

## Two Remarkably Luminous Galaxy Candidates at $z \approx 11 - 13$ Revealed by *JWST*

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### ABSTRACT

The first few hundred Myrs at  $z > 10$  mark the last major uncharted epoch in the history of the Universe, where only a single galaxy (GNz11 at  $z \approx 11$ ) is currently spectroscopically confirmed. Here we present a search for luminous  $z > 10$  galaxies with *JWST*/NIRCam photometry spanning  $\approx 1 - 5\mu\text{m}$  and covering 49 arcmin<sup>2</sup> from the public *JWST* Early Release Science programs (CEERS and GLASS). Our most secure candidates are two  $M_{\text{UV}} \approx -21$  systems: GLASS-z13 and GLASS-z11. These galaxies display abrupt  $\gtrsim 2.5$  mag breaks in their spectral energy distributions, consistent with complete absorption of flux bluewards of Lyman- $\alpha$  that is redshifted to  $z \approx 13$  and  $z \approx 11$ . Lower redshift interlopers such as dusty quiescent galaxies with strong Balmer breaks would be comfortably detected at  $> 5\sigma$  in multiple bands where instead we find no flux. From SED modeling we infer that these galaxies have already built up  $\sim 10^9$  solar masses in stars over the  $\lesssim 300 - 400$  Myrs after the Big Bang. The brightness of these sources enable morphological constraints. Tantalizingly, GLASS-z11 shows a clearly extended exponential light profile, potentially consistent with a disk galaxy of  $r_{50} \approx 0.7$  kpc. These sources, if confirmed, join GNz11 in defying number density forecasts for luminous galaxies based on Schechter UV luminosity functions, which require a survey area  $> 10\times$  larger than we have studied here to find such luminous sources at such high redshifts. They extend evidence from lower redshifts for little or no evolution in the bright end of the UV luminosity function into the cosmic dawn

epoch, with implications for just how early these galaxies began forming. This, in turn, suggests that future deep *JWST* observations may identify relatively bright galaxies to much earlier epochs than might have been anticipated.

*Keywords:* High-redshift galaxies (734), Galaxy formation (595), Galaxy evolution (594), Early universe (435)

## 1. INTRODUCTION

When and how the first galaxies formed remains one of the most intriguing questions of extragalactic astronomy and observational cosmology (see [Dayal & Ferrara 2018](#); [Robertson 2021](#), for recent reviews). Although deep observations with the Hubble Space Telescope (HST) have pushed our cosmic horizon to within the first 400 Myr of the Big Bang, galaxies at  $z \gtrsim 12$  cannot be observed with HST due to the limit of its wavelength coverage at  $1.6 \mu\text{m}$ .

With the advent of *JWST*, we now have an unprecedented view of the Universe at  $\sim 2-5 \mu\text{m}$  thanks to the extremely sensitive NIRCam instrument (see, e.g., [Rieke et al. 2005](#)). The extended wavelength coverage enables the study of rest-frame optical wavelengths up to  $z \sim 10$  and allows for rest-frame UV selections of galaxies out to much higher redshifts.

Here we present first results from a search for particularly luminous  $z > 10$  sources across the two *JWST* Early Release Science deep fields. The most luminous galaxies are of particular importance. They may trace overdensities and thus pinpoint where galaxy formation first started in the early Universe (e.g., [Leonova et al. 2021](#); [Endsley et al. 2021](#); [Larson et al. 2022](#)). Furthermore, they provide the most stringent constraints on early galaxy build-up and promise rich scientific returns.

One particular example of this is provided by GN-z11 ([Oesch et al. 2016](#)) that was detected with HST. Its discovery in the two CANDELS/GOODS fields that cover a search volume of only  $\sim 10^6 \text{ Mpc}^3$  was initially quite surprising. Theoretical and empirical models of early galaxy formation predicted that a 10-100 $\times$  larger survey would have been required to find one such bright galaxy at  $z = 11$  (e.g. [Waters et al. 2016](#); [Mutch et al. 2016](#)). This highlights the potential of the brightest galaxies at the cosmic frontier to set unique constraints on the physics of galaxy formation (see also [Behroozi & Silk 2018](#)). In particular, the number density of such bright sources, i.e. the bright end cutoff of the UV luminosity function, is a very powerful tool to test the efficiency of star-formation and potential feedback mechanisms in the very early Universe ([Bowler et al. 2014](#); [Tacchella et al. 2020](#); [Bowler et al. 2020](#)).

These results have been extended over the last few years, and evidence is emerging for a differential evolution of the galaxy population during the reionization epoch at  $z > 6$ . While the number densities of fainter galaxies continue to decline with redshift, the most UV-luminous sources seem to be in place rather early (e.g.,

[Stefanon et al. 2019](#); [Bowler et al. 2020](#); [Morishita et al. 2020](#); [Harikane et al. 2022](#); [Bagley et al. 2022](#)). Furthermore, several authors found evidence for pronounced Balmer breaks in bright  $z \sim 8-10$  galaxies, which would indicate a very early formation epoch with intense star-formation (e.g., [Hashimoto et al. 2018](#); [Roberts-Borsani et al. 2020](#); [Laporte et al. 2021](#)). However, others find very young ages for the average population ([Stefanon et al. 2022a,b](#)). These inferences, at the moment, are also highly sensitive to the prior adopted on the star-formation history (e.g., [Tacchella et al. 2022](#); [Whitler et al. 2022](#)). Timing the onset of first star-formation in bright galaxies out to  $z \sim 10$  is thus still highly uncertain, and probing the number density of the most luminous sources at even higher redshifts is the most direct way of addressing this.

The brightest galaxies are also the most amenable to follow-up studies through spectroscopy. For instance, GN-z11 had its redshift confirmed both through grism spectroscopy with HST and with emission lines from ground-based Keck observations (see [Oesch et al. 2016](#); [Jiang et al. 2021](#)). With the combination of NIRCam and NIRSpect, we enter a new era – the rest-frame optical features of galaxies in the Epoch of Reionization ( $z \approx 6-9$ , e.g., [Mason et al. 2019](#)) will come fully into view. However, the strongest emission lines of galaxies at  $z > 10$  will still remain out of reach. Spectroscopically confirming such sources will require measuring order of magnitude fainter lines or strong continuum breaks. Identifying luminous systems at  $z > 10$  to facilitate these measurements is therefore a crucial step in fulfilling *JWST*'s mission of charting cosmic dawn.

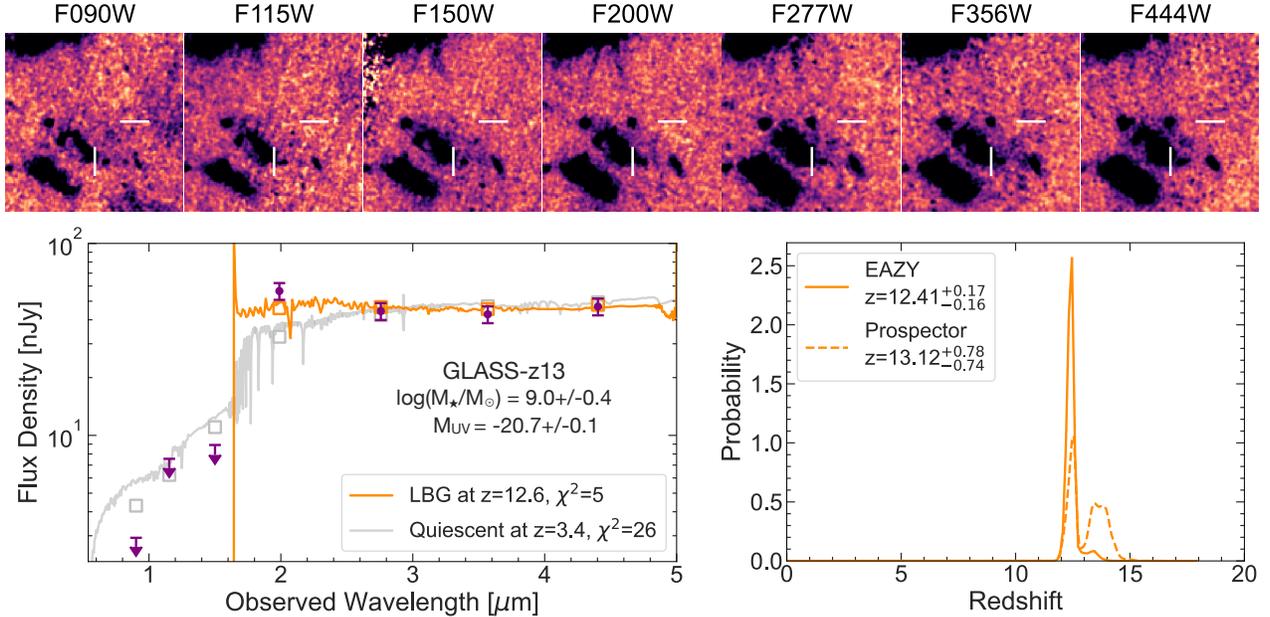
This paper is organized as follows – §2 describes the datasets analyzed in this work, §3 presents our sample selection, and in section §4 we show our results. A discussion on the implications follows in §5, before we conclude with a summary and an outlook in §6.

Magnitudes are in the AB system (e.g., [Oke & Gunn 1983](#)). For summary statistics we report medians along with 16<sup>th</sup> and 84<sup>th</sup> percentiles. We adopt a [Planck Collaboration et al. \(2015\)](#) cosmology.

## 2. DATA

### 2.1. Early Extragalactic *JWST* Observations

Our analysis is based on some of the first *JWST*/NIRCam datasets that have been observed and released over extragalactic fields. In particular, we analyze the two Early Release Science programs GLASS and CEERS.



**Figure 1.** Summary of photometry and redshift solution for GL-z13. **Top:**  $4.5'' \times 4.5''$  images spanning  $\approx 0.9 - 4.5 \mu\text{m}$  centered on the  $z \approx 13$  candidate highlighted with white crosshairs. The source is well-detected ( $> 20\sigma$ ) in F200W and all redder bands, and abruptly drops out in the bluer filters. **Bottom left:** Photometry for the source is shown in purple, with upper limits for non-detections plotted at the  $1\text{-}\sigma$  level. The best-fit spectral energy distribution (SED) template from EAZY is shown in dark orange – a Lyman-break galaxy (LBG) at  $z = 12.4$ . The best-fit SED from EAZY constrained to lie at  $z < 6$  is plotted in silver, which corresponds to a quiescent galaxy at  $z \approx 3$  whose Balmer break produces a drop-off across F200W and F150W. However, such a quiescent galaxy is predicted to be easily detected ( $> 5\sigma$ ) in bluer bands, at odds with the dramatic  $> 2.5$  mag break observed. **Bottom right:** Probability distributions for the source redshift derived using EAZY (solid orange) and Prospector (dashed orange). We adopt a flat prior across the redshift range depicted ( $z = 0 - 20$ ). The derived distributions are in excellent agreement and suggest a redshift of  $z \approx 12.5 - 13.5$ , with no solutions found at  $z < 10$ .

The first is the NIRCcam parallel field of the ERS program GLASS (PID: 1324). This program obtained a single NIRCcam pointing in seven wide filters F090W, F115W, F150W, F200W, F277W, F356W, and F444W, observed for 3.3, 3.3, 1.7, 1.5, 1.5, 1.7, and 6.6 hrs, respectively.

We also analyzed the first four NIRCcam pointings from the ERS program CEERS (PID: 1345) that have been observed to date. The CEERS images include F115W+F277W, F115W+F356W, F150W+F410M, and F200W+F444W short- (SW) and long-wavelength (LW) exposure sets, for a typical integration time of 0.8 hr per filter, except for F115W that obtained double this integration time.

The combined area of these five NIRCcam fields used in our analysis amounts to  $49 \text{ arcmin}^2$  reaching an unprecedented  $5\sigma$  depth that ranges between 28.6 and 29.4 AB mag at  $4 \mu\text{m}$  as measured in  $0''.32$  diameter apertures (see Table 1).

## 2.2. Data Reduction

The JWST pipeline calibrated images up to level 2b were retrieved from the MAST archive and were

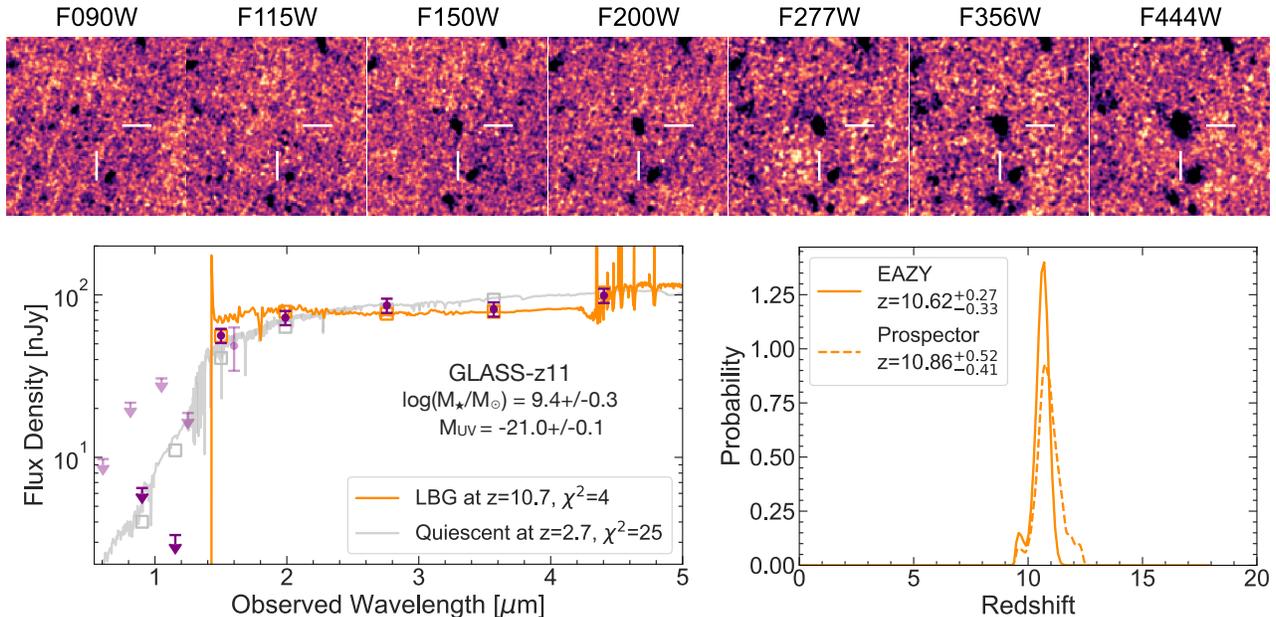
then processed with the `grizli`<sup>1</sup> pipeline (v1.5.1.dev65). This was used to properly align the images to a common WCS that was matched to the Gaia DR3 catalogs. To do this, `grizli` re-computes the traditional SIP distortion headers that were common for HST data. This allows us to use `astrodrizzle` as with HST images to combine the individual frames and produce distortion-corrected mosaics. Additionally, `grizli` mitigates the  $1/f$  noise and masks ‘snowballs’ that are most prominent in short-wavelength filters.

The pipeline was used to drizzle images at  $20\text{mas} / 40\text{mas}$  pixels for the SW and LW data, respectively. In the following, our analysis is based on pixel-matched  $40\text{mas}$  images, however. For more information on the `grizli` processing see Brammer et al., (in prep).

## 2.3. Multi-Wavelength Catalogs

After processing the new NIRCcam images, we produced photometric catalogs in all fields using the SExtractor software (Bertin & Arnouts 1996). Sources were detected in dual mode with two different detection images: F200W or a weighted combination of all

<sup>1</sup> <https://github.com/gbrammer/grizli/>



**Figure 2.** Summary of photometry and redshift solution for GL-z11, similar to Figure 1. **Top:** GL-z11 is well-detected in all but the two bluest bands. **Bottom left:** The best-fit low- $z$  solution (quiescent galaxy at  $z \approx 3$ ) is disfavored by the F115W image, where a  $> 5\sigma$  detection is expected. In addition to the JWST data (dark purple), we measure HST photometry (light purple) for this source from data acquired by the BUFFALO program (Steinhardt et al. 2020). The HST data are fully consistent with the JWST data as well as the best-fit SED. **Bottom right:** The EAZY and Prospector posteriors agree on a  $z \approx 11$  galaxy.

the LW filters. Fluxes were measured in small circular apertures of  $0''.32$  diameter and were corrected to total using the AUTO flux measurement from the detection image. An additional correction of typically a few percent only was applied for remaining flux outside of this aperture based on the predicted encircled energy for the JWST point-spread functions. Flux uncertainties were estimated based on sigma-clipped histograms of circular apertures placed throughout the images in random sky positions. These were then used to rescale the drizzled rms maps. Thus, our uncertainties are as close to the data as possible. The  $5\sigma$  depths derived in this way are listed in Table 1.

#### 2.4. Quality Control

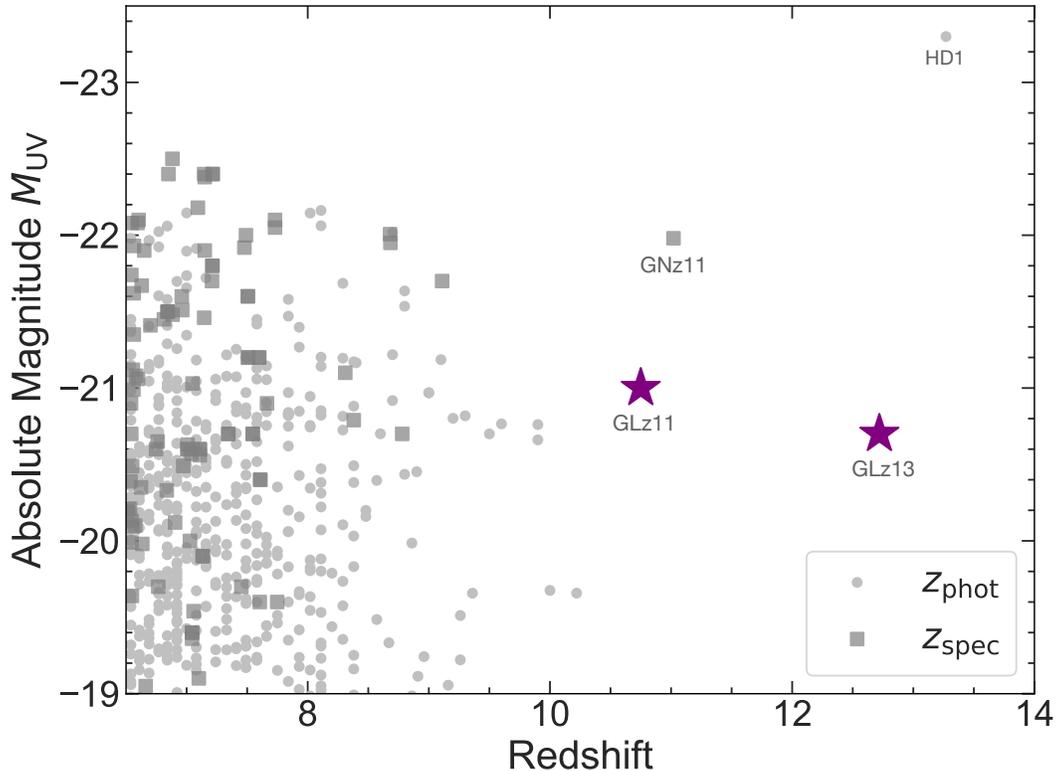
Given that JWST is a completely new facility for which calibration is still ongoing, it is important to test the resulting images for any issues. Indeed, the NIRCcam data revealed several features that are not accounted for in the standard pipeline. In particular, the SW data suffer from significant scattered light, if there are bright stars in the vicinity. This is particularly pronounced in the GLASS parallel field where a 10th mag star just outside of the field seems to cause artificial images across the field. This is particularly pronounced in the F090W filter in the B4 detector. However, also other detectors and filters seem to be effected, albeit to a lower extent. While this issue could be overcome with improved processing, or with additional observations at a different roll angle, this does not significantly affect the current anal-

ysis. Since we are looking for very high redshift galaxies that disappear at shorter wavelengths, these data issues only introduce some level of incompleteness. Most importantly, the areas of the two candidate sources presented later in this paper are not affected.

Where available, we compared our JWST photometry in the shorter wavelength filters with existing HST data to check both for issues with residual distortion or with magnitude zeropoint offsets. In particular, for the GLASS parallel field, we used HST images made available by Kokorev et al. (2022) from the BUFFALO survey (Steinhardt et al. 2020). However, only a small portion of the field is covered by both HST and JWST. For the CEERS data, we make use of re-reductions from the imaging taken by the CANDELS survey (e.g., Koekoemoer et al. 2012). No significant offsets or issues were detected. Zeropoint corrections remained small ( $< 15\%$ ; see next section).

### 3. SAMPLE SELECTION & METHODS

Photometric redshifts form the basis of our search for bright  $z > 10$  galaxies. We fit redshifts using EAZY (Brammer et al. 2008) adopting the “tweak\_fsps\_QSF\_12\_v3” template set derived from FSPS (Conroy et al. 2009, 2010; Conroy & Gunn 2010). The allowed range is  $0.1 < z < 20$  adopting a flat luminosity prior, after applying modest ( $< 15\%$ ) zero-point corrections that are derived iteratively. Candidates of interest are selected to have best-fit redshifts  $z > 10$  along with



**Figure 3.** Absolute UV magnitude vs. Redshift for a representative sample of known galaxies in the first billion years of the Universe. Galaxies with photometric redshifts, sourced from [Bouwens et al. \(2022\)](#), are shown as points, and those with spectroscopic redshifts compiled from the literature as squares. The candidates presented in this work are depicted as purple stars, and populate a hitherto unoccupied region of parameter space. The brightness of these sources present a unique opportunity to efficiently extend the spectroscopic frontier to the first few hundred Myrs after the Big Bang.

**Table 1.**  $5\sigma$  Depth of JWST Data in this Analysis

Band	GLASS-ERS	CEERS-ERS
<i>F090W</i>	28.9	...
<i>F115W</i>	28.9	28.6
<i>F150W</i>	28.7	28.5
<i>F200W</i>	28.9	28.8
<i>F277W</i>	29.0	28.9
<i>F356W</i>	29.0	28.9
<i>F410M</i>	...	28.2
<i>F444W</i>	29.4	28.6

NOTE—Measured in  $0''.32$  diameter circular apertures.

**Table 2.** Photometry in units of nJy

Band	GL-z11	GL-z13
<i>F090W</i>	$3 \pm 3$	$1 \pm 2$
<i>F115W</i>	$1 \pm 3$	$4 \pm 3$
<i>F150W</i>	$56 \pm 6$	$6 \pm 3$
<i>F200W</i>	$74 \pm 3$	$58 \pm 2$
<i>F277W</i>	$82 \pm 3$	$42 \pm 2$
<i>F356W</i>	$73 \pm 2$	$38 \pm 2$
<i>F444W</i>	$83 \pm 8$	$39 \pm 1$

NOTE—We set an error floor of 10% on our measured fluxes for **EAZY** and **Prospector** fits to account for systematic uncertainty not reflected in the errors stated above.

$> 84\%$  of their derived redshift probability distribution function,  $p(z)$ , lying at  $z > 10$ .

We further require  $> 10\sigma$  detections in both *F356W* and *F444W*. These bands sample the rest-frame UV at  $z > 10$  and are critical in establishing the flux levels with respect to which we seek strong Lyman breaks.

We inspect images of every candidate source for data quality issues (e.g., contamination from neighbors, diffraction spikes, location on the edge of the detector). In tandem, we examine plausible low- $z$  solutions

**Table 3.** Summary of properties.

	GL-z11	GL-z13
R.A.	+0:14:02.86	+0:13:59.76
Dec.	-30:22:18.7	-30:19:29.1
Redshift $z_{\text{Prospector}}$	$10.9^{+0.5}_{-0.4}$	$13.1^{+0.8}_{-0.7}$
Redshift $z_{\text{EAZY}}$	$10.6^{+0.3}_{-0.3}$	$12.4^{+0.2}_{-0.2}$
Stellar Mass $\log(M_*/M_\odot)$	$9.4^{+0.3}_{-0.3}$	$9.0^{+0.3}_{-0.4}$
UV Luminosity ( $M_{\text{UV}}$ )	$-21.0^{+0.1}_{-0.1}$	$-20.7^{+0.1}_{-0.1}$
UV Slope ( $\beta$ ; $f_\lambda \propto \lambda^\beta$ )	$-2.1^{+0.1}_{-0.1}$	$-2.3^{+0.1}_{-0.1}$
Age ( $t_{50}/\text{Myr}$ )	$111^{+43}_{-54}$	$71^{+32}_{-33}$
SFR <sub>50 Myr</sub> ( $M_\odot/\text{yr}$ )	$12^{+9}_{-4}$	$7^{+4}_{-3}$
$r_{\text{eff}}$ [kpc]	0.7	0.5
Sersic Index $n$	0.8	1.0

NOTE—SED fitting assumes a continuity prior on the star-formation history and a Chabrier (2003) IMF.

for the candidates by running EAZY constrained to  $z < 6$  (primarily dusty, quiescent galaxies with Balmer breaks masquerading as Lyman breaks). We inspect low- $z$  solutions with the understanding that the errors on fluxes in the dropout band may be underestimated in some cases (in e.g., image areas with residual striping), which can have an important impact on the  $p(z)$ . For instance, we find one bright source in CEERS with a confident  $z_{\text{EAZY}} \approx 17$  and  $z_{\text{Prospector}} \approx 17$  whose  $z > 10$  solution assumes a secure non-detection in F150W – unfortunately, the source falls in a low-SNR region of the F150W image and it is difficult to judge the reality of the non-detection.

We find 5 plausible  $z > 10$  candidates that survive all our conservative checks – 3 in CEERS, and 2 in GLASS. Of these, the two identified in GLASS – GL-z11 ( $z_{\text{EAZY}} = 10.6^{+0.3}_{-0.3}$ ) and GL-z13 ( $z_{\text{EAZY}} = 12.4^{+0.2}_{-0.2}$ ) – stand out as being particularly luminous and secure. No other objects have a  $p(z)$  with all modes contained at  $z > 10$  such that  $p(z > 10) \approx 100\%$ . Further, the GLASS candidates are among the most luminous found – GL-z11, in particular, is by far the brightest of all sources (by  $> 2\times$  in F444W). For the rest of this work, we focus on these two particularly luminous candidates and we defer the rest of the sources to future papers that present an analysis of the full  $z > 10$  galaxy population in these fields.

## 4. RESULTS

### 4.1. Two Luminous $z > 10$ Galaxy Candidates

We confirm the photometric redshifts for the two GLASS candidates and derive stellar population properties using the Prospector SED fitting code (Leja et al. 2017, 2019; Johnson et al. 2021). The SED parameter space explored by Prospector is more expansive than EAZY’s linear template combinations, and therefore it

acts as an important check on our derived redshifts. We use FSPS (Conroy et al. 2009, 2010; Conroy & Gunn 2010) with the MIST stellar models (Choi et al. 2017). We adopt the 19-parameter physical model and parameter choices described in Tacchella et al. (2022) that fits for the redshift, stellar and gas-phase metallicities, stellar mass, star-formation history, dust properties, AGN emission, and scaling of the IGM attenuation curve. We make slight modifications to their setup – in particular we explore a broader redshift range of  $z = 0.1 - 20$  and keep two bins fixed at lookback times of 0 – 5 Myr and 5 – 10 Myrs in the star-formation history following Whittler et al. (2022) to capture recent bursts that may be powering extreme nebular emission expected to occur generically at the redshifts of interest (e.g., Labbé et al. 2013; De Barros et al. 2019; Endsley et al. 2019). We adopt a “continuity” prior on the star-formation history, which limits the amount of variance across consecutive time-bins resulting in smooth histories (Leja et al. 2019; Tacchella et al. 2022). For further details we direct readers to Table 1 and §3.4 of Tacchella et al. (2022).

The redshift fits from Prospector are in excellent agreement with EAZY – we find  $z_{\text{Prospector}} = 10.9^{+0.5}_{-0.4}$  for GL-z11 and  $z_{\text{Prospector}} = 13.1^{+0.8}_{-0.7}$  for GL-z13. The photometry and redshift inference for these sources are summarized in Figures 1 and 2, with fluxes listed in Table 2. We confirm that no significant data quality issues affects the  $z > 10$  candidacy of the sources in the imaging. We derive  $p(z > 10) \approx 100\%$  for both sources, with their dramatic  $\gtrsim 2.5$  mag breaks explained by total absorption of photons bluewards of Lyman- $\alpha$  by neutral Hydrogen in the intergalactic medium.

Both galaxies are detected at very high significance in all filters longward of their break, by virtue of our selection. While they appear very luminous in the JWST data, these sources have UV absolute magnitudes ( $M_{\text{UV}} = -21$ ) that correspond to  $L_{\text{UV}}^*$  at  $z \sim 8-10$  (see, e.g., Bouwens et al. 2021). This also makes them 1 mag fainter than GN-z11 and even 2.5 mag fainter than the possible  $z \sim 13$  galaxy candidate HD1 (Harikane et al. 2022). Hence, these sources are not really extreme outliers (see also Fig. 3). Nevertheless, it is interesting that the first few images with JWST already reveal two such bright sources. We will discuss their implications on the UV LF in a later section.

### 4.2. Possible Lower Redshift Contamination

The non-detections of both sources in deep, shorter wavelength images essentially rules out a lower redshift solution. Nevertheless, it is interesting to explore the nature of possible contaminants. We thus rerun our photometric redshift codes and force them to find lower redshift fits. The best  $z < 6$  solutions in our low- $z$  EAZY runs for these sources are  $\approx 10^{8-9} M_\odot$  quiescent galaxies at  $z \approx 3.4$  ( $z \approx 2.7$ ) with Balmer breaks straddling the dropout filter (silver SEDs in Figs. 1, 2). However note that Balmer breaks, even in the most pathological cases

(e.g.,  $4000\text{\AA}$  falls just redward of the dropout filter in a super-solar galaxy as old as the age of the Universe at  $z \approx 2 - 3.5$ ), can only produce drops of  $\lesssim 1.5$  mag. In other words, the best-fit low- $z$  solutions predict  $> 5\sigma$  detections in bands where we find no flux.

In order to allow for possible systematic effects in the new JWST data, we perform further testing. We re-fit redshifts to multiple versions of photometry for these sources – e.g., by adding PSF corrections using `WebbPSF`, by increasing the error floor on the photometry, by extracting photometry using different apertures and detection bands. The only test that produces viable low- $z$  solutions is when we set a 10 nJy error-floor on all photometry – this is roughly the level in the SW filters at which the strongest Balmer breaks at  $z \approx 2 - 3$  can no longer be ruled out (see open silver squares in bottom-left panels of Figures 1 and 2). This test is a vivid demonstration of why the sensitivity of JWST/NIRCam is required to identify objects like GL-z11 and GL-z13 with confidence.

#### 4.3. Physical Properties – Billion $M_{\odot}$ Galaxies within $\approx 400$ Myrs of the Big Bang

While the discovery of GN-z11 has already demonstrated that the formation of billion solar mass galaxies was well underway at  $\sim 400$  Myr after the Big Bang, the discovery of these two new sources allows us to derive further constraints on the physical properties of galaxies at this very early epoch of the Universe. The `Prospector` results are summarized in Table 3. In order to efficiently sample the redshift range of interest, we assume a tighter redshift prior (a Gaussian centred on the EAZY  $p(z)$  with width set to the 84<sup>th</sup> - 16<sup>th</sup> percentile) than in our previous runs when fitting for the redshift.

The stellar mass for both objects is constrained to be  $\approx 10^9 M_{\odot}$ , comparable to GNz11 (Oesch et al. 2016; Johnson et al. 2021; Tacchella et al. 2022). We have verified the stellar mass is stable to changes in the star-formation history prior by also testing the “bursty” prior from Tacchella et al. (2022) which allows more rapid fluctuations in the SFH from time-bin to time-bin than the fiducial model. The star-formation rates averaged over the last 50 Myrs ( $\text{SFR}_{50}$ ) are typical for galaxies of comparable mass at  $z \approx 7 - 10$  (e.g., Stefanon et al. 2022a). The SEDs are consistent with negligible dust attenuation and have blue UV slopes,  $\beta < -2$ . We note that all these derived properties from the SED fits are collectively consistent with a  $z > 10$  interpretation for these galaxies.

#### 4.4. The Sizes of Luminous $z \sim 11 - 13$ Galaxies

We fit the sizes of both candidates in the F444W imaging ( $\lambda_{\text{rest}} \sim 3100 - 3800\text{\AA}$ ) using `GALFIT` (Peng et al. 2010). We create 100-pixel cutouts around each galaxy, then use `photutils` and `astropy` to create a segmentation map to identify nearby galaxies. We simultaneously fit any sources with magnitudes (estimated from the seg-

mentation map) up to 2.5 magnitudes fainter than the target galaxy that have centers within  $3''$  of the galaxy; we mask fainter or more distant galaxies. In our fits, we constrain the center of the target galaxy to be within 10 pixels ( $0''.4$ ) of the input value, the sersic index  $n$  to be between 0.01 and 8, the magnitude to be between 0 and 45, and the half-light radius  $r_e$  to be between 0.3 and 200 pixels ( $0''.012 - 8''.0$ ). We calculate and subtract off a scalar sky background correction from each cutout, estimated from the masked, sigma-clipped cutout, then fix the sky background component in `GALFIT` to zero. We use a theoretical PSF model generated from `WebbPSF` at our  $0''.04$  pixel scale; we oversample the PSF by a factor of 9 in order to minimize artifacts as we rotate the PSF to the GLASS observation angle calculated from the APT file, then convolve with a  $9 \times 9$  pixel square kernel and downsample to the mosaic resolution.

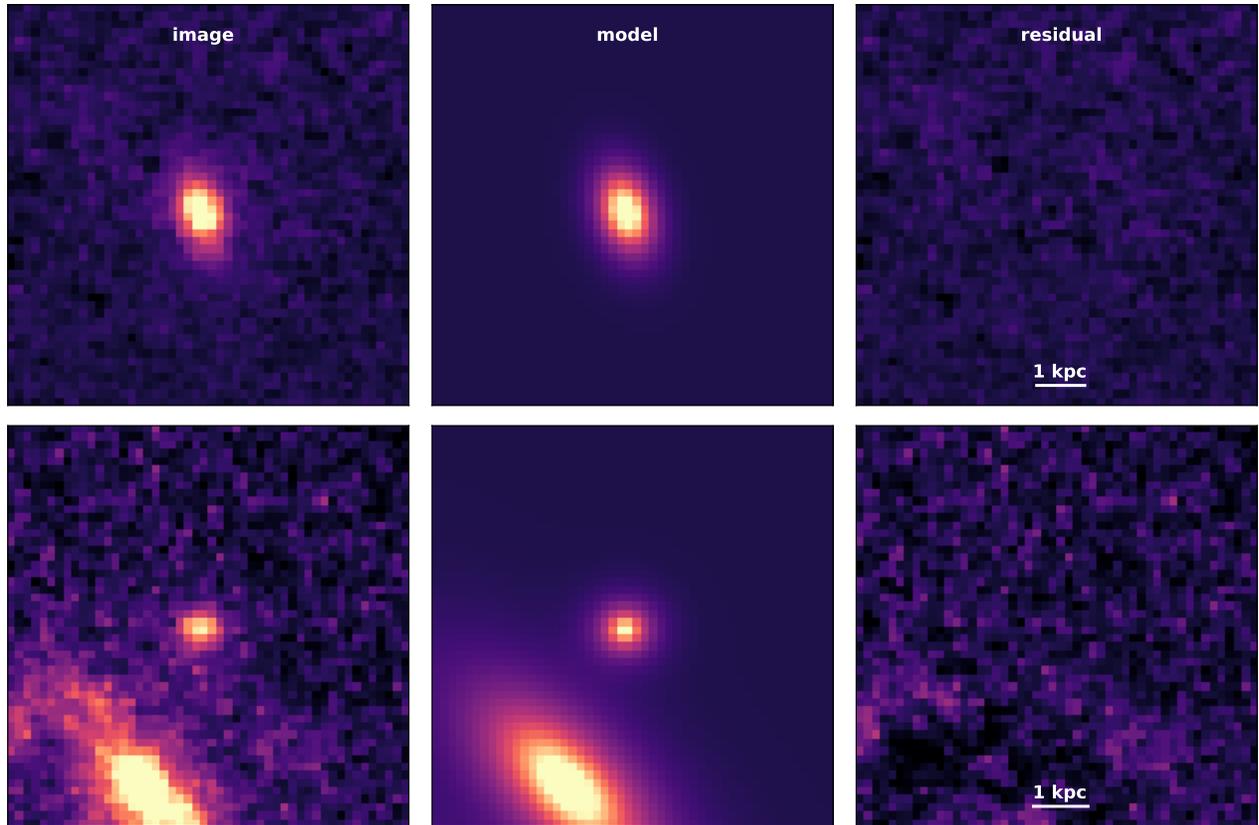
We find reliable Sersic fits for both galaxies, with half-light radii of 0.5 and 0.7 kpc, respectively, and disk-like profiles ( $n = 1$  and  $n = 0.8$ , respectively). The models are shown in Fig. 4, and the size and Sersic profile estimates are listed in Table 3.

The resulting sizes of 0.5 and 0.7 kpc are typical for luminous  $L^*$  galaxies at  $z \sim 6 - 9$ , where measurements have been possible to date (e.g., Holwerda et al. 2015; Shibuya et al. 2015; Bowler et al. 2017; Kawamata et al. 2018; Yang et al. 2022). They are also consistent with expectations from simulations for  $z > 9$  galaxies (e.g., Roper et al. 2022; Marshall et al. 2022). However, at  $z \sim 7$ , the most luminous sources often break up in multiple clumps (Bowler et al. 2017). This is not the case for these two sources, at least down to the resolution limit of order 500 pc for the F444W bandpass. Interestingly, GL-z11 even shows tantalizing evidence for being an ordered disk galaxy at  $z \sim 11$ , based on the exponential light profile and elliptical morphology. If we interpret GLz11’s projected axis ratio of 0.65 using a sample of randomly oriented axisymmetric oblate rotators (following e.g., Holden et al. 2012, Chang et al. 2013, van der Wel et al. 2014) and adopt  $c/a \leq 0.4$  as a threshold for disks, we find that the observed axis ratio implies  $P(\text{disk}) \sim 0.5$ . Our analysis shows the unparalleled power of JWST to provide accurate profile measurements of early Universe galaxies.

## 5. DISCUSSION

### 5.1. Caveats

The key caveat, as well as the key animating spirit of this work, is that these data are among the first deep extragalactic fields collected by a new Great Observatory. Systematic uncertainties (e.g., zero-point corrections, treatment of artefacts) can still be significant. We have tested for zero-point offsets by comparing HST and JWST photometry for brighter sources where possible and have not found any major issues at the  $\lesssim 10\%$  level. Nevertheless, we have attempted to account for remaining uncertainties with conservative choices – e.g., a 10%



**Figure 4.** Results of the `GALFIT` morphology analysis for our two sources (GL-z11 top and GL-z13 bottom). The different columns from left to right correspond to the original data (in the F444W filter), the model, and the residual. The sizes and Sersic profiles of both sources are well constrained. GL-z11 shows some clear extension, consistent with a disk galaxy of 0.7 kpc at  $z \sim 11$ . GL-z13 appears quite compact with an estimated size of 0.5 kpc.

error floor on all fluxes and focusing on bright galaxies whose  $> 2$  mag breaks are robust to even major uncertainties.

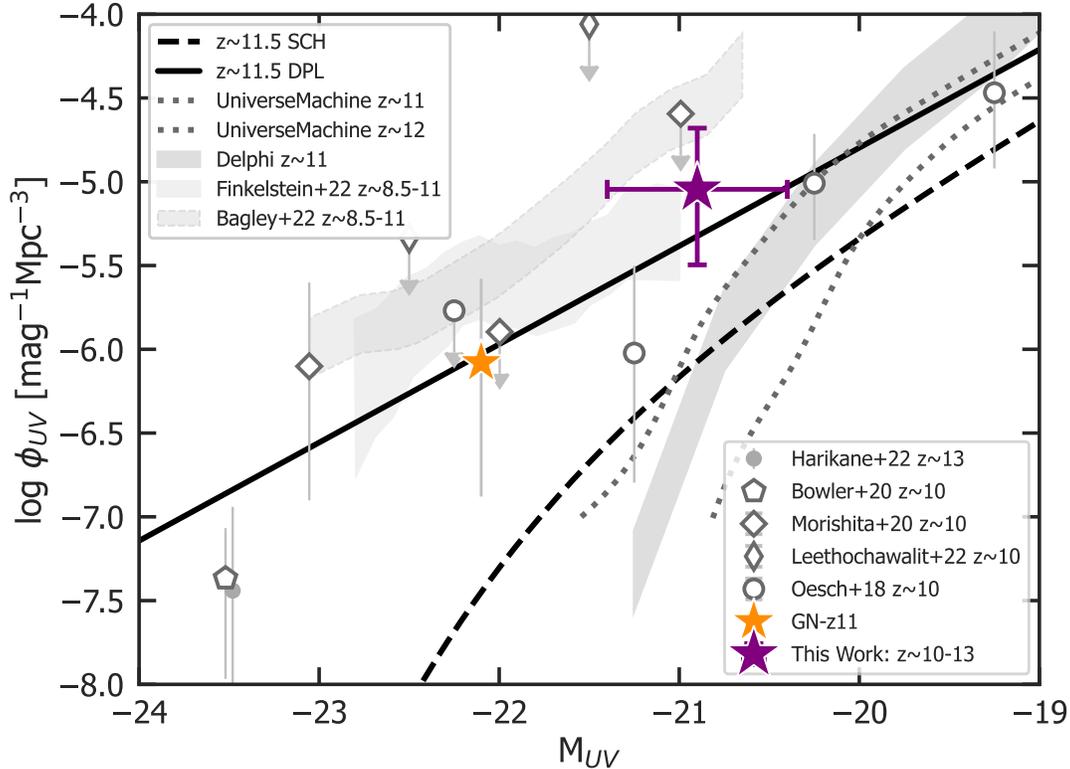
A next caveat applies to the SED models underpinning the stellar population parameters and photo- $z$  fitting. Important details about the nebular emission and nature of massive stars at low metallicities, which dominate the light in these few hundred Myr old star-forming systems, remain unconstrained (e.g., [Stanway et al. 2020](#)). This uncertainty directly translates to the parameters we recover from SED fitting and the sources for which we are able to fit high quality redshifts. Fortunately, for our redshift range of interest, extreme nebular emission from strong rest-frame optical lines is shifted out of all NIRCcam bands and the most important feature for the photo- $z$ s in the bright galaxies we study is the Lyman break.

### 5.2. Implication: The Number Density of Luminous Galaxies in the Early Universe

These two galaxies enable a first estimate of the number densities of relatively luminous sources at  $z = 10 - 13$ . Given the large uncertainties in redshift, we conservatively estimate a selection volume across this full

redshift range, i.e.,  $\Delta z = 3$ . Given that the depth of all the fields we studied is far deeper than the bright magnitude of these two sources, these galaxies would have been identified over the full area, without foreground galaxies. This amounts to a volume of  $2.2 \times 10^5 \text{ Mpc}^3$ . The detection of two galaxies with  $M_{\text{UV}} = -21$  thus results in an estimated UV LF point of  $\log \phi [\text{Mpc}^{-3} \text{mag}^{-1}] = -5.05^{+0.37}_{-0.45}$ .

In Figure 5, we compare this estimate with previous UV LF determinations and with extrapolations from lower redshifts. In particular, we show that an extrapolation of the Schechter function trends estimated at  $z = 3 - 10$  results in an LF at  $M_{\text{UV}} = -21$  that is a factor  $> 10\times$  lower than our estimate. Interestingly, however, when extrapolating the trends in the double-power law LFs from [Bowler et al. \(2020\)](#) to  $z \sim 11.5$  (the mean redshift of our sources), we find relatively good agreement. In fact, GN-z11 also lies on this extrapolated LF. However, this would indicate very little evolution in the bright galaxy population at  $z > 8$ . Indeed, our estimate is in good agreement with previous  $z \sim 10$  UV LF determinations and constraints at the bright end from [Oesch et al. \(2018\)](#); [Bouwens et al. \(2019\)](#); [Stefanon et al.](#)



**Figure 5.** Constraints on the bright end of the UV LF at  $z \sim 10 - 13$ . The current JWST data allow us to derive a first estimate of the number density of galaxies with  $M_{UV} \sim -21$  at these redshifts (purple star). While this estimate lies a factor  $\sim 10\times$  above the extrapolation of Schechter function constraints to  $z = 11.5$  from Bouwens et al. (2021, dashed black line), they are in very good agreement with extrapolated double-power law LFs from Bowler et al. (2020, black solid line). In fact, GN-z11 (orange star) is also consistent with the double-power law LF. Other LF estimates and upper limits at  $z \sim 10$  are shown as open symbols (see legend for references). Simulated predictions are shown from the UniverseMachine models at  $z \sim 11$  and  $z \sim 12$  (dotted lines) and from the Delphi model at  $z \sim 11$  (darker grey shaded region).

(2019); Morishita et al. (2020); Finkelstein et al. (2022); Bagley et al. (2022); Leethochawalit et al. (2022).

Finally, we also briefly compare our estimates with simulated LFs from the UniverseMachine model (Behroozi et al. 2019) and from the Delphi model (Dayal et al. 2014, 2022). While our estimate is in rough agreement with these prediction at  $z \sim 11$ , the model LFs evolve very rapidly at these early times, such that the  $z \sim 12$  LF is already  $> 30\times$  below our estimate. This is a general trend of model predictions: a relatively rapid evolution of the LF at  $z > 10$ , driven by the underlying evolution of the dark matter halo mass function (see also Oesch et al. 2018; Bouwens et al. 2021). However, the handful of bright galaxies that have been found at  $z \sim 10 - 13$  to date appear to oppose this trend. It is still unclear what the physical reason for this might be. Evidence is mounting that the star-formation efficiency in the early Universe may be very high in a few sources, thus resulting in the early appearance of UV-luminous galaxies with stellar masses as high as  $10^9 M_{\odot}$  already a few hundred Myr after the Big Bang. Wider area datasets will be required to increase the search volume,

for more reliable constraints on the number densities of luminous sources.

## 6. SUMMARY & OUTLOOK

This paper presented a search for luminous  $z > 10$  galaxies across the two JWST Early Release Science programs in extragalactic fields. We find the following –

- We identify two particularly luminous sources in the GLASS ERS program. These sources, GL-z11 and GL-z13, have continuum magnitudes of  $\sim 27$  at  $2 \mu\text{m}$  and display dramatic  $> 2$  mag breaks in their SEDs that are best fit as Lyman breaks occurring at redshifts of  $z \approx 11$  and  $z \approx 13$  respectively. [Fig. 1, Fig. 2, §4.1]
- SED modeling of these sources shows they have properties (e.g.,  $\beta$  slopes, specific star-formation rates) expected of  $z > 10$  galaxies. These systems are a billion solar mass galaxies, having built up their mass only  $< 300 - 400$  Myrs after the Big Bang. [Table 3, §4.3]

- The brightness of these objects present a unique opportunity for detailed spectroscopic and morphological follow-up at  $z > 10$ . As a demonstration, we model the morphology of both galaxies finding that they are well-described by disk-like profiles with small sizes (half-light radii  $\sim 0.6$  kpc). GL-z11, in particular, shows an extended exponential light profile, that may be tantalizing evidence for a disk already in place at  $z \approx 11$ . [Fig. 4, §4.4]
- These two objects already place novel constraints on galaxy evolution in the cosmic dawn epoch. They indicate that the discovery of GNz11 was not simply a matter of good fortune, but that there is likely a population of UV luminous sources with very high star-formation efficiencies capable of compiling  $> 10^9 M_\odot$  at  $z > 10$ . [Fig. 3, §5.2]
- The inferred number-density of  $M_{UV} \approx -21$  sources from our search ( $\log \phi [\text{Mpc}^{-3} \text{mag}^{-1}] = -5.05^{+0.37}_{-0.45}$ ) strongly supports a significant deviation from the Schechter UV luminosity function at the bright end, and is consistent with the double-power law evolution reported at lower redshifts. The physical mechanisms driving this departure are yet to be definitively established. These lumi-

nous sources highly conducive to NIRSpec spectroscopy may hold the key. [Fig. 5, §5.2]

If these candidates are confirmed spectroscopically, and indeed two  $z \approx 11 - 13$  candidates lie awaiting discovery in every  $\sim 50$  arcmin<sup>2</sup> extragalactic field, it is clear that JWST will prove highly successful in pushing the cosmic frontier all the way to the brink of the Big Bang.

*Facilities:* JWST, HST

*Software:* IPython (Pérez & Granger 2007), matplotlib (Hunter 2007), numpy (Oliphant 2015), scipy (Virtanen et al. 2020), jupyter (Kluyver et al. 2016), Astropy (Astropy Collaboration et al. 2013, 2018)

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