

DREAMS.

JWST Spectroscopy of a $z = 8.3$ Galaxy with an ALMA Dust Continuum Detection: Early Dust, Very High T_{dust} , and a Multi-wavelength [O III] Ratio Discrepancy

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ABSTRACT

We present a deep DREAMS *JWST*/NIRSpec MSA medium-grating spectrum of MACS0416-Y1, a galaxy at $z = 8.312$ with the highest-redshift ALMA dust continuum detection to date, in order to characterize its properties together with archival IFU and ALMA data. The deep NIRSpec spectrum reveals a broad $H\beta$ line with a width of $\sim 1100 \text{ km s}^{-1}$. We interpret it as a broad-line AGN whose line diagnostics are **consistent with AGN activity across its clumpy structure**, given the absence of little red dot signatures. MACS0416-Y1 clearly shows [OIII] 4363 emission, suggesting a moderately low metallicity of $12 + \log(\text{O}/\text{H}) = 7.86^{+0.09}_{-0.08}$ ($0.15 Z_{\odot}$). The combination of [CII] $158\mu\text{m}$ and dust continuum emission indicates low dust mass ratios of $\log(M_{\text{dust}}/M_{\text{gas}}) = -3.60^{+0.29}_{-0.22}$ and $\log(M_{\text{dust}}/M_{\text{metal}}) = -0.95^{+0.29}_{-0.20}$. Because the metallicity of MACS0416-Y1 is around the critical metallicity of $0.1\text{--}0.2 Z_{\odot}$, the system is expected to undergo dust growth, explaining these low dust mass ratios as well as its small dust mass, $M_{\text{dust}} \sim 10^6 M_{\odot}$. The intense UV radiation from the AGN may contribute to a high dust temperature of $T_{\text{dust}} \simeq 91^{+62}_{-35} \text{ K}$, boosting the dust-continuum emission above the ALMA detection limit despite the small M_{dust} at $z > 8$. We find a very high total flux ratio of $[\text{OIII}] 88\mu\text{m}/[\text{OIII}] 5007 = 0.26 \pm 0.06$ in MACS0416-Y1, above predictions from single ionized nebular models at any electron density. This discrepancy suggests that the [OIII] $88\mu\text{m}$ and [OIII] 5007 trace largely distinct regions, with the optical line suppressed in dusty nebulae, and thus **requires careful interpretation when combining optical and infrared emission lines in JWST+ALMA studies**.

1. INTRODUCTION

Dust is a fundamental component of the interstellar medium (ISM) in galaxies, influencing the observational properties, energy budget, and physical conditions. In the local Universe, dust heated by interstellar radia-

tion fields typically reaches equilibrium temperatures of $\sim 20\text{--}40$ K (Dunne et al. 2000; Casey 2012). However, recent far-infrared (FIR) and submillimeter observations have revealed that dust in high-redshift galaxies, particularly at $z > 6$, exhibits unexpectedly high temperatures of $50\text{--}100$ K, likely due to intense radiation fields associated with compact star formation and/or conditions that enhance dust heating, including low dust mass or active galactic nucleus (AGN) activity (Nakazato et al. 2026; Viero et al. 2022; Sommovigo et al. 2022; Mitsuhashi et al. 2024; Tsukui et al. 2023).

Understanding the origin of these high dust temperatures and the physical conditions of the ISM requires combining dust continuum measurements with constraints on the gas properties. A multi-wavelength approach that combines FIR/submillimeter continuum observations with near-infrared spectroscopy is therefore essential for characterizing dust and ISM properties in early galaxies. FIR and submillimeter observations probe the emission from dust and FIR fine-structure emission lines, while near-infrared spectroscopy provides emission line diagnostics that trace gas properties including electron temperature, density, ionization state, and chemical composition (Osterbrock & Ferland 2006; Draine 2011). The combination of these datasets enables a more comprehensive understanding of the physical conditions in high- z galaxies. For example, measurements of the gas-phase metallicity can provide constraints on grain growth processes in the early universe (e.g., Asano et al. 2013; Popping et al. 2017; Toyouchi et al. 2025).

MACS J0416-Y1 (hereafter Y1) is a star-forming galaxy at $z = 8.31$ that exhibits an elevated dust temperature and a complex ISM structure characterized by three emission peaks in the rest-frame UV and two emission peaks in the rest-frame FIR continuum. It was originally identified as a $z > 8$ Lyman break galaxy candidate based on multiband *Hubble Space Telescope* Wide Field Camera 3 (*HST*/WFC3) observations (Infante et al. 2015; Laporte et al. 2015) in the Hubble Frontier Fields (HFF, Lotz et al. 2017) survey of the MACS J0416.1-2403 cluster. Follow up observations with the Atacama Large Millimeter/submillimeter Array (ALMA) spectroscopically confirmed its redshift, $z = 8.312$, through detections of the [OIII] $88\mu\text{m}$ (Tamura et al. 2019) and [CII] $158\mu\text{m}$ (Bakx et al. 2020) emission lines. Y1 exhibits a high [OIII] $88\mu\text{m}$ /[CII] $158\mu\text{m}$ luminosity ratio of ~ 9 (Bakx et al. 2020). Hagimoto et al. (2025) suggested that this can be explained by a porous ISM geometry with a low neutral-gas covering fraction. Dust continuum emission was first reported in ALMA Band 7 (Tamura et al. 2019), representing the highest-redshift

dust continuum detection to date. Dust continuum emission has subsequently been detected across multiple ALMA bands (Tamura et al. 2019; Harshan et al. 2024; Bakx et al. 2025). By combining these detections with upper limits from nondetections (Bakx et al. 2020; Jones et al. 2024; Bakx et al. 2025), the dust temperature has been constrained to 91^{+62}_{-35} K (Bakx et al. 2025), significantly warmer than typical values observed in local galaxies (~ 25 K; e.g., Schreiber et al. 2018). The origin of the high dust temperature and the detection of dust continuum at such a high redshift remain under debate. Tamura et al. (2019) suggested that the observed dust mass requires an earlier episode of star formation to pre-enrich the system, rather than production in a single young burst. Bakx et al. (2020) argue that the high inferred dust temperature itself reduces the required dust mass, alleviating the tension with rapid dust production. More recently, observations with the James Webb Space Telescope/Near Infrared Spectrograph (*JWST*/NIRSpec) and *JWST*/Near Infrared Camera (NIRCam) have revealed the clumpy morphology, ionized gas properties, and stellar populations (e.g., Ma et al. 2024; Harshan et al. 2024). Harshan et al. (2024) proposed that merger-driven star formation and/or a possible AGN contribution inferred from emission line diagnostics could account for the strong dust heating.

Despite these advances, several key questions remain unresolved, including the origin of the dust heating, the mechanism responsible for the dust enrichment, and the connection between the rest-frame UV/optical-emitting regions observed with *JWST* and the rest-frame FIR-emitting regions observed with ALMA. Addressing these questions requires a multiwavelength analysis of the ionized gas, cold gas, and dust components using both *JWST* and ALMA observations. In this study, we present new deep *JWST*/NIRSpec Micro-Shutter Assembly (MSA) spectroscopy of Y1, combined with archival NIRSpec Integral Field Unit (IFU) and ALMA data, to investigate its ISM properties and the mechanism of dust production and heating. The remainder of this paper is organized as follows. Section 2 describes the observations and datasets used in this study. Section 3 outlines the data reduction and analysis methods. In Section 4, we present the main results, including emission-line properties and ISM diagnostics. Section 5 discusses the implications for dust heating, production, and ISM structure. Finally, Section 6 summarizes our conclusions. Throughout this paper, we assume a flat Λ CDM cosmology with $H_0 = 67.66$ km s $^{-1}$ Mpc $^{-1}$, $\Omega_m = 0.3111$, and $\Omega_\Lambda = 0.6889$ (Planck Collaboration et al. 2020).

2. OBSERVATIONS AND DATA

2.1. Observations

We have observed MACS J0416-Y1 (Y1) with *JWST*/NIRSpec MSA on 2024 November 5, as part of the General Observers (GO) program Deep Reconnaissance of Early Assemblies of Metal-poor Star formation (DREAMS; proposal ID: 4750; Nakajima et al. in preparation). These observations were primarily designed to obtain deep NIRSpec MSA spectroscopy of LAP1-B in the MACS J0416 field (Nakajima et al. 2025). Y1, located close to LAP1-B within the NIRSpec MSA footprint, was simultaneously observed together with other high-redshift galaxies in the same field. The observations were carried out using the F290LP/G395M filter/grating configuration, covering 2.87–5.10 μm at a spectral resolution of $R \sim 1000$. The total effective exposure time was 23 ks.

2.2. Archival data

2.2.1. *JWST*/NIRSpec IFU

We use archival *JWST*/NIRSpec IFU data obtained as part of the Guaranteed Time Observation program # GTO 1208 (CANUCS; Willott et al. 2022) on 2023 February 13. The observations were carried out using the F290LP/G395H filter/grating configuration, covering 2.87–5.14 μm at a spectral resolution of $R \sim 2700$. The observations were conducted with eight dithers and a medium cycling pattern. The total effective exposure time was 18 ks.

2.2.2. *JWST*/NIRCam Imaging

We use archival *JWST*/NIRCam F150W and F444W images of the MACS0416 field observed as part of the Guaranteed Time Observation programs # GTO 1176 (PEARLS; Windhorst et al. 2023) and # GTO 1208 (CANUCS; Willott et al. 2022). The total integration times are 15 ks and 18 ks for F150W and F444W images, respectively. Y1 lies behind the Hubble Frontier Fields cluster MACS J0416.1–2403 and is moderately magnified by gravitational lensing, with a magnification factor of $\mu = 1.60^{+0.01}_{-0.02}$ (Harshan et al. 2024), derived using the lens model presented by (Rihtaršič et al. 2024). Unless otherwise stated, we do not apply corrections for lensing magnification in this work.

2.2.3. ALMA

We use archival ALMA Band 7 data with project IDs #2016.1.00117.S (PI: Y. Tamura; Tamura et al. 2019), #2017.1.0025.S (PI: Y. Tamura; Tamura et al. 2023), #2017.1.00486.S (PI: R. Ellis), and #2018.1.01241.S (PI: Y. Tamura; Tamura et al. 2023), observed in Cycles 4–6 from 2016 October to 2019 August at frequen-

cies around ~ 353 GHz (see Table 1 of Tamura et al. 2023). The total on-source integration times are 27.52 and 18.89 hours for the continuum and [OIII] 88 μm observations, respectively. The baseline lengths range from 15 to 3637 m. We independently re-reduced and analyzed the data and confirmed consistency with the results presented by Tamura et al. (2023). We therefore adopt their dataset in this work.

3. DATA REDUCTION AND ANALYSIS

3.1. Data Reduction

3.1.1. *JWST*/NIRSpec MSA

We reduced the data using the *JWST* Science Calibration Pipeline (version 1.17.1) with the Calibration Reference Data System (CRDS) context file `jwst_1298.pmap`. A detailed description of the reduction procedure will be presented in Nakajima et al. (in preparation; see also Nakajima et al. 2025).

3.1.2. *JWST*/NIRSpec IFU

We reduced the raw data retrieved from the Mikulski Archive for Space Telescopes (MAST) portal using the *JWST* Science Calibration Pipeline with the CRDS context file `jwst_1364.pmap`. We follow the NIRSpec/IFU Data Reduction Pipeline developed by the *JWST* Early Release Science (ERS) Targeting Extremely Magnified Panchromatic Lensed Arcs and their Extended Star formation (TEMPLATES; Rigby et al. 2025) team through stage 1 and stage 2, and replace stage 3 with custom processing using the `reproject` and `reproject_interp` packages. In stage 1, `calwebb_detector1` is applied to perform detector-level corrections for each exposure, followed by $1/f$ noise removal using the `NSClean` package. In stage 2, `calwebb_spec2` is used for WCS assignment, wavelength and flux calibration, flat-fielding, and pass-loss correction. The calibrated data are then combined using drizzle weighting to achieve a spaxel scale of $0''.05$. Finally, we construct the median-stacked 3D data cube using the `reproject` and `reproject_interp` packages, with the background modeled and subtracted as a polynomial function of wavelength.

3.1.3. *JWST*/NIRCam Imaging

JWST/NIRCam raw imaging data were retrieved from MAST archive and reduced using the *JWST* Calibration Pipeline (version 1.12.5) and the CRDS context file `jwst_1193.pmap`, with custom modifications following Harikane et al. (2023a). The final images are drizzled to a pixel scale of $0''.015$.

3.1.4. ALMA

We calibrated and imaged the ALMA raw data, retrieved from the ALMA Science Archive using

Common Astronomy Software Applications (CASA; CASA Team et al. 2022). Data for each program are calibrated using the corresponding CASA pipelines versions: 4.7.0, 5.4.0-68, 5.1.1, and 5.4.0-70 for #2016.1.00117.S, #2017.1.0025.S, #2017.1.00486.S, and #2018.1.01241.S, respectively. All calibrated measurement sets are concatenated into one measurement set using CASA task `concat`. The concatenated data are then imaged with the CASA task `tclean`. Data from spectral windows (spw) covering 364.1–364.7 GHz were used for [OIII] 88 μ m line cube imaging with a velocity resolution of 12.85 km s⁻¹, and all remaining data are used to create the continuum image with a pixel size of 0''.01 pixel⁻¹. We adopted natural weighting, resulting in synthesized beam sizes of 81.1 $\times$ 112.2 mas and 73.9 $\times$ 96.1 mas with position angles of 89°.4 and 93°.8 for the line and continuum images, respectively.

3.2. Astrometric Alignment

We calibrated the astrometry of the *JWST* NIRCam and *JWST* NIRSpec/IFU data using an *HST* image aligned to the *Gaia* DR3 (Gaia Collaboration et al. 2021) as the astrometric reference. For the *HST* image, we used the public *HST* Frontier Fields Epoch 2 data release for MACSJ0416.1–2403 (Proposal ID: 13496; PI: J. Lotz; Lotz et al. 2017), obtained from MAST. To increase the number of *Gaia* sources for astrometric alignment, we utilized the *HST* F125W image to transfer the astrometry from *Gaia* to *JWST*. The *HST* image has a wider field of view and contains fewer saturated sources than the *JWST* images. The *HST* astrometry was first aligned to *Gaia* DR3 catalog coordinates using 4 *Gaia* sources within the field of view. The NIRCam images were then aligned to the *HST* image using 4 stars detected in both datasets. We constructed a pseudo F444W image of Y1 from NIRSpec/IFU data and aligned it to the NIRCam F444W image. After astrometric calibration, the mean positional offset among the matched reference sources is 10 mas.

3.3. Line Flux and Profile Measurements

We fit the emission lines in the NIRSpec/MSA and IFU spectra using a Markov Chain Monte Carlo (MCMC) method with `emcee` (Foreman-Mackey et al. 2013). Flux uncertainties correspond to the 16th and 84th percentiles of the posterior distributions. The flux-density uncertainties were estimated as 1 σ of the flux density in nearby line-free spectral windows within the same extraction region. The emission-line FWHMs were constrained to be larger than the FWHM of the instrumental line spread function (LSF) measured from planetary nebula spectra in Isobe et al. (2023). The intrinsic emission-line velocity widths presented in this paper

were derived by deconvolving a Gaussian profile whose FWHM matches that of the LSF measured by Isobe et al. (2023).

4. RESULTS

4.1. Morphology, Spectrum, and Dynamics

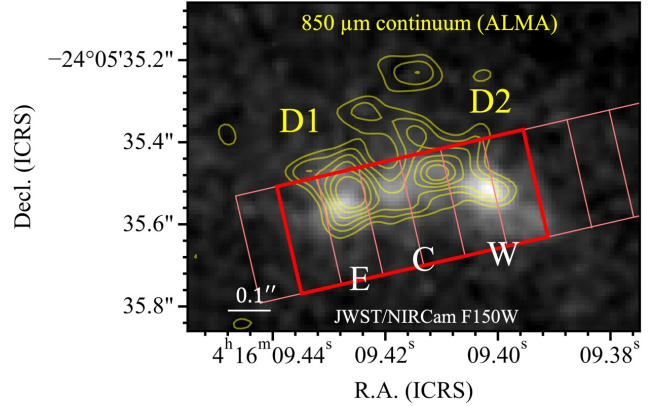


Figure 1. *JWST*/NIRSpec F150W image (rest-frame UV continuum) of Y1 in grayscale with 850 μ m continuum contours at 2 σ , 3 σ , 4 σ , 5 σ , 6 σ , and 7 σ levels overlaid in yellow. The rest-frame UV peaks, E, C, and W, are labeled in white, while the dust continuum peaks, D1 and D2, are marked in yellow. The red boxes indicate the slit footprint, with each segment corresponding to an individual spaxel.

Figure 1 shows a *JWST*/NIRCam F150W (rest-frame UV) image of Y1 in grayscale, with the 850 μ m continuum contours overlaid in yellow. We define three distinct peaks in the F150W image as E, C, and W from east to west. The dust continuum exhibits two peaks, D1 (east) and D2 (west). The red boxes indicate the slit footprint, with each segment corresponding to an individual spaxel. The slit footprint shown in the figure is based on the *JWST* Astronomer’s Proposal Tool¹⁵, and the spaxel grid is constructed by shifting the slit minor axis in parallel steps of 0''.1 from the reference position.

Figure 2 presents the moment maps of [OIII] 5007, which has the highest signal-to-noise ratio among all detected emission lines. The moment maps are constructed by fitting the emission line profile in each spaxel. The moment 0 map corresponds to the integrated line flux. The moment 1 map represents the line-of-sight velocity, computed from the shift of the line center relative to the systemic velocity defined by the [OIII] 88 μ m and [CII] 158 μ m redshift of Y1 ($z = 8.312$; Tamura et al. 2019; Bakx et al. 2020). The moment

¹⁵ <https://www.stsci.edu/scientific-community/software/astrometers-proposal-tool-apt>

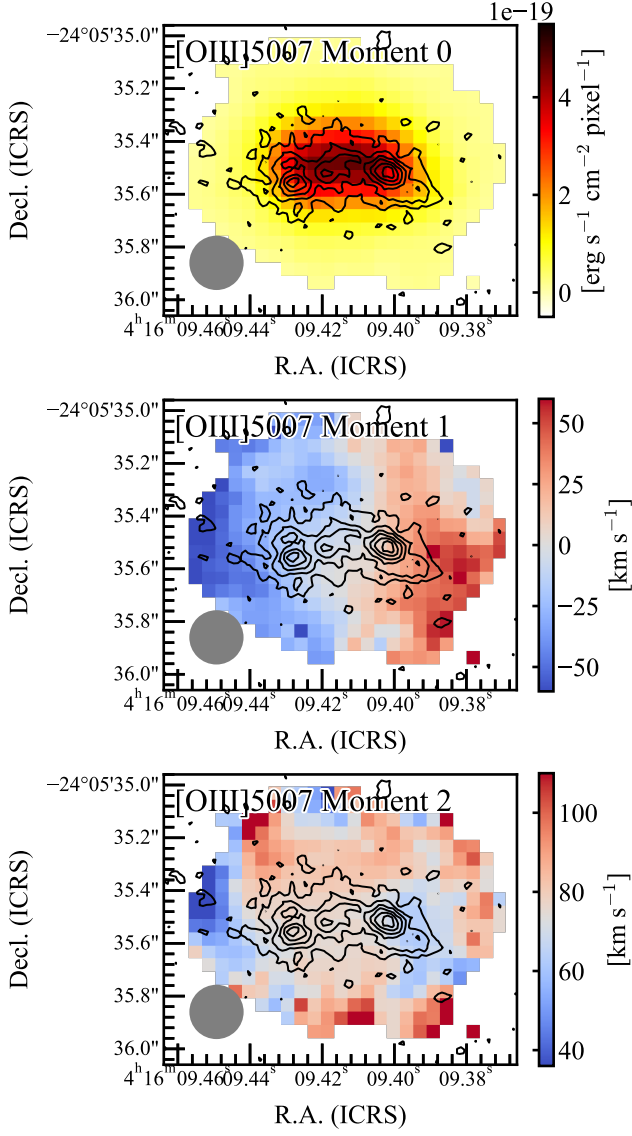


Figure 2. Moment 0 (top), 1 (middle), and 2 (bottom) maps of [OIII] 5007. Pixels with $S/N < 5$ are masked. The contours show the NIRCcam F150W image at 2σ , 5σ , 8σ , 11σ , 14σ , and 17σ levels. The gray circle indicates the PSF at the observed wavelength of [OIII] 5007. The PSF FWHM is estimated using the wavelength-dependent relation derived from serendipitous star in the IFU field of view by D'Eugenio et al. (2024).

2 map traces the velocity dispersion, derived from the fitted line width after correcting for instrumental broadening. The moment 1 map in the central panel shows a velocity gradient of $\sim \pm 60 \text{ km s}^{-1}$, with redshifted emission on the eastern side and blueshifted emission on the western side, consistent with rotational motion. A similar velocity gradient is also observed in [CII] $158\mu\text{m}$ (Bakx et al. 2020).

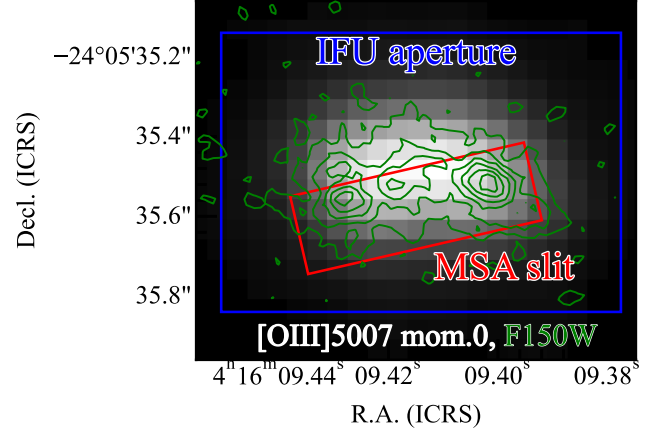


Figure 3. Color map of [OIII] 5007 moment-0 map, overlaid with the green contours of NIRCcam F150W image at 2σ , 5σ , 8σ , 11σ , 14σ , and 17σ levels, and the red (blue) box denotes the MSA slit integration region (IFU aperture) used for spectral extraction. The IFU aperture size is determined from a growth-curve analysis.

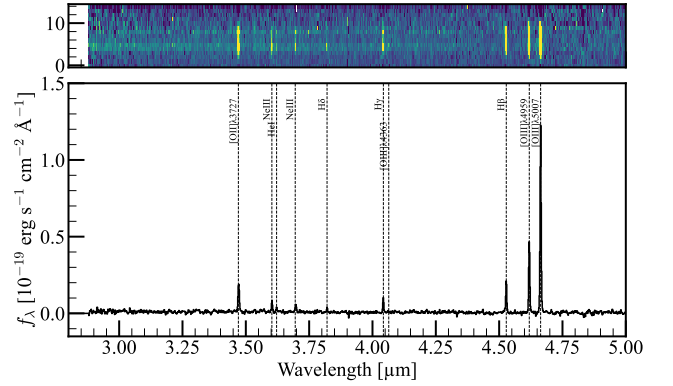


Figure 4. Top: *JWST*/NIRSpec MSA two-dimensional spectrum of Y1. Bottom: Extracted one-dimensional spectrum integrated over the spaxels shown by the red box in Figure 1. Emission lines are marked with dashed vertical lines. Flux density is shown in units of $10^{-19} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$ as a function of observed wavelength.

The red box in Figure 3 indicates the slit spaxels used to construct the MSA one-dimensional spectrum, corresponding to the thick red box in Figure 1. The one-dimensional spectrum integrated over these spaxels is shown in the bottom panel of Figure 4. The top panel presents the two-dimensional spectrum, where the vertical axis corresponds to spaxel position, the horizontal axis to wavelength, and the color scale to flux density. Emission lines are marked with dashed vertical lines. The emission-line profiles of $\text{H}\beta$ and [OIII] 5007 are analyzed in Section 4.2.1.

The blue box in Figure 3 indicates the aperture used to extract the IFU-integrated spectrum. The colormap

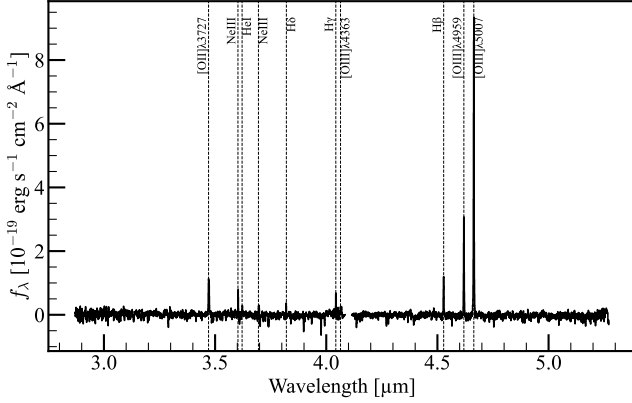


Figure 5. *JWST*/NIRSpec IFU one-dimensional spectrum integrated over the blue box in Figure 3. Emission lines are marked with dashed vertical lines. Flux density is shown in units of $10^{-19} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$ as a function of observed wavelength.

shows the same [OIII] 5007 moment 0 map as in Figure 2. The IFU aperture is determined from 90% coverage of [OIII] 5007 from the growth curve of the [OIII] 5007 flux, with a fixed aspect ratio of 3:4. The resulting aperture size is $\text{R.A.} \times \text{Decl.} = 0''.86 \times 0''.64$. We masked spaxels with flux densities below -10σ over the wavelength range $4.0394\text{--}4.0427 \mu\text{m}$ in the northeastern region of Y1 to exclude strong negative artifacts, where σ is the flux-density uncertainty per spaxel estimated from the line-free channels. The IFU-integrated spectrum extracted within this aperture is shown in Figure 5. Emission lines are marked with dashed vertical lines. The MSA integration region (red box) covers less than 30% of the total [OIII] 5007 flux. We therefore use the IFU data to derive the global physical properties of Y1.

4.2. AGN Signatures

4.2.1. Broad H β Emission

We perform multi-component Gaussian fitting to search for broad components in the H β line. This analysis is based on *JWST*/NIRSpec MSA data, which provide a higher signal-to-noise ratio than the NIRSpec/IFU observations. A broad component is added when the Akaike Information Criterion (AIC; Akaike 1974) decreases by more than 10, $\Delta\text{AIC} = \text{AIC}_{\text{double}} - \text{AIC}_{\text{single}} < -10$, following the statistical model-selection criterion of Burnham & Anderson (2004). Figure 6(a) shows the double-Gaussian fit to the H β line for the spaxel corresponding to the region indicated by the red box in Figure 7, which is the only spaxel satisfying the criterion of $\Delta\text{AIC} < -10$. The velocity FWHM of the broad H β component is $1100^{+800}_{-500} \text{ km s}^{-1}$, exceeding the typical threshold used

to identify AGN, 1000 km s^{-1} (e.g., Harikane et al. 2023b; Matthee et al. 2024; Kiyota et al. 2025). Figure 6(b) shows the double component fit of [OIII] 5007 ($\Delta\text{AIC} = -7$) for the same spaxel. The velocity FWHM of the broad [OIII] 5007 component is $420^{+120}_{-100} \text{ km s}^{-1}$, narrower than that of H β at the $\sim 1\sigma$ level. Broad [OIII] 5007 emission is commonly associated with outflows, whereas the line is expected to be suppressed in the high-density broad-line region ($n_e = 10^{9-11} \text{ cm}^{-3}$; Osterbrock & Mathews 1986) because its critical density ($n_{\text{crit}} = 6.8 \times 10^5 \text{ cm}^{-3}$; Osterbrock & Ferland 2006) is far below typical broad-line region densities. If the broad H β emission originated from outflowing gas, a comparable velocity width would be expected in [OIII] 5007. The observed difference in line width therefore argues against an outflow origin for the broad H β component. In addition, Xu et al. (2025) found that galaxies without AGN typically exhibit outflow velocities of at most $\sim 500 \text{ km s}^{-1}$, further arguing against an origin of the broad H β component solely from outflows. Instead, this suggests that the broad H β line is emitted from a compact and dense broad-line region in the vicinity of an AGN. The observed H β broad-line flux is $f_{\text{H}\beta, \text{broad}} = 1.43^{+0.62}_{-0.60} \times 10^{-19} \text{ erg s}^{-1} \text{ cm}^{-2}$. After correcting for lensing magnification, the black hole mass is estimated to be $M_{\text{BH}} = 1.6^{+3.0}_{-1.0} \times 10^6 M_{\odot}$ using the relation in Greene & Ho (2005). Given the stellar mass of $M_{\star} \sim 10^9 M_{\odot}$ (Harshan et al. 2024), the inferred black hole mass of $M_{\text{BH}} \sim 10^6 M_{\odot}$ corresponds to $M_{\text{BH}}/M_{\star} \sim 10^{-3}$, consistent with the $M_{\text{BH}}\text{--}M_{\star}$ scaling relations in local galaxies (e.g., Greene et al. 2016), suggesting that the black hole is neither significantly overmassive nor undermassive. Figure 7 shows that the red box, corresponding to the spaxel where broad-line component is detected, coincides with the western dust continuum peak, D2. The relation between the elevated dust temperature and AGN activity is discussed in Section 5.1.

4.2.2. LRD Test

We apply the Little Red Dot (LRD) color selection criteria from Greene et al. (2024) to the NIRCам photometry to test whether Y1 satisfies the LRD selection criteria. The upper panel of Figure 8 shows the color criterion used to identify the characteristic V-shaped spectral energy distribution (SED) of LRDs. The V-shaped criterion is defined by

$$(-0.5 < \text{F115W} - \text{F200W} < 1.0) \wedge (\text{F277W} - \text{F444W} > 1.0). \quad (1)$$

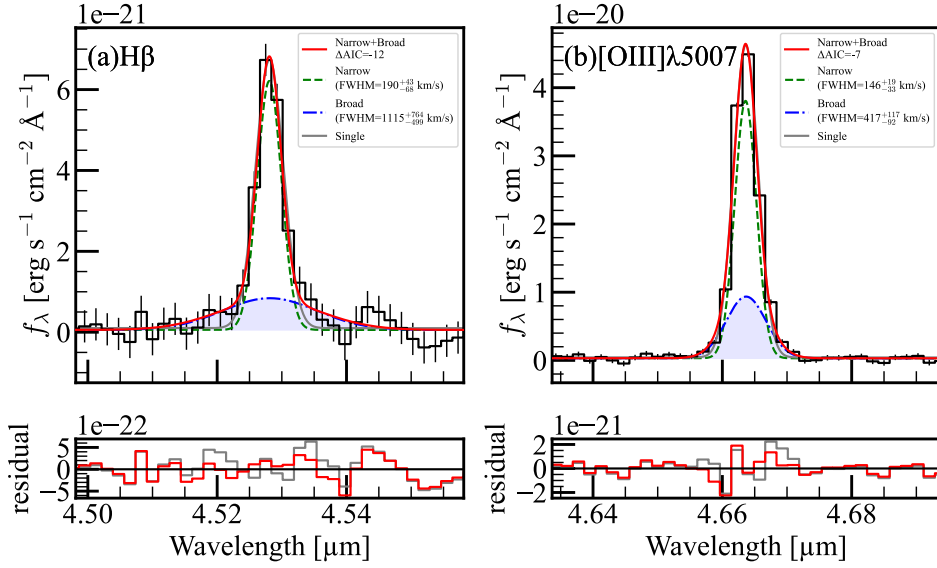


Figure 6. Emission-line profile fitting of (a) $H\beta$ and (b) $[OIII]\lambda 5007$, extracted from the spaxel marked by red box in Figure 7. The black stepped curves and error bars show the observed spectra and their 1σ uncertainties. The green dashed, blue dashed-dotted, and red solid curves represent the narrow, broad, and combined narrow+broad Gaussian profiles, respectively. The gray curves show the single-Gaussian fits. The bottom panels show the residuals.

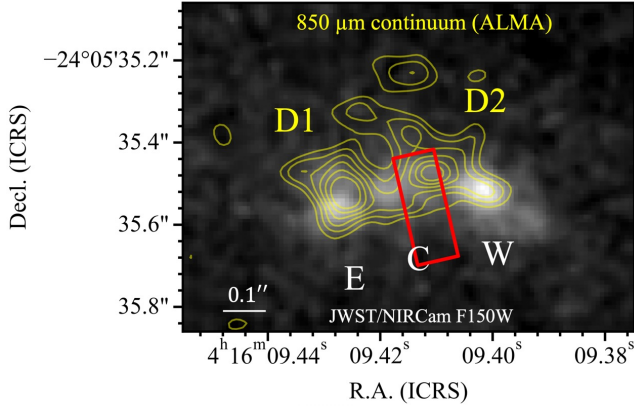


Figure 7. *JWST*/NIRCam F150W image of Y1 overlaid with ALMA 850 μm continuum contours at 2σ , 3σ , 4σ , 5σ , 6σ , and 7σ levels in yellow. The rest-frame UV peaks, E, C, and W, are labeled in white. The dust continuum peaks, D1 and D2, are marked in yellow. The red box indicates the position of the spaxel with broad $H\beta$ emission.

The lower panel of Figure 8 shows the color criterion used to identify red sources,

$$F277W - F356W > 1.0. \quad (2)$$

LRD candidates are required to satisfy both the V-shaped and red color criteria (as well as the compactness criterion) [Greene et al. \(2024\)](#). No individual clumps or the integrated photometry of Y1 satisfy all of these criteria, suggesting that Y1 is not classified as an LRD.

4.2.3. MEx Diagram

In Section 4.2.1, we find a broad $H\beta$ line component at the position corresponding to D2, whereas no significant broad-line component is detected at the position of D1. However, the absence of a broad-line component does not rule out the presence of an AGN. To investigate the ionization properties of all clumps including those without detected broad-line components, we examine their locations on the Mass-Excitation (MEx) diagram, which empirically separates AGN from star-forming galaxies using the $[OIII]\lambda 5007/H\beta$ ratio and stellar mass ([Juneau et al. 2011](#)). For $\log_{10}(M_*/M_\odot) < 9.9$, the dividing curve is given by $\log_{10}([OIII]\lambda 5007/H\beta) = 0.37/(\log_{10}(M_*/M_\odot) - 10.5) + 1$ ([Juneau et al. 2011](#)). Figure 9 shows the location of each clump on this plane. The line ratios are derived from the NIRSpect IFU spectra extracted with a $0''.08$ aperture centered on each clump. For stellar masses, we adopt the SED-fitting results from [Harshan et al. \(2024\)](#). All three clumps lie in the MEx-AGN regime, suggesting high ionization conditions consistent with AGN activity. However, we note that this diagnostic was calibrated using galaxies at $0.3 < z < 1$ and, similar to the BPT diagram, may not be directly applicable to the ISM conditions of high-redshift galaxies (e.g., [Kewley et al. 2013](#); [Steidel et al. 2014](#); [Shapley et al. 2015](#); [Sanders et al. 2016](#); [Topping et al. 2020](#)).

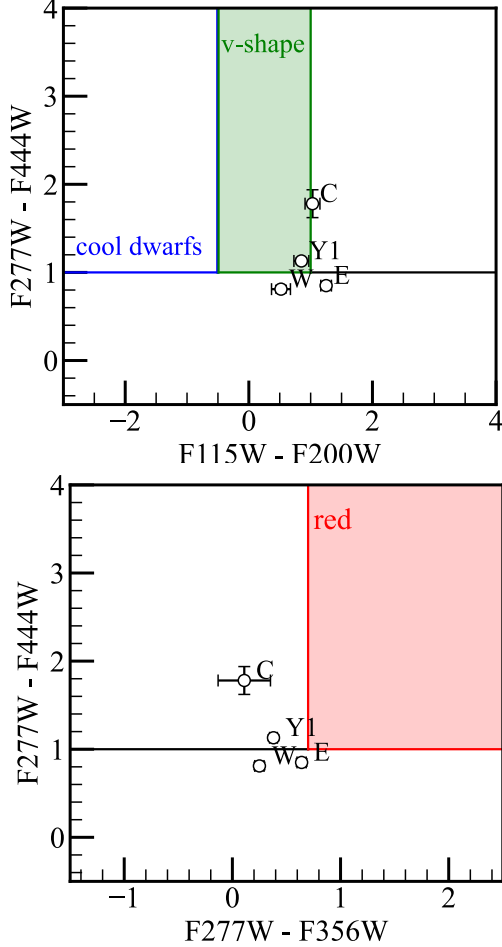


Figure 8. Top: Color criterion used to identify the characteristic V-shaped spectral energy distributions (SEDs) of LRDs in the F277W – F444W versus F115W – F200W plane. The green shaded region indicates the selection window for V-shaped spectral sources, while the blue region marks the locations of cool dwarfs. Bottom: Color criterion used to identify red sources in the F277W – F444W versus F277W – F356W plane. The red shaded region denotes the color-selection criterion for red sources. LRD candidates are required to satisfy the V-shaped, red, and compactness criteria. The labeled points with error bars (Y1, C, W, and E) show the measured colors of Y1 and its three clumps. Photometric measurements are taken from Ma et al. (2024).

4.3. Metallicity

4.3.1. Direct Method

We derive the gas-phase metallicity using the direct method. Figure 10 presents the spectra of $H\gamma$ and $[\text{OIII}]\lambda 4363$. The IFU-integrated spectrum, the MSA spectrum, and the IFU spectrum integrated over the MSA aperture are shown as thick black, green, and blue stepped curves, respectively. The MSA spectrum and the IFU spectrum integrated over the MSA aper-

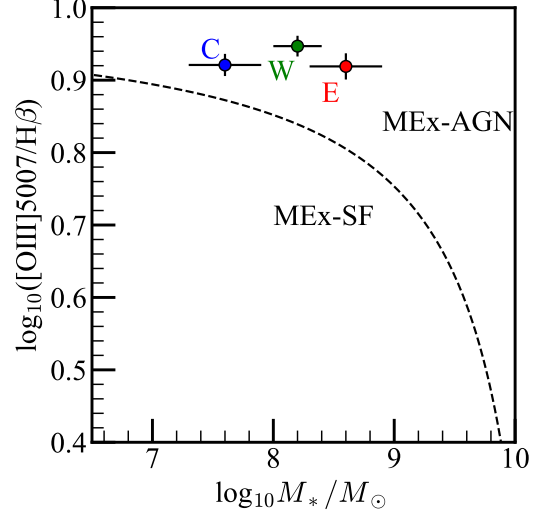


Figure 9. Mass-Excitation (MEx) diagram showing $\log_{10}([\text{OIII}]\lambda 5007/H\beta)$ versus stellar mass. The dashed curve marks the empirical division between star-forming galaxies (MEx-SF) and AGN-dominated systems (MEx-AGN) (Juneau et al. 2011). The measured values for clumps E (red), C (blue), and W (green) are shown with uncertainties. Stellar masses are taken from Harshan et al. (2024).

ture are normalized to the IFU-integrated spectrum at the peak of $H\gamma$. The broader line widths in the MSA spectrum compared to the IFU spectrum arise from the larger LSF FWHM of the medium-grating MSA mode relative to the higher-resolution IFU observations. To characterize the global properties of the galaxy, we derive the metallicity from the IFU-integrated spectrum. For the IFU-integrated spectrum, southeastern spaxels without $[\text{OIII}]\lambda 4363$ coverage due to wavelength gaps are masked prior to integration for this analysis. The resulting flux loss corresponds to 27% of the total $[\text{OIII}]\lambda 5007$ flux. The red curve in the Figure 10 represents the best-fit profile to the IFU-integrated spectrum. The velocity width and redshift of $[\text{OIII}]\lambda 4363$ are fixed to those of $[\text{OIII}]\lambda 5007$. We derive an electron temperature for the $[\text{OIII}]\lambda 4363$ region from the $[\text{OIII}]\lambda 4363/[\text{OIII}]\lambda 5007$ line ratio, obtaining $T_e^{[\text{OIII}]} = 17300 \pm 1500$ K. Using the relation between $T_e^{[\text{OIII}]}$ and the electron temperature of the $[\text{OII}]\lambda 4454$ region ($T_e^{[\text{OII}]} = 0.7 \times T_e^{[\text{OIII}]} + 3000$ K; Stasińska 1982; Campbell et al. 1986), we estimate $T_e^{[\text{OII}]} = 15100^{+1100}_{-1000}$ K. Using these electron temperatures and the fluxes of $[\text{OII}]\lambda 4454$ and $[\text{OIII}]\lambda 5007$, we derive a gas-phase metallicity of $12 + \log(\text{O}/\text{H}) = 7.86^{+0.09}_{-0.08} \sim 0.15 Z_\odot$. The calculation is performed using PyNeb (Luridiana et al. 2015), assuming an electron density of $n_e = 100 \text{ cm}^{-3}$. We neglect ions with ionization states higher than O^{2+} .

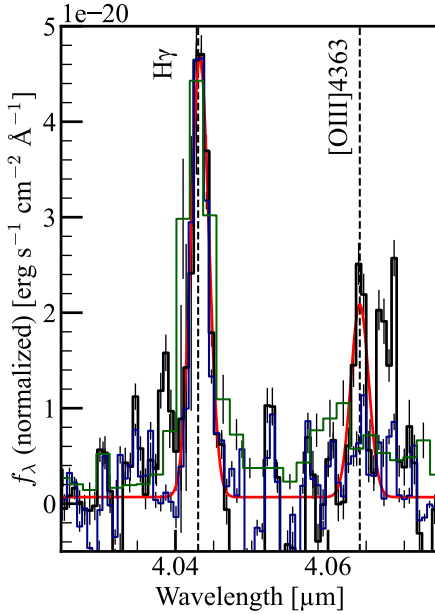


Figure 10. Spectra and best-fit profiles of $H\gamma$ and $[OIII] 4363$. The IFU-integrated spectrum, MSA spectrum, and the IFU spectrum integrated over the MSA aperture are shown in thick black, green, and blue, respectively. The MSA spectrum and the IFU spectrum integrated over the MSA aperture are normalized to the IFU-integrated spectrum at the peak of $H\gamma$. The red curve shows the best-fit model to the IFU-integrated spectrum. The broader line widths in the MSA spectrum compared to the IFU spectra are due to the larger LSF FWHM in the medium-grating MSA mode relative to the high-resolution IFU observations.

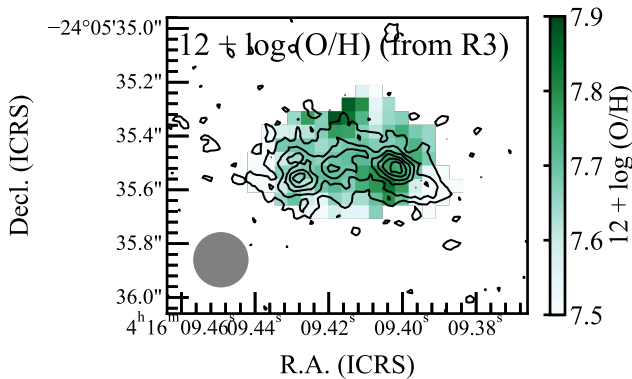


Figure 11. Metallicity $12 + \log(O/H)$ derived from $R3$ using the [Hirschmann et al. \(2023\)](#) relation. Spaxels with $S/N < 5$ are masked. The contours correspond to the NIR-Cam F150W image at 2σ , 5σ , 8σ , 11σ , 14σ , and 17σ levels. The gray circle indicates the PSF at the observed wavelength of $[OIII] 5007$. Because the PSF FWHMs at the observed wavelengths of $[OIII] 5007$ and $H\beta$ differ by only $\sim 0''.01$, no PSF matching is applied.

4.3.2. Strong Line Method

We also estimate the gas-phase metallicity using a strong line method. Based on fluxes measured from the *JWST*/NIRSpec IFU data, we compute the $R3$ index ($=\log_{10}([OIII] 5007/H\beta)$). Metallicity is then inferred from $R3$ using calibrations based on empirical relations ([Nakajima et al. 2022](#)) and cosmological simulations ([Hirschmann et al. 2023](#)). From the IFU-integrated spectrum, we obtain $R3 = 0.90 \pm 0.02$, where the uncertainty is estimated by propagating the posterior samples of the $[OIII]$ and $H\beta$ fluxes. Using the [Hirschmann et al. \(2023\)](#) relation, this $R3$ value corresponds to a metallicity of $12 + \log(O/H) = 7.73 \pm 0.04$, with the spatial distribution shown in Figure 11. The [Nakajima et al. \(2022\)](#) calibration does not intersect with this $R3$ value (lower than the observation), but its maximum corresponds to a metallicity of $12 + \log(O/H) = 7.94$. From these results, we estimate a metallicity of $12 + \log(O/H) \approx 7.7$ – 8.0 based on the $R3$ index. This is consistent with the results from the direct method within uncertainties.

4.4. Electron Density

4.4.1. $[OII] 3729/3726$

We derive the electron density from the $[OII]$ doublet ratio using high spectral resolution *JWST*/NIRSpec IFU data. The electron density is computed using *PyNeb*. We adopt the electron temperature derived in Section 4.3.1. The left panel of Figure 12 shows examples of spaxel-wise $[OII]$ doublet spectra and the corresponding fitting results. The two components of the doublet are clearly resolved. We perform fitting for each spaxel and construct a high-S/N integrated spectrum by summing only spaxels with $[OII]$ detections at $S/N > 5$. The spectrum and its best-fit model are shown in the center panel of Figure 12. From this spectrum, we obtain an electron density of $n_e = 730^{+150}_{-140} \text{ cm}^{-3}$. The right panel of Figure 12 shows the spatial distribution of the electron density on a logarithmic scale for the spaxels used to construct the high-S/N integrated spectrum. The entire system exhibits relatively high electron densities of several hundred to several thousand cm^{-3} . We also derive the electron density from the IFU-integrated spectrum, and obtain $n_e = 862^{+310}_{-242} \text{ cm}^{-3}$, consistent within uncertainties with the values derived from high-S/N spectrum.

4.4.2. $[OIII] 88\mu m/5007$

We derive the rest-frame FIR to optical line ratio $[OIII] 88\mu m/[OIII] 5007$ by combining ALMA and IFU observations. For the $[OIII] 88\mu m$ flux, we use the value reported by [Tamura et al. \(2019\)](#), $0.66 \pm$

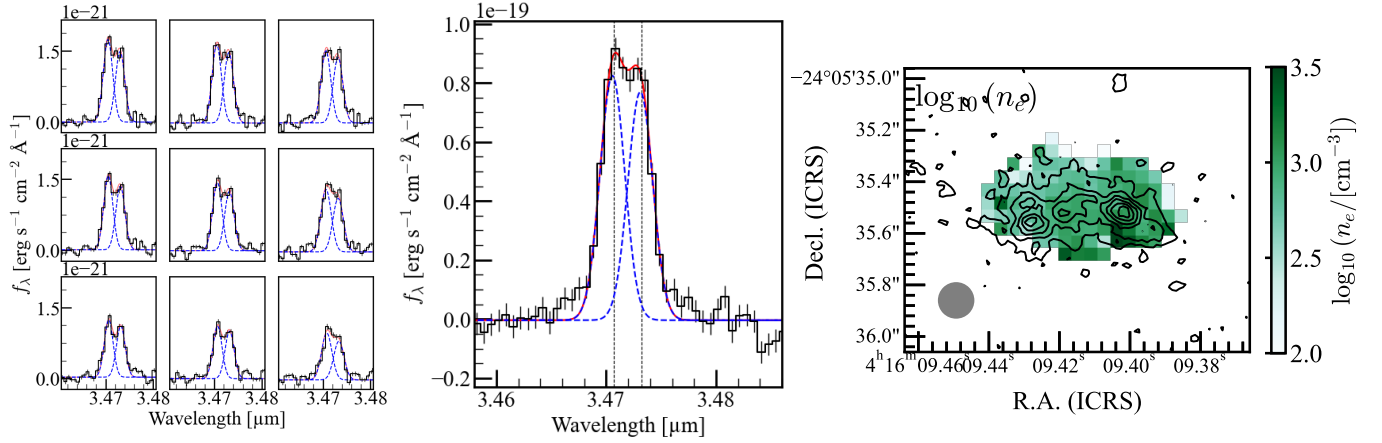


Figure 12. Left: Example spaxel-wise Gaussian fits to the [OII] 3726,3729 doublet for a 3×3 grid. Center: Integrated [OII] spectrum constructed by summing only spaxels with $S/N > 5$. Solid red curves show the best-fit Gaussian profile to the [OII] doublet, and blue dashed curves show the individual components. Right: Spatial distribution of electron density on a logarithmic scale. Spaxels with $S/N < 5$ are masked. The contours correspond to the NIRCам F150W image at 2σ , 5σ , 8σ , 11σ , 14σ , and 17σ levels. The gray circle indicates the PSF at the observed wavelength of [OII] doublet.

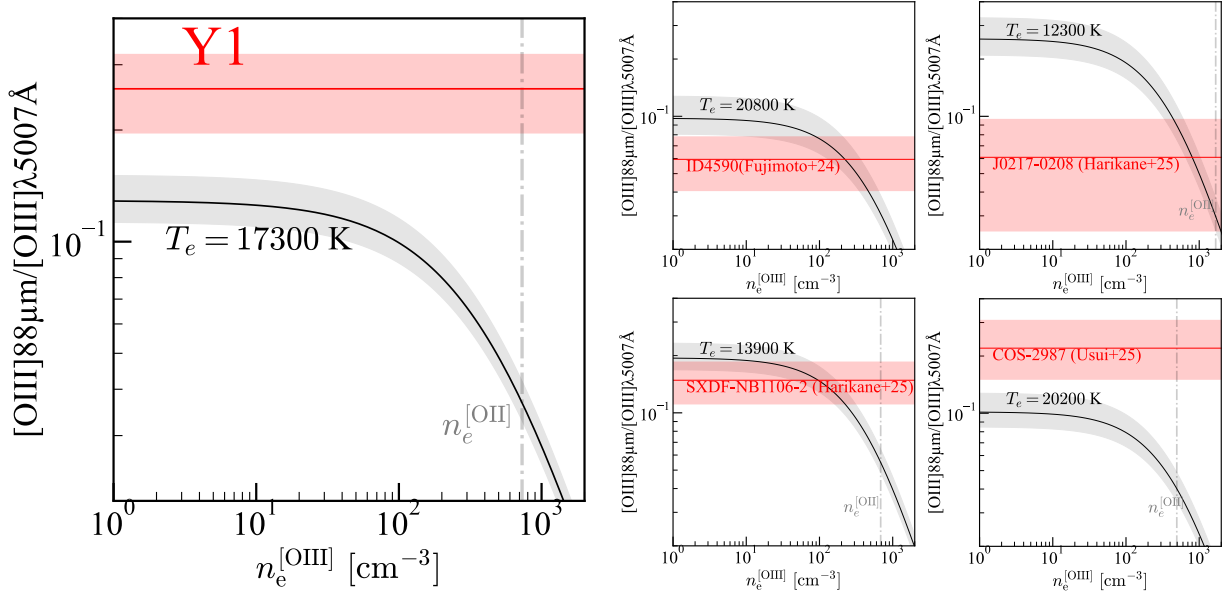


Figure 13. Left: Ratio of [OIII] $88\mu\text{m}$ to [OIII] $5007\text{\AA}$ as a function of electron density ($n_e^{\text{[OIII]}}$). The black curve shows the theoretical relation assuming an electron temperature of $T_e = 17300 \pm 1500$ K, corresponding to the value measured for Y1, and the gray shaded region represents the uncertainty. The red horizontal line and shaded region indicate the observed ratio and its uncertainty for Y1. The vertical dashed line marks the electron density inferred from the optical [OII] diagnostic. Right: Same as the left panel, but for ID4590 (top left; Fujimoto et al. 2024), J0217-0208 (top right; Harikane et al. 2025), SXDF-NB1106-2 (bottom left; Harikane et al. 2025), and COS-2987 (bottom right; Usui et al. 2025).

$0.16 \text{ Jy km s}^{-1}$. The [OIII] 5007 flux is measured from the IFU-integrated spectrum, $(3.10 \pm 0.02) \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$. From these values, we obtain an [OIII] line ratio of $[\text{OIII}] 88\mu\text{m} / [\text{OIII}] 5007 = 0.26 \pm 0.06$. This value and uncertainty are shown in the left panel of Figure 13. The theoretical relation between the [OIII] line ratio and electron density at $T_e = 17300$ K (the electron temperature derived using direct method, see

Section 4.3.1) is also plotted as the black curve. The gray shaded region presents the uncertainty propagated from the electron temperature. The figure shows that, under the assumption of a single homogeneous ionized nebula, the observed ratio cannot be reproduced for any electron density. Further discussion of this discrepancy and the right panels of Figure 13 is given in Section 5.2.

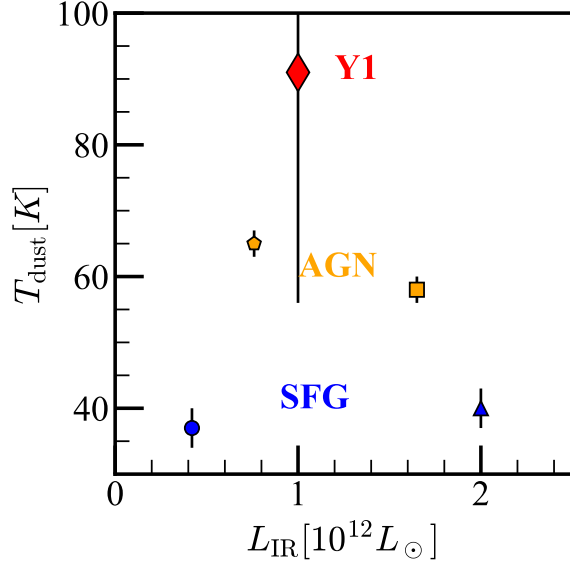


Figure 14. Dust temperature T_{dust} as a function of infrared luminosity (L_{IR}). The red diamond shows Y1 from Bakx et al. (2025), compared with stacked measurements of $z \sim 1$ (blue circle) and $z \sim 2$ (blue triangle) star-forming galaxies, silicate AGN (orange square), and featureless AGN (orange pentagon) from Kirkpatrick et al. (2012).

5. DISCUSSION

5.1. Sources of Dust Heating

Y1 has been observed with ALMA Bands 3–9, with continuum emission detection in Bands 5–9 (Tamura et al. 2019, 2023; Bakx et al. 2020, 2025; Jones et al. 2024; Harshan et al. 2024). Bakx et al. (2025) report dust temperature and dust mass of 91^{+62}_{-35} K and $1.4^{+1.3}_{-0.5} \times 10^6 M_{\odot}$, respectively, based on SED fitting of these observations. This temperature is higher than typical values inferred for galaxies at $z \gtrsim 7$ (40–60 K; Sommovigo et al. 2022; Mitsuhashi et al. 2024).

The origin of such elevated dust temperatures remains under debate. A redshift evolution of dust temperature has been reported, with T_{dust} increasing toward higher redshift (Béthermin et al. 2015; Sommovigo et al. 2022; Mitsuhashi et al. 2024). Extrapolation of empirical relations derived at $z \lesssim 7$ predicts dust temperatures of ~ 40 –60 K at $z \sim 8.3$. This trend has been interpreted as a consequence of the lower metallicity and dust mass at high- z , which reduce dust shielding and enable more efficient absorption of UV radiation (e.g., Sommovigo et al. 2022). These effects are expected to be relevant for Y1, which exhibits both low metallicity and low dust mass. Theoretical studies have shown that high dust temperatures can be achieved in compact star-forming

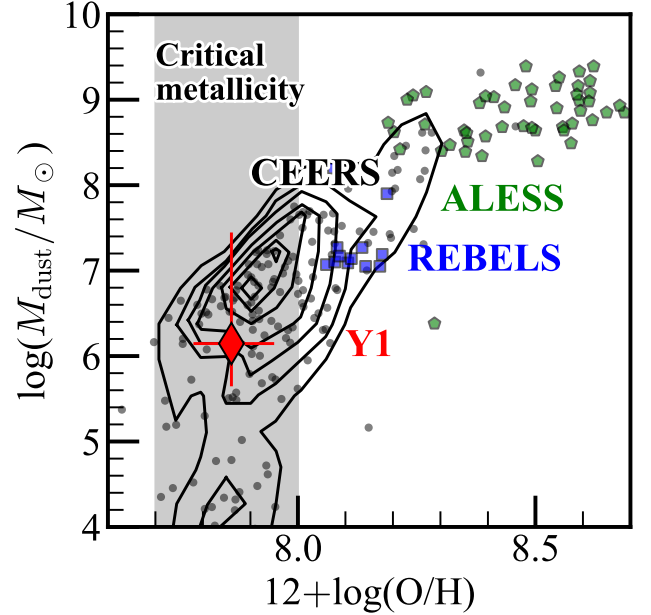


Figure 15. Dust mass as a function of gas-phase metallicity. The red diamond marks Y1. The gray shaded region indicates the critical metallicity range (0.1 – $0.2 Z_{\odot}$). The blue squares and green pentagons represent the REBELS ($z \sim 7$; Algera et al. 2025) and ALESS ($z \sim 1$ –6; da Cunha et al. 2015) samples, respectively. The black contours and points show the distribution of galaxies at $4 < z < 11$ from CEERS (Burgarella et al. 2025). For all galaxies except for Y1, the metallicities are estimated from stellar masses using the mass–metallicity relation at $z = 4$ –10 (Nakajima et al. 2023).

regions (e.g., Nakazato et al. 2026). Kano et al. (2026) suggest that the high dust temperature in Y1 may be explained by an extremely dense cold neutral medium ($\sim 10^{3-4} \text{ cm}^{-3}$), which enhances UV photon trapping and increases the efficiency of dust heating. Although current observations do not indicate an elevated star-formation rate surface density for Y1 on global scales (Harshan et al. 2024), compact star-forming regions on unresolved scales may still contribute to the dust heating.

On the other hand, we detect a broad $H\beta$ line (Section 4.2.1), indicating the presence of an AGN. The spatial coincidence between the broad-line emission and one of the dust continuum peaks suggests that AGN radiation may contribute locally to dust heating. Kirkpatrick et al. (2012) show that AGN-host galaxies exhibit higher dust temperatures than star-forming galaxies based on stacked SED analyses. They interpret this as evidence that UV–optical radiation from the AGN is absorbed by surrounding dust and re-emitted in the infrared, producing a warm dust component in addition to that ex-

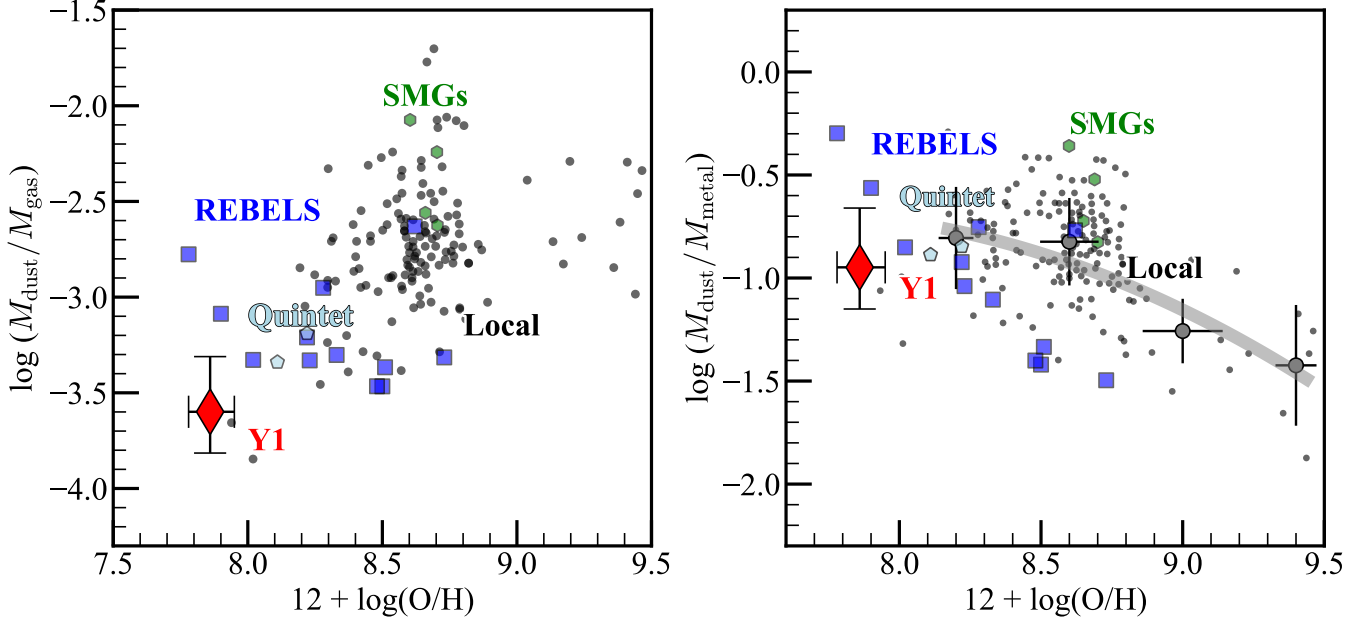


Figure 16. Left: Dust-to-gas ratio, $\log(M_{\text{dust}}/M_{\text{gas}})$, as a function of gas-phase metallicity, $12 + \log(\text{O}/\text{H})$. The blue squares, light blue pentagons, green heptagons, and black points show REBELS galaxies ($z \sim 7$; [Algera et al. 2025](#)), Quintet YD1 and YD4YD6 ($z \sim 7.9$; [Umemata et al. 2025](#)), submillimeter galaxies (SMGs) ($z \sim 2$; [Shapley et al. 2020](#)) and local galaxies ([De Vis et al. 2019](#); [Casasola et al. 2020](#)), respectively. The red diamond marks Y1. Right: Same as the left panel, but for the dust-to-metal ratio, $\log(M_{\text{dust}}/M_{\text{metal}})$, on the vertical axis. The gray points indicate the median values of local galaxies at $12 + \log(\text{O}/\text{H}) > 8.0$, binned with a width of $\Delta(12 + \log(\text{O}/\text{H})) = 0.4$. The gray curve shows a polynomial fit to these median values.

pected from star formation alone. Figure 14 illustrates this trend, where AGN-host galaxies (orange) are offset toward higher dust temperatures by ~ 20 K compared to star-forming galaxies (blue). Spatially resolved observations (e.g., [Tsukui et al. 2023](#); [Villanueva et al. 2024](#); [Meyer et al. 2025](#); [Fernández Aranda et al. 2025](#)) and theoretical studies (e.g., radiative transfer modeling of a quasar at $z \sim 6$; [Schneider et al. 2015](#)) further suggest that AGN can heat dust and contribute to the infrared emission on sub-galactic scales. In particular, the $z \sim 6.9$ quasar host galaxy J2348–3054 exhibits a dust temperature of 88 ± 2 K within the central $r < 216$ pc region ([Fernández Aranda et al. 2025](#)). A similar AGN-driven heating mechanism may contribute to the elevated dust temperature observed in Y1. We therefore interpret the high dust temperature of Y1 as the result of multiple contributing factors, including redshift-dependent ISM conditions (e.g., low metallicity and low dust mass), compact star formation, and AGN heating.

Next, we consider the dust production mechanisms. Dust production mechanisms are broadly categorized into stellar sources (e.g., supernovae and AGB stars) and grain growth in the ISM through accretion of gas-phase metals onto pre-existing dust grains ([Dwek 1998](#); [Asano et al. 2013](#)). Chemical evolution models suggest that stellar sources can dominate dust production in

low-metallicity galaxies, while grain growth in the ISM becomes dominant as galaxies evolve and enrich metals ([Mancini et al. 2015](#)).

Previous studies have shown that the efficiency of ISM grain growth is dependent on metallicity ([Asano et al. 2013](#); [Burgarella et al. 2025](#)). In particular, grain growth is expected to become the dominant source of dust production above a critical metallicity, Z_{crit} ([Asano et al. 2013](#); [Burgarella et al. 2025](#)). Although Z_{crit} depends on model assumptions and physical conditions, such as the star formation timescale and the dust grain size distribution, it is typically estimated to be in the range of $\sim 0.1\text{--}0.2 Z_{\odot}$ (e.g., [Asano et al. 2013](#); [Burgarella et al. 2025](#)). Figure 15 shows the relation between M_{dust} and gas-phase metallicity, where the range of Z_{crit} is indicated by the gray shaded region. Y1 has a metallicity of $Z \sim 0.15 Z_{\odot}$ (red diamond), placing it around the critical metallicity and in the low-metallicity regime along the sequence traced by the Cosmic Evolution Early Release Science Survey (CEERS; [Burgarella et al. 2025](#)), the ALMA survey of LABOCA Extended Chandra Deep Field South Survey sources (ALESS; $z \sim 1\text{--}6$; [da Cunha et al. 2015](#)), and the Reionization Era Bright Emission Line Survey (REBELS; $z \sim 7$; [Algera et al. 2025](#)) galaxies. This suggests that grain growth in the ISM is becoming efficient in Y1.

To further investigate the dust content, we examine the dust-to-gas and dust-to-metal ratios as a function of metallicity, following Kiyota et al. (2025) (see also Palla et al. 2024; Algera et al. 2025), as shown in Figure 16. The molecular gas mass is estimated from the [CII] luminosity using the empirical relation:

$$\log\left(\frac{L_{[\text{CII}]}}{L_{\odot}}\right) = -1.28 + 0.98 \log\left(\frac{M_{\text{H}_2}}{M_{\odot}}\right) \quad (3)$$

(Zanella et al. 2018). Adopting a conversion factor $M_{\text{gas}} = \xi(M_{\text{HI}} + M_{\text{H}_2})$ with a metallicity-dependent factor of $\xi = 1.34$, and assuming $M_{\text{HI}} \ll M_{\text{H}_2}$, we derive a total gas mass of $M_{\text{gas}} = 5.56^{+0.61}_{-0.61} \times 10^9 M_{\odot}$, where the inferred gas mass does not include the ionized gas component. The total metal mass is then estimated as $M_{\text{metal}} = Z M_{\text{gas}} + M_{\text{dust}}$, yielding $M_{\text{metal}} = 1.24^{+0.18}_{-0.13} \times 10^6 M_{\odot}$. Here, Z is the metallicity $Z = Z/Z_{\odot} \times Z_{\odot} = 10^{12+\log(\text{O/H})-8.69} \times Z_{\odot} = 0.00198$, adopting a solar metallicity of $Z_{\odot} = 0.0134$ (Asplund et al. 2009).

From these values, we obtain $\log(M_{\text{dust}}/M_{\text{gas}}) = -3.60^{+0.29}_{-0.22}$ and $\log(M_{\text{dust}}/M_{\text{metal}}) = -0.95^{+0.29}_{-0.20}$. These ratios are shown as red diamonds in Figure 16. Both ratios are lower than the sequences observed in high- z samples from the REBELS (blue; $z \sim 7$; Algera et al. 2025) and Quintet YD1 and YD4YD6 (light blue; $z \sim 7.9$ Umehata et al. 2025), as well as local galaxies (black and gray (binned); De Vis et al. 2019; Casasola et al. 2020), and submillimeter galaxies (SMGs; green; Shapley et al. 2020), indicating that Y1 is relatively dust-poor compared to its gas and metal content. These results suggest that Y1 is in an early stage of dust enrichment, consistent with grain growth becoming efficient near the critical metallicity. We note that [CII] does not uniquely trace molecular gas, as it can originate from multiple ISM phases (Casavecchia et al. 2025; Vallini et al. 2025). In addition, its luminosity depends on metallicity (i.e., carbon abundance) and ISM conditions, introducing systematic uncertainties in the inferred gas mass.

5.2. [OIII] 88 μm /5007 Ratio

As discussed in Section 4.4.2, Y1 has a high integrated flux ratio of [OIII] 88 μm /[OIII] 5007 = 0.26 ± 0.06 . Under the assumption of a single homogeneous ionized nebula, this ratio cannot be reproduced for any electron density. In contrast, the electron density inferred from the [OII] 3726,3729 doublet is $\gtrsim 700 \text{ cm}^{-3}$, resulting in an inconsistency between the densities inferred from [OII] and [OIII] diagnostics. Similar discrepancies have been reported in other high-redshift galaxies (Harikane et al. 2025; Usui et al. 2025), suggesting that this may be

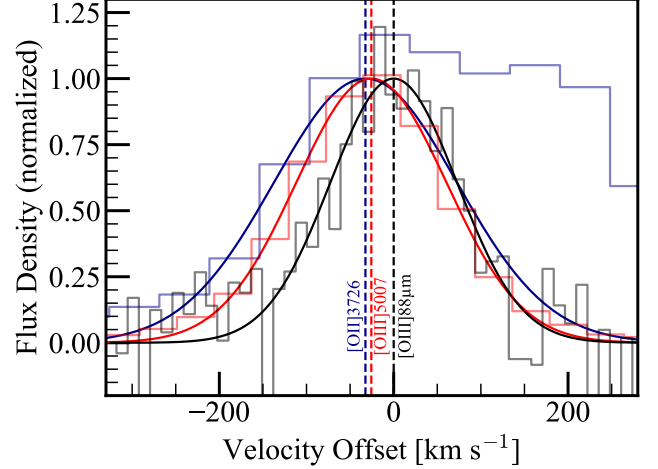


Figure 17. Velocity-offset profiles of [OII] 3726 (blue) and [OIII] 5007 (red) relative to [OIII] 88 μm (black; reference frame). Solid curves show Gaussian fits to each profile. Vertical dashed lines mark the center velocity of each component.

common in high- z ISM environments (Choustikov et al. 2026).

One possible explanation is that the [OIII] 88 μm and optical emission lines originate from physically and kinematically distinct gas components. To investigate this possibility, we compare the line-of-sight velocities of [OII] 3726, [OIII] 5007, and [OIII] 88 μm . Figure 17 shows the velocity offsets of the rest-frame optical lines relative to the [OIII] 88 μm line. The [OII] 3726 and [OIII] 5007 spectra are obtained from the IFU-integrated spectrum, and the [OIII] 88 μm spectrum is constructed by integrating all spaxels with $S/N > 3$ in the moment 0 map over the same aperture used for IFU-integrated spectra. According to the *JWST* User Documentation, IFU data have the wavelength calibration uncertainty of $\sim 20 \text{ km s}^{-1}$ ¹⁶. Accounting for this uncertainty, we find velocity offsets of $-32^{+37}_{-37} \text{ km s}^{-1}$ for [OII] 3726 and $-26^{+30}_{-30} \text{ km s}^{-1}$ for [OIII] 5007 relative to [OIII] 88 μm . These offsets are consistent with zero within the uncertainties, indicating that there is no significant velocity separation between the FIR and optical line emitting regions. This suggests that the observed discrepancy is unlikely to arise from kinematically distinct components, but instead reflects different physical conditions within spatially connected regions.

Dust attenuation is required to explain the discrepancy between the observed and theoretical [OIII] line ratios. If the electron density inferred from [OIII] is assumed to be consistent with that derived from the

¹⁶ <https://jwst-docs.stsci.edu/jwst-calibration-status/nirspec-calibration-status/nirspec-ifu-calibration-status#gsc.tab=0>

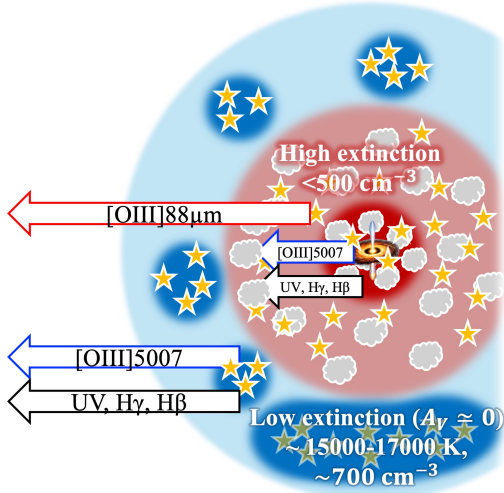


Figure 18. Schematic illustration of the spatial origin of the emission lines and the effects of dust attenuation. The system consists of a dust-rich inner region and a dust-poor outer region. The innermost compact high-density region, associated with an AGN, is dust-obscured and contributes little to the observed [OIII] 88 μ m emission because of its high electron density. Surrounding this component is a lower-density dusty region ($n_e \lesssim 500 \text{ cm}^{-3}$), where [OIII] 88 μ m emission can efficiently arise. In these dusty inner regions, dust attenuation suppresses the escape of UV and optical emission. In contrast, the outer low-extinction region dominates the observed UV continuum and optical emission lines. The outer region is characterized by low dust extinction, as suggested by the $H\gamma/H\beta$ ratio being consistent with the Case B value. The optical diagnostics therefore primarily trace the ionized gas in this outer component, with an electron density of $\sim 700 \text{ cm}^{-3}$ inferred from the [OII] doublet ratio and an electron temperature of $T_e \sim 15000\text{--}17000 \text{ K}$ inferred from the optical [OIII] line ratio. Because this electron density exceeds the critical density of [OIII] 88 μ m, the outer low-extinction region is unlikely to contribute significantly to the observed [OIII] 88 μ m emission. Blue, black, and red arrows denote [OIII] 5007, UV/ $H\gamma/H\beta$, and [OIII] 88 μ m emission, respectively. Gray clouds denote dust, and yellow stars indicate stellar sources.

[OII] 3726,3729 doublet, then extinction is estimated to be $A_V \sim 1.7$, adopting the Small Magellanic Cloud (SMC) reddening law (Gordon et al. 2003). However, the integrated Balmer decrement measured from the IFU data, $H\gamma/H\beta = 0.47^{+0.05}_{-0.04}$, indicates little or no dust attenuation assuming Case B recombination. The fluxes used to derive this ratio are measured from the spectrum extracted after masking spaxels affected by the wavelength gap, using the same masked region described in Section 4.3.1. The intrinsic ratio calculated using Pyneb is $H\gamma/H\beta = 0.47$ for Case B conditions with $T_e = 17300 \text{ K}$ and $n_e = 100\text{--}1000 \text{ cm}^{-3}$. This apparent inconsistency among the multi-wavelength line

diagnostics suggests that the observed optical emission lines preferentially trace low-extinction regions.

Figure 18 presents a schematic illustration of the ISM structure that can explain these observations. The system consists of a dust-rich inner region and a dust-poor outer region. The center of the dust-rich region hosts a compact, high-density region associated with an AGN. Because the critical density of [OIII] 88 μ m is $\sim 500 \text{ cm}^{-3}$, the innermost region is unlikely to contribute significantly to the observed [OIII] 88 μ m emission. Surrounding this central component is a lower-density dusty region with $n_e \lesssim 500 \text{ cm}^{-3}$, where [OIII] 88 μ m can arise efficiently. In these dusty inner regions, dust attenuation suppresses the escape of UV and optical emission, limiting their contribution to the observed UV-optical emission. The outer region is characterized by low dust extinction, as suggested by the $H\gamma/H\beta$ ratio being consistent with the Case B value. As a result, the UV continuum and optical emission lines are not significantly affected by dust extinction, and the observed UV-optical emission is dominated by this component. Under this interpretation, the optical diagnostics primarily reflect the physical conditions of the ionized gas in the outer low-extinction region, with an electron density of $\sim 700 \text{ cm}^{-3}$ inferred from the [OII] doublet ratio and an electron temperature of $T_e \sim 15000\text{--}17000 \text{ K}$ inferred from the optical [OIII] line ratio. Because this electron density exceeds the critical density of [OIII] 88 μ m, the outer low-extinction region is unlikely to contribute significantly to the observed [OIII] 88 μ m emission.

This picture is broadly consistent with observations of other high-redshift galaxies. The right panels of Figure 13 show the observed [OIII] 88 μ m/[OIII] 5007 ratios and the theoretical relations between [OIII] 88 μ m/[OIII] 5007 and electron density based on the measured electron temperatures for ID4590 ($z \sim 8.5$; Fujimoto et al. 2024), J0217-0208 ($z \sim 6.2$; Harikane et al. 2025), SXDF-NB1106-2 ($z \sim 7.2$; Harikane et al. 2025), and COS-2987 ($z \sim 6.8$; Usui et al. 2025). ID4590, J0217-0208, and SXDF-NB1106-2, shown in the top left, top right, and bottom left panels, respectively, do not exhibit the discrepancy seen in Y1, as there exists an electron density consistent with the observed [OIII] 88 μ m/[OIII] 5007 ratio under the measured electron temperature. Dust continuum emission has not been detected in these galaxies (Fujimoto et al. 2024; Inoue et al. 2016; Ren et al. 2023; Harikane et al. 2025), consistent with our interpretation that they do not contain sufficiently dust-obscured regions to strongly suppress the optical emission lines and produce the observed discrepancy. In contrast, COS-2987, shown in the bottom right panel,

exhibits a discrepancy between the observed and theoretical line ratios similar to that seen in Y1 (Usui et al. 2025). Although dust continuum emission has not been detected in this galaxy (Smit et al. 2018; Witstok et al. 2022), the nondetection is still consistent with our interpretation. Assuming a dust mass comparable to that of Y1 ($M_{\text{dust}} \sim 10^6 M_{\odot}$), the dust continuum flux density in COS-2987 is expected to be below 1/4 of the current observational limit ($M_{\text{dust}} \lesssim 4 \times 10^6 M_{\odot}$ assuming $T_{\text{dust}} = 50$ K and $\beta_{\text{IR}} = 1.5$; Witstok et al. 2022). Therefore, COS-2987 may still host dusty regions comparable to those inferred for Y1, where the optical emission lines are significantly suppressed.

Our findings and comparison with other high- z galaxies support a picture in which dust extinction causes the observed optical and FIR emission to be dominated by different regions within the galaxy. As a result, optical and FIR lines do not necessarily trace the same ionized gas components, leading to discrepancies between optical line diagnostics and diagnostics combining optical and FIR lines. This interpretation is qualitatively consistent with studies suggesting that FIR-emitting regions are more compact than UV-emitting regions in high-redshift galaxies (e.g., Fujimoto et al. 2017; Rupakarn et al. 2016; Boogaard et al. 2024; Kiyota et al. 2026). Combining *JWST* rest-frame optical spectroscopy with ALMA FIR line observations therefore requires careful interpretation, particularly when deriving global ISM properties under single-zone assumptions.

6. SUMMARY

We have presented a comprehensive multi-wavelength analysis of MACS0416-Y1, a galaxy at $z = 8.312$ with the highest-redshift ALMA dust continuum detection to date. By combining deep *JWST*/NIRSpec MSA spectroscopy with archival *JWST*/NIRSpec IFU and ALMA data, we investigate the AGN activity, dust properties, and ISM conditions of Y1. Our main findings are summarized as follows.

1. The deep NIRSpec spectrum reveals a broad $\text{H}\beta$ component with a velocity width of $\sim 1100 \text{ km s}^{-1}$, indicating the presence of a broad-line AGN. In addition, all clumps lie in the AGN regime of the MEx diagram, consistent with high ionization conditions across the clumps, potentially associated with AGN activity. We also perform a Little Red Dot test using the NIRCам photometry and find that none of the individual clumps or the integrated photometry of Y1 satisfy the LRD selection criteria.

2. Using the direct method, we derive a gas-phase metallicity of $12 + \log(\text{O}/\text{H}) = 7.86^{+0.09}_{-0.08}$ ($\sim 0.15 Z_{\odot}$). Strong-line metallicity estimate based on the $R3$ index is consistent with this result. The metallicity places Y1 near the critical metallicity ($\sim 0.1\text{--}0.2 Z_{\odot}$), where dust grain growth in the ISM is becoming efficient.
3. Combining the metallicity, ALMA dust continuum measurements, and the gas mass inferred from $[\text{CII}]$, we derive low dust mass ratios of $\log(M_{\text{dust}}/M_{\text{gas}}) = -3.60^{+0.29}_{-0.22}$ and $\log(M_{\text{dust}}/M_{\text{metal}}) = -0.95^{+0.29}_{-0.20}$. These values indicate that Y1 is relatively dust-poor despite its dust continuum detection, consistent with an early stage of dust enrichment where grain growth is becoming efficient.
4. The high dust temperature of $T_{\text{dust}} \simeq 91^{+62}_{-35}$ K may be driven by multiple factors, including low metallicity and dust mass, compact star formation, and AGN heating. Previous studies have shown that AGN can produce elevated dust temperature. The spatial coincidence between the broad line emission and one of the dust continuum peaks is consistent with such AGN-driven dust heating in Y1, suggesting that AGN may contribute to the high dust temperature in Y1.
5. We find a high integrated line ratio of $[\text{OIII}] 88\mu\text{m}/[\text{OIII}] 5007 = 0.26 \pm 0.06$, which cannot be reproduced by a single homogeneous ionized nebula model for any electron density. Explaining this ratio requires dust attenuation, whereas the Balmer decrement indicates little or no attenuation in the observed optical emission. We propose that dust attenuation causes the observed optical and FIR lines to preferentially trace different regions within the galaxy, with observed optical emission dominated by low-extinction regions and FIR emission tracing more obscured regions. This implies that joint analysis of *JWST* optical spectroscopy and ALMA FIR line observations should be treated with caution, particularly when assuming single-zone ISM.

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