High-Redshift Galaxy Candidates at $z = 9 - 13$ as Revealed by JWST Observations of WHL0137-08

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ABSTRACT

The James Webb Space Telescope (JWST) was designed to peer into the distant universe and study galaxies nearer the beginning of time than previously. Here we report the discovery of 12 galaxy candidates observed 300 – 600 Myr after the Big Bang with photometric redshifts between $z \sim 8.5 - 13$ measured using JWST NIRCam imaging of the galaxy cluster WHL0137-08 observed in 8 filters span-
ning 0.8–5.0 μm, plus 9 HST filters spanning 0.4–1.7 μm. Three of these candidates are gravitationally lensed by the foreground galaxy cluster and have magnifications of μ ~ 3 – 8. The remaining nine candidates are located in a second JWST NIRCam module, centered ~ 2′9 from the cluster center, with expected magnifications of μ < 1.1. Our sample of high-redshift candidates have observed F200W AB magnitudes between 25.9 and 28.1 mag and intrinsic F200W AB magnitudes between 26.4 and 29.7 mag (M_{UV} = −22.5 to −17). We find the stellar masses of these galaxies are in the range log M_*/M_{\odot} = 8 – 9, and down to 7.5 for the lensed galaxies. All are young with mass-weighted ages < 100 Myr, low dust content A_V < 0.15 mag, and high specific star formation rates sSFR ~ 10 – 50 Gyr^{−1} for most. One z ~ 9 candidate is consistent with an age < 5 Myr and a sSFR ~ 250 Gyr^{−1}, as inferred from a strong F444W excess, implying [O III] +Hβ rest-frame equivalent width ~2000 Å, although an older and redder z ~ 10 object is also allowed. Another z ~ 9 candidate WHL0137–ID9356 is lensed into an arc 2′6 long by the effects of strong gravitational lensing (μ ~ 8), and has at least two bright knots of unevenly distributed star formation. This arc is the most spatially-resolved galaxy at z ~ 9 known to date, revealing structures ~30 pc across. Follow-up spectroscopy of WHL0137–08 with JWST/NIRSpec is planned for later this year, which will validate some of these candidates and study their physical properties in more detail.

Keywords: Galaxies (573), High-redshift galaxies (734), Strong gravitational lensing (1643), Galaxy clusters (584)

1. INTRODUCTION

The James Webb Space Telescope (JWST), with its 6.5m aperture and infrared capabilities (Rigby et al. 2022), has opened a new window to study galaxies in the early universe. In the first weeks of JWST science observation, a wealth of distant galaxy candidates (Naidu et al. 2022a; Donnan et al. 2022; Finkelstein et al. 2022; Atek et al. 2022; Castellano et al. 2022; Adams et al. 2022; Harikane et al. 2022; Yan et al. 2022) have already been reported from the JWST Early Release Observations (ERO; Pontoppidan et al. 2022) and the Cosmic Evolution Early Release Science (CEERS) (Finkelstein et al. 2017) and Through the Looking GLASS (GLASS-JWST) (Treu et al. 2022) Early Release Science (ERS) programs that surpass the distance record set by the Hubble Space Telescope (HST) at z = 11.1 (Oesch et al. 2016). These independent studies have revealed an unexpectedly large abundance of bright galaxies (M_{UV} < −21; e.g., Finkelstein et al. 2022; Atek et al. 2022; Furtak et al. 2022; Naidu et al. 2022a) that could pose a challenge to our current models of galaxy formation (Ferrara et al. 2022; Harikane et al. 2022; Naidu et al. 2022b). Similarly, some z ~ 7 – 11 candidates were reported to have surprisingly large stellar masses M_* > 10^{10} M_{\odot} (Labbe et al. 2022) in apparent tension with ΛCDM (Boylan-Kolchin 2022; Lovell et al. 2022) unless these galaxies have lower masses (Endsley et al. 2022; Steinhardt et al. 2022) or incorrect redshifts.

Simulations suggest we should not have expected to find overly massive galaxies in early JWST observations, but rather that we have likely only discovered the youngest, most actively star forming galaxies given imaging depths to date of AB mag ~29 (Mason et al. 2022). Analyses of these z ~ 9 – 16 candidates observed in JWST imaging further reveal young stellar ages ~ 10–100 Myr (Whitler et al. 2022; Furtak et al. 2022), younger than the median ages ~ 100 Myr measured at slightly lower redshifts z ~ 7 – 9 (Leethochawalit et al. 2022; Endsley et al. 2022). Evidence that some of these galaxies are extremely young, < 10 Myr, z ~ 7 – 9 is provided by very strong emission lines in NIRSpec spectroscopy (Carnall et al. 2022; Tacchella et al. 2022; Trusler et al. 2022), with flux excesses also clearly observed in photometry, especially when imaging is available in four NIRCam long-wavelength filters F277W, F356W, F410M, and F444W.

Gravitational lensing by massive galaxy clusters can address these problems in some detail as it provides magnified distant galaxies, boosting their luminosity and revealing small-scale structures that would otherwise be unobservable. Using these “cosmic telescopes”, surveys such as CLASH (Postman et al. 2012), the Hubble Frontier Fields (Lotz et al. 2017), and RELICS (Coe et al. 2019) have revealed hundreds of galaxy candidates in the reionization epoch. Using this technique, we have discovered highly magnified (Bradley et al. 2008; Zheng et al. 2012; Hoag et al. 2017; Bouwens et al. 2012).
Gravitational lensing has also provided us the ability to study small-scale structures and star clusters within high-redshift galaxies down to scales of a few parsec (e.g., Welch et al. 2022a; Vanzella et al. 2022; Meštrić et al. 2022). The Reionization Lensing Cluster Survey (RELICS) HST Treasury Program (Coe et al. 2019) was designed to efficiently discover high-redshift galaxy candidates bright enough for follow-up observations with current and future observatories, including the Atacama Large Millimeter/submillimeter Array (ALMA) and JWST. By observing 41 strong lensing galaxy clusters with Hubble and Spitzer, RELICS discovered and studied over 300 high-redshift candidates in the first billion years (Salmon et al. 2020; Strait et al. 2021), including the brightest robust candidates known at z ~ 6, the Sunrise Arc, a 2′5 long arc at z ~ 6 (Salmon et al. 2020), and the most distant spatially-resolved lensed arc, SPT0615-JD1, at z ~ 10 (Salmon et al. 2018). Remarkably, the RELICS survey also discovered the gravitationally lensed star WHL0137-LS, nicknamed Earendel, with a photometric redshift z\textsubscript{phot} = 6.2 ± 0.1 (Welch et al. 2022b).

Earendel was discovered within the z ~ 6 Sunrise Arc (Welch et al. 2022a) lensed by the massive galaxy cluster WHL J013719.8−082841 (hereafter WHL0137−08; RA = 01:37:25.0, Dec = −08:28:23, J2000), which is the focus of this paper. WHL0137−08 was discovered by Wen et al. (2012) based on photometric redshifts in SDSS-III DR8 (Aihara et al. 2011) and has a spectroscopic redshift of z = 0.566 based on two cluster members within r500 = 0.82 Mpc from its brightest cluster galaxy (Wen & Han 2015). The Planck SZ survey also identified this cluster (WHL-J24.3324-8.477) as the 31st most massive in the Planck PSZ2 catalog with M\textsubscript{500} = (8.9±0.7)×10\textsuperscript{14} M\textsubscript{\odot} (Planck Collaboration et al. 2016).

In this paper, we present high-redshift candidates at z ~ 8.5 − 13 discovered in JWST NIRCam imaging of WHL0137−08, obtained primarily to study Earendel (Welch et al. 2022c) and the Sunrise Arc in more detail. Our sample includes both strongly-lensed galaxy candidates discovered behind the cluster and candidates in the nearby NIRCam module, centered ~ 2′9 from the cluster center, with weak magnifications of μ ≤ 1.1. We use the AB magnitude system, m\textsubscript{AB} = 31.4 − 2.5\log(f\nu/nJy) (Oke 1974; Oke & Gunn 1983). Where needed, we adopt a Planck 2018 flat ΛCDM cosmology (Planck Collaboration et al. 2020) with H\textsubscript{0} = 67.7 km s\textsuperscript{-1} Mpc\textsuperscript{-1}, Ω\textsubscript{m} = 0.31, and Ω\textsubscript{\Lambda} = 0.69, for which the universe is 13.8 billion years old and 1″ ~ 4.6 kpc at z = 9.

All of the JWST and HST data of WHL0137−08 are public. Reduced images, catalogs, lens models, and analysis code are available via our website.\footnote{https://cosmic-spring.github.io}

2. OBSERVATIONS

2.1. JWST Data

We obtained JWST NIRCam imaging of WHL0137−08 (GO 2282, PI Coe) in July 2022 as part of a program to further study Earendel and the Sunrise Arc. The NIRCam observations cover eight filters (F090W, F115W, F150W, F200W, F277W, F356W, F410M, and F444W) spanning 0.8 − 5.0 μm with 2104 s of exposure time in each filter. Each exposure uses the SHALLOW5 readout pattern with ten groups and one integration. We use the INTRAMODULEBOX dither pattern with four dithers to fill the 5′′ gaps in the short wavelength detectors and to maximize the area with full exposure time. The dither pattern also mitigates the effects of bad pixels and image artifacts and also improves the spatial resolution of the resampled/drizzled images. The NIRCam imaging was obtained over two 2′26 × 2′26 fields separated by 40.5″, covering 10.2 arcmin\textsuperscript{2} in total. The WHL0137−08 cluster was centered on NIRCam module B while NIRCam module A obtained observa-
Figure 1. JWST NIRCam color image (using all eight filters) of the WHL0137−08 cluster field. The locations of the three (of 12 total) strongly lensed high-redshift candidates in the WHL0137−08 cluster field are indicated with red circles or ellipses. The locations of the other nine high-redshift candidates are shown in Figure 2.

2.2. HST Data

The RELICS HST Treasury program (GO 14096; Coe et al. 2019) obtained the first HST imaging of the galaxy cluster WHL0137−08 in 2016 with three orbits of ACS (F435W, F606W, and F814W) and two orbits of WFC3/IR (F105W, F125W, F140W, and F160W) data spanning 0.4−5.0 μm. Two follow-up HST imaging programs (GO 15842 and GO 16668; PI: Coe) have thus far obtained an additional 5 orbits of HST ACS imaging in F814W, 2 orbits in F475W, and 4 orbits with WFC3/IR in F110W. Two more orbits of WFC3/IR F110W data are yet to be obtained from the Earendel monitoring program (GO 16668). The HST data cover only the cluster field.

In total, the JWST and HST observations of WHL0137−08 include imaging in 17 filters spanning 0.4−5.0 μm. We show color images of the JWST data in Figures 1 and 2. The observations are summarized in Table 1.
Figure 2. *JWST* NIRCam color image (using all eight filters) of the nearby field (NIRCam A module), centered \( \sim 2'9 \) from the WHL0137–08 cluster center. The locations of the nine (of 12 total) high-redshift candidates in this field are indicated with red circles. The locations of the other three high-redshift candidates are shown in Figure 1.

3. METHODS

3.1. Data Reduction

We retrieved the *HST* FLT data and the *JWST* pipeline-calibrated level-2 imaging products and processed them using the GRIZLI pipeline (Brammer et al. 2022). The *JWST* data were processed with version 1.5.3 of the calibration pipeline with CRDS context `jwst_0942.pmap`, which includes photometric calibrations based on in-flight data. The *JWST* level-2 data were subsequently scaled with detector-dependent factors based on a NIRCam flux calibration using the flux calibration standard star J1743045. While calibration of *JWST* instruments is still ongoing, our updated photometric zeropoints are similar to those derived by other teams analyzing the M92 globular cluster data obtained from the *JWST* Resolved Stellar Populations ERS program (Boyer et al. 2022; Nardiello et al. 2022). A more recent calibration based on CAL program data.

\(^2\) [https://zenodo.org/record/7143382](https://zenodo.org/record/7143382)
Table 1. HST and JWST Observations, Exposure Times, and Depths

| Camera       | Filter  | Wavelength (µm) | Observation Date | Exposure Time (s) | $m_{\text{lim}}^a$ (AB) | $f_{\text{lim}}^b$ (nJy) |
|--------------|---------|----------------|------------------|------------------|------------------------|------------------------|
| HST ACS/WFC  | F435W   | 0.37–0.47      | 2016 Jun         | 2072             | 27.7                   | 30.2                   |
| HST ACS/WFC  | F475W   | 0.4–0.55       | 2019 Nov         | 3988             | 28.5                   | 14.5                   |
| HST ACS/WFC  | F606W   | 0.47–0.7       | 2016 Jul         | 2072             | 28.3                   | 17.4                   |
| HST ACS/WFC  | F814W   | 0.7–0.95       | 2016 Jun; 2019 Nov–Dec | 13326       | 28.7                   | 12.0                   |
| HST WFC3/IR  | F105W   | 0.9–1.2        | 2016 Jun–Jul     | 1411             | 27.8                   | 27.5                   |
| HST WFC3/IR  | F110W   | 0.9–1.4        | 2019 Nov; 2021 Nov; 2022 Jan | 10047       | 29.1                   | 8.3                    |
| HST WFC3/IR  | F125W   | 1.1–1.4        | 2016 Jun–Jul     | 711              | 27.3                   | 43.7                   |
| HST WFC3/IR  | F140W   | 1.2–1.6        | 2016 Jun–Jul     | 711              | 27.4                   | 39.8                   |
| HST WFC3/IR  | F160W   | 1.4–1.7        | 2016 Jun–Jul     | 1961             | 27.8                   | 27.5                   |
| JWST NIRCam  | F090W   | 0.8–1.0        | 2022 Jul         | 2104             | 28.3                   | 17.4                   |
| JWST NIRCam  | F115W   | 1.0–1.3        | 2022 Jul         | 2104             | 28.4                   | 15.8                   |
| JWST NIRCam  | F150W   | 1.3–1.7        | 2022 Jul         | 2104             | 28.5                   | 14.5                   |
| JWST NIRCam  | F200W   | 1.7–2.2        | 2022 Jul         | 2104             | 28.7                   | 12.0                   |
| JWST NIRCam  | F277W   | 2.4–3.1        | 2022 Jul         | 2104             | 29.1                   | 8.3                    |
| JWST NIRCam  | F355W   | 3.1–4.0        | 2022 Jul         | 2104             | 29.3                   | 6.9                    |
| JWST NIRCam  | F410M   | 3.8–4.3        | 2022 Jul         | 2104             | 28.6                   | 13.2                   |
| JWST NIRCam  | F444W   | 3.8–5.0        | 2022 Jul         | 2104             | 29.0                   | 9.1                    |

$a$ 5σ limiting AB magnitude in a $r = 0\prime.1$ circular aperture

$b$ 5σ limiting flux in a $r = 0\prime.1$ circular aperture

just_0989.pmap is consistent within 3% for all filters analyzed here.

For the JWST data, the GRIZLI reduction pipeline applies a correction to reduce the effect of 1/f noise and masks “snowballs”3 that are are caused by large cosmic ray impacts to the NIRCam detectors. The GRIZLI pipeline also includes a correction for faint, diffuse stray light features, called “wisps”4 that are present at the same detector locations in NIRCam images. These stray-light features are most prominent in the NIRCam A3, B3, and B4 detectors in the F150W and F200W data. A “wisp” template was subtracted from each of these detectors for both the F150W and F200W data.

The GRIZLI pipeline aligns the HST and JWST data to a common world coordinate system registered to the GAIA DR3 catalogs (Gaia Collaboration et al. 2021). The fully-calibrated images in each filter were combined and drizzled to a common pixel grid using ASTRODRIZZLE (Koekemoer et al. 2003; Hoffmann et al. 2021).

3 https://jwst-docs.stsci.edu/data-artifacts-and-features/snowballs-artifact
4 https://jwst-docs.stsci.edu/jwst-near-infrared-camera/nircam-features-and-caveats/nircam-claws-and-wisps

The HST and JWST NIRCam long-wavelength (LW) filters (F277W, F365W, F410M, and F444W) were drizzled to a grid of 0′′04 per pixel while the JWST short-wavelength NIRCam filters (F090W, F115W, F150W, and F200W) were drizzled to a grid of 0′′02 per pixel.

These GRIZLI reduced images are available publicly, alongside images and catalogs from other JWST programs with public data.5

3.2. Photometric Catalogs

To produce the photometric catalogs, the NIRCam SW images were first rebinned to a pixel scale of 0′′04 per pixel, placing the images for all 17 filters on the same pixel grid. Sources were then identified in a detection image comprised of a weighted sum of all NIRCam LW images (F277W, F356W, F410M, and F444W) using PHOTUTILS (Bradley et al. 2022) image-segmentation tools. Visual inspection of the segmentation image revealed a 2′6 long lensed arc that had been segmented into five separate components. Therefore, we combined the sepa-

5 https://s3.amazonaws.com/grizli-v2/JwstMosaics/v4/index.html
rate arc segments into a single source before performing photometry.

Source fluxes were measured with PHOTUTILS in isophotal, circular, and elliptical Kron apertures (with scale factors of both 1.5 and 2.5). The photometry was corrected to total fluxes by comparing the total (scale factor of 2.5) Kron flux measurements to the flux measurements in the detection image.

3.3. Photometric Redshifts

We derive initial photometric redshifts using EAZYPY (Brammer et al. 2008), which fits the observed photometry of each galaxy using a set of templates added in a non-negative linear combination. We use the photometry measured in elliptical Kron apertures with a scale factor of 1.5. Both JWST and HST photometry is included in the photometric redshift calculations for the WFI0137−08 cluster field, while only JWST photometry is used for the Module A field. The photometric redshifts were calculated using a template set comprised of the 12 “tweak̂fsps_QSF_12.v3” templates derived from the Flexible Stellar Population Synthesis (FSPS) library (Conroy et al. 2009, 2010; Conroy & Gunn 2010), which include a range of galaxy types (e.g., star-forming, quiescent, dusty) and realistic star formation histories (e.g., bursty, slowly rising, slowly falling). To these FSPS templates, we add six templates from Larson et al. (2022, in prep) that span bluer colors than the fiducial FSPS templates. These additional templates were found to provide better photometric-redshift accuracies for bluer galaxies at $z > 9$ (Larson et al. 2022, in prep). We allow the redshifts to span from 0.1 < $z$ < 20, in steps of 0.01, and adopt a flat luminosity prior as we are just beginning to explore galaxies at these epochs.

3.4. High-Redshift Candidate Selection

We select our initial sample of high-redshift candidate galaxies using a combination of criteria using both signal-to-noise and photometric redshift measurements. Selecting high-redshift galaxy candidates using photometric redshifts is generally more robust than a Lyman break color-color selection, especially when using multiband photometry in a large number of filters. The photometric signal-to-noise (SNR) criteria are used to both ensure non-detections in filters blueward of the Lyman break and to ensure robust photometric detections in multiple filters redward of the break, which minimizes spurious noise detections. We also visually inspect each candidate galaxy in each filter image and its best-fit SED to remove detector artifacts and other spurious sources such as diffraction spikes, misidentified parts of larger galaxies, and spurious noise close to the detector edge.

We used the following criteria to select our initial sample of high-redshift candidates between 8.5 ≤ $z$ ≤ 13:

- SNR < 1.5 in F090W
- SNR > 4.5 in each of F200W and F277W
- SNR > 4.0 in F356W
- SNR > 3.5 in F444W
- Best-fit photometric redshift measured by EAZYPY of 8.5 ≤ $z_{\text{best}}$ ≤ 13
- Integral of the EAZYPY posterior redshift probability (P($z$)) at $z > 8$ of $\int P(z > 8) \, dz > 0.8$
- $\chi^2$ of the best-fit EAZYPY spectral-energy distribution (SED) of $\chi^2 < 30$

We decrease the SNR criteria in the redder NIRCam filters (F356W and F444W) so as not to exclude sources with rest-frame UV slopes bluer than $\beta = -2$, as expected for young star-forming galaxies at these epochs.

We used the following criteria to select high-redshift candidates at $z > 13$, as more of the NIRCam filters fall blueward of the Lyman break at this high redshift:

- SNR < 1.5 in each of F090W, F115W, and F150W
- SNR > 4.5 in F277W
- SNR > 4.0 in F356W
- SNR > 3.0 in F444W
- Best-fit photometric redshift measured by EAZYPY of $z_{\text{best}} > 13$
- Integral of the EAZYPY P($z$) at $z > 8$ of $\int P(z > 8) \, dz > 0.8$
- $\chi^2$ of the best-fit EAZYPY SED of $\chi^2 < 30$

As an additional check, we also calculated photometric redshifts using EAZYPY with the recently-added SFHZ templates. These templates have redshift-dependent star formation histories (SFH) that disfavor star formation starting earlier than the age of the universe at a given epoch. We excluded candidates from our high-redshift sample where these templates prefer a low-redshift ($z_{\text{best}} < 8.2$) solution.

Our results do not appear to be strongly dependent on the current uncertainties in the NIRCam zeropoints, which appear to be converging based on in-flight data (Boyer et al. 2022; Nardiello et al. 2022). The most recent calibration jwst_0989_pmap alters flux measurements by <3% for all filters analyzed here. Uncertainties may remain at the few-percent level, which will improve in the coming months with ongoing calibration of the JWST detectors.
4. RESULTS AND DISCUSSION

4.1. High-Redshift Sample

After visual inspection of all candidates meeting the above criteria in all filters, our high-redshift sample consists of 12 candidates at $8.5 \lesssim z \lesssim 13$. Three of these candidates lie in the cluster field, while the remaining nine are located in the nearby field.

To further refine our selection and to measure the physical properties of our candidates, we also perform SED fitting to the photometry of these galaxies using the Bayesian Analysis of Galaxies for Physical Inference and Parameter Estimation (BAGPIPES; Carnall et al. 2018) Python package and the BayEscan Analysis of GaLaxy sEds (BEAGLE; Chevallard & Charlot 2016) tool (as described in Section 4.3) with redshift as a free parameter.

The measured (uncorrected for magnification) JWST photometry of our high-redshift candidates is presented in Table 2. For the three lensed high-redshift candidates in the cluster field, we also present their measured (uncorrected for magnification) HST photometry in Table 3. In Figures 3–8 we present 3'' × 3'' cutout images, the best-fit SEDs, and the posterior redshift distributions, $P(z)$, for each candidate. The posterior redshift distributions include plots for eazypy (for both the FSPS+Larson and SFHZ template sets), BAGPIPES, and BEAGLE. We plot in Figures 3–8 the BAGPIPES best-fit high-redshift ($z \geq 7$) SED along with the best-fit low-redshift SED constrained with redshift $z < 7$.

As observed from the cutout images presented in Figures 3–8, about half of our candidates are located within 1''5 of a brighter foreground galaxy. Our deep JWST images show a clear and distinct separation between the high-redshift candidates and their neighboring galaxies, with the possible exception of WHL0137–ID7009, which is directly adjacent to the foreground galaxy in the segmentation image. The high-redshift galaxy candidates also have distinct colors from their neighbors suggesting they are not likely physically associated (e.g., embedded in the outer regions of the foreground galaxies). Based on integrated number densities in non-lensed fields (see Windhorst et al. 2022, Figure 10), we would statistically expect a ∼22% probability of finding an unrelated foreground galaxy to < 25 AB mag. Our results are slightly above this probability at 33% (3 of 9), which could possibly suggest that one of our sources is a contaminant. However, this result may also be due to small number statistics.

4.2. Magnifications

To estimate source magnifications, we use the lens models constructed to analyze Earendel and the Sunrise Arc published in Welch et al. (2022b) and which were made publicly available. These models were generated using four independent lens modeling software packages: Light-Traces-Mass (LTM, Zitrin et al. 2009, 2015; Broadhurst et al. 2005), Glafic (Oguri 2010), WSLAP+ (Diego et al. 2005, 2007), and Lenstool (Jullo et al. 2007; Jullo & Kneib 2009). Due to a lack of multiply-imaged sources in this cluster, the slope of the lensing potential in these models varies by a factor of six, which adds considerable uncertainty to our magnification estimates. For further details about each model, please see Welch et al. (2022b).

Three of the candidates in our sample are strongly lensed by the WHL0137–08 galaxy cluster, while the other nine candidates, located in the nearby NIRCam module, are expected to have only weak magnifications of $\mu \leq 1.1$. The three lensed candidates are WHL0137–ID2796, WHL0137–ID7009, and WHL0137–ID9356. Using the four lens models described above, WHL0137–ID2796 has a magnification in the range from $\mu = 1.3 – 9.6$, with a mean value of $\mu = 6.1$. WHL0137–ID7009 extends beyond the range of the Glafic lens model, so its magnification is based on the other three lens models. This source has a magnification in the range from $\mu = 1.5 – 5.2$, with a mean value of $\mu = 2.9$. WHL0137–ID9356 has the largest magnification with a magnification in the range from $\mu = 2.4 – 20.2$, with a mean value of $\mu = 7.9$. The mean magnifications and uncertainties are quoted in Tables 4 and 5.

4.3. Spectral Energy Distribution (SED) Fitting

4.3.1. BAGPIPES

For each galaxy in our high-redshift sample, we estimate its physical properties using SED fitting. We first performed SED fitting using the BAGPIPES (Carnall et al. 2018) Python package. BAGPIPES generates model galaxy spectra over the multidimensional space of physical parameters and fits these to the photometric data using the MULTINEST nested sampling algorithm (Feroz & Hobson 2008; Feroz et al. 2009; Feroz & Skilling 2013). BAGPIPES uses the stellar population synthesis models from the 2016 version of the BC03 (Bruzual & Charlot 2003) models. These models were generated using a Kroupa (2002) initial mass function (IMF) and include nebular line and continuum emission based on CLOUDY (Ferland et al. 2013), with the logarithm of ionization
Figure 3. Cutout images, best-fit spectral energy distributions (SEDs), and posterior redshift distributions for the high-redshift galaxy candidates WHL0137–ID2796 and WHL0137–ID3407. **Top panels:** 3′′ × 3′′ JWST cutout images spanning 0.9 – 4.5 μm centered on each candidate. **Bottom-left panels:** Source photometry is shown as blue data points or triangle upper limits. Non-detections are plotted as upper limits at the 1σ level. The best-fit BAGPIPES spectral energy distribution (SED) model at high-redshift (z ≥ 7) is shown in orange with squares indicating the expected photometry in a given band. The best-fit BAGPIPES SED for a low-redshift (z < 7) solution is shown in gray. **Bottom-right panels:** Posterior probability distributions (P(z)) for the source photometric redshift derived using EAZYPY (using both the FSPS+Larson and SFHZ template sets), BAGPIPES, and BEAGLE.
Table 2. *JWST* photometry for the complete sample of high-redshift candidates

| Object ID | RA          | Dec         | F090W   | F115W   | F150W   | F200W   | F227W   | F356W   | F410M   | F444W   |
|-----------|-------------|-------------|---------|---------|---------|---------|---------|---------|---------|---------|
|           |             |             | nJy     | nJy     | nJy     | nJy     | nJy     | nJy     | nJy     | nJy     |
| WHL0137-2796 | 24 35 27.828 | −8 44 35.249 | −20.3 ± 6.3 | 18.8 ± 6.3 | 42.4 ± 7.2 | 28.5 ± 5.9 | 24.7 ± 4.6 | 30.1 ± 4.2 | 12.5 ± 7.6 | 52.6 ± 6.4 |
| WHL0137-3407 | 24 33 81.002 | 9.3 ± 12.2 | 64.2 ± 10.5 | 68.8 ± 8.7 | 36.0 ± 7.0 | 51.0 ± 6.3 | 30.8 ± 11.1 | 50.2 ± 9.6 |
| WHL0137-4162 | 24 34 99.086 | 1.2 ± 6.4 | 21.2 ± 6.5 | 89.6 ± 6.0 | 95.3 ± 4.9 | 93.4 ± 4.0 | 123.3 ± 3.7 | 145.9 ± 6.2 | 257.7 ± 5.4 |
| WHL0137-5021 | 24 34 16.298 | −8 41 08.836 | 6.9 ± 8.5 | 7.7 ± 8.8 | −8.8 ± 7.0 | 33.1 ± 5.9 | 23.3 ± 2.5 | 20.5 ± 2.3 | 20.9 ± 3.9 | 24.2 ± 3.3 |
| WHL0137-5124 | 24 35 31.948 | −8 40 06.886 | −4.8 ± 4.6 | −3.2 ± 4.7 | 2.6 ± 4.1 | 21.5 ± 4.0 | 23.2 ± 2.8 | 22.5 ± 2.6 | 24.6 ± 4.3 | 23.2 ± 3.7 |
| WHL0137-5330 | 24 32 05.269 | −8 40 73.176 | 5.3 ± 8.8 | −19.8 ± 9.0 | 35.2 ± 7.6 | 34.2 ± 6.3 | 30.6 ± 4.6 | 38.1 ± 4.2 | 34.9 ± 7.3 | 45.0 ± 6.3 |
| WHL0137-5347 | 24 34 72.215 | −8 40 70.851 | −4.9 ± 15.4 | 2.4 ± 15.3 | 72.3 ± 13.2 | 77.3 ± 11.1 | 74.0 ± 6.4 | 83.5 ± 5.7 | 68.5 ± 9.7 | 90.6 ± 8.3 |
| WHL0137-6334 | 24 33 09.474 | −8 39 71.224 | 7.8 ± 9.0 | 58.5 ± 9.4 | 106.3 ± 8.1 | 97.2 ± 6.6 | 81.7 ± 4.7 | 74.5 ± 4.3 | 91.4 ± 7.6 | 79.5 ± 6.4 |
| WHL0137-7009 | 24 34 16.073 | −8 47 34.376 | −3.3 ± 18.4 | 93.6 ± 18.7 | 174.7 ± 15.1 | 152.8 ± 12.6 | 107.8 ± 9.2 | 107.9 ± 8.3 | 82.3 ± 15.5 | 107.9 ± 12.6 |
| WHL0137-8737 | 24 35 19.451 | −8 41 25.272 | −4.5 ± 8.5 | 13.8 ± 8.7 | 69.2 ± 7.7 | 64.4 ± 6.2 | 34.1 ± 5.2 | 48.0 ± 4.6 | 39.8 ± 7.9 | 39.7 ± 6.8 |
| WHL0137-8907 | 24 33 41.444 | −8 40 71.934 | 8.2 ± 8.8 | 35.1 ± 9.1 | 101.7 ± 7.9 | 84.0 ± 6.5 | 68.0 ± 5.4 | 66.4 ± 4.8 | 83.0 ± 8.3 | 61.2 ± 7.2 |
| WHL0137-9356 | 24 35 56.275 | −8 44 70.187 | −12.8 ± 17.5 | 52.7 ± 19.0 | 169.8 ± 14.9 | 135.0 ± 12.2 | 127.4 ± 9.1 | 113.5 ± 8.3 | 101.5 ± 15.2 | 190.1 ± 12.5 |

Note—Observed fluxes, uncorrected for magnification. \( m_{AB} = 31.4 - 2.5 \log(f_{\nu}/nJy) \).

Table 3. *HST* Photometry of the three lensed high-redshift candidates

| Object ID | F105W nJy | F110W nJy | F125W nJy | F140W nJy | F160W nJy | F175W nJy | F435W nJy | F444W nJy |
|-----------|------------|------------|------------|------------|------------|------------|------------|------------|
| WHL0137-2796 | 6.1 ± 4.3 | 6.2 ± 4.6 | −39.6 ± 50.8 | 5.2 ± 42.1 | 41.3 ± 29.2 | 7.1 ± 22.5 | −31.4 ± 10.4 | −9.9 ± 13.7 | 2.2 ± 7.7 |
| WHL0137-7009 | 167.5 ± 85.7 | 48.3 ± 16.3 | 84.0 ± 149.1 | −9.1 ± 127.2 | 71.2 ± 85.4 | 45.6 ± 42.1 | −31.5 ± 20.4 | 27.3 ± 25.6 | −36.6 ± 15.5 |
| WHL0137-9356 | 111.4 ± 55.3 | 44.6 ± 11.3 | 41.0 ± 98.0 | 11.4 ± 82.2 | 39.6 ± 57.2 | −8.4 ± 46.5 | 16.5 ± 21.0 | 18.0 ± 26.8 | −11.3 ± 15.4 |

Note—Observed fluxes, uncorrected for magnification. \( m_{AB} = 31.4 - 2.5 \log(f_{\nu}/nJy) \).
Figure 4. Same as Figure 3, but for the high-redshift galaxy candidates WHL0137–ID4162 and WHL0137–ID5021. For WHL0137–ID4162 we also plot the best-fit BEAGLE SED model (see Section 4.4) in green with squares indicating the expected photometry in a given band.
Figure 5. Same as Figure 3, but for the high-redshift galaxy candidates WHL0137–ID5124 and WHL0137–ID5330.
Figure 6. Same as Figure 3, but for the high-redshift galaxy candidates WHL0137–ID5347 and WHL0137–ID6334.
Figure 7. Same as Figure 3, but for the high-redshift galaxy candidates WHL0137–ID7009 and WHL0137–ID8737.
Figure 8. Same as Figure 3, but for the high-redshift galaxy candidates WHL0137–ID8907 and WHL0137–ID9356.
parameter (log U) allowed to vary between −4 to −2. We perform our SED fitting using a delayed exponentially declining SFH where the star formation rate (SFR) is of the form SFR(t) ∝ t exp(−t/τ). Models assuming a constant star formation rate yield younger ages and higher sSFRs, as discussed below in §4.4.

For SED fits constrained to be at low redshift (z < 7), we assume a Calzetti law (Calzetti et al. 2000) for dust attenuation. For SED fits constrained to be a high redshift (z > 7), we assume a Small Magellanic Cloud (SMC) dust law (Salim et al. 2018). For both cases, we also include a second component to the dust model that includes birth-cloud dust attenuation that is a factor of two larger around H II regions as in the general ISM within the galaxy’s first 10 Myr. We allow dust extinction to range from A_V = 0 − 5 magnitudes and we vary metallicity in logarithmic space from log Z/Z⊙ = 0.005 − 5. Formation ages vary from 1 Myr to the age of the universe.

4.3.2. BEAGLE

We also perform SED fitting on each candidate galaxy using the BEAGLE tool (Chevallard & Charlot 2016) with simplified version of the configuration, fit parameters, and parameter space used in Atek et al. (2022) and Furtak et al. (2022). BEAGLE uses SED templates by Gutkin et al. (2016), which also combine the 2016 version of the BC03 stellar population synthesis models with CLOUDY to account for nebular emission. The templates include ionization parameters varying from −4 to −1. These templates all assume a Chabrier (2003) IMF and model the intergalactic attenuation using the Inoue et al. (2014) attenuation curves. As with BAGPIPES, we assume a delayed exponential SFH, but with the possibility of an ongoing star-burst over the last 10 Myr. This allows for maximum flexibility of the SFH to be either rising or declining with a maximum at t = τ. We account for dust attenuation by assuming an SMC-like dust attenuation law (Pei 1992), which has been found to fit high-redshift galaxies best at low metallicities (Capak et al. 2015; Reddy et al. 2015, 2018; Shivaei et al. 2020). Due to the relatively large number of free parameters, we fix the metallicity to Z = 0.1 Z⊙ while the stellar mass, current SFR, maximal stellar age and dust attenuation are allowed to vary freely in the ranges log(M⋆/M⊙) ∈ [6, 11], log(ψ/M⊙ yr−1) ∈ [−4, 4], log(t_age/yr) ∈ [6, t_universe] and A_V ∈ [0, 3] respectively.

4.4. Physical Properties

The derived physical properties for our candidate high-redshift galaxies using BAGPIPES and BEAGLE are presented in Tables 4 and 5, respectively. The BAGPIPES results are quoted for high-redshift solutions restricted to z > 7.

For each of the three gravitationally-lensed candidates, we divide by its mean magnification (see Section 4.2) to calculate intrinsic stellar mass and SFR.

We measure intrinsic stellar masses of log(M⋆/M⊙) ≈ 7.5 − 9 for all galaxies with BAGPIPES and for most with BEAGLE. With BEAGLE, the full range spans almost 4 orders of magnitude between log M⋆/M⊙ = 6.3 − 10.2. The typical SFRs range from ∼ 1 − 9 M⊙/yr, with full range between 0 − 61 M⊙/yr. In all cases, the SED fitting reveals relatively young ages of < 100 Myr. For all candidates, we also find low dust content with A_V < 0.15, as expected due to the relatively blue rest-frame UV slopes in our sample of β = −1.6 to −3.1. Specific star formation rates range from sSFR = 20 − 250 Gyr−1.

Note the BEAGLE run considers the most recent 10 Myr of star formation, so the sSFR results are capped at 100 Gyr−1 = 1/(10 Myr).

Median age estimates from BAGPIPES are typically ∼50 Myr, while BEAGLE median ages are typically younger ∼15 Myr. Switching BAGPIPES to a constant star formation history (CSFH) also results in younger median ages typically ∼20 Myr and sSFR typically higher by 0.2 dex (up to 1.2 dex).

The BEAGLE SED fits of WHL0137–ID4162 have the largest stellar mass with log M⋆/M⊙ = 10.19±0.04 coupled with the lowest star formation rate of 0.08±0.07 M⊙/yr. This is a result of BEAGLE fitting the red F410M − F444W = 0.6 color as a Balmer break (see Figure 4; top), with a relatively old mass-weighted age of 227±41 Myr. On the other hand, BAGPIPES fits this galaxy as an extremely young (3±0.05 Myr) galaxy with a high sSFR rate of ∼250 Gyr−1 and strong inferred [O iii] + Hβ emission (rest-frame equivalent width of ∼2000 Å). The BAGPIPES fit yields a more typical mass of log M⋆/M⊙ = 8.42±0.05.

WHL0137–ID2796 and WHL0137–ID9356 also have relatively red F410M − F444W colors of ≥ 0.6. For these two candidates, both BAGPIPES and BEAGLE fit these galaxies with a SED template containing strong [O iii] + Hβ optical emission lines. BEAGLE gives very young ages for both of these galaxies of < 5 Myr, while BAGPIPES yields ages of ∼32 and 14 Myr for WHL0137–ID2796 and WHL0137–ID9356, respectively.

4.5. A gravitationally-lensed arc at z ∼ 9

One of our lensed high-redshift candidates, WHL0137–ID9356, is stretched into an arc 2′6 long
by the effects of strong gravitational lensing. The arc has at least two bright knots of unevenly distributed star formation (see Figure 9). This candidate has a lensed F200W AB magnitude of $26 \pm 0.1$. Assuming a magnification of $\mu = 7.9$ ($\mu = 2.4 - 20.2$; see Section 4.2), its intrinsic AB magnitude is $28.2 \pm 0.1$.

After correcting for magnification, the BAGPIPES results yield a stellar mass of $M_*/M_\odot = 7.71^{+0.34}_{-0.49}$ and a star formation rate of $2.6^{+0.9}_{-0.8} M_\odot/yr$. This places WHL0137-9356 slightly above the Speagle et al. (2014) time-dependent SFR–$M_*$ main sequence relation extrapolated out to $z \sim 9$. The galaxy is very young with a mass-weighted age of $14^{+66}_{-52}$ Myr and a formation redshift of $z_{\text{form}} = 9.1$ ($t_{\text{form}} = 538$ Myr).

The BEAGLE results yield a lower stellar mass of $M_*/M_\odot = 6.67^{+0.90}_{-0.73}$ and a significantly higher star formation rate of $18.9^{+1.1}_{-1.6} M_\odot/yr$, placing it well above (i.e., higher SFR for given stellar mass) the extrapolated

\begin{table}[h]
\centering
\begin{tabular}{lccccccccc}
\hline
Object ID & $\mu_{\text{mean}}^a$ & $z_{\text{phot}}^b$ & $z_{\text{phot}}^c$ & log $M_*/M_\odot$ & SFR$^d$ & log sSFR/Gyr & Age$^e$ & $A_V$ & $t_{\text{form}}^f$ \\
\hline
WHL0137-2796 & $6^{+2}_{-5}$ & $8.7^{+1.5}_{-8.3}$ & $8.5^{+1.5}_{-14.6}$ & $7.46^{+0.41}_{-0.59}$ & $0.8^{+1.0}_{-0.4}$ & $1.4^{+1.0}_{-0.5}$ & $32^{+95}_{-30}$ & $0.06^{+0.05}_{-0.04}$ & $538$ \\
WHL0137-3407 & $10.5^{+1.0}_{-10.5}$ & $10.7^{+0.9}_{-1.6}$ & $8.78^{+0.17}_{-0.33}$ & $7.3^{+2.5}_{-1.2}$ & $1.1^{+4.0}_{-0.0}$ & $70^{+150}_{-44}$ & $0.04^{+0.03}_{-0.02}$ & $371$ \\
WHL0137-4162 & $8.8^{+0.0}_{-0.3}$ & $8.8^{+0.1}_{-1.0}$ & $8.42^{+0.05}_{-0.03}$ & $61.4^{+17.3}_{-9.6}$ & $2.4^{+0.1}_{-0.1}$ & $3^{+1}_{-1}$ & $0.13^{+0.02}_{-0.02}$ & $558$ \\
WHL0137-5021 & $12.8^{+1.1}_{-12.5}$ & $12.8^{+1.2}_{-12.1}$ & $8.53^{+0.18}_{-0.32}$ & $5.1^{+1.9}_{-1.1}$ & $1.5^{+0.4}_{-0.2}$ & $58^{+37}_{-37}$ & $0.05^{+0.04}_{-0.06}$ & $277$ \\
WHL0137-5124 & $12.8^{+1.9}_{-12.4}$ & $12.7^{+1.8}_{-1.5}$ & $8.65^{+0.20}_{-0.30}$ & $6.9^{+3.2}_{-1.9}$ & $1.5^{+0.2}_{-0.2}$ & $59^{+35}_{-37}$ & $0.12^{+0.08}_{-0.06}$ & $276$ \\
WHL0137-5330 & $10.4^{+1.1}_{-7.9}$ & $10.4^{+1.1}_{-1.1}$ & $8.77^{+0.16}_{-0.26}$ & $6.4^{+2.6}_{-1.8}$ & $1.0^{+0.3}_{-0.2}$ & $83^{+51}_{-48}$ & $0.11^{+0.07}_{-0.06}$ & $388$ \\
WHL0137-5347 & $10.2^{+0.9}_{-9.7}$ & $10.2^{+0.9}_{-1.7}$ & $9.01^{+0.21}_{-0.37}$ & $14.6^{+3.5}_{-3.5}$ & $1.1^{+0.5}_{-0.3}$ & $62^{+54}_{-43}$ & $0.09^{+0.05}_{-0.04}$ & $397$ \\
WHL0137-6334 & $8.4^{+8.2}_{-0.4}$ & $8.5^{+0.3}_{-1.7}$ & $8.75^{+0.19}_{-0.14}$ & $9.2^{+2.2}_{-1.3}$ & $1.2^{+0.3}_{-0.2}$ & $50^{+33}_{-25}$ & $0.02^{+0.01}_{-0.02}$ & $547$ \\
WHL0137-7009 & $3^{+1}_{-1.5}$ & $8.4^{+0.3}_{-0.4}$ & $8.4^{+0.4}_{-0.4}$ & $8.16^{+0.18}_{-0.23}$ & $5.1^{+1.4}_{-0.8}$ & $1.5^{+0.3}_{-0.3}$ & $22^{+12}_{-6}$ & $0.01^{+0.01}_{-0.01}$ & $755$ \\
WHL0137-8737 & $3^{+10}_{-1.0}$ & $9.2^{+1.0}_{-0.7}$ & $8.46^{+0.24}_{-0.29}$ & $6.0^{+1.6}_{-1.0}$ & $1.3^{+0.4}_{-0.3}$ & $40^{+45}_{-25}$ & $0.01^{+0.02}_{-0.02}$ & $480$ \\
WHL0137-8907 & $8.8^{+0.5}_{-0.8}$ & $8.8^{+0.4}_{-0.4}$ & $8.69^{+0.16}_{-0.21}$ & $8.2^{+1.7}_{-1.1}$ & $1.3^{+0.3}_{-0.2}$ & $49^{+36}_{-30}$ & $0.01^{+0.01}_{-0.01}$ & $512$ \\
WHL0137-9356 & $8^{+12}_{-6}$ & $8.9^{+0.5}_{-0.4}$ & $8.8^{+0.5}_{-0.5}$ & $7.71^{+0.49}_{-0.34}$ & $2.6^{+3.3}_{-0.9}$ & $1.7^{+0.7}_{-0.7}$ & $14^{+60}_{-12}$ & $0.03^{+0.03}_{-0.02}$ & $538$ \\
\hline
\end{tabular}
\end{table}

\textbf{Table 4.} BAGPIPES photometric redshifts and physical properties of the high-redshift galaxy candidates

Note—Physical parameter results are quoted for high-redshift solutions restricting $z > 7$. We quote the median and the 1σ range of the joint posterior distributions for each galaxy. We have modeled star formation histories as exponential delayed $\tau$ model. If constant star formation histories are assumed, age estimates decrease and sSFR increases. For the three lensed sources, stellar masses and SFRs are corrected for the mean magnification. Multiply these values by $\mu_{\text{mean}}/\mu$ to apply a different magnification. We did not propagate magnification uncertainties to those parameter uncertainties.

$^a$Mean magnification and uncertainties based on multiple independent lens models. Candidates in the nearby field are estimated to have magnifications of $\mu \leq 1.1$.

$^b$Photometric redshift with 2σ uncertainties, using the Calzetti dust law (Calzetti et al. 2000).

$^c$Photometric redshift restricted to $z > 7$ with 2σ uncertainties, using the SMC dust law (Salim et al. 2018).

$^d$Star formation rate during the past 1 Myr.

$^e$Mass-weighted age for the delayed $\tau$ star formation history.

$^f$Formation time in Myr after the Big Bang based on the mass-weighted age.
tainty to predictions of counter image locations. While some models (Lenstool) predict two merging images of the arc, and a third image near the cluster center, other models (LTM) predict no counter images. Although it is not the case with the current lens models, it is possible that the two knots in the arc could be multiple images if the critical curve happens to pass through the arc. Despite the lensing uncertainties, we have identified a promising counter image 3′9 to the west of the arc (RA = 24.3593097°, Dec = −8.4477677°, J2000) with a similar color. While this source is ∼2 mag fainter than the z ∼ 9 arc, EAZYPy estimates its zphot = 8.3 ± 0.2 (2σ), with range that encompasses the photometric redshift zphot = 8.8 of the main arc. Additional lens modeling is ongoing to further investigate this possibility.

4.6. Number Counts

Harikane et al. (2022) identified 16 robust z ∼ 9 – 12 candidates in GLASS NIRCam parallel imaging of a “blank” field with similar area ∼10 arcmin² to that studied here, reaching about a magnitude deeper in 7 filters (missing F410M). This is somewhat more than our 12 candidates, as expected given the deeper GLASS imaging.

At z ∼ 8, faint number counts in lensed fields should roughly match those in blank fields (e.g., Coe et al. 2015), given the UV luminosity function (LF) faint-end slope α ∼ −2 (Bradley et al. 2012; Bouwens et al. 2022). The galaxy cluster can hamper detections somewhat, though advanced methods can model and/or filter out the brighter cluster light to recover many faint distant galaxies (e.g., Livermore et al. 2017; Bhatawdekar & Conselice 2021).

At higher redshifts z ∼ 9 – 13, we expect steeper LF faint end slopes, increasing the advantage for lensing to reveal faint galaxies at these redshifts. In this dataset, the lensed field yielded 3 candidates, fewer than the 9 identified in the nearby blank field. There could be several reasons for this, including small number statistics. Also, only the lensed field had HST coverage that might have helped rule out lower redshift interlopers. More detailed analysis injecting artificial sources and mea-

### Table 5. Beagle photometric redshifts and physical properties of the high-redshift galaxy candidates

| Object ID      | μmean | zphot | log M*/M⊙ | SFR | log sSFR/Gyr | Age | Av | β | MUV |
|----------------|-------|-------|-----------|-----|-------------|-----|----|---|-----|
| WHL0137-2796   | 6±5   | 8.3±0.4 | 6.37±0.74 | 4.6±0.7 | 2.0±0.9 | 5±12 | 0.09±0.05 | −2.9±0.4 | −17.0 |
| WHL0137-3407   | 6±5   | 8.3±0.4 | 6.37±0.74 | 4.6±0.7 | 2.0±0.9 | 5±12 | 0.09±0.05 | −2.9±0.4 | −17.0 |
| WHL0137-4162   | 6±5   | 8.3±0.4 | 6.37±0.74 | 4.6±0.7 | 2.0±0.9 | 5±12 | 0.09±0.05 | −2.9±0.4 | −17.0 |
| WHL0137-5021   | 6±5   | 8.3±0.4 | 6.37±0.74 | 4.6±0.7 | 2.0±0.9 | 5±12 | 0.09±0.05 | −2.9±0.4 | −17.0 |
| WHL0137-5124   | 6±5   | 8.3±0.4 | 6.37±0.74 | 4.6±0.7 | 2.0±0.9 | 5±12 | 0.09±0.05 | −2.9±0.4 | −17.0 |
| WHL0137-5330   | 6±5   | 8.3±0.4 | 6.37±0.74 | 4.6±0.7 | 2.0±0.9 | 5±12 | 0.09±0.05 | −2.9±0.4 | −17.0 |
| WHL0137-5347   | 6±5   | 8.3±0.4 | 6.37±0.74 | 4.6±0.7 | 2.0±0.9 | 5±12 | 0.09±0.05 | −2.9±0.4 | −17.0 |
| WHL0137-6334   | 6±5   | 8.3±0.4 | 6.37±0.74 | 4.6±0.7 | 2.0±0.9 | 5±12 | 0.09±0.05 | −2.9±0.4 | −17.0 |
| WHL0137-7009   | 6±5   | 8.3±0.4 | 6.37±0.74 | 4.6±0.7 | 2.0±0.9 | 5±12 | 0.09±0.05 | −2.9±0.4 | −17.0 |
| WHL0137-8737   | 6±5   | 8.3±0.4 | 6.37±0.74 | 4.6±0.7 | 2.0±0.9 | 5±12 | 0.09±0.05 | −2.9±0.4 | −17.0 |
| WHL0137-8907   | 6±5   | 8.3±0.4 | 6.37±0.74 | 4.6±0.7 | 2.0±0.9 | 5±12 | 0.09±0.05 | −2.9±0.4 | −17.0 |
| WHL0137-9356   | 6±5   | 8.3±0.4 | 6.37±0.74 | 4.6±0.7 | 2.0±0.9 | 5±12 | 0.09±0.05 | −2.9±0.4 | −17.0 |

Note—Results are quoted as the median and the 1σ range of the joint posterior distributions for each galaxy. For the three lensed sources, stellar masses and SFRs are corrected for magnification. Multiply these values by μmean/μ to apply a different magnification. We did not propagate magnification uncertainties to those parameter uncertainties.

a Mean magnification and uncertainties based on multiple independent lens models. Candidates in the nearby field are estimated to have magnifications of μ ≤ 1.1.
b Star formation rate during the past 1 Myr.
c Specific star formation rate, capped at 100 Gyr⁻¹ = 1/(10 Myr).
d Mass-weighted age in Myr.
e Rest-frame UV slope.
f Rest-frame absolute UV magnitude in the band that contains 1500 Å at the galaxy’s photometric redshift.
suring completeness will be required of this and other fields to quantify the lensing advantage at $z \approx 9$ and higher redshifts. Confirmed suppression of lensed number counts could indicate LF faint-end slopes hovering around $\alpha \sim -2$ rather than steepening as expected from both simulations and trends at lower redshifts.

5. CONCLUSIONS

We present a search for very high-redshift galaxies in the first JWST NIRCam observations of the lensing cluster WHL0137–08 and a nearby parallel field centered $\sim 2\arcmin$ from the cluster center. Combined with RELICS HST observations, the JWST and HST observations of WHL0137–08 include imaging in 17 filters spanning 0.4–5.0 $\mu$m in which we use to search for high redshift galaxies.

We use the eazypy photometric-redshift fitting code with two independent sets of templates to determine the initial redshift of every galaxy in our fields. Our high-redshift candidates galaxies were selected using a combination of both signal-to-noise criteria and photometric redshift measurements to minimize contamination from low-redshift sources and spurious noise detections. Additionally, we also visually inspect each candidate galaxy in each filter image and its best-fit SED to remove detector artifacts and other spurious sources.

Our final sample of robust candidate high-redshift galaxies consists of 12 candidates at $8.5 \lesssim z \lesssim 13$. Three of these candidates lie in the cluster field, while the remaining nine are located in the nearby parallel field. Using four independent lens models of the WHL0137–08 galaxy cluster constructed to analyze Earendel and the Sunrise Arc, we estimate the magnifications of each of our lensed high-redshift candidates. These sources have magnifications of $\mu \sim 3 – 8$.

Furthermore, we perform SED fitting to the photometry of these galaxies using the independent SED-fitting codes bagpipes and beagle to measure the physical properties of our candidates. We find: stellar masses in the range $\log M_*/M_\odot = 7.5 – 9$, specific star formation rates $sSFR \sim 10 – 250 \text{ Gyr}^{-1}$, young mass-weighted ages $< 100 \text{ Myr}$, low dust content with values $A_V < 0.15$, and rest-frame UV slopes of $\beta = -1.6$ to $-3.1$.

Other JWST analyses have estimated similarly young ages $< 100 \text{ Myr}$ for $z \sim 9 – 16$ candidates (Whitler et al. 2022; Furtak et al. 2022). Discovering such young galaxies is consistent with expectations from simulations given our image depths down to AB mag $\sim 29$ (Mason et al. 2022). Deeper JWST imaging is required to reveal older (and thus fainter) $\sim 100 \text{ Myr}$ populations at $z > 9$, perhaps typical for the more numerous fainter galaxies in the early universe.

One of our high-redshift candidates, WHL0137–ID9356, is magnified to AB mag 26 and stretched into an arc $2\arcmin 6$ long by the effects of strong gravitational lensing. The JWST data reveal at least two bright knots of unevenly distributed star formation within the arc. This candidate also has the largest magnification $\mu = 8^{+12}_{-6}$. WHL0137–ID9356 is now the most spatially-resolved galaxy at $z \sim 9$ known to date, similar in length to the $z \sim 10$ candidate SPT0615-JD1 (Salmon et al. 2018).

JWST GO 2282 will obtain follow-up spectroscopy of WHL0137–08 with JWST NIRSpec observations scheduled later this year. We plan to obtain spectroscopy of some these candidates, likely those within the cluster field, to validate these sources and study their physical properties in more detail.

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**Software:** ASTROPY (The Astropy Collaboration et al. 2022; Astropy Collaboration et al. 2018), PHOTUTILS (Bradley et al. 2022), GRIZLI (Brammer et al. 2022), EAZYPPY (Brammer et al. 2008), BAGPIPES (Carnall et al. 2018), BEAGLE (Chevallard & Charlot 2016), JDAVIZ (JDADF Developers et al. 2022)

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