

A weak Ly α halo for an extremely bright Little Red Dot

Indications of enshrouded SMBH growth

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Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

The abundant population of “Little Red Dots” (LRDs)—compact objects with red UV to optical colors and broad Balmer lines at high redshift—is unveiling new insights into the properties of early active galactic nuclei (AGN). Perhaps the most surprising features of this population are the presence of Balmer absorption and ubiquitous strong Balmer breaks. Recent models link these features to an active supermassive black hole (SMBH) cocooned in very dense gas ($N_{\text{H}} \sim 10^{24} \text{ cm}^{-2}$). We present a stringent test of such models using VLT/MUSE observations of A2744-45924, the most luminous LRD known to date ($L_{\text{H}\alpha} \approx 10^{44} \text{ erg s}^{-1}$), located behind the Abell-2744 lensing cluster at $z = 4.464$ ($\mu = 1.8$). We detect a moderately extended Ly α nebula ($h \approx 5.7 \text{ pkpc}$), spatially offset from the point-like H α seen by JWST. The Ly α emission is narrow (FWHM = $270 \pm 15 \text{ km s}^{-1}$), spatially offset to H α , and faint (Ly $\alpha = 0.07\text{H}\alpha$) compared to Ly α nebulae typically observed around quasars of similar luminosity. We detect compact N IV]1486 emission, spatially aligned with H α , and a spatial shift in the far-UV continuum matching the Ly α offset. We discuss that H α and Ly α have distinct physical origins: H α originates from the AGN, while Ly α is powered by star formation. In the environment of A2744-45924, we identify four extended Ly α halos ($\Delta z < 0.02$, $\Delta r < 100 \text{ pkpc}$). Their Ly α luminosities match expectations based on H α emission, indicating no evidence for radiation from A2744-45924 affecting its surroundings. The lack of strong, compact, and broad Ly α and the absence of a luminous extended halo, suggest that the UV AGN light is obscured by dense gas cloaking the SMBH with covering factor close to unity.

Key words. Galaxies: high-redshift – Galaxies: halos – Galaxies: active

1. Introduction

JWST’s significantly enhanced sensitivity in near-infrared imaging and spectroscopy is offering a new perspective on galaxies in the distant Universe (see Adamo et al. 2024, for an overview). One of the most debated discoveries since the first data arrived in 2022 is the nature of a loosely defined class of objects that became known as the Little Red Dots (LRDs; Matthee et al. 2024a). These objects are characterized by their compact morphologies and red rest-frame optical colors, often in combination with blue UV colors resulting in a particular “V” shape (e.g., Labbe et al. 2025; Akins et al. 2024; Kokorev et al. 2024a; Barro et al. 2024). By now, ~ 1000 LRDs have been photometrically identified over redshifts $z \approx 2 - 9$ spanning luminosities $L_{\text{H}\alpha} \sim 10^{41-44} \text{ erg s}^{-1}$, with number densities $\sim 10^{-5}$ to $10^{-4} \text{ cMpc}^{-3}$ (e.g., Harikane et al. 2023; Akins et al. 2024; Kokorev et al. 2024a; Greene et al. 2024; Maiolino et al. 2024; Matthee

et al. 2024a; Lin et al. 2025); 1000 to 10 000 times higher than those of UV-selected quasars at similar redshifts (e.g., Niida et al. 2020; Matsuoka et al. 2023). These numbers imply that they constitute a significant fraction of the galaxy population ($\sim 1\%$). These high number densities and their moderate overdensities (e.g., Pizzati et al. 2024; Matthee et al. 2024b; Arita et al. 2025) suggest that the majority of LRDs reside in relatively low mass galaxies in low mass halos ($M_{\text{star}} \sim 10^8 M_{\odot}$, $M_{\text{halo}} \sim 10^{11} M_{\odot}$). In many cases, the Balmer emission lines show significant broad components with widths $> 1000 \text{ km s}^{-1}$ (e.g., Kocevski et al. 2023; Matthee et al. 2024a; Taylor et al. 2024; Lin et al. 2024), which are indicative of AGN activity (e.g., Pérez-González et al. 2024; Kokorev et al. 2024b; Leung et al. 2024; Volonteri et al. 2025). Other AGN indicators are the detection of high-ionization UV lines (Treiber et al. 2024) and Fe II emission (Labbe et al. 2024) and indications of time variability in the Balmer emission lines (Ji et al. 2025; Furtak et al. 2025) and in the Balmer Break strength (Ji et al. 2025) in select LRDs.

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On the other hand, LRDs typically lack the IR emission associated with a hot torus (e.g., Williams et al. 2024; Akins et al. 2024; Setton et al. 2025), and they also show weak or no radio (e.g., Latif et al. 2025; Perger et al. 2025; Gloudemans et al. 2025; Mazzolari et al. 2024) and X-Ray emission (e.g., Yue et al. 2024; Ananna et al. 2024; Maiolino et al. 2025).

A particularly intriguing feature observed in a significant subset of LRDs is the presence of strong narrow Balmer absorption in the $H\alpha$ and $H\beta$ lines (e.g., Matthee et al. 2024a; Juodžbalis et al. 2024; Taylor et al. 2024; D’Eugenio et al. 2025), along with a pronounced Balmer break appearing consistently at rest-frame wavelength $\approx 3645 \text{ \AA}$ (e.g., Setton et al. 2024; Wang et al. 2024). These two properties may be correlated and can be explained by very dense gas along the line of sight ($n_{\text{H}} \sim 10^9 \text{ cm}^{-3}$ and column densities $N_{\text{H}} \sim 10^{24} \text{ cm}^{-2}$; e.g., Inayoshi & Maiolino 2025; Ji et al. 2025; Naidu et al. 2025; Taylor et al. 2025), which could also explain the X-Ray weakness (e.g., Kocevski et al. 2023) due to Compton thick absorption (e.g., Juodžbalis et al. 2024; Maiolino et al. 2025). The abrupt and consistent Balmer break of many LRDs could otherwise only be explained by classical models with a very unusual and specific combination of young and old stellar populations and dust attenuation laws (e.g., Wang et al. 2024; Labbe et al. 2024, 2025; Ma et al. 2025). Moreover, the strongest Balmer breaks observed cannot be reproduced by stellar population models, even assuming extreme dust attenuation laws (de Graaff et al. 2025; Naidu et al. 2025).

Recent studies have proposed models in which a very dense, turbulent, and dust-free gas completely cocoons the supermassive black hole (SMBH) of LRDs (*Black Hole Star* models; BH*; Naidu et al. 2025; Rusakov et al. 2025; de Graaff et al. 2025). In these models, the observed Balmer line profiles could have been broadened partly by scattering in the dense gas (Rusakov et al. 2025; Naidu et al. 2025). This would imply that the single epoch virial estimators of black hole (BH) mass can not be simply applied to the broad components of the emission-lines, implying that the BH mass is overestimated—with significant implications for the interpretation of the BH-stellar mass relation (cf. Pacucci & Loeb 2024). However, it remains an open question whether the dense gas fully obscures the central SMBH (covering factor $f_{\text{cov}} \sim 1$), or whether the absorption arises from an irregular distribution of clouds along the line of sight ($f_{\text{cov}} < 1$). Assessing the covering factor is crucial to understanding SMBH growth at high redshift, offering insights into the rapid early assembly of black holes in the very early Universe. Determining f_{cov} is also essential for evaluating the impact of AGN on their surroundings, particularly whether they produce enough ionizing photons to significantly contribute to cosmic reionization.

A detailed study of the UV spectrum of LRDs is key to determine f_{cov} . In particular, the strength, spatial distribution, and spectral profile of the Lyman-alpha ($\text{Ly}\alpha$) emission line are highly sensitive to the presence and distribution of neutral gas (e.g., Neufeld 1990; Steidel et al. 2011). If $f_{\text{cov}} \ll 1$, the escape fraction of $\text{Ly}\alpha$ and ionizing photons must be high, therefore we would expect to see large and luminous $\text{Ly}\alpha$ nebulae around LRDs, like the ones seen around luminous quasars. On the contrary, if f_{cov} is close to unity, the extremely dense gas would strongly suppress $\text{Ly}\alpha$ emission and the ionizing continuum, and the $\text{Ly}\alpha$ halo would be weak.

In this work, we present deep VLT/MUSE observations of A2744-45924, the most luminous LRD known (Greene et al. 2024; Labbe et al. 2024), providing the first $\text{Ly}\alpha$ halo study of an LRD and its environment. MUSE has demonstrated the existence

of large $\text{Ly}\alpha$ halos around quasars (e.g., Borisova et al. 2016), which are powered by elevated photoionization levels in the vicinity of quasars. The surface brightness depends slightly on UV luminosity (e.g., Mackenzie et al. 2021) and Type II AGNs tend to have more elongated halos (e.g., den Brok et al. 2020), exemplifying the use of extended $\text{Ly}\alpha$ nebulae to probe AGN covering factors and escaping ionizing luminosity. The $\text{Ly}\alpha$ surface brightness around quasars is significantly elevated compared to $\text{Ly}\alpha$ halos around star-forming galaxies (e.g., Leclercq et al. 2017). The key questions that we aim to answer include: What is the influence of the AGN on the circumgalactic medium (CGM) gas? What is the covering factor of A2744-45924’s central SMBH?

This paper is structured as follows. In Sect. 2 we describe the observational data from VLT/MUSE and JWST/NIRCam used throughout this work. In Sect. 3, we describe the spatially resolved properties of the rest-frame UV spectrum of A2744-45924. In Sect. 4 we analyze the $\text{Ly}\alpha$ emission of the galaxies in the environment of A2744-45924. In Sect. 5 we discuss the implications of our results for the interpretation of the origin of the $\text{Ly}\alpha$ emission. In Sect. 6 we discuss about the possible interpretations of our results in the context of LRD models involving dense gas enshrouded SMBH growth. Finally, in Sect. 7 we summarize our main findings.

Throughout this work we use a Λ CDM cosmology as described by Planck Collaboration et al. (2020), with $\Omega_{\Lambda} = 0.69$, $\Omega_{\text{M}} = 0.31$, and $H_0 = 67.7 \text{ km s}^{-1} \text{ Mpc}^{-1}$. All photometric magnitudes are given in the AB system (Oke & Gunn 1983).

2. Data

2.1. JWST

Among the LRD population, A2744-45924 stands out for its luminosity $L_{\text{H}\alpha} \approx 10^{44} \text{ erg s}^{-1}$ (Labbe et al. 2024), which places it in the (obscured) quasar regime. Found behind the lensing cluster Abell-2744 (A2744 Abell et al. 1989) at $z \approx 4.464$, A2744-45924 is magnified by a factor $\mu = 1.8$, with $\mu_t = 1.684$ and $\mu_r = 1.072$ being the transverse and radial magnification, respectively, relative to $\theta = 19.9^\circ$ (Furtak et al. 2023; Price et al. 2025).

A2744-45924 was first identified in the Cycle 1 Treasury program #2561 (UNCOVER; Bezanson et al. 2024) DR1 images and selected as an LRD based on the compact morphology in the long wavelength and V-shaped SED. NIRSpec/PRISM spectroscopy confirmed the AGN nature through the detection of broad $\text{H}\alpha$ emission (Greene et al. 2024). A2744-45924 was also observed in the JWST Cycle 2 survey #3516 (ALT; Naidu & Matthee et al. 2024, object ID 66543). The ALT survey targeted the A2744 lensing cluster, taking imaging data over $\sim 30 \text{ arcmin}^2$ using the NIRCam short-wavelength channel broad-band filters F070W and F090W and deep grism observations in F356W. These grism observations covered the $\text{H}\alpha$ line with a resolution of $R \sim 1600$, revealing broad non-Gaussian wings and narrow $\text{H}\alpha$ absorption (Fig. 5 in Labbe et al. 2024).

The NIRCam imaging revealed a compact yet resolved rest-frame UV morphology, along with a more extended and fainter component showing up in the far-UV (Labbe et al. 2024). It shows broad Balmer lines, $\text{H}\alpha$ absorption, a Balmer break and various Fe II emission lines: all signs of AGN activity. Despite its rest-frame optical luminosity and unlike quasars, A2744-45924 is not strongly detected in the sub-mm (neither continuum nor [C II] emission) and the faintness in JWST/MIRI data indicates the lack of hot dust emission (Setton et al. 2025). Akins

et al. (2025) identified faint [C I] emission from neutral gas with ALMA, possibly spatially offset in a similar direction as the extended component in the far UV. Moreover, Chen et al. (2025) studied the extended component of A2744-45924, identifying it as a star forming galaxy with stellar mass $\log_{10}(M/M_{\odot}) = 8.17 \pm 0.08$ and blue rest-frame UV colors ($\beta_{UV} = -2.12$). A2744-45924 is located in the largest galaxy overdensity in the A2744 field, as evidenced by the elevated number of H α emitters in its vicinity ($\Delta z = 0.1$).

2.2. MUSE

Here we present new VLT/MUSE observations of A2744-45924. These data were obtained using the VLT/MUSE integral field spectrograph (Bacon et al. 2010) as part of the ESO P114 program 114.27M6 (PI: Matthee). Observations were taken under clear conditions over the 10–31 October 2024 period. We used MUSE with the wide field mode which has a field of view of $1' \times 1'$, nominal wavelength coverage (470–935 nm) and assisted with ground-layer adaptive optics. Individual exposure times were 675s and we rotated the position angle by 90 degrees between every exposure. To improve the Random dithering offsets between $0.2''$ and $1.5''$ were used between each exposure to improve the background subtraction. The pointing was roughly centered on A2744-45924 and the starting PA was 30 degrees to maximise the number of sources with known spectroscopic redshifts from ALT (Naidu & Matthee et al. 2024) in the pointing. The total exposure time was 18.9 ks.

Basic data reduction was carried out using version 2.8 of the MUSE pipeline (Weilbacher et al. 2020). Each exposure was aligned to the JWST/F070W WCS and resampled onto a common grid. A superflat correction was applied to mitigate slicer stack transition artifacts (see Bacon et al. 2023), and pixels with fewer than 2000 valid wavelength layers were masked. Additional PCA-based sky subtraction was performed using ZAP (Soto et al. 2016). The aligned exposures were then mean-combined voxel by voxel using a 6σ clipping threshold. In the final cube, we applied a DC offset correction to bring empty sky regions to zero, and replaced the formal variance with an empirically estimated effective variance that accounts for non-propagated covariances (Urrutia et al. 2019; Weilbacher et al. 2020).

The astrometric corrections and the effective PSF of the MUSE datacube are derived using the JWST F070W image as a reference. This broad-band filter includes the wavelength of Ly α at $z = 4.464$. First, we use the IMPHOT package¹ to re-project the F070W image onto the same RA-DEC grid as the MUSE datacube. Next, we generate a pseudo broad-band image by convolving the MUSE datacube with the JWST F070W filter’s transmission cube and align it to the JWST counterpart using IMPHOT. This process yields small astrometric corrections of $\Delta(\text{RA}, \text{DEC}) = (-0.01656'', -0.00346'')$ and an effective PSF FWHM of $0.7396''$, assuming a Moffat profile with index $\beta = 2.5$. For this, we assume that the effective PSF FWHM of the F070W image is significantly smaller than that of MUSE. The spectral resolution at the Ly α wavelength of A2744-45924 is $R \approx 2700$ (Bacon et al. 2017).

When analyzing the Ly α emission from galaxies in the large scale environment of A2744-45924, we also make use of deep public MUSE data from Richard et al. (2021) which covers a $2.3 \times 2.3'$ region in the A2744 field centered on the most massive

Table 1. Collection of relevant properties of the rest-frame UV and Ly α emission of A2744-45924.

Property	Value	Notes
RA	00h 14m 20.34s	^a
DEC	-30:20:37.06	^a
z	4.464	^b
Ly α	20 ± 5	^c
N IV] λ 1483	0.8 ± 0.5	^c
N IV] λ 1486	2.5 ± 0.6	^c
O III] λ 1661	0.9 ± 0.5	^c
O III] λ 1666	1.9 ± 0.9	^{c*}
H α	310 ± 16	^{c†}
N IV] λ 1483/N IV] λ 1486	0.32 ± 0.21	^d
EW ₀ (Ly α)	$97 \pm 28 \text{ \AA}$	^e
EW ₀ (N IV] λ 1483)	$2.8 \pm 1.7 \text{ \AA}$	^e
EW ₀ (N IV] λ 1486)	$9 \pm 2 \text{ \AA}$	^e
FWHM _{Lyα}	$270 \pm 15 \text{ km s}^{-1}$	^f
$\Delta v_{\text{Ly}\alpha, \text{red}}$	$183 \pm 5 \text{ km s}^{-1}$	^g
h_{halo}	$5.7 \pm 0.7 \text{ pkpc}$	^h
$M_{\text{UV}, \text{MUSE}}$	$-19.39^{+0.12}_{-0.10}$	ⁱ

Notes. ^aRight ascension and declination (J2000). ^bSystemic redshift, measured from H α in NIRCcam grism data. ^cEmission line fluxes in units of $10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$, corrected for magnification. ^dFlux ratio of the N IV] λ 1483,1486 doublet. ^eRest-frame equivalent widths. ^fFWHM of the Ly α emission line. ^gVelocity offset of the Ly α red peak with respect to the H α systemic redshift. ^hExponential scale length of the Ly α halo. ⁱUV magnitude at 1500 \AA , measured from the MUSE 1D spectrum. *The flux of O III] λ 1666 is affected by a skyline, and may be regarded as an upper limit. †From Labbe et al. (2024), added here for completeness.

core of the cluster. As the JWST coverage is virtually identical, these data serve to increase the statistics.

3. The spatially resolved properties of A2744-45924

LRDs are compact objects in the rest-frame optical, however A2744-45924 shows a complex multi-component morphology in the rest-frame UV (Fig. 1). The gentle effective magnification of $\mu = 1.8$ virtually increases the exposure time by a factor $\mu^2 \approx 3$, making A2744-45924 ideal to study its different components to shed light into the relation of SMBHs in LRDs with their host galaxies.

3.1. NIRCcam UV morphology

We use the JWST/NIRCcam F070W and F090W images to fit the UV morphology of A2744-45924. The purpose of this analysis is to establish a baseline for our MUSE IFU study rather than providing a detailed examination of the UV continuum morphology. At the redshift of A2744-45924 ($z = 4.464$) F070W covers the rest-frame wavelengths 1140–1429 \AA (which include Ly α), and F090W covers 1455–1839 \AA .

We use the IMFIT² package (Erwin 2015) to fit the morphology of A2744-45924. We test multi-component models, combinations of 2D elliptical Gaussians and exponentials that minimize χ^2 , convolved with the PSF of the corresponding filter—the effective PSFs of the NIRCcam images were computed as described in Weibel et al. (2024). The fitted models are shown in

¹ <https://github.com/musevlt/imphot>

² <https://github.com/perwin/imfit>

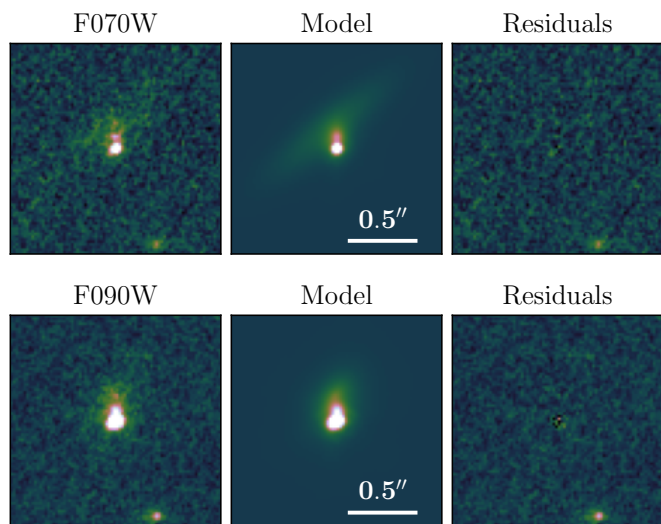


Fig. 1. Morphological model of NIRCcam rest-frame UV of A2744-45924 (PSF FWHM $\approx 0.03''$). The left panels display the F070W and F090W stamps, corresponding to central rest-frame wavelengths of approximately 1290 Å and 1651 Å, respectively. The center panels show the best-fit models obtained with `IMFIT`, while the right panels present the residuals. The F070W image, probing the bluest part of the rest-frame UV spectrum of A2744-45924, including Ly α , reveals a prominent extended component. In contrast, this component is less clear in F090W.

Fig. 1. Both F070W and F090W show clear multi-component morphologies. The shape of A2744-45924 in F070W appears to be composed of a compact core plus a more extended and diffuse structure. The core component has two clumps: one well fitted by a gaussian with $\sigma = 0.016''$ (smaller than the PSF hence can be considered point-like) and an exponential with scale length $0.05''$ (marginally resolved). The extended component is well fitted by a gaussian with high ellipticity $e = 0.73$, position angle of $\theta = 128^\circ$ and $\sigma = 0.35''$. Labbe et al. (2024) similarly fitted a Sérsic profile to this extended component in the F070W image, arguing that its surface brightness ($23.5 \text{ mag arcsec}^{-2}$) is much higher than would be expected if it was scattered light from the central source.

Since the F070W filter includes Ly α emission, its morphology may be affected by this emission line. Therefore, we also analyze F090W. The F090W data show a slightly more complex morphology. The core component is best-fitted by three Gaussians (unresolved components with $\sigma = 0.016''$, $0.02''$ and $0.025''$). The F090W image of A2744-45924 also shows a diffuse component, rather extended although less prominent than that of F070W. This extended component is best-fitted with an exponential with a similar position angle of $\theta = 142^\circ$, ellipticity $e = 0.36$ and scale length $h = 0.1''$, aligned with the diffuse F070W component, although less extended, hinting that the diffuse component in F070W has bluer UV color—as confirmed by the spatial shift of the continuum emission centroid in the MUSE data (see Sect. 3.2 below). See Appendix A for an alternative fitting procedure in which we attempt to fix the geometrical parameters within both filters.

3.2. MUSE spatially resolved UV spectroscopy

Motivated by the complex rest-frame UV morphology seen in the NIRCcam images, we examine the spatial distribution of the rest-frame UV continuum emission in the MUSE data. These

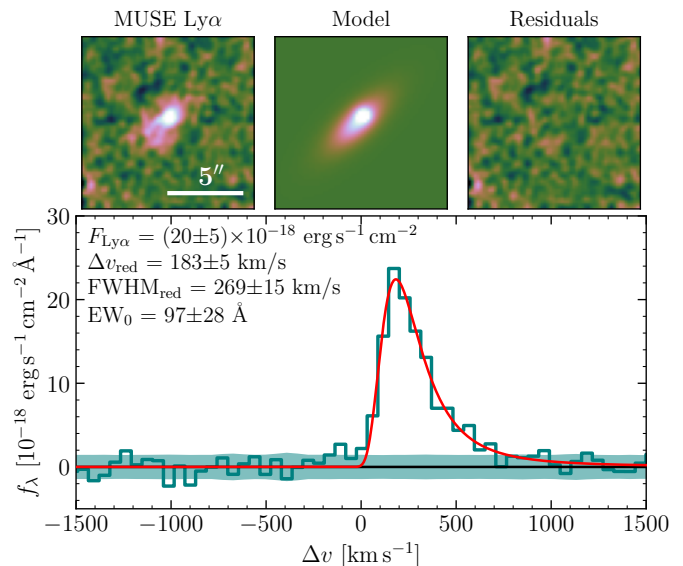


Fig. 2. Ly α spatial morphology and 1D spectrum. **Top:** We show a MUSE pseudo-narrow-band of the Ly α emission (left), the core+halo model (center) and the residuals of the fit (right). The morphology of the Ly α halo is fitted to a two-component model composed of a 2D Gaussian and exponential. The scale length of the exponential component (halo) is $h = 5.7 \pm 0.7 \text{ pkpc}$, correcting for magnification. **Bottom:** Optimally extracted 1D spectrum of Ly α . We show the fitted Gaussian model (red line). The Ly α line shows a narrow single peaked profile, typical of star-forming galaxies.

data cover the rest-frame UV of A2744-45924 up to $\lambda_0 = 1712 \text{ Å}$. We define two spectral intervals: 1235–1430 Å (*cont. blue*) and 1555–1712 Å (*cont. red*), deliberately avoiding the wavelengths of the prominent UV emission lines N iv] and C iv. After integrating the MUSE datacube over these intervals, we observe noticeable offsets between the positions of the two continuum components: $\Delta(\text{RA}, \text{DEC}) = (0.15'', 0.22'')$. We show the collapsed images for the corresponding intervals in Fig. B.1. The offset between *cont. blue* and *cont. red* suggests that the UV continuum of A2744-45924 arises from two distinct components, with the extended one exhibiting bluer colors.

ALMA observations presented in Akins et al. (2025) revealed narrow ($\text{FWHM} = 80^{+38}_{-22} \text{ km s}^{-1}$) [C I](2–1) emission from A2744-45924. The [C I] emission appears $0.4''$ northeast of the spatial coordinates of the LRD. Akins et al. (2025) argue that its position is consistent with emission from the phase center given the low S/N of their data. However, we note that this displacement aligns with our spatial centroids of the *cont. blue* and Ly α emission. Thus, the observed shift in [C I] may be physical, suggesting that it originates from the extended associated galaxy and traces its cold gas.

3.3. Extended Ly-alpha emission

We use the MUSE data to characterize extended Ly α emission from A2744-45924. We produce a pseudo-narrow-band by collapsing the MUSE datacube along the observed vacuum wavelength axis between 6638.75 and 6665.00 Å, covering the red Ly α peak observed in a first optimal extraction (between -165.7 km s^{-1} and 1019 km s^{-1} with respect to the H α systemic redshift). We subtract a continuum band, obtained in the same manner in the range 6750–7800 Å (1235–1427 Å in the rest-frame). We choose this wide interval assuming a roughly flat UV

continuum ($\beta_{UV} \sim -2$, see Labbe et al. 2024). The result is the continuum subtracted Ly α image shown in the upper left panel of Fig. 2. We fit this image using a two-component model, consisting of a 2D elliptical Gaussian (core) plus a 2D exponential (halo), convolved with the effective PSF of the MUSE datacube (see Sect. 2.2). We also considered adding the fitted F090W morphology as a core component (since this filter does not include Ly α), convolved with the MUSE PSF and applying a scaling factor, however this component is completely unconstrained in our fits. We therefore conclude that there is no significant Ly α emission from the compact components seen in the NIRCcam images (for a similar procedure see Leclercq et al. 2017).

The observed Ly α halo is well fitted by our two-component Gaussian model. We fit an exponential with scale length of 1.28 ± 0.18 arcsec, and ellipticity of $e = 0.66 \pm 0.06$, with an angle of $\theta = (137 \pm 3)^\circ$. For the core Gaussian component we fit FWHM = $0.43''$, marginally resolved given the PSF (Sect. 2.2), and implying a size of $r_e \lesssim 2$ pkpc (magnification corrected). The decomposition of both components of the fit is shown in Fig. C.1. To derive the physical geometrical parameters of the exponential halo in the source plane, we apply the radial and transverse magnification corrections (see Sect. 2.1). The halo is more strongly magnified along a direction approximately aligned with the major axis of the observed ellipse. However, even after applying these corrections, the halo remains significantly elliptical, with a scale length of $h = 5.7 \pm 0.7$ pkpc and ellipticity $e = 0.56$. A schematic representation of the ellipses in the source and image planes is shown in Fig. C.2.

The total flux ratio between the halo and more compact Gaussian component is ~ 5.4 , indicating that a large fraction of the Ly α flux comes from an extended component. This is opposed to H α , which presents a point-like morphology centered in the compact UV core (see Labbe et al. 2024). The Ly α halo is consistent with the ones typically found around star-forming galaxies as we will discuss in Sect. 5.1.

3.4. Ly α profile

We now turn to the spectral profile of the Ly α emission from A2744-45924. We perform an optimal extraction (Horne 1986) of Ly α using the model fitted as described in Sect. 3.3. The extracted profile is shown in Fig. 2. We fit a skewed Gaussian to the Ly α profile (e.g., Shibuya et al. 2014) obtaining best-fit parameters of $v_{\text{red}} = 183 \pm 5$ km s $^{-1}$ (red peak velocity offset), $A = (22.7 \pm 0.7) \times 10^{-18}$ erg s $^{-1}$ cm $^{-2}$ \AA^{-1} (amplitude), $a_{\text{asym.}} = 0.25 \pm 0.02$ (asymmetry parameter) and FWHM $_{\text{red}} = 270 \pm 15$ km s $^{-1}$. By integrating this best-fit curve, we obtain a total line flux of $F_{\text{Ly}\alpha} = (20 \pm 5) \times 10^{-18}$ erg s $^{-1}$ cm $^{-2}$, corresponding to a luminosity of $10^{42.63 \pm 0.11}$ erg s $^{-1}$ (magnification corrected flux and luminosity). We compute the EW of the Ly α , first obtaining the continuum flux from the optimally extracted 1D spectrum in the range 1220-1450 \AA , after masking sky lines. We measure EW $_{\text{Ly}\alpha} = 97 \pm 28$ \AA from the MUSE spectrum. We find moderate spatial variations of the fitted skewed Gaussian parameters, with peak velocities ranging from 100 to 200 km s $^{-1}$, and FWHM from 200 to 300 km s $^{-1}$ across the halo (Fig. D.1). These spectral variations are typical in Ly α halos of star-forming galaxies, and may be related to gas dynamics (e.g., Erb et al. 2018).

In Fig. 3 we compare the absolute fluxes of the Ly α and H α lines of A2744-45924. We measure a ratio of Ly α /H α = 0.065 (0.2 if we would consider only the narrow component of H α fitted in Labbe et al. 2024). This ratio is far from the theoret-

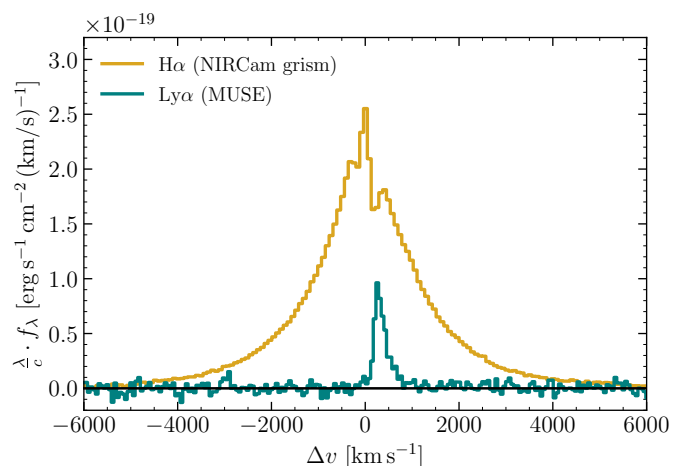


Fig. 3. Flux density in velocity space of the H α and Ly α lines of A2744-45924, centered in the systemic velocities of the two lines at $z = 4.464$. The ratio between line fluxes is Ly α /H α = 0.066. In addition, H α has a prominently broad profile (FWHM ≈ 4500 km s $^{-1}$; Labbe et al. 2024), while Ly α presents the classical shape of a single narrow red peak (FWHM = 270 km s $^{-1}$; see Fig. 2).

ical Ly α /H α = 8.7 ratio for $f_{\text{esc}}(\text{Ly}\alpha) = 1$, under the traditional assumption of case B recombination and a gas temperature of $T = 10^4$ K, typical of H II regions. This ratio is also very small in comparison to that measured in composite quasar spectra Ly α /H α ~ 3 (Vanden Berk et al. 2001). The Ly α EW and $v_{\text{Ly}\alpha, \text{red}}$ of A2744-45924 are comparable to typical star-forming galaxies in the field (Mascia et al. in prep.).

3.5. Rest-frame UV emission lines

The rest-frame UV spectrum was already covered by the NIRCspec/PRISM data presented in Labbe et al. (2024), but the very low spectral resolution ($R \sim 50$ – 100) of those data challenged the detection and characterisation of various emission-lines. In the UV spectrum of A2744-45924 in the MUSE data, which has a lower sensitivity but a much higher resolution, we also find a 4σ detection of N IV] $\lambda 1486$ at a redshift consistent with the H α redshift. We fit a Gaussian profile to this emission line, and we measure a flux of $F_{\text{N IV]}\lambda 1486} = (2.5 \pm 0.6) \times 10^{-18}$ erg s $^{-1}$ cm $^{-2}$ (EW $_{\text{N IV]}\lambda 1486} = 9 \pm 2$ \AA). After Ly α , this is the most prominent UV emission line in our data (see Sect. 3.5). By collapsing the MUSE datacube in 10 \AA around the position of N IV] $\lambda 1486$ we obtain the continuum subtracted stamp shown in the top right panel of Fig. 4. The width of the Gaussian fit to N IV] $\lambda 1486$ is well resolved as FWHM = 270 ± 50 km s $^{-1}$. Then, we fit a second Gaussian centered on the expected position of the other component of the N IV] doublet, $\lambda 1483$, fixing the width of the Gaussian to be the same. We get a tentative flux of $F_{\text{N IV]}\lambda 1483} = (0.8 \pm 0.5) \times 10^{-18}$ erg s $^{-1}$ cm $^{-2}$ (EW $_{\text{N IV]}\lambda 1483} = 2.8 \pm 1.7$ \AA). We measure a doublet ratio of $f_{1483}/f_{1486} = 0.31 \pm 0.19$, which is suggestive of very high gas density ($n_e > 10^5$ from Fig. 2 in Kewley et al. 2019). Similarly low ratios were also observed in GN-z11 (Maiolino et al. 2024) and CEERS-1019 (Marques-Chaves et al. 2024), both luminous high-redshift objects with suggested AGN activity.

We also marginally detect the O III] $\lambda\lambda 1661, 1666$ doublet (individual components with S/N ≈ 2). The continuum-subtracted MUSE image suggests a clear detection (bottom right panel of Fig. 4), however, the flux of O III] is affected by a skyline, and

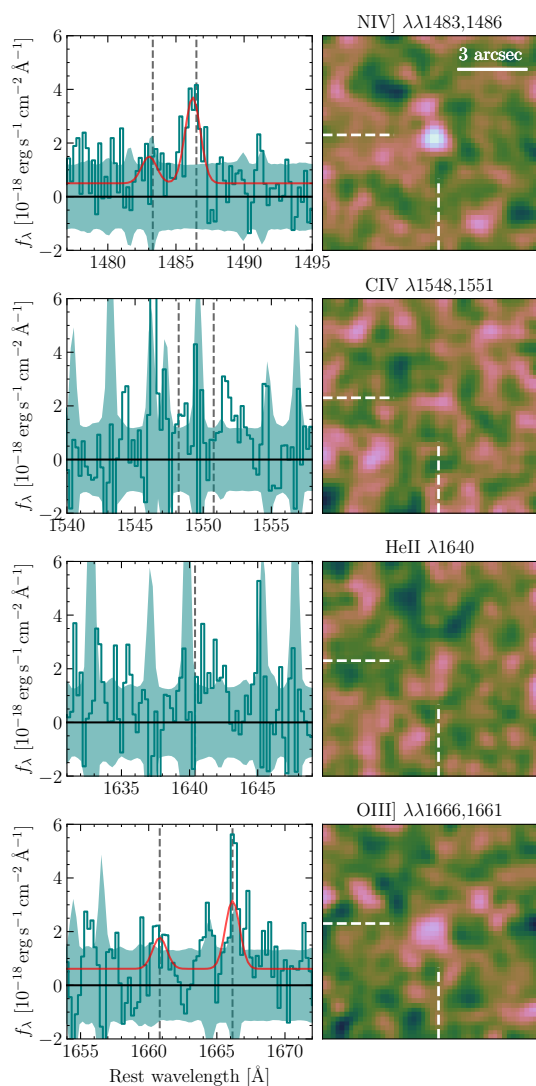


Fig. 4. Rest-frame UV emission lines of A2744-45924. The **left column** shows the 1D spectrum around the wavelength of selected UV emission lines: N IV] ($\lambda\lambda 1483, 1486$), C IV ($\lambda\lambda 1548, 1551$), He II ($\lambda 1640$) and O III] ($\lambda\lambda 1661, 1666$). In the case of N IV] and O III] we also show the best-fitting two-component Gaussian model with fixed width. The **right column** shows images obtained collapsing the MUSE datacube in an interval of 10 \AA centered on the selected lines (for doublets, both components stacked), and subtracting the continuum measured 1000 \AA around the position of the line (masking other emission lines and sky-lines).

may be regarded as an upper limit. The strong N IV] emission, together with the [O III] flux reported in Labbe et al. (2024), suggests a moderate N/O abundance, with $\log_{10}(\text{N/O}) \gtrsim -1.1$ (e.g., Pérez-Montero et al. 2013) under the assumption of an electron temperature $T_e = 10^4 \text{ K}$. However, deeper observations of both N IV] and O III] are required to robustly determine the N/O ratio, as the O III] fluxes are sensitive to T_e .

Lastly, we neither find significant detection of He II ($\lambda 1640$) or C IV ($\lambda\lambda 1548, 1551$). Labbe et al. (2024) measure a C IV flux that is comparable to that of N IV] in the NIRSpect prism spectrum of A2744-45924, yet we do not detect C IV. It is possible that the C IV line is much broader than N IV], hence hindering the detectability in our spectrum. Moreover, several sky lines affect the measurement of this line, as evidenced by the uncertainty spikes in the left panel of the second row of Fig. 4.

4. Large-scale Ly α emission

We investigate the Ly α emission of other sources in the vicinity of A2744-45924. We identify Ly α halos using the SHINE³ tool, presented in Tornotti et al. (2025). We look for halos using this tool between observed wavelength 6600 and 6674 \AA , corresponding to $z_{\text{Ly}\alpha} = 4.43\text{--}4.49$. The field of view (FoV) of the MUSE data corresponds to a box with side $1.3'$ roughly centered in A2744-45924, hence we probe a volume of $\sim 172 \text{ cMpc}^3$ (after correcting by the mean magnification of all the sources in the field, $\langle \mu \rangle = 1.8$, with values ranging from 1.5 to 2.9). We use a Gaussian smoothing kernel with $\sigma = 2 \text{ px}$ in the spatial directions, and impose a minimum spatial area of 50 px , 500 minimum connected voxels, and a size between 3 and 100 spectral pixels. After a visual inspection of the output 40 halo candidates produced using SHINE, we identify $4\text{--}5$ extended Ly α halos between $z \sim 4.45$ and 4.47 . These halos are shown in Fig. 5. All the Ly α halos have redshifts consistent with the spectroscopic redshifts of the sources they spatially overlap (Naidu & Matthee et al. 2024), with expected differences of a few hundred km s^{-1} , in line with the typical shift of Ly α red peaks relative to the systemic redshift. Within the MUSE FoV, we identify five additional sources with spectroscopic redshifts within the probed interval, but none of them exhibits significant Ly α emission. Additionally, we detect one extra Ly α emitter located $\sim 50''$ to the southeast, which shows prominent but compact Ly α emission (not shown in Fig. 5). The discarded candidates were either clearly extended continuum sources, or line emitters associated to sources with photometric or spectroscopic redshifts incompatible with Ly α . Note that we use rather permissive search parameters in order to be able to spot even the fainter Ly α halos.

We also study the strength of the Ly α overdensity in relation with H α . For this, we analyze the Ly α emission of the spectroscopic sample of H α emitters in the MUSE datacube centered in A2744-45924, as well as in the data presented in Richard et al. (2021) centered in the A2744 cluster. The FoV of both MUSE cubes are covered by NIRCcam grism spectroscopy by the ALT survey that probes H α at $3.8 < z < 5.1$. Matthee et al. (2024b) found evidence for a large overdensity ($1 + \delta_{1\text{cMpc}} \approx 30$) of galaxies (H α emitters) around A2744-45924. Likewise, the detection of 4 prominent Ly α halos in the neighborhood of A2744-45924 indicates an excess of Ly α emission with respect to random. To determine whether excess ionizing radiation—such as that produced by the AGN in A2744-45924—has enhanced the photoionizing background and contributed to the excess Ly α emission from halos around A2744-45924, we must account for the underlying galaxy overdensity. The excess of Ly α emission in $z = 4.464 \pm 0.02$ in the FoV of both MUSE fields is $\delta + 1 \approx 20$ (comparing with the mean value in our data), while the excess of H α is $\delta + 1 \approx 54$, when comparing the total flux of these lines with respect to the mean across $z = 3.8\text{--}5.5$ in the same footprint.

We first extract MUSE spectra of all the H α emitters in the ALT spectroscopic catalog using as extraction mask the morphology of the H α emission, as described in Mascia et al. (in prep.). The Ly α profile is then fitted in the 1D spectrum with a double skewed Gaussian to obtain priors for the line parameters, specifically the red peak wavelength and FWHM. Then, we re-extract Ly α , this time accounting for possible extended halos. To achieve this, we construct optimal weight masks by collapsing the MUSE datacubes along the spectral direction within a range defined by the FWHM and peak position of the red Ly α

³ <https://github.com/matteofox/SHINE>

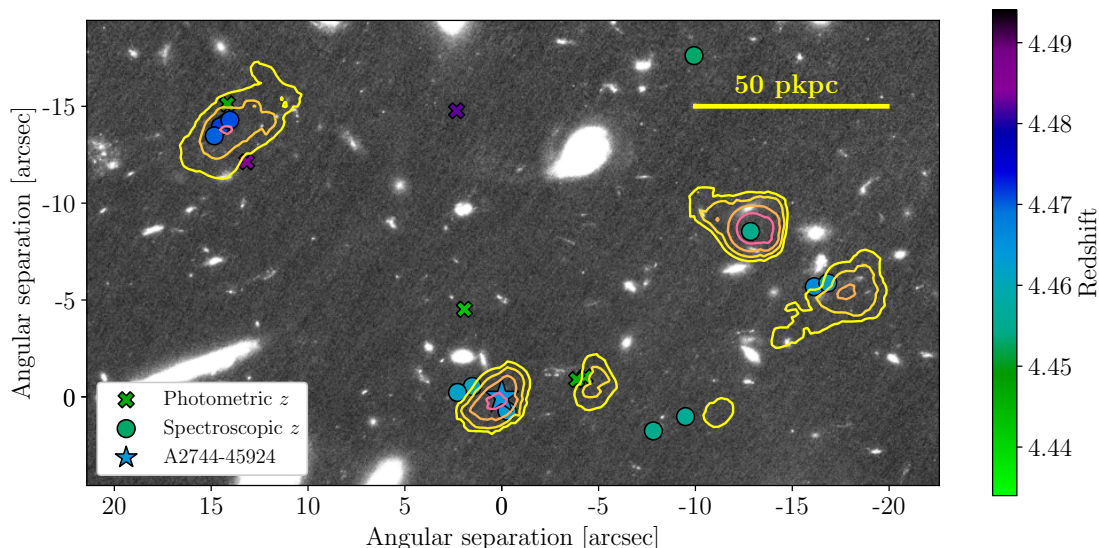


Fig. 5. Detected Ly α halos in the vicinity of A2744-45924. The background image is the NIRCcam F070W cutout. We performed the search in a box volume of $\approx 170 \text{ cMpc}^3$ (correcting with the mean magnification of the sources in the field) defined by the FoV of the MUSE data ($1.3' \times 1.3'$), however we only show a cutout where the halos are detected. We show contours of the Ly α emission detected at $z = 4.464 \pm 0.02$. Each contour level corresponds to a surface brightness increase by a factor of 1.5 (baseline $1.8 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$). We also show the positions of the JWST objects with spectroscopic (circles) and photometric (crosses) redshift in the same interval (Naidu & Matthee et al. 2024, Suess et al. 2024). We detect an elevated number of Ly α halos in the environment of A2744-45924, however, this result is consistent with the galaxy overdensity (Matthee et al. 2024b). The total flux of Ly α is moderate to low when compared with the total H α emission of A2744-45924's neighbors (See Fig. 6).

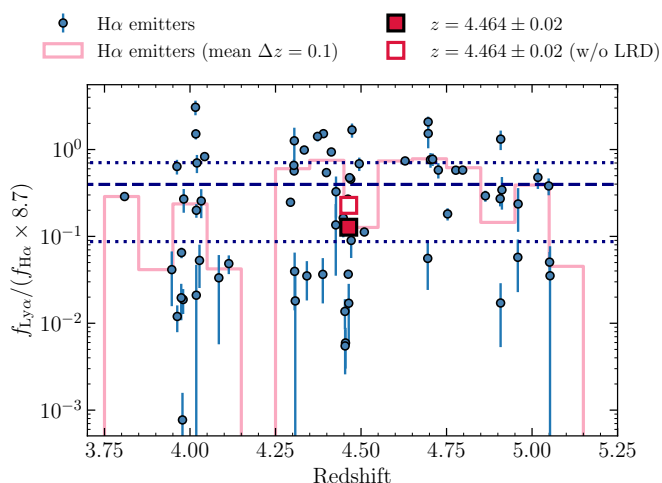


Fig. 6. Ratio of total Ly α to H α flux for all the H α emitters in the FoV of the MUSE data presented in this work, and the data from Richard et al. (2021) in the A2744 cluster. We include a $1/8.7$ factor for direct comparison with the Case B ($T = 10^4 \text{ K}$) ratio. The dashed and dotted blue lines show the mean and standard deviation in the field, respectively. We note that the fluxes are not dust-corrected. We show the total flux ratio variation in bins of redshift $\Delta z = 0.1$ (pink line), and within $\Delta z = 0.02$ around the redshift of A2744-45924, itself included (red filled square) and excluded (empty square). The Ly α /H α ratio in the environment of A2744-45924 is moderate in comparison with other overdensities in our data, despite the large intrinsic overdensity of H α emitters (Labbe et al. 2024; Matthee et al. 2024b).

component. We mask pixels below a S/N threshold of 3 after applying a Gaussian smoothing kernel with $\sigma = 2 \text{ px}$. Finally, we re-extract the spectra of all H α emitters and measure the Ly α fluxes by performing a fits to double skewed Gaussian profiles.

Figure 6 shows the ratio between the observed Ly α and H α emission from the H α emitters within the two deep MUSE cubes in the A2744 field. We highlight the average Ly α to H α ratio at the redshift of A2744-45924. Our main finding is that despite the large overdensity of H α emitters, the Ly α produced by these sources is moderate to low in comparison with other overdensities in the field, yet within the typical values (mean Ly α /H α = 0.4, standard deviation 0.3). This result makes it unlikely that the observed Ly α halos near A2744-45924 could be partly powered by its AGN, via scattering of Ly α or photoionization (e.g., Cantalupo et al. 2014). Moreover, A2744-45924 has three very close neighbors (angular separation $< 3''$, $< 15 \text{ pkpc}$ in projection, $\Delta z \lesssim 0.02$; $\Delta v \lesssim 1000 \text{ km s}^{-1}$), which totally lack detection of Ly α emission despite being detected in H α ($L_{\text{H}\alpha} \approx 10^{42} \text{ erg s}^{-1}$), hence, there is no evidence that any escaping ionizing radiation from A2744-45924 is significantly affecting the CGM of these galaxies.

5. What powers the Ly α emission from A2744-45924?

5.1. A weak halo for an extremely bright LRD

We begin by investigating the origin of the Ly α emission by analyzing the properties of the extended Ly α halo of A2744-45924. Extended Ly α nebulae are ubiquitous around bright quasars (Borisova et al. 2016; Arrigoni Battaia et al. 2019). Mackenzie et al. (2021) reported a 100% detection rate of Ly α halos around fainter quasars⁴, with extensions exceeding 60 pkpc. They also found that the extent of quasar Ly α halos remains roughly independent of source luminosity, differing only by a normalization factor. In contrast, we find a relatively compact Ly α halo around

⁴ However, see also Herenz et al. (2015), who reported 0% detection rate in 5 radio-quiet quasars.

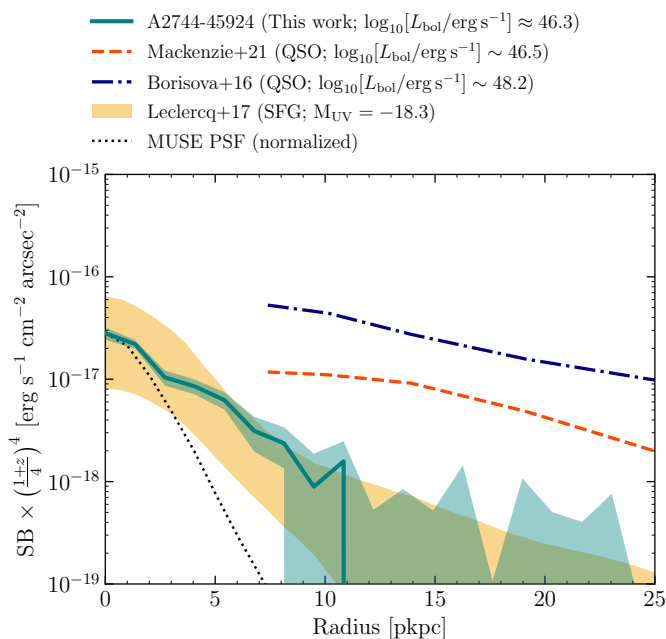


Fig. 7. Radially average surface brightness (SB) profile of the Ly α emission of A2744-45924. We show the SB profile measured in the MUSE image (teal solid line; shaded area shows the 1σ dispersion), and the Ly α model (black dashed line). We also show the SB produced by a point source for reference (black dotted line), normalized to the peak Ly α emission of A2744-45924. We compare our measurements to the halos measured around star-forming galaxies ($3 < z < 6$; $-22 < M_{UV} < -15$; Leclercq et al. 2017, shaded orange region between 16th and 84th percentiles). We also compare to Ly α halos of quasars at $z \sim 3.2$ (blue dot-dashed and orange dashed lines, Borisova et al. 2016; Mackenzie et al. 2021, respectively). The Ly α halo of A2744-45924 is comparable to that of SFGs both in terms of absolute SB and exponential scale length, despite having L_{bol} comparable to that of quasars from Mackenzie et al. (2021).

A2744-45924, whose surface brightness profile⁵ is shown in Fig. 7. Fitting an exponential profile to this halo yields a scale length of $h = 5.7 \pm 0.7$ pkpc (see Sect. C.1).

Figure 7 compares the Ly α surface brightness profile of A2744-45924 with that around star-forming galaxies from Leclercq et al. (2017), as well as halos powered by luminous quasars ($M_{UV} \approx -29$) from Borisova et al. (2016) and fainter quasars ($M_{UV} \approx -25$) from Mackenzie et al. (2021). The distinction between these populations is evident: quasar halos exhibit flatter profiles and extend over significantly larger distances.

A2744-45924 shows a very high bolometric luminosity $\log_{10}(L_{bol}/\text{erg s}^{-1}) = 46.3 \pm 0.2$ (inferred from the H α luminosity and FWHM; see Matthee et al. 2024b, and references therein), placing it in the regime of luminous quasars (Shen et al. 2020). For comparison, the average bolometric luminosities in Borisova et al. (2016) and Mackenzie et al. (2021) are $\log_{10}(L_{bol}/\text{erg s}^{-1}) \approx 48.2$ and 46.5, respectively, estimated using the bolometric corrections from Richards et al. (2006). The latter is comparable to the H α -inferred bolometric luminosity of A2744-45924, yet their Ly α halos are ~ 10 times brighter. In turn, the halo of A2744-45924 is consistent with the halos found by Leclercq et al. (2017) around star-forming galaxies with M_{UV} between -15 and -22 (A2744-45924 has $M_{UV} = -19.39^{+0.12}_{-0.10}$),

⁵ The SB was measured in radii intervals in the source plane, considering radial and transverse magnification factors of $\mu_r = 1.68$, $\mu_t = 1.07$, and a shear angle $\theta_\mu = 19.9^\circ$ (Furtak et al. 2025; Price et al. 2025).

which have a median scale length of $h = 4.5$ pkpc (ranging from 1 to 18 pkpc). Overall, we find no evidence that the AGN in A2744-45924 is leaking enough ionizing photons to power a Ly α halo like those observed around quasars with similar bolometric luminosities, either in terms of scale length or absolute surface brightness.

5.2. Spatial shift of UV continuum and Ly α emission

Our data revealed different spatially resolved components of A2744-45924: extended Ly α emission (Sect. 3.3), two rest-frame UV continuum components (Sect. 3.2), and a spatially compact N iv] emission line (Sect. 3.5, Fig. 4). In Fig. 8 we show the contours of the Ly α halo, overlaid on the F070W image, and we mark the spatial positions of the centroids of the MUSE continuum components and N iv], peak Ly α , and the coordinates of H α from NIRCcam. Although the PSF of NIRCcam and MUSE are very different, it is clear that the peak of the Ly α emission is consistent with the center of the diffuse extended component seen in F070W (see Fig. 1). Both these peaks are shifted $\sim 0.2''$ from the core component that marks the position of the AGN. The implications of this spatial shift are discussed in detail in Sect. 5.1.

The unresolved morphology of N iv] might suggest that it is originated close to the AGN component (see Sect. 3.5). We fit a 2D Gaussian with FWHM = $0.65''$ (for comparison, MUSE average effective PSF of $0.75''$), whose center is shown in Fig. 8. The centroid of the N iv] emission aligns with *cont. red* and the NIRCcam centroids.

From the spatial offset between the Ly α peak and the core component (Fig. 8) it is suggested that no significant Ly α is emitted directly by the core along our line of sight. Additionally, the shift of the UV continuum centroid toward the Ly α peak at bluer wavelengths implies that the Ly α emission likely originates from this component. This is consistent with a scenario in which the core continuum is suppressed and a shifted component with bluer rest-UV colors dominates in the far-UV. The alignment of the compact N iv] emission with the JWST coordinates of H α ensures that our measured Ly α to UV offset is robust against WCS uncertainties. The question to answer is whether the Ly α emission is powered by star formation in a host galaxy or by the AGN through resonant scattering or photoionization.

5.3. Can star formation power the Ly α emission?

In star-forming galaxies at $z \approx 0 - 2$, observations have shown that the observed EW of Ly α correlates with $f_{esc}(\text{Ly}\alpha)$ (Verhamme et al. 2017; Sobral et al. 2017). A2744-45924 shows a fairly high Ly α EW $_0 = 97 \pm 28 \text{ \AA}$ with a narrow line-profile (FWHM = $270 \pm 15 \text{ km s}^{-1}$), suggesting a moderate $f_{esc}(\text{Ly}\alpha) = 0.48 \pm 0.18$ (Sobral & Matthee 2019). If the Ly α emission of the halo is produced by star formation, we should see the corresponding component of H α in the grism data, with a total flux of $(2.4 \pm 0.7) \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$ (magnification corrected and assuming a ratio of Ly α /H α = 8.7). However, this component is likely outshined by the broad H α emission from the central engine, with a flux of $\approx 40 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$, which we could not disentangle in the grism spectrum. Chen et al. (2025) identified the extended component of A2744-45924 as a star forming galaxy with a blue rest-frame UV slope ($\beta_{UV} = -2.12$) and little dust attenuation. We estimate the star formation rate needed to power the Ly α emission from A2744-45924 following Eq. 8 in Sobral & Matthee (2019), obtaining $\text{SFR}_{\text{Ly}\alpha} = 4.5 \pm 2.7 M_\odot \text{ yr}^{-1}$

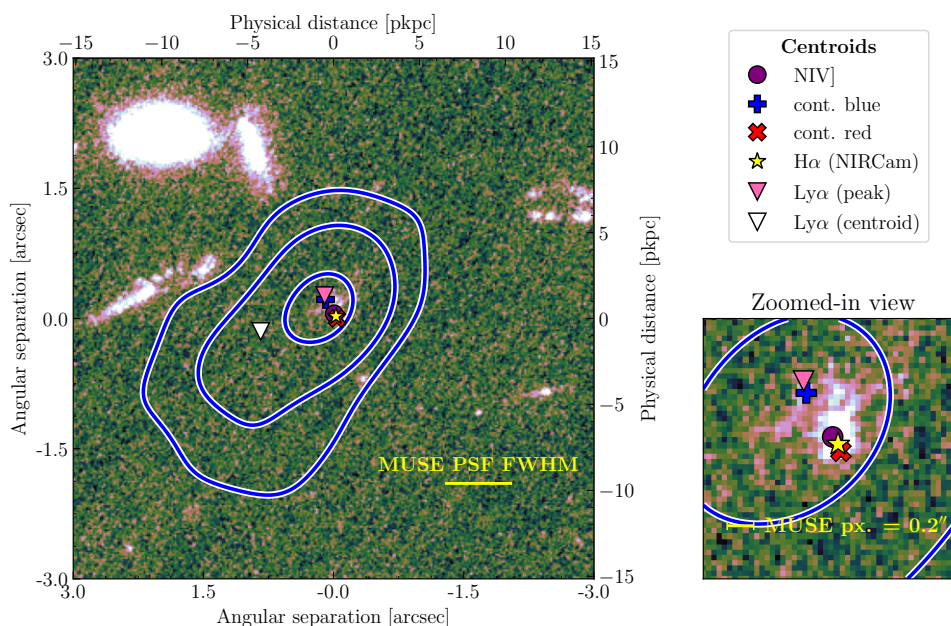


Fig. 8. Ly α contours and centroids of different spectral components of A2744-45924, over the NIRCам F070W cutout. We show contours corresponding to 10%, 50% and 90% of the peak Ly α flux (see Sect. 3.3). We also show the flux averaged centroids of the compact NIRCам H α emission (yellow star), the MUSE collapsed continuum in the ranges 1235–1430 Å (*cont. blue*) and 1555–1712 Å (*cont. red*; blue and red crosses). We also show the centroid of the N IV] (purple circle) and Ly α lines (white triangle), as well as the position of the peak Ly α (pink triangle). The bottom right panel shows a zoomed-in view of A2744-45924. The spatial centroid of *cont. red* is consistent with the centroids of the NIRCам and the position of N IV], while *cont. blue* is shifted towards the position of the peak Ly α and the diffuse extended component in F070.

(assuming $f_{\text{esc}}(\text{LyC}) = 0$). We compare this value with the SFR obtained from the UV luminosity. From the morphological model of F090W (Sect. 3.1), we measure the UV luminosity subtracting the more compact component (assuming it is originated from the AGN), and obtain $M_{\text{UV}} = -18.8 \pm 0.10$, whilst the value from the full morphological model is $M_{\text{UV}} = -19.4 \pm 0.1$. For comparison, measuring the continuum from the MUSE optimally extracted spectrum, after masking emission lines, we likewise obtain $M_{\text{UV}} = -19.39^{+0.12}_{-0.10}$. The star formation rate associated to the UV luminosity minus the compact component is $\text{SFR}_{\text{UV}} = 3.6 \pm 0.3 M_{\odot} \text{ yr}^{-1}$ (Kennicutt & Evans 2012), fully compatible with the SFR inferred from Ly α . This result suggests that the Ly α emission of A2744-45924 can be fully powered by star formation from the extended host galaxy, without any contribution from AGN photoionization or scattering.

6. Implications for the nature of A2744-45924

6.1. A fully enshrouded SMBH?

Our results clearly indicate that Ly α emission in the A2744-45924 system is not centred on the main UV component—almost certainly hosting an AGN, based on the co-spatial luminous and broad H α emission—, but rather on the secondary UV component, probably a star-forming companion or satellite of the former. Furthermore, as discussed in Sect. 5, the extended Ly α emission appears consistent in luminosity, size and EW with being powered by star formation in the secondary UV component, with little or no influence from the AGN, despite its high H α -inferred bolometric luminosity and close proximity (~ 1.7 pkpc in projection, after correcting for magnification).

Here we discuss how these findings can be reconciled with the fact that Type 1 AGN with a similar intrinsic luminosity are invariably surrounded by significantly more luminous and extended Ly α nebulae (e.g., Mackenzie et al. 2021). One possibil-

ity is that the L_{bol} of A2744-45924 derived from $L_{\text{H}\alpha}$ is overestimated, so that the true intrinsic bolometric luminosity of A2744-45924 is much lower, falling into a regime for which the ubiquity of luminous and extended Ly α nebulae has not been conclusively established yet. However, if the intrinsic luminosity of A2744-45924 has not been strongly overestimated, another simple explanation for the lack of a luminous Ly α nebula centred on it could be that the AGN photons usually responsible for powering Ly α emission around objects of similar luminosities do not reach the surrounding CGM due to some form of nuclear obscuration.

An obscuration scenario is qualitatively consistent with the fact that A2744-45924 (as well as other LRDs) is a Type 2 AGN, thence obscured at least along our line of sight. Obscuration only along our line of sight (with a covering factor $f_{\text{cov}} \ll 1$), however, would not be sufficient to explain our findings, as AGN photons escaping in other directions would still be able to power a luminous Ly α nebula, as observed for instance around other Type 2 AGN (e.g., den Brok et al. 2020). Our findings therefore suggest that the obscuring material around the AGN in A2744-45924 (and possibly other LRDs) is likely to have a large covering factor $f_{\text{cov}} \sim 1$. This is consistent with the fact that the unobscured counterparts of LRDs has not yet been observed—That is, objects with similar broad H α luminosities and similar number density, but bluer colours. A high f_{cov} scenario is also consistent with the hypothesis, recently brought forward to explain LRDs, of a SMBH covered by a very dense envelope of gas (Inayoshi & Maiolino 2025; Ji et al. 2025; Rusakov et al. 2025; Naidu et al. 2025; de Graaff et al. 2025), the so-called BH* model.

6.2. Fate of AGN ionising and Ly α photons

To gain further insight on the implications of our observations for the properties of the obscuring gas, we need to make assumptions on the exact powering mechanism for AGN Ly α nebulae, thence the wavelength range of the photons that need to be obscured in the case of A2744-45924 and in turn the properties of the material that could be responsible for the obscuration. The dominant emission mechanism for AGN-powered Ly α nebulae is not fully clear and still subject to debate, the two most commonly invoked mechanisms being recombination and resonant scattering (e.g., Cantalupo et al. 2014)⁶.

In the first (“recombination”) scenario, ionising photons reach and ionise the CGM, triggering the emission of recombination lines including Ly α . If this interpretation is correct (as indicated for instance by the detection of non-resonant recombination lines from at least some AGN-powered Ly α nebulae; e.g., Langen et al. 2023), then our main result—the lack of a luminous and extended Ly α nebula centred on the AGN—suggests a high covering factor of material that is optically thick to hydrogen-ionising photons, requiring neutral hydrogen column density $N_{\text{HI}} > 10^{17.2} \text{ cm}^{-2}$. This is very consistent with (albeit not conclusive proof of) the BH* model, which predicts $N_{\text{HI}} \sim 10^{24} \text{ cm}^{-2}$, fully sufficient to completely suppress the hydrogen ionising flux, but is also subject to caveats, as discussed in Sect. 6.3 below.

In the second (“scattering”) scenario, part of the Ly α photons from the AGN broad line region (BLR) reach the CGM and are scattered by neutral hydrogen atoms therein into our line of sight. The Ly α to H α ratio within $\sim 135 \text{ km s}^{-1}$ around the Ly α centroid is ~ 0.07 , implying that a Ly α escape fraction of $\sim 10\%$ (assuming case B recombination) would be sufficient, making this scenario energetically feasible ($f_{\text{esc}}(\text{Ly}\alpha) < 1$), although it may be difficult to reconcile with the high gas densities inferred from other diagnostics. Under the scattering hypothesis, the observed lack of a luminous Ly α nebula implies a high f_{cov} of obscuring material which is able to destroy AGN Ly α photons. Intriguingly, this is also in line with the observed lack of broad Ly α emission from A2744-45924. Note that this observation could in principle be explained by a proximate damped Ly α (PDLA) system (e.g., Marino et al. 2019). This interpretation, however, is disfavoured by the fact that a similar lack of broad Ly α emission is also observed in other LRDs (e.g., Ning et al. 2024), suggesting, on statistical grounds, that the suppression of AGN Ly α photons is more likely due to an absorbing medium intrinsic to the system and surrounding the AGN with high f_{cov} .

One possible agent for the destruction of Ly α photons is dust. Dust obscuration is however disfavoured in A2744-45924 by the observed flat rest-IR slopes by NIRC/MIRI and the far-IR and radio non-detections (Spitzer/Herschel, ALMA), which indicate no significant emission of reprocessed light by hot dust (Setton et al. 2024). On the other hand, we should recall that resonant scattering of Ly α photons through a large column density of neutral hydrogen—as expected in the envelope of a BH*—increases the effective path length of Ly α photons and therefore the efficiency of dust-induced suppression also for relatively low dust content (Scarlata et al. 2009). For example, even for low values of dust attenuation such as $A_V \approx 0.1$, one can obtain, for a static medium with $N_{\text{HI}} = 10^{20} \text{ cm}^{-2}$ (10^{21} cm^{-2}), escape fractions as low as $f_{\text{esc,Ly}\alpha} \sim 0.03$ (0.004) (Neufeld 1990; Calzetti et al. 2000;

Verhamme et al. 2006). Overall, there is no evidence that Ly α photons from the AGN in A2744-45924 are being destroyed by dust, but this possibility cannot be fully discarded without more detailed modelling.

Another mechanism for Ly α suppression is efficient l -changing ($2p \rightarrow 2s$) collisions. A Ly α scattering event can be described as a succession of one Ly α absorption, inducing a transition of a neutral hydrogen atom from the $1s$ state to the $2p$ state, followed by spontaneous re-emission, accompanied by a decay back to the ground level ($2p \rightarrow 1s$). It is however possible that, in between these two events, a collision—for instance with a proton—induces an l -changing transition from the $2p$ state to the $2s$ state, from which Ly α emission is not possible due to quantum selection rules. The transition back to the ground level will then occur through either 2-photon decay (for $n \lesssim 10^4 \text{ cm}^{-3}$), or collisional de-excitation (for $n \gtrsim 10^4 \text{ cm}^{-3}$; Spaans & Silk 2006; Neufeld 1990), in either case resulting in the effective destruction, rather than scattering, of the initial Ly α photon. For each scattering event, an l -changing ($2p \rightarrow 2s$) collision, resulting in the destruction of a Ly α photon, is the most likely outcome only for extremely high densities $n_p \gtrsim n_{p,\text{crit}} = A_{\text{Ly}\alpha}/q_{2p2s} = 3.5 \times 10^{12} \text{ cm}^{-3}$, where $A_{\text{Ly}\alpha} = 6.25 \times 10^8 \text{ s}^{-1}$ is the Einstein coefficient for Ly α emission and $q_{2p2s} = 1.8 \times 10^{-4} \text{ cm}^3 \text{ s}^{-1}$ is the coefficient for a proton-induced $2p \rightarrow 2s$ collisional transition (Dijkstra et al. 2016). However, even for densities $n_p \ll n_{p,\text{crit}}$, repeated scatterings across a path with high N_{HI} boosts the probability of a Ly α photon being destroyed before escaping the system. Along similar lines as in Dijkstra et al. (2016), the number of required scattering events for Ly α destruction can be estimated as $N_{\text{scatt}} = n_{p,\text{crit}}/n_p$. For the fiducial density $n_e \sim 10^9 \text{ cm}^{-3}$ of the BH* model (Naidu et al. 2024), a number of scatterings $N_{\text{scatt}} = 3.5 \times 10^3$ would be sufficient, achievable (for a static medium and at line center) with a neutral hydrogen column density $N_{\text{HI}} \gtrsim 6 \times 10^{16} \text{ cm}^{-2}$ (see equation 3 in Dijkstra et al. 2016) and abundantly met for $N_{\text{HI}} \sim 10^{24} \text{ cm}^{-2}$, as in the BH* models. A more detailed analysis of this scenario would require taking into account the impact of kinematical effects, such as turbulence or possible inflow or outflow motions, on Ly α radiative transfer and is left for future investigation.⁷

Overall, our findings provide support for the presence of obscuring material with a large covering factor ($f_{\text{cov}} \sim 1$) of neutral hydrogen with at least a column density ($N_{\text{HI}} \gtrsim 10^{17.2} \text{ cm}^{-2}$) around the AGN at the centre of A2744-45924. Furthermore, under the assumption that the dominant emission mechanism for AGN-powered Ly α nebulae is Ly α scattering, our observations appear fully consistent with the high gas density and hydrogen column densities expected in the envelope of a BH*.

6.3. Origin of the compact UV emission and high-ionization emission lines

One final important aspect to address, in the context of nuclear obscuration with $f_{\text{cov}} \sim 1$, is the nature of the main compact UV component in A2744-45924, as well as the presence of the of emission lines of highly ionized species, such as O III], N IV] and C IV, in the spectrum (see Section 3.5 above, as well as Labbe et al. 2024).

In one of the scenarios explored by Labbe et al. (2024), the UV portion of the spectrum of A2744-45924 could repre-

⁶ A third mechanism, collisional excitation, is also expected to play a role in extended Ly α emission around galaxies (e.g., Dijkstra & Loeb 2009) but is disfavoured for AGN nebulae due to photo-ionization effects (e.g., Pezzulli & Cantalupo 2019).

⁷ Note that, in the presence of differential motions with a constant velocity gradient, the required N_{HI} to obtain a given value of N_{scatt} is only increased by a factor $\sim v_{\text{max}}/v_{\text{thermal}}$ (Bonilha et al. 1979; Dijkstra et al. 2016).

sent AGN light escaping through unobscured channels and being scattered by free electrons into our line of sight. This scenario would imply $f_{\text{cov}} < 1$ and could also naturally explain the presence of high-ionization emission lines. Quantitatively, however, further work would be needed to determine the minimum fraction of the free (unobscured) solid angle ($f_{\text{uncov}} = 1 - f_{\text{cov}}$) required to explain the observed UV and line fluxes in this scenario and verify whether it is consistent with $f_{\text{uncov}} \ll 1$, as indicated by our findings in this work.

A second scenario considered by Labbe et al. (2024) is that the UV spectrum may be dominated by a young, compact and metal-poor stellar population, which, in the context of the present discussion, could be interpreted as a compact nuclear star cluster surrounding the SMBH and its envelope. Because, in this scenario, the UV light originates outside the obscuring envelope, it would be consistent with $f_{\text{cov}} = 1$, provided however that the high-ionization emission lines are powered by star-formation rather than the AGN. This would be somewhat unusual, considering the high ionising potential for producing N IV] and C IV, but perhaps not impossible considering the very blue observed slope ($-\beta_{UV} = 2.2 - 2.9$; Labbe et al. 2024), plausibly accompanied by an ionising spectrum correspondingly harder than usual (Topping et al. 2025). This picture could also be supported by our finding that the N IV] λ 1486 line is quite narrow (FWHM $\sim 270 \text{ km s}^{-1}$; see Sect. 3.5) and therefore possibly arising from the interstellar medium (ISM) rather than the immediate proximity of the accretion disc. We note, in particular, that the relatively high density $n_{\text{H}} \sim 10^5 \text{ cm}^{-3}$ inferred from the f_{1483}/f_{1486} doublet ratio (Sect. 3.5) would in this case be indicative of a relatively dense ISM surrounding the even denser BH* envelope. For the implied ISM density $n \sim 10^5 \text{ cm}^{-3}$, an ISM neutral hydrogen column density $N_{\text{HI}} \sim 6 \times 10^{20} \text{ cm}^{-2}$ could already be sufficient to suppress also the Ly α photons from this hypothetical compact star-forming region through l -changing collisions, as well as any hydrogen-ionizing photons. This could possibly explain why such a nuclear star cluster is not in turn powering an extended Ly α halo centred on the compact source.

One third possibility is that the compact UV component is due to AGN photons that traverse the dense gas envelope without being entirely absorbed. The BH* scenario is designed so that a non-negligible fraction of the hydrogen atoms in the envelope is collisionally excited to the $n = 2$ level, capable of producing absorption features in Balmer lines, as well as producing a Balmer break by suppressing the Balmer continuum. Crucially, the photo-ionization cross-section for $n = 2 \rightarrow \infty$ (i.e., the Balmer continuum) transitions decreases with decreasing wavelength (roughly as $\propto \lambda^3$). Therefore, we can expect that for high but not extreme column densities, UV photons could be able to traverse the envelope, possibly explaining the emergence of a blue UV spectrum and consistent with $f_{\text{cov}} = 1$. This scenario requires tailored modeling and will be the subject of future investigation. Note that, if produced *within* the envelope (a few AU from the accretion disc in the model of Naidu et al. 2025), UV high-ionization emission lines, such as N IV] λ 1486, would also, in principle, be able to traverse the envelope, with attenuated flux but conserved doublet ratio and EW. It would be more difficult, however, to explain the narrow width. If instead the N IV] λ 1486 line is produced outside the envelope (as suggested by the small FWHM), this scenario would need either a non-vanishing f_{uncov} , or some contribution from a compact young stellar population with a hard ionising spectrum, as Lyman continuum photons encountering the envelope would be expected to be completely suppressed, in contrast to the Balmer continuum.

7. Summary

In this paper, we presented MUSE observations of A2744-45924, an extremely bright LRD ($L_{\text{H}\alpha} \approx 10^{44} \text{ erg s}^{-1}$), revealing a narrow Ly α emission line, and a moderately extended Ly α halo. Below we summarize our main findings.

1. A2744-45924 shows a narrow (FWHM = $270 \pm 15 \text{ km s}^{-1}$), single-peaked Ly α emission line, with $\text{EW}_0 = 97 \pm 28 \text{ \AA}$ and a velocity separation of $\Delta v_{\text{red}} = 183 \pm 5 \text{ km s}^{-1}$ with respect to the systemic redshift. The Ly α emission has an extended spatial morphology, which can be well fitted by a combination of 2D Gaussian and exponential. The Ly α nebula has an exponential scale length of $h = 5.7 \pm 0.7 \text{ pkpc}$ and ellipticity $e = 0.46 \pm 0.05$ (Sect. 3.4).
2. We also report a significant (4σ) detection of N IV] λ 1486, which exhibits a very compact spatial morphology. This emission line is associated with AGN activity, and the low ratio with the marginally detected (1.6σ) N IV] λ 1483 suggest a high gas density (Sect. 3.5).
3. The Ly α emission peaks with a spatial offset of $\sim 0.4''$ relative to the NIRCcam centroid of the compact core of A2744-45924. This offset aligns with the position of the extended UV component seen in NIRCcam. Additionally, the UV continuum detected with MUSE shows a shift towards shorter rest-frame wavelengths (1235–1430 \AA) compared to longer wavelengths (1555–1712 \AA). The spatial centroid of N IV] is consistent with the compact core, supporting its AGN origin and confirming that the observed Ly α and UV continuum shifts are not due to astrometry uncertainties (Sect. 5.2).
4. We investigate the Ly α emission of sources in the neighborhood of A2744-45924, in the MUSE field of $\sim 1.3' \times 1.3'$. We find 4 extended Ly α halos between 4.45 and 4.47 (in a volume corresponding to $\sim 172 \text{ Mpc}^3$). We find an excess of total Ly α emission in an interval of $\Delta z = 0.02$ around A2744-45924 ($1 + \delta_{\text{Ly}\alpha} \approx 20$). However, the ratio between the total Ly α emission with respect H α is moderately low with respect to the average in the same FoV within $z = 3.75\text{--}5.25$, but still within 1σ . This result implies that A2744-45924 does not significantly enhance the Ly α luminosity of nearby halos through scattered Ly α light (Sect. 4).
5. The extended Ly α halo of A2744-45924 resembles those of star-forming Ly α emitters, more than quasars, in both scale length ($h = 5.7 \pm 0.7 \text{ pkpc}$) and surface brightness (Leclercq et al. 2017). The narrow Ly α line contrasts with the broad H α (FWHM $\approx 4500 \text{ km s}^{-1}$), suggesting different origins. We show that the Ly α emission can be fully explained by star formation in the host galaxy, without AGN contribution (Sects. 5.1 and 5.3).
6. We discuss the implications of our findings for a scenario in which the compact continuum emission and H α are explained by a SMBH enshrouded in a dense cloud of gas (BH* models). We argue that the absence of a luminous Ly α halo, as seen in similarly bright Type I and II AGN, can be explained by obscuring neutral hydrogen gas with a covering factor $f_{\text{cov}} \sim 1$ and column density $N_{\text{HI}} \gtrsim 10^{17.2} \text{ cm}^{-2}$. However, the main caveat for these interpretations is that L_{bol} could be largely overestimated (Sects. 6.1 and 6.2).
7. Finally, we consider the implications of the UV continuum and high-ionization emission lines for the dense obscuring gas hypothesis. The observed properties are consistent with a BH* model with $f_{\text{cov}} \sim 1$, although the exact interpretation depends on the gas distribution and geometry. Further modeling and observations are required to constrain key parameters of the BH* model—i.e., f_{cov} , N_{HI} , n_e , etc. (Sect. 6.3).

Acknowledgements. We thank Sebastiano Cantalupo for comments on the draft. Based on observations collected at the European Organisation for Astronomical Research in the Southern Hemisphere under ESO programme 114.27M6.001. Funded by the European Union (ERC, AGENTS, 101076224). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them. We acknowledge funding from *JWST* program GO-3516. MG thanks the Max Planck Society for support through the MPRG. FDE acknowledges support by the Science and Technology Facilities Council (STFC), by the ERC through Advanced Grant 695671 “QUENCH”, and by the UKRI Frontier Research grant RISEandFALL. TU acknowledges funding from the ERC-AdG grant SPECMAP-CGM, GA 101020943. GK acknowledges support from the MERAC foundation.

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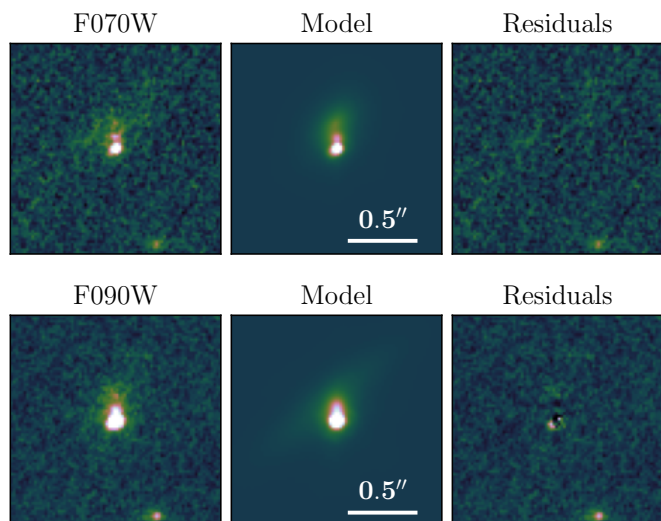


Fig. A.1. Alternative best-fit models of the UV morphology of A2744-45924 in the NIRCcam filters F070W (top) and F090W (bottom). This figure is analogous to Fig. 1, but here, for each filter, we apply the best-fitting model from the other filter, keeping its geometrical parameters fixed and allowing only the intensities to vary. The residuals of the extended component reveal that its geometry differs between the two filters. The more extended morphology seen in F070W may reflect a significant contribution from Ly α emission to the flux in this band.

Appendix A: Additional morphology fits to NIRCcam F070W and F090W

In Sect. 3.1, we model the UV morphology of A2744-45924 in both F070W and F090W using two 2D elliptical Gaussians and one exponential component. The main difference between the fits in the two filters lies in the scale length of the exponential, which is significantly larger in F070W. In Fig. A.1, we present an alternative fitting approach in which the best-fitting model from F070W is used to fit the F090W image, and vice versa. In both cases, the positions and geometric parameters of all components are fixed to the best-fit values in one filter, allowing only the amplitudes to vary. The resulting residuals suggest that the geometry of the extended component is not consistent between filters, with F070W favoring a more extended exponential profile. This difference may point to a significant contribution from Ly α emission to the F070W flux.

Appendix B: Continuum centroids

In Fig. B.1 we show MUSE images, result of collapsing the datacube in the specified wavelengths. We deliberately avoid the rest-frame wavelength range in which N IV] and C IV are located, to capture only continuum emission. We observe a clear shift in the spatial centroid of the continuum, as can be visually seen in the Fig. B.1, with the black cross marking the NIRCcam coordinates of A2744-45924 as reference. The flux weighted centroids of these components are shown in Fig. 8 in relation to the positions of other spectral features (N IV], Ly α and NIRCcam rest-frame UV centroids).

Appendix C: Ly α morphology fit

In Fig. C.1, we present the contours of the fitted model for the Ly α halo of A2744-45924. The fit was performed using the

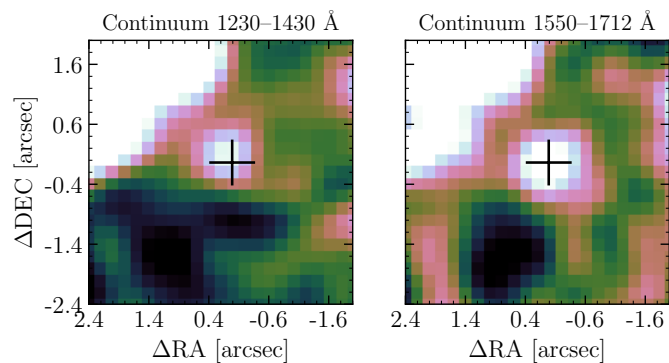


Fig. B.1. MUSE images of the continuum bands probing 1230–1430 Å (*cont. blue*) and 1550–1712 Å (*cont. red*). The centroid of the emission shows a clear shift, of $\approx 0.2''$. The centroids of these two components are shown in Fig. 8, in comparison with the positions of other spatially resolved spectral features. The bright source in the northeast corner is the blend of two low- z interlopers, clearly visible in Fig. 5.

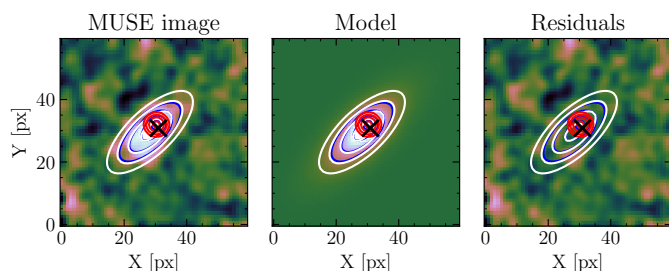


Fig. C.1. Morphological fit to the Ly α emission of A2744-45924. We fit a combination of exponential (white) and gaussian (red). Combination of the two in blue. We show contours corresponding to 80%, 40%, 20% and 10% of the peak flux of each component. We mark the JWST coordinates of A2744-45924 with a black cross.

Python package LMFIT with the `leastsq` method. We tested various combinations of exponential and Gaussian components and found that a model consisting of one exponential and one Gaussian provided the lowest χ^2 . We initially tested models including the morphology of NIRCcam F090W (Sect. 3.1) as a core component at the position of A2744-45924 with a small shift to allow for astrometric uncertainties (see e.g., Matthee et al. 2020). However, we found that the fitting method could not satisfactorily constrain this component.

In Fig. C.2 we show the ellipses defined by the exponential fit to the Ly α halo at the exponential scale length. The image is more strongly magnified in the direction of the semi-major axis of the image. However, after applying the transformation to the source plane, the fitted exponential remains fairly elliptical with $e = 0.56$.

Appendix D: Spatial variations of the Ly α profile in the halo

We study the spatially resolved Ly α line profile of A2744-45924. For this, we fitted a skewed Gaussian defined as:

$$f(\nu) = A \exp\left(-\frac{(\nu - \nu_0)^2}{2[a_{\text{asym}}(\nu - \nu_0) + d]^2}\right) \quad (\text{D.1})$$

(e.g., Shibuya et al. 2014) to every pixel in a box of $3'' \times 3''$ around the coordinates of A2744-45924, and after applying a

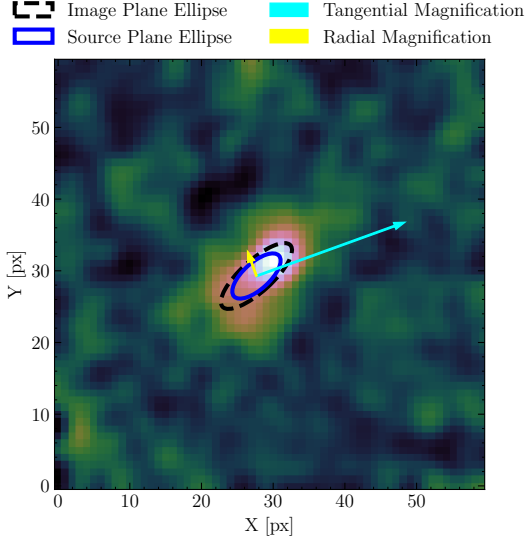


Fig. C.2. We show the ellipse defined by the fitted exponential at the scale length h in the image plane (dashed black) and the transformation into the image plane (dark blue). We plot these ellipses over the MUSE image of the Ly α halo of A2744-45924 after applying a smoothing Gaussian filter of $\sigma = 1$ px. We also show the directions of the radial and transverse magnification μ_r and μ_t (yellow and cyan arrows, respectively). The length of the arrows is proportional to $\mu_r - 1$ and $\mu_t - 1$.

Gaussian smoothing kernel with $\sigma = 2$ px in the spatial directions. In Fig. D.1 we show the spatial maps of three parameters of the skewed Gaussian: the peak velocity offset with respect to the systemic redshift $z = 4.464$ (v_0), the FWHM of the line profile⁸, and the asymmetry parameter (a_{asym}).

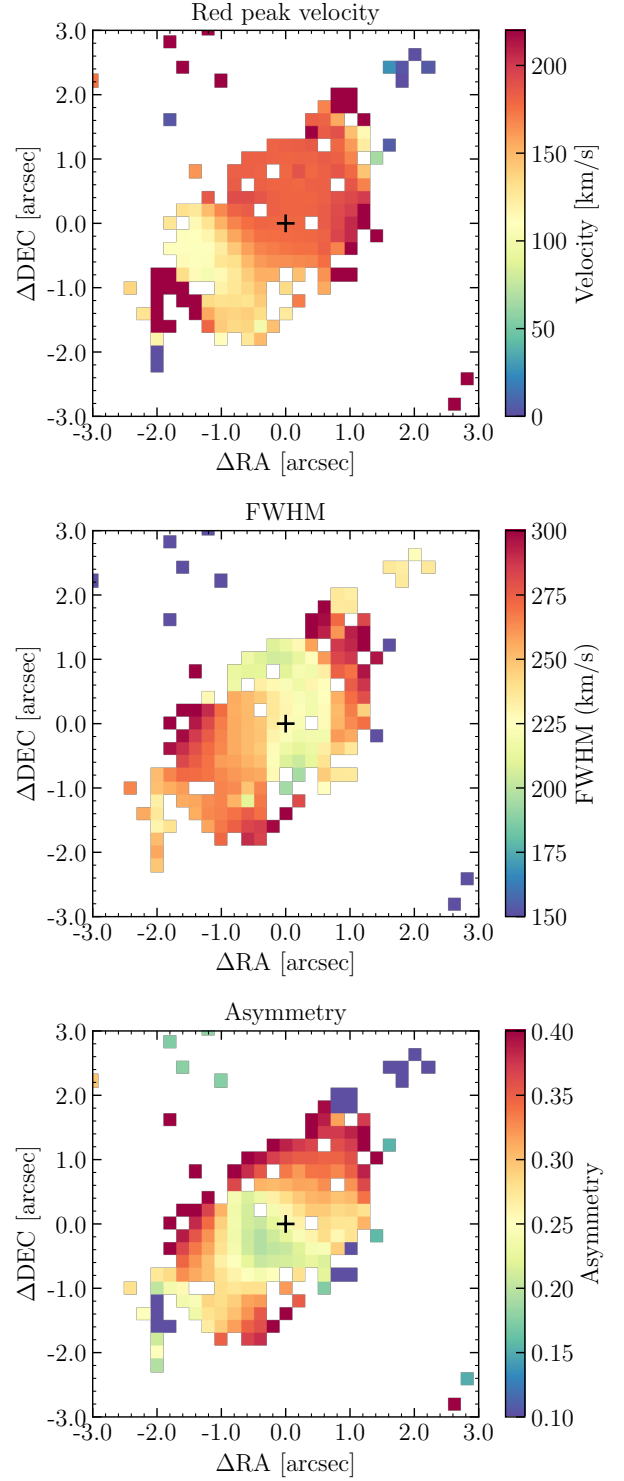


Fig. D.1. Spatial distribution of the fitted skewed Gaussian properties to the Ly α halo of A2744-45924. We show the velocity of the peak emission (top), the FWHM of the line in velocity space (middle) and the asymmetry parameter (see Eq. D.1; bottom). In these maps, we have masked out the pixels with a model amplitude (A in Eq. D.1) with $S/N < 3$. We spot spatial variations of these parameters across the halo, in particular, a region with a slightly broader line profile and lower peak velocity toward the southwest. However, these differences are typical in Ly α halos of star-forming galaxies in the literature (e.g., Erb et al. 2018), and can be attributed to gas dynamics in the CGM.

⁸ With the definition of skewed Gaussian of Eq. D.1, the full width at half maximum is obtained as $\text{FWHM} = \frac{2d\sqrt{2\ln 2}}{1 - (2\ln 2)a_{\text{asym}}^2}$