

A Steep-Extinction QSO at $z=4.6$: JWST Evidence for Abundant Small Dust Grains

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ABSTRACT

The rapid accumulation of massive dust reservoirs in the early Universe remains a major challenge in astrophysics. While core-collapse supernovae can inject large dust grains ($a \gtrsim 0.1 \mu\text{m}$) on short timescales, explaining the total dust budgets in the early Universe likely **requires efficient grain growth in the interstellar medium (ISM)**. Such growth depends critically on an abundant population of small grains, which maximize the surface area available for accretion and may be generated by rapid dust-processing or dust-formation channels. Here, we report the discovery of a QSO UDS-27023 at $z = 4.556 \pm 0.003$, identified using JWST/NIRSpec spectroscopy. By quantitatively comparing the spectra to QSO composite templates, we find that UDS-27023 displays an exceptionally steep far-UV extinction curve ($A_{1500}/A_V \approx 8$) but notably lacks the 2175 Å bump, indicating a dominance of small silicate dust grains. We interpret this phenomenology as evidence for active small-grain production and processing in the QSO environment. Mechanical shattering of pre-existing large grains by QSO-driven shocks and outflows provides one natural pathway, while in-situ condensation of silicate grains inside dense QSO-driven winds may offer an additional route. Such a population of steep-extinction QSOs (SEQs) may therefore reveal a short-lived phase in which luminous AGN generate, process, and redistribute small grains, potentially facilitating rapid ISM grain growth and enriching the circumgalactic medium.

1. INTRODUCTION

Dust is a fundamental constituent of galaxies across cosmic time, regulating the thermodynamic state of the gas, catalyzing the formation of molecular clouds, and obscuring star formation tracers (B. T. Draine 2003; A. Li & J. M. Greenberg 2003). Understanding the origin and evolution of dust in the first billion years of the Universe remains one of the most contentious frontiers in astrophysics (R. Schneider & R. Maiolino 2024). One of the primary diagnostics is the dust grain size distribution, which fundamentally dictates both the total dust mass budget and the slope of the extinction curve (*e.g.*, H. Hirashita 2012; R. S. Asano et al. 2013). Specifically,

an abundance of small grains leads to a steep rise in extinction at ultraviolet (UV) wavelengths, whereas a distribution dominated by large grains results in a flatter, “grey” extinction curve.

The initial injection of dust into the early interstellar medium (ISM) is believed to be dominated by core-collapse supernovae (CCSNe), which typically produce large grains ($a > 0.1 \mu\text{m}$) on short timescales (< 10 Myr; *e.g.*, P. Todini & A. Ferrara 2001; R. Maiolino et al. 2004; C. Gall et al. 2011). This large-grain dominance is supported by recent JWST spectroscopic studies, which show that dust attenuation curves at higher redshift are generally flatter than those at lower redshift (V. Markov et al. 2025; I. Shvaei et al. 2025). However, this creates a tension with the total dust mass observed in the epoch of reionization (EoR). Over the past decade, ALMA ob-

servations have revealed surprisingly mature dust reservoirs ($\gtrsim 10^7 M_\odot$) in galaxies as early as $z \sim 7-8$ (e.g., D. A. Riechers et al. 2013; D. Watson et al. 2015; Y. Tamura et al. 2019; H. Inami et al. 2022; H. S. B. Algera et al. 2026), initiating a long-standing debate known as the “dust budget crisis” (e.g., R. Valiante et al. 2011; K. Rowlands et al. 2014). While some theoretical models propose that maximal supernova efficiency, combined with minimal destruction, could marginally account for these massive dust reservoirs (e.g., A. Leńiewska & M. J. Michałowski 2019), the consensus increasingly points to the necessity of rapid ISM grain growth to explain these masses.

To facilitate rapid grain growth, the ISM requires a large surface area-to-mass ratio, which can be achieved through an abundance of small grains (T.-M. Kuo & H. Hirashita 2012; R. S. Asano et al. 2013). The presence of such small grains in the EoR has recently been suggested by the detection of the 2175 Å bump, a feature attributed to small carbonaceous dust grains, such as polycyclic aromatic hydrocarbons (PAHs) or graphite (J. Witstok et al. 2023; V. Markov et al. 2025; R. Fisher et al. 2025). However, identifying the origin of these grains remains complex. In the early Universe, where the contribution from asymptotic giant branch (AGB) stars is limited by evolutionary timescales (e.g., R. Valiante et al. 2009), small grains may be produced through several rapid channels, including mechanical shattering of large supernova-produced grains via grain-grain collisions in turbulent environments (e.g., H. Hirashita 2010) and, in luminous AGN, direct dust formation within dense QSO-driven winds (e.g., M. Elvis et al. 2002). These channels have two important consequences: they increase the grain surface area available for accretion, thereby catalyzing dust-mass assembly within galaxies, and they generate small-grain populations that can be entrained in outflows and expelled into the halo. This latter effect has recently been inferred by JWST observations of dusty star-forming galaxies (DSFGs) at $z \sim 3.5$ (F. Sun et al. 2026), which reveal large reservoirs of small silicate grains in the circumgalactic medium (CGM).

However, linking the massive dust reservoirs in DSFGs to these enriched halos requires identifying the active phase of small-grain production and processing. In this work, we present observational evidence for such a phase in the QSO UDS-27023 at $z = 4.6$, identified via JWST/NIRSpec spectroscopy. Unlike typical high-redshift sources, this object exhibits an extremely steep extinction curve without a 2175 Å bump, signaling a violent environment dominated by small silicate dust grains. We argue that such a category of steep-

extinction QSO (SEQ) may mark a transitional phase in which AGN feedback both processes pre-existing grains and possibly forms new grains within QSO-driven winds, while redistributing the resulting small-grain population into the ISM and CGM. In Section 2, we describe observational data and analysis. We present the result of a steep dust extinction curve in Section 3 and explore the interpretation in Section 4. Finally, we summarize our major results and conclusions in Section 5. Throughout this work, magnitudes are given in the AB system (J. B. Oke & J. E. Gunn 1983). We adopt a flat Λ CDM cosmology with $\Omega_m = 0.3$ and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. In this cosmology, $1''$ corresponds to 6.57 kpc of physical length at $z = 4.556$. The pivot wavelengths of the V- and B-bands are 5500 Å and 4400 Å, respectively.

2. DATA AND ANALYSIS

The target UDS-27023 is located in the UKIDSS Ultra Deep Survey (UDS) field (A. Lawrence et al. 2007), which is the core region of the Subaru-XMM Deep Field (SXDS; H. Furusawa et al. 2008). The equatorial coordinates (J2000) of this target are R.A. = 34.33730 deg, Decl. = -5.14365 deg. The source ID 27023 is from the CANDELS multiwavelength catalog (A. Galametz et al. 2013). Before JWST observation, UDS-27023 at $z_{\text{spec}} = 4.556 \pm 0.003$ was identified as a quiescent galaxy hosting an IR-AGN at $z_{\text{phot}} = 2-3$ (V. A. Bruce et al. 2012; M. J. Cowley et al. 2016; P. Patil et al. 2019; A. C. Carnall et al. 2020; D. Kodra et al. 2023). Even when using the *Prospector* SED modeling framework (B. D. Johnson et al. 2021) on the JWST photometry, with a non-parametric star formation history and the star-forming main sequence (SFMS) prior (Q. Duan et al. 2026), UDS-27023 is still classified as a quiescent or post-starburst galaxy at $z_{\text{phot}} = 2-3$. We further discuss this underestimated photometric redshift in Appendix A.

2.1. JWST imaging and spectroscopy

We use the JWST/NIRCam imaging observed by two programs: PRIMER (GO#1837; PI: J. Dunlop) and MINERVA (GO#7814; PIs: A. Muzzin, D. Marchesini, and K. Suess). We download the calibrated single exposures (`_cal.fits`) from the MAST data archive and apply customized data-reduction steps, including WISP removal, 1/f noise removal, sky background subtraction, and astrometric correction. The final mosaic images are drizzled to a pixel size of $0''.03$. The $2'' \times 2''$ cutout images in each filter band and an RGB image are shown in the top panels of Fig. 1. We find that in all bands, the source is point-source-dominated. We perform aperture photometry within EE80-radius apertures (Table 3 in JWST-DOCS), and then an 80% aperture correction is applied to obtain the total fluxes.

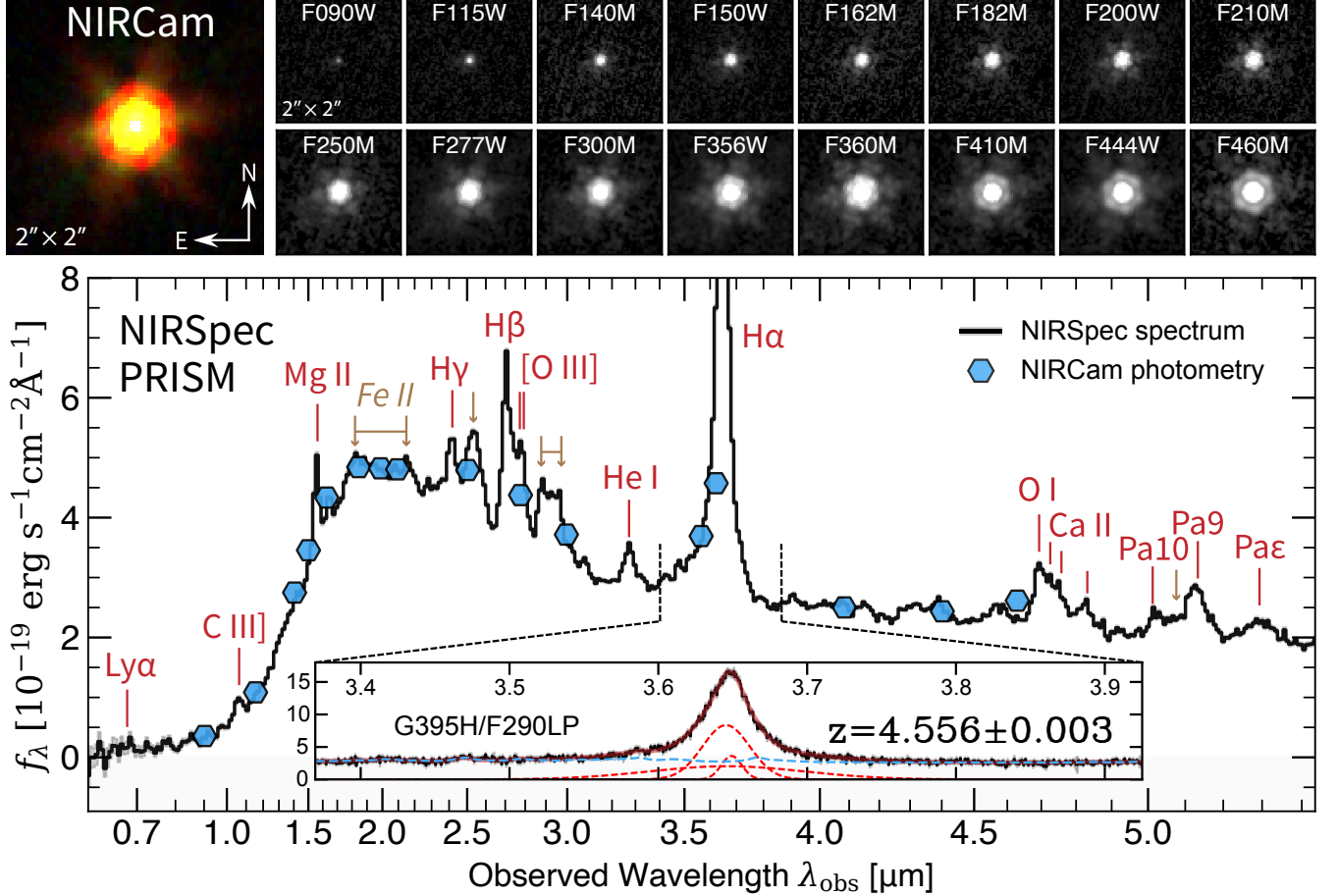


Figure 1. JWST imaging and spectroscopy of UDS-27023. *Top:* $2'' \times 2''$ JWST/NIRCam cutouts in the available filters and an RGB composite (left), showing that the source is compact and dominated by a point source in all bands. *Bottom:* JWST/NIRSpec PRISM spectrum (black) overlaid with the NIRCam photometry (blue hexagons), illustrating the bright continuum and strong broad emission lines characteristic of a Type I QSO. The spectrum shows a strongly suppressed rest-frame UV continuum relative to the rest-frame optical emission, suggesting an exceptionally steep extinction curve. *Inset:* Zoom-in on the G395H/F290LP spectrum around $H\alpha$, together with a multi-component fit (solid red; dashed components). The spectroscopic redshift of UDS-27023 is measured to be $z = 4.556 \pm 0.003$.

We utilize the JWST/NIRSpec MSA spectroscopic data in PRISM and G395H/F290LP modes as part of the GTO#1215 project (PI: N. Luetzgendorf; M. V. Maseda et al. 2024). The reduced spectra are retrieved from the Dawn JWST Archive (DJA)¹⁰, which are reduced using the MSAEXP pipeline¹¹ (G. Brammer 2023), introduced by K. E. Heintz et al. 2024; A. de Graaff et al. 2025. We perform a slit-loss correction by matching the NIRSpec spectrum to the NIRCam photometry, scaling with a best-fit quadratic polynomial function. The resulting NIRSpec spectra and NIRCam photometry are shown in the bottom panel of Fig. 1.

JWST observations show that UDS-27023 is a reddened Type I QSO at $z \simeq 4.56$ (Fig. 1). The NIRCam cutouts show that an unresolved point source dominates the emission in all available filters, and the NIRSpec spectra exhibit prominent Fe II emission and a series of broad permitted lines, characteristic of a high- z Type I QSO. Compared with the normalized QSO composite spectrum (J. Selsing et al. 2016), we find a strongly suppressed UV continuum blueward of rest-frame wavelength $\lambda_{\text{rest}} \sim 3000 \text{ \AA}$ relative to the intrinsic composite (Fig. 2 left). The reddening has two regimes: moderate in the rest-optical but extreme in the UV, suggesting that the dust extinction toward the QSO continuum rises much more steeply toward shorter wavelengths than canonical extinction laws.

To measure the basic QSO properties of UDS-27023, we model the $H\alpha$ complex observed in G395H grat-

¹⁰ <https://dawn-cph.github.io/dja>

¹¹ <https://github.com/gbrammer/msaexp>

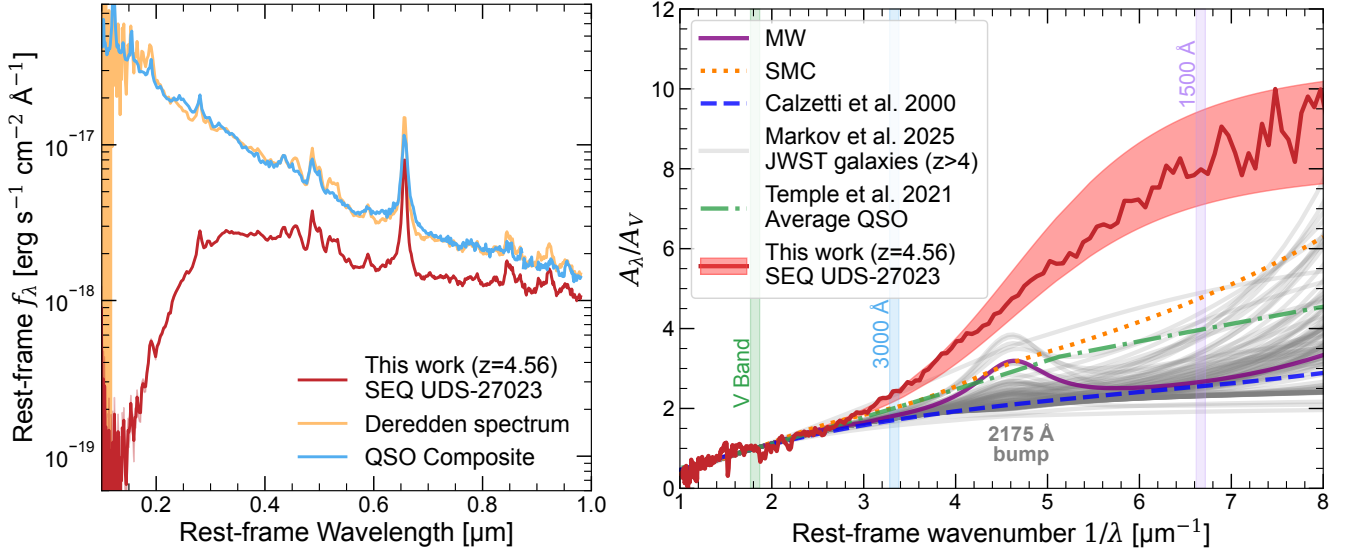


Figure 2. Rest-frame SED and inferred line-of-sight extinction curve of UDS-27023. *Left:* Rest-frame UV–optical–NIR spectrum of UDS-27023 (red) compared to an intrinsic blue-QSO composite (blue). The orange curve shows the spectrum corrected using the best-fit extinction curve, illustrating that the dereddened continuum approaches the intrinsic QSO template over the wavelength range. *Right:* Extinction curve reconstructed for UDS-27023 shown as A_λ/A_V versus wavenumber ($1/\lambda$; thick red curve), with the shaded red band indicating the corresponding best-fit parametric extinction model with uncertainty. For comparison, we plot the Milky Way and SMC extinction curves, the D. Calzetti et al. (2000) starburst attenuation law, the average QSO extinction curve (M. J. Temple et al. 2021), and the set of attenuation curves measured for JWST galaxies at $z > 4$ by V. Markov et al. 2025 (thin grey curves). Vertical shaded bands mark the V band and rest-frame 3000 Å and 1500 Å; the location of the 2175 Å bump is indicated for reference. The SEQ extinction curve rises substantially more steeply into the UV than any of these commonly used laws.

ing (Fig. 1 inset). We fit the spectrum with a linear continuum, a QSO FeII template (M.-P. Véron-Cetty et al. 2004), and multiple Gaussian components of H α emission. All components are fit simultaneously. The best-fitting model requires three broad H α components, yielding a total flux of $F_{H\alpha} = (6.6 \pm 0.2) \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ and an effective line width of $\text{FWHM}_{H\alpha} = 2803 \pm 49 \text{ km s}^{-1}$. Notably, the spectrum is well reproduced without invoking a narrow H α component ($\lesssim 500 \text{ km s}^{-1}$) or forbidden lines from narrow line region such as [N II], [S II], and [O I]; adding these components does not statistically improve the fit, indicating that their contribution is negligible in this source. In addition to the non-detection or negligible contribution of [N II], [S II] and [O I], we note that no high-ionization lines are detected in the NIRSpectra. The spectroscopic redshift of UDS-27023 is derived to be $z = 4.556 \pm 0.003$, with uncertainty accounting for both fitting errors and multi-component velocity offsets. Based on the assumed cosmology, the H α line luminosity is measured to be $L_{H\alpha} = (1.38 \pm 0.04) \times 10^{44} \text{ erg s}^{-1}$. We also measure the flux density at rest-frame 5100 Å from the prism spectrum to be $f_{5100\text{Å}} = (2.13 \pm 0.11) \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1}$, which converts to a luminosity of $L_{5100\text{Å}} = (2.28 \pm 0.11) \times 10^{45} \text{ erg s}^{-1}$.

Using the broad H α virial estimator based on $\text{FWHM}_{H\alpha}$ and $L_{H\alpha}$ (J. E. Greene & L. C. Ho 2005), we infer a black-hole mass of $M_{\text{BH}} = (2.5 \pm 0.5) \times 10^8 M_\odot$. Assuming a typical bolometric correction of $\text{BC}_{5100} = 6.43 \pm 1.84$ for Type I QSOs (J. Chen et al. 2025), we estimate the QSO bolometric luminosity to be $L_{\text{bol}} = (1.46 \pm 0.43) \times 10^{46} \text{ erg s}^{-1}$, which gives an Eddington ratio of $\lambda = L_{\text{bol}}/L_{\text{edd}} = 0.5 \pm 0.2$.

2.2. ALMA imaging

We use ALMA data observed as part of two ALMA programs: 2012.1.00326.S (PI: Ikarashi) and 2015.1.01074.S (PI: Inami). The ALMA spectral windows do not cover any significant emission lines, and the integrated continuum fluxes are measured to be $1.39 \pm 0.18 \text{ mJy}$ at 1.13 mm (ALMA source name SXDF1100.027; S. Ikarashi et al. 2015; P. Patil et al. 2019) and $2.84 \pm 0.53 \text{ mJy}$ at 0.87 mm (ALMA source name UDSb_55). The continuum emission is marginally resolved at both wavelengths. Image-plane morphology fitting yields source sizes of FWHM major and minor axes $0.46 \pm 0.05 \text{ arcsec}$ and $0.32 \pm 0.03 \text{ arcsec}$ (P.A. = $82.6^\circ \pm 9.1^\circ$) at 1.13 mm, and $0.25 \pm 0.03 \text{ arcsec}$ and $0.19 \pm 0.02 \text{ arcsec}$ (P.A. = $-43.6^\circ \pm 17.8^\circ$) at 0.87 mm.

We estimate the cold dust mass (M_d) of the target galaxy using the detected dust continuum emission at

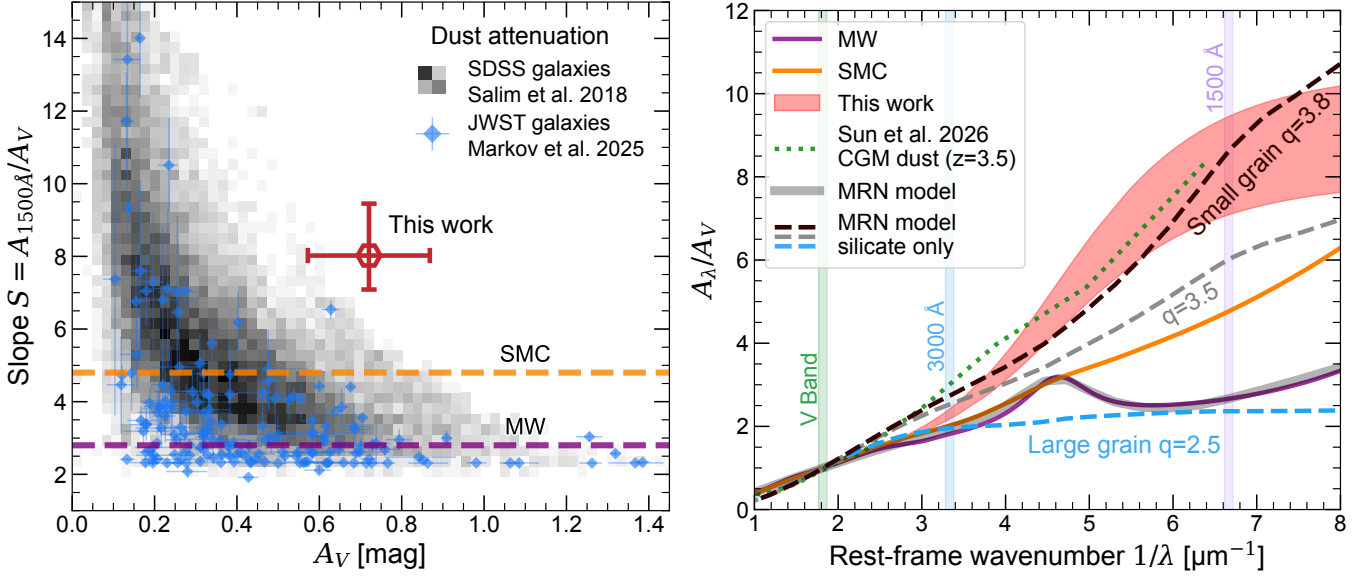


Figure 3. Physical interpretation and context for the steep extinction toward UDS-27023. *Left:* Location of SEQ (red symbol) in the plane of dust-law steepness, $S \equiv A_{1500}/A_V$, versus A_V . The grey-scale background shows the distribution of dust attenuation slopes inferred for SDSS galaxies from the GSWLC survey (S. Salim et al. 2016, 2018), and the blue points show the $z \approx 2$ –10 JWST galaxy attenuation constraints from V. Markov et al. (2025). Horizontal dashed lines indicate the values expected for standard Milky Way and SMC extinction curves, illustrating that SEQ lies at significantly larger S than both typical low- and high-redshift galaxy extinction and attenuation laws at moderate A_V . *Right:* Comparison of the SEQ extinction curve (red band; normalized at V-band) to common empirical laws (MW and SMC) and to illustrative MRN grain-size models (J. S. Mathis et al. 1977) computed from optical properties of silicate and graphite (B. T. Draine & H. M. Lee 1984; J. C. Weingartner & B. T. Draine 2001; A. Laor & B. T. Draine 1993). The grey curves show an MRN-like size distribution ($dn/da \propto a^{-3.5}$) with a standard silicate+graphite mixture (solid) and silicate-only dust (dashed). Colored curves demonstrate how varying the size-distribution slope q (defined by $dn/da \propto a^{-q}$) changes the UV rise: small-grain-weighted distributions (larger q) produce substantially steeper far-UV extinction than large-grain/gray cases (smaller q). The green dotted line denotes a CGM dust extinction curve with a steep slope (F. Sun et al. 2026) at $z = 3.5$. Vertical bands mark rest-frame 3000 Å and 1500 Å and the V band. Together, these panels show that SEQ probes an extreme, line-of-sight extinction law, qualitatively consistent with a dust population strongly weighted toward small grains.

1.13 mm and 0.87 mm. Since the available bands sample only the long-wavelength side of the thermal dust emission and leave the SED peak unconstrained, we cannot independently fit for the dust temperature (T_d) or spectral index (β). Instead, we derive a range of consistent dust masses by adopting a grid of canonical parameters typical for high-redshift star-forming galaxies with a modified blackbody spectrum ($\nu^\beta B_\nu$, where B_ν is a blackbody law). We adopt a typical dust mass absorption coefficient of $\kappa_{850\mu\text{m}} = 0.077 \text{ m}^2 \text{ kg}^{-1}$ (B. T. Draine & H. M. Lee 1984), scaling it to the rest-frame wavelength of the observations as $\kappa_\nu \propto \nu^\beta$. To account for the uncertainty in the intrinsic dust properties, we compute M_d over a parameter grid of $T_d \in [25, 55] \text{ K}$ and $\beta \in [1.5, 2.0]$, which encompasses the standard range of values observed in $z > 4$ galaxies (e.g., N. Scoville et al. 2016; M. Béthermin et al. 2020). The resulting dust mass is $M_d = (4.1 \pm 3.5) \times 10^8 M_\odot$, with the uncertainty derived from the weighted average of the estimates across this grid, accounting for both photomet-

ric errors and systematic uncertainties in the assumed parameters. This indicates a host galaxy with a rich interstellar dust environment.

2.3. Other multi-wavelength data

The Chandra X-UDS survey identifies a bright X-ray counterpart of UDS-27023 (ID XUDS-270 in D. D. Kocevski et al. 2018). The observed X-ray flux is $\log(F_{0.5-8 \text{ keV}}/\text{erg s}^{-1} \text{ cm}^{-2}) = -14.54$. Assuming a power law index of $\Gamma = 1.70$ and a column density of $\log N_H/\text{cm}^{-2} = 20.00$, the X-ray luminosity of UDS-27023 is $\log(L_{2-10 \text{ keV}}/\text{erg s}^{-1}) = 44.42$ at $z = 4.556$, consistent with the normal QSO distribution at this luminosity (F. Duras et al. 2020). This gives an X-ray bolometric correction factor of $k_X = L_{\text{bol}}/L_{2-10 \text{ keV}} \approx 55$. In the radio regime, the source remains undetected down to an RMS of $1.6 \mu\text{Jy/beam}$ using VLA at 1–2 GHz (I. Heywood et al. 2020). Other multi-wavelength observations reveal bright rest-frame mid- to far-IR emission (JWST/MIRI, Spitzer/MIPS, Herschel-PACS/SPIRE). A comprehensive SED decomposition

incorporating these data is beyond the scope of this work.

3. STEEP DUST EXTINCTION CURVE

The visual comparison with the QSO composite template spectrum reveals a notable suppression of UV fluxes (left panel of Fig. 2), which strongly suggests a steep dust extinction along the line of sight of UDS-27023. Quantitatively, we model and characterize the dust extinction curve toward UDS-27023 using the parametric formalism (the Drude approach) introduced by A. Li et al. (2008). The extinction law, normalized by A_V , is expressed as a summation of Drude profiles:

$$\begin{aligned} A_\lambda/A_V = & \frac{c_1}{(\lambda/0.08)^{c_2} + (0.08/\lambda)^{c_2} + c_3} \\ & + \frac{233 [1 - c_1 / (6.88^{c_2} + 0.145^{c_2} + c_3) - c_4/4.60]}{(\lambda/0.046)^2 + (0.046/\lambda)^2 + 90} \\ & + \frac{c_4}{(\lambda/0.2175)^2 + (0.2175/\lambda)^2 - 1.95}, \end{aligned} \quad (1)$$

where λ is in μm . Here, the three terms correspond to the far-UV extinction, the near-IR/visible component, and the 2175 Å bump strength (controlled by c_4), respectively. To determine the intrinsic flux, we utilize the QSO composite spectrum ($f_{\lambda, \text{template}}$) of J. Selsing et al. (2016), displayed in Figure 2. We model the intrinsic QSO spectrum ($f_{\lambda, \text{int}}$) by applying a power-law modification to this template to account for slope variations:

$$f_{\lambda, \text{int}} = N_{\text{norm}} f_{\lambda, \text{template}} \left(\frac{\lambda}{\lambda_0} \right)^{\alpha_0 - \alpha_\lambda}, \quad (2)$$

where N_{norm} is the flux normalization factor, $\lambda_0 = 1 \mu\text{m}$, and the template slope is $\alpha_0 = 1.7$. We explore intrinsic slope values in the range $\alpha_\lambda = 1.3 - 1.7$, which encompasses the intrinsic continuum slopes typically observed in QSOs (see Table 2 in J. Selsing et al. 2016). We derive the extinction parameters by fitting the observed flux ratio defined as:

$$A_\lambda = -2.5 \log \left(\frac{f_\lambda}{f_{\lambda, \text{int}}} \right). \quad (3)$$

In our initial fit, we allow c_1 , c_2 , c_3 , c_4 , A_V , and N_{norm} to vary freely, while treating α_λ as a grid parameter with a step size of 0.05. Wavelengths bluer than Ly α are excluded, and those containing bright emission lines are masked during the fitting process. The results yield a c_4 value consistent with zero, suggesting the absence of a 2175 Å bump. This absence is also visually suggested by the empirical extinction law (deep red line) in Figure 2. Therefore, for the final analysis, we set $c_4 = 0$ and re-optimize the model with the remaining five free parameters. The fitting parameters are $c_1 = 2.37^{+0.68}_{-0.48} \times 10^3$, $c_2 = -6.28 \pm 0.14$, $c_3 = 357^{+53}_{-46}$, and $A_V = 0.72 \pm 0.15$.

We apply the best-fit dust extinction model to deredden the observed spectra (Fig. 2, left panel), revealing good agreement with the template continuum outside of wavelength ranges of major emission lines (illustrated for $\alpha_\lambda = 1.5$). The resulting extinction curve (A_λ/A_V v.s. $1/\lambda$) is shown in the right panel of Fig. 2, including the 1σ uncertainty band derived from the MCMC posterior. The extinction toward UDS-27023 is distinctive when compared to standard benchmarks, including the Milky Way (J. A. Cardelli et al. 1989), SMC (K. D. Gordon et al. 2003) extinction curves, the D. Calzetti et al. (2000) starburst attenuation laws, and the attenuation curves inferred for $z > 4$ galaxies observed by JWST/NIRSpec (V. Markov et al. 2025). We observe moderate optical attenuation of $A_V = 0.72 \pm 0.15$ with a canonical total-to-selective extinction ratio $R_V \equiv \frac{A_V}{A_B - A_V} = 3.13^{+0.07}_{-0.10}$, where A_B is the B-band ($0.44 \mu\text{m}$) dust extinction. However, the extinction curve exhibits a significantly steeper rise into the UV, with a measured effective UV-optical slope (steepness) of $S \equiv A_{1500\text{\AA}}/A_V = 8.0^{+1.4}_{-0.9}$. This steep slope, combined with moderate V-band attenuation, positions the dust properties of UDS-27023 at the extreme end of the currently known distribution (Fig. 3, left panel).

4. DISCUSSION

4.1. Abundant small dust grains

The extinction curve of UDS-27023 is remarkable for its extreme steepness ($S = 8.0^{+1.4}_{-0.9}$) and the absence of the 2175 Å bump. To interpret the physical properties of the dust responsible for this signature, we compare the observed extinction curve with theoretical models based on the MRN grain-size distribution (J. S. Mathis et al. 1977), assuming a power-law distribution $dn/da \propto a^{-q}$ with varying slope indices q (Fig. 3, right panel). Standard dust models for the Milky Way typically require $q = 3.5$, $a_{\text{min}} = 0.005 \mu\text{m}$, and $a_{\text{max}} = 0.25 \mu\text{m}$ to reproduce the observed balance of optical and UV extinction. As shown in the right panel of Fig. 3, a standard Milky Way mixture (solid grey curve) and a flatter extinction curve given by $q = 2.5$ (blue dashed curve) are far too flat to reproduce the UV rise observed in UDS-27023. Instead, the data are well qualitatively matched by a significantly steeper size distribution with $q = 3.8$ (dashed black curve). In the Rayleigh regime ($a \ll \lambda/2\pi$), absorption is determined by the total volume of dust, but in the UV, extinction becomes highly sensitive to the surface area provided by small grains. The steep power-law index $q = 3.8$ implies a grain mass distribution heavily skewed toward very small sizes

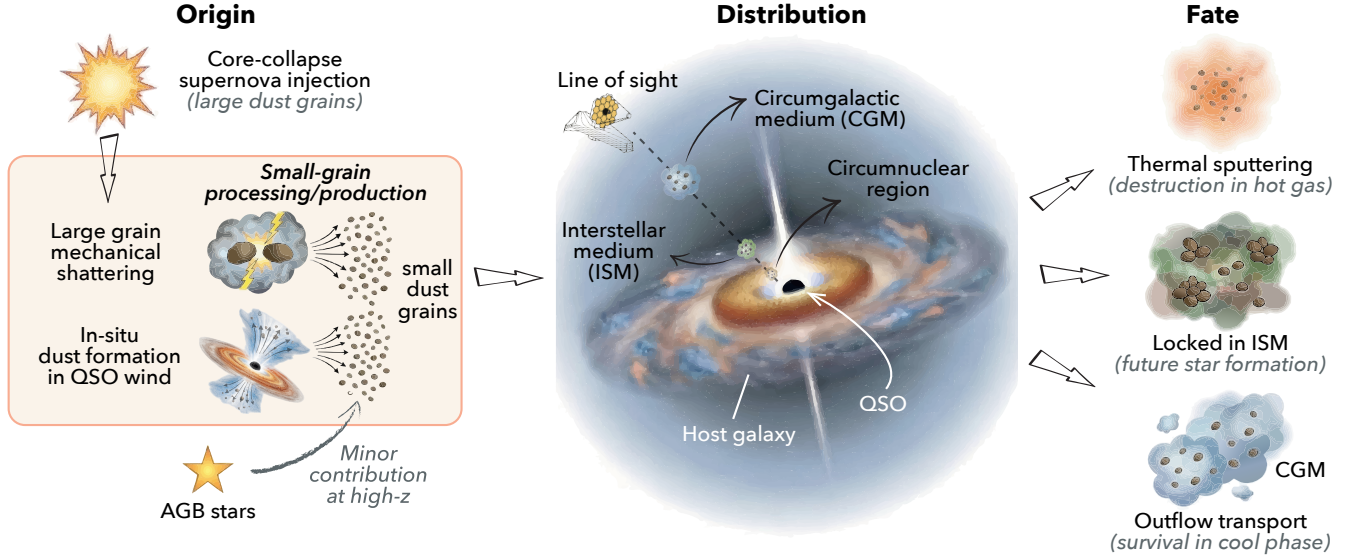


Figure 4. Schematic illustration of the origin, distribution, and fate of small dust grains in the steep-extinction QSO. *Left (Origin):* In the early Universe, dust is predominantly injected as large grains by core-collapse supernovae (CCSNe), with minor contributions from AGB stars. Small grains may then be produced through two rapid channels in the QSO environment. In the first pathway, violent feedback drives grain–grain collisions, mechanically shattering large grains into small fragments. In the second pathway, silicate grains may condense in situ within dense QSO-driven winds. *Middle (Distribution):* The JWST line of sight probes through the circumnuclear region, the host galaxy’s interstellar medium (ISM), and the circumgalactic medium (CGM), directly detecting the steep extinction signature of an abundant small-grain population against the background QSO continuum. *Right (Fate):* These small grains face three primary evolutionary pathways: they may be destroyed via thermal sputtering in hot, shock-heated gas; they may remain locked in the ISM to facilitate subsequent molecular-cloud and star formation; or they may be entrained in cool-phase outflows and transported to the CGM, populating the extended, small-grain-rich halos recently observed around massive galaxies at high redshift.

($a \sim 0.01 \mu\text{m}$), providing the necessary UV opacity without over-attenuating the optical continuum.

Furthermore, the absence of the $2175 \text{ \AA}$ feature imposes a critical constraint on grain composition. This feature is widely attributed to sp^2 -bonded carbonaceous grains, such as graphite or PAHs (B. T. Draine & H. M. Lee 1984). Its absence in UDS-27023 is consistent with a grain population dominated by small-grain silicates, which exhibit a smooth, featureless rise into the far-UV.

This phenomenology stands in stark contrast to recent statistical studies of high-redshift galaxies. For instance, V. Markov et al. (2025) found that attenuation curves at $z > 4$ are generally flatter than the SMC law, reflecting the dominance of large grains injected by core-collapse supernovae. UDS-27023 therefore could represent a distinct evolutionary phase or environment where the large-grain population has been fundamentally altered to abundant small dust grains. However, we caution against over-interpreting the comparison between attenuation and extinction curves, as even a steep extinction curve can result in a flat attenuation curve (e.g., S. Gallerani et al. 2010).

A complementary view emerges from low-ionization broad absorption line (LoBAL) and iron LoBAL (FeLoBAL) QSOs, which frequently exhibit steep red-

dening, with some of them accompanied by prominent $2175 \text{ \AA}$ bumps (e.g., P. B. Hall et al. 2002; P. Jiang et al. 2013; H. Meusinger et al. 2016; J.-K. Krogager et al. 2016; S. Zhang et al. 2022). A similar steep extinction without prominent bumps has been reported in larger samples of reddened QSOs (T. Zafar et al. 2015) and in narrow-line Seyfert 1 galaxies (H. Zhou et al. 2006), which are usually reproduced by silicate-dominated small dust grains. The bump features are interpreted as small carbonaceous grains (graphite/PAHs) surviving in the nuclear region, protected by dense outflow clouds that shield them from the intense AGN UV/X-ray radiation.

The coexistence of steep extinction curves and BAL troughs in these systems indicates that powerful AGN-driven outflows play a central dual role: they shatter large grains into small silicates (producing the featureless, ultra-steep UV extinction) while simultaneously shielding fragile carbonaceous grains in denser clumps (allowing $2175 \text{ \AA}$ bumps to survive). However, for UDS-27023, the relatively low spectral resolution of our NIR-Spec PRISM data ($R \sim 100$ in the rest-frame UV) makes it challenging to securely identify or rule out the presence of BAL troughs. Consequently, while UDS-27023 appears as a classical Type I QSO without evident BAL

signatures, we cannot definitively classify it as a non-BAL steep-extinction QSO or as a LoBAL/FeLoBAL analog viewed through a shattering-active sightline. Nevertheless, the available X-ray constraint disfavors the latter interpretation in its most classical, heavily obscured form. The source has an X-ray-to-bolometric luminosity ratio consistent with the standard QSO relation, suggesting minimal X-ray absorption. This contrasts with the strong X-ray weakness commonly observed in optically selected LoBAL/FeLoBAL QSOs, which is typically attributed to large absorbing columns reaching $N_{\text{H}} \sim 10^{23}\text{--}10^{24}\text{ cm}^{-2}$ in FeLoBALs (e.g., P. J. Green et al. 2001; S. C. Gallagher et al. 2006; J. A. Rogerson et al. 2011; L. K. Morabito et al. 2011). Thus, although an X-ray-bright BAL orientation cannot be ruled out, the X-ray detection makes a heavily X-ray-suppressed LoBAL/FeLoBAL analog less likely. High-resolution follow-up spectroscopy (e.g., with the NIRSpec grating, ground-based optical/near-IR spectrographs, or future IFU observations), together with deeper X-ray data sufficient to constrain α_{OX} and intrinsic absorption, will be essential for resolving this ambiguity.

A particularly relevant low-redshift analog is the UV-cutoff QSO SDSS J2317+0005 at $z = 0.32$, reported by H. Guo et al. (2016). In that object, the rest-frame UV continuum at $\sim 3000\text{ \AA}$ suddenly dimmed by a factor of ~ 3.5 on a timescale of only 23 days, while the broad emission-line fluxes remained nearly unchanged, and the source appeared to recover within the following several tens of days. The extinction curve inferred from the dim state is substantially steeper than the SMC law, and was interpreted as a possible eclipse by a dusty cloud, potentially associated with a rapid inflow or outflow crossing the line of sight to the central engine. Although UDS-27023 is currently observed only in a single spectroscopic epoch, the close phenomenological similarity suggests that SEQs may not necessarily represent a long-lived quasar subtype. Instead, they may mark a very short-lived transiting phase, during which a compact, small-grain-rich dusty structure temporarily intercepts the line of sight to the accretion disk. If the duty cycle of this phase is indeed as short as days to months in the rest frame, such objects would be intrinsically rare in single-epoch spectroscopic surveys. Systematic JWST/NIRSpec searches for SEQs, together with repeat NIRSpec spectroscopy and multi-band NIRCам monitoring, will therefore be essential for measuring their occurrence rate, lifetime, redshift evolution, and connection to QSO-driven dust processing.

While the current sample of steep-extinction QSOs (SEQs) at high redshift ($z > 3$) remains limited, UDS-

27023 is not an isolated case. This object was identified through visual inspection of a small sample of luminous QSOs observed in JWST/NIRSpec programs. In addition to UDS-27023, at least one other SEQ has been identified at $z = 3.71$ (ID 209777 in JWST-GTO-1180), though a detailed analysis is beyond the scope of this work. These discoveries suggest that a population of such SEQs exists at high redshifts, potentially representing a common yet previously under-recognized evolutionary phase in the dust processing of early AGN hosts.

4.2. *Origin, distribution, and fate of small dust grains*

Building upon this diversity of small-grain production and processing channels in luminous AGN, Fig. 4 summarizes the possible lifecycle of the small silicate grains that dominate the line-of-sight extinction toward UDS-27023. One natural pathway begins with large grains ($a \gtrsim 0.1\text{ }\mu\text{m}$) injected by core-collapse supernovae on short timescales ($\lesssim 10\text{ Myr}$; P. Todini & A. Ferrara 2001; R. Maiolino et al. 2004; C. Gall et al. 2011). Within the dense, turbulent ISM and circumnuclear environment of this luminous QSO host, powerful shocks and outflows driven by the central engine can induce grain-grain collisions. These collisions efficiently shatter large grains into small fragments (H. Hirashita & H. Yan 2009; H. Hirashita 2010; H. Hirashita & H. Kobayashi 2013), generating a silicate-dominated population of very small grains ($a \sim 0.01\text{ }\mu\text{m}$) that reproduces the exceptionally steep, featureless far-UV extinction observed along the JWST sightline. This mechanical pathway dramatically increases the total grain surface area available for accretion, enabling rapid grain growth in the ISM and helping to alleviate the long-standing dust-budget crisis at high redshift (T.-M. Kuo & H. Hirashita 2012; R. S. Asano et al. 2013).

A further possibility, not mutually exclusive with mechanical shattering, is that part of the small-grain population forms *in situ* within the QSO-driven wind itself. This “smoking quasar” scenario was originally proposed by M. Elvis et al. (2002), in which dense broad-line clouds embedded in an outflow expand and cool until they enter the dust-formation window. More detailed calculations by A. Sarangi et al. (2019) show that AGN accretion-disk winds can provide favorable conditions for silicate dust formation over parsec scales, especially in luminous systems accreting at a substantial fraction of the Eddington limit. Importantly, these models predict distinct regions within the flow: in some zones, seed nuclei can form but do not efficiently accrete or coagulate, while in others they grow into silicate grains. The freshly formed dust is therefore expected to be domi-

nated by small silicate grains, with some grains remaining at sizes on the order of a few hundred Angstroms or below before further growth or processing. This provides an intriguing additional pathway for producing the very small, silicate-dominated grains inferred in UDS-27023. Given its large black-hole mass and high Eddington ratio, UDS-27023 may therefore be probing a phase in which QSO feedback both processes pre-existing grains through shocks and produces new dust directly within the outflow. Current data constrain the grain population but do not uniquely distinguish between these two channels; high-resolution spectroscopy capable of identifying outflow/BAL signatures, together with future constraints on the infrared-to-submillimeter dust SED, will be required to determine their relative importance.

Once produced, either through mechanical shattering or in-situ condensation within the QSO wind, these small grains follow three primary evolutionary pathways. (1) In hot, post-shock gas ($T \gtrsim 10^6$ K), they are rapidly destroyed by thermal sputtering on timescales of $\sim 10^4$ – 10^5 yr (B. T. Draine & E. E. Salpeter 1979; A. P. Jones et al. 1996). (2) In shielded, dense molecular clouds, they survive and grow by accretion, fueling further dust-mass assembly and contributing to the substantial cold-dust reservoir detected at submillimeter wavelength (H. Hirashita 2012). (3) Some fraction may be entrained in cool-phase outflows, ubiquitous around high- z QSOs, and expelled into the CGM (C. Ciccone et al. 2018; S. Laha et al. 2021). Radiation pressure and galaxy interactions/mergers are therefore more naturally interpreted as redistribution mechanisms acting after small grains are produced, selectively exposing unshielded grains to destruction while allowing grains embedded in dense clumps to survive. This channel could directly populate the extended reservoirs of small silicate grains recently revealed by JWST/NIRCam grism spectroscopy around $z \sim 3.5$ massive galaxies, where steep extinction of background sources at 7–30 kpc indicates high dust surface densities ($\gtrsim 10^{-1} M_\odot \text{ pc}^{-2}$, $\sim 10\times$ local CGM values) and solar-like enrichment (F. Sun et al. 2026). Shattering within turbulent cool CGM clumps can further amplify the small-grain population on timescales of a few 10^8 yr (H. Hirashita & T.-W. Lan 2021).

In this way, UDS-27023 exemplifies how AGN at high redshift can play a dual role in the dust lifecycle: they may both process pre-existing grains through shocks and turbulence, and produce new dust directly within dense QSO-driven winds. The resulting small grains can subsequently grow in the ISM or be redistributed into the circumgalactic medium. Steep-extinction QSOs therefore bridge supernova dust injection, interstellar dust

processing, QSO-wind dust formation, and halo enrichment, thereby closing the observational loop between the massive dust reservoirs seen in early galaxies and the small-grain-rich halos that regulate future star formation.

5. SUMMARY

In this work, we report the discovery of a steep-extinction QSO (SEQ) UDS-27023 at $z = 4.556$ using JWST/NIRSpec spectroscopy, revealing an exceptionally steep far-UV extinction curve ($S \equiv A_{1500}/A_V = 8.0^{+1.4}_{-0.9}$) without a detectable 2175 Å bump. This signature, combined with a moderate visual extinction $A_V = 0.72 \pm 0.15$ and a silicate-dominated small-grain model ($q = 3.8$ in the MRN-like distribution), indicates an abundance of very small dust grains ($a \sim 0.01 \mu\text{m}$) along the line of sight. ALMA observations further confirm a substantial cold-dust reservoir ($M_d \approx 4 \times 10^8 M_\odot$), consistent with a host galaxy undergoing rapid dust growth. We interpret this as evidence for an active small-grain production/processing phase driven by the QSO. One natural mechanism is mechanical shattering, in which powerful shocks and outflows pulverize supernova-injected large grains into small silicates; an additional possibility is direct condensation of small silicate grains within the QSO wind itself. These channels could alleviate tensions in the high-redshift dust-budget problem by enabling efficient ISM accretion and growth, while also enriching the CGM with small-grain reservoirs. In addition to UDS-27023, at least one other SEQ has been identified at $z = 3.71$ (ID 209777 in JWST-GTO-1180). SEQs like UDS-27023 could represent a transitional evolutionary stage in luminous AGN, bridging supernova dust injection, interstellar dust processing, QSO-wind dust formation, and circumgalactic enrichment. Future high-resolution spectroscopy will refine the BAL/outflow classification, while deeper infrared and submillimeter observations will help constrain the dust emission, grain composition, and duty cycle of this small-grain production phase.

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is an initiative of the Cosmic Dawn Center (DAWN), which is funded by the Danish National Research Foundation under grant DNR140. All the JWST raw data used in this paper can be found in MAST: [10.17909/yscx-cd19](https://mast.stsci.edu/portal/#doc/10.17909/yscx-cd19). This paper makes use of the following ALMA data: ADS/JAO.ALMA#2012.1.00326.S and ADS/JAO.ALMA#2015.1.01074.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), MOST and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Facilities: JWST (NIRCam, NIRSpec), ALMA, CXO

APPENDIX

A. PHOTOMETRIC MISCLASSIFICATION BEFORE AND AFTER JWST

Prior to the JWST spectroscopic confirmation, UDS-27023 was consistently classified as a massive quiescent galaxy at photometric redshift $z_{\text{phot}} \approx 2-3$, often with evidence for an embedded infrared-active AGN (V. A. Bruce et al. 2012; M. J. Cowley et al. 2016; P. Patil et al. 2019; A. C. Carnall et al. 2020; D. Kodra et al. 2023). This mis-identification stemmed from the object’s unusual photometric colors, which were interpreted under the assumption of standard galaxy templates without accounting for the extremely steep-extinction QSO (SEQ) nature revealed by NIRSpec.

Figure 5 illustrates the photometric selection biases induced by SEQ-like extinction. In the left panels, JWST/NIRCam color-color diagrams show that UDS-27023 (red symbol) falls outside typical loci for AGN and QSOs. Synthetic tracks for an intrinsic QSO composite (J. Selsing et al. 2016), representative little red dot (LRD) colors (Z. Zhang et al. 2025), and our SEQ extinction model (evaluated as a function of redshift) demonstrate how the steep UV suppression shifts the object into regions mimicking lower-redshift dusty galaxies. The grey background, drawn from sources in the JADES survey field, highlights this displacement. The right panel adapts the UVJ diagram from A. C. Carnall et al. (2020), showing the inferred UVJ track for UDS-27023 when forced to $z = 2-3$ in galaxy-only SED fitting (color-coded by assumed redshift). This track lands squarely within the standard UVJ-quiescent selection region (black solid lines), aligning with prior classifications as a $z \approx 2.5$ quiescent galaxy.

We further demonstrate that even photometric redshift and SED fitting of the new JWST photometry fails to yield a reliable (high-redshift) photometric redshift. Following the approach of Q. Duan et al. (2026), we perform the fitting using the *Prospector* code (B. D. Johnson et al. 2021), adopting a non-parametric star formation history (SFH) (J. Leja et al. 2019; S. Tacchella et al. 2022) with the star-forming main sequence (SFMS) prior, and allowing the redshift to vary freely. We refer the reader to Q. Duan et al. (2026) for the technical details of the parameters and priors used in the SED fitting. Brief information is provided here. The SFMS SFH prior is constructed by assuming that galaxies form and evolve along the SFMS with substantial scatter, and is applied as a prior on the non-parametric SFH. In the non-parametric SFH framework, the SFH is discretized into different age bins, within which the SFR is allowed to vary. The ratios between the SFRs in adjacent age bins are fitted as free parameters in the SED modeling, and the prior on these ratios follows a Student’s t distribution. The SFMS prior modifies the expected value, μ , of this Student’s t distribution to the value expected from the SFMS, while using $\nu = 2.0$ and $\sigma = 0.5$. This means that the expected SFH is centered on the SFMS, while still allowing substantial scatter and deviations when supported by the data. Therefore, if a galaxy is quiescent, the prior assigns a lower probability to this solution relative to an SFMS-like history. However, if the galaxy is genuinely quiescent, as strongly supported by the data, this penalty

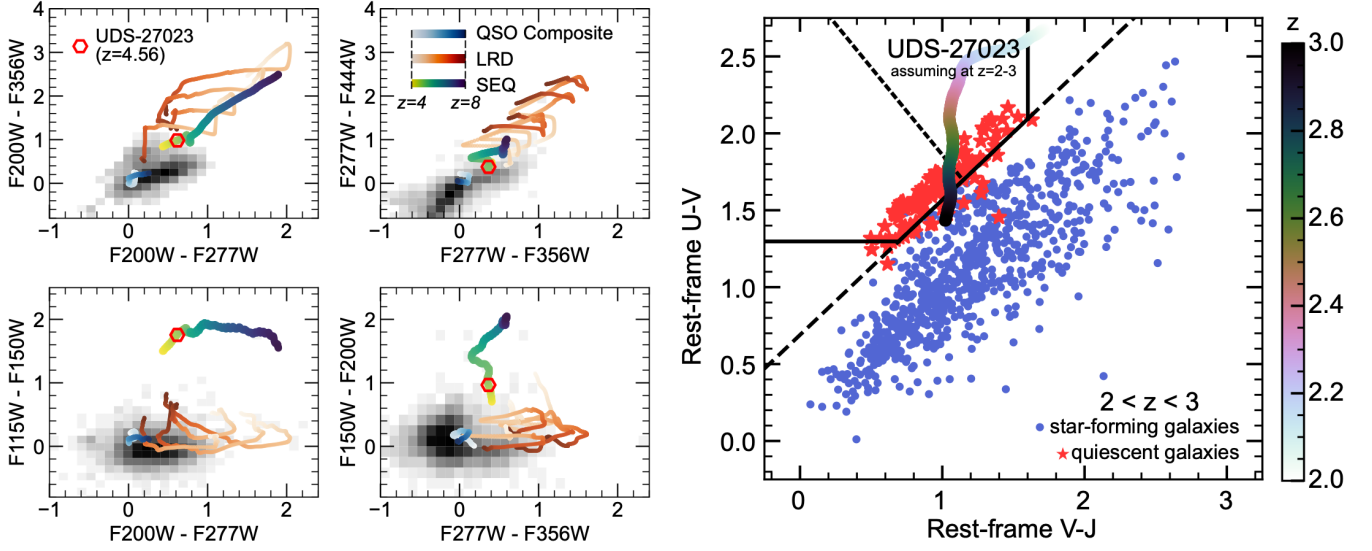


Figure 5. Photometric selection biases induced by SEQ-like extinction. *Left:* A set of illustrative JWST/NIRCam color-color diagrams demonstrating that UDS-27023 (red symbol) lies outside common loci for AGN and QSOs in multiple color spaces. Colored tracks show synthetic colors for an intrinsic QSO composite (J. Selsing et al. 2016), representative LRD-like colors (Z. Zhang et al. 2025), and the SEQ extinction model, evaluated as a function of redshift (color-coded). The grey background indicates the distribution of field sources from the JADES survey (B. E. Robertson et al. 2026) in the same diagrams. *Right:* UVJ diagram adapted from Fig. 2 of A. C. Carnall et al. (2020), illustrating possible misclassification of SEQ under an incorrect low-redshift interpretation. We overlay the inferred UVJ track of UDS-27023 when forced to $z = 2-3$ (color-coded by assumed redshift) in galaxy-only SED fitting. It falls within the standard UVJ-quiescent selection region (within black solid lines), consistent with its previous identification as a candidate of $z \approx 2.5$ quiescent galaxy.

term will not affect the posterior inference to any significant extent, and the posterior can still favor a data-driven quiescent solution. Even with this state-of-the-art framework, the best-fit model (Fig. 6) still classifies UDS-27023 as a quiescent or post-starburst galaxy at $z_{\text{phot}} \approx 2.6$ ($z_{\text{phot}} = 2.59^{+0.05}_{-0.08}$). We note that the derived star-formation history is unreliable due to an incorrect redshift.

The steep far-UV extinction effectively mimics the red colors of an old stellar population with moderate dust, while the QSO continuum boosts the rest-frame near-IR, further supporting an AGN-hosting quiescent interpretation. This case underscores the challenges of photometric redshifts for reddened AGN without spectroscopic observations. The JWST/NIRSpec spectrum resolves this ambiguity, confirming the true redshift and revealing the object’s genuine QSO nature. Future surveys should incorporate flexible extinction models to mitigate such biases and assemble a more complete census of high- z sources.

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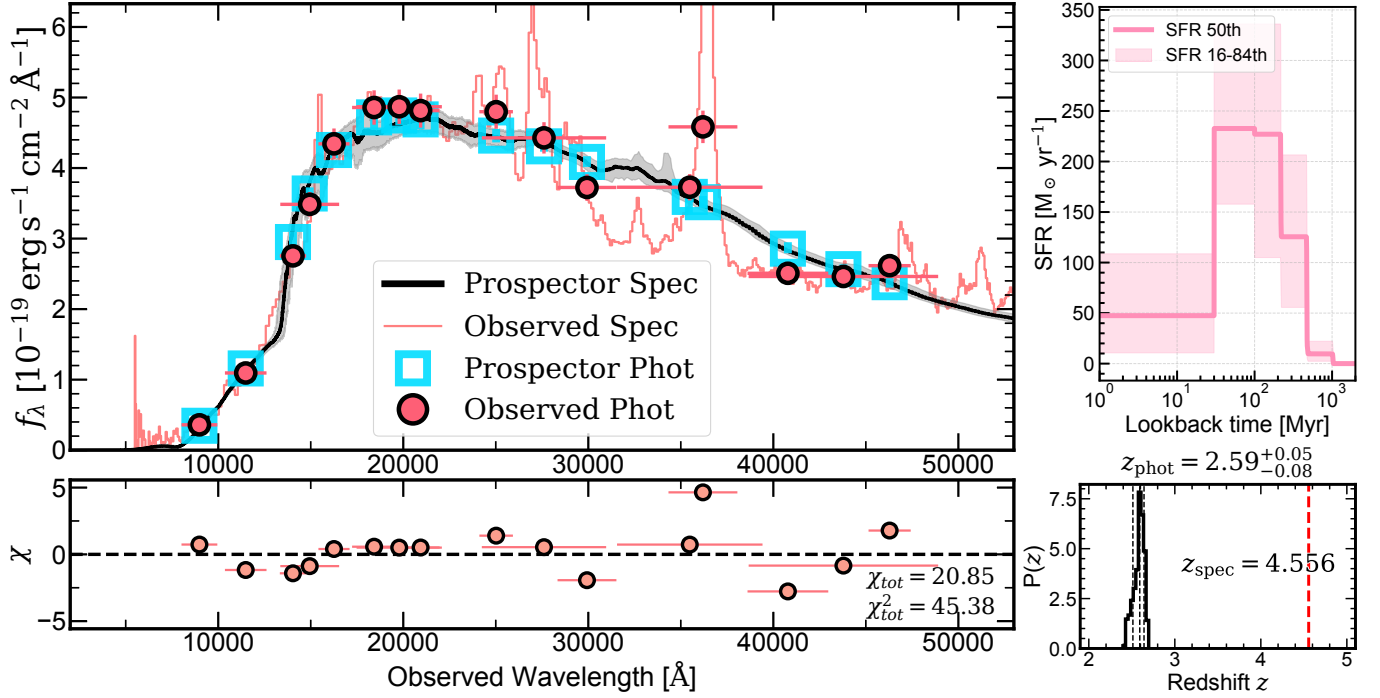


Figure 6. Photometric redshift and SED modeling on the JWST photometry for UDS-27023 using the *Prospector* code, still revealing a quiescent/post-starburst galaxy at $z_{\text{phot}} \approx 2.6$. *Left:* Observed spectrum (thin red line) and photometry (filled red circles with error bars) compared with the best-fit *Prospector* model spectrum (thick black line) and synthetic photometry (open cyan squares). Fit residuals χ are shown in the lower panel, with total χ^2 values for the fit indicated. *Top right:* Posterior star-formation rate (SFR) as a function of lookback time. *Bottom right:* Photometric redshift probability distribution $P(z)$. The spectroscopic redshift $z_{\text{spec}} = 4.556$ is marked by the vertical red dashed line.

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