

A census of quiescent galaxies across $0.5 < z < 8$ with JWST/MIRI: Mass-dependent number density evolution of quiescent galaxies in the early Universe

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ABSTRACT

JWST observations reveal numerous quiescent galaxies (QGs) at high redshift ($z \sim 4-8$), challenging models of early galaxy formation and quenching. Accurate number density estimates are crucial for comparison with theory but remain uncertain. We systematically study QGs at $0.5 < z < 8$ using a mass-complete sample from the JWST/PRIMER survey with deep NIRCам and MIRI imaging. The MIRI data, probing rest-frame near-infrared at $z \sim 3-8$, are vital for robust stellar mass measurement and QG identification. We find that nearly all photometrically selected, point-like QG candidates located in the UVJ QG region are actually “Little Red Dots”, for which the UVJ colors were wrongly estimated due to inaccurate photometric redshift estimation. MIRI reduces significantly contamination to high-mass QGs from star-forming galaxies, yielding lower number densities than previous studies. The evolution of QG number density is strongly mass-dependent. The density of high-mass QGs ($\log(M_*/M_\odot) > 10.3$) decreases rapidly from $n = 1 \times 10^{-5} \text{ Mpc}^{-3}$ at $z = 3-4$ to $n = 2 \times 10^{-6} \text{ Mpc}^{-3}$ at $z = 4-5$, becoming negligible ($n \lesssim 10^{-6} \text{ Mpc}^{-3}$) at $z > 5$. Conversely, low-mass QGs ($9 < \log(M_*/M_\odot) < 10.3$) maintain a nearly constant number density ($n \sim 3 \times 10^{-6} \text{ Mpc}^{-3}$) across $z = 4-8$. This suggests low-mass QGs at $z > 4$ are likely temporarily quenched, akin to *mini-quenched* galaxies. Comparison with major hydrodynamical and semi-analytical models shows most underestimate high-mass QG densities at $z > 4$ and fail to reproduce the constant low-mass QG density at $z > 5$.

Keywords: Galaxy evolution (594) — High-redshift galaxies (734) — Galaxy quenching (2040) — Post-starburst galaxies (2176)

1. INTRODUCTION

Understanding the origin of the bimodality of galaxies, or the quenching of star formation, is a fundamental

challenge in extragalactic astronomy. Obtaining stringent constraints on the cosmic evolution of the number density and physical properties of quiescent galaxies (QGs) is therefore essential. Over the past two decades, the evolution of the number density of QGs and quenched fractions down to $M_* \sim 10^{10} M_\odot$ at $0 < z < 3$

has been well established (A. Muzzin et al. 2013; C. M. S. Straatman et al. 2016; G. B. Brammer et al. 2011). The number density of QGs decreases rapidly with increasing redshifts, with quiescent fraction increasing with stellar mass up to $z \sim 3$ (A. Fontana et al. 2009; V. Wild et al. 2016; B. Forrest et al. 2018; M. Clausen et al. 2024). These findings imply that high-mass galaxies tend to quench easier than low-mass galaxies, a phenomenon commonly called *downsizing*. The dependence of quenched fraction on stellar mass and redshift are expected to extend to $z > 3$ (L. Xie et al. 2024). Limited by data quality, the quiescent fraction of high-mass galaxies at $z > 3$ is estimated to be $\sim 20\%$, while low-mass QGs are nearly undetected (J. R. Weaver et al. 2023).

Recent JWST observations have extended our knowledge of QGs to higher redshifts. The number of spectroscopically confirmed QGs at $z \gtrsim 3$ by JWST has grown rapidly in recent years. Many of these QGs come from deep, pencil-beam surveys and have large stellar masses (F. Valentino et al. 2023; A. C. Carnall et al. 2023a, 2024; T. Kakimoto et al. 2024; A. Weibel et al. 2024), raising debate about whether their abundance exceeds model predictions. A small subset appears to have formed most of their stars at very early times ($z \gtrsim 6$, possibly $z \gtrsim 10$) and have been quiescent since then (K. Glazebrook et al. 2024; A. De Graaff et al. 2024). Inferring from their spectrum, the progenitor of these massive QGs should exhibit extremely high star formation rate (SFR), which stands in great contrast to the scarcity of extreme starbursts at higher redshifts. Moreover, a few low-mass quiescent galaxies ($\log M_*/M_\odot \lesssim 9.5$) have been discovered at $z \sim 4 - 7$ (T. J. Looser et al. 2024; V. Strait et al. 2023; W. M. Baker et al. 2025a), which challenges the downsizing picture. Accurate determinations of QG number densities and physical properties are therefore crucial to resolve these tensions; however, the estimate of the number density of QGs remains highly uncertain (see the summary in F. Valentino et al. 2023) for high-mass ones, and constraints on low-mass galaxies are even more scarce (W. M. Baker et al. 2025b).

In this study, we exploit the deep and wide-area JWST/MIRI (F770W and F1800W bands) survey from the PRIMER program to explore the number densities and fractions of QGs at $0.5 < z < 8$. Recent studies demonstrate that MIRI is crucial for obtaining accurate stellar-mass estimates for massive galaxies at $z > 5$ (C. Papovich et al. 2023; T. Wang et al. 2025), where the longest NIRCам filter (F444W) only probes the rest-frame optical. Because MIRI probes the rest-frame J-band at high redshift, its photometry is also essential

for robustly identifying true QGs at $z > 3$ using the commonly employed UVJ diagram.

Our analysis confirms that QGs are rare at $z > 4$ with quenched fractions $f_q < 5\%$. The evolution of the number density of QGs is mass-dependent: at early times, the number density of low-mass galaxies remains nearly constant, whereas that of high-mass galaxies increases steadily. State-of-the-art galaxy formation models reproduce the evolution of the QG fraction reasonably well but exhibit discrepancies in the number-density trends.

The structure of this paper is as follows. Section 2.1 provides detailed information about the data. Section 3 presents the selection criteria and results, along with images of all QGs in our sample, and the publicly available spectra. In Section 4, we evaluate the role of MIRI in SED fitting and QG classification, and present the evolution of the number density and fraction of QGs up to $z = 8$. The discussion and conclusions are given in Section 5 and Section 6, respectively.

Throughout this work, we adopt a Λ CDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. DATA AND SED FITTING METHOD

2.1. Data

In this study, we utilize the Public Release Imaging for Extragalactic Research (PRIMER, GO 1837, PI: James Dunlop), one of the largest and deepest surveys that provides JWST/NIRCам and MIRI imaging. The survey spans ten passbands: NIRCам F090W, F115W, F150W, F200W, F277W, F356W, F444W and F410M, plus MIRI F770W and F1800W. The imaging reaches ultra-deep depths (e.g., ~ 29.7 mag in F277W and ~ 25.5 mag in F770W). We also incorporate available imaging observations within the PRIMER fields from other programs; detailed information about the imaging data can be found in T. Wang et al. (2025) (hereafter W25). This compilation is among the most comprehensive datasets using MIRI to date, providing a strong balance between field of view and multi-band coverage. Most galaxies in our dataset have photometric measurements in more than 30 bands, and the effective MIRI-covered area is 323.0 arcmin^2 . To mitigate contamination from Little Red Dots (LRDs; see Section 3.2), we restrict the analysis to sources simultaneously covered by F115W, F150W, F200W, F277W, F356W, F444W, and F770W, resulting in a working area of 227 arcmin^2 .

We process all NIRCам and MIRI data with a customized JWST Calibration Pipeline (v1.13.4), which produces higher-quality images than the default pipeline. Source detection is performed using SExtractor v2.25.0 (E. Bertin & S. Arnouts 1996) on a combined detection image constructed from F277W,

F356W, F410M, and F444W. Photometry is measured in six circular apertures (0.2", 0.3", 0.4", 0.5", 0.7" and 1.0") and an elliptical Kron aperture; we apply aperture corrections and adaptively choose the best aperture for each source. Full details of the reduction, source detection, and the multi-wavelength photometric catalog will be presented in a forthcoming paper (Sun et al., in prep). The 7σ detection limit in F444W is 28.1 mag for point sources, enabling a mass-complete selection down to $\log M_*/M_\odot > 9$ out to $z = 8$. Within this mass range, the photometric sample includes 14,814 sources at $0.5 < z < 8$.

Among the photometric sample, we selected sources with publicly available spectral data to construct a spectral sample. The spectroscopic data for galaxies in this sample are obtained via the DAWN JWST Archive (DJA)¹³, yielding 564 sources with $3 < z_{\text{spec}} < 8$ observed from multiple programs (JWST-GTO-1214 PI:Nora Luetzgendorf; JWST-GTO-1215 PI:Nora Luetzgendorf; JWST-GO-1810 PI:Sirio Belli; JWST-GO-1879 PI:Mirko Curti; JWST-GO-1914 PI:Alice Shapley; JWST-GO-2565 PI:Karl Glazebrook; JWST-GO-3543 PI:Adam Carnall; JWST-GO-4233 PI:Anna de Graaff; JWST-GO-6368 PI:Mark Dickinson; JWST-GO-6585 PI:David Coulter). These spectra are processed using the `msaexp` pipeline (G. Brammer 2023), following procedures described in K. E. Heintz et al. (2024) and A. d. Graaff et al. (2025). This spectral subsample has a redshift distribution and mass distribution that are broadly consistent with those of the parent (photometry) sample.

2.2. SED fitting method

Photometric redshifts are computed using EAZY (G. B. Brammer et al. 2008) for all sources with $\text{SNR}_{F444W} > 7$ and MIRI coverage, adopting the `sfhz_blue_13` template set. The dense band coverage provides reliable, high-quality photo- z estimates. The photometric-spectroscopic redshift comparison is presented in W25, yielding a normalized median absolute deviation of $\sigma_{\text{NMAD}} = 0.017$ (see G. B. Brammer et al. (2008) for definition).

We perform SED fitting using BAGPIPES. For sources with MIRI coverage but SNR below 2σ , we adopt a 2σ flux upper limit. We adopt the stellar population synthesis model of G. Bruzual & S. Charlot (2003), with $\text{age} \in [0.03, 10]$ Gyr and metallicity $Z/Z_\odot \in [0, 2.5]$. We use the dust attenuation model of D. Calzetti et al. (2000) ($A_V \in [0, 5]$), nebular emission constructed by N. Byler et al. (2017) ($\log U \in [-5, -2]$) and a de-

layed exponentially declining star formation history ($\tau \in [0.01, 10]$ Gyr). We do not include AGN template in fitting. When a spectroscopic redshift is available, the redshift is fixed to the spectroscopic value during fitting.

We conducted multiple rounds of fitting with different settings, using spectral samples to test how various factors affect QG classification: In section 3.1, to determine an optimal UVJ selection criterion, we perform a combined photometric and spectroscopic SED fitting with nonparametric SFH by BAGPIPES. The emission lines (H_α and [O III]) are masked out when inferring SFH. The spectra and posterior SFH are shown in 1. In section 3.2, to examine the contamination of QG samples by LRDs, we perform a photometric-only SED fitting and evaluate the reliability of the results based on spectral observations. In section 4.1, to test the influence of MIRI, we perform two photometric-only fittings—one including MIRI photometry and one excluding it—while fixing the redshift to the spectroscopic value.

3. SAMPLE OF QUIESCENT GALAXIES

3.1. Selection methods

The UVJ diagram is a commonly used technique to select QGs based on photometric data. This technique was first proposed by R. J. Williams et al. (2009) and has been used in numerous studies (e.g., A. Muzzin et al. 2013; C. M. S. Straatman et al. 2014; A. van der Wel et al. 2014) to select QGs at $z < 3$. This method effectively distinguishes QGs from dust-obscured galaxies by leveraging J-band photometry and the selected QGs are typically massive and dominated by old stellar populations (typically $t_{50} > 500\text{Myr}$), we refer to these as passive galaxies (PGs) in this paper.

At $z \sim 3$, a population of younger quiescent systems—known as post-starburst galaxies (PSBs)—has been identified (e.g., S. Belli et al. 2019). PSBs are younger than PGs and show a steeper ultraviolet slope because they are observed shortly after a recent star-formation episode. Since PSBs may dominate the QG population at higher redshifts (C. D'Eugenio et al. 2020), several studies have extended the UVJ selection to include them (e.g., C. C. Lovell et al. 2023; S. E. Cutler et al. 2023; S. Alberts et al. 2023).

Although the UVJ method is widely used, there is no consensus on the exact selection boundaries for high-redshift galaxies. To address this, we make use of the galaxies with spectra in the photometric sample (564/14,814) to construct an experimental UVJ color diagram (shown in Figure 1) and define the following selection criteria:

¹³ <https://dawn-cph.github.io/dja/index.html>

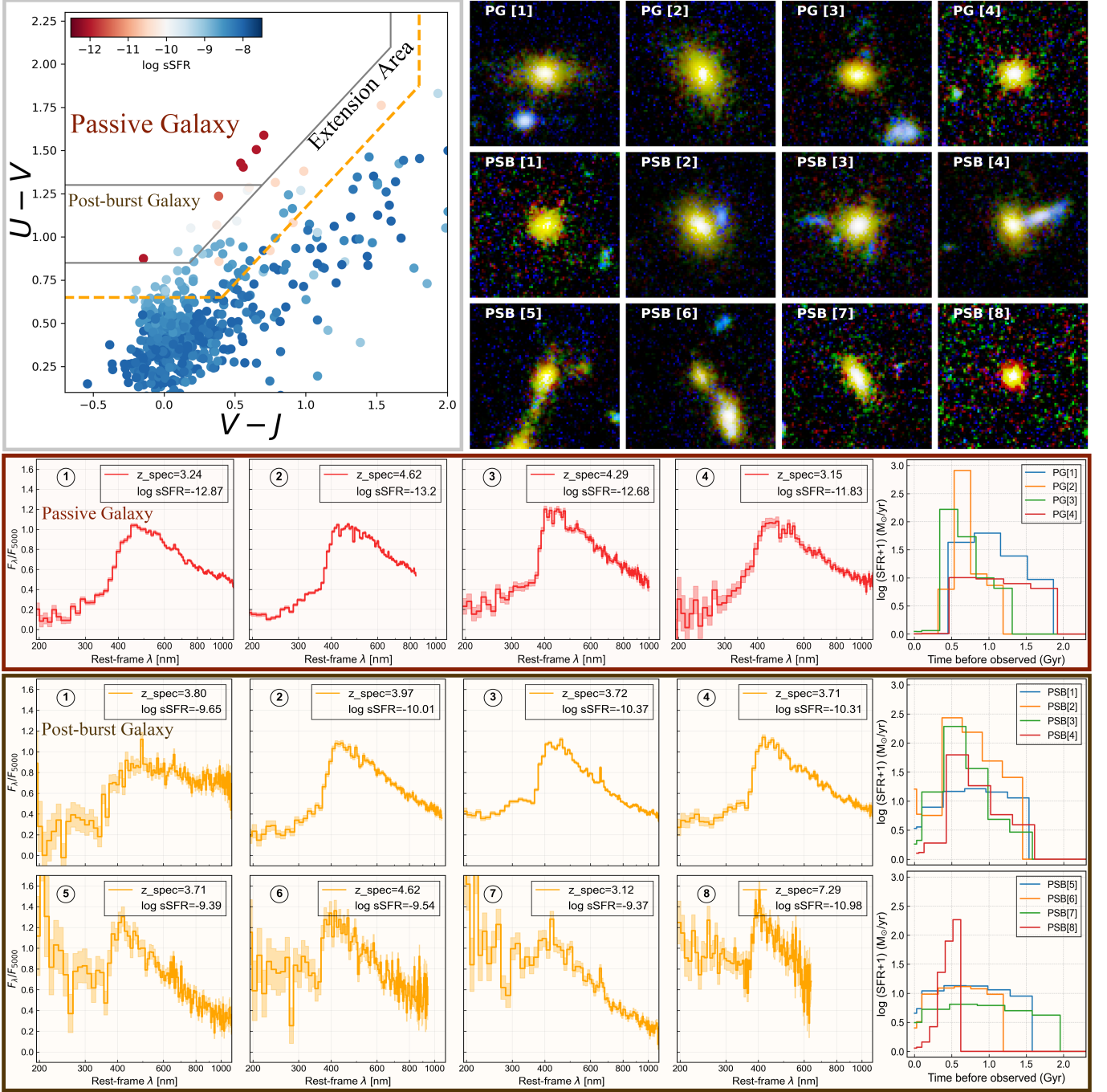


Figure 1. UVJ diagram of all galaxies with publicly available spectra at $3 < z_{\text{spec}} < 8$, color-coded by $sSFR$ derived with BAGPIPES. There are two black horizontal dividing lines: the upper one at $UV=1.3$ was proposed by [R. J. Williams et al. \(2009\)](#). This work shifts this line downward to 0.85 to include high-redshift PSBs. We also define an extension area where the properties of galaxies mostly fall between those of SFGs and QGs. Because we aim at assess the results of the photometric sample selection, the UVJ colors here are derived from SED fitting using only photometric data. However, when fitting the SFH, we include spectral with the emission lines (H_α and $[O\ III]$) masked out. A total of 12 galaxies fall within the PG+PSB region (4 PGs, 8 PSBs); their images, spectra, and fitted SFHs are shown in the figure, numbered in descending order of UV color. The SFHs of different galaxies are aligned together, with x-axis label represents the time before the galaxies are observed.

$$(V - J) < 1.6 \quad (1)$$

$$(U - V) > 0.88 \cdot (V - J) + 0.69 \quad (2)$$

$$(U - V) > 1.3 \quad (3)$$

These criteria is the widely used UVJ selection introduced by [R. J. Williams et al. \(2009\)](#). In this classification region (marked as passive galaxies in Fig 1), the selected galaxies are all relatively old with very low specific star formation rate (sSFR). The reconstructed star-formation histories (SFH) typically show rapid quenching about $\sim 500\text{Myr}$ earlier, resulting in a strong Balmer break.

Below the original region (marked as post-starburst galaxies in Fig 1), we also find a group of galaxies that show clear quiescent features (Balmer break, weak emission lines, and low current SFR) despite comparatively high sSFR. To include these objects, we lower the original $U - V = 1.3$ threshold to $U - V = 0.85$.

Some studies suggest an even larger selection area at high redshift ([S. Belli et al. 2019](#); [C. C. Lovell et al. 2023](#); [W. M. Baker et al. 2024](#)). To test how different selection choices affect the results, we adopt a broadened selection (orange dashed lines in Fig 1) defined as:

$$(V - J) < 1.8 \quad (4)$$

$$(U - V) > 0.88 \cdot (V - J) + 0.29 \quad (5)$$

$$(U - V) > 0.65 \quad (6)$$

This extension area approximately covers the selection ranges proposed in previous work ([W. M. Baker et al. 2024](#); [F. Valentino et al. 2023](#); [C. C. Lovell et al. 2023](#)). However, this extension introduces considerable contamination. Typical QGs only account for $\sim 10\%$ of the newly included sources. Many other galaxies inside the region also show a Balmer break but differ in other properties: some have weaker Balmer breaks and high current SFR (i.e., are not fully quenched), while others show strong emission lines that may indicate AGN activity. These galaxies are not typical QGs, although they may be evolutionarily related. We quantify the impact of including these galaxies in Appendix A.

The sSFR threshold is another commonly used selection method. However, in spectral samples (shown in Fig 1), some PSBs do not satisfy the commonly used sSFR cuts (e.g., $\log\text{sSFR}(\text{yr}^{-1}) < -10$ or $\text{sSFR} < 0.2/t_{\text{Hubble}}$). These galaxies typically exhibit continuous star formation for more than 1.5Gyr , but they show a pronounced decline in the last few hundred Myr (e.g., PSB1, PSB5, PSB6, PSB7). Compared with the UVJ method, sSFR therefore provides a stricter high-redshift

selection: it preferentially selects galaxies that experienced rapid quenching and have remained quenched for a relatively long time. For completeness, we also report statistical results using the sSFR-based selection in Appendix A.

3.2. Reduce LRD Contamination

While the UVJ technique is proven to be effective in selecting QGs, its reliability when applied to purely photometric data requires careful verification. In particular, recent JWST observations reveal a prevalent population of red, point-like, broad-line AGN candidates with V-shaped SEDs at $z \gtrsim 3$ (Little Red Dots, LRDs, [I. Labbé et al. 2023](#); [Z. Li et al. 2024](#); [J. E. Greene et al. 2024](#); [J. Matthee et al. 2024](#)). Despite their blue UV slopes, LRDs show similarly red UV-to-optical colors as QGs. Broad optical emission lines, including [O III], $\text{H}\alpha$, and $\text{H}\beta$, are ubiquitous in these LRDs and can mimic a strong Balmer break, leading to incorrect photometric redshifts ([G. Desprez et al. 2024](#); [G. Barro et al. 2024](#)). With erroneous photo-zs, LRDs can fall into the same region as QGs on the UVJ diagram.

To reduce LRD contamination, we subdivide all photometric UVJ-selected galaxies at $z > 3$ (76 galaxies) into three groups by combining the LRD selection methods from [I. Labbé et al. \(2023\)](#) and [D. D. Kocevski et al. \(2024\)](#). Leveraging the available spectrum, we examine the properties of galaxies in these three categories to assess the reliability of UVJ-based QG selection:

- 1 LRD group: Galaxies that satisfy the LRD criteria in either paper (15 members, 3 have spectrum).
- 2 Clean group: Galaxies that do not meet the LRD criteria in both papers (26 members, 6 have spectrum).
- 3 Uncertain group: Galaxies for which the SNR in at least one band required by the selection criteria is below 3, making classification unreliable (35 members, 14 have spectrum).

Spectral analysis shows that all 3 LRD group members exhibit broad optical emission lines. Similarly, 4 out of 6 sources in the uncertain group show broad lines, compact morphology and large photometric-spectroscopic redshift offsets ($\Delta z \gtrsim 1.5$). These findings indicate that a considerable fraction of point-like, UVJ-selected galaxies may be LRDs rather than genuine QGs. This underscores the need for caution when applying the UVJ technique at high redshift using only photometric data.

By contrast, 12 of the 14 clean-group sources display spectra with a clear Balmer break and weak H II-region

emission (shown in Fig 1), consistent with quiescent stellar populations. This suggests that removing LRD candidates substantially improves the purity of a photometrically selected QG sample. All spectra discussed here are shown in Appendix A.3 and Appendix 1.

Therefore, we treat only the galaxies in the clean-group as robust QGs for the following analysis. The uncertain group, which consist of both true QGs and contamination, is treated as part of the full sample and serves as an upper limit on QG numbers.

The step of removing LRD was not applied to galaxies at $z < 3$, because LRD is almost nonexistent in that redshift range. Low-redshift QGs are therefore directly treated as robust samples.

3.3. galaxies in clean sample

Figure 2 shows the UVJ diagrams of the photometric sample over $0.5 < z < 8$, excluding the uncertain and LRD groups. The redshift bins are chosen to have equal comoving volumes (except the highest-redshift bin) so that the diagrams directly reflect the number density evolution of QGs and SFGs. Most QGs at $z > 3$ lie in the PSB region, consistent with their young stellar populations and recent quenching. At low redshifts, the dividing line between QGs and SFGs corresponds approximately to $\text{sSFR} = 10^{-10} \text{ yr}^{-1}$, but this correspondence becomes less clear at higher redshift.

A small population of galaxies lie outside the selection boxes (even the extension region) yet have $\text{sSFR} < 10^{-10} \text{ yr}^{-1}$ (e.g., the upper left of the sub-panel of $2.1 < z < 2.6$). Most of these objects exhibit point-like morphologies in JWST/NIRCam images, indicating that their rest-frame colors may be strongly influenced by AGN. None of these sources have spectroscopic observations, so their nature remains uncertain. However, because their number is small (only 3 at $z > 3$) and they do not materially affect our main results, we exclude them from the QG sample in this study.

4. RESULT

4.1. The importance of MIRI in QG classification

Previous studies indicate that the absence of JWST/MIRI data can lead to overestimated stellar masses for galaxies at redshifts $z > 5$ (W25; C. Papovich et al. 2023; G. C. K. Leung et al. 2024), which may artificially inflate the number density of high-mass QGs at these epochs. In addition, missing MIRI photometry, which probes the rest-frame J band at $z > 3$, can bias $V - J$ color measurements and thus affect QG classification.

To assess the impact of MIRI data on SED fitting, we run two sets of SED fittings with the redshift fixed

at the spectroscopic value: one including all available photometry (the MIRI sample), and the other excluding MIRI photometry (the no-MIRI sample). Based on the UVJ classification derived from these two fits, the MIRI sample contains 14 QGs (8 high-mass and 6 low-mass), while the no-MIRI sample contains 13 QGs (9 high-mass and 4 low-mass). The two groups partially overlap. The right panel in Figure 3 displays the UVJ colors of galaxies whose classifications differ between the two fits. For clearer visualization, we adopt a rotated UVJ coordinate system:

$$\begin{aligned} S_Q &= 0.75(V - J) + 0.66(U - V) \\ C_Q &= -0.66(V - J) + 0.75(U - V) \end{aligned}$$

Judging from the spectroscopic data of these galaxies, whenever the two fits yield inconsistent classifications, the results from the MIRI-inclusive fits are correct. More than half of the galaxies exhibit a significant difference in V-J color estimation, implying that the absence of MIRI bands introduces large uncertainty in the SED fitting for these galaxies. A smaller subset shows little or no displacement and falls into the extension region; these are mostly emission-line Balmer-break galaxies. Their influence is discussed in Appendix A.

The impact of MIRI also depends on stellar mass. For high-mass galaxies, the no-MIRI sample is substantially contaminated by star-forming galaxies (4 out of 9, 44%), and these sources are correctly identified as star-forming after incorporating MIRI data (e.g., middle panel of Fig. 3). By contrast, the no-MIRI sample is generally clean for low-mass galaxies (only one object is excluded after including MIRI). However, the no-MIRI sample still misses some true quiescent galaxies that are recovered when MIRI data are added (e.g., the right panel in Fig. 3).

This difference likely arises from the age-attenuation degeneracy. Without MIRI, for a galaxy showing a clear Balmer break/D4000 break, the SED fitting tends to favor an older, dust-poor solution. This causes some dusty galaxies to be misidentified as QGs. The effect is reversed for low-mass galaxies because low-mass objects are generally very young PSB galaxies that still have bright UV flux, causing the SED to favor younger ages and higher dust attenuation.

4.2. Number density and Fraction of Quiescent galaxies

We present the evolution of number density of robust QGs in Figure 4. We divide the sample at $10^{10.3} M_\star$ into low-mass and high-mass subsamples. Both subsamples show a rapid decline in number density with increasing

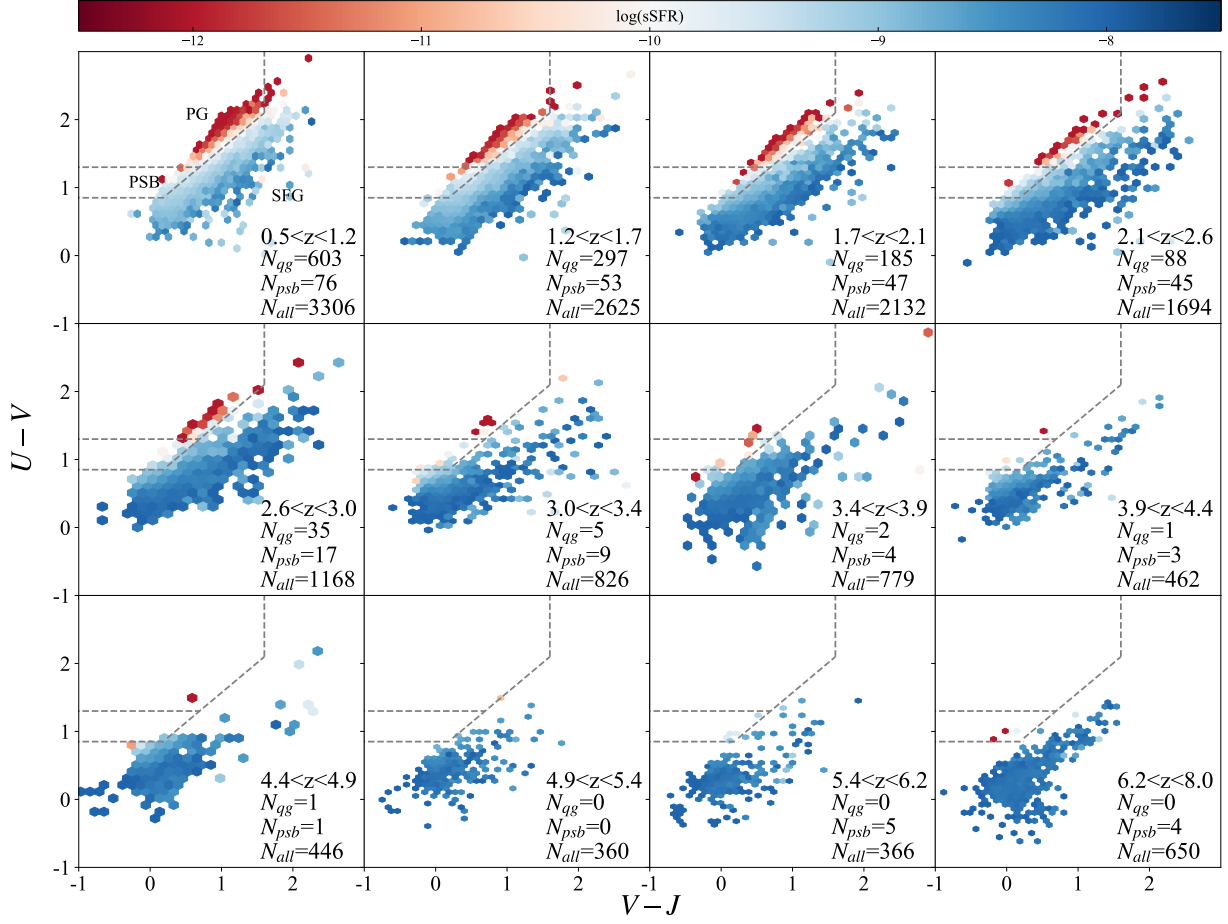


Figure 2. The UVJ color-color diagram with $M_* > 10^9 M_\odot$ in photometric sample, color-coded by sSFR. The comoving volume of all redshift slices is nearly the same (except for the highest-redshift bin), allowing direct interpretation of the evolution in QG and SFG number densities.

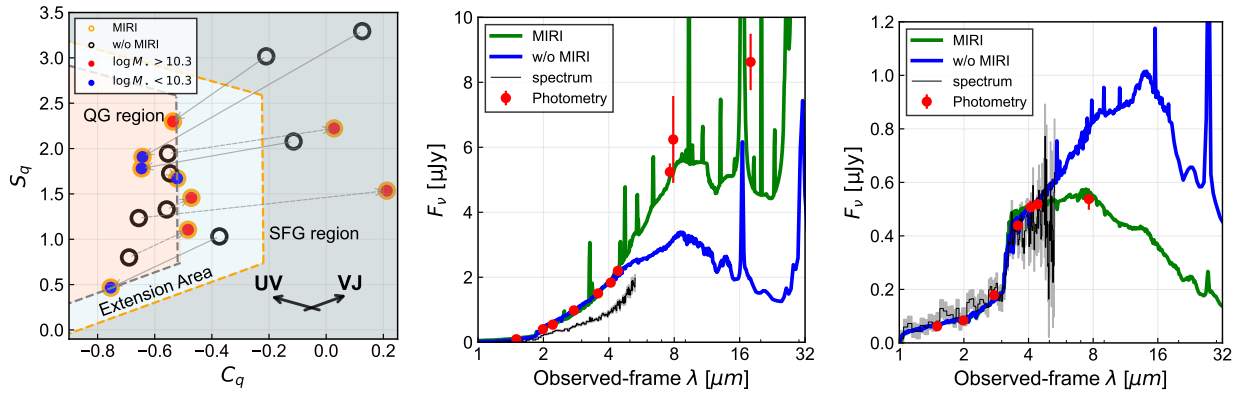


Figure 3. Impact of MIRI photometry on UVJ color classifications. We show the UVJ colors of galaxies in the spectroscopic sample that exhibit inconsistent classifications between the MIRI and no-MIRI runs. The left panel displays the rotated UVJ diagram. Black and yellow open circles, connected by arrows, denote the same galaxies in the MIRI and no-MIRI groups, respectively; blue and red circles indicate galaxies of different masses. The two panels on the right present representative SED fitting results for two conditions (MIRI-exclude QG and MIRI-include QG), respectively.

redshift at $z < 4$, but their evolutionary trajectories diverges at $z > 5$.

The number density of high-mass QGs decreases rapidly with increasing redshift, reaching $n \sim 3 \times 10^{-6} \text{ Mpc}^{-3}$ at $4 < z < 5$ and falling to the single detection limit at $z > 6$ ($n \sim 2 \times 10^{-6} \text{ Mpc}^{-3}$; i.e., only one source is detected in this redshift bin). By contrast, the number density of low-mass QGs remains nearly constant from $z = 4$ to $z = 8$, at approximately $n \sim 3 \times 10^{-6} \text{ Mpc}^{-3}$.

We further investigate the evolution of the quenched fraction of galaxies as a function of stellar mass and redshift, as illustrated in Fig. 5. At high redshift ($z > 4$), QGs are exceedingly rare across all stellar masses, with quenched fractions consistently below 5%. As redshift decreases, the growth in the QG fraction diverges significantly depending on stellar mass. At the high-mass end, the fraction of QGs rises rapidly starting below 5% at $z = 4$ and reaching 40% by $z = 2$. Conversely, at the low-mass end, the fraction of QGs increases slowly and has not reached 20% in the local universe.

5. DISCUSSION

In this work, we estimate the number density of QGs at $0.5 < z < 8$ using multi-wavelength data, including MIRI observations. We find a mass-dependent evolution of the number density, providing new constraints on galaxy quenching at high redshift.

5.1. Comparison with observation and galaxy formation models

For high-mass galaxies, our mass range extends 0.3 dex beyond that of previous work, yet we measure even lower densities. This discrepancy persists in the high-SNR redshift bin ($3 < z < 4$) for the full sample. This is consistent with the idea that the absence of MIRI constraints for massive galaxies allows contamination from dusty star-forming galaxies and/or lower-mass galaxies.

We probe a broader low-mass range ($9 < \log M < 10.3$) than previous works and find lower number densities than reported for $9.5 < \log M < 10.6$ (F. Valentino et al. 2023) at $3 < z < 4$ even take a 50% cosmic variance into consideration. This suggests that QGs with $9 < \log M < 9.5$ are much rarer than those with $10.3 < \log M < 10.6$, or some of the QGs in F. Valentino et al. (2023) may have stellar mass intrinsic lower than reported due to lack of MIRI. Whereas at $4 < z < 6$, the discrepancies lie within the error margin. The highest-redshift QG is at $z = 7.2$, spectroscopically confirmed by A. Weibel et al. (2024). They derive a number density of $10^{-5.8} \text{ Mpc}^{-3}$ at $z \sim 7$, assuming this source is

unique. This value agrees with ours, although the density is roughly twice as high in the full sample.

We compare our results with five galaxy formation models, including two cosmological hydrodynamical suites:

- the IllustrisTNG simulation (TNG; A. Pillepich et al. 2018; F. Marinacci et al. 2018; J. P. Naiman et al. 2018; D. Nelson et al. 2018; V. Springel et al. 2018). We use the TNG100-1, with box size of $L_{\text{box}} = 100.7 \text{ Mpc}$.
- the Virgo Consortium’s Evolution and Assembly of Galaxies and their Environments (EAGLE; J. Schaye et al. 2015). We use the Fiducial_models..RefL0100N1504, with box size of $L_{\text{box}} = 100 \text{ Mpc}$.

and three semi-analytical models:

- the GALaxy Evolution and Assembly model (GAEA; G. De Lucia et al. 2024; M. Hirschmann et al. 2016; L. Xie et al. 2020), with box size $L_{\text{box}} = 500 \text{ Mpc}$.
- L-Galaxies (B. M. B. Henriques et al. 2015; W. Pei et al. 2024), with box size $L_{\text{box}} = 676 \text{ Mpc}$.
- Shark2024 (C. D. P. Lagos et al. 2018, 2024), with box size $L_{\text{box}} = 376 \text{ Mpc}$.
- Shark2025 (Oxland et al. submitted). The Shark2025 is an updated version of the Shark2024. The only difference with respect to the version presented in C. D. P. Lagos et al. (2024) is the ram pressure stripping (RPS) proceeds in a slow fashion, instead of the RPS invoked by C. D. P. Lagos et al. (2024). Oxland et al. found that a slow RPS is required to reproduce the fractions of quenched galaxies in groups and clusters and as a function of cluster centric distance presented in M. Oxland et al. (2024). The difference between Shark2024 and 2025 in high-mass end is negligible, so we only present Shark2025 data in low-mass end for clarity.

The single-detection limit of the two hydrodynamical models is 10^{-6} Mpc^{-3} , roughly consistent with observations. The three semi-analytical models have much larger box sizes, yielding a much lower single-detection limit. All of the referenced theoretical models adopt a Chabrier IMF. Some models predict reasonable agreement with JWST measurements of number density up to $z \sim 5$ (C. D. P. Lagos et al. 2024; G. De Lucia et al. 2024). In this work, we extend the comparison

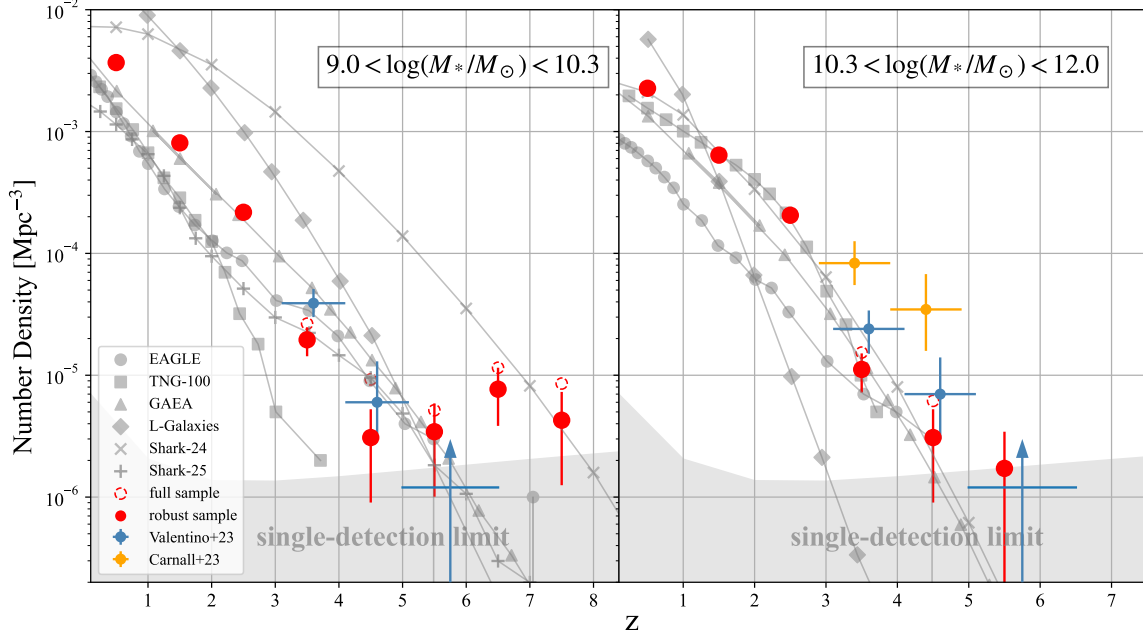


Figure 4. The mass-dependent number density evolution of QGs. The error bars represent Poisson errors only. The relative error for the low-redshift data is approximately 10%, and is not visible in the figure. Results from [F. Valentino et al. \(2023\)](#) and [A. C. Carnall et al. \(2023b\)](#) are also shown, but the mass range is slightly different from ours. Empty circles mark the density calculated in the full sample. The single detection limit, defined as the inverse of the volume, marks the upper limit of the number density if only one source is detected in this redshift range. The result is compared with the number density in EAGLE, Illustris-TNG, GAEA, L-Galaxies, and Shark. We use the sSFR threshold $\text{sSFR} < 0.2/t_{\text{Hubble}}$ to select QGs in models.

between observations and models to $z = 8$. To select QG in models, we adopt an sSFR threshold method of $\text{sSFR} < 0.2/t_{\text{Hubble}}$ to select QGs, because most models do not provide UVJ colors.

For the fraction of QGs, most of theoretical models predict values that agree well with observations across all redshift bins within the uncertainties, but some models underestimate the QG fraction at high redshift (for example, data points from EAGLE and TNG are plotted only up to $z \sim 4$, indicating an absence of QGs at higher redshifts.) — a result echoed by multiple studies (e.g., [A. Weibel et al. 2024](#); [A. S. Long et al. 2023](#)). However, Shark2024 apparently overestimate the QG fraction in the low-mass end, but this bias disappears in Shark2025, which implying the importance of environment quenching for low-mass QGs. It should be note that these discrepancies may not solely reflect the quenching prescriptions, as the QG fraction depends on both QGs and SFGs. Furthermore, as the QG fraction approaches zero at high redshift, the relative Poisson uncertainty grows, which reduces the constraining power of the ratio for numerical models.

In terms of number density, most galaxy formation models systematically underestimate the abundance of high-mass QGs compared to observations, although a

few theoretical models remain consistent within the uncertainties. The models that show the best agreement with data at high redshift generally incorporate stronger AGN feedback (e.g., [GAEA & SHARK F. Fontanot et al. 2020](#); [C. d. P. Lagos et al. 2025](#)), which is consistent with recent works that point to an evolutionary connection between quasars and massive PSBs (e.g., [L. Xie et al. 2024](#); [M. Onoue et al. 2025](#); [Y. Wu et al. 2025](#)). This interpretation is compatible with the number density comparison: The number density of quasars is about 10^{-7}Mpc^{-3} at $z \sim 6$ ([I. D. McGreer et al. 2013](#)) which is much lower than the QG density at face value. However, when accounting for the duty cycle, the total number density of quasars (including potential quasars) would be similar to that of QGs.

For low-mass galaxies, most models match the decreasing tendency up to $z = 6$; beyond this, however, simulated values fall below observations and fail to replicate the observed plateau. The only exception is Shark, the Shark2024 successfully predicts the number density of low-mass QGs at $z > 6$, but it significantly overestimates them at $z \lesssim 6$. After modifying the RPS effect, the overestimation at $z \lesssim 6$ was resolved, but it then underestimated the galaxy number density at $z \lesssim 6$, similar to other models. This highlights the rise of environmen-

tal quenching likely responsible for quenched low-mass galaxies and suggests that the interplay among environmental effects, AGN feedback, and galaxy evolution cycle is more complex at $z > 6$. Current galaxy formation theories still need refinement.

However, other factors may also cause discrepancies between theoretical models and observations. For example, the timescale used to calculate the SFR in galaxy formation models is relatively long (e.g., ~ 200 Myr for GAEA when $z > 5$), which may lead to the omission of some recently quenched PSBs. To investigate this possibility, a careful comparison of the SFH of galaxies in observations and models is needed in future work.

5.2. Mass-dependent Evolutionary Histories of quiescent Galaxies at $z \gtrsim 4$

For high-mass galaxies, the number density decreases rapidly with redshift. This population is nearly extinct at higher redshift ($n < 10^{-6} \text{Mpc}^{-3}$ and $f_q < 5\%$), showing that it should be difficult to fully quench a massive galaxy at high redshift. This low number density also suggests that the QG reported by K. Glazebrook et al. (2024), which was assumed to quench its star formation very early, belongs to a very rare population and remains within the framework of the Λ CMD model.

For low-mass galaxies, as with high-mass galaxies, the number density steadily declines at $z < 5$. However, beyond that, the evolution flattens and the number density remains constant at $\sim 3 \times 10^{-6} \text{Mpc}^{-3}$. This plateau at $z > 4$ suggests that these low-mass QGs are likely in a dynamic equilibrium, transitioning between quiescent and star-forming phases. In other words, these galaxies may be in a temporary quiescent phase between starbursts. The gaseous component may undergo consumption, dispersal, or thermalization; the cold gas phases requires a timescale of several hundred Myr to reform. Alternatively, a static hypothesis may also explain the flat density: a population of QGs appears by $z = 8$ and persist until $z = 5$. However, this scenario must also account for the apparent lack of newly emerging QGs at $5 < z < 8$. Furthermore, the fact that most QGs exhibit bright UV flux (see Fig. 1) implies recent or ongoing star formation, which supports the dynamic (rejuvenation) scenario. We note that a very recent study also reveals a flat number density evolution of QGs with $9.5 < \log(M_*/M_\odot) < 10.5$ based on NIRCам data only (E. Merlin et al. 2025), though with systematically higher number density than what we observed here. A more detailed comparison is beyond the scope of this work and may be addressed in a future study.

Galaxy rejuvenation is uncommon at low redshift (S. Tacchella et al. 2022; T. S. Tanaka et al. 2023) with a

reported fraction of $\lesssim 10\%$, while at higher redshift, this fraction may increase to $\gtrsim 20\%$ (R.-S. Remus & L. C. Kimmig 2023). Our results suggest that rejuvenation could be common at $z > 5$ among low-mass galaxies. In this scenario, the gas reservoir of a high-redshift galaxy may be expelled by supernovae or AGN feedback, but can be replenished soon through accretion, triggering a new round of star formation. To investigate rejuvenation mechanisms, deep spectroscopic observations are needed to constrain star-formation histories and to measure gas kinematics.

A direct indication of the temporarily quenched nature of the low-mass QGs at $z > 4$ is that it is very difficult to fully quench a low-mass (central) galaxy at high redshift. On the other hand, the rapid rise of the number density of low-mass QGs at $z < 3$ is likely driven by environmental effects Y. J. Peng et al. (2010). Recent studies on nearby galaxies suggest that a large black hole (BH) ($M_{\text{BH}} \gtrsim 10^{7.5} M_\odot$) is necessary to fully quench a group central galaxy (A. F. L. Bluck et al. 2023; T. Wang et al. 2024). The lack of truly quenched low-mass QGs at high redshift is consistent with this scenario. In a forthcoming paper (Chen et al. in prep, also see R. A. Sato et al. 2024), we find that high- and low-mass QGs have different mass-size relations (MAR). This further supports that high- and low-mass QGs are quenched by different mechanisms: massive galaxies are likely quenched by BH feedback in massive star-forming progenitors, while low-mass galaxies are quenched mainly by environmental effects.

6. SUMMARY

This study measures the number density evolution of QGs to $z = 8$ using the PRIMER survey, which provides JWST/NIRCам and MIRI imaging over 227 arcmin^2 . We perform a detailed, homogeneous reduction of JWST imaging and combine these with complementary space- and ground-based observations. Photometric-redshifts and SED fitting are implemented by EAZY and BAGPIPES respectively. We select QGs using a padded UVJ color box and remove LRD contamination via a hybrid technique based on I. Labbe et al. (2023) and D. D. Kocevski et al. (2024). We identify 35 robust QGs and 26 potential candidates at $3 < z < 8$. Our main findings are:

- **MIRI improves the purity and completeness of selecting QG samples at $z > 4$:** MIRI photometry is essential to obtain accurate M_* and rest-frame UVJ colors at $z > 4$, which efficiently eliminates dusty SFG contamination among high-mass QGs and enhances the selection of low-mass QGs at high redshifts.

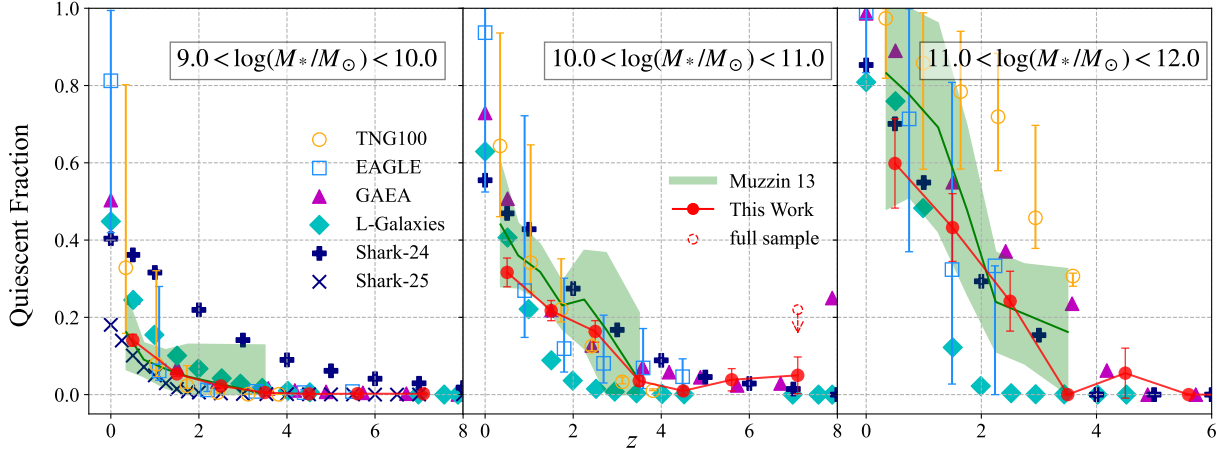


Figure 5. The evolution of QG fractions with redshifts for at different mass bins. Results from EAGLE, Illustris-TNG, GAEA, L-Galaxies, and Shark, together with observational data from A. Muzzin et al. (2013), are also plotted. Results for the full sample are shown as open circles and are plotted only when they exceed the Poisson error. The QG selection criterion for models is $sSFR < 0.2/t_{\text{Hubble}}$. Data points from EAGLE and TNG are plotted only up to $z \sim 4$, indicating an absence of QGs at higher redshifts. Although not perfect, the best galaxy formation models reproduce the evolution of the QG fraction up to $z = 8$.

- **High-mass QGs are rare at $z > 4$ with their number densities decreasing rapidly with increasing redshift:** The number density of high-mass QGs ($\log(M_*/M_\odot) > 10.3$) decreases rapidly from $n = 1 \times 10^{-5} \text{ Mpc}^{-3}$ at $z = 3 - 4$ to $n = 2 \times 10^{-6} \text{ Mpc}^{-3}$ at $z = 4 - 5$, becoming negligible ($n \lesssim 10^{-6} \text{ Mpc}^{-3}$) at $z > 5$. The low number density of these high-mass QGs at high redshift is compatible with that of SDSS quasars ($n \sim 10^{-7} \text{ Mpc}^{-3}$) when duty cycle is taken into account, supporting the hypothesis that quasars are progenitors of high-mass QGs.
- **Low-mass QGs are prevalent at $z > 4$ with a nearly constant number density across $z \sim 4 - 8$:** Low-mass QGs ($9 < \log(M_*/M_\odot) < 10.3$) are detected up to $z > 7$, which maintain a nearly constant number density ($n \sim 3 \times 10^{-6} \text{ Mpc}^{-3}$) across $z = 4 - 8$. This plateau suggests that most low-mass QGs are likely only temporarily quenched and rejuvenation may be common among low-mass galaxies at high redshift.
- **Most current galaxy formation models tend to underestimate the number density of high redshift QGs:** Most galaxy formation models underestimate the observed number density of high-mass QGs and the differences in AGN feedback are likely responsible for the variation between better- and worse-performing models. Simultaneously, the plateau observed in the evolution of low-mass QG number density is also missed in current models, indicating that quenching and

rejuvenation mechanisms (e.g., environment effect, AGN feedback, gas accretion/replenishment) require further refinement.

Our current work remains limited in several respects: first, in the current sample, the number of QGs at $z > 4$ is still very limited (less than five) within a single redshift bin, which leads to significant Poisson and cosmic variance errors. Second, around 60% QGs in our robust sample lack spectroscopic confirmations, which could still be misidentified. In particular, at $z > 3$, it is difficult to distinguish between LRDs and QGs based solely on multi-wavelength photometry and morphological properties. Although the comparison between the full and robust samples suggests that this issue does not affect the overall evolutionary trends and main conclusions, the absolute number density for low-mass galaxies at $z > 4$ may be uncertain by a factor of two to three. Future spectroscopic follow-up observations and medium-band surveys of large samples of high-redshift QGs are essential for reliably determining their properties.

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Software: EAZY (G. B. Brammer et al. 2008), BAGPIPES (A. C. Carnall et al. 2018)

APPENDIX

A. IMPACT OF SELECTION CRITERIA ON RESULTS

In Figure A.1, we relax the selection boundary to the extension area and show the impact of this extended color selection on the results. The UV colors of galaxies in the extension area are largely similar to those of quiescent galaxies, so most of these galaxies exhibit a Balmer break. A small proportion of these Balmer break galaxies ($\sim 10\%$ in the extension area) are typical QGs, lacking emission lines and dust, with extremely low instantaneous star formation rates (such as the leftmost one in the lower panel). However, more of the Balmer break galaxies are in transition from SFGs to QGs, with moderate break strengths and high instantaneous star formation rates. There are also some Balmer break galaxies with strong emission lines, which may be due to central AGN or recent rejuvenation. These galaxies differ from strictly defined QGs but are closely evolutionarily related (unless the Balmer break originates from an AGN. (K. Inayoshi & R. Maiolino 2024)). This region also includes some contamination from star-forming galaxies (the rightmost one in the lower panel), but the proportion is low ($\sim 20\%$ those data points without a black circle). Broadening the selection criteria has little impact on the evolution of the number density of high-mass quiescent galaxies, while the number of low-mass quiescent galaxies increases significantly. Even so, the plateau phase at $z > 4$ still persists.

The evolution of the number density of QGs selected by the sSFR threshold is also shown in Figure A.1. We adopt $sSFR < 0.2/t_{Hubble}$ to select QGs. It has no significant effect on high-mass galaxies, but the number of low-mass QGs decreases significantly. However, the overall evolutionary trend does not change significantly.

B. STELLAR MASS FUNCTION ESTIMATES AND LIMITATIONS

In figure A.2, we present supplementary results on stellar mass function (SMF) estimates at $0.5 < z < 8$. The SMF, constructed from the robust sample, is fitted with a single Schechter function (see H. Sun et al. (2024) for methodology), with best-fit parameters listed in Table A.1. Due to the limited field size, the SMF uncertainties are substantial.

Key features highlighted in the figures include: 1. Above $z = 4$, the low-mass end of the SMF shows smaller evolution compared to the high-mass end, suggesting that galaxy quenching is mass-dependent. 2. The characteristic mass (M^*) decreases substantially from $4 < z < 6$ to $6 < z < 8$, possibly indicating systematic differences in the underlying quenching mechanisms at these epochs.

We caution that, given the limited field size and there are no deeper observations to verify completeness, these conclusions require further observation for confirmation. The results here are presented as a reference and motivation for future follow-up studies.

C. SPECTRUM IN NON-ROBUST SAMPLE

We present the spectra of galaxies belonging to the LRD group and the uncertain group. As shown in Fig A.3, a substantial fraction of these galaxies exhibit clear signs of star formation—such as strong emission lines or blue continuum—suggesting that many are misclassified and are not truly quiescent.

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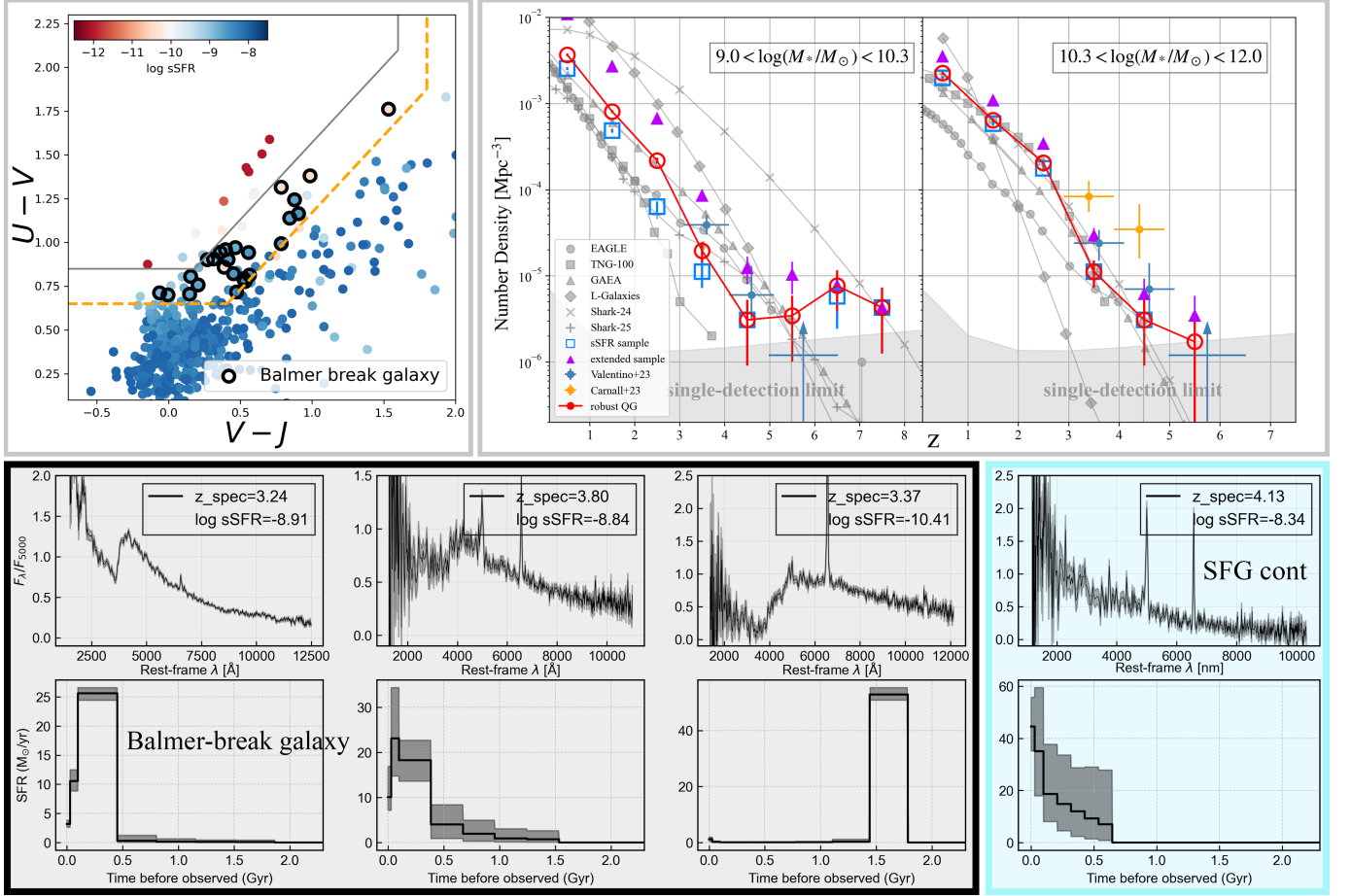


Figure A.1. This figure illustrates the impact of relaxing selection criteria to extension area on the galaxy sample and statistical results. The majority of galaxies within the extended region are so-called Balmer-break galaxies (indicated by black circles), which generally exhibit properties intermediate between SFGs and QGs. The typical spectra of these galaxies are plotted within the black box in the lower left. A small fraction of galaxies within the extended region are contaminants from SFGs, mainly due to their emission lines are identified as Balmer break incorrectly. A typical spectrum of SFG contamination is plotted within the blue box in the lower right. The number density evolution obtained using the extended UVJ selection criteria (extended sample) and the sSFR threshold (ssfr sample) is plotted in the upper right panel.

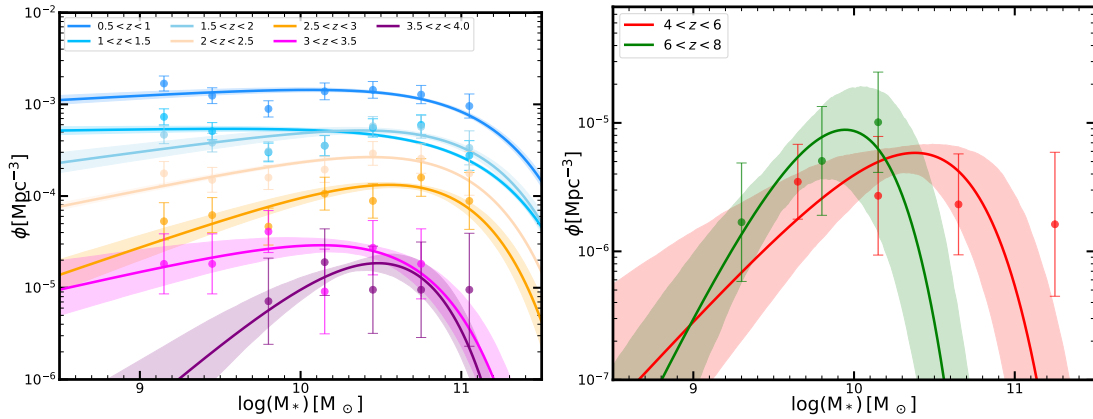


Figure A.2. The Stellar Mass Function (SMF) for quiescent galaxies at $0.5 < z < 8$, fitted by single Schechter function. The data points and best-fit Schechter functions are shown, with the fitting process consistent with that described in [H. Sun et al. \(2024\)](#).

Table A.1. Best-fit Parameters of the SMF of QGs

Redshift	$M_*(\log M_\odot)$	$\phi^*(\times 10^{-5} \text{Mpc}^{-3})$	α
0.5–1.0	11.07 ± 0.02	162.21 ± 4.90	-0.90 ± 0.02
1.0–1.5	11.08 ± 0.03	80.42 ± 3.40	-0.97 ± 0.03
1.5–2.0	11.00 ± 0.03	144.84 ± 4.91	-0.76 ± 0.03
2.0–2.5	10.88 ± 0.04	90.04 ± 4.24	-0.64 ± 0.06
2.5–3.0	10.77 ± 0.05	53.80 ± 2.62	-0.39 ± 0.08
3.0–3.5	10.52 ± 0.08	9.97 ± 1.06	-0.60 ± 0.12
3.5–4.0	10.30 ± 0.12	6.81 ± 0.72	0.52 ± 0.44
4.0–6.0	10.24 ± 0.19	8.00 ± 0.84	0.37 ± 0.50
6.0–8.0	9.52 ± 0.13	4.13 ± 1.13	1.63 ± 0.88

NOTE—Best-fit results for quiescent galaxies fitted with a single Schechter function (see [H. Sun et al. 2024](#), for methodology). The sample includes all robust PG and PSB with $\log(M_*/M_\odot) > 9$ at $0.5 < z < 8$. Fitting results are shown in Figure [A.2](#).

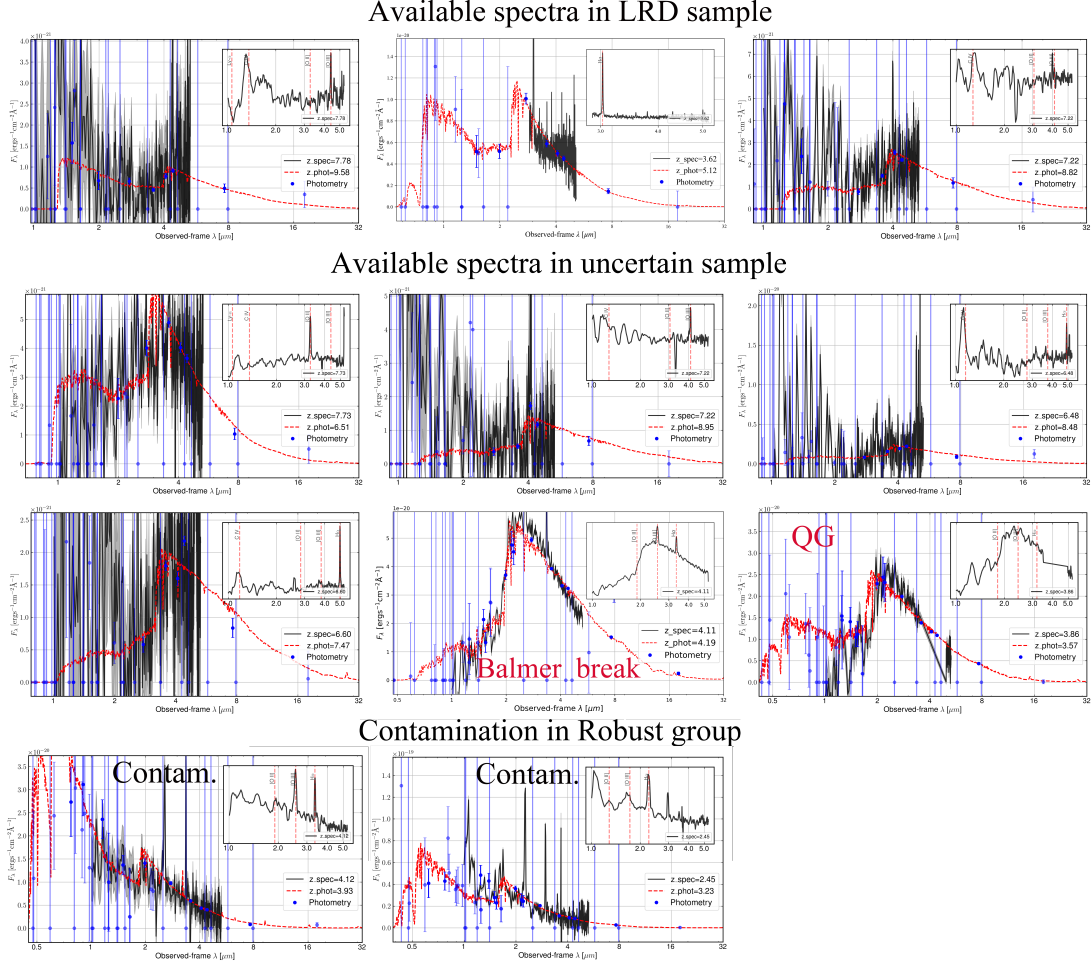


Figure A.3. The spectra for the galaxies in the uncertain group and LRD group (see Section 3). The red dotted line is the SED fitting result based on photometric data only. Most of the galaxies in these two groups are classified incorrectly because the SED code identifies the strong H_α or $[O III]$ as a Balmer break, leading to an incorrect redshift estimation. We omit all the sources that fit the LRD criteria to ensure the purity of the QG sample and include the uncertain group of galaxies as part of the full sample to estimate the upper limit of the number of QGs. The bottom panel shows the spectra of two contamination in robust samples. The contamination rate is approximately 14% (2/14).

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