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Unresolved $z \sim 8$ Point Sources and Their Impact on the Bright End of the Galaxy Luminosity Function

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Abstract

The distribution and properties of the first galaxies and quasars are critical pieces of the puzzle in understanding galaxy evolution and cosmic reionization. Previous studies have often excluded unresolved sources as potential low-redshift interlopers. We combine broadband color and photometric redshift analysis with morphological selections to identify a robust sample of candidates consistent with unresolved point sources at redshifts $z \sim 8$ using deep Hubble Space Telescope images. We also examine G141 grism spectroscopic data to identify and eliminate dwarf star contaminants. From these analyses, we identify three bright ($M_{UV} \lesssim -22$ AB mag) dropout point sources at $7.5 < z < 8.1$. Spectral energy distribution analyses suggest that these sources are either quasars or compact star-forming galaxies. The flux captured by the IRAC 4.5 μm channel suggests that they have moderate Hβ + [O III] equivalent widths. We calculate the number density of point sources at $z \sim 7–8$, and find that a double-power-law model well describes the point-source distribution. We then extend our analysis to estimate the combined point-source galaxy luminosity function and find that the point sources have a nonnegligible contribution to the bright-end excess. The fact that the point sources dominate only at $M_{UV} \lesssim -22$ suggests that their contribution to cosmic reionization is likely limited. While spectroscopic follow-up is needed to confirm the nature of these point sources, this work demonstrates that the inclusion of Lyman-dropout point sources is necessary for a complete census of early galaxies at the epoch of cosmic reionization.

Unified Astronomy Thesaurus concepts: Hubble Space Telescope (761); High-redshift galaxies (734); Galaxy formation (595); Galaxy photometry (611); Quasars (1319); Luminosity function (942); Reionization (1383)

1. Introduction

Statistical studies of the first galaxies and quasars are crucial to understanding their formation and evolution processes. To date, a tremendous amount of effort has been made to probe the early universe with high-redshift surveys like CANDELS (Grogin et al. 2011; Koekemoer et al. 2011; Bouwens et al. 2019), BoRG (Trenti et al. 2011; Bradley et al. 2012; Morishita et al. 2018; Morishita 2021), HUDF12 (Ellis et al. 2013), XDF (Illingworth et al. 2013), CLASH (Postman et al. 2012), HFF (Lotz et al. 2017), RELICS (Coe et al. 2019), ULTRAVISTA (McCracken et al. 2012; Stefanon et al. 2017a, 2019; Bowler et al. 2020), among others. These surveys combined with follow-up spectroscopy have successfully identified some of the earliest galaxies up to $z \sim 9–10$, yet the characterization of the number densities and the physical properties of these early sources remains incomplete. It is necessary to accurately quantify the early populations with observational constraints.

Characterizing the luminosity function is a fundamental step in estimating the contribution from various luminous sources; it describes the number density of sources as a function of luminosity, or absolute magnitude. Since ultraviolet (UV) emission is primarily dominated by ionizing sources, the restframe UV luminosity function is a useful tool in investigating the early galaxy populations. In particular, the shape of the luminosity function can provide insights into the different physical processes such as star formation and quasar activity that drive galaxy formation.

The faint end of the luminosity function is believed to be the key driver of cosmic reionization (e.g., Ishigaki et al. 2018; Atek et al. 2018), in which the early universe transitioned from completely neutral to almost ionized (Ouchi et al. 2010; Konno et al. 2014; Pentericci et al. 2014; Robertson et al. 2015; Mason et al. 2018, 2019; Hoag et al. 2019). It is believed that reionization paved the way for the formation of the first galaxies (Loeb & Barkana 2001), yet the question of what astrophysical objects are primarily responsible for reionization remains debated.

The bright end of the luminosity function is composed of the brightest sources that may be signposts of in situ star formation or even quasar activity. The discovery of luminous quasars (Mortlock et al. 2011; Bañados et al. 2018b; Yang et al. 2020; Wang et al. 2021b) and luminous star-forming galaxies at $z \gtrsim 7$ (Zitrin et al. 2015; Oesch et al. 2016; Hashimoto et al. 2018;
Jiang et al. (2021) may be indicative of populations of luminous sources that are unaccounted for. There is no consensus on the shape of the bright end of the luminosity function; some even suggest that the early galaxy luminosity function may depart from the standard Schechter form (Harikane et al. 2022). This departure manifests as a bright end excess (e.g., Morishita et al. 2018), and its origins remain unclear. Theoretical studies suggest that this bright excess may be caused by intense and compact star-forming clumps (e.g., Ma et al. 2018) or even stochastic quasar activity (e.g., Ren et al. 2020). Luminous sources are also believed to contribute to cosmic reionization to some degree, yet the consensus on their contribution remains controversial (e.g., Willott et al. 2010; Finkelstein et al. 2015; Jiang et al. 2016; Matsuoka et al. 2019; Naidu et al. 2020). The characterization of the brightest sources at high redshifts remains elusive.

High-redshift sources are typically identified with Lyman-dropout photometric selection (Steidel et al. 1996) combined with follow-up spectroscopic confirmation. The complication is that the redshifted spectral energy distribution (SED) of these sources at the end of cosmic reionization, $z \sim 7-8$, overlaps with those of low-mass foreground stars. As a result, previous studies have often excluded compact, unresolved sources with starlike morphology in preference for more galaxy-like sources with extended morphology. However, there is evidence from lensing surveys that early galaxies are very compact (e.g., Bouwens et al. 2017; Salmon et al. 2020). Some even predict compact star-forming clumps (Ma et al. 2018). So there is a possibility that certain populations of quasars and compact galaxies at $z \sim 7-8$ are rejected with the standard selection.

There is renewed interest in examining these overlooked point sources. A recent medium-depth, wide ($\sim 0.4$ deg$^2$) Hubble Space Telescope (HST) survey (SuperBoRG; Morishita et al. 2020; Morishita 2021) has identified several $z \gtrsim 8$ point sources as potential quasar candidates. The key features of these $z \sim 8$ point sources are their blue rest-frame UV slopes and a Spitzer/IRAC flux excess in the SED, which may be indicative of the significant H$\beta$ and [O III] emission often seen in quasars. Observations suggest that these point sources are unlikely to be foreground stars and may contribute to the bright end of the luminosity function.

In this study, as part of our HST archival program (AR 15804; PI: Morishita), we reexamine the selection of high-redshift compact unresolved (point) sources that have been overlooked in previous studies. We take advantage of the successful SuperBoRG study to revisit $z \sim 7-8$ point sources in the CANDELS legacy HST fields. Since the selection criteria of our study and of SuperBoRG are complementary, we combine the results of both studies to characterize the $z \sim 7-8$ dropout point sources and to quantify their contribution to the total galaxy luminosity function. For simplicity, we will refer to these sources as “point sources” throughout the paper.

This paper is organized as follows. In Section 2 we describe the data reduction and target selection from 3D-HST. In Section 3 we explore the properties of the targets selected. And in Section 4 we discuss the physical implications of these objects. We use the AB magnitude system (Oke & Gunn 1983; Fukugita et al. 1996) and adopt an $h = 0.7$, $\Omega_M = 0.3$, and $\Omega_L = 0.7$ cosmology.

2. Target Selection

2.1. Source Catalog

Our primary focus is to identify sources that satisfy the dropout color selection and have point-source morphology in the CANDELS fields. We begin our analyses with the publicly available photometric catalogs provided by the 3D-HST team (Brammer et al. 2012; van Dokkum et al. 2013). 3D-HST is an HST near-infrared (NIR) spectroscopic survey designed to study galaxies across the universe. It has surveyed nearly 700 arcmin$^2$ of the well-studied HST/CANDELS Treasury fields to obtain direct images and spectroscopic data with the ACS/G800L and WFC3/G141 grisms. 3D-HST covers about 75% of the original CANDELS area. When all the fields are combined, their photometric observations of $H_{160}$ reach median 5σ depths at 26 mag at a 1″ aperture. Further details of the survey and the published catalog can be found in Skelton et al. (2014) and Momcheva et al. (2016).

The reason for our choice of using the 3D-HST catalog over the catalogs published by the CANDELS team (Guo et al. 2013; Galametz et al. 2013; Nayyeri et al. 2017; Stefanon et al. 2017b; Barro et al. 2019) is that uniform analysis was performed on all five CANDELS fields by the 3D-HST team to create the source catalog. This vastly simplifies the source detection procedure (Section 2.2) and the completeness simulation analysis (Section 3.3), for calculating the number density of the target population. However, due to inconsistencies in the filter coverage, we only analyze four of the five CANDELS fields (AEGIS, COSMOS, GOODS-South, and UKIDSS-UDS), where the F814W, F125W, and F160W filters are available (Section 2.2). We also exploit the published G141 grism data to identify low-redshift interlopers (Section 2.4).

We obtain deep HST data from the publicly available 3D-HST database. The HST image mosaics used have already been corrected for distortions and drizzled to the plate scale of 0′′.06 pixel$^{-1}$. The photometric source catalogs were produced using point-spread function (PSF)-matched aperture photometry, reduced using SExtractor (Bertin & Arnouts 1996), and flux-calibrated to an aperture radius of 0′′.7. The HST ACS and WFC3 images were convolved to match the HST/F160W PSF ($\sim$0′′.14). Ground-based optical, NIR, and Spitzer/IRAC fluxes were similarly PSF-matched to a combination of F125W, F140W, and F160W priors and aperture-corrected to F160W (or F140W, otherwise).

2.2. Color Dropout and Shape Selection

Our strategy in identifying $z \sim 7-8$ point-source candidates from 3D-HST is twofold. First, we identify sources with the Lyman-break dropout technique (Steidel et al. 1996) from the photometric catalog. Then, we select point sources from the list of Lyman-dropout sources. The color selection is only based on deep HST photometry. A caveat is that unlike the Morishita et al. (2020) and Morishita (2021) selection, which uses the F105W/F125W/F160W ($Y_{105}/Y_{125}/Y_{160}$) filters, the 3D-HST catalog does not include $Y_{105}$ fluxes. Instead, we use the Bouwens et al. (2015) color dropout criteria, which are based
on an F814W/F125W/F160W ($I_{814}/I_{125}/H_{160}$) selection:

\[
\begin{align*}
S/N_{I_{125},160} & > 5.0 \\
S/N_{I_{814}} & < 2.0 \\
I_{814} - I_{125} & > 2.2 \\
I_{125} - H_{160} & < 0.4 \\
I_{814} - J_{125} & > 2 \times (J_{125} - H_{160}) + 2.2.
\end{align*}
\]

Compared to the Morishita et al. (2020) selection, this color selection results in a broader $z \sim 7$–8 range. Also, the GOODS-North catalog does not include $I_{814}$ data, so we only examine four of the five CANDELS fields. Where available, we use the HST/ACS blue filters ($I_{814}$ and bluer) to determine the Lyman dropout with strict blue signal-to-noise ratio (S/N) constraints, combined with the nondetection flag from the HST pipeline catalog. Since we require $2\sigma$ nondetections for $I_{814}$ fluxes, we calculate the resulting $I_{814} - J_{125}$ lower-limit color as

\[
(I_{814} - J_{125})_{\text{lim}} = -2.5 \log_{10}(2\sigma_{I_{814}}/I_{125}).
\]

We do not include sources with $I_{814} - J_{125}$ that fall below the nondetection limit (i.e., that fall outside the selection box in Figure 1). While additional ground-based fluxes are available, higher-S/N HST fluxes are prioritized for color selection here (but see Section 2.4).

From the color dropouts, we identify point sources based on two morphological parameters, elongation and flux concentration, measured in the $H_{160}$ filter. The selection criteria are defined by Morishita et al. (2020):

\[
e < 1.2 \\
f_{3}/f_{10} > 0.5.
\]

Elongation, $e$ (the ratio of the semimajor/semiminor axes), describes the circularity of the source, and the flux concentration (the flux ratio between the inner and outer radii) describes the compactness. Morishita (2021) found light concentration is an appropriate metric for point-source selection. We obtain $e$ from the 3D-HST catalog. To calculate flux concentration, we run SExtractor on the image mosaics, matching the 3D-HST detection parameters, and obtain detailed aperture photometry of the targets. We extract the aperture fluxes to calculate the flux ratios. After careful comparison of the different $H_{160}$ flux ratios at different radii, we determine the $f_{3}/f_{10}$ flux concentration, the flux ratios taken within the 5 pixel (0\text{"}3) and 10 pixel (0\text{"}6) radii, to be the appropriate criteria. This decision is based on the ability to concurrently recover known dwarf star contaminants due to the point-source selection (see Section 2.4). Although the 3D-HST source catalogs include the star\textunderscore class flag, which classifies a source as starlike or otherwise, Finkelstein et al. (2015) and Morishita (2021) have demonstrated that this flag is not complete down to fainter magnitudes; it fails to distinguish between fuzzy circular objects and compact point sources in the faint magnitude ranges up to $\sim 24$ mag. We note that other studies (e.g., Bouwens et al. 2015; Roberts-Borsani et al. 2016) have successfully identified sources by combining color dropout, stellarity parameters, and SED properties. Our aim is to identify additional sources that may be missed with the standard method.

Of the 169,614 objects listed in the 3D-HST catalog, we identify 22 $I_{814}/I_{125}/H_{160}$ dropout point sources. Of these point sources, seven meet the photometric redshift selection of $z_{ph} > 7$, discussed in Section 2.3. We show the $J_{125} - H_{160}$ versus $I_{814} - J_{125}$ color–color diagram of all color and $z_{ph} > 7$ selected point sources in Figure 1. Then, we check the grism spectra to further eliminate any low-redshift interlopers, discussed in Section 2.4. Our final $z \sim 7$–8 point-source candidate list consists of three point sources, which are listed in Table 1. We also visually inspect the HST images of the $z_{ph}$-selected targets to eliminate image artifacts and/or other spurious detections; postage-stamp images of the final sample are shown in Figure 2 and discussed in Section 4. The observed fluxes of the point sources are shown in Table 2. We also list low-confidence, $I_{814} - J_{125}$ limited, noncandidate point sources in Appendix A.

### 2.3. Photometric Redshifts and SED Fits

The Lyman-break color selection is comprehensive but also allows low-redshift sources with similar colors to migrate into the selection window. To filter out these contaminants, we apply a further selection based on the photometric redshift measurement discussed here.

Following the similar approach by Roberts-Borsani et al. (2021), we estimate the photometric redshift, $z_{ph}$, using the photometric redshift code EAZY (Brammer et al. 2008). While photometric redshifts are also included in the public 3D-HST catalog, they were calculated with a maximum limiting redshift of $z = 6$. Hence, we re-reduce the redshift estimates for all of our color-selected samples. We use EAZY in the default setup (v1.3 templates) to derive the best-fit SED and redshift.
posterior probability, \( p(\z_{ph}) \). To ensure a more accurate redshift derivation, we use all available photometric data points, including ground-based fluxes that are excluded in our initial color selection in Section 2.2. We turn off magnitude priors in the fit to avoid any biased redshift selections, and fit between 0 \( \leq \z_{ph} \leq 9 \). The \( \z_{ph} \) fit range is based on the redshift probability from the survey completeness (Section 3.3). From this analysis, we eliminate low-redshift interlopers by making a cut in which the probability of \( \z_{ph} > 6 \) is greater than 70%. The \( \z_{ph} \) and corresponding probability of our targets are shown in Table 1.

Upon determining \( \z_{ph} \), we refine the SED fits using Bagpipes (Carnall et al. 2018) to determine their physical properties. Morishita et al. (2020) note that distinguishing between luminous galaxies and quasars at \( \z \sim 7-8 \) is ambiguous and challenging without spectroscopy. In Figure 3 we plot both the best-fit quasar (described in Appendix B) and star-forming galaxy SEDs (from the Bagpipes fitting described next), which clearly show degenerate profiles, with the exception of EGS 29337 (to be discussed later). Since precise modeling is beyond the scope of this study, in this paper we instead assume that the sources are well represented with a young stellar spectrum with nebular emission with Bagpipes modeling and explore the inferred properties.

We describe our Bagpipes fit methodology here. The redshift is fixed to \( \z_{ph} \) from EAZY, and we freely fit for other properties. The model fit priors are listed in Table 3, following the treatment in Roberts-Borsani et al. (2021) as a guide. The best-fit Bagpipes SEDs and EAZY \( \z_{ph} \) probability distributions are shown in Figure 3. For each source, we use the best-fitting SED model to extract the source’s rest-frame UV luminosity, \( M_{UV} \), and other stellar parameters of interest for subsequent analysis, which is discussed in Section 3. The best-fit Bagpipes model parameters are shown in Table 4.

2.4. Excluding Low-redshift Contaminants

To further exclude low-redshift interlopers among the selected point sources, we utilize G141 grism spectra made available by the 3D-HST team. As alluded to earlier, dwarf star SEDs have a sharp 1 \( \mu \)m drop-off that resembles the Lyman break of \( \z \sim 7-8 \) objects, making them likely interloper contaminants. There are notable spectral features at 1, 1.25, and 1.6 \( \mu \)m that are captured by the G141 grism. We find that some of our point sources are not listed in the grism catalog, due either to the extraction limit (\( H_{140} \approx 26 \) mag) or to incomplete spectral coverage (landing on/outside of the detector edge). It is noted that the G141 grism does not cover the redshifted Ly\( \alpha \) break at \( \z \sim 7-8 \), making confirmation as high-redshift sources difficult. Therefore, the objective of our inspection here is to exclude interlopers through the detection of continuum spectral features instead of characterizing their spectra.

When extracted grism spectra are available for the sources selected in Section 2.2, we perform spectral fits to low-mass L and T dwarf template spectra that were observed with the SpeX spectograph on the NASA Infrared Telescope Facility (Rayner et al. 2003). The template spectra are obtained from the SpeX Prism Library (Burgasser 2014). Based on the spectral fits, we identify four T dwarfs with clear spectral features. Their 1D spectra are shown in Appendix C. In fact, three of these dwarf stars were also identified in a recent 3D-HST dwarf star study (Aghan et al. 2022). We exclude these targets from the final point-source list. We note that none of our final redshift-selected point-source candidates were identified by Aghan et al. (2022). However, the Aghan et al. (2022) selection was limited to spectra with S/N > 10, and thus their selected sources are all brighter than our final targets (\( H_{140} \lesssim 24 \) mag). This may simply reflect the limitations of the 3D-HST grism data instead of differences in selection. We also fit the photometric SEDs with the SpeX dwarf star templates using EAZY. In Table 1 we list the \( \chi^{2}_{\nu,ph} \), and in Figure 3 we show the best-fit SEDs. When these are compared to the \( \chi_{o} \), the \( \z_{ph} \) fits, we find that our final point sources are better constrained as \( \z \sim 7-8 \) sources.

2.5. Visual Inspection of Point Sources

As the final step of our sample selection, here we examine the images to identify and to eliminate any spurious fluxes in HST and Spitzer. Once we eliminate false detections, we repeat and refine the EAZY \( \z_{ph} \) estimates and Bagpipes SED fits.

Postage-stamp images of our final point sources are shown in Figure 2. The images are extracted from the available deep HST (Grogin et al. 2011; Koekemoer et al. 2011; Skelton et al. 2014) and Spitzer (Dickinson et al. 2003; Ashby et al. 2013) data that make up the 3D-HST catalogs. From the images, we clearly see blue color dropouts, which are also reflected in the SED fits. Some sources show suspicious blue detections. For example, the GDS 29369 images show suspicious \( I_{814} \) fluxes, despite meeting the nondetection criteria. After comparing the different filter images, we conclude that this is likely noise artifacts because their flux centroids do not match and the size is on the same order as the surrounding noise structure. The catalog also suggests spurious ground-based blue fluxes observed with Subaru (Taniguchi et al. 2007) for GDS 45797. However, careful examination of the Subaru images suggests that they are artifacts due to diffraction spikes from a nearby star. So, we treat these blue fluxes as nondetections in our analysis. Fortunately, the inclusion of these blue fluxes...
does not have a major effect on the ∆z_{ph} or the SED fit results. Another uncertainty comes from the Spitzer/IRAC fluxes, which suffer from lower spatial resolution. The 3D-HST catalog includes IRAC contamination flags for each channel; however, the flags are based on contamination within 3ʼ apertures, whereas our fluxes are taken at 0ʼʼ7 apertures. As a result, we individually inspect the IRAC images to decide whether to include them in our analysis. If we visually confirm obvious contamination within a channel, we omit its flux.

2.6. Cross-matching with Chandra X-Ray Catalog

Finally, we also cross-match our HST-selected sources with the deep X-ray Chandra catalogs for GOODS-South (Luo et al. 2017) and AEGIS (Nandra et al. 2015). Significant X-ray emission would strengthen the case for quasar candidacy. Previous targeted observations, at shallower depths, have detected z∼7 low-luminosity quasars (e.g., Bañados et al. 2017a; Wang et al. 2021a); however, no clear X-ray emission was detected at 0.5–7 keV. We place upper limits on the fluxes and luminosities of our targets in Table 5. Moreover, there are known Compton-thick z>7 quasar candidates with faint X-rays (Fujimoto et al. 2022), so this is not entirely unusual. Detailed X-ray analyses will be left for future study.

3. Results: Nature of Point Sources

3.1. On the Point-source Selection

We cross-match our point-source selection with findings from Bouwens et al. (2015), which examined the CANDELS, HUDF09, HUDF12, ERS, and BoRG/HiPPIES fields to estimate the galaxy UV luminosity function. Both studies apply similar Lyman-dropout color selections. The main difference is that we explicitly search for point sources with the morphology selection defined in Section 2.2 using the $f_{3}/f_{10}$ flux ratios, while Bouwens et al. (2015) implemented the stellarity parameter (i.e., the star_class flag), combined with SED fit photometry, to eliminate point sources.

We find that only EGS 29337 is detected in both catalogs (EGSY-0120800269) with a separation of δr = 0′′11, which is well within the PSF uncertainty. In fact, this object has also been spectroscopically confirmed as a galaxy at z_{ph} = 7.477 (Roberts-Borsani et al. 2016; Stark et al. 2017). This proves that some near pointlike sources are in fact bona fide galaxies. We discuss the implications in Section 4. Our SED modeling in Figure 3 also supports these conclusions. We note that the other sources were not identified by other z∼7–8 studies (e.g., Bouwens et al. 2015; Roberts-Borsani et al. 2016; Stark et al. 2017). In fact, these sources have larger $f_{3}/f_{10}$ values compared to EGS 29337, which suggest that they appear more pointlike, and thus are more likely to have been rejected in the galaxy selection. Thus, a unique aspect of this study is that we explore the z∼7–8 dropout point sources that were often excluded in earlier studies of high-redshift galaxies.

3.2. Stellar SED Fit Properties of Point Sources

We list the best-fit stellar population properties of the point sources, which are estimated with Bagpipes SED fits, in Table 4. Due to the limitation of the data, we assume that our detected point sources are well represented by a young stellar spectrum. The fit results predict subsolar metallicities for nearly all of our point sources. Considering the young age of the universe, the metallicity estimates are not surprising. However, since uncertainties in broadband SED fits are strongly influenced by assumptions on the star formation history and age–metallicity–dust degeneracies (e.g., Figure 12 in Morishita et al. 2019), it is difficult to place any confident constraints on the metallicity evolution in the early universe. Instead we examine the size and star formation rate (SFR) density properties of the point sources.

We derive the projected physical size, $R_{eff}$, from the half-light radius, which is calculated with SExtractor. When compared to the 3D-HST PSF limit, 0′′14, we find that two of the calculated $R_{eff}$ are upper limits. This is similar to the Morishita et al. (2020) results, as shown in Figure 4. This means that these sources are likely unresolved by HST, despite meeting our point-source selection criteria.

Using the SFR estimated from the Bagpipes modeling, we also calculate the SFR density, $\Sigma_{SFR}$, which is defined as the average SFR within a circle with radius $R_{eff}$:

$$\Sigma_{SFR} = \frac{SFR}{2\pi R_{eff}^2}$$

The calculated $\Sigma_{SFR}$ serves as a lower limit since its uncertainty is dependent on the upper-limit uncertainty in $R_{eff}$. We compare it with the inferred $\Sigma_{SFR}$, which is calculated from the $M_{UV}$–SFR relation (Kennicutt 1998; Ono et al. 2013) defined...
as follows:

\[ M_{UV} = -2.5 \log_{10} \left[ \frac{\Sigma_{SFR} \cdot \pi R_{eff}^2}{2.8 \times 10^{-28} (M_{\odot} \text{yr}^{-1})} \right] + 51.59. \quad (5) \]

It appears that our point-source candidates are highly compact star-forming objects. In Figure 4, we plot \( R_{eff} \) and \( \Sigma_{SFR} \) against their corresponding \( M_{UV} \). We also compare the \( \Sigma_{SFR} \) redshift evolution. Our results appear to be consistent with the trends of high-redshift galaxies discussed in Ono et al. (2013) and Holwerda et al. (2018), which predict a greater number of compact galaxies with high SFRs at earlier epochs.

Using the best-fit Bagpipes SEDs, we calculate the UV continuum slope \( \beta_{UV} \). We adopt the formula defined as follows (e.g., Dunlop et al. 2013):

\[ \beta_{UV} = -2.0 + 4.39 \times (J_{125} - H_{60}). \quad (6) \]

where \( J_{125} \) and \( H_{60} \) are the best-fit magnitudes from the best-fit Bagpipes SEDs. The calculated \( \beta_{UV} \) are listed in Table 4 with a mean slope of \( \beta_{UV} = -1.90 \pm 0.35 \). The resulting \( \beta_{UV} \) is consistent with the \( \beta_{UV} \) of known bright galaxies at \( z \approx 7-8 \) (e.g., Dunlop et al. 2013; Bouwens et al. 2014).

Lastly, we estimate the rest-frame equivalent width (EW) due to the \( H_{\beta} + [O \text{ III}] \) emission lines from the best-fit SED for objects with sufficient IRAC fluxes. This is possible because \( H_{\beta} + [O \text{ III}] \) emission from \( z \approx 7-9 \) sources is well sampled by IRAC CH1 and CH2, 3.6 \( \mu \text{m} \) and 4.5 \( \mu \text{m} \) (Roberts-Borsani et al. 2016). We calculate the EWS as

\[ EW_{H_{\beta} + [O \text{ III}]} = \frac{(f_{ch2} - f_{cont}) \Delta \lambda_{ch2}}{f_{cont} (1 + z_{ph})}, \quad (7) \]

where \( f_{cont} \) is the underlying continuum flux obtained from the best-fit Bagpipes spectrum, \( f_{ch2} \) is the observed Spitzer/IRAC CH2 flux, \( \Delta \lambda_{ch2} \approx 1 \mu \text{m} \) is the FWHM of the CH2 filter, and \( z_{ph} \) is from the EAZY. Comparing the values in Table 4 and the SED plots in Figure 3, we see that the \( EW_{H_{\beta} + [O \text{ III}]} \) estimates can be applied to three targets. These objects show a moderate \( EW_{H_{\beta} + [O \text{ III}]} \) of 500–1000 \( \AA \), similar to estimates from other high-redshift surveys (Labbé et al. 2013; Schenker et al. 2013; Smit et al. 2014, 2015; Morishita et al. 2020). However, this is based on the assumption that \( z_{ph} \) is correct. We compare the redshift evolution of the measured \( EW_{H_{\beta} + [O \text{ III}]} \) in Figure 4, and our results appear to be consistent with other survey results. Future infrared observations with higher resolution and sensitivity are needed to better characterize the predicted \( H_{\beta} + [O \text{ III}] \) emission.

### 3.3. Number Density of Point Sources

From the survey data, we constrain the point-source luminosity function at \( z \approx 7-8 \). We produce our own completeness simulation to calculate the effective volume, \( V_{eff} \), probed by 3D-HST. We follow the completeness simulation treatment in Leethochawalit et al. (2021) to calculate \( V_{eff} \) (Oesch et al. 2012; Calvi et al. 2016; Carrasco et al. 2018; Morishita et al. 2018).

We inject 500 sources into each 3D-HST image at each \( (M_{UV}, z) \) bin: 100 \( \Delta M_{UV} \) bins across \(-26 \leq M_{UV} \leq -16 \) and 13 \( \Delta z \) bins across \( 7 \leq z \leq 9.4 \). All simulated sources in a given \( (M_{UV}, z) \) grid have the same UV slope, which are randomly drawn from a Gaussian distribution with a mean slope of \( \beta_{UV} = -2.2 \pm 0.4 \). Source fluxes are calculated in the same way as in Skelton et al. (2014). We extract the simulated point sources according to our selection criteria described in Section 2.1. We repeat this process for every field. We show the redshift and magnitude probability distribution functions of the extraction completeness in Figure 5.

After we calculate \( V_{eff} \), we estimate the number density of the point sources shown in Table 6 within each \( \Delta M_{UV} = 0.5 \) mag bin. We quote Poisson uncertainties for the number density (Gehrels 1986). In Figure 6, we plot the estimated number density of our point sources and compare it with results from previous surveys of point sources and galaxies at \( z \approx 7-8 \).

We fit the point-source number density with both the Schechter function (Equation (8), Schechter 1976) and a double power law (DPL) function (Equation (9); Hopkins et al. 2007), where \( \phi^* \) is the characteristic normalization, \( M_{UV}^* \) is the characteristic UV luminosity defined at \( M_{UV} = 1540 \) \( \AA \), \( \alpha \) defines the faint-end slope, and \( \beta \) defines the bright-end slope:

\[ \phi_{Sche} = \frac{\ln 10}{2.5} \phi^* \times 10^{-0.4(M_{UV} - M_{UV}^*)} \times \exp[-10^{-0.4(M_{UV} - M_{UV}^*)}] \quad (8) \]

\[ \phi_{DPL} = \frac{\ln 10}{2.5} \phi^* \times 10^{0.4(\alpha + 1)(M_{UV} - M_{UV}^*)} + 10^{0.4(\beta + 1)(M_{UV} - M_{UV}^*)}. \quad (9) \]

To properly include the bins of nondetection of the point-source population at the faintest and brightest ends in fitting evaluation, we incorporate the upper limits from nondetections following the derivations from Sawicki (2012) for \( \chi^2 \) minimization. The derivations for \( M_{UV} \) and the \( \chi^2 \) minimization are shown in Appendix D. We perform Markov Chain Monte Carlo sampling, using the emcee package (Foreman-Mackey et al. 2013), to constrain the luminosity function. First we fit the luminosity function for point sources from this study.
Table 3

| Parameter | SED Fit Priors Assuming a Young Stellar Population Model |
|-----------|---------------------------------------------------------|
| $z$       | EAZY $z_{ph}$                                           |
| $\tau_{age}$ | (Gyr) [0.001, 1]                                    |
| $\log_{10}(M_{*}/M_{\odot})$ | ... [6, 15]                                  |
| $Z$       | (Z$_{\odot}$) [0, 1]                                   |
| $A_V$     | mag [0, 1]                                             |
| $\log_{10} U$ | ... $-3$                                             |

Note. The model redshifts are fixed to the EAZY-derived $z_{ph}$ found in Table 1. $\tau_{age}$ is the range of universe ages calculated with the exponential star formation history model; $M_{*}$ is the final stellar mass formed, $Z$ is the metallicity, $A_V$ measures the dust attenuation, and $U$ is the nebular ionization parameter, which captures the nebular emission and continuum components.

(3D-HST selections). Then we apply the fits on all point sources selected from both this study and SuperBoRG.

If we freely fit for all of the parameters, the fit parameters do not converge to physically meaningful values. This is likely due to the lack of data points at both the faint and bright magnitude ranges. Instead, we opt for a more conservative approach and follow the known luminosity function shapes of $z \sim 7$–8 galaxies and $z \sim 6$ quasars. We fix both the faint-end and bright-end slopes and freely fit for $\phi^*$ and $M_{UV}^*$. For the Schechter model fits, we fix the faint-end slope to $\alpha = -2.2$, which is the observed galaxy luminosity function at $z \sim 7$–8 (Bouwens et al. 2021). For the DPL model fits, we fix the faint-end slope to $\alpha = -1.2$ and the bright-end slope to $\beta = -2.7$ based on extrapolations of quasar luminosity at $z \sim 6$ (Matsuoka et al. 2018; Harikane et al. 2022).

With the deeper exposures of the 3D-HST survey, we improve the point-source luminosity function fits estimated by Morishita et al. (2020). The best-fit luminosity function parameters of the point sources are shown in Table 7. If we freely fit for $M_{UV}^*$, we find that the DPL fit produces more reasonable parameters ($M_{UV}^* \approx -24$) than the best-fit Schechter function, which instead suggests an unrealistically bright UV cutoff ($M_{UV}^* \approx -38$, not shown). This may suggest that the point-source luminosity function is more consistent with the high-redshift quasar luminosity function (at $z \sim 6$; Matsuoka et al. 2018). On the other hand, if we force a lower bound on the $M_{UV}^*$, then it is difficult to confidently favor either function over the other. For both cases, the best-fit normalization $\phi^*$ deviates from the Matsuoka et al. (2018) extrapolation by nearly $\times 100$. This may be because 3D-HST is volume-limited, similar to the results in Morishita et al. (2020).

3.4. Number Density of Point-source + Galaxy Populations

Finally, we fit the combined point-source and galaxy luminosity functions. Here, we remove EGS 29337 from the point-source luminosity function since it is already included in the Bouwens et al. (2015) determination (discussed in Section 3.1). First, we fit with the slopes fixed, and then we freely fit over all parameters. With the current survey volume by HST, it is difficult to confidently favor either function over the other for the combined luminosity function. With the Schechter model, both the fixed-slope and freely fit runs produce brighter UV cutoffs at $M_{UV}^* \approx -21.9$, compared to $M_{UV}^* = -22.8$ by Bouwens et al. (2021), suggesting an excess of bright sources. The freely fit DPL model produces a superposition of point-source Schechter and galaxy Schechter functions also with a slight excess of $M_{UV}^* = -20.0$ and a steep $\beta = -3.6$.

The exact shape of the galaxy luminosity function is under debate. For example, Harikane et al. (2022) performed a two-component luminosity function fit (i.e., DPL+Schechter) to the combined quasar+galaxy populations. In contrast, we model a single-component function across all magnitudes for both the point-source and galaxy number densities (i.e., Schechter or DPL). The main difference between the two studies is that Harikane et al. (2022) extrapolated the...
\[ \text{Table 4} \]

| Target          | \( R_{\text{eff}} \) (kpc) | \( M_{\text{UV}} \) (AB mag) | \( \beta_{\text{UV}} \) | SFR \( (M_\odot \text{yr}^{-1}) \) | \( \tau_{\text{avg}} \) (Gyr) | \( \log_{10}(M_\odot / M_\odot) \) | \( \log_{10}(Z/Z_\odot) \) | \( \Sigma_{\text{SFR}} \) \( (M_\odot \text{yr}^{-1} \text{kpc}^{-2}) \) | \( E\lambda_{23}\) (\AA) |
|-----------------|----------------------------|-------------------------------|-----------------|-------------------------------|-----------------|-------------------------------|-----------------|-----------------|-----------------|
| GDS 45797       | <0.7                       | -22.56                        | 12 ± 7          | 0.5 ± 0.3                     | 9.1 ± 0.2       | -1.70 ± 0.43                  | >34             | ...             | ...             |
| EGS 515         | 0.8 ± 0.7                  | -21.86                        | 15 ± 7          | 0.6 ± 0.3                     | 9.2 ± 0.3       | -0.57 ± 0.43                  | >9              | 1200 ± 500      | ...             |
| EGS 29337       | 0.8 ± 0.7                  | -21.85                        | 46 ± 27         | 0.6 ± 0.2                     | 10.3 ± 0.2      | -0.60 ± 0.42                  | >11             | 500 ± 200       | ...             |

Note: The model redshifts are fixed to the \( z_{\text{obs}} \) in Table 1. The model priors are listed in Table 3. PSF-limited \( R_{\text{eff}} \) are shown as upper limits.

\[ \text{Table 5} \]

| Target          | \( F_{0.5–2 \text{keV}} \) \( (\text{erg cm}^{-2} \text{s}^{-1}) \) | \( L_{2–10 \text{keV}} \) \( \text{erg s}^{-1} \) |
|-----------------|-------------------------------------------------|----------------------------------|
| GDS 45797       | <4.3 \times 10^{17}                             | <4.3 \times 10^{33}              |
| EGS 515         | <8.0 \times 10^{17}                             | <6.2 \times 10^{33}              |
| EGS 29337       | <4.0 \times 10^{17}                             | <3.1 \times 10^{33}              |

Note: We assume a simple power law with \( \Gamma = 2 \) at \( z_{\text{obs}} \) without any obscuration.

We compare the point-source number density and luminosity function against the galaxy luminosity function measured at \( z \sim 7 \sim 8 \) (Bouwens et al. 2021). We quantify the fraction of extended galaxies among all sources (galaxies and point sources) as a function of \( M_{\text{UV}} \) as follows:

\[
\phi_{\text{galaxy}}(M_{\text{UV}}) = \frac{\phi_{\text{galaxy}}}{\phi_{\text{galaxy}} + \phi_{\text{points}}}
\]

where \( \phi_{\text{galaxy}} \) is the galaxy number density from the luminosity function (Bouwens et al. 2021) and \( \phi_{\text{points}} \) is the observed point-source number density listed in Table 6. The uncertainty in \( \phi_{\text{galaxy}} \) simply reflects the uncertainty in the number count of point sources (i.e., Poisson). We plot \( \phi_{\text{galaxy}} \) alongside the luminosity function fits in Figure 7 and compare them with the results from Harikane et al. (2022). We find that these point sources dominate at the bright \( M_{\text{UV}} \) magnitudes. This suggests that the bright-end excess implied by the new point sources is not likely dominated by a typical population that has been identified in previous studies of high-redshift galaxies. We discuss the physical interpretations of this measured excess in the following section.

4. Discussion

Although our sources are selected with slightly different colors and from different surveys, the inferred number density of our point sources at \( M_{\text{UV}} < -21.5 \) mag agrees with the SuperBoRG point-source study. This indicates that these \( z \sim 7–8 \) dropout point sources are abundant enough to be detected in both surveys and are representative of similar populations. The inferred \( M_{\text{UV}} \) suggests that these objects are driven by intense phenomena that occur in a small physical scale, such as central starburst or quasar activity, which also shape their observed morphology pointlike. In this section we explore the physical properties and implications of these sources.

4.1. Point Sources as Compact Starburst Galaxies

With the exception of EGS 29337, it is currently difficult to distinguish whether our final candidates are nonactive galaxies or quasar-hosting galaxies, as the inferred sizes of the point sources are consistent with the observed trends of smaller galaxy sizes in the early universe (Oesch et al. 2010; Ono et al. 2013; Holwerda et al. 2015). If these point sources are compact nonactive galaxies, we predict a high \( \Sigma_{\text{SFR}} \) based on our SED fitting analysis. Previously, Oesch et al. (2010) and Ono et al. (2013) observed constant \( \Sigma_{\text{SFR}} \) from \( z < 4 \) to \( z \sim 7 \) with a weak increase toward higher redshifts. Our SED analysis of the point sources appears to support this increasing \( \Sigma_{\text{SFR}} \) trend, although we predict even larger values, as shown in Figure 4. Finally, given their predicted SFRs and stellar masses, these sources may be progenitors of massive quiescent galaxies that were already present in the early universe (e.g., van Dokkum et al. 2008; Damjanov et al. 2009). This may suggest that our sources are UV-enhanced starbursts and/or that additional physics may be at play. In fact, EGS 29337 has been shown to be one of the brightest \( z > 7 \) known galaxies with a high SFR (Robert-Borsani et al. 2016; Stark et al. 2017).

4.2. Point Sources as Low-luminosity Quasars

While much of our SED analysis assumes the star-forming SED properties, Figure 3 clearly shows that the SEDs of quasars and star-forming galaxies are degenerate. Theoretical predictions of early quasar properties suggest that variations in the quasar duty cycle may lead to an enhancement of UV-bright quasars (Ren & Trenti 2021). With the detection of potentially UV-bright quasars, there are also implications on the obscured quasar fraction, which is unknown at these redshifts (Vito et al. 2018, 2019; Inayoshi et al. 2020). Either there is an enhancement in the population of unobscured quasars or some physical mechanisms, such as powerful outflows, may drive obscured quasars to appear as luminous as unobscured quasars. Also, while nondetections from deep Chandra images suggest that no luminous quasar is present, the possibility of heavy Compton-thick obscuration may complicate this result (Ni et al. 2020). Another possibility is that these sources are quasars embedded in star-forming galaxies, similar to the \( z \sim 7 \) sources identified by Laporte et al. (2017). In fact, the possibility of either a compact starburst or a quasar is
supported by the recent discovery of a UV-compact, red-bright, X-ray-faint object at $z \sim 7$, which is hypothesized to be either a compact dusty star-forming region or a Compton-thick super-Eddington quasar (Fujimoto et al. 2022).

Although we cannot distinguish between these possibilities with the current HST data, the James Webb Space Telescope’s spatial resolution and sensitivity is expected to reach below the predicted scales and magnitudes of our sources at the range of $-22 \leq M_{\text{UV}} \leq -18$. Marshall et al. (2021) predicted that deep observations by NIRCam may allow us to study the quasars and their host galaxies at $z \sim 7$. Its imaging and spectroscopic capability may enable us to confidently distinguish the sources as quasars or as compact star-forming galaxies. If they are revealed as quasars, they will become some of the most distant quasars ever discovered.

4.3. Investigating the Impact on the Bright-end Excess

In this section, we focus on understanding the point sources’ contribution to the bright end of the galaxy luminosity function. In Figure 7, we show the combined point-source and galaxy luminosity function. Once the point sources from 3D-HST and SuperBoRG are incorporated, we find that the best-fit luminosity functions suggest the existence of a bright point-source population that may be missed by galaxy surveys. This may support the existence of a bright-end excess in the early universe. While ground-based observations (e.g., Bowler et al. 2020) may detect unresolved sources, these studies are limited to select fields. Thus, we stress the importance of large-volume studies to accurately quantify the luminosity function.

Indeed, Harikane et al. (2022) presented a comprehensive analysis of the luminosity function by combining the quasar and galaxy populations identified in the Hyper Suprime-Cam program. They proposed several explanations for the apparent bright-end excess seen in galaxy luminosity functions. Physical mechanisms such as inefficient mass quenching due to high star formation activity and/or poor quasar feedback, low dust obscuration in the host galaxy (Marques-Chaves et al. 2020, 2021), or even additional hidden quasar activity may increase the observed rest-frame UV luminosity.
Figure 5. The $M_{\text{UV}}$- and redshift-dependent selection probability distribution as determined from our completeness simulation. The plot shows the ratio of color-selected point sources recovered to all input sources as a function of redshift and $M_{\text{UV}}$. The color bar to the right indicates this recovery fraction. At brighter $M_{\text{UV}} \lesssim -21$ mag, at least 50% of the simulated color-selected point sources are recovered (blue contour line). At fainter magnitudes, the recovery fraction decreases due to the combined effect of color selection and source detection (gray contour lines at 40% and 75% detection). We also indicate the observed point-source candidates at their respective $z_{\text{ph}}$ and $M_{\text{UV}}$ (red stars).

Figure 6. The derived number density of the 3D-HST point sources in red, of the SuperBoRG point sources (Morishita et al. 2020) in blue, and of galaxies at $z \sim 7$–8 (Bouwens et al. 2021) in black. The $z \sim 7$ number density from Harikane et al. (2022) is in green. Open symbols indicate observed data, and filled symbols indicate upper limits, which are estimated from the completeness simulation. Our number density values are listed in Table 6.

Table 6

| $M_{\text{UV}}$ (AB mag) | $V_{\text{eff}}$ ($10^3$ Mpc$^3$) | $\Phi$ (Mpc$^{-3}$ mag$^{-1}$) |
|--------------------------|-------------------------------|-----------------|
| $\ast$-26.0              | 1941                          | $<5 \times 10^{-7}$ |
| $\ast$-25.5              | 1918                          | $<5 \times 10^{-7}$ |
| $\ast$-25.0              | 1870                          | $<5 \times 10^{-7}$ |
| $\ast$-24.5              | 1884                          | $<5 \times 10^{-7}$ |
| $\ast$-24.0              | 1900                          | $<5 \times 10^{-7}$ |
| $\ast$-23.5              | 1885                          | $<5 \times 10^{-7}$ |
| $\ast$-23.0              | 1864                          | $<5 \times 10^{-7}$ |
| $\ast$-22.5              | 1910                          | $<5 \times 10^{-7}$ |
| $\ast$-22.0              | 1790                          | $(11 \pm 8) \times 10^{-7}$ |
| $\ast$-21.5              | 1611                          | $<6 \times 10^{-7}$ |
| $\ast$-21.0              | 1139                          | $<9 \times 10^{-7}$ |
| $\ast$-20.5              | 680                           | $<1 \times 10^{-6}$ |
| $\ast$-20.0              | 410                           | $<2 \times 10^{-6}$ |
| $\ast$-19.5              | 146                           | $<7 \times 10^{-6}$ |
| $\ast$-19.0              | 26                            | $<4 \times 10^{-5}$ |
| $\ast$-18.5              | 8                             | $<1 \times 10^{-4}$ |
| $\ast$-18.0              | 2                             | $<5 \times 10^{-5}$ |
| $\ast$-17.5              | 0.1                           | $<1 \times 10^{-2}$ |

Note. $M_{\text{UV}}$ is the rest-frame UV luminosity at 1450 Å obtained from the best-fit Bagpipes SED. $V_{\text{eff}}$ is calculated by the completeness simulation (Leethochawalit et al. 2021). The 1σ uncertainties in $\Phi$ are based on Gehrels (1986). We also show the 1σ upper limits for $\Phi$, where appropriate. We take $\Delta M_{\text{UV}} \approx 0.5$ mag bins to match Bouwens et al. (2021).

(Mirocha 2020). Variations in the quasar duty cycle can also enhance the UV luminosity and contribute to the bright end (Ren & Trenti 2021). Our predictions of compact star-forming galaxies or quasars are consistent with these possibilities.

Other possibilities include the superposition of lensed galaxies or even merging galaxies. However, these may be unlikely since the point-source criteria require small elongation values. Our sources also do not appear to be close to potential lensing sources (see Figure 2). Moreover, Mason et al. (2015) showed that the effect of magnification bias on luminosity function determination is small. Shibuya et al. (2022) calculated a merger fraction of 10% to 70% for bright $-24 \lesssim M_{\text{UV}} \lesssim -22$ galaxies (Harikane et al. 2022). Considering the inferred $M_{\text{UV}}$ of our sources, there is a nonzero possibility of merger contaminants, especially since galaxy formation in the early universe may involve major mergers.

If the point sources are revealed to be quasars by future spectroscopic follow-ups, then a substantial population of low-luminosity quasars may be inferred to exist in the early universe. Since quasar activity is associated with rapid accretion, this may allow a pathway for the rapid formation of massive black hole seeds. Distinguishing between compact sources and contaminants may require higher spatial resolution than the capabilities of HST. What is clear is that point sources selected from both deep 3D-HST and medium–deep SuperBoRG consistently suggest a bright-end excess. With the derived upper limit in their number density, we also find that the number density of the point-source population dominates only $\lesssim 5\%$ over the galaxy population at $M_{\text{UV}} \gtrsim -21$ mag (Figure 7). This suggests that their contribution to the faint-end luminosity function, and thus to cosmic reionization, is likely limited.

4.4. Caveat: Low-redshift Interlopers

As demonstrated in this paper, color and morphology selection using current HST capabilities is still challenging when distinguishing between $z \sim 7$–8 sources and Galactic interloper stars. The difficulty is further compounded by the fact that these objects are detected at low S/N. We also note that the astrometry analysis does not show significant differences in the apparent proper motion following the analysis used in Morishita et al. (2020), so high-quality spectroscopic analysis is the only reliable, albeit incomplete,
metric in eliminating low-redshift contaminants. We also calculate the $\beta_{UV}$, defined in Equation (6), of all SpeX dwarf star template spectra, in case the stars are misidentified as galaxies. We find a mean slope of $\beta_{UV} = -1.2 \pm 1.2$, which is nearly indistinguishable from those of galaxies (Dunlop et al. 2013). However, the range of predicted $\beta_{UV}$ is also large, spanning $-5.32 \leq \beta_{UV} \leq 6.76$, which suggests that $\beta_{UV}$ is not a useful metric to distinguish galaxies (including quasars) from dwarf stars. In fact, the $\beta_{UV}$ of spectroscopically confirmed dwarf stars (see Appendix C) have a mean slope of $\beta_{UV} = -4.1$. Thus, we require spectroscopic follow-up to confirm the redshifts and spectroscopic properties of the targets identified in this study. Therefore, for now, our luminosity function estimates serve as an upper limit to the quasar number density at $z \sim 7$–8.

Despite this fact, our study shows that low-resolution spectroscopy around 1 $\mu$m is an effective method for identifying foreground stars. It is noted that when we opt to use the $Y_{105}/J_{125}/H_{160}$ color selection (Morishita et al. 2020; Morishita 2021; Roberts-Borsani et al. 2021) for the field available (i.e., the GOODS-South field), no dwarf star contaminants are confirmed by the grism data (Y. Ishikawa 2022, in preparation). This may be indicative of the observation that $Y_{105}$ is an effective $z > 7$ selector in the absence of other filter observations as proposed by Morishita (2021). Despite this challenge, we eliminate a few dwarf star contaminants with grism spectroscopy. For very faint point sources that do not have sensitive spectroscopic data, we demonstrate that the SED fits favor $z_{ph} \sim 7$–8 sources over dwarf stars.

5. Conclusion

We searched for $z \sim 8$ Lyman-dropout point sources with the archival 3D-HST data. 3D-HST surveys nearly 700 arcmin$^2$ of CANDELS fields, reaching depths of $J_{125}$ and $H_{160} \sim 26$ mag. We combined Lyman-dropout color and point-source selections, with additional photometric redshift estimates and grism spectroscopy to eliminate low-redshift contaminations, and identified three $z \sim 7$–8 point-source candidates.

We then investigated the physical properties of the point sources by using the available multiband photometric data. SED analyses suggest that these sources are potentially quasars or compact star-forming galaxies. Assuming these sources are galaxies, the fitting results reveal high star formation surface density. This is consistent with the redshift trend of previously identified luminous galaxies of comparable luminosity, $M_{UV} \sim -22$; however, we found even larger $\Sigma_{SFR}$ values than those predicted by the relation. We measured the EW$_{H_{\alpha} + [O \text{ III}]}$ for the three targets with Spitzer/IRAC photometry available and found moderately large EWs of $\sim 500$–1000 $\AA$.

We calculated the number density distribution and derived the luminosity function of the point sources. Similar to

### Table 7

Best-fit Luminosity Function Parameters

| Survey                                    | Model   | $\phi^* \ (\text{Mpc}^{-3} \text{mag}^{-1})$ | $M^*_{\text{UV}} \ (\text{AB mag})$ | $\alpha$ | $\beta$ |
|-------------------------------------------|---------|---------------------------------------------|-------------------------------------|----------|---------|
| Point sources: this work                  | Schechter | $(1.5 \pm 0.3) \times 10^{-8}$              | $-24.8 \pm 0.9$                        | $[-2.2]$ | $\cdots$ |
|                                          | DPL     | $(3.4 \pm 0.8) \times 10^{-7}$              | $-23.5 \pm 1.0$                        | $[-1.2]$ | $[-2.7]$ |
| Point sources: this work + SuperBoRG      | Schechter | $(1.0 \pm 0.3) \times 10^{-8}$              | $-24.7 \pm 0.9$                        | $[-2.2]$ | $\cdots$ |
|                                          | DPL     | $(2.1 \pm 0.4) \times 10^{-7}$              | $-23.6 \pm 1.5$                        | $[-1.2]$ | $[-2.7]$ |
| Point sources + galaxies (fixed $\alpha$, $\beta$) | Schechter | $(2.7 \pm 0.4) \times 10^{-5}$              | $-21.9 \pm 0.2$                        | $[-2.2]$ | $\cdots$ |
|                                          | DPL     | $(7.7 \pm 0.6) \times 10^{-3}$              | $-17.6 \pm 0.3$                        | $[-1.2]$ | $[-2.7]$ |
| Point sources + galaxies (freely fit)     | Schechter | $(3.4 \pm 0.3) \times 10^{-9}$              | $-22.8 \pm 0.3$                        | $-2.5 \pm 0.3$ | $\cdots$ |
|                                          | DPL     | $(4.1 \pm 0.1) \times 10^{-4}$              | $-20.0 \pm 0.3$                        | $-2.0 \pm 0.3$ | $-3.6 \pm 0.3$ |

*Note.* For the point sources, we fix both the $\alpha$ and $\beta$ slopes depending on the model used and freely fit for $\phi^*$ and $M^*_{\text{UV}}$. Parameters that are fixed are shown in square brackets. The Schechter model slope is fixed to the galaxy faint-end slope from Bouwens et al. (2021), and the DPL slopes are fixed to the active galactic nucleus function slopes based on $z \sim 6$ (Matsukawa et al. 2018; Harikane et al. 2022). We also fit for a combined galaxy and point-source model with the slopes fixed and with freely fit parameters. The fit contours corresponding to the errors are shown in Figure 8.

**Figure 7.** (Top) Comparison of Bouwens et al. (2021) galaxy vs. point-source fraction. Point sources dominate a larger fraction of the bright end starting at $\sim 22$ mag. We compare this with the Harikane et al. (2022) galaxy fraction in gray. (Bottom) We compare the best-fit $z \sim 7$–8 luminosity functions for the combined, freely fit point sources and galaxies in purple curves against the galaxy-only models by Bowler et al. (2020) and Bouwens et al. (2021) in black and gray; Schechter in solid lines, DPL in dashed lines. The purple squares indicate the combined effective number density. EGS 29337 has been removed from the point-source number density to avoid duplicate counting. Open symbols indicate observed data, and filled symbols indicate upper limits. The curves are shown with 1σ uncertainties.
previous HST $z \sim 7$–8 point-source surveys, we found that the inclusion of point sources reveals an excess in the bright end at $M_{UV} \lesssim -22$, consistent with the SuperBoRG point-source survey. We combined the $z \sim 7$–8 point-source candidates with published galaxy number densities to estimate the total galaxy luminosity function. We found that the best-fitting models all point to a bright $M_{UV}$ cutoff, which departs from the known galaxy luminosity function.

The deeper observations of 3D-HST allowed us to extend the dynamic range covered by our previous work in SuperBoRG. We did not identify point sources in the faint end. Moreover, we found that they make up less than 5% of the galaxy fraction at the faint end. Thus it is unlikely that these point sources have major contributions to cosmic reionization.

If these $z \sim 7$–8 point sources are confirmed to be quasars, our results suggest that quasars in this luminosity range may be more abundant in the early universe. If they turn out to be a galaxy population, it would indicate the presence of compact and intense star formation in the early universe. Further follow-up observations are required to confirm the inferred properties of our point sources. Future surveys using the infrared optimized James Webb Space Telescope and the large field-of-view capable Roman Space Telescope may resolve the current limitations of HST.

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Software: astropy (Astropy Collaboration et al. 2013), EAZY (Brammer et al. 2008), Bagpipes (Carnall et al. 2018), SExtractor (Bertin & Arnouts 1996), LMFIT (Newville et al. 2014), emcee (Foreman-Mackey et al. 2013), xspec (Arnaud 1996), CIAO (Fruscione et al. 2006).

Appendix A

Other Point Sources of Interest

In Table 8 we list the three noncandidate point sources that meet the selection criteria (color, shape, and $z_{ph}$), but have large $I_{814}$ uncertainties and land outside the selection box. A deeper $I_{814}$ image will determine their $I_{814} - J_{125}$ color.

Appendix B

Composite Quasar Spectrum

We generate a composite quasar spectrum for the SED fits in Section 2.3. We combine the low-redshift templates (Vanden Berk et al. 2001; Glikman et al. 2006) and $z \sim 6$ spectra from SDSS (Pâris et al. 2018). Since the neutral hydrogen absorption due to the intergalactic medium is unknown at $z \sim 7$–8, we assume full absorption at $\lambda < 1215$ Å. We do not adjust the emission lines such as Ly$\alpha$, which will be affected by
intergalactic absorption; [C IV], which is expected to show a blueshifted profile (e.g., Yang et al. 2021); or Hβ + [O III]. As we can see in Figure 3, our composite quasar spectrum lacks strong nebular emission lines, which are predicted by the Bagpipes star-forming galaxy SEDs. Detailed spectroscopic analysis is beyond the scope of this study, and will be left for future study. The final composite quasar spectrum is shown in Figure 9.

Appendix C
Dwarf Star Selections

Due to the nature of point-source selection, it is inevitable that we find dwarf star contaminants as discussed in Section 2.4. From the shortlist of color dropout point sources, we identify four dwarf stars (GDS 45889, COS 16730, COS 25286, and EGS 17053) based on 3D-HST grism spectroscopic data. We perform a least-squares fit, minimizing the residual, \((F_d - F_m)/\sigma\). \(F_d\) is the observed grism flux, \(F_m\) is the scaled template flux, and \(\sigma_d\) is the uncertainty of the grism flux. The sources are best fit with T7, T7.5, T8, and T5.5 templates, respectively, to within 3\(\sigma\). We note that the best-fitting templates are approximate and are only used to identify dwarf star contaminants. Accurate characterization will require careful stellar modeling, as demonstrated by Aganze et al. (2022).

With the exception of COS 25286, all of these sources were identified by Aganze et al. (2022); it is possible that COS 25286 did not make their selection due to its low S/N. These targets have F125W magnitudes ranging between 25.65 \(\lesssim I_{125} \lesssim 22\) mag. While three of the four dwarf stars are much brighter than our final targets, some like COS 25286 can appear as faint as \(z \approx 8\) candidates. If we calculate the \(\beta_{\nu}\) of these targets using Equation (6), we find very blue slopes of \(\beta_{\nu} = -4.1 \pm 0.5\). We show the target fluxes in Table 9; the grism spectra and their best-fitting SpeX templates (Rayner et al. 2003; Burgasser 2014) are shown in Figure 10.

Appendix D
Fitting the Luminosity Function

We calculate the absolute rest-frame UV magnitude, \(M_{\nu}\), at \(z_{\text{ph}}\) as follows:

\[
M_{\nu} = m_{\nu}(1 + z_{\text{ph}}) - 25 - 5 \log_{10} [3 \text{Mpc}^{-1} \times (1 + z_{\text{ph}}) \times \Delta A(z_{\text{ph}}) - 5 \log_{10} h] + 2.5 \log_{10}(1 + z_{\text{ph}}),
\]

where \(h\) is the Hubble parameter and \(\Delta A(z_{\text{ph}})\) is the angular diameter distance in Mpc, calculated with astropy. To fully reflect the estimated number densities, including upper limits,
we fit the luminosity function by minimizing Equation (D2) as derived by Sawicki (2012), which is also rewritten in a more convenient form for computation:

\[
\chi^2_{\text{mod}} = \sum_i \left( \frac{\phi_i - \phi_{m,i}}{\sigma_i} \right)^2 \\
- 2 \sum_j \int_{-\infty}^{\phi_{\text{lim},j}} \exp \left[ -\frac{1}{2} \left( \frac{\phi - \phi_{m,j}}{\sigma_j} \right)^2 \right] d\phi \\
= \sum_i \left( \frac{\phi_i - \phi_{m,i}}{\sigma_i} \right)^2 \\
- 2 \sum_j \int \left\{ \sqrt{\frac{\pi}{2}} \sigma_j \left[ 1 + \text{erf} \left( \frac{\phi_{\text{lim},j} - \phi_{m,j}}{\sigma_j} \right) \right] \right\},
\]

where \( \text{erf}(x) = \left( \frac{2}{\sqrt{\pi}} \right) \int_0^x e^{-t^2} dt \). Here \( \phi_{di} \) is the observed number density at a given \( \Delta M_{\text{UV}} \) bin, \( \phi_{m,j} \) is the model luminosity function value at the same \( M_{\text{UV}} \) bin, \( \phi_{\text{lim},j} \) is the upper-limit number density, and \( \sigma \) is the uncertainty in the observed number density. When detections are made at all bands, the second summation (\( j \)-index) goes to zero, revealing the standard \( \chi^2 \) form.

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**Figure 10.** The observed 3D-HST grism spectra in black with the best-fit SpeX templates in red.
