

BlackTHUNDER: Shedding light on a dormant and extreme little red dot at $z = 8.50$

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ABSTRACT

Recent photometric surveys with JWST have revealed a significant population of mysterious objects with red colours, compact morphologies, frequent signs of active galactic nucleus (AGN) activity, and negligible X-ray emission. These ‘Little Red Dots’ (LRDs) have been explored through spectral and photometric studies, but their nature is still under debate. As part of the BlackTHUNDER survey, we have observed UNCOVER_20466, the second most distant LRD known ($z = 8.5$), with the JWST/NIRSpec IFU. Previous JWST/NIRCam and JWST/NIRSpec MSA observations of this source revealed its LRD nature, as well as the presence of an AGN. Using our NIRSpec IFU data, we confirm that UNCOVER_20466 contains an overmassive black hole. However, our observed Balmer decrements imply negligible dust attenuation, resulting in a lower $H\beta$ -based bolometric luminosity and λ_{Edd} ($\sim 10\%$) than previously found. $\text{Ly}\alpha$ emission is strongly detected, implying $f_{\text{esc}}^{\text{Ly}\alpha} \sim 30\%$. The extremely high $[\text{OIII}]\lambda 4363/\text{H}\gamma$ ratio is indicative of not only AGN photoionization and heating, but also extremely high densities ($n_e \sim 10^7 \text{ cm}^{-3}$), suggesting that this black hole at such high redshift may be forming in an ultra-dense protogalaxy.

Key words: galaxies: active – quasars: supermassive black holes – galaxies: high-redshift

1 INTRODUCTION

The advent of JWST has revolutionised the field of high-redshift galaxy evolution, including the spectroscopic confirmation of galaxies at $z > 10$ (within the first ~ 500 Myr of the Universe; e.g., Curtis-Lake et al. 2023; Carniani et al. 2024; Naidu et al. 2025b), the construction of UV luminosity functions out to high redshift (e.g., Donnan et al. 2024; Robertson et al. 2024; Whitler et al. 2025), and new constraints on the role of galaxies in the epoch of reionisation (e.g., Endsley et al. 2024; Simmonds et al. 2024). One of the more

surprising findings was the discovery of numerous compact, red objects in JWST/NIRCam data, which were given the name ‘little red dots’ (LRDs; Matthee et al. 2024). While a few red, compact sources were found to be local brown dwarfs (Langeroodi & Hjorth 2023; Hainline et al. 2024), LRDs are primarily high-redshift galaxies (i.e., peaking in number between $4.5 < z < 8.0$; e.g., Kocevski et al. 2025).

The red nature of these galaxies is usually caused by a distinctive ‘v’-shaped continuum from rest-optical to rest-UV, which is caused by red UV slopes ($\beta_{\text{UV}} \sim -1.5$) and positive optical slopes ($\alpha_{\text{opt}} > 0$ where slopes are defined as $F_\lambda \propto \lambda^{\beta_{\text{UV}} || \alpha_{\text{opt}}}$; e.g., Greene et al. 2024). In addition, many show broad hydrogen Balmer emission lines (e.g.,

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Furtak et al. 2023b; Greene et al. 2024; Matthee et al. 2024; Hviding et al. 2025), and are undetected in X-ray (e.g., Ananna et al. 2024; Mazzolari et al. 2024; Maiolino et al. 2025b; Sacchi & Bogdán 2025; Yue et al. 2024) or submm/radio observations (e.g., Casey et al. 2025; Mazzolari et al. 2025; Orozco et al. 2025; Setton et al. 2025; Xiao et al. 2025).

The nature of these sources is still under debate, as their properties are not trivially explained by common galactic models. This ambiguity is partially due to the fact that their natures can be described either by active galactic nucleus (AGN)-dominated galaxies or compact, dusty, star-forming galaxies (e.g., Baggen et al. 2024). Some investigations have looked into this by using different spectral energy distribution (SED) models: galaxy-only, AGN-only, and a combination of an AGN and host galaxy (hybrid; e.g., Kokorev et al. 2023; Leung et al. 2024; Tripodi et al. 2024b; Ronayne et al. 2025). While these models can all fit the observed photometry of LRDs, the hybrid models return significantly lower stellar mass and dust attenuation (A_V ; e.g., Carranza-Escudero et al. 2025).

Previous works have suggested that LRDs represent black holes (either single or binary systems) embedded in massive gaseous envelopes (e.g., Begelman & Dexter 2025; Inayoshi et al. 2025; Kido et al. 2025; Lin et al. 2025b; Ji et al. 2025a; Naidu et al. 2025b), possibly in the earliest phase of accretion (Inayoshi 2025; Maiolino et al. 2025a), while others explore whether their properties could be explained by self-interacting dark matter halos (e.g., Roberts et al. 2025; Feng et al. 2025), super-Eddington accretion (e.g., Liu et al. 2025), or population III supermassive stars (e.g., Jockel et al. 2025; Nandal & Loeb 2025). Additional spectral observations are needed to constrain the nature of LRDs.

Among the most extreme LRDs is the source UNCOVER_20466 ($\alpha = 3.640409$, $\delta = -30.386437$, $z = 8.50$), which was observed with JWST/NIRCam as part the JWST Cycle 1 Treasury program ‘Ultra-deep NIRCam and NIRSpec Observations Before the Epoch of Reionization’ (UNCOVER; Bezanson et al. 2024). Labbe et al. (2025) searched these data for objects with red colours (based on F115W to F444W colours) and compact morphology ($(f_{F444W}(r < 0.2'')/f_{F444W}(r < 0.1'')) < 1.7$) that were well-detected in F444W ($S/N > 14$). This resulted in a sample of 26 reddened AGN candidates out of a parent sample of 5×10^4 sources. UNCOVER_20466 was included as an AGN candidate¹ with a very compact morphology ($r_e = 0.026''$) indistinguishable from the point spread function (PSF). Although UNCOVER_20466 is gravitationally lensed by the Abell 2744 galaxy cluster, Furtak et al. (2023a) find that UNCOVER_20466 is only gravitationally magnified by a factor $\mu = 1.33^{+0.01}_{-0.02}$. The best-fit photometric redshift was quite low ($z_{\text{phot}} = 5.17$), resulting in skewed best-fit parameters (e.g., M_{UV} , M_*). The properties of UNCOVER_20466 appeared to qualify it for the classification of an LRD, and Langeroodi & Hjorth (2023) confirmed that the LRD nature of UNCOVER_20466 represents an extragalactic object rather than a brown dwarf.

UNCOVER_20466 was then observed with the JWST/NIRSpec MSA, using the PRISM/CLEAR disperser/filter combination (spectral resolving power $R \sim 100$) and an exposure time of 2.7 hr. By analysing the resulting spectrum, Kokorev et al. (2023) found a higher spectroscopic redshift ($z_{\text{spec}} = 8.50$, resulting in $M_{UV} = -18.11$; Fujimoto et al. 2024) and strong evidence for the presence of a broad-line AGN (see also analysis of Greene et al. 2024). A fit of the H β line revealed a narrow and broad component, where $FWHM_{\text{broad}} = 3439 \pm 413 \text{ km s}^{-1}$. This broad component is not

present in the well-detected [OIII] $\lambda\lambda 4959, 5007$ lines, implying that it originates from a high-density broad line region (BLR) of an AGN (e.g., Baskin & Laor 2005). UNCOVER_20466 is also classified as an AGN based on the narrow emission line ratio diagnostics proposed by Mazzolari et al. (2024).

After correcting for lensing magnification, Kokorev et al. (2023) used the relations of Greene & Ho (2005) to derive $\log_{10}(M_{\text{BH}}/M_{\odot}) = 8.17 \pm 0.42$ (from broad H β luminosity and width) and $\log_{10}(M_{\text{BH}}/M_{\odot}) = 8.01 \pm 0.40$ (from a calibration based on L_{5100}). Assuming the conservative case of a stellar-only continuum (i.e., no AGN), Kokorev et al. (2023) determine $\log_{10}(M_*/M_{\odot}) < 8.7$ (corrected for gravitational lensing). The bolometric luminosity is estimated as $L_{\text{bol}} = (6.6 \pm 3.1) \times 10^{45} \text{ erg s}^{-1}$, using the H β -based relation of Stern & Laor (2012).

Together, this suggests that UNCOVER_20466 features an extremely overmassive black hole, undergoing rapid accretion ($\lambda_{\text{Edd}} \sim 40\%$). This was further explored by Zhang et al. (2025b), who used the empirical model TRINITY (Zhang et al. 2023) to show that the black hole of UNCOVER_20466 is overmassive for its redshift, similar to other high-redshift galaxies detected with JWST (e.g., UHZ1; Nataraajan et al. 2024). While many other overmassive black holes have been discovered at $z > 5$ (e.g., Goulding et al. 2023; Übler et al. 2023; Furtak et al. 2024; Maiolino et al. 2024, 2025a; Napolitano et al. 2024; Akins et al. 2025; D’Eugenio et al. 2025a; Naidu et al. 2025a; Juodžbalis et al. 2025a; Rinaldi et al. 2025a), UNCOVER_20466 remains among the earliest and most overmassive black holes in the observable Universe.

In this work, we present new JWST/NIRSpec IFU observations of UNCOVER_20466, taken as part of the BlackTHUNDER survey. In Section 2, we detail the JWST/NIRSpec IFU data used for this work, as well as archival JWST/NIRCam data. Section 3 is an overview of our spectral extraction and fitting routine. We use the best-fit values to estimate several properties of UNCOVER_20466 in Section 4, and discuss the nature and evolution of this source in Section 5. We conclude in Section 6.

We assume a concordance cosmology throughout, with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$. At the redshift of UNCOVER_20466 ($z = 8.50$), $1''$ corresponds to 4.63 pkpc . Combining this with the gravitational magnification of UNCOVER_20466 ($\mu = 1.33$; Furtak et al. 2023a), $1''$ in the image plane therefore corresponds to approximately 3.48 pkpc in the source plane. Emission lines are named based on their air wavelength, while we use their vacuum wavelengths for analysis (e.g. $\lambda_{\text{rest, [OIII]}\lambda 5007} = 5008.24 \text{ \AA}$).

2 OBSERVATIONS AND DATA REDUCTION

2.1 JWST/NIRSpec IFU

The JWST/NIRSpec IFU data studied in this work originate from the BlackTHUNDER Large Programme (Black holes in THE early Universe aNd their DensE surRoundings; PID 5015; PIs: H. Übler, R. Maiolino). UNCOVER_20466 was observed on 4–5 December, 2024 in PRISM/CLEAR (hereafter R100, $R \sim 30–300$, $0.60 \mu\text{m} < \lambda_{\text{obs}} < 5.30 \mu\text{m}$) and G395H/F290LP (hereafter R2700, $R \sim 2000–3700$, $2.87 \mu\text{m} < \lambda_{\text{obs}} < 5.14 \mu\text{m}$) using a 14-point medium cycling dither pattern (see Table 1 for more observation details).

The raw data from these observations were downloaded from the

¹ UNCOVER_20466 was given the ID 13556 in Labbe et al. (2025).

Disperser/Filter	Readout Pattern	Groups/Int	On-source Time [ks]
G395H/F290LP	NRSIRS2	26	26.8
PRISM/CLEAR	NRSIRS2RAPID	34	7.2

Table 1. BlackTHUNDER NIRSpec-IFU observation properties.

the Barbara A. Mikulski Archive for Space Telescopes (MAST²). Calibration was performed using a customised version of the official pipeline (v1.15.0; Bushouse et al. 2025; see Perna et al. 2023 for more details of customisation) with CRDS context 1293. These customisations account for 1/f noise correction, drizzling (Fruchter & Hook 2002), the subtraction of median values from count rate maps, manually masked cosmic rays and snowballs, open MSA slits, outliers in all dithers, and outlier rejection (D’Eugenio et al. 2024, 99.5% for R100, 98% for R2700). This results in two calibrated data cubes with spaxels of 0.05″. We also removed pixels associated with artifacts by calculating the standard deviation of each spectral channel of the ERR extension (sigma_clipped_stats from astropy.stats).

Next, we performed background subtraction on each cube using the Background2D task of photutils (Bradley et al. 2021). First, the spatial region of UNCOVER_20466 was masked in each cube, in order to exclude the signal from the background estimation. We then use Background2D to divide the field of view into boxes of width 10 px (0.5 arcsec), calculate the sigma-clipped noise level in each box (3σ), spatially smooth the resulting background cube using a square filter of 5 px (0.25 arcsec), and apply a median filter of width 25 spectral pixels to find a final background cube. We inspected both background cubes to ensure that no narrow features were present, and used them to create background-subtracted cubes.

2.2 JWST/NIRCam

UNCOVER_20466 was observed with NIRCam as part of two programs: UNCOVER (PID 2561; PI: I. Labbe; Bezanson et al. 2024) and ‘Medium Bands, Mega Science’ (PID 4111; PI: K. Suess; Suess et al. 2024). Combined, these surveys imaged UNCOVER_20466 in 20 different filters (see Appendix A for details of each filter used in this work). We downloaded all available JWST/NIRCam images with stage 3 calibration from the MAST archive.

3 SPECTRAL ANALYSIS

Due to the very compact nature of UNCOVER_20466 with respect to the JWST/NIRSpec IFU PSF, we do not spatially resolve the emission. Therefore, our primary analysis is focused on integrated spectra from the R100 and R2700 data cubes. While the field also contains a serendipitous source at lower redshift (‘BlackBolt-1’, see Appendix B), we defer detailed analysis of this other object to a future work.

3.1 Spectral extraction

The extraction aperture for UNCOVER_20466 should be carefully considered, as it must be small enough to maximise the S/N of each line, but large enough to contain all significant emission. Because UNCOVER_20466 is very compact, it may be considered a point

source for our observations, so the observed morphology will be dictated by the PSF.

We extract spectra from both the R100 and R2700 data cubes using a circular aperture of radius 0.125″ centred on the observed emission. Each spectrum is corrected for gravitational magnification (i.e., $\mu = 1.33$, as assumed by Kokorev et al. 2023) and aperture loss (see Appendix C for details of aperture loss correction).

As noted by other works (e.g., Übler et al. 2023, 2024), the ERR extension of each data cube contains the wavelength-dependent noise variation, but underestimates the true uncertainty. To correct for this, we follow the standard approach of determining the RMS scatter in a spectral range with no significant emission lines and scaling the error spectrum from ERR to feature the same scatter.

3.2 Spectral fitting

Due to the availability of both R100 and R2700 data, we perform spectral fitting in two stages. First, we consider the data redwards of the Balmer limit ($\lambda_{\text{rest}} < 0.3645 \mu\text{m}$; Section 3.2.1), or the location where many LRDs have been observed to feature a change in the spectral slope continuum (i.e., creating a ‘v’-shape; e.g., Setton et al. 2024; Hviding et al. 2025; Naidu et al. 2025a). This wavelength range is only covered by the R100 data. Next, we consider the data bluewards of the Balmer limit, and fit the R100 and R2700 data simultaneously (Section 3.2.2).

3.2.1 Blue fit

First, we consider R100 data between $1050 \text{ \AA} \leq \lambda_{\text{rest}} \leq 3645 \text{ \AA}$ ($1.00 \mu\text{m} < \lambda_{\text{obs}} < 3.46 \mu\text{m}$). We note that while this data cube contains data at $\lambda_{\text{obs}} < 1.00 \mu\text{m}$, it is excluded due to high noise levels.

While the majority of the continuum emission may be described by a power law model with spectral slope β_{UV} , the spectral slope here may deviate from the previously measured β_{UV} due to contributions from two-photon continuum or damped Ly α clouds (e.g., Cameron et al. 2024; Tacchella et al. 2025). In addition, this spectral region contains the Ly α break which, when observed with the low spectral resolution of the PRISM disperser, may result in an artificial Ly α damping wing. Thus, we follow the approach of other works (e.g., Jones et al. 2025a) to model the continuum here, as discussed below.

An initial high-resolution model spectrum is created (channels of width $0.005 \mu\text{m}$), and all spectral channels below the observed Ly α wavelength ($\lambda_{\text{obs}} < (1 + z_{\text{Ly}\alpha}) \times 0.1216 \mu\text{m}$) are set to a constant value³. The continuum between the Ly α break and $\lambda_{\text{rest}} = 1500 \text{ \AA}$ is modelled as a power law ($F_{\lambda} \propto \lambda_{\text{obs}}^{\beta_{\text{Ly}\alpha}}$), and Ly α flux is added to the first channel redwards of the Ly α break. The continuum between $\lambda_{\text{rest}} = 1500 \text{ \AA}$ and the Balmer break is modelled as a separate power law ($F_{\lambda} \propto \lambda_{\text{obs}}^{\beta_{\text{UV}}}$), where we enforce continuity at $\lambda_{\text{rest}} = 1500 \text{ \AA}$.

The resulting continuum and Ly α model is convolved with the wavelength-dependent line spread function (LSF⁴) and rebinned to match the wavelength bins of the observed data. We then add model Gaussians representing CIII] $\lambda\lambda 1907, 1910$ and MgII $\lambda\lambda 2796, 2803$, where the intrinsic widths and redshifts of each line are set to be

³ Ideally, this continuum value below the Ly α break should be zero. However, we allow it to vary to account for calibration or imaging artifacts.

⁴ We determine the LSF using the fiducial resolving power curves recorded at <https://jwst-docs.stsci.edu/jwst-near-infrared-spectrograph/nirspec-instrumentation/nirspec-dispersers-and-filters>.

² <https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html>

equal. Due to the spectral resolution of the R100 data, we model each line pair as a single Gaussian. We account for the effect of the LSF by adding the intrinsic linewidth and LSF in quadrature. The free parameters of this approach are the continuum parameters (constant value bluewards of Ly α break, value at $\lambda_{\text{rest}} = 1500\text{\AA}$, $\beta_{\text{Ly}\alpha}$, β_{UV}), line fluxes (Ly α , CIII] $\lambda\lambda 1907, 1910$ and MgII] $\lambda\lambda 2796, 2803$), and intrinsic linewidths ($FWHM_N$).

We use LMFIT (Newville et al. 2014) in ‘least_squares’ mode to fit the extracted R100 spectrum, using the inverse variance as a weight. Due to the low spectral resolution of the R100 data, we fixed the redshift of each line and the Ly α break to be $z = 8.50$. Additionally, we fix the intrinsic linewidths to be 250 km s^{-1} . Our fits suggest that MgII] $\lambda\lambda 2796, 2803$ is undetected, so we set the flux of this line doublet to 0 in the model and use the error spectrum to derive an upper limit on its flux. The best-fit parameters are listed in Table 2.

3.2.2 Red fit

Next, we consider data between $3645\text{\AA} \lesssim \lambda_{\text{rest}} \lesssim 5475\text{\AA}$ ($3.46\text{ }\mu\text{m} < \lambda_{\text{obs}} < 5.2\text{ }\mu\text{m}$)⁵. This range is covered by both the R100 and R2700 data, so we fit a model to both spectra simultaneously.

The continuum is modelled as a single power-law component ($F_\lambda \propto \lambda_{\text{obs}}^{\alpha_{\text{opt}}}$), and we include emission from [OII] $\lambda\lambda 3727, 3729$, [NeIII] $\lambda\lambda 3869, 3968$, H δ , H γ , [OIII] $\lambda\lambda 4363$, H β , and [OIII] $\lambda\lambda 4959, 5007$. The ratios of [NeIII] $\lambda\lambda 3869$ /[NeIII] $\lambda\lambda 3968 = 3.320$ and [OIII] $\lambda\lambda 5007$ /[OIII] $\lambda\lambda 4959 = 2.983$ (which are independent of ISM conditions) are derived using PYNEB (Luridiana et al. 2015). For each Balmer line (H δ , H γ , and H β), we include both narrow and broad components. All lines are modelled as Gaussians with the same redshift, while the intrinsic linewidth ($FWHM_N$) of all narrow lines are set to be identical. The intrinsic FWHM of the broad component of the Balmer lines are separately set to be identical ($FWHM_{B,Ba}$).

It is important to note that due to flux and wavelength calibration differences, the spectra extracted from JWST/NIRSpec prism and grating data cubes spectra may not yet be compared on a 1:1 basis. Works investigating JWST/NIRSpec MSA spectra have found that the medium-resolution ($R \sim 1000$) grating flux is $\sim 10 - 15\%$ higher than the prism flux (but with considerable scatter; e.g., Bunker et al. 2024; D’Eugenio et al. 2025c). The same works also find a redshift difference of $z_{R100} - z_{R1000} \approx 0.004$, which corresponds to a velocity offset of $\sim 125\text{ km s}^{-1}$ at $z = 8.5$. Works using both prism and high-resolution ($R \sim 2700$) data have found an even higher redshift difference ($z_{R100} - z_{R2700} \approx 0.006 - 0.009$; Pérez-González et al. 2025; Jones et al. 2025b; $\sim 190 - 285\text{ km s}^{-1}$ at $z = 8.5$). The ratio of line fluxes measured in R100 data to those measured in R2700 data has been found to vary widely between NIRSpec IFU observations ($F_{R100}/F_{R2700} \sim 0.35 - 1.70$; Arribas et al. 2024; Ji et al. 2024, 2025a; Scholtz et al. 2025). With these results in mind, we allow the systemic redshift to vary between the R100 and R2700 data, and include a wavelength-independent flux ratio between the two observed spectra.

Similarly to Section 3.2.1, we use LMFIT in ‘least_squares’ mode to fit our model to the data. But in this case, we fit the model to both the R100 and R2700 data at the same time. The free parameters are: the continuum slope (α_{opt}) and normalisation at $\lambda_{\text{rest}} = 4959\text{\AA}$ (C_{opt}), the systemic redshift in each dataset (z_{R100} , z_{R2700}), the flux ratio of the R100 and R2700 data (F_{R100}/F_{R2700}), the intrinsic linewidths

of the narrow and broad components ($FWHM_N$, $FWHM_{B,Ba}$), and the fluxes of each line ([OII] $\lambda\lambda 3727, 3729$, [NeIII] $\lambda\lambda 3869, 3968$, [OIII] $\lambda\lambda 4363$, [OIII] $\lambda\lambda 4959, 5007$, and the narrow and broad components of H δ , H γ , and H β). These properties are used to create model R100 and R2700 spectra that account for the LSF, spectral gridding, flux offset, and velocity offset of each dataset. To perform the simultaneous fit, we calculate and concatenate the residual spectrum (i.e., difference between data and model, weighted by inverse error) for each observed spectrum and use LMFIT to find the parameters that minimize this residual.

The flux ratio of [OII] $\lambda\lambda 3727$ /[OII] $\lambda\lambda 3729$ is a strong tracer of electron density (e.g., Isobe et al. 2023), varying from 0.67–2.88 for $\log_{10}(n_e/\text{cm}^{-3}) = 0 - 8$ (as derived with PYNEB, assuming $T_e = 10^4\text{ K}$). While higher temperatures result in a higher ratio, most of the variation is due to density (e.g., [OII] $\lambda\lambda 3727$ /[OII] $\lambda\lambda 3729 = 0.69 - 2.96$ for the same density range, but assuming $T_e = 10^7\text{ K}$). The R100 data does not resolve the doublet, and the R2700 data does not include a strong detection of both lines. Because of this, it is not possible to place a strong constraint on the [OII] $\lambda\lambda 3727$ /[OII] $\lambda\lambda 3729$ ratio as a free parameter. Instead, we tested fits using a range of physically motivated [OII] $\lambda\lambda 3727$ /[OII] $\lambda\lambda 3729$ ratios (0.7, 0.8, ..., 3.0) and recorded the goodness of fit values for each run (i.e., χ^2 , reduced χ^2 , and Bayesian Information Criterion [BIC]). The best fit was found to be [OII] $\lambda\lambda 3727$ /[OII] $\lambda\lambda 3729 = 0.7$, with increasingly poor fits for higher ratios. Thus, we fix [OII] $\lambda\lambda 3727$ /[OII] $\lambda\lambda 3729 = 0.7$ in our model. This corresponds to an estimated density of $\log_{10}(n_e/\text{cm}^{-3}) \sim 1.7$ for $T_e \sim 10^4\text{ K}$, or $\log_{10}(n_e/\text{cm}^{-3}) \sim 2.4$ for more extreme temperatures ($T_e \sim 10^7\text{ K}$).

We note that while an initial fit was performed with broad and narrow components for each Balmer line (H β , H γ and H δ), this resulted in a poor fit. Because H γ falls into the detector gap for the R2700 data, we cannot measure the narrow component of this line. The fit was improved by including broad components for all three lines, and a narrow component for H β . The narrow component of H β is found to have a flux $\sim 1/6^{\text{th}}$ that of the broad component, so our current data do not allow us to detect the narrow components of the weaker H δ or H γ .

3.2.3 Fitting results

Following the fitting procedure of Sections 3.2.1 and 3.2.2, we derive best-fit continuum and line parameters for UNCOVER_20466 from both the R100 and R2700 data. The resulting R100 and R2700 fits are shown in Figures 1 and 2, respectively. The best-fit blue and red models for the R100 data are concatenated to create a complete model. The best-fit values are listed in Table 2.

Both spectra are well fit by the same intrinsic model, but we find a significant velocity offset ($182 \pm 10\text{ km s}^{-1}$) and flux ratio (0.85 ± 0.01) between the R100 and R2700 data. As noted in Section 3.2.2, these values are expected from calibration differences. The flux ratio is identical to the value assumed by D’Eugenio et al. (2025b), and falls within the scatter of F_{R100}/F_{R2700} ratios found by Scholtz et al. (2025). Other works find flux ratios of > 1 (e.g., Arribas et al. 2024; Ji et al. 2024), which may be due to calibration differences (e.g., updates to calibration files) or an intrinsic scatter in this ratio. The velocity offset corresponds to $z_{R100} - z_{R2700} \approx 0.006$, while the flux ratio implies that the grating flux is $\sim 17\%$ higher than the prism flux. Each value is comparable to previous results (e.g., Bunker et al. 2024; D’Eugenio et al. 2025c; Pérez-González et al. 2025; Jones et al. 2025b).

The residuals in each fit are generally low (i.e., $< 2\sigma$). One exception is the fit of [OIII] $\lambda\lambda 5007$ in the R2700 data (Figure 2), which

⁵ Similarly to above, we exclude $\lambda_{\text{obs}} > 5.20\text{ }\mu\text{m}$ data due to poor background subtraction.

features a central flux excess with neighbouring negative troughs. This residual pattern has been interpreted to indicate the need for a second Gaussian component, possibly representing an outflow (e.g., [Ginolfi et al. 2020](#)). This hypothesis is weakened by the fact that the addition of an outflow component to the model did not result in a better fit. Alternatively, it may be an example of the wavelength-dependent continuum oscillations (or ‘wiggles’) seen in NIRSpect IFU data around bright emission lines (e.g., [Perna et al. 2023](#)). However, these wiggles are artifacts caused by single-spaxel extraction, and extend over wide swathes of each spectrum. Since we use a circular aperture, and the features are isolated to the proximity of [OIII] λ 5007, these are likely not wiggles. An additional possibility is that these artifacts are caused by a non-Gaussian LSF. In any case, the low amplitude of the residuals allows us to neglect them in our analysis.

In Table 2, we include a comparison to the values of [Kokorev et al. \(2023\)](#), who observed UNCOVER_20466 using the JWST/NIRSpect MSA in R100. While many of the same emission lines are detected, we note that our measured fluxes, broad linewidths, and redshifts are significantly different. Because UNCOVER_20466 was positioned on the very edge of the MSA slit, [Kokorev et al. \(2023\)](#) scaled their extracted spectrum to match measured NIRCам photometry. Our IFU data allow us to extract the full aperture-corrected spectrum from the source, resulting in more reliable fluxes. We find a similar placement of UNCOVER_20466 on the line ratio diagnostic plots of [Mazzolari et al. \(2024\)](#), adding credence to the classification of this source as an AGN (Section 4.5).

If we fit the R100 data only, then we measure a $FWHM_{B,Ba}$ value within 1σ of [Kokorev et al. \(2023\)](#) and other works that analysed the R100 data ([Trefoloni et al. 2025](#); [Greene et al. 2024](#)). But this linewidth is weighed down by the R2700 data during the simultaneous fit, resulting in a $\sim 2\sigma$ smaller value. This difference may be caused by deviations from the fiducial LSF, which was computed assuming a fully illuminated IFU aperture. Since UNCOVER_20466 is a point source and the LSF is expected to vary over the field of view, such deviations are possible and may be explored in a future work.

4 PROPERTIES OF UNCOVER_20466

The spectral fits of the previous Section result in a number of constraints on line and continuum properties of UNCOVER_20466. Here, we utilise these best-fit values to characterise the black hole and host galaxy of this system.

4.1 Dust attenuation

Previously, [Kokorev et al. \(2023\)](#) measured a best-fit ratio of Balmer line fluxes ($(F_{H\gamma}/F_{H\beta})_{\text{obs}} = 0.31 \pm 0.06$) and derived A_V using:

$$A_V = R_V \frac{2.5}{k(\lambda_{H\beta}) - k(\lambda_{H\gamma})} \log_{10} \left[\frac{(F_{H\gamma}/F_{H\beta})_{\text{obs}}}{(F_{H\gamma}/F_{H\beta})_{\text{int}}} \right] \quad (1)$$

assuming case B recombination and the reddening law found for the bar of the Small Magellanic Cloud (SMC; [Gordon et al. 2003](#)). This reddening law is commonly adopted for high-redshift quasars (e.g., [Greene et al. 2024](#); [Mazzolari et al. 2025](#); [Trefoloni et al. 2025](#); [D’Eugenio et al. 2025a](#); [Ji et al. 2025a](#)). Using this line flux ratio and an intrinsic ratio of $(F_{H\gamma}/F_{H\beta})_{\text{int}} = 1/2.14$ results in $A_V = 2.1^{+1.1}_{-1.0}$, or a colour excess of $E(B - V) \equiv A_V/R_V = 0.8 \pm 0.4$. However, the $H\gamma$ flux used in this calculation included a contribution from the

broad component, while the $H\beta$ flux was from the narrow component only.

We derive further constraints on $E(B - V)$ using all observed Balmer decrements. We only consider pairs of lines from the same emission origin (narrow or broad). The intrinsic ratios are derived using PYNEB, assuming the ISM conditions found for a stack of $4 < z < 7$ Type I AGN from JADES ([Isobe et al. 2025](#), $T_e \sim 2 \times 10^4$ K, $n_e \sim 10^4 \text{ cm}^{-3}$). As seen in Table 3, we are able to estimate the colour excess of the broad component using three ratios ($H\delta/H\beta$, $H\gamma/H\beta$, and $H\delta/H\gamma$). All three of these show negligible attenuation, with $E(B - V)$ values within 2σ of 0. When combined with the results of [Kokorev et al. \(2023\)](#), we find no significant evidence for reddening in the broad or narrow Balmer lines.

Of course, this result is dependent on a few assumptions. First, we adopt the SMC bar extinction curve of [Gordon et al. \(2003\)](#). Because each dust attenuation curve is normalised by the value at the approximate wavelength of the $H\beta$ -[OIII] λ 4959,5007 complex (i.e., V-band), the choice of extinction law does not introduce strong changes in the observed values of these lines. As a test, we adopt the starburst reddening law of [Calzetti et al. \(2000\)](#), resulting in nearly identical values (i.e., $< 1\sigma$ discrepant). However, we note that the choice of extinction curve will affect the observed rest-UV line fluxes and the continuum slope.

Next, we consider the fact that the intrinsic Balmer ratios are derived using PYNEB and our fiducial ISM conditions. For most densities ($\log_{10}(n_e/\text{cm}^{-3}) \lesssim 6$), these ratios feature a slight dependence on density (e.g., $H\gamma/H\beta$ changes by $\lesssim 5\%$ between $\log_{10}(n_e/\text{cm}^{-3}) = 0 - 7$ and $T_e = (0.5 - 3.0) \times 10^4$ K). At extreme densities ($\log_{10}(n_e/\text{cm}^{-3}) \gtrsim 7$), the ratio transitions to be density dependent. Changing the temperature and density in these ranges does not result in a significant (i.e., $> 1\sigma$) change in the $E(B - V)$ value.

An additional possibility is that we are observing a system where case B recombination is not applicable (e.g., [Pirzkal et al. 2024](#); [Scarlati et al. 2024](#); [McClymont et al. 2025b](#); [Sun & Yan 2025](#)). Our observed Balmer decrements suggest minimal dust attenuation (assuming case B), but the fact that our derived $E(B - V)$ values are not significantly negative does not provide strong evidence against case B.

We note that [Kokorev et al. \(2023\)](#) reported a large dust attenuation ($A_V \sim 1.9$) from fitting an AGN-only model to the continuum of UNCOVER_20466. At face value, this appears to disagree with the negligible attenuation found through analysis of Balmer ratios. However, as noted by other works, AGN-only models return higher dust attenuation than star+AGN models (e.g., [Leung et al. 2024](#)). In addition, the Balmer and continuum emission may emerge from different regions, or feature a different geometry. Thus, this difference in A_V could be used as evidence for a stellar component that contributes to the continuum emission, and/or a dusty AGN surrounded by less obscured line-emitting gas.

The non-detection of warm dust emission in a sample of 60 LRDs at $5 \leq z \leq 8$ ([Casey et al. 2025](#)) suggests that this class of objects may not feature significant warm dust reservoirs (i.e., $M_{\text{dust}} < 10^6 M_{\odot}$). UNCOVER_20466 only features a single ALMA non-detection, from the Deep UNCOVER-ALMA Legacy High- z (DUALZ) survey ([Fujimoto et al. 2025](#)). They do not detect significant $\lambda_{\text{obs}} = 1.2 \text{ mm}$ emission from UNCOVER_20466, implying a 3σ upper limit of $S_{1.2\text{mm}} < 99 \mu\text{Jy}$. From this single limit, it is not possible to solve the degeneracy inherent in FIR SED modelling (i.e., between dust temperature T_{dust} , dust mass M_{dust} , dust emissivity index β_{IR}).

Assuming a modified blackbody model that accounts for the effect

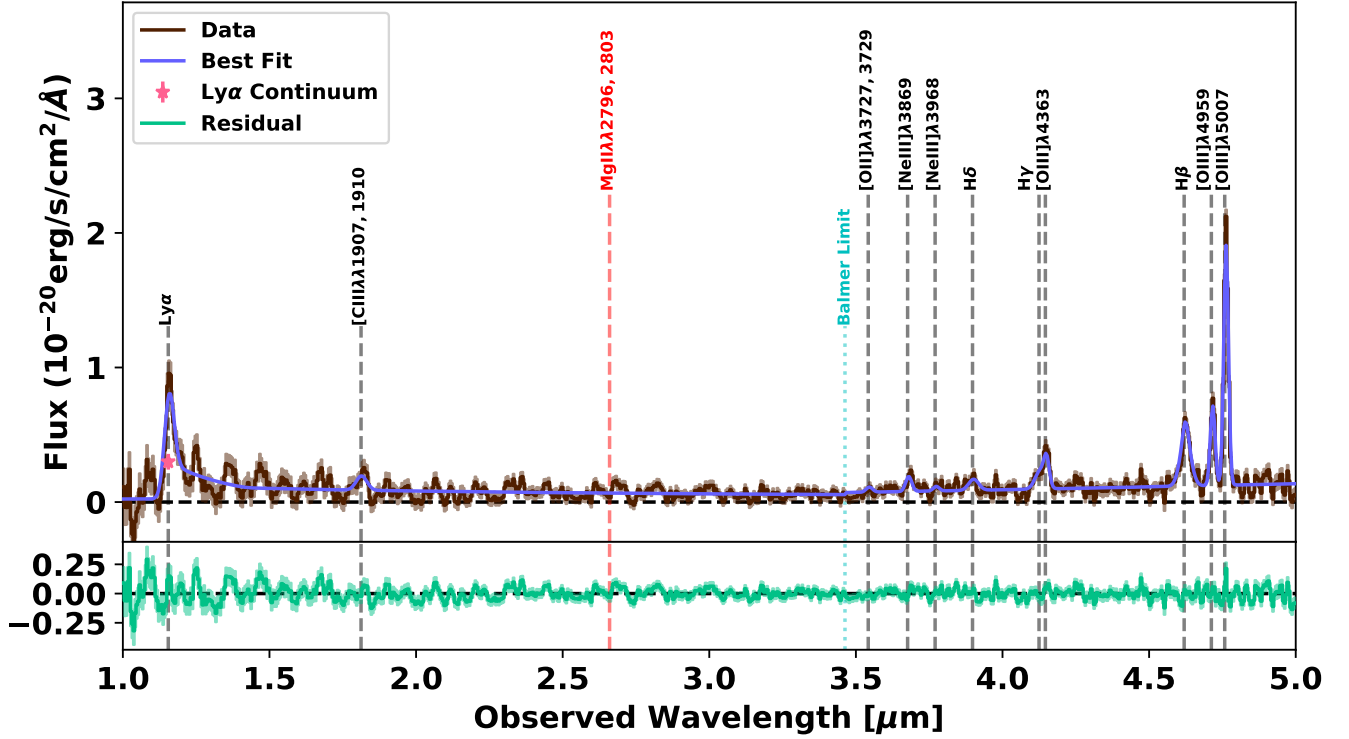


Figure 1. Spectrum extracted from NIRSpec IFU R100 data cube using a circular aperture of radius $0.125''$ (brown line). A concatenation of the best-fit red and blue models is shown by the blue line, where the dividing wavelength (i.e., the Balmer break) is shown by a dotted cyan line. Model residuals are shown in the lower portion of the panel (green line). The best-fit centroid wavelengths of the narrow components of each line are shown by dashed vertical black lines, whereas red dashed lines indicate undetected emission lines. The best-fit continuum underlying $\text{Ly}\alpha$ is shown by a pink star. Uncertainties (1σ) for the extracted spectrum and residuals are shown by shaded regions.

of the CMB at high redshift (e.g., [Carniani et al. 2019](#)) and adopting a standard value of $\beta_{\text{IR}} = 1.8$ suitable for most high-redshift galaxies (e.g., [Witstok et al. 2023](#)), we find that this observed flux density upper limit does not constrain the dust mass (i.e., even models with $M_{\text{dust}} = 10^{10} M_{\odot}$ are in agreement) in the case of cold gas ($T_{\text{dust}} = 30$ K, or the lower limit for LRDs found by [Li et al. 2025b](#)). By adopting the conservative limit of $M_{\text{dust}} \leq M_{*} < 10^{9.7} M_{\odot}$, we find that the upper limit is only met for $T_{\text{dust}} \lesssim 40$ K. Thus, while we may rule out a large reservoir of hot ($T_{\text{dust}} > 40$ K) dust, additional ALMA observations (i.e., deeper and at different wavelengths) are required to say more.

4.2 Black hole mass estimation

The black hole mass may be estimated using the properties of the broad $\text{H}\beta$ line, which originates from the BLR nearby the black hole, and so-called single-epoch virial relations. The most common method is that of [Greene & Ho \(2005\)](#):

$$\log_{10}(M_{\text{BH, GH05, H}\beta}/M_{\odot}) = (6.56 \pm 0.02) + (0.56 \pm 0.02) \log_{10} \left(\frac{L_{\text{H}\beta}}{10^{42} \text{ erg s}^{-1}} \right) + 2 \log_{10} \left(\frac{\text{FWHM}_{\text{H}\beta}}{10^3 \text{ km s}^{-1}} \right) \quad (2)$$

We also consider the relations of [Vestergaard & Peterson \(2006\)](#),

who derived a similar method based on $\text{H}\beta$:

$$\log_{10}(M_{\text{BH, VP06, H}\beta}/M_{\odot}) = (6.67 \pm 0.03) + 0.63 \log_{10} \left(\frac{L_{\text{H}\beta}}{10^{42} \text{ erg s}^{-1}} \right) + 2 \log_{10} \left(\frac{\text{FWHM}_{\text{H}\beta}}{10^3 \text{ km s}^{-1}} \right) \quad (3)$$

and a relation from the same work that replaces the $\text{H}\beta$ luminosity with the continuum emission underlying $[\text{OIII}]\lambda 5007$ ($\lambda_{\text{rest}} = 5100\text{\AA}$):

$$\log_{10}(M_{\text{BH, VP06, 5100}}/M_{\odot}) = (6.91 \pm 0.02) + 0.50 \log_{10} \left(\frac{\lambda L_{\lambda}(5100)}{10^{44} \text{ erg s}^{-1}} \right) + 2 \log_{10} \left(\frac{\text{FWHM}_{\text{H}\beta}}{10^3 \text{ km s}^{-1}} \right) \quad (4)$$

where each relation has an intrinsic scatter of ~ 0.4 dex.

We implement these relations with the best-fit properties of the R100 and R2700 data, resulting in values of $\log_{10}(M_{\text{BH}}/M_{\odot}) = 7.4 - 7.6$, with uncertainties of ~ 0.4 dex (i.e., with uncertainties dominated by the scatter of each relation; Table 3). This value is lower than the value of $\log_{10}(M_{\text{BH}}/M_{\odot}) = 8.0 - 8.2$ (with uncertainties of ~ 0.4 dex) derived by [Kokorev et al. \(2023\)](#), but not significantly ($< 2\sigma$ discrepant). This different value is partially due to the fact that we do not detect significant evidence for dust attenuation from the Balmer decrement, while [Kokorev et al. \(2023\)](#) corrected $\text{H}\beta$ using $A_V \sim 2$. In addition, the other work found a larger FWHM and line flux of the broad component of $\text{H}\beta$.

It is worthwhile noting that the single-epoch methods have been calibrated on galaxies in the local Universe, and their application to high-redshift sources is not straightforward. Indeed, recent works

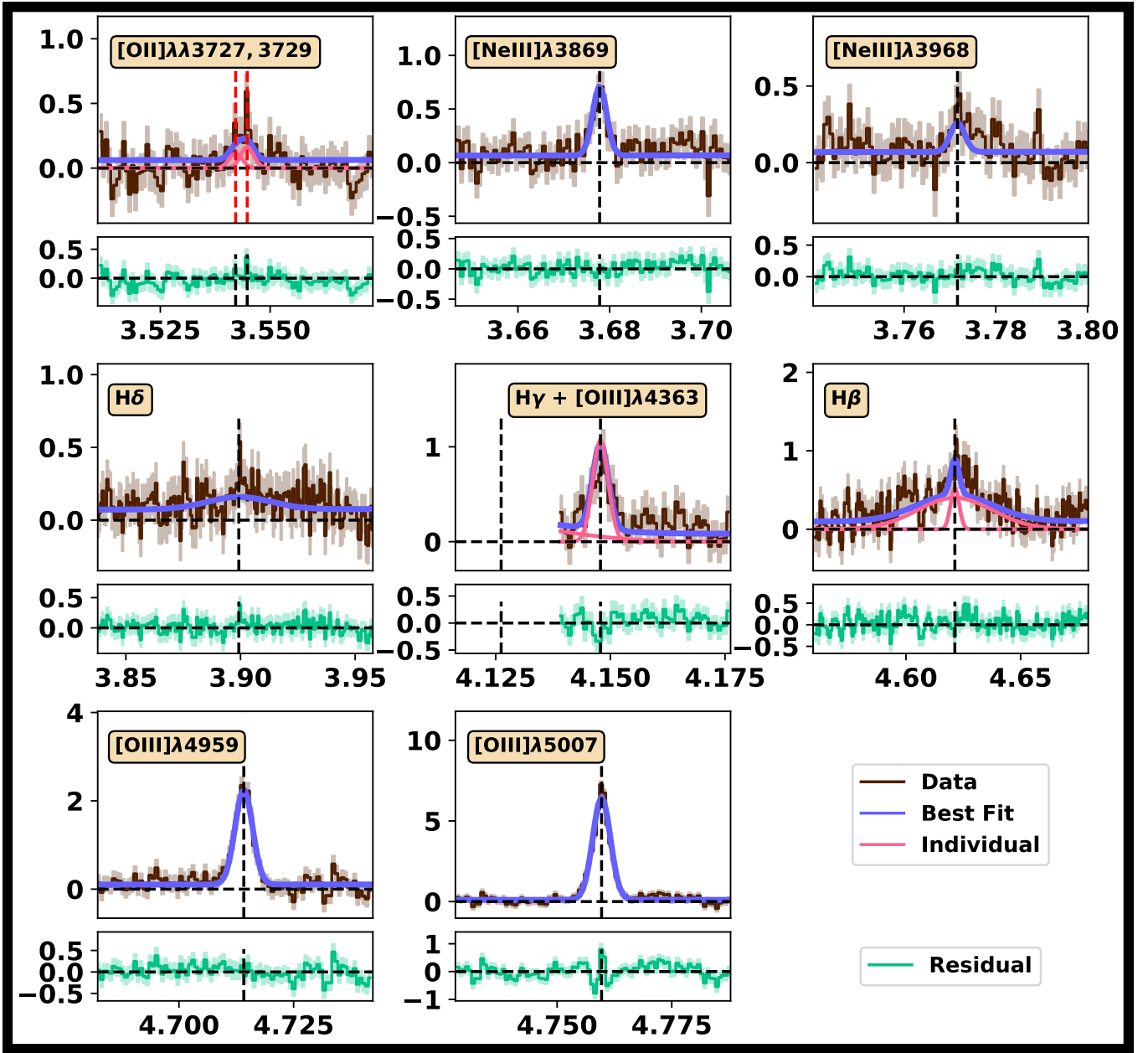


Figure 2. Spectrum extracted from NIRSIFU R2700 data cube using a circular aperture of radius $0.125''$ (brown lines). The best-fit model is shown as blue lines. When two components or lines are overlapping, they are shown by pink lines. Model residuals are shown in the lower portion of each panel (green lines). The best-fit centroid wavelengths of the narrow components of each line are shown by dashed vertical lines. We only show the wavelength range around emission lines of interest. Uncertainties (1σ) for the extracted spectrum and residuals are shown by shaded regions.

have suggested that, for LRDs, the broad emission is due to electron scattering rather than bulk motion around a black hole (Rusakov et al. 2025), resulting in a much lower (≥ 2 dex) M_{BH} estimate. While this would move many high-redshift AGN onto the local $M_{\text{BH}} - M_*$ relation (see Section 5), this interpretation is the subject of debate (e.g., Brazzini et al. 2025; Juodžbalis et al. 2025a). More recently, Juodžbalis et al. (2025b) directly measured the black hole mass in a lensed LRD at $z = 7$ by resolving its sphere of influence, finding a mass fully consistent with the virial relations. We consider further these results for our discussion of the black hole vs. galaxy properties in Section 5.

4.3 Luminosities & Eddington ratio

The bolometric luminosity can be found from the $\text{H}\beta$ broad luminosity using the relation from Stern & Laor (2012):

$$L_{\text{bol}} = 130 \times L_{\text{H}\beta, \text{B}} \times (F_{\text{H}\alpha}/F_{\text{H}\beta}) \quad (5)$$

Quantity	R100	R2700	Units	This work	Kokorev et al. (2023)
z_{sys}	X	X	-	8.5095 ± 0.0003	8.502 ± 0.003
$\Delta v_{\text{R100-R2700}}$	X	X	[km s ⁻¹]	182 ± 10	-
$FWHM_{\text{N}}$	X	X	[km s ⁻¹]	270 ± 5	203 ± 154
$FWHM_{\text{B,Ba}}$	X	X	[km s ⁻¹]	2503 ± 176	3439 ± 413
$\beta_{\text{Ly}\alpha}$	X		-	-5.0 ± 0.9	-
β_{UV}	X		-	-0.7 ± 0.1	-
C_{1500}	X		[10 ⁻²⁰ erg s ⁻¹ cm ⁻² Å ⁻¹]	0.11 ± 0.01	-
α_{opt}	X	X	-	1.8 ± 0.2	-
C_{4959}	X	X	[10 ⁻²⁰ erg s ⁻¹ cm ⁻² Å ⁻¹]	0.12 ± 0.01	-
$F_{\text{Ly}\alpha}$	X		[10 ⁻²⁰ erg s ⁻¹ cm ⁻²]	259.8 ± 23.0	414.1 ± 85.2
$EW_{0,\text{Ly}\alpha}$	X		[Å]	91 ± 20	240 ± 30
$F_{[\text{CIII}]\lambda\lambda 1907,1910}$	X		[10 ⁻²⁰ erg s ⁻¹ cm ⁻²]	48.9 ± 12.0	-
$F_{\text{MgII}\lambda\lambda 2796,2803}$	X		[10 ⁻²⁰ erg s ⁻¹ cm ⁻²]	< 34.8	62.5 ± 15.1
$F_{[\text{OIII}]\lambda\lambda 3727,3729}$	X	X	[10 ⁻²⁰ erg s ⁻¹ cm ⁻²]	10.4 ± 2.0	15.0 ± 8.0
$F_{[\text{NeIII}]\lambda 3869}$	X	X	[10 ⁻²⁰ erg s ⁻¹ cm ⁻²]	29.3 ± 2.5	62.2 ± 15.4
$F_{\text{H}\delta,\text{N}}$	X	X	[10 ⁻²⁰ erg s ⁻¹ cm ⁻²]	< 23.3	12.2 ± 6.5
$F_{\text{H}\delta,\text{B}}$	X	X	[10 ⁻²⁰ erg s ⁻¹ cm ⁻²]	34.9 ± 5.0	-
$F_{\text{H}\gamma,\text{N}}$	X	X	[10 ⁻²⁰ erg s ⁻¹ cm ⁻²]	< 27.2	-
$F_{\text{H}\gamma,\text{B}}$	X	X	[10 ⁻²⁰ erg s ⁻¹ cm ⁻²]	59.2 ± 7.9	-
$F_{[\text{OIII}]\lambda 4363}$	X	X	[10 ⁻²⁰ erg s ⁻¹ cm ⁻²]	45.9 ± 3.6	83.0 ± 7.2
$F_{\text{H}\beta,\text{N}}$	X	X	[10 ⁻²⁰ erg s ⁻¹ cm ⁻²]	25.0 ± 5.0	78.6 ± 5.9
$F_{\text{H}\beta,\text{B}}$	X	X	[10 ⁻²⁰ erg s ⁻¹ cm ⁻²]	164.7 ± 9.4	232.6 ± 17.3
$F_{[\text{OIII}]\lambda 5007}$	X	X	[10 ⁻²⁰ erg s ⁻¹ cm ⁻²]	359.5 ± 5.1	412.6 ± 11.3
$F_{\text{R100}}/F_{\text{R2700}}$	X	X	-	0.85 ± 0.01	-

Table 2. Best-fit emission line properties, as derived from fits to R100 and R2700 data. The two datasets feature a significant velocity offset ($\Delta v_{\text{R100-R2700}}$) and flux ratio ($F_{\text{R100}}/F_{\text{R2700}}$), which are listed here. Redshift and fluxes are reported as measured in the R100 frame. We mark which properties were derived with the R100 data (second column) and the R2700 data (third column). All values have been corrected for gravitational magnification and aperture losses. For undetected lines, we present 3σ upper limits on their flux. For Ly α , we present both the best-fit flux ($F_{\text{Ly}\alpha}$) and rest-frame equivalent width ($EW_{0,\text{Ly}\alpha}$).

Quantity	This work	Kokorev et al. (2023)
$E(B - V)_{\text{H}\delta/\text{H}\beta,\text{B}}$	0.3 ± 0.2	-
$E(B - V)_{\text{H}\gamma/\text{H}\beta,\text{B}}$	0.5 ± 0.3	-
$E(B - V)_{\text{H}\delta/\text{H}\gamma,\text{B}}$	-0.2 ± 0.7	-
$\log_{10}(M_{\text{BH,GH05,H}\beta}/M_{\odot})$	7.44 ± 0.40	8.17 ± 0.42
$\log_{10}(M_{\text{BH,VP06,H}\beta}/M_{\odot})$	7.57 ± 0.40	-
$\log_{10}(M_{\text{BH,VP06,5100}}/M_{\odot})$	7.58 ± 0.40	8.01 ± 0.40
$\log_{10}(L_{\text{bol}}/\text{ergs}^{-1})$	44.72 ± 0.02	$45.82^{+0.17}_{-0.28}$
$\log_{10}(L_{\text{Edd,GH05,H}\beta}/\text{ergs}^{-1})$	45.5 ± 0.4	-
$\log_{10}(L_{\text{Edd,VP06,H}\beta}/\text{ergs}^{-1})$	45.7 ± 0.4	-
$\log_{10}(L_{\text{Edd,VP06,5100}}/\text{ergs}^{-1})$	45.7 ± 0.4	-
$\log_{10}(\lambda_{\text{Edd,GH05,H}\beta})$	-0.83 ± 0.40	~ -0.40
$\log_{10}(\lambda_{\text{Edd,VP06,H}\beta})$	-0.95 ± 0.40	-
$\log_{10}(\lambda_{\text{Edd,VP06,5100}})$	-0.96 ± 0.40	-

Table 3. Properties of UNCOVER_20466, as derived from spectral fits to R100 and R2700 data. All values have been corrected for gravitational magnification and aperture losses.

where $(F_{\text{H}\alpha}/F_{\text{H}\beta}) = 2.74$ is the intrinsic ratio of these lines, assuming case B recombination and the fiducial ISM conditions of Section 4.1⁶.

⁶ Assuming a higher density ($\log_{10}(n_{\text{e}}/\text{cm}^{-3}) = 7$), as suggested by the analysis Section 4.5, results in a fiducial $(F_{\text{H}\alpha}/F_{\text{H}\beta}) = 2.71$, or a decrease of $\sim 1\%$.

We find a value of $\log_{10}(L_{\text{bol}}) = 44.72 \pm 0.02$, which is considerably lower than the value of $\log_{10}(L_{\text{bol}}) = 45.82^{+0.17}_{-0.28}$ found by Kokorev et al. (2023). This difference is partially ascribable to our different treatments of dust attenuation (see Section 4.1). If a high attenuation of $A_{\text{V}} = 2$ is taken into account, then the intrinsic H β flux increases by a factor of $\sim 20\times$, resulting in higher estimates of L_{bol} . As a test, we applied this dust correction to our values, resulting in L_{bol} values within 1σ of Kokorev et al. (2023).

Similarly, the Eddington luminosity (e.g., Fabian 2012) is expressed as:

$$L_{\text{Edd}} = \frac{4\pi G M_{\text{BH}} m_{\text{p}} c}{\sigma_{\text{T}}} = 1.26 \times 10^{38} \left(\frac{M_{\text{BH}}}{M_{\odot}} \right) [\text{erg s}^{-1}] \quad (6)$$

This is commonly used to calculate the Eddington ratios ($\lambda_{\text{Edd}} \equiv L_{\text{bol}}/L_{\text{Edd}}$). Regardless of the method used to derive the black hole mass, we find $\lambda_{\text{Edd}} \sim 10\%$. This is lower than the value of $\sim 40\%$ measured by Kokorev et al. (2023), but due to the large uncertainty on L_{Edd} , they are $< 2\sigma$ discrepant. We note that both L_{bol} and L_{Edd} are functions of $L_{\text{H}\beta}$ (using the calibration of Greene & Ho 2005), and a higher H β flux (or a lower $FWHM$ of the broad component of H β) will result in a higher λ_{Edd} . Since we adopt the same equations, this lower ratio is due to a combination of different dust attenuation assumptions and different aperture loss corrections, as well as the different broad H β flux and smaller H β broad linewidth.

4.4 ISM conditions

While the broad emission opens a window into the nature of the black hole of UNCOVER_20466, the narrow lines instead allow us

to characterise the host galaxy (or nearby gas; e.g., Inayoshi et al. 2025; Lin et al. 2025b).

To begin, we use our observed line ratios and the code PYNEB to explore the electron density (n_e) through the [OII] $\lambda\lambda 3727, 3729$ line pair. As noted in Section 3.2.2, we are not able to directly fit for the ratio of [OII] $\lambda 3727$ /[OII] $\lambda 3729$ using our data. An exploration of line ratios finds that a low ratio (~ 0.7 , implying $\log_{10}(n_e/\text{cm}^{-3}) \sim 2$) yields a better fit. While this ratio has a weak dependence on T_e , a low ratio may only be caused by a low-density environment (i.e., at any temperature).

Next, we consider the [OIII] $\lambda 4363$ /[OIII] $\lambda 5007$ ratio, which is a strong indicator of T_e . This ratio is lower in our data (0.13 ± 0.01) than that of Kokorev et al. (2023, 0.20 ± 0.02). As noted in Kokorev et al. (2023), this ratio is much higher than expected for most galaxies. For an electron density of $n_e \sim 10^{1-4} \text{ cm}^{-3}$, PYNEB predicts a maximum ratio of $\lesssim 0.05$ for $T_e < 2.5 \times 10^4 \text{ K}$. While this line ratio is strongly dependent on T_e for $n_e < 10^5 \text{ cm}^{-3}$, it transitions to a strong dependence on n_e for $n_e > 10^5 \text{ cm}^{-3}$. While a ratio of $0.1-0.2$ could be theoretically explained by a high density ($n_e \sim 10^6 \text{ cm}^{-3}$) and temperature ($\sim 2 \times 10^4 \text{ K}$), this density is ~ 2 dex higher than the average value found for $4 < z < 7$ Type I AGN (Isobe et al. 2025) and ~ 3 dex higher than the average value for SFGs at the redshift of UNCOVER_20466 (e.g., Isobe et al. 2023; Li et al. 2025a). While high n_e is expected from some interpretations of LRD properties (e.g., Begelman & Dexter 2025; Rusakov et al. 2025), these conditions are extreme.

Together, these tracers appear to present contrasting ISM conditions: the low [OII] $\lambda 3727$ /[OII] $\lambda 3729$ ratio requires low n_e , while the high [OIII] $\lambda 4363$ /[OIII] $\lambda 5007$ ratio requires high n_e . One possible explanation is a two-phase ISM, with both low- and high-density emission regions (e.g., Ji et al. 2024; Harikane et al. 2025; Usui et al. 2025). Alternatively, the [OIII] $\lambda 4363$ /[OIII] $\lambda 5007$ ratio could suggest an extraordinarily high temperature (i.e., $> 2 \times 10^4 \text{ K}$). Similarly high [OIII] $\lambda 4363$ /[OIII] $\lambda 5007$ ratios have been observed in other $z > 7$ galaxies (e.g., Schaerer et al. 2022; Katz et al. 2023; Cullen et al. 2025), where they have been explained by a high degree of cosmic ray heating, the presence of high-mass X-ray binaries, or Wolf-Rayet stars. The extreme conditions implied by these ratios independently support the presence of an AGN in this galaxy (see Mazzolari et al. 2024; Übler et al. 2024, Section 4.5). These aspects will be discussed more thoroughly in the next Section, within the context of AGN and SF photoionization models.

Our observed line fluxes can also be used to estimate the gas-phase metallicity of UNCOVER_20466 using strong line ratio diagnostics (e.g., Curti et al. 2020; Cataldi et al. 2025). We will adopt the calibrations of Sanders et al. (2024), as they were created using JWST observations of galaxies in a redshift range that contains UNCOVER_20466 (i.e., $2.1 < z < 8.7$). Using the narrow-line flux ratios (O3, O2, R23, O32, Ne3O2, see Table 4 for ratio definitions), we find a best-fit value of $12 + \log_{10}(O/H) = 7.78 \pm 0.06$, or 0.12 ± 0.02 solar.

There are caveats with this metallicity derivation, including the possibility that [OII] $\lambda\lambda 3727, 3729$ and [OIII] $\lambda\lambda 4959, 5007$ (which are in every line ratio) originate from different components of a multi-phase ISM, the possibility that the electron temperature in this object is exceptionally high, or the unproven applicability of a metallicity calibration created using star-forming galaxies to LRDs. But most works investigating LRDs assume a low metallicity ($\lesssim 20\%$ solar; e.g., Kocovski et al. 2025; Donnan et al. 2025), in agreement with the finding of $\lesssim 10\%$ solar metallicity from individual studies of LRDs (e.g., De Graaff et al. 2025; D'Eugenio et al. 2025a; Maiolino et al.

Line ratio	Definition
O3	$F_{[\text{OII}]\lambda\lambda 3727, 3729} / F_{\text{H}\beta}$
O2	$F_{[\text{OII}]\lambda 5007} / F_{\text{H}\beta}$
R23	$(F_{[\text{OII}]\lambda\lambda 3727, 3729} + F_{[\text{OIII}]\lambda\lambda 4959, 5007}) / F_{\text{H}\beta}$
O32	$F_{[\text{OII}]\lambda 5007} / F_{[\text{OII}]\lambda\lambda 3727, 3729}$
Ne3O2	$F_{[\text{NeIII}]\lambda 3869} / F_{[\text{OII}]\lambda\lambda 3727, 3729}$
O3Hg	$F_{[\text{OIII}]\lambda 4363} / F_{\text{H}\gamma}$
O33	$F_{[\text{OIII}]\lambda 5007} / F_{[\text{OIII}]\lambda 4363}$

Table 4. Definitions of line ratios used in this work.

2025a). Our metallicity estimate is therefore in line with previous findings for high- z LRDs.

If [OIII] $\lambda 5007$ and [OII] $\lambda\lambda 3727, 3729$ originate from the same region, we may use our best-fit line fluxes to estimate a line ratio of O32 = 34 ± 9 . This O32 value is larger than the average value found for a sample of $z > 7$ galaxies by Tang et al. (2023, ~ 12), and is comparable to the most extreme O32 observed in the $z \sim 4-8$ sample of Mascia et al. (2023, ~ 35) and the $z \sim 5.5-9.5$ sample of Cameron et al. (2023, ~ 30). Our O32 value may then be converted to an approximate ionization parameter U using the photoionization models of Morisset et al. (2016), resulting in an approximate value of $\log_{10}(U) = -1.3 \pm 0.3$. This is higher than the standard assumption of $\log_{10}(U) = -2.0$ (e.g., Choustikov et al. 2025), and approaches the theoretical limit of $\log_{10}(U) < -1.0$ for HII regions (e.g., Yeh & Matzner 2012). We emphasize that there are ambiguities concerning these values (O32 and U) due to poor detection of [OII] $\lambda 3727$ and [OII] $\lambda 3729$, a possible multi-phase ISM, and the use of a photoionization model that may not be appropriate for a high-redshift LRD. Despite this, the fact that [OIII] $\lambda 5007$ is well detected while [OII] $\lambda\lambda 3727, 3729$ is not suggests a very high O32 in at least one component of the ISM, and thus a high level of ionisation.

4.5 AGN diagnostics and extreme densities

Since our NIRSpect data do not cover the wavelength range of H α , [NII] $\lambda\lambda 6548, 6584$, or [SII] $\lambda\lambda 6716, 6731$, we are unable to investigate the position of UNCOVER_20466 on the commonly used [NII]-BPT (Baldwin et al. 1981) or [SII]-VO87 (Veilleux & Osterbrock 1987) line ratio diagrams. However, a powerful set of alternative diagnostics are those of Mazzolari et al. (2024). In addition to O32 and Ne3O2, these diagnostics make use of the [OIII] $\lambda 4363$ auroral line through O3Hg = [OIII] $\lambda 4363$ /H γ and O3 = [OIII] $\lambda 4363$ /[OIII] $\lambda 5007$ (Figure 3). These are used to create line ratio diagrams, with regions in which only AGN are found, while other parts of the diagrams are populated by both AGN and star forming galaxies.

Previously, Mazzolari et al. (2024) used the measured values of Kokorev et al. (2023) to show that UNCOVER_20466 was indeed an AGN. Our newly measured line fluxes confirm this (Figure 3). While the H γ flux reported by Kokorev et al. (2023) include contributions from both the narrow and broad components, we only use the 3σ upper limit on the narrow component of H γ (Table 2) to find a similar result. Our limit lies below the demarcation line for the O3Hg – O33 plot (lower panels of Figure 3), but does not disagree with an AGN interpretation, given that this lower region is populated both by AGN and SF galaxies.

To place this in a broader context, we compare the location of UNCOVER_20466 in these line ratio diagrams to those of high-redshift ($z > 6$) sources from literature (Curti et al. 2023; Larson et al. 2023; Nakajima et al. 2023; Laseter et al. 2024; Juodžbalis

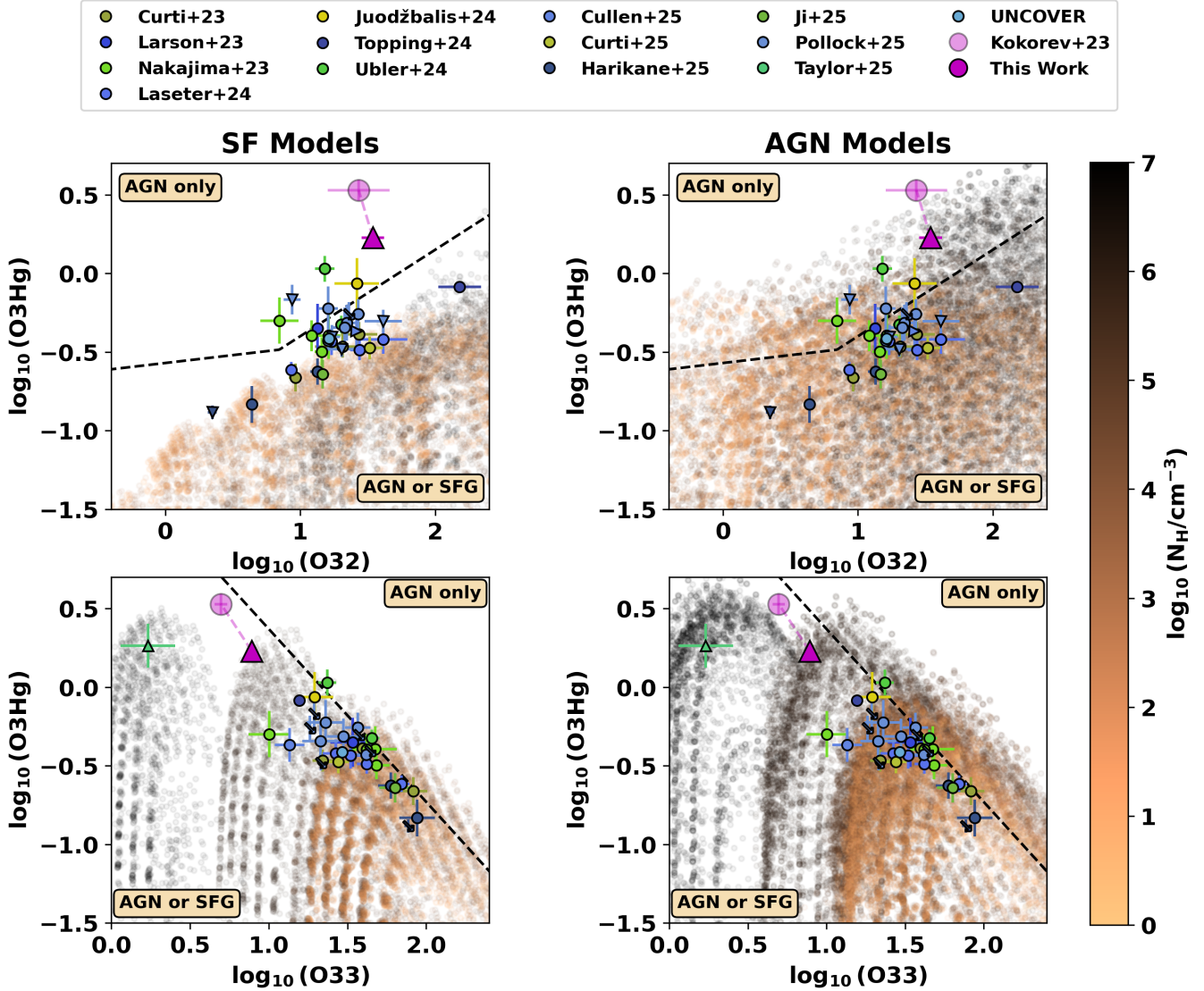


Figure 3. Line ratio diagnostic diagrams of Mazzolari et al. (2024), with the value for UNCOVER_20466 from Kokorev et al. (2023, magenta circle) and the limit from this work (magenta triangle). Points above each line suggest an AGN-only nature, while those below could be interpreted as AGN or star-forming galaxies (SFGs). For comparison, we include a collection of $z > 6$ measurements (Curti et al. 2023; Larson et al. 2023; Nakajima et al. 2023; Laseter et al. 2024; Juodžbalis et al. 2024; Topping et al. 2024; Übler et al. 2024; Cullen et al. 2025; Curti et al. 2025; Harikane et al. 2025; Ji et al. 2025b; Pollock et al. 2025; Taylor et al. 2025). Values from the HOMERUN models (Marconi et al. 2024) are coloured by hydrogen density, with star-forming models in the left column and AGN models in the right column.

et al. 2024; Topping et al. 2024; Übler et al. 2024; Cullen et al. 2025; Curti et al. 2025; Harikane et al. 2025; Ji et al. 2025b; Pollock et al. 2025; Taylor et al. 2025). We also collect all sources from UNCOVER DR4 (Bezanson et al. 2024; Price et al. 2025)⁷ with significant line detections, resulting in one additional source (UNCOVER_10646, $z = 8.5$). From this comparison, it is clear that UNCOVER_20466 features one of the highest O3Hg ratios among the observed galaxies. A rare exception in this sample is the upper limit of CAPERS-LRD-z9 (Taylor et al. 2025), which is comparable to ours. This source also features a very low O33, implying a high $[\text{OIII}]\lambda 4363/[\text{OIII}]\lambda 5007$ ratio of ~ 0.6 . As discussed in Section 4.4, even our estimated $[\text{OIII}]\lambda 4363/[\text{OIII}]\lambda 5007$ ratio of ~ 0.1 is

difficult to explain without requiring extreme conditions (i.e., unphysically high temperature or density). While CAPERS-LRD-z9 is a BL LRD with a similar M_{BH} (see Section 5.2), it lies far from the AGN demarcation line in the O3Hg – O33 diagnostic plot. Thus, UNCOVER_20466 remains one of the most clear AGN in these diagnostics.

The faint coloured points in each panel represent line ratios from a large library of single-cloud CLOUDY (Ferland 1993; Ferland et al. 2017) models used by Marconi et al. (2024) and Ceci et al. (2025) for the ‘Highly Optimized Multicloud Emission-line Ratios Using photo-ionization’ (HOMERUN) model. The star-forming galaxy CLOUDY models (left column) were computed with the following parameters. The ionizing continua are from stellar population models from BPASS v2.3 (Stanway & Eldridge

⁷ <https://jwst-uncover.github.io/DR4.html>

2018; Byrne et al. 2022) including binary stellar evolution and use a Kroupa (2001) initial mass function with an upper mass cut-off of $300 M_{\odot}$. The modelled stellar populations featured metallicities $\log_{10}(Z_{\star}) = -1.7(\text{solar}), -2.7, -4.0, -5.0$ and ages in $\log_{10}(\text{age/Myr}) = 6.0, 6.4, 6.6, 7.1, 8.0$. The ionized gas has ionization parameter $\log_{10}(U)$ ranging from -4.0 to -0.5 in steps of 0.5 , constant gas density $\log_{10}(N_{\text{H}}/\text{cm}^{-3})$ ranging from 0 to 7 in steps of 1 , and metallicities $\log_{10}(Z_{\text{gas}}/Z_{\odot})$ ranging from -4.3 to 0.4 in steps of 0.2 (with the constraint that the gas metallicity is within a factor 0.1 and 100 of the stellar metallicity). Models were considered both with and without dust.

The ionizing continuum for the AGN models (right column) is described by a power law with UV slope $\alpha_{\text{UV}} = -0.5$, an exponential cut-off $\exp(-h\nu/kT_{\text{max}})$ and an X-ray power-law with slope of $\alpha_{\text{UV}} = -1.0$ linked to the UV through the α_{ox} parameter. Models were computed with combinations of $\log_{10}(T_{\text{max}}/\text{K}) = 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0$ and $\alpha_{\text{ox}} = -1.2, -1.5, -1.8$. The other parameters are the same with the exception that the ionization parameter upper limit is 0.5 and that the gas metallicity always cover the range of $-2 \leq Z/Z_{\odot} \leq 1.0$ with steps of 0.2 .

The comparison of these SF (left panels) and AGN models (right) clearly indicate that these diagrams (and especially O3Hg vs O32) are extremely effective in identifying AGN, and that the dividing line between AGN-only and AGN+SF regions is likely very conservative. It is noticeable that even extremely high densities are not enough to reach high [OIII] $\lambda 4363/\text{H}\gamma$ values (at a given O32 value) when considering SF galaxies. In order to reach very high [OIII] $\lambda 4363/\text{H}\gamma$ the presence of an AGN is needed, likely because the hard AGN radiation field is very effective in heating the ISM, hence boosting the flux of the corona line.

The specific case of UNCOVER_20466 is particularly intriguing, as it requires not only AGN photoionization but also extremely high densities, of about 10^7 cm^{-3} . Together with the fact that this is the most distant of all sources in the sample shown, this may indicate that UNCOVER_20466 is forming embedded in the very dense gas of an early protogalaxy.

Recently, Lambides et al. (2025) analysed JWST/NIRSpec MSA data of the $z = 6.68476$ LRD THRILS_46403 (also known as CEERS-10444; Kocevski et al. 2025), revealing evidence for a very high $\log_{10}(\text{O3Hg}) = 1.16 \pm 0.06$. This ratio is higher than observed in UNCOVER_20466, and is also ~ 0.5 dex higher than the most extreme HOMERUN AGN models, suggesting uncommon conditions. However, we note the strong Balmer absorption observed in this source is not included in the $\text{H}\gamma$ line fit, resulting in an overestimation of the O3Hg ratio; additionally prominent FeII emission lines are observed in the spectrum, implying that the [OIII] $\lambda 4363$ is also likely contaminated by FeII. Even taking these aspects into account, THRILS_46403 represents an extreme galaxy similar to UNCOVER_20466.

4.6 Dynamical mass

To constrain the dynamical mass of the UNCOVER_20466 host galaxy, we use the same relation as Übler et al. (2023):

$$M_{\text{dyn}} = K(n)K(q)\sigma_{\star}^2 R_e/G \quad (7)$$

where n is the Sérsic index, q is the axis ratio, and $K(n) = 8.87 - 0.831n + 0.0241n^2$ and $K(q) = [0.87 + 0.38e^{-3.71(1-q)}]^2$ are taken from Cappellari et al. (2006) and Van der Wel et al. (2022), respectively. To convert our integrated narrow gas emission linewidth (see FWHM_N in Table 2) to an integrated stellar velocity dispersion ($\sigma_{\star}$), we adopt the empirical relations for $z \sim 1$ galaxies of Bezanson

Filter	q	n	R_e [kpc]	$\log_{10}(M_{\text{dyn}}/M_{\odot})$
F356W	0.18 ± 0.12	6.01 ± 1.47	0.36 ± 0.1	$9.8^{+0.1}_{-0.2}$
F410M	0.33 ± 0.21	5.13 ± 1.92	0.24 ± 0.07	$9.7^{+0.1}_{-0.2}$
F444W	0.19 ± 0.13	5.39 ± 1.81	0.2 ± 0.03	$9.6^{+0.1}_{-0.2}$
F460M	0.45 ± 0.26	4.39 ± 2.19	0.19 ± 0.04	$9.6^{+0.1}_{-0.2}$
F480M	0.48 ± 0.26	4.45 ± 2.27	0.18 ± 0.04	$9.6^{+0.1}_{-0.2}$
Mean	0.32 ± 0.09	5.07 ± 0.87	0.23 ± 0.03	$9.7^{+0.1}_{-0.1}$

Table 5. Best-fit morphological properties of UNCOVER_20466, as derived from PYSERVIC fits to JWST/NIRCam data. For each NIRCam filter, we list the axis ratio (q), Sérsic index (n), magnification-corrected effective radius in kpc (R_e), and the resulting dynamical mass.

et al. (2018) (as done by other works, e.g. Übler et al. 2023). This results in $\sigma_{\star} \approx 1.26 \times \text{FWHM}_N/2.355$, or $\sigma_{\star} = 144.3 \pm 2.7 \text{ km s}^{-1}$.

This mass is dependent on three morphological properties (n , q , R_e), which we determine from the JWST/NIRCam images using PYSERVIC (Pasha & Miller 2023) and the empirical PSFs. All 20 NIRCam images are fit, but due to the compact nature of the source, we find that only five images result in both strong detections ($> 3\sigma$ fluxes) and appear to resolve the source ($> 3\sigma$ effective radii). The best-fit parameters of each image are listed in Table 5.

While the aspect ratio q is not well determined, all of the Sérsic indices argue for a high value ($n \sim 4 - 6$). The effective radii range from $\sim 0.2 - 0.4$ kpc, slightly larger than the value derived through a similar analysis by Kokorev et al. (2023): $r_e = 0.165 \pm 0.020$ kpc. Adopting the mean morphological parameters of the NIRCam images (see Table 5), we estimate $\log_{10}(M_{\text{dyn}}/M_{\odot}) = 9.7 \pm 0.1$.

4.7 Ly α properties

As noted in previous works (e.g., Kokorev et al. 2023; Fujimoto et al. 2024), UNCOVER_20466 is a powerful Ly α emitting galaxy (LAE). The presence of another nearby LAE (within a projected distance of < 500 kpc and redshift difference $\Delta z \sim 0.01$ or $\Delta v \sim 300 \text{ km s}^{-1}$) suggests that both LAEs reside in the same ionised bubble (Fujimoto et al. 2024). We recover a lower Ly α flux ($2.60 \pm 0.23 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$) and equivalent width ($91 \pm 20 \text{ \AA}$) than previous results (e.g., Kokorev et al. 2023), but the resulting emission still meets the most conservative criterion for strong Ly α emission used by many studies (i.e., $EW_{0,\text{Ly}\alpha} > 75 \text{ \AA}$; e.g., Stark et al. 2010; Pentericci et al. 2018; Jones et al. 2025a).

From the R100 spectrum, we are able to estimate the Ly α escape fraction. The intrinsic ratio of $\text{Ly}\alpha/\text{H}\beta = 31.87$ is estimated using our fiducial ISM conditions (see Section 4.1) and PYNEB. Based on the best-fit fluxes of the narrow H β and Ly α emission, this results in $f_{\text{esc}}^{\text{Ly}\alpha} = 33 \pm 7\%$. If we instead assume a high density of $\log_{10}(n_e/\text{cm}^{-3}) = 7$, then PYNEB outputs a higher intrinsic ratio of $\text{Ly}\alpha/\text{H}\beta = 35.49$, resulting in a $< 1\sigma$ lower value of $f_{\text{esc}}^{\text{Ly}\alpha} = 29 \pm 6\%$. We find that UNCOVER_20466 falls on the strong correlations between $EW_{0,\text{Ly}\alpha} - f_{\text{esc}}^{\text{Ly}\alpha}$ (e.g., Begley et al. 2024; Goovaerts et al. 2024) and $EW_{0,\text{Ly}\alpha} - M_{\text{UV}}$ measured by other works (e.g., Jones et al. 2025a), as shown in Appendix D.

We also note that previous works found a link between O32 (tracing ionisation parameter) and $f_{\text{esc}}^{\text{Ly}\alpha}$ (e.g., Nakajima & Ouchi 2014; Yang et al. 2017; Roy et al. 2023, but see also e.g., Izotov et al. 2020; Saxena et al. 2024). Our high values (see Section 4.4 for O32 details) would appear to support this correlation, lying just beyond the scatter of values from other high-redshift works (e.g., Roy et al. 2023).

Some of the properties of UNCOVER_20466 (e.g., compact morphology, high Ly α escape fraction, nearby LAEs, high ionization parameter traced by O32) are also seen in the $z \sim 8.3$ metal-poor LAE CANUCS-A370-z8-LAE (Willott et al. 2025). But this other source is not an LRD, as it lacks broad Balmer emission or a v-shaped continuum. In addition, it is more metal poor. This highlights the diversity of strong LAEs in the early Universe.

4.8 Continuum properties

Based on JWST/NIRCam photometry, this source was classified as an LRD (Labbe et al. 2025). One of the defining characteristics of these objects is a v-shaped continuum, with a negative (positive) F_λ slope in the rest-UV (rest-optical). This was confirmed by the JWST/NIRSpec observations of Greene et al. (2024), who found $\alpha_{\text{opt}} = 0.5 \pm 0.3$ and $\beta_{\text{UV}} = -0.7 \pm 0.2$ (i.e., the ‘red’ nature is not due solely to emission lines). Our fits of the R100 spectrum return a redder optical slope ($\alpha_{\text{opt}} = 1.8 \pm 0.2$) and a similar UV slope ($\beta_{\text{UV}} = -0.7 \pm 0.1$). We note that these slopes meet the LRD criteria of $\alpha_{\text{opt}} > 0$ and $-2.8 < \beta_{\text{UV}} < -0.37$ used by classification studies (e.g., Kocevski et al. 2025; Hainline et al. 2025), confirming the LRD nature of UNCOVER_20466.

Because we fit the R100 spectrum in two parts (i.e., before and after the Balmer limit), there is a discontinuity at $\lambda_{\text{rest}} = 0.3645 \mu\text{m}$ with a red/blue flux ratio of 1.3 ± 0.2 (using the best-fit values and uncertainties of each continuum model). Balmer breaks are commonly observed in LRDs (e.g., De Graaff et al. 2025; Furtak et al. 2025; Ji et al. 2025a; Liu et al. 2025; Wang et al. 2025), and this ratio falls within the lower end of the scatter for observed Balmer breaks at high redshift (e.g., Kuruvanthodi et al. 2024; Vikaeus et al. 2024; Wang et al. 2024; Tang et al. 2025). However, the current data are not able to confirm a Balmer break in UNCOVER_20466.

5 DISCUSSION

5.1 Black hole - host galaxy scaling relations

Our derived properties allow us to consider the placement of UNCOVER_20466 on planes of M_{BH} as a function of M_* , σ_* , and M_{dyn} (Figure 4), which will inform us on the evolutionary state of the object. In each panel, we compare the placement of UNCOVER_20466 relative to other JWST-AGN at $z > 5$ (Goulding et al. 2023; Larson et al. 2023; Übler et al. 2023; Furtak et al. 2024; Maiolino et al. 2024, 2025a; Napolitano et al. 2024; Tripodi et al. 2024; Akins et al. 2025; D’Eugenio et al. 2025a; Juodžbalis et al. 2025a; Kiyota et al. 2025; Naidu et al. 2025a; Rinaldi et al. 2025a; Taylor et al. 2025; Zhang et al. 2025a), as well as correlations found for low-redshift galaxies (Kormendy & Ho 2013; Reines & Volonteri 2015; Greene et al. 2020; Bennert et al. 2021).

First, we consider the distribution of black hole mass as a function of stellar mass (Figure 4a). Most JWST-detected black holes lie above the local relation, reflecting overmassive black holes. Our new M_{BH} value is lower than that of Kokorev et al. (2023), but it is clear that the black hole of UNCOVER_20466 is overmassive, similar to many JWST-detected AGN ($M_{\text{BH}} \gtrsim 0.1 \times M_*$). This is especially evident when comparing to the Reines & Volonteri (2015) local relation, which is calibrated primarily on AGNs. Even if our single-epoch black hole mass would be overestimated by ~ 0.7 dex, as possibly indicated by the recent results for a highly super-Eddington black hole at $z \sim 2.3$ (Abuter et al. 2024), UNCOVER_20466 would remain overmassive in the black hole mass – stellar mass plane. Furthermore,

the low Eddington ratio we find in this work suggests that a possible correction towards lower black hole masses may not be as large (see discussion by Abuter et al. 2024). Additionally, the finding by Juodžbalis et al. (2025b) that the direct BH mass measurement in a LRD at $z = 7$ being consistent with local virial relations, supports the idea that the BH mass inferred by us in UNCOVER_20466 is reasonably accurate.

The relation between black hole mass and galaxy velocity dispersion (also known as the ‘M- σ ’ relation, Figure 4b) has been found to be constant over a range of redshifts ($z < 1$; e.g., Shen et al. 2015). This connection represents a coeval evolution of the black hole and the material surrounding it. As already pointed out by Maiolino et al. (2024) and Juodžbalis et al. (2025a), most of the JWST-detected AGN fall onto the local correlation, including UNCOVER_20466. One minor note is that the σ_* measured from JWST data represents the narrow linewidth from the full source (corrected for instrumental broadening and converted to stellar dispersion), while the same value from local galaxies is extracted only from the bulge. However, most galaxies entering the local relation are ellipticals or bulge-dominated galaxies, i.e. where the bulge contains most of the stellar mass.

The last correlation is between black hole mass and dynamical mass (Figure 4c). The JWST-detected AGN are scattered on both sides of the local relation, and UNCOVER_20466 agrees with the Bennert et al. (2021) relation.

We note that each of the low-redshift correlations originates from different samples. The $M_{\text{BH}}-\sigma_*$ and $M_{\text{BH}}-M_{\text{dyn}}$ correlations of Kormendy & Ho (2013) are found using a sample of local elliptical and bulge galaxies, where $M_{\text{dyn}} = M_{\text{bulge}}$. Similarly, Greene et al. (2020) fit $M_{\text{BH}}-\sigma_*$ and $M_{\text{BH}}-M_*$ using a sample of local spiral and elliptical galaxies. The sample used to derive the $M_{\text{BH}}-M_*$ relation of Reines & Volonteri (2015) consisted of local broad line AGN. Bennert et al. (2021) combined local broad line AGN and quiescent galaxies to examine all three correlations. Since their data allow for the spatial decomposition of the bulge and disk of each source, M_{dyn} is derived using the radius and velocity dispersion of the central bulge. On the other hand, the observed values for high-redshift galaxies are derived in similar ways.

Figure 4a shows that UNCOVER_20466 has an overmassive black hole (with respect to the stellar mass), especially compared to AGN in the local Universe. Despite this, it already lies on correlations between M_{BH} and bulge properties (velocity dispersion and dynamical mass, Figures 4b,c). The fact that UNCOVER_20466 falls on the same correlations suggests that it may evolve along those relations into a present-day massive early-type galaxy.

5.2 Black hole growth through cosmic time

It is clear that UNCOVER_20466 features a significant black hole mass at an early cosmic epoch ($t_{\text{H}} \sim 580 \text{ Myr}$). To explore this further, we compare the black hole mass to those of other $z > 6$ AGN (Figure 5).

First, we consider a simple model for how a black hole will grow through cosmic time. Their growth rate may be derived using their Eddington luminosity and Eddington ratio (e.g., Li 2012):

$$\dot{M}_{\text{BH}} = \frac{\lambda_{\text{Edd}} L_{\text{Edd}}}{\epsilon_o c^2} \quad (8)$$

where ϵ_o is the efficiency at which mass is converted to luminosity (here assumed to be 0.1). If each black hole has mass M_{seed} at cosmic time t_{seed} and we assume Eddington-limited accretion ($\lambda_{\text{Edd}} = 1$), then we may solve the above equation to determine the mass evolu-

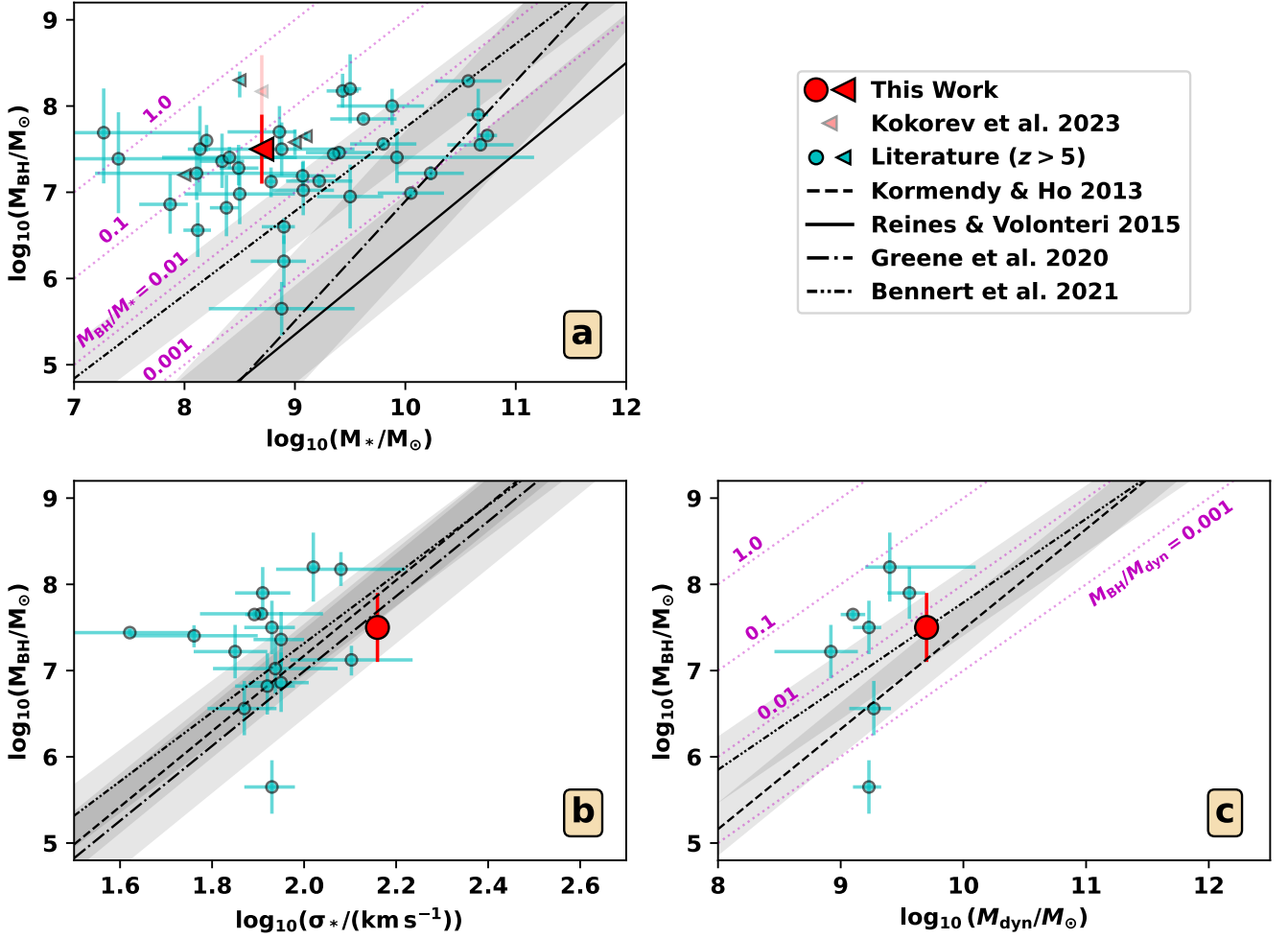


Figure 4. Placement of UNCOVER_20466 on planes of $M_{\text{BH}}-M_*$ (panel a), $M_{\text{BH}}-\sigma_*$ (panel b), and $M_{\text{BH}}-M_{\text{dyn}}$ (panel c, red point). For comparison, we include a sample of $z > 5$ AGN studied with JWST (Goulding et al. 2023; Larson et al. 2023; Übler et al. 2023; Furtak et al. 2024; Maiolino et al. 2024, 2025a; Napolitano et al. 2024; Tripodi et al. 2024a; Akins et al. 2025; D’Eugenio et al. 2025a; Juodžbalis et al. 2025a; Kiyota et al. 2025; Naidu et al. 2025a; Rinaldi et al. 2025a; Taylor et al. 2025; Zhang et al. 2025a). These values are compared to best-fit relations from local galaxies (Kormendy & Ho 2013; Reines & Volonteri 2015; Greene et al. 2020). The previous estimate of M_{BH} from Kokorev et al. (2023) is included in the $M_{\text{BH}}-M_*$ plot.

tion:

$$M_{\text{BH}}(t) = M_{\text{seed}} e^{(t-t_{\text{seed}})/0.045 \text{ Gyr}} \quad (9)$$

We use this equation to calculate three growth curves for seeds at $z = 25$: a direct collapse black hole with $M_{\text{seed}} = 10^4 M_{\odot}$, a supermassive star with $M_{\text{seed}} = 10^2 M_{\odot}$, and a seed tuned to match the observed properties of UNCOVER_20466 ($M_{\text{seed}} = 1.45 \times 10^3 M_{\odot}$).

When compared to the literature, UNCOVER_20466 is one of the highest-redshift massive black holes, lying close to other sources at $t_{\text{H}} \sim 0.5 - 0.6$ Gyr (i.e., Larson et al. 2023; Tripodi et al. 2024b; Juodžbalis et al. 2025a; Taylor et al. 2025). The black hole masses of these sources (which were also derived using Balmer line scaling relations) lie between the growth curves for the $10^2 M_{\odot}$ and $10^4 M_{\odot}$ seeds.

The application of M_{BH} scaling relations based on broad Balmer emission is limited by the maximum λ_{obs} of the data. Using the standard R100 wavelength limit of $\lambda_{\text{obs}} = 5.30 \mu\text{m}$, $\text{H}\alpha$ may only be observed up to $z < 7.07$, while $\text{H}\beta$ may be observed up to $z < 9.90$. Recent works have successfully extended the wavelength range of

JWST/NIRSpec data to $\lambda_{\text{obs}} \lesssim 5.5 \mu\text{m}$ (e.g., D’Eugenio et al. 2025a; Donnan et al. 2025; see also Dawn JWST Archive⁸ v4 NIRSpec data release), which allows for $\text{H}\alpha$ and $\text{H}\beta$ detection to higher redshifts. Balmer lines at even higher redshifts can be explored using the broad wavelength coverage of JWST/MIRI (e.g., Prieto-Jiménez et al. 2025). While lower-order Balmer lines (e.g., $\text{H}\gamma$, $\text{H}\delta$) are theoretically observable at higher redshift, their intrinsic faintness relative to $\text{H}\alpha$ and $\text{H}\beta$ make their detection difficult.

Instead, the black holes of higher-redshift galaxies may be measured in other ways. Three $z > 10$ AGN have been characterised, where two of them feature similar black hole masses to UNCOVER_20466 (Goulding et al. 2023; Napolitano et al. 2024). Due to the lack of observed Balmer lines, these masses were estimated using L_{bol} relations. In addition, both are X-ray luminous, suggesting a different nature than LRDs. Finally, the currently highest-redshift black hole (GN-z11; Maiolino et al. 2024) was estimated

⁸ <https://dawn-cph.github.io/dja/>

using a MgII scaling relation, but falls on the same growth curve as UNCOVER_20466.

5.3 Evolution of UNCOVER_20466

Here, we synthesise the previous subsections to consider the past and future evolution of UNCOVER_20466. The correlation plots of Section 5.1 show that UNCOVER_20466 features a black hole that is overmassive compared to its stellar mass, while it lies on the $M_{\text{BH}} - \sigma_*$ and $M_{\text{BH}} - M_{\text{dyn}}$ relations. Combined with the significant broad component of H β ($FWHM_{\text{B,Ba}} \sim 2500 \text{ km s}^{-1}$) and low Eddington ratio ($\sim 10\%$), this can be interpreted as evidence for rapid black hole accretion in the past (accompanied by low SFR, or small change in M_*) which has declined.

Through a comparison of the UNCOVER_20466 black hole mass to model and literature values, we find that while our M_{BH} for UNCOVER_20466 is lower than previously found (Kokorev et al. 2023), it still requires a heavy seed (i.e., $M_{\text{seed}} > 10^3 M_{\odot}$) at high redshift, assuming constant Eddington-limited accretion. Of course, a constant Eddington-limited accretion over nearly 600 Myr is not physical. The actual mass accretion rate will likely vary over time, with both sub- and super-Eddington periods (e.g., Li 2012; Hu et al. 2025; Schneider et al. 2023; Trinca et al. 2024). Regardless, the high black hole mass of UNCOVER_20466 and similar high-redshift AGN are more easily explained if they evolved from a heavy seed.

The future evolutionary track of UNCOVER_20466 is non-trivial to determine, as we only have a constraint on the mass of the black hole and limits on the stellar and warm dust components. If there is a reservoir of molecular gas, then one possibility is that the black hole accretion remains low (as evidenced by the low λ_{Edd}), while the gas is turned into stars. This would allow UNCOVER_20466 to stay on the $M_{\text{BH}} - M_{\text{dyn}}$ and $M_{\text{BH}} - \sigma_*$ relations of Figure 4c and 4b, while moving closer to the $M_{\text{BH}} - M_*$ relation of Figure 4a. However, the gas reservoir of this galaxy is not yet explored, and future ALMA observations are required. We note that the non-detection of [CII] or FIR emission in some LRDs (Xiao et al. 2025) suggests a small molecular gas reservoir. Alternatively, this system may have a substantial dark matter contribution, and later baryonic accretion may bring it closer to the local $M_{\text{BH}} - M_*$ relation (McClummont et al. 2025a).

However, the current black hole accretion rate is non-zero (i.e., $\lambda_{\text{Edd}} \sim 0.1$), so the black hole mass will increase with cosmic time. One extreme possibility is shown by the dotted line of Figure 5, which shows how M_{BH} would change with Eddington-limited accretion. This curve extends into the high-mass region of $z > 7$ QSOs (Fan et al. 2023), but a more physical sub-Eddington (or variable) growth would result in a lower mass, more similar to other observed LRDs at $z \sim 6 - 8$.

Together, we find that UNCOVER_20466 likely evolved from a heavy seed at high redshift, featured strong AGN activity in the past, and at will either evolve by $z \sim 6$ into a source similar to LRDs (assuming low or negligible black hole growth) or QSOs (assuming a high growth rate). Recent studies have found a sample of $z < 4$ galaxies with red inner regions and blue star-forming outskirts, either representing descendants of LRDs that have gained a blue envelope over time (Billand et al. 2025) or showing that LRDs may already have faint star-forming regions that are simply not detectable at high redshift (Rinaldi et al. 2025b). This represents a possible picture of UNCOVER_20466, but there are several questions that are not yet answered. First, we cannot yet constrain the formation mechanism for the ionised bubble (see discussion of Fujimoto et al. 2024) that results in a high Ly α escape fraction and equivalent width. This could

be caused by significant UV emission from young stars in the past, or by AGN activity (e.g., Witstok et al. 2024; Jiang et al. 2025). In addition, the dust geometry in the host galaxy and around the central black hole is not constrained. We also note the extremely large [OIII] $\lambda 4363$ /[OIII] $\lambda 5007$ ratio suggests either abnormally high density or temperature. UNCOVER_20466 represents one of the most extreme sources at high redshift, and requires additional observations to further constrain its properties.

6 CONCLUSIONS

In this work, we presented new JWST/NIRSpec IFU data of the $z = 8.50$ source UNCOVER_20466, taken as part of the BlackTHUNDER survey. While this source is spatially compact ($R_e \lesssim 200 \text{ pc}$), our data enable accurate spectral extraction using a PSF-defined aperture loss correction verified by comparison with JWST/NIRCam photometry. By extracting integrated spectra of both the PRISM/CLEAR and G395H/F290LP data cubes and fitting each, we are able to measure continuum and line properties, yielding constraints on the properties of this source.

- We confirm the LRD status of UNCOVER_20466, with a v-shaped continuum ($\beta_{\text{UV}} = -0.7 \pm 0.1$, $\alpha_{\text{opt}} = 1.8 \pm 0.2$) and compact morphology ($R_e = 0.23 \pm 0.03 \text{ kpc}$, based on fits to NIRCam images). Similarly to many other LRDs, this source features broad Balmer emission ($FWHM = 2503 \pm 176 \text{ km s}^{-1}$) and is FIR-faint (e.g., Casey et al. 2025; Fujimoto et al. 2025).

- The best-fit Balmer decrements are in agreement with the intrinsic values, suggesting negligible dust attenuation. The previous detection of higher attenuation ($A_V \sim 2$; Kokorev et al. 2023) is discussed, including possible reasons for the disagreement with our fiducial values of $A_V \sim 0$.

- The broad H β emission and underlying continuum was used to constrain the black hole properties ($M_{\text{BH}} \sim 10^{7.5-7.6} M_{\odot}$, $\lambda_{\text{Edd}} \sim 10\%$), which are slightly lower than previous estimates ($< 2\sigma$ discrepant). Using an upper limit on M_* from literature, we confirm that UNCOVER_20466 features an overmassive black hole.

- Our observed line ratios are combined with empirical relations and PYNEB to explore the properties of the host galaxy or gaseous envelope. We find a low [OII] $\lambda 3727$ /[OII] $\lambda 3729$ ratio and a high [OIII] $\lambda 4363$ /[OIII] $\lambda 5007$ ratio, which could be explained by a multi-phase ISM (i.e., diffuse gas and dense gas) or an exceptionally high temperature ($T_e \gtrsim 10^5 \text{ K}$). Other line ratios reveal a low gas-phase metallicity of 0.12 ± 0.02 solar (from high-redshift line ratio calibrations) and a high ionisation parameter of $\log_{10}(U) = -1.3 \pm 0.3$. While the applicability of these relations to high-redshift LRDs is not proven, this low-metallicity, high-ionisation, extreme environment aligns with the compact AGN nature of this source.

- By leveraging an extensive grid of photoionization models, we have found that the extremely high [OIII] $\lambda 4363$ /H γ ratio indicates that the gas in the host galaxy is not only ionized and over-heated by the AGN, but it also requires extremely high densities, of about 10^7 cm^{-3} . Together with the very high redshift at which this object is found (being the second most distant LRD), this finding is suggestive of a black hole that is forming in an ultradense protogalaxy in the early Universe.

- Ly α emission is significantly detected, and is used to estimate an escape fraction of $f_{\text{esc}}^{\text{Ly}\alpha} \sim 30\%$. This places UNCOVER_20466 on existing correlations of $EW_{0,\text{Ly}\alpha} - f_{\text{esc}}^{\text{Ly}\alpha}$ and $EW_{0,\text{Ly}\alpha} - M_{\text{UV}}$.

- While UNCOVER_20466 features an overmassive black hole, we find that it lies on local correlations of $M_{\text{BH}} - \sigma_*$ and $M_{\text{BH}} - M_{\text{dyn}}$.

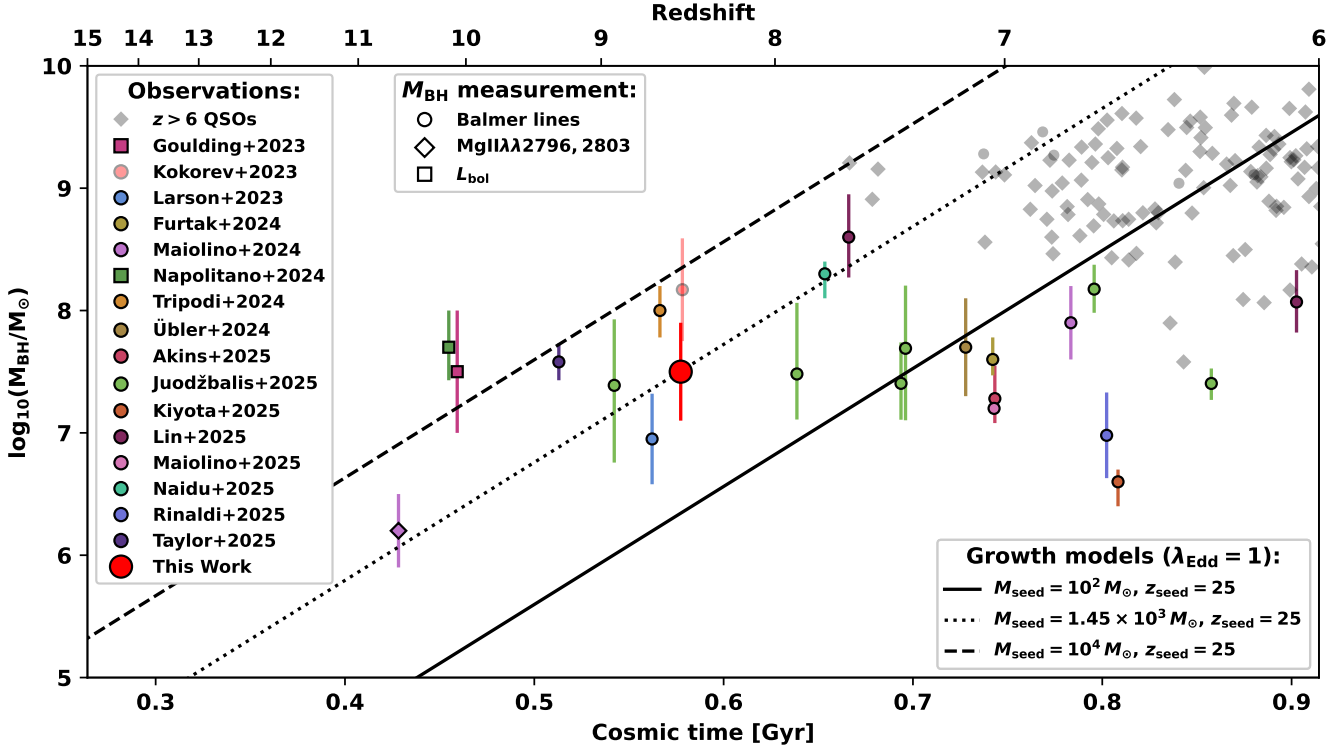


Figure 5. Distribution of black hole masses as a function of cosmic time. Our derived mass for UNCOVER_20466 is shown by a large red circle, while a faint circle shows the previously determined value of Kokorev et al. (2023). We include a collection of $z > 6$ QSOs (Fan et al. 2023; Marshall et al. 2023, 2024; Onoue et al. 2025) and AGN observed by JWST (Goulding et al. 2023; Larson et al. 2023; Furtak et al. 2024; Maiolino et al. 2024, 2025a; Napolitano et al. 2024; Tripodi et al. 2024a; Übler et al. 2024; Akins et al. 2025; Juodžbalis et al. 2025a; Kiyota et al. 2025; Lin et al. 2025a; Naidu et al. 2025a; Rinaldi et al. 2025a; Taylor et al. 2025) for comparison. Galaxies where M_{BH} was found through Balmer line (i.e., $\text{H}\alpha$ or $\text{H}\beta$) scaling relations are shown by circles, while diamonds show where $\text{MgII}\lambda\lambda 2796, 2803$ scaling relations were used, and studies that used bolometric luminosity scaling relations are shown as squares. Three simple growth models with different seed masses assuming a seeding redshift of 25 and constant Eddington-limited accretion are plotted as black lines.

Since these correlations were primarily determined using the properties of local bulges, the observable emission of UNCOVER_20466 may represent the progenitor of the central bulge of a lower-redshift galaxy.

- We compare the black hole mass of UNCOVER_20466 to other $z > 6$ AGN. While our new M_{BH} is lower than previous estimates, we find that it is still one of the highest-redshift and most massive black holes. Using a set of growth tracks assuming Eddington-limited accretion, we show that this source would likely require a heavy seed ($M_{\text{seed}} \gtrsim 10^3$ assuming $z_{\text{seed}} \sim 25$).

- The combination of properties is synthesised to predict the history and future evolution of this source. One possibility is that UNCOVER_20466 underwent a period of rapid black hole accretion in the recent past (which increased M_{BH} and σ_* of the host galaxy) which has now ended (as evidenced by the low λ_{Edd}). Depending on future accretion, it may evolve into a black hole similar to those of QSOs (high accretion) or LRDs (negligible accretion) at $z \sim 6$.

Our data show that UNCOVER_20466 is an exceptional source in the early Universe, with typical LRD properties, an overmassive black hole, evidence for a large ionised bubble, and extreme ISM conditions. Additional observations at different wavelengths (e.g., JWST/MIRI, ALMA [CII]158 μm) will help to reveal the complex nature of this source.

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DATA AVAILABILITY

The NIRSpec data used in this research was obtained within the NIRSpec-IFU GO programme ‘Unveiling the nature and impact of the first population of black holes: an extensive NIRSpec-IFU survey in the first billion years’ (PID 5015) and is publicly available. Data presented in this work will be shared upon reasonable request to the corresponding author.

REFERENCES

- Abuter R., et al., 2024, *Nature*, **627**, 281
- Akins H. B., et al., 2025, *ApJ*, **980**, L29
- Ananna T. T., Bogdán Á., Kovács O. E., Natarajan P., Hickox R. C., 2024, *ApJ*, **969**, L18
- Arribas S., et al., 2024, *A&A*, **688**, A146
- Baggen J. F. W., et al., 2024, *ApJ*, **977**, L13
- Baldwin J. A., Phillips M. M., Terlevich R., 1981, *PASP*, **93**, 5
- Baskin A., Laor A., 2005, *MNRAS*, **358**, 1043
- Begelman M. C., Dexter J., 2025, *arXiv e-prints*, p. [arXiv:2507.09085](#)
- Begley R., et al., 2024, *MNRAS*, **527**, 4040
- Bennert V. N., et al., 2021, *ApJ*, **921**, 36
- Bezanson R., et al., 2018, *ApJ*, **858**, 60
- Bezanson R., et al., 2024, *ApJ*, **974**, 92
- Billand J.-B., et al., 2025, *arXiv e-prints*, p. [arXiv:2507.04011](#)
- Bradley L., et al., 2021, *astropy/photutils*: 1.1.0, [doi:10.5281/zenodo.4624996](#)
- Brazzini M., D’Eugenio F., Maiolino R., Juodžbalis I., Ji X., Scholtz J., 2025, *arXiv e-prints*, p. [arXiv:2507.08929](#)
- Bunker A. J., et al., 2024, *A&A*, **690**, A288
- Bushouse H., et al., 2025, JWST Calibration Pipeline, [doi:10.5281/zenodo.6984365](#)
- Byrne C. M., Stanway E. R., Eldridge J. J., McSwiney L., Townsend O. T., 2022, *MNRAS*, **512**, 5329
- Calzetti D., Armus L., Bohlin R. C., Kinney A. L., Koornneef J., Storchi-Bergmann T., 2000, *ApJ*, **533**, 682
- Cameron A. J., et al., 2023, *A&A*, **677**, A115
- Cameron A. J., Katz H., Witten C., Saxena A., Laporte N., Bunker A. J., 2024, *MNRAS*, **534**, 523
- Cappellari M., et al., 2006, *MNRAS*, **366**, 1126
- Carniani S., et al., 2019, *MNRAS*, **489**, 3939
- Carniani S., et al., 2024, *Nature*, **633**, 318
- Carranza-Escudero M., et al., 2025, *ApJ*, **989**, L50
- Casey C. M., et al., 2025, *arXiv e-prints*, p. [arXiv:2505.18873](#)
- Cataldi E., et al., 2025, *arXiv e-prints*, p. [arXiv:2504.03839](#)
- Ceci M., et al., 2025, *arXiv e-prints*, p. [arXiv:2507.08077](#)
- Choustikov N., Stiskalek R., Saxena A., Katz H., Devriendt J., Slyz A., Sub-department of Astrophysics U. o. O., 2025, *MNRAS*, **537**, 2273
- Cullen F., et al., 2025, *MNRAS*, **540**, 2176
- Curti M., Mannucci F., Cresci G., Maiolino R., 2020, *MNRAS*, **491**, 944
- Curti M., et al., 2023, *MNRAS*, **518**, 425
- Curti M., et al., 2025, *A&A*, **697**, A89
- Curtis-Lake E., et al., 2023, *Nature Astronomy*, **7**, 622
- de Graaff A., et al., 2025, *arXiv e-prints*, p. [arXiv:2503.16600](#)
- D’Eugenio F., et al., 2024, *Nature Astronomy*, **8**, 1443
- D’Eugenio F., et al., 2025a, *arXiv e-prints*, p. [arXiv:2503.11752](#)
- D’Eugenio F., et al., 2025b, *arXiv e-prints*, p. [arXiv:2506.14870](#)
- D’Eugenio F., et al., 2025c, *ApJS*, **277**, 4
- Donnan C. T., et al., 2024, *MNRAS*, **533**, 3222
- Donnan C. T., et al., 2025, *arXiv e-prints*, p. [arXiv:2507.10518](#)
- Dumont A., et al., 2025, *arXiv e-prints*, p. [arXiv:2503.09697](#)
- Endsley R., et al., 2022, *MNRAS*, **517**, 5642
- Endsley R., et al., 2024, *MNRAS*, **533**, 1111
- Fabian A. C., 2012, *ARA&A*, **50**, 455
- Fan X., Bañados E., Simcoe R. A., 2023, *ARA&A*, **61**, 373
- Feng W.-X., Yu H.-B., Zhong Y.-M., 2025, *arXiv e-prints*, p. [arXiv:2506.17641](#)
- Ferland G. J., 1993, *Hazy, A Brief Introduction to Cloudy* 84
- Ferland G. J., et al., 2017, *Rev. Mex. Astron. Astrofis.*, **53**, 385
- Fruchter A. S., Hook R. N., 2002, *PASP*, **114**, 144
- Fujimoto S., et al., 2024, *ApJ*, **977**, 250
- Fujimoto S., et al., 2025, *ApJS*, **278**, 45
- Fuller S., et al., 2020, *ApJ*, **896**, 156
- Furtak L. J., et al., 2023a, *MNRAS*, **523**, 4568
- Furtak L. J., et al., 2023b, *ApJ*, **952**, 142
- Furtak L. J., et al., 2024, *Nature*, **628**, 57
- Furtak L. J., et al., 2025, *A&A*, **698**, A227
- Ginolfi M., et al., 2020, *A&A*, **633**, A90
- Goovaerts I., Thai T. T., Pello R., Tuan-Anh P., Laporte N., Matthee J., Nanayakkara T., Pharo J., 2024, *A&A*, **690**, A302
- Gordon K. D., Clayton G. C., Misselt K. A., Landolt A. U., Wolff M. J., 2003, *ApJ*, **594**, 279
- Goulding A. D., et al., 2023, *ApJ*, **955**, L24
- Greene J. E., Ho L. C., 2005, *ApJ*, **630**, 122
- Greene J. E., Strader J., Ho L. C., 2020, *ARA&A*, **58**, 257
- Greene J. E., et al., 2024, *ApJ*, **964**, 39
- Hainline K. N., et al., 2024, *ApJ*, **975**, 31
- Hainline K. N., et al., 2025, *ApJ*, **979**, 138
- Harikane Y., et al., 2025, *arXiv e-prints*, p. [arXiv:2505.09186](#)
- Hoag A., et al., 2019, *ApJ*, **878**, 12
- Hu H., Inayoshi K., Haiman Z., Ho L. C., Ohsuga K., 2025, *ApJ*, **983**, L37
- Husemann B., Wisotzki L., Sánchez S. F., Jahnke K., 2013, *A&A*, **549**, A43
- Husemann B., Jahnke K., Sánchez S. F., Wisotzki L., Nugroho D., Kupko D., Schramm M., 2014, *MNRAS*, **443**, 755
- Hviding R. E., et al., 2025, *arXiv e-prints*, p. [arXiv:2506.05459](#)
- Inayoshi K., 2025, *ApJ*, **988**, L22
- Inayoshi K., Shangguan J., Chen X., Ho L. C., Haiman Z., 2025, *arXiv e-prints*, p. [arXiv:2505.05322](#)
- Isobe Y., Ouchi M., Nakajima K., Harikane Y., Ono Y., Xu Y., Zhang Y., Umeda H., 2023, *ApJ*, **956**, 139
- Isobe Y., et al., 2025, *MNRAS*, **541**, L71
- Izotov Y. I., Schaerer D., Worseck G., Verhamme A., Guseva N. G., Thuan T. X., Orlitová I., Fricke K. J., 2020, *MNRAS*, **491**, 468
- Ji X., et al., 2024, *MNRAS*, **535**, 881
- Ji X., et al., 2025a, *arXiv e-prints*, p. [arXiv:2501.13082](#)
- Ji X., et al., 2025b, *MNRAS*, **541**, 2134
- Jiang D., Jiang L., Sun S., Liu W., Fu S., 2025, *arXiv e-prints*, p. [arXiv:2502.03683](#)
- Jockel C., Kawaguchi K., Fujibayashi S., Shibata M., 2025, *arXiv e-prints*, p. [arXiv:2507.15556](#)
- Jones G. C., et al., 2024, *A&A*, **683**, A238
- Jones G. C., et al., 2025a, *MNRAS*, **536**, 2355
- Jones G. C., et al., 2025b, *MNRAS*, **540**, 3311
- Jung I., et al., 2022, *arXiv e-prints*, p. [arXiv:2212.09850](#)
- Juodžbalis I., et al., 2024, *Nature*, **636**, 594
- Juodžbalis I., et al., 2025a, *arXiv e-prints*, p. [arXiv:2504.03551](#)
- Juodžbalis I., et al., 2025b, *arXiv e-prints*, p. [arXiv:2508.21748](#)
- Katz H., et al., 2023, *MNRAS*, **518**, 592
- Kido D., Ioka K., Hotokezaka K., Inayoshi K., Irwin C. M., 2025, *arXiv e-prints*, p. [arXiv:2505.06965](#)
- Kiyota T., et al., 2025, *arXiv e-prints*, p. [arXiv:2504.03156](#)
- Kocevski D. D., et al., 2025, *ApJ*, **986**, 126
- Kokorev V., et al., 2023, *ApJ*, **957**, L7
- Kormendy J., Ho L. C., 2013, *ARA&A*, **51**, 511
- Kroupa P., 2001, *MNRAS*, **322**, 231
- Kuruvanthodi A., Schaerer D., Marques-Chaves R., Korber D., Weibel A., Oesch P. A., Roberts-Borsani G., 2024, *A&A*, **691**, A310

- Labbe I., et al., 2025, *ApJ*, 978, 92
- Lambrides E., et al., 2025, *arXiv e-prints*, p. [arXiv:2509.09607](#)
- Langeroodi D., Hjorth J., 2023, *ApJ*, 957, L27
- Larson R. L., et al., 2023, *ApJ*, 953, L29
- Laseter I. H., et al., 2024, *A&A*, 681, A70
- Leung G. C. K., et al., 2024, *arXiv e-prints*, p. [arXiv:2411.12005](#)
- Li L.-X., 2012, *MNRAS*, 424, 1461
- Li S., et al., 2025a, *ApJ*, 979, L13
- Li Z., Inayoshi K., Chen K., Ichikawa K., Ho L. C., 2025b, *ApJ*, 980, 36
- Lin X., et al., 2025a, *arXiv e-prints*, p. [arXiv:2504.08039](#)
- Lin X., et al., 2025b, *arXiv e-prints*, p. [arXiv:2507.10659](#)
- Liu H., Jiang Y.-F., Quataert E., Greene J. E., Ma Y., 2025, *arXiv e-prints*, p. [arXiv:2507.07190](#)
- Luridiana V., Morisset C., Shaw R. A., 2015, *A&A*, 573, A42
- Maiolino R., et al., 2024, *A&A*, 691, A145
- Maiolino R., et al., 2025a, *arXiv e-prints*, p. [arXiv:2505.22567](#)
- Maiolino R., et al., 2025b, *MNRAS*, 538, 1921
- Marconcini C., et al., 2024, *MNRAS*, 533, 2488
- Marconi A., et al., 2024, *A&A*, 689, A78
- Marshall M. A., et al., 2023, *A&A*, 678, A191
- Marshall M. A., et al., 2024, *arXiv e-prints*, p. [arXiv:2410.11035](#)
- Marshall M. A., et al., 2025, *arXiv e-prints*, p. [arXiv:2502.20550](#)
- Mascia S., et al., 2023, *A&A*, 672, A155
- Matthee J., et al., 2024, *ApJ*, 963, 129
- Mazzolari G., et al., 2024, *A&A*, 691, A345
- Mazzolari G., et al., 2025, *A&A*, 700, A12
- McClymont W., et al., 2025a, *arXiv e-prints*, p. [arXiv:2506.13852](#)
- McClymont W., et al., 2025b, *MNRAS*, 540, 190
- Morisset C., et al., 2016, *A&A*, 594, A37
- Naidu R. P., et al., 2025a, *arXiv e-prints*, p. [arXiv:2503.16596](#)
- Naidu R. P., et al., 2025b, *arXiv e-prints*, p. [arXiv:2505.11263](#)
- Nakajima K., Ouchi M., 2014, *MNRAS*, 442, 900
- Nakajima K., Ouchi M., Isobe Y., Harikane Y., Zhang Y., Ono Y., Umeda H., Oguri M., 2023, *ApJS*, 269, 33
- Nandal D., Loeb A., 2025, *arXiv e-prints*, p. [arXiv:2507.12618](#)
- Napolitano L., et al., 2024, *arXiv e-prints*, p. [arXiv:2410.18763](#)
- Natarajan P., Pacucci F., Ricarte A., Bogdán Á., Goulding A. D., Cappelluti N., 2024, *ApJ*, 960, L1
- Newville M., Stensitzki T., Allen D. B., Ingargiola A., 2014, LMFIT: Non-Linear Least-Square Minimization and Curve-Fitting for Python, [doi:10.5281/zenodo.11813](#)
- Ono Y., et al., 2012, *ApJ*, 744, 83
- Onoue M., et al., 2025, *Nature Astronomy*,
- Orozco E. A., Jiménez-Andrade E. F., Murphy E. J., Smail I., Momjian E., Heywood I., Vega-Gutierrez M., DeCoursey C., 2025, *arXiv e-prints*, p. [arXiv:2506.20634](#)
- Pasha I., Miller T. B., 2023, *The Journal of Open Source Software*, 8, 5703
- Pentericci L., et al., 2018, *A&A*, 619, A147
- Pérez-González P. G., et al., 2025, *Nature Astronomy*,
- Perna M., et al., 2023, *A&A*, 679, A89
- Perrin M. D., Long J., Sivaramakrishnan A., Lajoie C.-P., Elliot E., Pueyo L., Albert L., 2015, WebbPSF: James Webb Space Telescope PSF Simulation Tool, Astrophysics Source Code Library, record ascl:1504.007
- Pirzkal N., et al., 2024, *ApJ*, 969, 90
- Pollock C. L., et al., 2025, *arXiv e-prints*, p. [arXiv:2506.15779](#)
- Price S. H., et al., 2025, *ApJ*, 982, 51
- Prieto-Jiménez C., et al., 2025, *A&A*, 701, A31
- Reines A. E., Volonteri M., 2015, *ApJ*, 813, 82
- Rinaldi P., et al., 2025a, *arXiv e-prints*, p. [arXiv:2504.01852](#)
- Rinaldi P., et al., 2025b, *arXiv e-prints*, p. [arXiv:2507.17738](#)
- Roberts M. G., Braff L., Garg A., Profumo S., Jeltama T., 2025, *arXiv e-prints*, p. [arXiv:2507.03230](#)
- Robertson B., et al., 2024, *ApJ*, 970, 31
- Ronayne K., et al., 2025, *arXiv e-prints*, p. [arXiv:2508.20177](#)
- Roy N., et al., 2023, *ApJ*, 952, L14
- Rusakov V., et al., 2025, *arXiv e-prints*, p. [arXiv:2503.16595](#)
- Sacchi A., Bogdán Á., 2025, *ApJ*, 989, L30
- Sanders R. L., Shapley A. E., Topping M. W., Reddy N. A., Brammer G. B., 2024, *ApJ*, 962, 24
- Saxena A., et al., 2024, *A&A*, 684, A84
- Scarlata C., Hayes M., Panagia N., Mehta V., Haardt F., Bagley M., 2024, *arXiv e-prints*, p. [arXiv:2404.09015](#)
- Schaerer D., Marques-Chaves R., Barrufet L., Oesch P., Izotov Y. I., Naidu R., Guseva N. G., Brammer G., 2022, *A&A*, 665, L4
- Schenker M. A., Stark D. P., Ellis R. S., Robertson B. E., Dunlop J. S., McLure R. J., Kneib J.-P., Richard J., 2012, *ApJ*, 744, 179
- Schneider R., Valiante R., Trinca A., Graziani L., Volonteri M., Maiolino R., 2023, *MNRAS*, 526, 3250
- Scholtz J., et al., 2025, *MNRAS*, 539, 2463
- Setton D. J., et al., 2024, *arXiv e-prints*, p. [arXiv:2411.03424](#)
- Setton D. J., et al., 2025, *arXiv e-prints*, p. [arXiv:2503.02059](#)
- Shen Y., et al., 2015, *ApJ*, 805, 96
- Simmonds C., et al., 2024, *MNRAS*, 535, 2998
- Song M., Finkelstein S. L., Livermore R. C., Capak P. L., Dickinson M., Fontana A., 2016, *ApJ*, 826, 113
- Stanway E. R., Eldridge J. J., 2018, *MNRAS*, 479, 75
- Stark D. P., Ellis R. S., Chiu K., Ouchi M., Bunker A., 2010, *MNRAS*, 408, 1628
- Stern J., Laor A., 2012, *MNRAS*, 423, 600
- Suess K. A., et al., 2024, *ApJ*, 976, 101
- Sun B., Yan H., 2025, *arXiv e-prints*, p. [arXiv:2503.21896](#)
- Tacchella S., et al., 2025, *MNRAS*, 540, 851
- Tang M., et al., 2023, *MNRAS*, 526, 1657
- Tang M., et al., 2025, *arXiv e-prints*, p. [arXiv:2505.06359](#)
- Taylor A. J., et al., 2025, *ApJ*, 989, L7
- Tilvi V., et al., 2020, *ApJ*, 891, L10
- Topping M. W., et al., 2024, *MNRAS*, 529, 3301
- Trefoloni B., et al., 2025, *A&A*, 700, A203
- Trinca A., et al., 2024, *arXiv e-prints*, p. [arXiv:2412.14248](#)
- Tripodi R., et al., 2024a, *arXiv e-prints*, p. [arXiv:2412.04983](#)
- Tripodi R., et al., 2024b, *A&A*, 692, A184
- Übler H., et al., 2023, *A&A*, 677, A145
- Übler H., et al., 2024, *MNRAS*, 531, 355
- Usui M., et al., 2025, *arXiv e-prints*, p. [arXiv:2507.02054](#)
- van der Wel A., et al., 2022, *ApJ*, 936, 9
- Vanzella E., et al., 2011, *ApJ*, 730, L35
- Veilleux S., Osterbrock D. E., 1987, *ApJS*, 63, 295
- Venturi G., et al., 2024, *A&A*, 691, A19
- Vestergaard M., Peterson B. M., 2006, *ApJ*, 641, 689
- Vikaeus A., et al., 2024, *MNRAS*, 529, 1299
- Wang B., et al., 2024, *ApJ*, 969, L13
- Wang B., et al., 2025, *ApJ*, 984, 121
- Whitler L., et al., 2025, *arXiv e-prints*, p. [arXiv:2501.00984](#)
- Willott C. J., et al., 2025, *ApJ*, 988, 26
- Witstok J., Jones G. C., Maiolino R., Smit R., Schneider R., 2023, *MNRAS*, 523, 3119
- Witstok J., et al., 2024, *A&A*, 682, A40
- Witstok J., et al., 2025, *Nature*, 639, 897
- Xiao M., et al., 2025, *A&A*, 700, A21
- Yang H., et al., 2017, *ApJ*, 844, 171
- Yeh S. C. C., Matzner C. D., 2012, *ApJ*, 757, 108
- Yue M., Eilers A.-C., Ananna T. T., Panagiotou C., Kara E., Miyaji T., 2024, *ApJ*, 974, L26
- Zamora S., et al., 2024, *arXiv e-prints*, p. [arXiv:2412.02751](#)
- Zhang H., Behroozi P., Volonteri M., Silk J., Fan X., Hopkins P. F., Yang J., Aird J., 2023, *MNRAS*, 518, 2123
- Zhang J., et al., 2025a, *arXiv e-prints*, p. [arXiv:2505.02895](#)
- Zhang H., et al., 2025b, *MNRAS*, 538, 503

APPENDIX A: JWST/NIRCAM FILTERS

UNCOVER_20466 benefits from a wealth of JWST/NIRCam imaging from two programs (see Section 2.2). We use a subset of these

Filter	PID	λ_{pivot} [μm]	$\text{FWHM}_{\text{PSF,emp}}$ ['']
F335M	4111	3.362	0.111
F356W†	2561	3.565	0.116
F360M	4111	3.623	0.120
F410M†	2561	4.083	0.137
F430M	4111	4.281	0.144
F444W†	2561	4.402	0.145
F460M†	4111	4.630	0.157
F480M†	4111	4.817	0.164

Table A1. Details of JWST/NIRCam filters used in this work. †Fit with PYSERVIC to find morphological properties (Section 4.6).

images to test the flux calibration of our data (Section C4), and to extract morphological properties of UNCOVER_20466 (Section 4.6). The filters of use are listed in Table A1, along with their program of origin, pivot wavelength⁹, and empirical PSF FWHM¹⁰ in Table A1.

APPENDIX B: SERENDIPITOUS SOURCE

Despite the small field of view of our NIRSpec IFU data ($\sim 3.6'' \times 3.8''$ due to dithering and drizzling), we also find a serendipitous line-emitting source which we name ‘BlackBolt-1’ (inspired by the theme of ‘BlackTHUNDER’). This source lies on the edge of the field of view, $\sim 2.2''$ to the north-west of UNCOVER_20466 (i.e., at 00:14:33.614 -30:23:09.4467). This location places it within $0.2''$ of an object in the ‘Medium Bands, Mega Science’ data release¹¹ (ID 21646; Suess et al. 2024) which has $z_{\text{phot}} = 6.68^{+0.03}_{-0.04}$ based on the JWST/NIRCam photometry.

Because of its location, we are not currently able to present a well-calibrated spectrum (i.e., some data are excluded due to high noise levels, and the PSF is not well determined). However, by extracting a spectrum from the R100 cube centred on this location using a circular aperture of radius $0.14''$, we may determine its spectroscopic redshift.

As seen in Figure B1, BlackBolt-1 features at least four strong line detections. We use these lines to identify the redshift to be $z_{\text{spec}} = 5.511$, based on the identification of the [OIII]-H β complex and H α , as well as the Ly α break.

Since this source is at a much lower redshift than our target, it is observed at a very different epoch (i.e., ~ 1.0 Gyr after the Big Bang, rather than ~ 0.58 Gyr for UNCOVER_20466). With this in mind, we do not include BlackBolt-1 in our analysis, but note that further analysis may be performed in a future work.

APPENDIX C: DETAILS OF APERTURE LOSS CORRECTION

When analysing the integrated spectra of UNCOVER_20466, we choose an extraction aperture of radius $0.125''$ in order to maximise the S/N of [OIII] $\lambda 5007$. This aperture captures most of the emission from this compact object, but some emission from the wings of the

PSF is missed. This fraction of missed flux is not constant, as the NIRSpec IFU PSF size changes with wavelength. In order to recover the total flux, an aperture loss correction is required (see similar analyses for NIRSpec IFU data in Arribas et al. 2024; Zamora et al. 2024). In this Appendix, we detail how we calculate wavelength-dependent aperture loss corrections for our extracted spectra.

C1 NIRSpec IFU PSF derivation

We begin by analysing the shape of the NIRSpec IFU PSF. An in-depth characterisation of the NIRSpec PSF was performed by D’Eugenio et al. (2024). This work found a strong evolution of the PSF FWHM with wavelength, as well as a significant difference in the PSF width across and along the NIRSpec slice directions (up to $\sim 40\%$). Although three approaches were utilised, no concrete PSF shape was found. The results of this work were adopted by many other NIRSpec/IFU studies (e.g., Marconcini et al. 2024; Venturi et al. 2024). To verify these results, we analyse archival observations of calibration stars, and compare the results to empirical models.

Observations of stars were included in programs in order to calibrate the PSF of NIRSpec (PSFSTARUHSJ0439 in PID 1222, PI C. J. Willott; PSFSTARULASJ1342 in PID 1219, PI N. Luetzgendorf). Additionally, we consider the calibration data of PID 1537 (PI: K. D. Gordon), who observed the white dwarf G191-B2B with the JWST/NIRSpec IFU with all three R1000 gratings and all three R2700 gratings. For all of these observations, we downloaded the calibrated (stage 3) data cubes from the MAST archive and fit the stellar emission in each spectral channel of each cube with a 2D Gaussian model. The geometric mean of the best-fit semi-major axes were recorded, resulting in curves of PSF FWHM as a function of wavelength.

The resulting curves are shown in Figure C1. Because the data of G191-B2B features significant oscillations in FWHM (‘wiggles’, see Perna et al. 2023; Dumont et al. 2025), we fit a third-order polynomial to each of the curves for this source. For comparison, we also display results from D’Eugenio et al. (2024) (methods II and III), and the FWHM values derived from QSO observations (Marshall et al. 2023, 2025) using the code QDEBLEND3D (Husemann et al. 2013, 2014).

It is clear that the curves of D’Eugenio et al. (2024) fall beneath those of the calibration star observations. This could be due to the fact that the serendipitous source studied by D’Eugenio et al. (2024) fell on the edge of the field of view rather than the pointing centre. Indeed, their analysis of a separate stellar observation (Method I) resulted in a larger PSF, in better agreement with the stars studied here.

Our star-based curves are in good agreement over most wavelengths, with the exception of PSFSTARULASJ1342 and PSFSTARUHSJ0439 between $\lambda_{\text{obs}} \sim 1.0 - 1.9 \mu\text{m}$. This may be due to saturation of the NIRSpec detector, which would result in a non-Gaussian source and thus an inflated FWHM.

Finally, we compare all of our approaches to the empirical curve outputted by STPSF¹², the successor to WEBBPSF (Perrin et al. 2015). This code takes many properties of the NIRSpec instrument into account (e.g., geometric distortion, detector charge transfer effects), resulting in physical models of the wavelength dependence of the PSF. The resulting PSF FWHM curve is in agreement with the results of calibration star observations, so we will use this model (hereafter referred to as the fiducial PSF) for our analyses.

⁹ Pivot wavelength taken from JDOX: <https://jwst-docs.stsci.edu/jwst-near-infrared-camera/nircam-instrumentation/nircam-filters>

¹⁰ NIRSpec PSFs taken from JDOX: <https://jwst-docs.stsci.edu/jwst-near-infrared-camera/nircam-performance/nircam-point-spread-functions>

¹¹ <https://jwst-uncover.github.io/DR3.html>

¹² <https://stpsf.readthedocs.io/en/latest/>

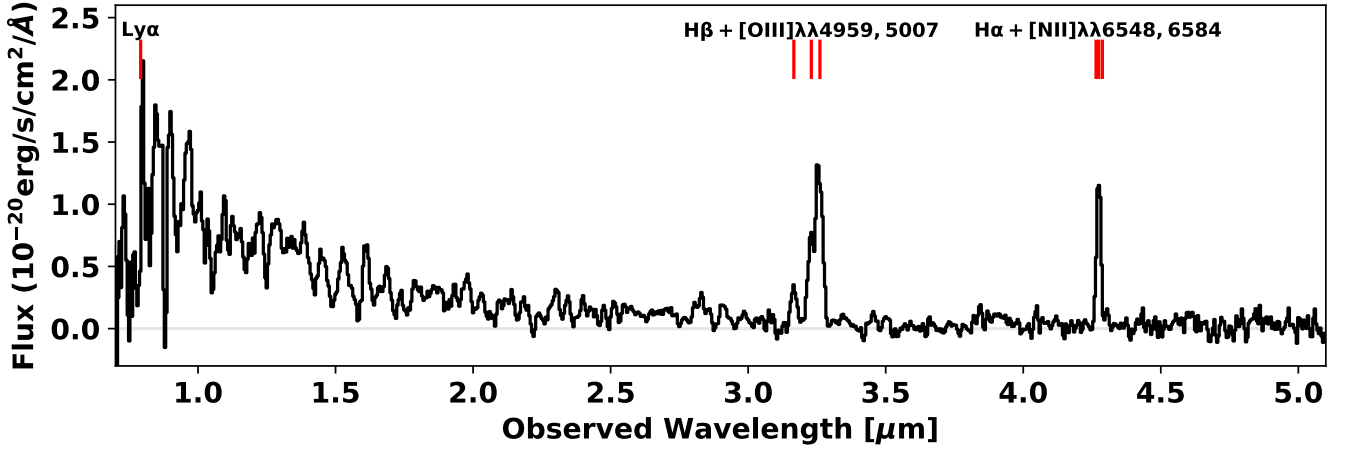


Figure B1. Integrated spectrum for a serendipitous source identified within the field of view (BlackBolt-1), extracted from 00:14:33.614 -30:23:09.4467 using a circular aperture of radius 0.14'' from the R100 cube. No corrections have been applied, and the line fluxes are affected by noise artifacts due to its location on the edge of the data cube. Despite this, we identify the spectroscopic redshift of $z_{\text{spec}} = 5.511$ based on several line detections.

C2 Comparison with observed curve of growth

While this fiducial PSF is in good agreement with the shapes of observed point sources, we note that Appendix C1 and other works (e.g., D'Eugenio et al. 2024) used a two-dimensional Gaussian to model the PSF. In reality, the JWST/NIRSpec PSF is more complex, with a bright core and a fainter six-pointed ‘snowflake’ pattern of maxima and minima. While a 2D Gaussian model can describe the dominant central emission, the lower-level emission deviates from this axisymmetric model. We explore this by creating curves of growth (CoGs) for the observed [OIII] λ 5007 emission in the R100 cube, our best-fit 2D Gaussian model to the PSF, and the fiducial PSF. The slope of these CoGs are directly related to the density of flux: a bright core will result in a rapid rise, while diffuse emission will create a more shallow increase.

To create the [OIII] λ 5007 CoG, we extracted spectra using circular apertures centred on UNCOVER_20466 with a range of radii (0.025'' – 0.500''), isolated the wavelength range around [OIII] λ 5007, fit the continuum and line emission in the resulting spectrum, and recorded the best-fit line flux for each aperture. The resulting CoG is shown as a red line in Figure C2. In order to create a similar CoG for the fiducial PSF of Section C1, we integrate the PSF within a range of apertures and normalise each flux to the value in the largest aperture ($r = 0.5''$; see magenta line with circular markers in Figure C2). Finally, we create CoGs for 2D Gaussian models with the same FWHM as the fiducial model, assuming a circular model ($q = 1.0$) and an elongated model ($q = 0.5$).

From this analysis, we see that all of the CoGs agree at small radii ($r \lesssim 0.125''$) and large radii ($r \gtrsim 0.4''$), but the 2D Gaussian model of the PSF deviates at intermediate radii ($0.125'' \lesssim r \lesssim 0.400''$). This behaviour indicates diffuse emission in the PSF that is not present in the 2D Gaussian model. Because the full PSF follows the observed CoG more closely, we will use this fiducial PSF rather than a Gaussian approximation.

C3 Aperture loss correction

We have now characterised the wavelength-dependent FWHM of the NIRSpec IFU PSF, and tested this model on our observations. The remaining step is to derive the aperture loss correction curve for our

adopted aperture ($r = 0.125''$). This is done by numerically integrating the full corresponding PSF and dividing by the value within the aperture. The resulting correction as a function of wavelength is shown in Figure C3.

C4 Comparison to NIRCам data

While this empirical model is a good match to observations of stars, it is not yet thoroughly tested on observational data of high-redshift galaxies, and thus may not be accurate. To validate this correction, we conduct a comparison of our R100 NIRSpec spectrum and archival JWST/NIRCам photometry of UNCOVER_20466.

First, we extract fluxes from each NIRCам image by fitting each with a 2D circular Gaussian model with a constant offset (to account for background emission), where the FWHM of the model is set to be the fiducial FWHM from JDOX (see Table A1). In order to compare these photometric points to the NIRSpec data directly, we first convolve the R100 cube with the throughput curve of each NIRCам filter to create a set of pseudo-photometric images, and measure the flux using a circular aperture of $r = 0.125''$. We apply the aperture loss correction derived in Appendix C3 to the NIRSpec fluxes, and compare the resulting values in Figure C4. We limit the comparison to NIRCам filters at $\lambda_{\text{obs}} > 3 \mu\text{m}$ due to elevated noise on the red side of the NIRSpec data. The resulting fluxes are comparable.

C5 Note on variability

By comparing JWST/NIRSpec MSA and IFU data taken at different times, Ji et al. (2025a) found that Abell2744-QSO1 featured significant variability. This analysis benefitted from the gravitationally lensed nature of the source: each of the three lensed images represented a different light travel time. Thus, they were able to show that $H\beta$ rest-frame equivalent width decreased by $\sim 50\%$ over an observer-frame time of ~ 20 yr.

While UNCOVER_20466 is not multiply lensed, it is possible that we could use the different data to explore the variability of this source. This is because of the different observation times: the NIRCам data were taken in two epochs (2 November 2022 for PID 2561, 11 November 2023 for PID 4111), while the JWST/NIRSpec

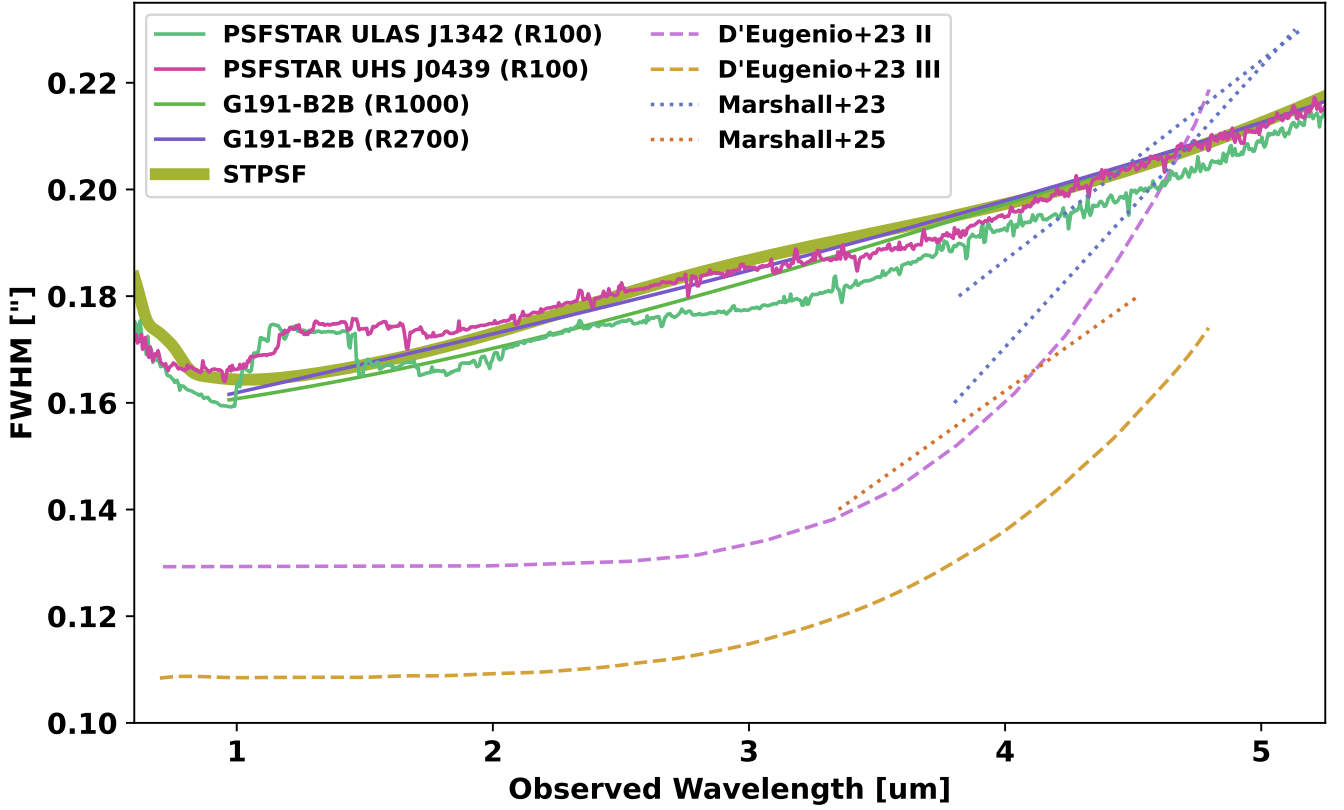


Figure C1. Best-fit FWHMs of the NIRSpec IFU PSF, derived using a variety of methods. Two methods of D'Eugenio et al. (2024) are shown by dashed lines, while the results of QDEBLEND3D fits to QSO observations are shown by dotted lines (Marshall et al. 2023, 2025). The FWHM curves derived from observations of three stars are shown by thin lines, while the empirical curve from STPSF is depicted with a thick line.

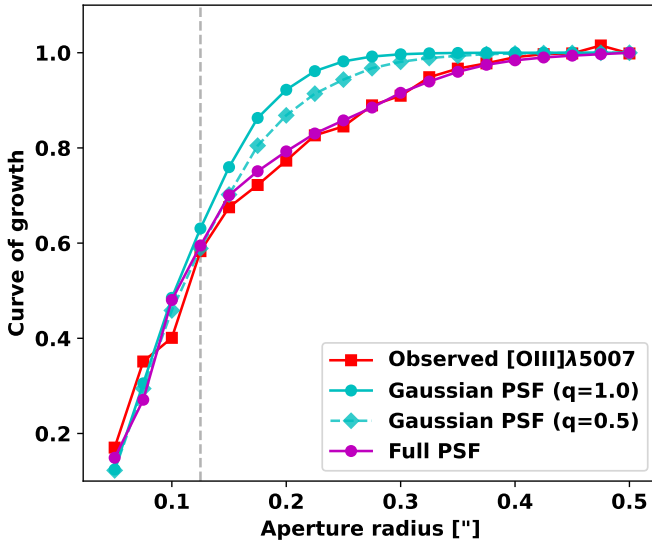


Figure C2. Curves of growth for our observations and models of the fiducial PSF. In red, we show the CoG for [OIII]λ5007, as extracted from the R100 cube. The blue lines show the CoG of 2D Gaussian models, assuming different axis ratios (q). The purple line shows the CoG of the fiducial model.

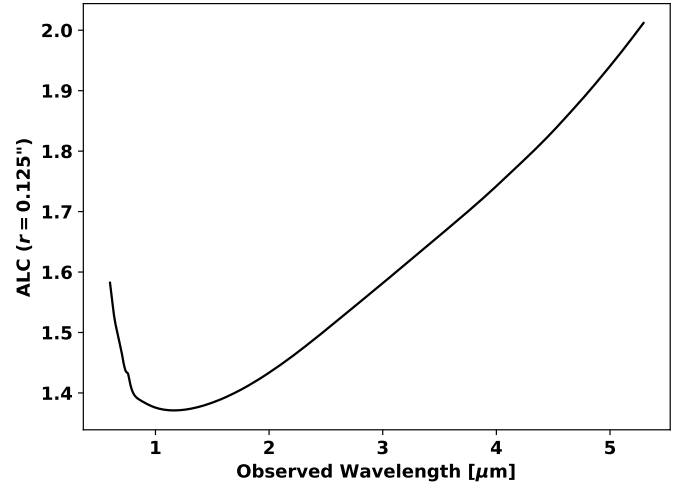


Figure C3. Aperture loss correction as function of observed wavelength for a circular aperture with radius 0.125". This was derived using the full PSF model from STPSF, rather than a Gaussian approximation.

MSA data were taken on 31 July 2023 and the JWST/NIRSpec IFU were taken on 5 December 2024. But as demonstrated in Appendix C4, we find good agreement between the NIRCам data taken on each

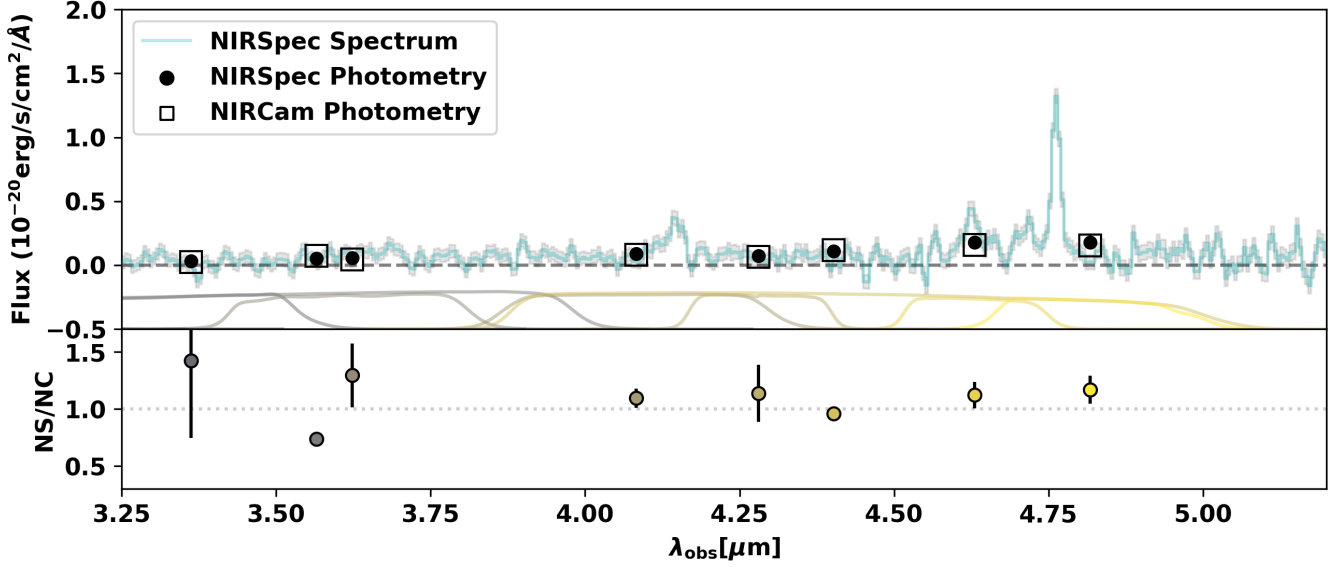


Figure C4. Comparison of the JWST/NIRSpec R100 spectrum and pseudo-photometry with JWST/NIRCam photometry (top panel). The pseudo-photometry was created using the throughput curves for each NIRCam filter, shown in the lower portion of the top panel. This results in ratio of NIRSpec to NIRCam photometric fluxes that are in broad agreement with the expected value from the empirical NIRSpec PSF (lower panel).

date and the IFU data, and thus no significant evidence for variability on the observer-frame timescale of ~ 2 yr.

APPENDIX D: LYMAN ALPHA CORRELATIONS

$\text{Ly}\alpha$ emission in galaxies appears to follow a few well-determined trends, where the $\text{Ly}\alpha$ equivalent width escapes with the $\text{Ly}\alpha$ escape fraction (e.g., Begley et al. 2024; Goovaerts et al. 2024), and with M_{UV} (e.g., Jones et al. 2024, 2025a). However, much of this work has been done at lower redshift ($z < 8$). While LAEs have been discovered well into the epoch of reionization ($z > 10$; e.g., Witstok et al. 2025), the high redshift and LRD nature of UNCOVER_20466 make it an interesting source to examine in light of these correlations.

In Figure D1, we show the placement of UNCOVER_20466 on two $\text{Ly}\alpha$ correlations, and compare it to a set of $z > 7$ LAEs from literature. This shows that it falls within the scatter of other similar LAEs, which may be interpreted as evidence as similar avenues of $\text{Ly}\alpha$ visibility.

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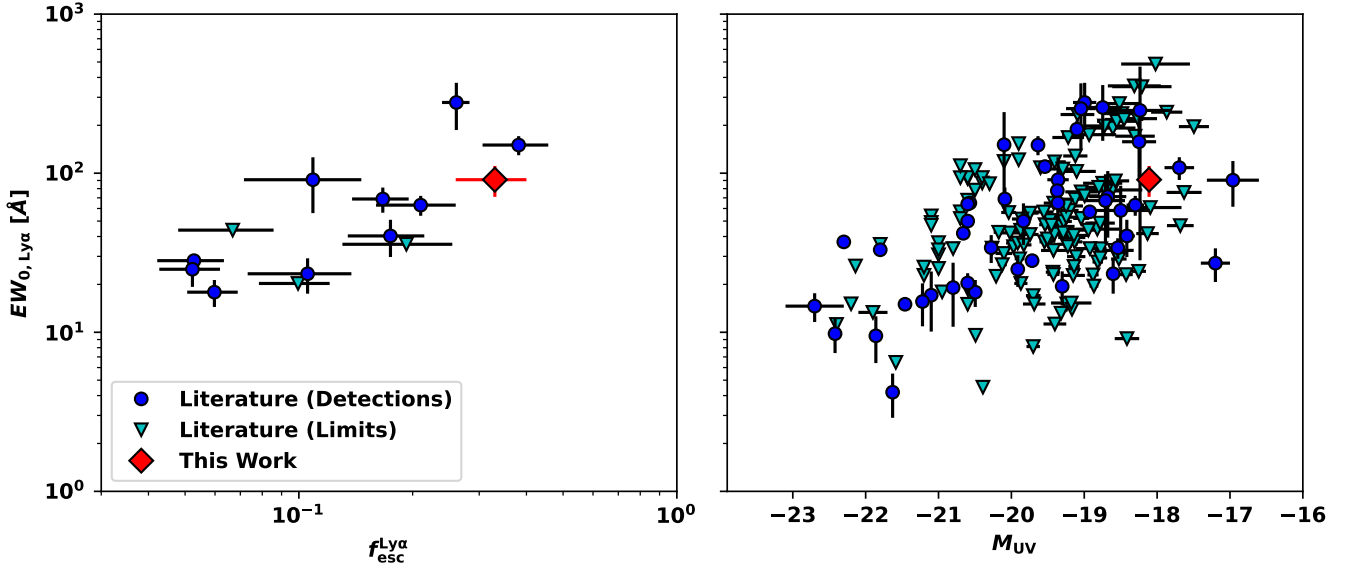


Figure D1. Placement of UNCOVER_20466 on correlations of $EW_{0, \text{Ly}\alpha}$ as a function of $f_{\text{esc}}^{\text{Ly}\alpha}$ (derived with fiducial ISM conditions; left panel) and M_{UV} (right panel), as shown by a red marker. For comparison, we plot the values of $z > 7$ galaxies from literature (Vanzella et al. 2011; Ono et al. 2012; Schenker et al. 2012; Song et al. 2016; Pentericci et al. 2018; Hoag et al. 2019; Fuller et al. 2020; Tilvi et al. 2020; Endsley et al. 2022; Jung et al. 2022; Tang et al. 2023; Jones et al. 2025a; Willott et al. 2025). The value of $M_{\text{UV}} = -18.11$ for UNCOVER_20466 is taken from Fujimoto et al. (2024).