sys} derived from [O III]), $V_{\text{exp}} \simeq 110 \text{ km s}^{-1}$,

$\log(N_{\text{HI}}/\text{cm}^{-2}) = 21.27 \pm 0.03$, and $\tau_a \simeq 0.30$. In this picture, the dominant red peak emerges from photons that back-scatter through the optically thick neutral slab, while the blue feature is produced by the much weaker cone-leakage path. This configuration naturally accounts for both the $\sim 400 \text{ km s}^{-1}$ separation between the two Ly α peaks and the profile of the red-component line wing. The inferred high N_{HI} and modest V_{exp} together imply an obscured, gas-rich circumnuclear environment with a biconical cavity oriented away from the line of sight.

While the integrated profile modeling clearly favors `Bicone_X_Slab_Out` over the other three `zELDA` families, the gas geometries explored here are, by construction, idealized. Each assumes a smooth, axisymmetric, homogeneous neutral medium with a single bulk outflow velocity and a Gaussian intrinsic Ly α source. The real ISM in galaxies is almost certainly more complex: multiphase, clumpy, and turbulent, with a distribution of cloud column densities and velocities along any sightline (M. Gronke et al. 2017). Shell-type fits are also known to carry strong internal degeneracies, particularly among V_{exp} , gas temperature, and the intrinsic Ly α line width, which are only partially broken when external constraints are available (Z. Li & M. Gronke 2022). Moreover, very clumpy geometries asymptotically converge to the same family of profiles as a smooth expanding shell once the number of clouds along the sightline becomes large (M. Gronke & M. Dijkstra 2016). We therefore make no claim that the neutral gas in LRD-204851 takes the exact form of a thin slab pierced by a

biconical cavity. Rather, our results only suggest that, among the four characteristic geometries available in **zELDA**, the integrated profile is most consistent with this configuration, and that the marginalized parameters provide a useful physical scale for the obscuring column and outflow speed. The spatial distribution of the line-emitting gas, examined in Section 3.3, provides a complementary and largely independent test: under the favored geometry, the blue cone-leakage component should be spatially displaced from the resonantly back-scattered red core along the cavity axis, while the tentative N v feature would align with the same direction as the blue Ly α component.

We further note that the slow expansion velocity inferred here is independently corroborated by the NIR-Spec R2700 spectrum of LRD-204851 reported by J. Matthee et al. (2026): their line-profile fit detects a blueshifted H α absorber at $\Delta v \approx -80 \text{ km s}^{-1}$, kinematically consistent with the $V_{\text{exp}} \approx 110 \text{ km s}^{-1}$ of the Ly α -emitting envelope inferred above. Since the Ly α and Balmer absorbers probe different transitions ($n=1$ and $n=2$, respectively) of the same partially ionized neutral medium, the agreement provides an independent check that the central source of LRD-204851 is enshrouded by a slowly expanding gas envelope or clumpy medium of the kind required by our **zELDA** modeling.

3.3. A spatially resolved view of the Ly α components and N v

We use the MUSE data cube to examine the spatial distribution of the Ly α and tentative N v emission in LRD-204851. The MUSE HUDF release provides narrow-band emission-line maps for both the integrated Ly α blend and N v $\lambda 1238$ (R. Bacon et al. 2023), and we adopt the latter directly. To spatially separate the multi-component Ly α profile, however, we construct three disjoint Ly α narrow-band maps over the wavelength windows illustrated in Figure 2: the blue component (7866.0–7870.6 Å), the red core (7875.0–7887.0 Å), and the red wing (7887.0–7900.0 Å). The maps are built using the MUSE Python Data Analysis Framework (MPDAF; L. Piqueras et al. 2019), following the same recipe used by the MUSE HUDF team (R. Bacon et al. 2023). We have verified that applying this recipe over the full Ly α window reproduces their published narrow-band map to better than one percent within the segmentation aperture.

Figure 3 shows the four MUSE narrow-band maps side by side. The red Ly α core map is centered on the rest-frame optical continuum (F460M) center to within one MUSE pixel (0.2''), and the red Ly α wing map appears to trace the same overall source. By contrast, the blue

Ly α component appears displaced to the southeast of the F460M centroid: a peak-pixel centroid measurement gives $\Delta\alpha \cos\delta = -0.34''$ and $\Delta\delta = +0.07''$, corresponding to a projected separation of $|\Delta r| = 0.34''$ ($\simeq 2.1 \text{ kpc}$ at $z = 5.482$). To assess the significance of this offset, we injected 10^4 synthetic point sources with matched blue-Ly α flux at random empty-sky positions within the $2 \times 2 \text{ arcmin}^2$ MUSE mosaic cutout around LRD-204851. We then recovered each centroid using the same centroiding algorithm. The recovered offsets have a mean consistent with zero and a per-axis standard deviation of $\sigma \simeq 0.10''$. Among the 10^4 realizations, 155 produced a recovered $|\Delta r| \geq 0.34''$, corresponding to a one-sided p -value of $p \simeq 0.016$ for the null hypothesis that the blue Ly α centroid coincides with the red Ly α core. The observed offset is therefore unlikely to be a spurious centroiding artifact.

The narrow-band map constructed for the tentative N v $\lambda 1238$ detection also shows a peak along the same south-eastern direction from the F460M continuum centroid as the blue Ly α peak, as shown in the rightmost panel of Figure 3. The fact that the N v peak both lies along the same direction as the blue Ly α component and shares a consistent blueshift relative to z_{sys} in the integrated spectrum (Section 3.2) provides circumstantial support for the otherwise tentative N v $\lambda 1238$ detection, although higher-S/N follow-up will ultimately be required to confirm it. We emphasize that the tentative N v feature is not required for the main morphological conclusion of this work. If future higher-S/N observations do not confirm the N v feature, the alignment between the blue Ly α component and the south-eastern [O III]/UV structure would remain unchanged, but the evidence for a very hard ionizing radiation field at this location would be weakened. We therefore treat N v as suggestive supporting evidence rather than as a necessary pillar of the interpretation.

The spatial picture from MUSE alone, therefore, is consistent with one in which the red Ly α core traces material spatially co-located with the LRD's optical continuum, while the blue Ly α component and the N v $\lambda 1238$ emission both peak $\sim 2 \text{ kpc}$ to the south-east. This is qualitatively the spatial signature expected if the blue Ly α component represents Ly α photons leaking through a low-column-density channel offset from the source, while the red core is the resonantly back-scattered emission from the optically thick neutral medium surrounding it, the same picture favored by the integrated profile analysis in Section 3.2. We caution, however, that the MUSE data alone cannot exclude the offset blue-Ly α and N v emission arising in a physically distinct structure (e.g., a close companion) rather than from cone

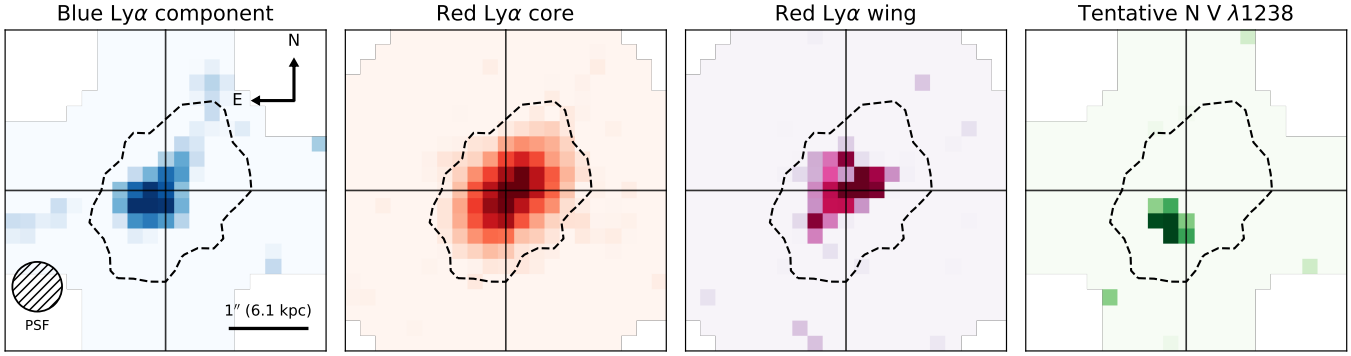


Figure 3. MUSE narrow-band maps of the multi-component $\text{Ly}\alpha$ emission and the tentative $\text{N v } \lambda 1238$ detection in LRD-204851. From left to right: the blue $\text{Ly}\alpha$ component, the red $\text{Ly}\alpha$ core, the red $\text{Ly}\alpha$ wing, and the $\text{N v } \lambda 1238$ narrow-band map. Per-panel color stretches saturate at the 99.5th percentile and use a lower limit of 1σ for the displayed map, so structures below the noise level fade to white. The black dashed contour shows the boundary of the $\text{Ly}\alpha$ segmentation map from the MUSE HUDF release and is identical in every panel; the thin black crosshairs mark the NIRCcam/F460M continuum centroid.

leakage connected to the central engine; we return to this possibility in Section 5.

4. OPTICAL EMISSION-LINE MAPS FROM NIRCAM IMAGING

Rest-frame optical emission lines provide powerful diagnostics of ionized gas, and at $z \approx 5.5$ these lines fall within the NIRCcam wavelength coverage. In this section, we use NIRCcam imaging to construct continuum-subtracted maps, which provide a sub-kpc-resolution view of $[\text{O III}]$, $\text{H}\beta$, and $\text{H}\alpha + [\text{N II}]$. LRD-204851 is particularly well suited for this analysis because it lies near the HUDF in GOODS-S, where JADES (D. J. Eisenstein et al. 2026) and JEMS (C. C. Williams et al. 2023) together provide deep NIRCcam imaging in 14 broad- and medium-band filters at the source position, spanning F090W to F480M. This dense coverage makes it possible to isolate individual rest-frame optical emission lines through on-band photometry while constraining the underlying continuum from line-free anchors.

4.1. Construction of the optical line maps

At $z = 5.482$, $\text{H}\alpha + [\text{N II}]$ falls at $\lambda_{\text{obs}} \approx 4.25\text{--}4.27 \mu\text{m}$, where F430M provides the cleanest medium-band coverage, with a transmission of $T \sim 0.50$ at the line wavelengths⁸. We do not attempt to separate $\text{H}\alpha$ from $[\text{N II}]$, nor to estimate the $[\text{N II}]$ contribution explicitly in this work. While the existing NIRSpect/R1000 spectrum (I. Juodžbalis et al. 2026) shows very weak $[\text{N II}]$ emission from the LRD’s optical continuum peak (slit position shown in Figure 1), we caution that LRD-204851 ex-

hibits complex spatial structure, so it remains unclear whether $[\text{N II}]$ is similarly weak across the entire galaxy. Resolving this would require NIR IFU observations.

For $[\text{O III}]$ and $\text{H}\beta$, separation using NIRCcam imaging alone is generally not feasible, since the two lines are typically covered by the same filter with similar throughputs. At the redshift of LRD-204851, however, both lines fall within F335M and F356W but with markedly different filter throughputs: at $\lambda_{\text{obs}}(\text{H}\beta) = 3.15 \mu\text{m}$, the F335M transmission is $T = 0.07$, compared to $T = 0.34$ in F356W, a factor of ~ 5 difference, while the $[\text{O III}]$ doublet falls on the central plateau of both filters with similar transmissions. This asymmetry makes F335M a nearly pure $[\text{O III}]$ tracer and F356W a mixed $[\text{O III}] + \text{H}\beta$ tracer, allowing us to separate the $[\text{O III}]$ and $\text{H}\beta$ maps.

Because the rest-frame UV and optical continua of LRD-204851 are described by distinct power laws that meet around the Balmer break (Figure 1), we estimate the continuum using only the remaining filters that sample $\lambda_{\text{rest}} \gtrsim 4000 \text{ \AA}$, where a single power law provides an adequate local description of the SED. We therefore adopt F277W, F460M, and F480M as line-free continuum anchors. We PSF-match all bands used in the analysis to the F480M resolution using kernels generated with *pypher* (A. Boucaud et al. 2016). For each pixel, we fit a power-law continuum, subtract the continuum prediction from each on-band filter, and convert the residual surface brightness to integrated line flux per pixel using the NIRCcam transmission curves (S. Pascual et al. 2007; Z. Ji et al. 2025).

4.2. Spatial distribution of the optical line emission

Figure 4 shows the resulting $[\text{O III}]$, $\text{H}\alpha + [\text{N II}]$, and $\text{H}\beta$ maps. These rest-frame optical lines reveal distinct morphological features. The $\text{H}\alpha + [\text{N II}]$ map is domi-

⁸ These lines are also covered by F410M ($T \sim 0.4$, lower than that of F430M) and by the broad-band F444W, but with lower line-to-continuum contrast. We therefore use F430M as the on-band tracer of $\text{H}\alpha + [\text{N II}]$.

nated by a bright central source whose inner surface-brightness profile is consistent with the PSF within $\sim 0.15''$ (Figure 5). Around this central source, the $\text{H}\alpha + [\text{N II}]$ emission also shows a thin, fainter elongated structure extending along the southeast-to-northwest axis.

The $[\text{O III}]$ map similarly shows a central clump at the F460M centroid, but this clump is resolved and inconsistent with being PSF-like (Figure 5). $[\text{O III}]$ also displays an elongated structure along the same southeast-to-northwest axis traced by $\text{H}\alpha + [\text{N II}]$ and the blue UV continuum, with a bright clump-like feature at the southeastern end of this structure that is visible in the UV continuum (Figure 1). The $\text{H}\beta$ map has relatively low S/N, but emission is detected both at the center of the LRD and in the southeastern $[\text{O III}]$ clump region.

The bottom row of Figure 4 overlays the MUSE $\text{Ly}\alpha$ components and the tentative N v contours on the optical line maps. The blue $\text{Ly}\alpha$ contour is offset to the south-east of the F460M continuum centroid, along the same direction as the elongated structure traced by the UV continuum, $\text{H}\alpha + [\text{N II}]$, and $[\text{O III}]$. Because the MUSE PSF ($\text{FWHM} \approx 0.7''$) is much coarser than the NIRCcam resolution, this agreement is robust only as an overall south-east alignment. The data do not constrain how closely the blue $\text{Ly}\alpha$ emission follows the optical structure in detail: they do not constrain either how thin and collimated it is or the degree to which the two are spatially coincident beyond the MUSE resolution. The tentative N v contour appears confined to the bright southeastern $[\text{O III}]$ clump region.

The corresponding $[\text{O III}]/(\text{H}\alpha + [\text{N II}])$ line-ratio map (Figure 6), a proxy for the ionization state of the photoionized gas, with higher values indicating more highly ionized gas (e.g., J. A. Baldwin et al. 1981; L. J. Kewley et al. 2019), further shows that this southeastern region exhibits the highest $[\text{O III}]/(\text{H}\alpha + [\text{N II}])$ ratios in the source, while the central LRD continuum peak has a much lower (0.7 dex) ratio. We caution that the broad-band-derived $[\text{O III}]/(\text{H}\alpha + [\text{N II}])$ ratio at the LRD continuum center is significantly diluted by the broad $\text{H}\alpha$ emission line. At the LRD continuum peak, the broad component carries $\approx 70\%$ of the total $\text{H}\alpha$ flux, with the narrow component contributing only $F(\text{H}\alpha, \text{narrow}) \approx 5 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$ (I. Juodžbalis et al. 2026). Removing the broad-line contribution and using only the narrow $\text{H}\alpha$ flux yields $\log_{10} F([\text{O III}] 5007)/F(\text{H}\alpha, \text{narrow}) \approx 0.34$ at the LRD centre, comparable to the highest values seen in the south-eastern clump on the broad-band ratio map. The narrow-line ionization state of LRD-204851 is therefore high across the entire source, with the apparent radial

gradient in Figure 6 driven primarily by the spatial concentration of the broad $\text{H}\alpha$ BLR rather than by a genuine change in the ionization state of the narrow-line gas. Notably, the tentative N v emission, which requires a very hard ionizing radiation field (the ionization potential to produce N^{4+} is $\sim 77 \text{ eV}$, compared to $\sim 35 \text{ eV}$ for O^{2+} ; see H. Treiber et al. 2025), peaks on top of this same southeastern high-ionization region, lending additional confidence to the otherwise tentative N v detection from MUSE.

In summary, our NIRCcam optical line maps reveal a compact, PSF-consistent $\text{H}\alpha + [\text{N II}]$ core at the LRD continuum centroid, an extended component along a southeast-to-northwest axis traced by these optical lines and matching the elongated UV continuum, and a bright $[\text{O III}]$ -dominated clump at the southeastern end of this axis where the $[\text{O III}]/(\text{H}\alpha + [\text{N II}])$ ratio peaks. This same southeastern region is aligned with the MUSE blue $\text{Ly}\alpha$ and tentative N v emission. We will elaborate on the physical origin of these features in Section 5.

5. DISCUSSION AND SUMMARY

The central engine of LRD-204851 has already been characterized in detail elsewhere, as reviewed in Section 1. The combined picture is broadly consistent with recent models invoking dense neutral gas clumps around AGNs or “black-hole-star”-like configurations for the broad-line emission of LRDs (e.g., K. Inayoshi & R. Maiolino 2025; R. P. Naidu et al. 2025; A. de Graaff et al. 2025b), in which the central black hole is enshrouded by a dense, partially ionized gas envelope of substantial column density. In LRD-204851 itself, spectroscopic evidence for slow outward motion of such a central envelope, of order 100 km s^{-1} , is provided by the P-Cygni Balmer absorber identified in a very recent NIRSpect R2700 spectrum by J. Matthee et al. (2026). Adopting this picture, we focus here on the question that the present study uniquely constrains: the origin of the remarkable $\sim \text{kpc}$ -scale elongated structure of LRD-204851, made visible in detail by the combination of MUSE rest-frame UV spectroscopy and JWST/NIRCcam optical emission-line mapping.

Our combined MUSE and NIRCcam data consistently support a scenario in which the central engine of LRD-204851 illuminates a $\sim \text{kpc}$ -scale region of its host galaxy through low- N_{HI} channels with small opening angles. The clearest empirical signature of this geometry is the thin, bipolar, elongated structure visible in the NIRCcam line maps and rest-frame UV continuum, which passes through the F460M continuum centroid and extends several kpc on either side of it along a southeast-to-northwest axis (Figure 1 and Section 4). Along the

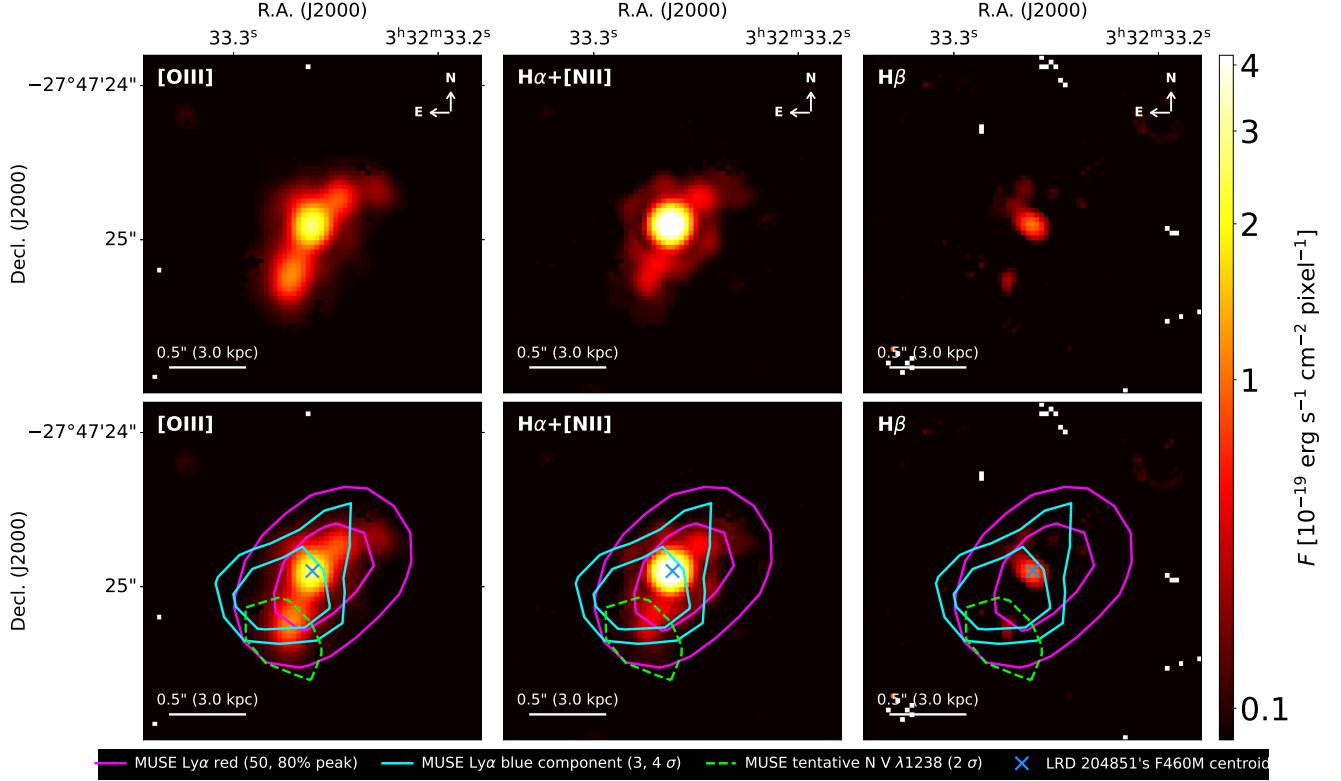


Figure 4. Optical emission-line maps of LRD-204851 constructed using NIRCcam imaging. From left to right: [O III], $H\alpha$ + [N II], and $H\beta$. The top row shows the maps alone; the bottom row overlays the MUSE red (magenta) and blue (cyan) $Ly\alpha$ component contours and the tentative N V $\lambda 1238$ contour (green dashed), with the NIRCcam/F460M continuum centroid marked by the blue $\times$. All panels share a common color scale of line flux per pixel.

same axis, three additional empirical diagnostics align: the spatial offset of the blue $Ly\alpha$ component, the location of the tentative N V peak, and a bright [O III] clump-like structure at the south-eastern end of the elongated structure and spatially aligned with the tentative N V emission. Together these features are naturally accommodated by the favored `Bicone_X_Slab_Out_zELDA` $Ly\alpha$ modeling results. The physical origin of this bipolar elongation, however, is not yet uniquely determined. Below we consider three configurations that are each consistent with the observed geometry.

The channel may have been actively carved by an outflow launched from the central engine, with the south-eastern clump tracing the working surface where outflowing material encounters the ambient ISM and is shock- or photo-ionized to the high values of [O III]/ $H\alpha$ we observe. Empirically, the very thin, bipolar morphology of the elongated structure requires a high degree of geometric collimation. This collimation can arise either intrinsically, as in a jet, with the resulting kpc-scale ionization structure morphologically reminiscent of those observed in low-redshift Seyferts and radio galaxies (e.g., P. J. McCarthy 1993; C. L. Carilli & P. D. Barthel 1996; C. Tadhunter 2016), or geometrically, in which a wider-

angle wind from the central engine is funneled through the narrow low- N_{HI} biconical opening of the surrounding dense cocoon. The current data do not discriminate between these two routes to collimation.

The kinematic constraints on this outflow remain modest. Our $Ly\alpha$ modeling yields a bulk expansion velocity $V_{exp} \simeq 110 \text{ km s}^{-1}$ in the favored biconical geometry (Section 3.2), in agreement with the P-Cygni $H\alpha$ absorber at $\Delta v \approx -80 \text{ km s}^{-1}$ (J. Matthee et al. 2026). We emphasize that this outflow is geometrically anisotropic and biconical, distinct from the spherically symmetric `Galactic_Wind` configuration that our `zELDA` model comparison decisively disfavors (Appendix B); the disfavored `Galactic_Wind` model reflects a geometric mismatch with the observed two-peak $Ly\alpha$ profile rather than the absence of outflow. Combining the intrinsic $Ly\alpha$ emission velocity offset ($\Delta v \approx -130 \text{ km s}^{-1}$ relative to systemic) with V_{exp} , the bulk near-side cone gas reaches a systemic-frame velocity of approximately -240 km s^{-1} , which sits at the lower edge of the $v_s \gtrsim 200\text{--}300 \text{ km s}^{-1}$ threshold required for collisional shock ionization of high-ionization species such as N V (e.g., M. A. Dopita & R. S. Sutherland 1996; M. G. Allen et al. 2008; R. S. Sutherland & M. A. Dopita 2017).

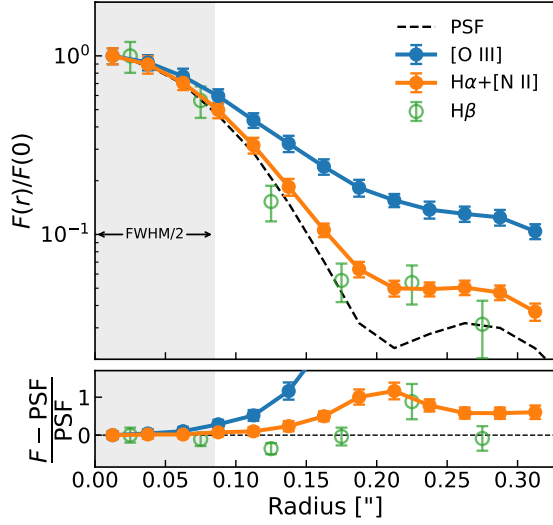


Figure 5. Azimuthally averaged radial surface-brightness profiles of the optical emission-line maps in LRD-204851 (Figure 4), normalized by the central-annulus value. The black dashed curve shows the radial profile of the PSF, and the gray shaded region marks the scale of the PSF’s FWHM/2. The bottom panel shows the relative difference from the PSF. The $\text{H}\alpha + [\text{N II}]$ profile tracks the PSF within $r \lesssim 0.15''$, while the $[\text{O III}]$ profile lies above the PSF, indicating a more extended light distribution than $\text{H}\alpha + [\text{N II}]$.

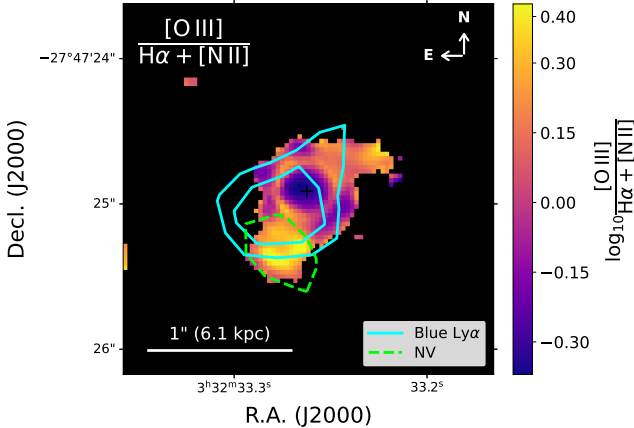


Figure 6. Map of the line ratio $\log_{10}([\text{O III}] / \text{H}\alpha + [\text{N II}])$ in LRD-204851, derived from the line maps shown in Figure 4. Pixels are masked where either line has $\text{S/N} < 3$. Overlaid contours show the MUSE blue $\text{Ly}\alpha$ component and the tentative $\text{N v } \lambda 1238$ emission, as in Figure 4.

Both photoionization by hard radiation escaping the central engine along the low- N_{HI} channels and modest shock ionization in the bulk outflow are therefore plausible mechanisms for the high-ionization line emission at the south-eastern clump. If the tentative $\text{N v } \lambda 1238$ detection is confirmed at higher S/N , its central velocity ($\Delta v \approx -467 \text{ km s}^{-1}$ relative to systemic) would lie

above the shock-ionization threshold, and both production channels would remain viable. We further note that, if confirmed, this N v velocity exceeds the bulk cone-gas value implied by combining $z_{\text{Ly}\alpha}$ and V_{exp} . This difference can be accommodated by the resonant nature of $\text{Ly}\alpha$, whose observed peak positions are a non-trivial function of V_{exp} , N_{HI} , geometry, and the intrinsic line profile, and can be reproduced by a range of bulk velocities once these parameters are varied (e.g., A. Verhamme et al. 2006, 2008).

It is worth noting that LRDs as a population have been reported to be radio-quiet at observed GHz frequencies (e.g., H. B. Akins et al. 2025; K. Perger et al. 2025). LRD-204851 itself is undetected in the ultra-deep VLA 3 and 6 GHz observations of the GOODS-S/HUDF region presented by J. Lyu et al. (2022) and S. Alberts et al. (2020), which reach pointing-center rms sensitivities of 0.75 and $0.32 \mu\text{Jy beam}^{-1}$, respectively, and remain among the deepest available at these frequencies. At $z = 5.482$, however, these observations probe rest-frame frequencies of ≈ 20 and 40 GHz . Non-thermal jet emission typically has a non-flat radio spectrum, either rising at low frequencies in synchrotron-self-absorbed compact young sources (e.g., C. P. O’Dea 1998) or steeply falling at high frequencies in optically thin extended lobes (e.g., M. C. Begelman et al. 1984); in both regimes the brightest non-thermal emission lies below the rest-frame frequencies probed here. Deep, lower-frequency radio observations would therefore be required to firmly constrain a low-power non-thermal jet contribution to the structure observed here.

A second possibility is that the channel is a quasi-static cavity in a clumpy host ISM, illuminated by hard photons escaping the central envelope. The south-eastern clump would then represent gas photoionized by the present-day or recently faded ionizing radiation of the central engine, akin to extended narrow-line regions in low-redshift Type-2 AGN (e.g., S. W. Unger et al. 1987; J. S. Mulchaey et al. 1996; T. Storchi-Bergmann et al. 2018), similar structures recently discovered at $z > 5$ with JWST/NIRSpec IFU (e.g., D. Wylezalek et al. 2022; G. Cresci et al. 2023; H. Übler et al. 2024; J. Lyu et al. 2025), and “ionization echo” systems such as Hanny’s Voorwerp (C. J. Lintott et al. 2009). The thin, bipolar morphology is naturally produced by a narrow cone opening angle. The static-cone interpretation, however, predicts that the south-eastern gas itself sits near the host systemic velocity, and would be directly disfavored by either a confirmed blueshifted N v emission or spatially resolved $[\text{O III}]$ kinematics along the elongated structure revealing significant velocity gradients.

A third possibility is that the elongated structure is a pre-existing host-galaxy feature, such as a tidal arm, an in-situ star-forming filament, or a low-mass companion, that happens to lie along the cone axis. This scenario, however, requires the host feature to be coincidentally aligned with the AGN cone axis and to align spatially with all of the cone-leakage diagnostics (the blue $\text{Ly}\alpha$ component, the tentative N V , and the high-ionization $[\text{O III}]$ clump), and therefore appears to be the least natural of the three configurations considered here.

To summarize, we have combined MUSE rest-frame UV integral-field spectroscopy with NIRC*am* rest-frame optical emission-line maps to characterize the gas geometry, kinematics, and ionization state of LRD-204851 at sub-kpc resolution. The MUSE $\text{Ly}\alpha$ profile is best described by $\text{Ly}\alpha$ radiative transfer through an expanding, dense neutral envelope pierced by a biconical low-column-density cavity, and the same data reveal a tentative blueshifted $\text{N V } \lambda 1238$ detection. The NIRC*am* line maps further reveal a thin, bipolar, elongated structure passing through the optical continuum centroid and extending several kpc on either side along a southeast-

to-northwest axis, with a bright high-ionization $[\text{O III}]$ clump-like structure at the south-eastern end aligned with the cone-leakage axis inferred from the $\text{Ly}\alpha$ modeling. While the current data do not yet uniquely distinguish among the possible physical origins of this elongated structure, the analyses presented here converge on a common picture in which the elongated emission of LRD-204851 is connected to radiation and/or gas flow from its central engine through a narrow, low-column-density biconical channel. LRD-204851 therefore represents one of the clearest currently known cases in which the impact of an LRD central engine on its host galaxy may be directly observable on $\sim\text{kpc}$ scales.

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APPENDIX

A. ASTROMETRIC CORRECTION FOR THE MUSE DATA

The astrometric solution of the MUSE-Wide mosaic is anchored to the Gaia-tied JADES NIRC*am* frame using a source-based registration to the JADES F090W mosaic. Reference sources are selected from the JADES DR5 photometric catalog (B. E. Robertson et al. 2026) within the MUSE field of view, requiring them to be bright ($18 < m_{\text{F606W}} < 24$). Sources separated from any other catalog neighbor by less than $0.8''$, comparable to the typical seeing of the MUSE HUDF observations (R. Bacon et al. 2023), are excluded to avoid blends in the MUSE data. For each of the N retained sources, we compute centroids in both a white-light collapse of the MUSE cube and the corresponding NIRC*am* F090W cutout using `photutils.centroids.centroid_com`. After requiring a centroid peak $\text{S/N} > 3$ in the MUSE white-light image, we retain $N \approx 1200$ sources for the astrometric correction.

The per-source sky offsets are sigma-clipped at 3σ , and their median gives a global astrometric correction of $(\Delta\alpha \cos \delta, \Delta\delta) = (-0.0675'', +0.1926'')$. A four-parameter quality-assurance fit, allowing for shift, rotation, and scale, confirms that the rotation and scale residuals are negligible ($\theta < 0.005^\circ$, $\Delta s < 3 \times 10^{-5}$); we therefore apply only a pure shift. Figure 7 shows the improvement after this astrometric correction: the median relative offset between JADES NIRC*am* and MUSE is consistent with zero, with a mean absolute deviation of $\sim 0.07''$.

B. COMPARISON OF THE FOUR ZELDA GEOMETRIES

In Section 3.2, we adopt the `Bicone_X_Slab_Out` geometry as our fiducial model; its full posterior is shown in Figure 8. Here we report the corresponding fits under the three alternative `zELDA` geometries, `Thin_Shell`, `Galactic_Wind`, and `Bicone_X_Slab_In`, and quantify their relative quality. All four runs use identical fitting windows (7855–7950 Å in the observed frame), identical priors, and identical nested-sampling settings in `dynesty`. The priors are flat in $\log V_{\text{exp}} [\text{km s}^{-1}] \in [1.0, 3.0]$, flat in $\log N_{\text{H I}} [\text{cm}^{-2}] \in [17, 22]$, flat in $\log \tau_a \in [-3, 1]$, and Gaussian in $z_{\text{Ly}\alpha}$, centered at $z_{\text{sys}} = 5.482$ with $\sigma_z = 0.05$. Because the four geometries share the same parameter dimensionality and priors, model comparison reduces to a straightforward Bayes-factor calculation using the `dynesty` marginal log-evidence, $\log \mathcal{Z}$ (R. E. Kass & A. E. Raftery 1995).

Relative to the fiducial `Bicone_X_Slab_Out` run, we find $\Delta \log \mathcal{Z} = -8.2$ for `Galactic_Wind`, $\Delta \log \mathcal{Z} = -16.3$ for `Thin_Shell`, and $\Delta \log \mathcal{Z} = -94.6$ for `Bicone_X_Slab_In`. All three alternatives are therefore significantly disfavored

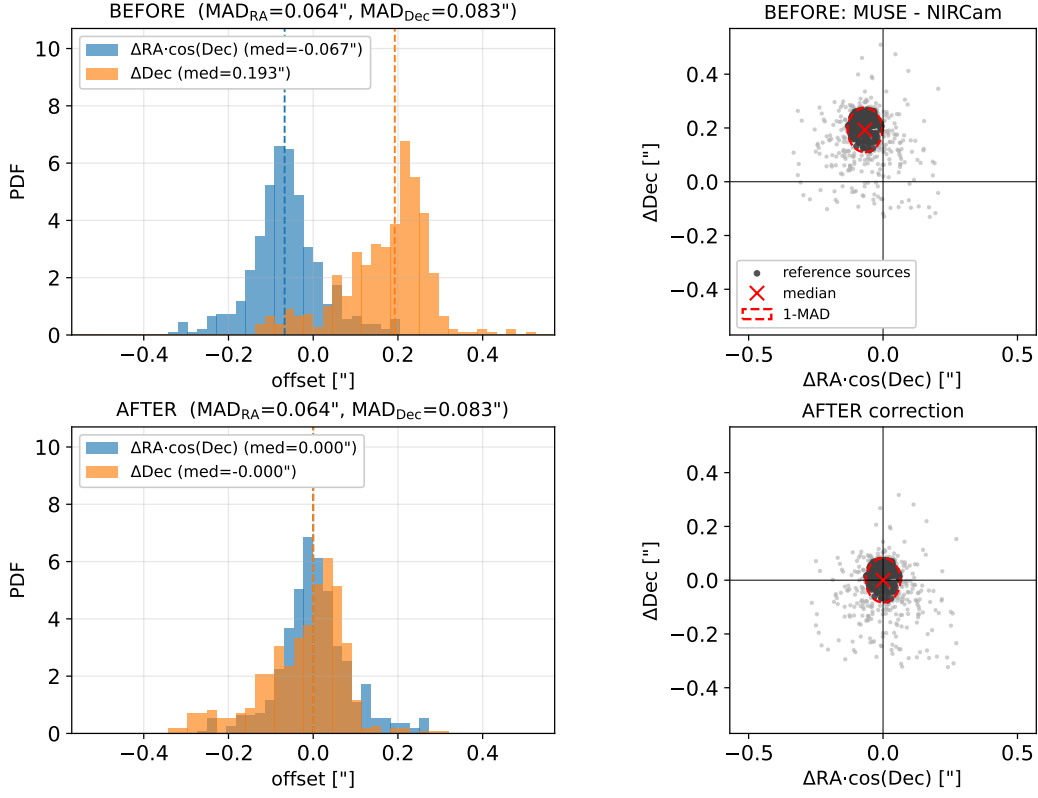


Figure 7. MUSE-to-NIRCam astrometric correction. **Left:** PDF of the per-source offsets for reference sources before (top) and after (bottom) correction. **Right:** 2-D astrometric residuals; the red dashed ellipse marks ± 1 mean absolute deviation (MAD) about the median. After correction both medians are zero.

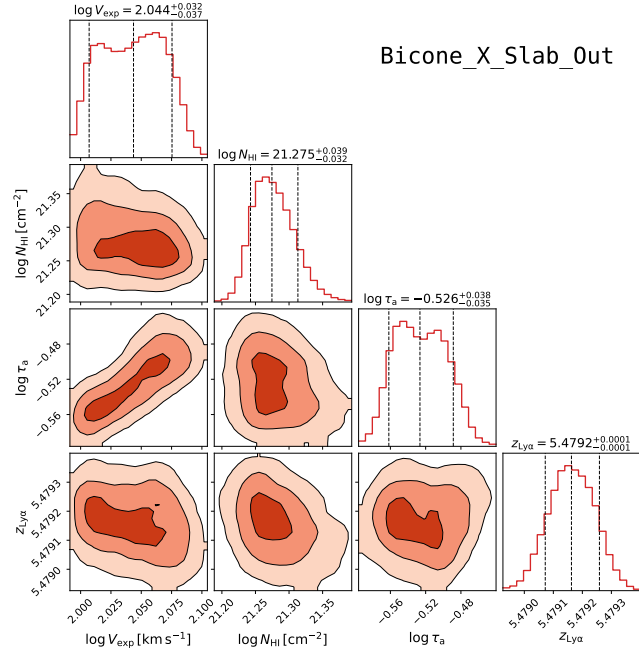


Figure 8. Joint and marginal posterior distributions for the four sampled parameters, $z_{Ly\alpha}$, $\log V_{exp}$, $\log N_{HI}$, and $\log \tau_a$, under the `Bicone_X_Slab_Out` geometry, which best reproduces the observed $Ly\alpha$ profile of LRD-204851.

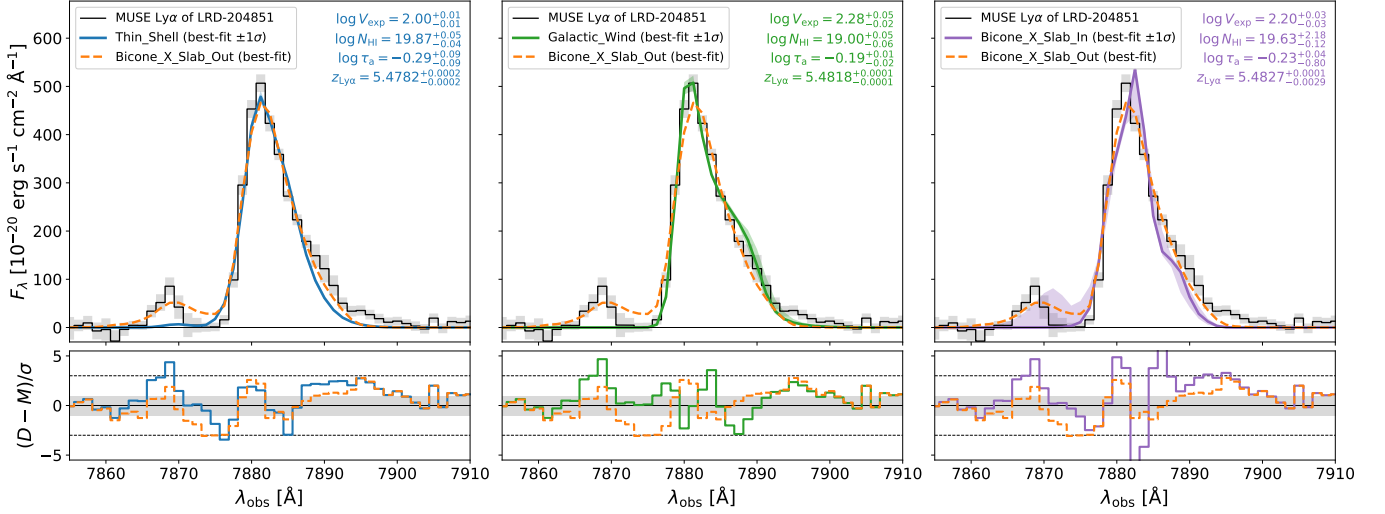


Figure 9. Best-fit zELDA Ly α profiles for the three alternative gas geometries, overlaid on the observed MUSE Ly α spectrum (black, with 1σ shading). The **Bicone_X_Slab_Out** model is shown in all panels as a red dashed line for comparison. The bottom panels show the residuals, demonstrating that **Bicone_X_Slab_Out** outperforms the other three geometries.

by the data ($|\Delta \log Z| > 5$ corresponds to “decisive” evidence, and $|\Delta \log Z| > 10$ to overwhelming evidence according to R. E. Kass & A. E. Raftery 1995).

The driver of these differences is apparent in Figure 9. Both spherically symmetric geometries (**Thin_Shell** and **Galactic_Wind**) reproduce the dominant red Ly α peak only by adopting a low neutral-hydrogen column ($\log(N_{\text{HI}}/\text{cm}^{-2}) \simeq 19$); they fail to produce a sufficiently blueshifted, narrow companion peak, because back-scattering through a uniform shell or wind always places the secondary peak much closer to systemic. The **Bicone_X_Slab_In** geometry (sight-line down the cone axis, i.e. face-on) suppresses the resonant-scattering pathway that would build the strong red peak, and its posterior runs to low N_{HI} and a large τ_a in an unsuccessful attempt to suppress the unobserved blue wing. Only **Bicone_X_Slab_Out** offers a two-channel escape: a high- N_{HI} static slab through which Ly α photons back-scatter to form the red peak, and a low-column biconical cavity that allows a small fraction of photons to escape with a much larger blueshift. This configuration naturally reproduces both the $\sim 400 \text{ km s}^{-1}$ separation between the two observed peaks and their $\sim 6\%$ flux ratio.

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