Revisiting the Color–Color Selection: Submillimeter and AGN Properties of NUV–r–J Selected Quiescent Galaxies

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Abstract

We examine the robustness of the color–color selection of quiescent galaxies (QGs) against contamination of dusty star-forming galaxies using the latest submillimeter data. We selected 18,304 QG candidates out to z ∼ 3 using the commonly adopted NUV–r–J selection based on the high-quality multiwavelength COSMOS2015 catalog. Using extremely deep 450 and 850 μm catalogs from the latest JCMT SCUBA-2 Large Programs, S2COSMOS and STUDIES, as well as the Atacama Large Millimeter/submillimeter Array submillimeter, VLA 3 GHz, and Spitzer MIPS 24 μm catalogs, we identified luminous, dusty, star-forming galaxies among the QG candidates. We also conducted stacking analyses in the SCUBA-2 450 and 850 μm images to look for less-luminous dusty galaxies among the QG candidates. By cross matching to the 24, 70 and 3 GHz data, we were able to identify a subgroup of “IR-radio-bright” QGs that possess strong 450 and 850 μm stacking signals. The potential contamination of these luminous and less-luminous dusty galaxies accounts for approximately 10% of the color-selected QG candidates. In addition, there exists a spatial correlation between the luminous star-forming galaxies and the QGs at a z < 1.5. Our data show a strong correlation between QGs and radio AGNs, which may suggest a connection between the quenching process and the radio-mode AGN feedback.

Unified Astronomy Thesaurus concepts: Galaxy formation (595); High-redshift galaxies (734); Quenched galaxies (2016); Early-type galaxies (429); Observational astronomy (1145); Active galactic nuclei (16); AGN host galaxies (2017); Submillimeter astronomy (1647); Astrostatistics (1882); Galaxy evolution (594); Galaxy quenching (2040); Extragalactic astronomy (506)

1. Introduction

Quiescent galaxies (QGs) are defined as galaxies whose star formation rates (SFRs) are lower than the average SFRs of star-forming galaxies (SFGs) of similar stellar masses at similar redshifts, i.e., below the “main sequence” (Daddi et al. 2007; Elbaz et al. 2007; Noeske et al. 2007; Wuyts et al. 2011; Cimabur et al. 2013). The quenching mechanism of QGs is an important topic, especially for high-redshift ones. Observations have shown that populations of massive QGs exist at z ∼ 1.0–2.0 (Belli et al. 2017b; Newman et al. 2018; Carnall et al. 2019) and that half of the most massive QGs were formed at z ∼ 1.5 (Ilbert et al. 2013; Muzzin et al. 2013). In recent studies, the QG population has been extended to z ∼ 4.0 (Straatman et al. 2014; Glazebrook et al. 2017; Merlin et al. 2018; Schreiber et al. 2018c; Carnall et al. 2020; Forrest et al. 2020a, 2020b; Valentino et al. 2020). Among these, Valentino et al. (2020) reported three QGs with stellar masses around 10^{11} M_☉ and with SFRs ranging from 1.1 to 24.0 M_☉ year^{-1} (1.0–2.1σ below the main sequence) at z ∼ 3.775, 4.012, and 3.767. How these high-z QGs can increase their mass and quench the star formation in such a short period is still not fully understood.

Active galactic nucleus (AGN) feedback is one of the scenarios proposed to explain the rapid quenching (Bower et al. 2006; Croton et al. 2006; Somerville et al. 2008; Fabian 2012; Man & Belli 2018). AGN activities may either provide kinetic energy to the interstellar medium in the host galaxies and reduce the star formation efficiency, or heat up the gas to prevent the gas from cooling, in cases of radio-mode AGN feedback (Bower et al. 2006; Croton et al. 2006; Fabian 2012; Somerville et al. 2008). AGN activities may also remove the gas and terminate the star formation,
in cases of quasar-mode AGN feedback (Somerville et al. 2008; Fabian 2012).

However, there are also other theoretical scenarios for the quenching mechanism. For example, the existence of turbulence may also provide kinetic energy to the system and result in morphological quenching (Dekel et al. 2009; Martig et al. 2009). Another example would be positive AGN feedback. In this case, AGN activities enhance star formation but rapidly consume the gas, resulting in a quenched galaxy (Ishibashi & Fabian 2012; Shangguan et al. 2020; Zhuang & Ho 2020). Other theoretical scenarios include mergers, stellar feedback, virial shock heating, etc. (see discussion in Man & Belli (2018), and references therein), and the quenching of massive galaxies could be a combination of some of these scenarios. Which of the aforementioned scenarios is the dominant channel of the quenching mechanism remains unclear.

Here, we would like to first focus on the foundation of the QG studies, the selection criteria of QGs. Rest-frame color–color diagrams are widely applied to selecting QGs. They are often composed of two rest-frame colors: a UV–to–optical color (typically as the y-axis) to distinguish blue SFGs from red QGs using the strong UV emission from young stars, and an optical–to–near-infrared color (typically as the x-axis) to distinguish old passive stellar populations from dusty/reddened young stellar populations. Such photometric selections are very convenient since only photometric data are needed. There are various kinds of color–color diagrams proposed for QG selections based on rest-frame absolute magnitudes, such as the $U$–$V$–$J$ diagram (Wyits et al. 2007; Williams et al. 2009; Muzzin et al. 2013), the $NUV$–$r$–$J$ diagram (Ilbert et al. 2013), and the $NUV$–$r$–$K$ diagram (Arnouts et al. 2013).

Despite the great success of using color–color diagrams to select large samples of QGs, there are potential issues in such selections. First, the selection boundary that separates QGs and SFGs in a color–color diagram was decided empirically (e.g., Williams et al. 2009; Ilbert et al. 2013; Muzzin et al. 2013). Whether a set of selection criteria are still applicable to different data sets should be examined. Second, either because of the intrinsic properties of SFGs and QGs, or because of photometric errors, the distribution of the two groups of galaxies can have unknown levels of overlap around the selection boundaries. It has been found that adjusting the position of the boundary by ±0.1 mag can greatly change the selection efficiency and the subsequent analyses based on the selected samples (Muzzin et al. 2013, Appendix B therein).

One important factor here is that our understanding of dusty galaxies is limited. The spectral energy distribution (SED) of these high-z dusty galaxies may be more complicated than what was initially assumed to set up color selection. The selected QG “candidates” may still suffer from contamination by red dusty SFGs at high z. For instance, a $z = 3.717$ QG candidate (Straatman et al. 2014; Glazebrook et al. 2017) has been detected at 450 and 870 μm (Simpson et al. 2017). This implies that the target is a dusty SFG, or is an interacting system consisting of a QG and a dusty galaxy (e.g., Schreiber et al. 2018c), or at least contains a significant dusty star-forming component. Such contamination may lead to an overestimated number density of QGs, especially at high z, which may have consequences in our pursuit of an understanding of the quenching mechanism.

Therefore, in this paper, we would like to revisit the selection of QGs using color–color diagrams. We will examine the quiescence of our color-selected QG candidates using submillimeter observations. Various previous studies have been carried out to analyze the star formation of color-selected QGs. Some studies have measured the SFR by either applying SED fittings from the UV to mid-infrared bands (Fumagalli et al. 2014; Merlin et al. 2018; Carnall et al. 2019; Toba et al. 2019), using spectroscopic data (Belli et al. 2017b; Schreiber et al. 2018b), or measuring Hα emission (Belli et al. 2017a). Others have searched for far-infrared dust emissions using Spitzer observations (Fumagalli et al. 2014; Man et al. 2016; Gobat et al. 2018; Magdis et al. 2021), Herschel observations (Viero et al. 2013; Straatman et al. 2014; Man et al. 2016; Gobat et al. 2018; Merlin et al. 2018; Magdis et al. 2021), or Atacama Large Millimeter/submillimeter Array (ALMA) observations (Simpson et al. 2017; Schreiber et al. 2018b; Santini et al. 2019). Others have also searched for gas content in QG candidates (Sargent et al. 2015; Young et al. 2011). In particular, Man et al. (2016) measured the dust emission of their color-selected QGs by stacking Herschel SPIRE data at 250, 350, and 500 μm (FWHM ≈ 18′′, 24′′, and 36′′), and they claimed that contamination of dusty SFG is ~15% among their QG candidates. We will follow the approach in Man et al. (2016) but re-examine the issue with higher angular resolutions using JCMT SCUBA-2 450 and 850 μm data (FWHM = 7′′9 and 13′′) and ALMA data.

In this study, we selected 18,304 QG candidates using the $NUV$–$r$–$J$ diagram with deep galaxy samples from the COSMOS field (Laigle et al. 2016) and analyzed the properties of the selected QG candidates. In the first part of our study, we estimated the contamination of dusty SFGs among the QG candidates by cross matching them to the multiwavelength catalogs as well as performing stacking analyses in the submillimeter images. We also estimated the effect of chance projection in the cross matching and estimated the degrees of small-scale clustering. In the second part of our study, we further investigated the AGN feedback as a potential quenching mechanism among QG candidates. We examined the relation between various AGNs and the QG candidates in our data by calculating the QG fractions in the AGN samples.

We describe our data in Section 2 and introduce the QG color–color selection in Section 3. In Sections 4 and 5, we analyze the contamination of dusty SFGs among the $NUV$–$r$–$J$ selected QG candidates. We also examine the small-scale clustering between dusty SFGs and QG candidates in Section 4.2. In Section 6, we discuss the QG fractions among our AGN samples. Section 7 gives a summary of our results. We use the Chabrier (2003) initial mass function (IMF) and an $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_{\Lambda} = 0.7$, and $\Omega_m = 0.3$ cosmology throughout this study.

2. Multiwavelength Data
2.1. COSMOS2015 Catalog

We selected galaxies from the multiwavelength band-merged COSMOS2015 catalog (Laigle et al. 2016). To use the rest-frame absolute magnitudes for our color selection, we excluded those labeled as failures in SED fitting in order to avoid bad absolute magnitudes. We also excluded samples that are labeled as stars. We excluded galaxies with extreme values in the catalog ($NUV$, $r$, and $J$ absolute magnitudes that are <−30 or >0, and negative redshifts), which are likely caused by either catastrophic failures in SED fitting or problematic photometry. These selection criteria reject ~57% (677,085/1,182,108) of the initial sample.

We further limited the errors of the magnitudes in $K_s$ band to be lower than 0.2. This uniform selection ensures that our
The Astrophysical Journal, 913:6 (19pp), 2021 May 20

Hwang et al.

sample has a robust set of photometry and avoids biasing against high-z samples. The limiting magnitude is 23.7 for $K_S$ band. The selection criterion of the $K_S$ band magnitude error further rejects $\sim 29\%$ (344,806/1,182,108) of the initial sample. Overall, the majority of the rejections are caused by their faintness: they either are not detected at $K_S$ or have $K_S > 24$.

With the above selection criteria, we obtained a total sample size of 160,217 galaxies from the COSMOS2015 catalog. They all have high-quality SED fitting results; all of them have SED fitting based on at least nine filters, and 98% of them have more than 28 filters. The sample covers an area of 1.58 deg$^2$ in the COSMOS field (Figure 1). We used stellar mass $M_*$, photometric redshift $z$, and rest-frame absolute magnitudes $M_{NVV}$, $M_r$, and $M_J$ from the COSMOS2015 catalog, which were derived from SED fittings. The members of this sample have stellar masses up to $M_* = 10^{12} M_\odot$ and redshifts over $z \sim 4$ (Figures 2(b) and (c)). The absolute magnitudes will be applied for our QG selection in the next section.

2.2. Submillimeter Data

We used submillimeter data in the COSMOS field from JCMT SCUBA-2 (Holland et al. 2013, 1999) at 450 $\mu$m (STUDIES; Wang et al. 2017; final data release in Z. K. Gao et al. 2021, in preparation) and 850 $\mu$m (S2COSMOS; Simpson et al. 2019), in order to search for dusty SFGs that contaminate the QG sample. The 450 $\mu$m map covers the central 151 arcmin$^2$ of COSMOS, while the 850 $\mu$m map covers the whole COSMOS field (Figure 1). The 450 and 850 $\mu$m maps have detection limits of about 3.5 mJy and 2 mJy, respectively. The detection limits are all substantially higher than the confusion noise: $\sigma_c \sim 0.7$ mJy at 450 $\mu$m (e.g., Lim et al. 2020) and $\sigma_c \sim 0.5$ mJy at 850 $\mu$m (e.g., Simpson et al. 2019).

In total, we selected 357 objects with 450 $\mu$m detection and 1147 objects with 850 $\mu$m detection from the SCUBA-2 maps.

Figure 1. Coverage maps of the COSMOS field. Background shows the S2COSMOS 850 $\mu$m image. Black polygon corresponds to the coverage of our $K_s$ band selected COSMOS2015 sample, while the white circle corresponds to the 151 arcmin$^2$ coverage of STUDIES 450 $\mu$m image. The MIPS 24 $\mu$m and VLA 3 GHz catalogs cover the whole area of the black polygon and are not shown in this figure.

Four of the 450 $\mu$m sources and 166 of the 850 $\mu$m sources are located outside the region occupied by our optically selected sample, because of the difference in area coverage and the masks in the COSMOS2015 catalog (Figure 1). Among the remaining 353 objects with 450 $\mu$m detection and 981 objects with 850 $\mu$m detection, 77 and 370, respectively, have ALMA observations from the AS2COSMOS and A3COSMOS catalogs (Section 2.3).

Since the SCUBA-2 maps have relatively low angular resolution, we could not reliably identify the optical counterparts to the submillimeter sources. We therefore include the auxiliary data in Section 2.3 for the process of cross-matching COSMOS2015 galaxies to SCUBA-2 sources, and the details will be described in Section 4.1.

2.3. Auxiliary Data

Because of their better astrometry, we included Spitzer MIPS 24 $\mu$m, VLA 3 GHz, and ALMA catalogs in our study, both when our submillimeter data do not have sufficient angular resolution as well as for analyzing QG properties.

For 24 $\mu$m data, we used the Spitzer MIPS S-COSMOS image from Sanders et al. (2007). In order to generate a catalog deeper than the archival MIPS catalog of Sanders et al. (2007), 24 $\mu$m sources were extracted using SExtractor (Bertin & Arnouts 1996), and their fluxes were recalibrated to their Spitzer General Observer Cycle 3 total fluxes. Our MIPS 24 $\mu$m catalog has a 3.5$\sigma$ detection limit of 57 $\mu$Jy, in contrast to the flux cut at 150 $\mu$Jy in Sanders et al. (2007). Our catalog is very similar to the catalog of Le Floc’h et al. (2009) in terms of total numbers of detections. The fluxes are also consistent within 6% (Lim et al. 2020), as we calibrated our fluxes to that of Sanders et al. (2007). We cross-matched the COSMOS2015 catalog with our MIPS 24 $\mu$m catalog using a search radius of 2$''$, which corresponds to about one-third of the beam size at 24 $\mu$m. A total of 26,999 galaxies (16.9%) are matched to the MIPS 24 $\mu$m sources.

For 3 GHz data, we directly adopted the identification of the COSMOS2015 objects in the VLA catalog of Smolčić et al. (2017b), which used a search radius of 0.8$''$. The 5$\sigma$ detection limit of the VLA catalog of Smolčić et al. (2017b) is 2.3 $\mu$Jy beam$^{-1}$. A total of 6002 galaxies (3.7%) are matched to the VLA 3 GHz sources.

We also used catalogs derived from ALMA observations, including the AS2COSMOS (Simpson et al. 2020) and A3COSMOS (Liu et al. 2019) catalogs. The AS2COSMOS catalog was derived from the follow-up 343 GHz observations of 186 bright 850 $\mu$m sources in the S2COSMOS catalog. The AS2COSMOS sources are essentially complete for the S2COSMOS sources above 6.2 mJy; only one S2COSMOS source does not have ALMA detection. The A3COSMOS catalog collects ALMA archival data in the COSMOS field, at wavelengths from 671 to 90.2 GHz. We cross-matched our optical sample with the ALMA catalogs using a search radius of 1$''$. This search radius should allow us to overcome the intrinsic offsets between starlight and submillimeter emission from dusty galaxies (e.g., 1$''$ offset of 0.55 in Chen et al. (2015)).

2.4. AGN Sample

We also examined the AGN properties of our sample. We cross-matched our sample with radio AGNs from the VLA catalog of Smolčić et al. (2017a), color-selected mid-IR AGNs
from Chang et al. (2017), and X-ray AGNs selected from Chandra data by Civano et al. (2016) and Marchesi et al. (2016).

The radio AGNs were selected by comparing the observed radio emission to the expected radio emission from IR-derived SFRs. Those exceeding 3σ in $L_{\log{SFR}}^{1.4\ GHz}$ are classified as radio AGNs (see the details in Delvecchio et al. (2017) and Smolčić et al. (2017a)). The mid-IR AGNs were selected in the rest-frame mid-IR color–color diagram. Those that exhibit red power-law SEDs in the mid-IR are classified as mid-IR AGNs (see the details in Lacy et al. (2004, 2007), Donley et al. (2012), and Chang et al. (2017)). The X-ray AGNs were selected with X-ray luminosity of $L_{\log{SFR}}^{2\ –\ 10\ keV} > 10^{42} \ ergs\ s^{-1}$ (Zezas et al. 1998; Ranalli et al. 2003; Szokoly et al. 2004). We note that, if such an X-ray luminosity is produced purely by X-ray binaries rather than an AGN, the inferred SFR would be $> 200 \ M_{\odot}\ yr^{-1}$ using the conversion between SFR and $L_{\chi}$ (e.g., Ranalli et al. 2003). Such a high SFR would be detected in our submillimeter analyses, but we do not observe it. Therefore, the majority of the $L_{\log{SFR}}^{2\ –\ 10\ keV} > 10^{42} \ ergs\ s^{-1}$ sources in our samples should be AGN-dominated.

3. Color–Color Diagram

We applied the rest-frame $NUV$–$r$–$J$ color–color diagram to our sample in order to select QG candidates. Various color–color diagrams were used for QG selection, including the $U$–$V$–$J$ diagram (Williams et al. 2009) and the $NUV$–$r$–$J$ diagram (Ilbert et al. 2013). Although the $U$–$V$–$J$ diagram is more widely used than the $NUV$–$r$–$J$ diagram, there are advantages of using the $NUV$ and $r$ bands instead of the $U$ and $V$ bands (Ilbert et al. 2013). The $NUV$ band is at a shorter wavelength, so it is more sensitive to emission from young stars and extinction. The $NUV$–$r$ color has a wider wavelength span than the $U$–$V$ color, so it is less vulnerable to photometric errors. The rest-frame $NUV$ band can be obtained from optical data toward higher redshifts, around $z > 2$, where the $U$ band starts to enter the near-IR. This leads to better sensitivities. Because of the above, we adopted the $NUV$–$r$–$J$ diagram in this study. We note that the selection results of using the two color–color diagrams are similar to each other. About 85% of our $NUV$–$r$–$J$ selected QG candidates overlap with the $U$–$V$–$J$ selected QG candidates, and the overlapping fraction slightly varies with redshift and the position of the selection boundary.
On the $NUV-r-J$ color–color diagram (Figure 2(a)), a blue color in the $y$-axis indicates starlight from young stars, while the color in $x$-axis breaks the degeneracy between age and dust reddening. QGs tend to locate in the upper left corner of the diagram. We adopted the criteria proposed by Ilbert et al. (2013):

$$M_{NUV} - M_r > 3(M_r - M_J) + 1,$$

$$M_{NUV} - M_J > 3.1.$$  

We selected 18,304 galaxies, i.e., $11.4 \pm 0.1\%$ of the total sample (Figure 2(a)), to be our QG candidates. The selected QG candidates have a redshift distribution peaking at $z \sim 1.0$ and extending to $\sim 3.0$ (Figure 2(d)). Our selection result is quite consistent with the flag “CLASS=0” in the COSMOS2015 catalog (Laigle et al. 2016), which applied the same $NUV-r-J$ selection method. Among the 24 $\mu$m detected galaxies, $5.9 \pm 0.1\%$ enter the QG selection region and therefore are QG candidates (Figure 3(a)). Among the 3 GHz detected galaxies, $17.8 \pm 0.5\%$ are QG candidates (Figure 3(b)). The redshift distributions of the 24 $\mu$m and 3 GHz detected QGs also peak at $z \sim 1.0$, but they have a larger fraction of QGs at high $z$ (Figure 3(c)). The QG selection of submillimeter-detected galaxies will be described in Section 4.1. The numbers of selected QG candidates are summarized in Table 1.

To better understand the diagrams, we show the reddening vector and the typical (median) errors of the two colors in Figures 2(a), 3(a), and 3(b). The reddening vector is derived from Calzetti et al. (2000) extinction. Unfortunately, with regard to the magnitude errors, the COSMOS2015 catalog does not provide errors in the absolute magnitudes. To have a rough idea of the errors, we followed the COSMOS2015 procedure (O. Ilbert & I. Davidzon 2021, private communication) to select the nearest broadband filter in the rest-frame that has a photometric error of $<0.3$. In addition, we use the photometric error of that filter band as the absolute magnitude error. This clearly does not account for the errors in the $K$-corrections derived from the fitted SEDs, nor the errors propagated from the photo-$z$ errors, but it should still include a substantial part of the error budget.

With the photometric errors estimated above, we could further estimate the fraction among the QG candidates that may originate from the SFG color space and be scattered into the QG color space by the photometric errors. For each QG candidate, we generated 1000 randomly perturbed $NUV$, $r$, and $J$-band absolute magnitudes that follow Gaussian distributions according to the photometric errors. We then calculated the percentage of the perturbed colors that are located in the SFG region, i.e., the probability of the QG candidate to be selected as an SFG if there were no photometric errors. The average probability among our QG candidates is $\sim 7.5\%$, meaning that $\sim 7.5\%$ of our selected QG may have moved from the SFG color space across the boundary into the QG color space, due to their photometric errors. The probabilities can help us to understand the nature of dusty SFG contamination in the color-selected QG population. We will further discuss this in Sections 4 and 5.

From Figure 3(a), we can see that most of the 24 $\mu$m detected QG candidates tend to be distributed close to the selection boundary in the diagram. They can be either dusty galaxies entering the QG color space because of atypical SED shapes, simply regular SFGs scattered into the QG color space because of photometric errors (cross in Figure 3(a)), or chance projections in the cross matching. By measuring the search area of matching through $2^{\prime}$ search radius, we estimated that 382 $\pm$ 20 out of the 1596 matches (23.9 $\pm$ 1.2\%) may be chance projections. In Table 1, 24 $\mu$m detected galaxies have lower QG fractions than...
that of all the COSMOS2015 sample. The 24 μm sources are sensitive to dust emission, and the low fraction suggests a low dusty-galaxy contamination in the QG color selection.

On the other hand, the 3 GHz detected QG candidates distribute well into the QG selection region in Figure 3(b). If we calculate their vertical distances to the selection boundary, we obtain median values of 0.4 and 0.7 for the 24 μm and 3 GHz detected QG candidates, respectively. The median distance for the 3 GHz detected QGs is much larger than the typical photometric error (cross in Figure 3(b)), so they are not SFGs scattered into the QG color space. A large fraction of them should be real QGs harboring radio AGNs (see Section 6 and Figure 8 for further evidence). In Table 1, the QG fraction among them is considerably higher than those of all the other subgroups. This gives us a hint about the correlation between radio AGN and QG candidates, which will be discussed in Section 6.

4. Bright Submillimeter Galaxies among QG Candidates

In this section, we conduct a thorough analysis of the contamination of bright submillimeter galaxies among our QG candidates. In Section 4.1, we cross-match our sample with the SCUBA-2 450 μm and 850 μm catalogs, using the positions of MIPS 24 μm, VLA 3 GHz, and ALMA submillimeter sources. In Section 4.2, we further perform a blind cross matching and report the finding of small-scale clustering between QG candidates and SCUBA-2 sources.

4.1. Traditional Cross Matching

4.1.1. Counterpart Identification Using Auxiliary Data

We have searched for MIPS 24 μm, VLA 3 GHz, and ALMA counterparts in the COSMOS2015 catalog with data presented in Section 2.3. We can therefore search for the optical counterparts to the low-resolution SCUBA-2 submillimeter sources by including the high-resolution multiband information. Such a two-step counterpart identification method is traditionally used on SCUBA-2 sources. In general, this method was shown to be able to pick up some 2/3 of SCUBA-2 source counterparts (e.g., Casey et al. 2013; Koprowski et al. 2016; Cowie et al. 2017; Michałowski et al. 2017; An et al. 2018; Lim et al. 2020; Simpson et al. 2020), but the exact fractions depend on the sensitivity of the high-resolution observations in the mid-IR, submillimeter, or radio.

We first cross-matched our optical sample with the SCUBA-2 450 μm and 850 μm sources using a search radius of 4″ and 7″, respectively. The search radii are approximately half of the full widths at half maximum of the beams (FWHM = 7″ at 450 μm and 13″ at 850 μm). Such larger search radii (see 1/3 FWHM for the 24 μm matching) are required because the SCUBA-2 positional accuracy is more impacted by confusion effects and telescope pointing errors, rather than just the beam sizes. Then, from the matched sample, we narrowed down the optical counterparts by searching for ALMA-detected galaxies from the AS2COSMOS and A3COSMOS catalogs (described in Section 2.3). For the remaining sources without ALMA detection, we identified their optical counterparts by searching for 24 μm and 3 GHz detected galaxies (described in Section 2.3). Those without MIPS and VLA counterparts are likely to be at higher redshifts (z ≥ 3; see Section 3.3 in Lim et al. 2020) and are not the main targets of interest in this paper, given the redshift distributions in Figure 2. We note that, when there are multiple sources within the search radius, we consider all of the sources and narrow down the possible counterparts only with multiband information, without considering their distances to the SCUBA-2 position.

The results of the cross matching are summarized in Table 1. For the SCUBA-2 450 μm sources, we matched 58 COSMOS2015 galaxies through ALMA observations and 181 through the MIPS and VLA catalogs. We defined them as 450 μm detected galaxies. Two out of the 58 galaxies and six out of the 181 galaxies are selected as QG candidates in the NUV−r−J diagram (Figure 4(a)). For the SCUBA-2 850 μm sources, there are 289 matches when using the ALMA catalogs and 364 matches when using the MIPS and VLA catalogs. We defined them as 850 μm detected galaxies. Eleven out of the 289 galaxies and 19 out of the 364 galaxies are selected as QG candidates in the NUV−r−J diagram (Figure 4(b)).

One thing worth noting here is the distribution of 450 μm and 850 μm detected QG candidates in the NUV−r−J diagrams in Figure 4. Although these sample sizes are small, these QG candidates do not appear to have a tendency to locate near the selection boundaries (see the 24 μm case in Figure 3(a)), as

| | SFGs+QGs | QGs | QGs/(All SFGs+QGs) | QGs/(All QGs) | QGs by Chance Projection |
|---|---|---|---|---|---|
| Total in the COSMOS field | 160217 | 18304 | 11.4 ± 0.1% | 100% | ... |
| 24 μm detected | 26999 | 1596 | 5.9 ± 0.1% | 8.72 ± 0.22% | 382 |
| 3 GHz detected | 6002 | 1066 | 17.8 ± 0.5% | 5.82 ± 0.18% | ... |
| 850 μm detected | 653 | 30 | 4.6 ± 0.8% | 0.16 ± 0.03% | ... |
| 850 μm + ALMA | 289 | 11 | 3.8 ± 1.1% | ... | 1.3 |
| Total in the STUDIES field | 15296 | 1846 | 12.1 ± 0.3% | 100% | ... |
| 450 μm detected | 239 | 8 | 3.3 ± 1.2% | 0.43 ± 0.15% | 2.5 |
| 450 μm + ALMA | 58 | 2 | 3.4 ± 2.4% | ... | 0.3 |
| 450 μm + 24 μm + 3 GHz | 181 | 6 | 3.3 ± 1.4% | ... | 2.1 |
| Radio AGN | 1378 | 563 | 40.9 ± 1.7% | 3.08 ± 0.13% | ... |
| Mid-IR AGN | 791 | 95 | 12.0 ± 1.2% | 0.52 ± 0.05% | ... |
| X-ray AGN | 2267 | 413 | 18.2 ± 0.9% | 2.26 ± 0.11% | ... |

Notes. The errors are set to be Poissonian, and they only reflect the uncertainties caused by the finite sample sizes. The 850 and 450 μm detected samples are determined through both the low-resolution SCUBA-2 data and the high-resolution auxiliary data. The auxiliary data are either ALMA data, or 24 μm and 3 GHz data (see Section 4.1 for details).
Symbols show the position of the lensed system described in the Appendix. The empty circles are samples matched to 24 μm sources through ALMA observations. This allows us to detect more QGs at 450 μm, while the latter increases the probability of chance projection between unrelated QGs and 450 μm sources. If we remove the expected number of chance projections (Section 4.1.2), the difference reduces to ~1.3σ. Thus, the reason for the difference between the fractions at 450 and 850 μm remains unclear due to our small sample sizes.

We further split the populations into redshift bins (Table 2 and Figure 5). We can see that the fraction of 850 μm detected QG candidates increases with redshift and rises up to 3.51 ± 2.48% at z > 2. This higher contamination rate at z > 2 could come from either a real redshift evolution or simply larger photometric uncertainties on high-redshift sources. Nevertheless, this contamination rate of a few percent is still quite low. In conclusion, our QG candidates could be contaminated by bright dusty SFGs at a 0.16% to 0.43% level, and the contamination rises up to ~1.7% to 3.5% at higher redshift. We note that the contamination rates may be underestimated because we may not pick up all SCUBA-2 source counterparts in the two-step counterpart identification. We will perform a “blind” cross matching in Section 4.2 to provide a different estimate of the contamination.

We analyze the role of photometric errors in the bright SMG contamination. In Section 3, we estimated the probability of intrinsically being in the SFG color space but scattered into the QG color space by photometric errors for each QG candidate. The mean probabilities are 9.6% and 6.2% for 450 and 850 μm detected QGs, respectively. These both account for less than 10% of the SMG contaminations. Therefore, the bright SMG contamination is mainly due to intrinsic properties of the QGs rather than photometric errors.

In the above, we used both the AS2COSMOS and the A3COSMOS catalogs during the cross matching. We can also estimate the contamination by matching QG candidates to only the AS2COSMOS catalog, which contains a homogeneous selection and complete observations of SCUBA-2 850 μm sources with S_{850 μm} > 6.2 mJy in the S2COSMOS map. If we match our QG candidates to 850 μm sources through only the AS2COSMOS catalog, we find seven galaxies to be 850 μm detected QG candidates. If we assume the same QG fraction for all SCUBA-2 850 μm sources, we estimate that there should be 36.9 ± 14.0 QG candidates. This accounts for 0.2 ± 0.1% among all the QG candidates. This agrees with the 0.16 ± 0.03% contamination mentioned above.

Furthermore, the SCUBA-2 catalog has a detection limit of 2 mJy but is not complete for sources above 2 mJy. The complete number of 850 μm sources can be estimated via the source counts corrected for completeness, from Simpson et al. (2019). If we estimate the complete number of sources above 2 mJy and assume the same QG fraction in the AS2COSMOS catalog, we obtain a dusty galaxy contamination rate of 0.6 ± 0.3%. The relative uncertainty here is slightly larger than that simply propagated from the number of QGs in the AS2COSMOS catalog, since the source counts also contain an uncertainty. Nevertheless, this value is larger than the previously estimated value of 0.16 ± 0.03%, and is probably a more realistic estimate if we do have a deeper and more complete survey at 850 μm.

We note that one out of the 11 QG candidates (ID = 659416 in the COSMOS2015 catalog) that are matched to SCUBA-2 850 μm sources through ALMA catalogs is likely to be a

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**Figure 4.** Distributions of the 450 μm (a) and 850 μm (b) detected sample in the NUV–r–J diagram. Filled circles are samples matched to ALMA sources, while empty circles are samples matched to 24 μm or 3 GHz sources. Star symbols show the position of the lensed system described in the Appendix. The reddening vector derived from Calzetti et al. (2000) extinction and the typical errors in the two colors for the submillimeter sources are also shown with arrows and crosses, respectively. The color errors of the 850 μm sources are larger because these sources are generally fainter in the optical than 450 μm sources.
lensed system, because of its unusual submillimeter/radio flux ratio (see Appendix for details). This example demonstrates that, when matching QG candidates to the submillimeter sources, a match does not imply the QG candidate and the long-wavelength source to be the same object. They could be physical associations such as the lensed system here, or an interacting galaxy pair consisting of a QG and a dusty object (e.g., Schreiber et al. 2018c). Based on our small sample size, the probability of such association is about 9% (1/11). Such spatial correlation effects caused by lensing or galaxy interaction will be further discussed in Section 4.2.

### 4.2. Blind Cross Matching

#### 4.2.1. Matching with Large Radii and Estimate of Chance Projection

In the cross matching aided by 3 GHz and 24 μm astrometry described in Section 4.1, there is a possibility that the real optical counterparts of the submillimeter sources are undetected at 3 GHz and/or 24 μm. The different redshift dependences of sensitivities in the submillimeter, radio, and mid-IR may introduce such a bias. To avoid this, we can perform a “blind” cross matching to the SCUBA-2 sources. We directly match the QG candidates with SCUBA-2 450 μm and 850 μm sources using 4″ and 7″ search radii, respectively, without relying on radio and mid-IR positions. The large matching radii here will unavoidably lead to larger numbers of chance projections, so we need to more precisely estimate the number of chance projections.

To do this, we simulated the matching results using SCUBA-2 submillimeter sources with random positions. We do not apply the $1 - e^{-nA/a}$ method here, because the distribution of QGs may not be random at the scale of the relatively large search radii for SCUBA-2 sources and therefore the dispersion in the mean cannot be estimated. We calculated the expected number of QG candidates located within a search radius from the randomly distributed submillimeter sources and compared the results with the actual number of matched QG candidates. The simulation is repeated 1000 times. The estimated number of matches and its error are set to be the mean and the 68% interval of the 1000 results. The results are summarized in Table 3, and the fractional difference between the expected matches (chance projections) and the actual matches are also shown in Figure 6. We note that the detection limit of the SCUBA-2 450 μm, 850 μm, and ALMA sources are different.

#### Table 2

| Total in the COSMOS field | 850 μm Detected | Percentage | Total in the STUDIES field | 450 μm Detected | Percentage |
|---------------------------|-----------------|------------|---------------------------|-----------------|------------|
| all                       | 18304           | 30         | 0.16 ± 0.03%              | 1846            | 8          | 0.43 ± 0.15% |
| $z \leq 1$                | 11562           | 8          | 0.07 ± 0.02%              | 1314            | 5          | 0.38 ± 0.17% |
| $1 < z \leq 2$            | 6045            | 10         | 0.17 ± 0.05%              | 475             | 1          | 0.21 ± 0.21% |
| $z > 2$                   | 697             | 12         | 1.72 ± 0.50%              | 57              | 2          | 3.51 ± 2.48% |

Note. The errors are set to be Poissonian. The 850 and 450 μm detected samples are determined through both the low-resolution SCUBA-2 data and the high-resolution auxiliary data.

![Figure 5](image.png)  
Figure 5. Percentage of bright submillimeter galaxies (450 and 850 μm detected QGs) among COSMOS2015 QGs (Table 2) in logarithmic scale. Data points of 450 μm detected QGs are slightly offset along x-axis for clarity. The error bars of the 450 μm detected QGs are larger because of the smaller coverage of the STUDIES map. Errors here are Poissonian.

Given the small numbers of matched objects in the previous section, we would like to examine whether the matches between our QG candidates and bright submillimeter sources are caused by chance projection or by real spatial correlation. We could estimate the effect of chance projection via simple calculations.

First, we calculated the search area in our two-step cross matching. For the SCUBA-2 sources with ALMA observation, we used a search radius of 1″ for the ALMA sources. For the remaining ones, we used search radii of 2″ and 0.8″ for 24 μm and 3 GHz sources, respectively. If a 3 GHz source located within the 2″ search radius of a 24 μm source, we only adapted the search area of the 3 GHz source. We then calculated the expected fraction of randomly distributed QG candidates located in the search area with $1 - e^{-nA/a}$, where $A$ is the survey area, $n$ is the number of searched sources in the high-resolution catalogs, and $a$ is the search area per source. The estimated numbers of chance projections are given in the last column of Table 1. When we matched through ALMA catalogs, the numbers of chance projections were significantly lower. When we matched through 24 μm and 3 GHz catalogs, we found the probability of chance projections to be about 1/3: 2.1 out of 6 (35.0%) and 5.8 out of 19 (30.5%) matches can be chance projections for 450 and 850 μm detected QG candidates.

We conclude that, among the submillimeter-detected QG candidates mentioned in the previous section, accounting for 0.16%–0.43% among our QG candidates, the majority are real physical associations. The estimated bright dusty SFG contamination is not mainly driven by chance projections.
We also estimated the probability that the expected number is equal to or larger than the actual number (Table 3). We show the results of SFGs for comparison in Table 4.

The first and fifth rows of Tables 3 and 4 presents simple cross matching between the QGs/SFGs and single-dish submillimeter samples without information from ALMA. For SCUBA-2 450 μm sources, the actual matches are 42.6 ± 22.9% larger than the expected random matches. Although the significance is only about 2σ (Figure 6(a)), the estimated probability that the expected number equals to or is larger than the actual number is 0.05, which is quite low. This result suggests that there are 8.7 ± 4.3 QGs physically associated with the 353 450 μm sources. This corresponds to 0.47 ± 0.23% of the 1846 QGs in the 450 μm map area. The statistically derived number of 8.7 ± 4.3 matches also nicely agrees with the eight matches found with high-resolution data (Section 4.1 and Table 1). Also, for comparison, 316.3 ± 12.7 SFGs are physically associated with the 353 450 μm sources. This is as expected, since dusty submillimeter sources should be dominated by SFGs.

For SCUBA-2 850 μm sources, the actual matches are 52.6 ± 8.9% larger than the expected random matches (see also Figure 6(b)), which is significant (∼6σ). The estimated probability that the expected number is equal to or larger than the actual number is nearly zero. This means that, among the 206 matches between the QGs and 850 μm sources, 71 ± 12 are real physical associations. These ∼71 sources account for 0.39 ± 0.07% of the 18,304 QGs. We note that the number of 71 is significantly different from the number of 30 quoted in Table 1, or 23 after removing the expected number of chance projections. This is because here we do not require high-resolution multiband data to pin down the cross matching. This suggests that a significant fraction of QG-850 μm associations in our data do not have 24 μm, 3 GHz, or ALMA counterparts. This is perhaps partially because of the insufficient sensitivity (24 μm and 3 GHz cases) and incomplete coverage (ALMA cases). However, we will soon show that a large fraction of these 71 sources are clustered around the SCUBA-2 sources at a ∼3′′ scale, but they are not the submillimeter, mid-IR, or radio emitters. Finally, as in the case for 450 μm cross matching, the overlap between 850 μm sources and SFGs is much larger than that for QG, which is expected.

### 4.2.2. Verification and Comparison with ALMA Sources

The above “blind” matching between QG candidates and SCUBA-2 sources using large matching radii (1/2 of the single-dish beam FWHM) and the comparison between actual matches and simulations allows us to statistically assess the numbers of real physical associations. Now with the ALMA data, we can pin down the cross matching with a much smaller matching radius, with a smaller subsample. We split the SCUBA-2 sources into those with and without ALMA observations. The results are listed in the remaining rows of Tables 3 and 4.

As a simple sanity check, we ran cross matching with large matching radii over the subsamples. The fractional differences between actual and expected random matches do not change significantly between the ALMA and non-ALMA subsamples for QGs (Figures 6(a) and (b)). This is even true for the 450 μm sample, albeit with small sample sizes and therefore large errors. This implies that there is no special selection bias in the ALMA observations regarding their QG-submillimeter properties.

For the SCUBA-2 sources with ALMA observations, the expected numbers for matches under a 1′′ search radius and random spatial distributions are always small in comparison to the actual matches. This is reflected in the large fractional differences between the actual matches and expected random matches, which are 534.9 ± 217.7% for the 450 μm sources and 771.6 ± 58.5% for the 850 μm sources (Figure 6(c), the fourth and eighth rows). This means that the majority of the observed matches between QGs and ALMA sources under a 1′′ matching radius are real physical associations.

An interesting comparison is to see if the 1′′ matching pinned down by ALMA agrees with the statistical estimates of real physical associations derived from the large-radius blind matching. Tables 3 and 4 show that, if we match the 77 SCUBA-2 450 μm sources to QGs and SFGs using a 4′′ matching radius, we expect 0.4 ± 2.6 out of the 5 QG matches and 67.5 ± 3.5 out of the 100 SFG matches to be real associations. These can be compared with the ALMA results for the same subsample: 1.7 ± 1.0 and 53.8 ± 2.9 real associations for the QGs and the SFGs. The values for QG–SMG associations agree nicely, the small sample size notwithstanding. This probably validates the statistical method for estimating the number of real associations and chance projections using simulations and random distributions.

On the other hand, the values for SFG–SMG associations (67.5 and 53.8) differ by 25%, and the difference is about 2σ. The excess in the number of SFGs around SMGs within 4′′, compared to the number of true associations pinpointed by ALMA, suggests a weak clustering of SFGs around SMGs. This excess is only 2σ and is not
We measured the submillimeter emission from the SCUBA-2 maps at the positions of our selected QG candidates and calculated the error-weighted average of their fluxes. As our sources are point-like under JCMT’s resolution and the SCUBA-2 maps were beam-matched to produce maximum-likelihood flux for point sources, fluxes are measured by directly reading the map values in Jy beam$^{-1}$ at the positions of the QGs. We excluded QG candidates that we matched to the bright submillimeter sources in Section 4.1, depending on the angular scales to which the observations are sensitive. They could be the correct submillimeter counterparts to the QG candidates. There are also situations where the QG candidates are not submillimeter emitters, but are physically associated with submillimeter galaxies through effects like galaxy–galaxy lensing (e.g., Figure 11), galaxy interaction, or clustering effects at scales of a few arcseconds.

5. Faint Submillimeter Galaxies among QG Candidates

In Section 4, we matched our QGs candidates to submillimeter sources and demonstrated that fractions of the matched QG candidates are physically related to the submillimeter sources. However, the 450 μm and 850 μm sources have respective detection limits of about 3.5 mJy and 2 mJy, which correspond to SFRs of roughly 60 and 180 $M_\odot$ yr$^{-1}$ at $z = 1$. Therefore, we further perform stacking analysis in order to search for fainter submillimeter emissions among the QG candidates.

5.1. Stacking Analysis

We measured the submillimeter emission from the SCUBA-2 maps at the positions of our selected QG candidates and calculated the error-weighted average of their fluxes. As our sources are point-like under JCMT’s resolution and the SCUBA-2 maps were beam-matched to produce maximum-likelihood flux for point sources, fluxes are measured by directly reading the map values in Jy beam$^{-1}$ at the positions of the QGs. We excluded QG candidates that we matched to the bright submillimeter sources in Section 4.1, as well as QG candidates whose measured SCUBA-2 fluxes exceed $3\sigma$, in

$$3.5 \pm 0.7 \text{ and } 489.0 \pm 23.0 \text{ for QGs and SFGs, respectively. However, the numbers revealed by ALMA observations are much smaller: } 9.7 \pm 0.3 \text{ and } 267.1 \pm 3.9.$$
order to prevent our results from being biased by the small number of bright submillimeter sources. To estimate the bias and uncertainty in such a stacked flux, we then stacked at 1000 random positions and repeated this 10,000 times. In this process, bright submillimeter sources are removed according to the same criteria as above. The mean from these random stacks is considered as the bias in stacking. It is consistent with zero, because of the zero-sum nature of the match-filtered SCUBA-2 maps. Nevertheless, this small bias is subtracted from the mean of the QGs. The dispersion among the 10,000 measurements of the random samples is considered as the uncertainty of stacking 1000 sources. It is scaled by \( \sqrt{N} \) to be the uncertainty of the QG stacking. We also stacked different numbers of random sources to verify this. The stacking results are shown in Tables 5 and 6. The first rows of the two tables show that, if we simply stack all QG candidates, we can reach a 6.3\( \sigma \) statistical detection at 850 \( \mu m \) but not a significant detection at 450 \( \mu m \). The nondetection at 450 \( \mu m \) may be due to the smaller coverage of the STUDIES map. Furthermore, we can divide the QG candidates into subgroups according to their properties, to see if there is a particular group of QGs that contributes to the majority of the stacked signal. We classified QG candidates either with 24 \( \mu m \) counterparts or with 3 GHz counterparts labeled with SFG flags in the VLA catalog (Smolčić et al. 2017a) as “IR-radio-bright” QGs, and the rest as “IR-radio-faint” QGs. Our terminology differs slightly from that in Man et al. (2016). Man et al. (2016) defined QG candidates with SFRs derived from 24 \( \mu m \) over 100 \( M_\odot \text{year}^{-1} \) as “IR-bright” QGs, and the rest as “IR-faint” QGs. They used 24 \( \mu m \) data and SFR constraints to classify the subgroups, while we used 24 \( \mu m \) data, 3 GHz data, and radio AGN classification in our work. For the 850 \( \mu m \) stacking, because of the larger area of the SCUBA-2 map and consequently greater number of available QGs, we can further divide the QG sample into various redshift and stellar mass bins.

Overall, we see that QG candidates with 24 \( \mu m \) counterparts and QG candidates with 3 GHz counterparts that are not radio AGNs (i.e., IR-radio-bright QGs) exhibit the strongest stacking signal at both 450 \( \mu m \) and 850 \( \mu m \). These IR-radio-bright QGs account for 9.7 \( \pm \) 0.2% (1769/18,304) of all the QG candidates. In general, we do not reach significant detections of IR-radio-faint QGs. However, even with the low signal-to-noise ratio (S/N), the stacked 850 \( \mu m \) fluxes for high-mass (>10\( ^{10.5} M_\odot \)) IR-radio-faint QGs are consistently higher than those for low-mass IR-radio-faint QGs. This suggests that even the IR-radio-faint QGs have dust emission in the rest-frame far-IR, or they are clustered around dusty objects (see below). On the other hand, among IR-radio-bright QGs, it is not apparent that the high-mass ones show consistently higher 850 \( \mu m \) fluxes than the low-mass ones. This suggests that we are not seeing a population of well-behaved galaxies who follow the star formation main sequence. This is expected for QGs.

| SCUBA-2 sources | Group | Match Radius* | Number | Expected Matched SFG | Actual Matched SFG | Difference | Fractional Probability |
|----------------|-------|---------------|--------|-----------------------|---------------------|------------|-----------------------|
| 450 \( \mu m \) sources | All 4° | 353 | 149.7 \( \pm \) 12.3 | 466 | 316.3 \( \pm \) 12.7 | 211.3 \( \pm \) 2.6 | 0 |
| 850 \( \mu m \) sources | All 7° | 981 | 1045.7 \( \pm \) 10.5 | 2087 | 1041.5 \( \pm \) 15.5 | 99.6 \( \pm \) 3.4 | 0 |

### Table 4

Cross-matches and Expected Chance Projections between SFGs and Submillimeter Sources

| SCUBA-2 sources | Group | Match Radius* | Number | Expected Matched SFG | Actual Matched SFG | Difference | Fractional Probability |
|----------------|-------|---------------|--------|-----------------------|---------------------|------------|-----------------------|
| All 4° | Without ALMA | 276 | 116.4 \( \pm \) 10.0 | 366 | 249.6 \( \pm \) 10.4 | 214.3 \( \pm \) 2.0 | 0 |
| All 7° | With ALMA | 77 | 32.5 \( \pm \) 5.5 | 100 | 67.5 \( \pm \) 5.5 | 207.8 \( \pm \) 16.9 | 0 |

### Table 5

450 \( \mu m \) QG Stacking Results

| Groups | \( \log M_\ast^* \) (log(M_\odot)) | \( z^b \) | Number | \( S_{450 \mu m} \) (mJy) | S/N | \( \log(L_{IR}) \) (log(L_\odot)) | SFR_{450 \mu m} (M_\odot \text{yr}^{-1}) | SFR_{optical} (M_\odot \text{yr}^{-1}) |
|--------|-----------------------------|--------|--------|---------------------|-----|-----------------------------|-----------------------------|-----------------------------|
| All QG | 10.7 \( \pm \) 0.3 | 0.9 | 1799 | 0.06 \( \pm \) 0.05 | 1.3 | 9.3 \( \pm \) 0.3 | 0.2 \( \pm \) 0.2 | 2.5 \( \pm \) 0.4 |
| 24 \( \mu m \) counterpart | 10.9 \( \pm \) 0.3 | 0.8 | 155 | 0.66 \( \pm \) 0.16 | 4.1 | 10.6 \( \pm \) 0.1 | 3.6 \( \pm \) 0.9 | 11.2 \( \pm \) 0.4 |
| 3 GHz counterpart | 11.2 \( \pm \) 0.2 | 0.9 | 103 | 0.60 \( \pm \) 0.20 | 3.0 | 10.5 \( \pm \) 0.2 | 3.5 \( \pm \) 1.2 | 9.5 \( \pm \) 0.4 |
| 3 GHz counterpart: SFG | 11.1 \( \pm \) 0.2 | 0.9 | 45 | 0.85 \( \pm \) 0.30 | 2.8 | 10.8 \( \pm \) 0.2 | 6.4 \( \pm \) 2.3 | 10.3 \( \pm \) 0.8 |
| 3 GHz counterpart: AGN | 11.2 \( \pm \) 0.2 | 0.9 | 58 | 0.39 \( \pm \) 0.26 | 1.5 | 10.2 \( \pm \) 0.2 | 1.5 \( \pm \) 1.0 | 8.9 \( \pm \) 0.6 |
| IR-radio-faint QG | 10.6 \( \pm \) 0.3 | 0.9 | 1620 | 0.00 \( \pm \) 0.05 | 0.0 | 10.5 \( \pm \) 0.3 | 0.0 \( \pm \) 0.2 | 1.7 \( \pm \) 0.4 |
| IR-radio-bright QG | 11.0 \( \pm \) 0.3 | 0.8 | 179 | 0.65 \( \pm \) 0.15 | 4.3 | 10.6 \( \pm \) 0.1 | 3.6 \( \pm \) 0.8 | 10.2 \( \pm \) 0.4 |

### Notes

* The parameters follow those in Table 3.

** Mean and 68% interval of stellar mass in logarithmic scale.

* Median of redshift.

* Mean of SFRs from COSMOS2015. The error shows the typical error in COSMOS2015 scaled by \( \sqrt{N} \). Uncertainty of template fitting is not included, but may be large for the QG population.
We can compare our stacked $450 \mu m$ fluxes with the Herschel $500 \mu m$ stacked fluxes in Man et al. (2016). Our mean $450 \mu m$ flux of IR-radio-faint QGs is $0.00 \pm 0.02 \ mJy$, with a $1\sigma$ upper limit that is over 10 times lower than their stacked $500 \mu m$ fluxes of IR-faint QGs, which range from 0.2 to 2.5 mJy in different mass and redshift bins. The differences with regard to defining the two QG subsamples (SFRs derived from 24 $\mu m$ to be under or over 100 $M_\odot$ year$^{-1}$ in Man et al. (2016)) may be one of the possible explanations. However, our mean $450 \mu m$ flux of IR-radio-bright QGs, $0.65 \pm 0.15 \ mJy$, is still lower than most of the above mean $500 \mu m$ fluxes of IR-faint QGs (0.2–2.5 mJy), except for some of those with $M_\ast < 10^{10.06} M_\odot$.

Our stacked $450 \mu m$ fluxes are also lower compared with results in Magdis et al. (2021). They selected QG candidates with several color–color diagrams and stacked samples without $24 \mu m$ detection, so we compare our stacked fluxes of IR-radio-faint QGs with their results. Their stacked Herschel $500 \mu m$ fluxes, ranging from 0.12 to 0.59 mJy in various redshift bins, are also much higher than our stacked $450 \mu m$ flux, $0.00 \pm 0.02$ mJy. On the other hand, their stacked SCUBA-2 $850 \mu m$
fluctuations, ranging from 0.04 to 0.1 mJy, are at levels similar to those of our stacked 850 μm fluxes.

A possible explanation for the differences between the SCUBA-2 450 μm and Herschel 500 μm stacked fluxes is that the stacked Herschel fluxes were biased by source clustering at the scale of the large 35′ Herschel 500 μm beam (e.g., Viero et al. 2013; also see discussion in Béthermin et al. 2017). Although Magdis et al. (2021) modeled the emission of all the stacked images to separate surrounding sources, it appears that their 500 μm stacked fluxes are higher. Although Man et al. (2016) applied SIMSTACK to stack and deblend simultaneously, it remains possible that the effects of source blending and clustering were not completely removed.

The above comparison confirms the well-known bias in submillimeter stacking analysis: when source are clustered at scales comparable to the beam size, the stacked flux is overestimated. This bias becomes quite severe under Herschel’s large beams in the two longest wave bands. How about our SCUBA-2 stacked fluxes? In the previous section, we showed that QG candidates are clustered around 850 μm sources at scales of SCUBA-2’s beam. Thus, if we blindly stack these QGs in the 850 μm image, the stacked flux will be overestimated. Fortunately, the majority of our 850 μm stacking signal comes from the IR-radio-bright subsample. Their 24 μm and 3 GHz counterparts are likely to be 850 μm sources themselves, and the bias caused by clustering should therefore be negligible. On the other hand, the IR-radio-faint sample does not have deep high-resolution data to confirm that the QGs are responsible for the detected 850 μm fluxes. Therefore, strictly speaking, our stacked 850 μm fluxes for IR-radio-bright QGs should be considered as upper limits. Even if a detection is reached on a certain subsample of IR-radio-faint QGs, the detected flux should be only an indication that these QG candidates are physically related to faint submillimeter emitters, rather than evidence for in situ star formation in the QG candidates.

Finally, we can examine whether the strong 850 μm detection (8.6σ) of the IR-radio-bright QGs really come from galaxies in the QG color–color space in the NUV–r–J diagram, or from galaxies originally in the SFG color space scattered by photometric errors across the selection boundary. In Section 3, we show that such SFG contamination caused by photometric errors accounts for about 7.5% of the selected QGs. With the same method, the estimated fraction for misidentified IR-radio-bright QGs caused by photometric errors is slightly higher, at 8.9%. Moreover, we identified individual IR-radio-bright QGs whose probabilities of being scattered from the SFG color space are >0.05. These sources account for 33% of our IR-radio-bright QGs (584/1769). We excluded them and reid the stacking on the remaining IR-radio-bright QGs, and still obtained a strong detection of 0.22 ± 0.04 mJy (5.9σ) despite the very generous probability cut of >0.05. These results imply that misidentified QG candidates due to photometric errors account for only <10% of our estimated dusty SFG contamination, and this minor population does not dominate our stacking results. The majority of the dusty SFG contamination is caused by their intrinsic properties rather than photometric errors.

5.2. Examining the Quiescence

To examine whether our subsamples are consistent with a quiescent population, we need to derive their SFRs and compare those with their stellar masses. We calculated the IR luminosity from the mean submillimeter fluxes and the median redshift of each group of the stacking sample. Since we only conducted measurements at 450 and 850 μm, we performed single-band SED “fitting” by assuming that there is a unique relation between SED shape and IR luminosity. To do so, we adopt the luminosity-dependent dust SED templates of J. K. Chu et al. (2021, in preparation), which are based on the latest WISE and Herschel photometry for 201 local IR-selected galaxies (Chu et al. 2017). This set of templates covers IR luminosity of $7 \times 10^8$ to $1.7 \times 10^9 L_\odot$. We further supplement the submillimeter galaxy SED from the zLESS program (Danielson et al. 2017), which has an IR luminosity of $5.2 \times 10^2 L_\odot$. We redshifted these SEDs to the redshifts of our targets and calculated their observed 450 μm or 850 μm fluxes. We picked the templates with redshifted fluxes closest to our stacked flux and interpolated between the template fluxes to obtain the IR luminosity of our targets. To estimate the 1σ error of the IR luminosity, we scaled the IR luminosity by a factor equal to the quotient of 1 divided by the S/N. For groups with negative mean flux, we calculated the corresponding IR luminosity of the flux error to estimate 1σ upper limit of the IR luminosity. The results are presented in the seventh columns of Tables 5 and 6.

To verify the results based on the local SEDs of Chu et al., we also repeated the calculations using the SED library of Schreiber et al. (2018a). Overall, we find no systematic differences if we assume main-sequence galaxies ($R_{SB} = 1$) for the Schreiber et al. library. The mean difference in the calculated $L_{IR}$ is less than 0.1 dex for the nonzero entries in Tables 5 and 6, while the rms dispersion is within 0.25 dex. This small difference can be further reduced if we assume a sub-main-sequence $R_{SB}$ for the IR-radio-faint subsamples in Table 6 and a starburst $R_{SB}$ for the IR-radio-bright subsamples. This tuning of the $R_{SB}$ parameter is consistent with our interpretation of these two subgroups (see below). In our subsequent analyses, we adopt the calculations based on the SEDs of Chu et al.

After calculating the IR luminosity, we followed the $L_{IR}$–SFR calibration applied in Man et al. (2016). We estimate the SFR by applying the relation applicable for SFGs (Kennicutt 1998):

$$SFR(M_\odot \text{ yr}^{-1}) = 1.7 \times 10^{-10} L_{IR}(L_\odot).$$

We then adjusted the obtained SFR to the Chabrier (2003) IMF by applying the calibration used in Man et al. (2016):

$$SFR_{Chabrier} = SFR_{Salpeter}/1.7.$$

The results are presented in the eighth columns of Table 5 and Table 6 as SFR$_{450 \mu m}$ and SFR$_{850 \mu m}$, respectively. A few observations can be made here. First, the 850 μm derived SFR is, in general, higher than the 450 μm derived SFR. This is partly caused by the sensitivity of the SCUBA-2 450 μm imaging being much deeper in luminosity, as well as the <3σ thresholds we imposed in the stacking procedure. If we remove this threshold in the 450 μm imaging, the difference reduces to within a factor of 2, which is not very significant if we consider the overall low S/N of the 450 μm stacked fluxes and the small number of sources available for the 450 μm stacking.

We compute our results with SFRs derived from optical SED fitting in COSMOS2015 (last column in Tables 5 and 6). Their mean SFRs of IR-radio-faint QGs are higher than ours at high z, but their mean SFRs of IR-radio-bright QGs are lower. This can be explained with the age-extinction degeneracy in the SED fitting when there is an absence of far-IR photometry.

We compare our submillimeter-derived SFRs with the stellar masses of the galaxies in Figure 7. We show the star formation “main sequence” of Speagle et al. (2014) with black solid lines and the ±0.9 dex ranges with shaded areas.
We show the results from Man et al. (2016) for comparison (Figure 7). Our results are in broad agreement with theirs, but tend to have slightly lower SFRs for low-z samples. In the $0.5 < z \leq 1.0$ and $1.0 < z \leq 1.5$ redshift bins, their massive IR-bright QGs are located on or $\sim$1 to $2\sigma$ above the main sequence, while our IR-radio-bright QGs are located $\sim$2 to $3\sigma$ below the main sequence. Their IR-faint QGs are located $\sim$3$\sigma$ below the main sequence, while our IR-radio-faint QGs are located $>3\sigma$ below the main sequence. Other than these, our derived SFRs are fairly consistent. We note that the SFR of Man et al. (2016) was derived from SED fitting using stacked fluxes across the entire far-IR range. This explains why their 500 $\mu$m stacked fluxes are much higher than ours, but their SFRs are not.

We also show the results from Magdis et al. (2021) in Figure 7. Their SFRs are about the same as or slightly lower than ours, thus differing from the comparison with Man et al. (2016). We note that their IR luminosities were derived from SED fitting using stacked fluxes from mid-IR to radio data. They then also obtained SFRs by applying the relation in Kennicutt (1998), but they used a Salpeter IMF and added an SFR derived from the optical photometry. We converted their IR luminosity to an SFR via the same process in Man et al. (2016) and this work, for a fair comparison. We also show the SFRs obtained via the original conversion in their work, for reference; in general, they are closer to the SFRs from Man et al. (2016).

The conclusion we can draw from Figure 7 is that the IR-radio-faint QGs are, in general, below the star formation main sequence, while the majority of the IR-radio-bright QGs are consistent with the main sequence, probably except for the high-mass end in the two low-redshift bins and in the highest-redshift bin.

To sum up, our stacking results show that only the IR-radio-bright QGs have SFRs similar to those of main-sequence galaxies. These are likely to be faint dusty SFGs that contaminate the QG color selection. However, the population of the IR-radio-bright QGs is small, which accounts for $9.7 \pm 0.7\%$ (179/1846) and $9.7 \pm 0.2\%$ (1769/18304) of all the QG candidates, respectively, in the 450 and 850 $\mu$m images. The fractions range from 7% to 12% in different redshift bins and do not have a strong redshift dependence. We conclude that the contamination of dusty SFGs is $\sim$10% among the color-selected QG candidates, and that the contamination can be removed using multiwavelength data—such as the 24 $\mu$m and 3 GHz data for the COSMOS field.

For comparison, Man et al. (2016) suggested that the maximum contamination is 15% and could be removed by using 24 $\mu$m observations. In this study, we used submillimeter data with better sensitivities and resolutions, and our estimate...
of contamination is somewhat tighter (10%) than that in Man et al. (2016).

Like what we did in Section 4.1.1, if we assume the same fraction of QGs among AS2COSMOS sources, we can estimate the number of faint submillimeter sources that are QGs. For the number of faint submillimeter sources, we again applied the 850 μm number count in Simpson et al. (2019) and extrapolated it to a flux level of $S_{850 μm} = 0.5$ mJy. This leads to 707 ± 462 QGs among faint submillimeter sources, and a dusty galaxy contamination rate among QGs of 3.9 ± 2.5%. We can further extrapolate the counts to 0.26 mJy, the stacked 850 μm flux of IR-radio-bright QGs. This will further increase the estimated contamination rate. However, such an extrapolation is is probably too aggressive, given the uncertainty in the faint-end counts. Nevertheless, considering the unknown uncertainty of extrapolating the number count to a flux level lower than the detection limit, we concluded that the above estimation is not inconsistent with the ~10% contamination derived from the stacking of IR-radio-bright QGs.

Finally, using either 24 μm or 3 GHz data to pinpoint star-forming contaminants among color-selected QG candidates may not work well at high redshifts ($z > 3$ or 4). This is because mid-IR and radio suffer from the strong K-correction and are not sensitive to high-redshift SFGs. Our 3.4 GHz detection in the 850 μm stacking of the IR-radio-faint QGs at $z > 2$ seems to agree with this, i.e., there may exist dusty galaxy contamination that are faint in the mid-IR and radio. In other words, the effectiveness of QG color selection at high redshift remains untested in this framework. Since the formation of QGs at higher redshifts require both rapid growth of the stellar population and rapid quenching, identifications of high-redshift QGs are of great interest (Straatman et al. 2014; Merlin et al. 2018; Carnall et al. 2020; Valentino et al. 2020). Removing dusty contaminants among high-redshift QGs is beyond the sensitivities of Spitzer, Herschel, and the current VLA, and will require deep ALMA data.

### 6. AGN Properties

In this section, we discuss the properties of the AGNs among our QG candidates. Figure 8 shows the distribution of three different classes of AGN samples in the $NUV - r - J$ diagram, including radio AGNs, mid-IR AGNs, and X-ray AGNs (Section 2.4) in two mass bins. The stellar mass of the samples were limited to above $10^{10.5} M_\odot$. This is because the samples are likely to be incomplete below $10^{10.5} M_\odot$ at $z \sim 2$ (see Figure 2(b)). This mass limit is also consistent with the 90% completeness limit found by Laigle et al. (2016) for QGs at high redshifts. We therefore applied this stellar mass cut for fair comparisons of the QG fractions. In Figure 8, we can see that the distribution of the radio AGNs is different from those of the other two. A similar distinction also exists between radio selected sources and 24 μm selected sources in Figure 3. Figure 8 provides evidence that the difference in Figure 3 is driven by radio AGNs.

We calculated the QG fractions in different classes of the AGN samples in different redshift and mass bins (Figure 9). The QG fraction of the radio AGNs is (~0.1 to 1.9σ), higher than that of the non-AGN samples at $z < 1.5$ in both two mass bins, while the QG fractions of the other two AGN classes are significantly lower. The trend does not persist beyond $z \sim 1.5$, and this may be due partially to the detection limit of the radio AGNs, or a real redshift evolution. The high QG fraction among radio AGNs implies a correlation between radio jets and our QG candidates.

We also calculated the AGN fractions in our COSMOS2015 sample (Figure 10). The radio AGN fraction among QG candidates
is (∼0.2 to 1.7σ) higher than that among the COSMOS2015 QG and SFG sample, also at $z < 1.5$ and in both mass bins. The situation is the opposite for both the mid-IR and X-ray AGNs, where the AGN fractions among the QG+SFG sample are higher. The higher radio AGN fraction among QGs also suggests a correlation between radio jets and our QG candidates.

The above correlation between radio AGNs and QGs may provide some clues about the quenching mechanism. Our data suggest that the formation of radio jets and quenching of star formation are connected, but the exact causality is unclear. One possible scenario is that radio-mode AGN feedback, particularly radio jets with high kinetic energy, could have impacts on the host galaxy and its environment (e.g., Somerville et al. 2008; Fabian 2012). Either the interstellar medium in the host galaxy may be disrupted by the jets (e.g., Somerville et al. 2008; Fabian 2012), or the gas in the halo can be heated up and be prevented from cooling and falling onto the host galaxy (e.g., Bower et al. 2006; Croton et al. 2006; Somerville et al. 2008). Although the radio AGNs fraction is only ∼10 to 20% among QG candidates (Figure 10), this can be explained by the AGN duty cycle in the massive galaxies.

On the other hand, it is also possible that radio AGNs are not directly linked to the quenching process. Instead, it may just be easier to trigger radio AGNs in galaxies that are already quenched. In the local universe, it is well-known that there is a dominant tendency for radio galaxies to reside in early-type hosts (e.g., Govoni et al. 2000; Hamilton et al. 2002), which is consistent with what we found on QGs and radio AGNs. The lack of cool gas in early-type (quenched) galaxies can lead to radiatively inefficient accretion that is associated with the radio-mode AGN feedback (Bower et al. 2006; Croton et al. 2006; Somerville et al. 2008).

Observationally, the stacking result in Man et al. (2016) also showed a similar trend. Those authors compared the radio stacked fluxes and the Herschel stacked fluxes of their sample. Their SFRs derived from the two are consistent for SFGs, but there exists a radio excess for massive IR-faint QGs with $M_*>10^{11}M_\odot$ at $z<1.5$. They further measured the FIR-to-radio luminosity ratio and concluded that most of their massive QGs host low-luminosity radio AGNs. Also, Smolčič et al. (2009) found that the radio AGN fraction among red galaxies increases from $z\sim 0.5$ to 1, showing that radio AGNs play an important role at $z \sim 1$. It is also known that SFR is correlated with AGN accretion rate (Zhuang & Ho 2020), and that AGNs with low accretion rates are radio-loud (Ho 2002, 2008). This implies that QGs tend to be radio AGNs. All these results suggest that there is a correlation between QGs and synchrotron radiation from radio AGNs.

We could also see a weak correlation between X-ray AGNs and QG candidates at $z > 2.5$. In Figure 9, the QG fractions among

![Figure 9](image_url)  
**Figure 9.** QG fraction among different classes of AGN samples in redshift bins with $M_*>10^{11}M_\odot$ (a) and $10^{10.5}M_\odot< M_* \leq 10^{11.0}M_\odot$ (b). Data points are slightly offset along x-axis for clarity. Errors here are Poissonian.

![Figure 10](image_url)  
**Figure 10.** Different classes of AGN fraction among COSMOS2015 optical sample in redshift bins with $M_*>10^{11}M_\odot$ (a) and $10^{10.5}M_\odot< M_* \leq 10^{11.0}M_\odot$ (b). Solid lines represent AGN fraction among QG candidates, while dotted line represent AGN fraction among all the galaxies (QGs and SFGs). Data points are slightly offset along x-axis for clarity. Errors here are Poissonian.
X-ray AGNs are ~0.6 to 1.5σ larger than those among non-AGNs in z > 2.5 redshift bins, with respect to their own error bars. In Figure 10, the AGN fraction among QGs is ~0.9σ larger than that among the full sample in the z > 2.5 and $M_{*} > 10^{11} M_{\odot}$ bin. This may be caused by either selection bias or a real evolution trend. The evolution trend could be explained by the role of quasar-mode AGN feedback (Somerville et al. 2008; Fabian 2012), gas inflow in X-ray AGNs that removes gas and quenches star formation. One possibility is that the mode of AGN quenching may change from quasar-mode to radio-mode from high z to low z. Another possibility could be that X-ray AGNs are related to the initial quenching, while radio AGNs are responsible for the maintenance of the quiescence. This could also explain the increasing radio AGN fraction among QG candidates in Figure 10 at lower redshift. Nevertheless, the rises in the X-ray AGNs in Figures 9 and 10 only occur in the highest-redshift bins where the sample sizes are the smallest and the selection completeness is not as well-understood. This has to be further tested with more data and careful examination of various selection biases in the high-redshift ends.

To sum up, our data show a strong correlation between radio AGNs and QGs, but do not point to the right scenario. Our data also do not show whether radio AGNs are related to the initial quenching, or just related to the maintenance of the quiescence.

7. Summary

In this study, we examined the submillimeter properties of NUV–$r$–$J$ selected QG candidates at $z \lesssim 3$. We cross-matched the QG candidates with bright submillimeter sources detected by JCMT SCUBA-2 and ALMA. For the former, we used Spitzer 24 μm and VLA 3 GHz data to refine their positions to overcome the low angular resolution of JCMT. This way, we found that 0.16 ± 0.03% to 0.43 ± 0.15% among our QG candidates are likely to be bright 850 and 450 μm submillimeter galaxies, respectively. The contamination increases to 1.72 ± 0.50% to 3.51 ± 2.48% at z > 2. We further performed stacking analysis of QG candidates in the JCMT 450 and 850 μm images. We can obtain strong stacking detections on a subsample of QGs with Spitzer 24 μm and VLA 3 GHz counterparts that are not radio AGNs. This special class of “IR-radio-bright” QGs account for about 10% of the entire QG sample, and they are likely to be faint submillimeter sources with SFRs of a few tens to about a hundred $M_{\odot}$ yr$^{-1}$. These results are broadly consistent with the contamination rates derived from a small sample of ALMA-detected QGs and the 850 μm number counts. We conclude that the dusty star-forming galaxy contamination rate among NUV–$r$–$J$ selected QG candidates is up to ~10%, but such contamination can be removed by 24 μm, submillimeter, or 3 GHz observations at current sensitivity levels.

When we cross-matched the QG candidates with JCMT SCUBA-2 850 μm SMGs without relying on high-resolution data, we adopted a large matching radius of 7″ because of the large SCUBA-2 beam size. This leads to a large fraction of chance projections among the matched QGs. We estimated the number of chance projections with simulations by assuming random spatial distributions for SCUBA-2 sources. After statistically subtracting the chance projections, we found that, on average, 0.096 (35.4/370) QGs are physically related to an 850 μm selected SMG, while ALMA observations indicate that only 0.026 (9.7/370) QGs really coincide with an SMG within 1″. This implies a clustering between these two populations at a scale of 1″ to 7″, and should be a future topic of investigation.

Finally, we examined the QG fractions among our AGN samples and found a correlation between our QG candidates and radio AGNs. When we limited our studies to galaxies with stellar masses larger than $10^{10.5} M_{\odot}$, we found the QG fraction of radio AGNs to be larger than those of the non-AGN samples, IR AGNs, and X-ray AGNs at z < 1.5. This suggests a connection between the radio jets and the quenching or the maintenance of the quiescence of the QGs, or the so-called radio-mode AGN feedback. However, our data do not rule out the possibility that radio AGNs are just more easily triggered in quenched galaxies, rather than being responsible for the initial quenching.

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Appendix

Lensed System

One of the 850 μm detected QG candidates (ID = 659416 in the COSMOS2015 catalog; star symbol in Figure 4) is likely to be a lensed system because of its unusual submillimeter/radio flux ratio. The $K_{s}$-band image and the ALMA image of the
lensed system are shown in Figure 11. The QG candidate is at 
z = 0.36 and is surrounded by two ALMA Band-7 sources, AS2COS0005.1 and AS2COS0005.2. The two ALMA sources have 343 GHz fluxes of 8.84 mJy and 2.20 mJy, respectively. The 3 GHz fluxes are 27.0 μJy and 7.9 μJy. These values lead to very similar 343-to-3 GHz flux ratios of 0.33, and 0.28. Under the framework of “millimetric redshift” (Carilli & Yun 1999), the similar flux ratios imply similar redshifts. The estimated redshifts are 2.7 and 2.6, if we assume a spectral slope of 0.8 to infer the 1.4 GHz fluxes and if we adopt the millimetric redshift formula of Barger et al. (2000):

\[ z + 1 = 0.98 \times (S_{\text{850 \, \mu m}}/S_{\text{1.4 GHz}})^{0.26}. \]

The estimated redshifts are much higher than the QG photometric redshift. Therefore, the two ALMA sources are likely to be background sources, rather than dust emission from the QG candidate. Indeed, the elongated morphology of AS2COS0005.1 (Figure 11) and the relative positions of the two ALMA sources strongly suggest that they are multiple images of the same background dusty galaxy lensed by the foreground QG.

This target was also identified as a lensed system in Bertoldi et al. (2007) by using the same submillimeter/radio flux ratio approach. The authors measured the Max-Planck Millimeter Bolometer Array (MAMBO-2) 250 GHz flux of the target (labeled as MM J100024+021748 or Cosbo-7) and obtained 
z \sim 2.8, consistent with our estimation. Jin et al. (2018) also reported this lensed system (labeled as ID2000308) and derived a photometric redshift of 4.0 \pm 0.6 from 24 μm to radio SED fitting. In our study, we further confirmed their results by including the high-resolution ALMA image, which resolved the background target into two sources with elongated morphology.

We note that there are, in total, three QG candidates with photometric redshifts lower than 1 among those matched to SCUBA-2 sources through ALMA catalogs, and we examined their millimetric redshifts. Besides the target discussed above, the other two low-z targets also show higher submillimeter/radio flux ratios. However, we do not further discuss these two targets, as the estimated millimetric redshifts are not significantly high.

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