



HAL
open science

JWST/NIRCam observations of stars and H II regions in $z \sim 6-8$ galaxies: properties of star-forming complexes on 150 pc scales

Zuyi Chen, Daniel P. Stark, Ryan Endsley, Michael Topping, Lily Whitler,
Stéphane Charlot

► **To cite this version:**

Zuyi Chen, Daniel P. Stark, Ryan Endsley, Michael Topping, Lily Whitler, et al.. JWST/NIRCam observations of stars and H II regions in $z \sim 6-8$ galaxies: properties of star-forming complexes on 150 pc scales. Monthly Notices of the Royal Astronomical Society, 2023, 518, pp.5607-5619. 10.1093/mnras/stac3476 . insu-03947314

HAL Id: insu-03947314

<https://insu.hal.science/insu-03947314>

Submitted on 10 Jul 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

JWST/NIRCam observations of stars and H II regions in $z \simeq 6\text{--}8$ galaxies: properties of star-forming complexes on 150 pc scales

Zuyi Chen ¹★, Daniel P. Stark,¹ Ryan Endsley ¹, Michael Topping ¹, Lily Whitler ¹
and Stéphane Charlot²

¹Steward Observatory, University of Arizona, 933 N Cherry Ave, Tucson, AZ 85721 USA

²Sorbonne Université, UPMC-CNRS, UMR7095, Institut d'Astrophysique de Paris, F-75014 Paris, France

Accepted 2022 November 23. Received 2022 November 22; in original form 2022 July 26

ABSTRACT

The onset of the *JWST*-era provides a much-improved opportunity to characterize the resolved structure of early star-forming systems. Previous *Spitzer* observations of $z \gtrsim 6$ galaxies revealed the presence of old stars and luminous H II regions (via [O III]+H β emission), but the poor resolution stunted our ability to map their locations with respect to the star-forming regions identified in the rest-UV. In this paper, we investigate the internal structure of 12 of the most luminous $z \simeq 6\text{--}8$ galaxies in the EGS field observed with recent *JWST*/NIRCam imaging. The systems appear clumpy in the rest-UV, with more than half of the light coming from $\simeq 10^7$ to $10^9 M_{\odot}$ star-forming complexes that are $\simeq 150\text{--}480$ pc in size. The clumps tend to be dominated by young stars (median = 36 Myr), but we also find large variations in clump ages within individual galaxies. The [O III]+H β EW varies significantly across individual galaxies (reflecting differences in stellar and gas properties), but the H II regions largely track the UV-bright complexes. Perhaps surprisingly, the rest-optical continuum is just as clumpy as the UV, and we do not find older (and redder) nuclear stellar components that were previously undetected or faint in the UV. The majority of the stellar mass in bright $6 < z < 8$ galaxies appears to be contained in the $\gtrsim 150$ pc-scale clumpy star-forming complexes, reflecting the very active phase of assembly that is common in reionization-era galaxies.

Key words: galaxies: evolution – galaxies: high-redshift – dark ages, reionization, first stars.

1 INTRODUCTION

Over the last two decades, the *Hubble Space Telescope* (*HST*) has conducted a series of deep near-infrared imaging campaigns, enabling the identification of large samples of star-forming galaxies at $z \simeq 6\text{--}10$ (Bouwens et al. 2015; Finkelstein et al. 2015; McLeod, McLure & Dunlop 2016; Bouwens et al. 2022b; see Robertson 2022 for a review). At these redshifts, *HST* images are limited to the rest-frame ultraviolet (UV), revealing the unobscured star-forming component of these early star-forming systems. Observations at $3\text{--}5 \mu\text{m}$ with the *Spitzer Space Telescope* have extended our view into the rest-frame optical, providing a more robust census of the total stellar content of early galaxies. By combining *HST* and *Spitzer* photometry for large samples at $z \gtrsim 6$, the bulk integrated properties of the population have been established (see Stark 2016 for a review), revealing relatively low stellar masses ($\lesssim 10^{10} M_{\odot}$), large-specific star formation rates (sSFRs; $\gtrsim 5\text{--}10 \text{ Gyr}^{-1}$), and blue UV continuum slopes ($\beta \approx -2$) indicative of minimal dust reddening. Collectively, these observations are consistent with reionization-era galaxies undergoing rising star formation histories, leading to rapid mass growth and typical light-weighted stellar ages of $50\text{--}200$ Myr (e.g. Laporte et al. 2021; Stefanon et al. 2022; Whitler et al. 2022a).

Meaningfully building on this picture of early galaxy assembly will require a resolved view of the stars, gas, and dust within z

$\gtrsim 6$ galaxies. The internal structure of early star-forming systems has long been mostly out of reach observationally, with a picture mostly limited to the rest-frame UV. Moderate resolution *HST*/WFC3 images full width at half-maximum (FWHM = 0.2 arcsec) often reveal multiple-component kpc-scale clumpy structures in massive and UV-luminous reionization era galaxies (e.g. Bowler et al. 2017; Marrone et al. 2018; Matthee et al. 2017, 2019). Separations between the individual clumps are often upwards of 5 kpc in individual UV-luminous systems at $z \simeq 7$ (e.g. Bowler et al. 2017). Gravitational lensing has extended these studies to intrinsically fainter galaxies in deep cluster fields imaged by *HST*. After correcting for magnification, these dwarf galaxies are commonly revealed to be star-forming components of size $\simeq 100$ pc, with the most highly magnified sources probing 10 pc scales similar to super star clusters (e.g. Kawamata et al. 2015; Vanzella et al. 2019, 2020; Bouwens et al. 2022a). These galaxies appear smaller than expected from extrapolation of size-luminosity scaling relations (e.g. Shibuya, Ouchi & Harikane 2015), leading some to suggest that the lowest luminosity galaxies probed by *HST* may only host a single star-forming complex (e.g. Bouwens et al. 2022a). If true, the rest-UV properties (i.e. UV slope, M_{UV}) would potentially only be applicable to a small subregion within a larger galaxy (e.g. Zick, Weisz & Boylan-Kolchin 2018).

Observations of gas and dust in luminous $z \simeq 7\text{--}8$ galaxies with the Atacama Large Millimeter Array (ALMA) have begun to complement the rest-UV picture from *HST* (Matthee et al. 2017; Hashimoto et al. 2018; Smit et al. 2018; Bowler et al. 2022; Bouwens

* E-mail: zychen@arizona.edu

et al. 2022c). In some galaxies, the dust continuum is offset from the UV emission, suggesting that there are heavily obscured star-forming components that are faint or undetected in existing *HST* imaging (e.g. Bowler et al. 2022). In other systems with ALMA data, the dust emission is co-spatial but more extended than the UV (Bowler et al. 2022), again revealing star-forming regions not well recovered in the *HST* imaging. Meanwhile, ALMA detections of far-infrared fine structure emission lines (i.e. [O III] λ 88 μ m and [C II] λ 158 μ m) are changing our view of galaxies thought to have low stellar masses ($\simeq 10^9 M_{\odot}$) based on UV to optical spectral energy distributions (SEDs) dominated by very young ($\lesssim 10$ Myr) stellar populations. Recent works have revealed significant spatial variations of [O III] emission-line properties (tracing ionized gas) in $z \simeq 7$ galaxies, suggesting these galaxies could be comprised of several stellar populations at different ages (Akins et al. 2022; Witstok et al. 2022; Wong et al. 2022). It has also been shown that these systems can have orders of magnitude larger dynamical masses (i.e. $10^{11} M_{\odot}$), potentially accommodating an older ($\gtrsim 100$ Myr) stellar population which (together with a large gas fraction) dominates the mass but is outshined by a recent burst (Topping et al. 2022).

A complete picture of the internal structure of $z \gtrsim 6$ galaxies will ultimately require higher resolution imaging at longer wavelengths where the spatial distribution of old stars can clearly be established. At lower redshifts ($z \simeq 1.5$ – 2.5), the clumpy star-forming structures tend to be located at the outskirts of an older and dustier stellar component; the derived stellar mass distribution in these systems is much less clumpy than the rest-frame UV (e.g. Wuyts et al. 2012; Lee et al. 2013). The poor resolution of *Spitzer* (FWHM ≈ 2 arcsec) has long stood in the way of such an investigation at $z \gtrsim 6$, and as such it is not clear whether the UV-emitting regions identified by *HST* are co-spatial with the older stellar populations, or whether they are embedded (or at the outskirts) of a larger structure of older stars and gas.

The spatial resolution provided by *JWST* at 2–5 μ m enables the first resolved view of the rest-optical continuum emission in reionization-era galaxies, allowing the distribution of young and old stellar populations to be mapped within early galaxies. In this paper, we use NIRCam imaging of the EGS field to study the internal structure of 12 reionization-era galaxies. The data were taken as part of the CEERS Early Release Science observations (ERS:1345, PI: Finkelstein). The systems chosen for this study are bright $z \simeq 6$ – 8 galaxies (F200W = 24.9–26.6) identified photometrically in Bouwens et al. (2015) via *HST* imaging of the EGS field. We describe the sample selection, NIRCam imaging reduction, and analysis in Section 2. In Section 3, we use the NIRCam imaging to create maps of UV and optical continuum emission across each galaxy, investigating whether the star-forming complexes are offset from the older stellar population, which may dominate the light at longer wavelengths. We also probe the star-forming regions via maps of strong rest-optical emission lines ([O III]+H β) created from NIRCam long wavelength (LW) filters that are dominated by line emission. For each galaxy, we characterize the size and physical properties of the star-forming complexes (i.e. stellar mass, age, and SFR surface density). Finally, we discuss implications for the build-up of galaxies in the reionization era, comparing these structures to systems at lower redshifts.

Throughout this paper, we adopt a flat Λ CDM cosmology with $H_0 = 70$ km s $^{-1}$ Mpc $^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$. All magnitudes are measured in the AB system (Oke & Gunn 1983) unless otherwise stated. The equivalent widths are calculated in the rest frame with positive values for emission.

2 DATA & SAMPLE ANALYSIS

In this section, we first describe the NIRCam imaging used for our analysis (Section 2.1), before discussing the sample selection and integrated galaxy properties (Section 2.2) and our spatially resolved analysis (Section 2.3).

2.1 NIRCam imaging

The *JWST*/NIRCam imaging utilized in this work were taken as part of the Cosmic Evolution Early Release Science (CEERS;¹ ERS:1345; Finkelstein et al. 2017) survey during 2022 June (see Bagley et al. 2022 for a more detailed description of the observations). These NIRCam data include imaging in six broad-band filters (F115W, F150W, F200W, F277W, F356W, and F444W), as well as one medium-band filter (F410M) across four independent pointings, for a total on-sky coverage of ≈ 40 arcmin 2 . Imaging in the short wavelength (SW) filters (F115W, F150W, and F200W) and LW filters (F277W, F356W, F444W, and F410M) have a resolution of 0.062 and 0.125 arcsec, respectively. At $z \approx 6$ – 8 , these filters simultaneously probe the rest-frame UV light dominated by young massive stars and the optical emission from the nebular and stellar continuum as well as strong emission lines (e.g. H β , [O III], and H α). This enables us to resolve reionization-era galaxies in the rest UV and optical at comparably high resolution. While a detailed description of the NIRCam imaging data reduction can be found in Endsley et al. (2022), we briefly summarize the major steps below.

To produce co-added mosaics for each NIRCam filter, we first retrieve the calibrated flat-fielded individual exposures (`*.cal.fits`) from the MAST Portal² and subsequently perform a global background subtraction on each science exposure using the SEP package.³ To provide the best possible astrometric alignment, we next process images through `calwebb_image3`⁴ separately for each NIRCam filter, pointing, and module combination given a slight (~ 0.2 arcsec) offset in the world coordinate system of the NIRCam module A versus B fits file headers (private communication with NIRCam instrument team). In this process, we have corrected the $1/f$ noise, obtained robust background estimates, and implemented updated photometric calibrations specific to each NIRCam detector derived by Gabe Brammer⁵ (see Endsley et al. 2022). Each of the output co-adds (`*.i2d.fits`) are then separately aligned to the *Gaia* astrometric frame using the TWEAKREG package,⁶ adopting the *Gaia*-aligned *HST*/WFC3 F160W mosaic from Complete Hubble Archive for Galaxy Evolution (CHARGE; see below) as a reference image. It was not possible to perform direct astrometric alignment to the *Gaia* frame for each co-added NIRCam image due to the low density of unsaturated *Gaia* stars with proper motion measurements in the EGS field ($\lesssim 3$ per pointing and module combination). None the less, with TWEAKREG, we are able to achieve sub-pixel accuracy of the resulting astrometry, with an RMS offset of ≈ 6 – 15 mas relative to the *HST* CHARGE mosaics. We then combine all co-added images for each filter into a single mosaic by resampling them onto a grid with a pixel scale of 30 mas pixel $^{-1}$, where

¹<https://ceers.github.io/>

²<https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html>

³<https://sep.readthedocs.io/en/v1.0.x/index.html>

⁴<https://jwst-pipeline.readthedocs.io/en/latest/index.html>

⁵<https://github.com/gbrammer/grizli/pull/107>

⁶<https://drizzlepac.readthedocs.io/en/latest/tweakreg.html>

Table 1. UV-bright galaxies at $z \simeq 6-8$ in the CEERS NIRCcam imaging footprint of the EGS field. Our final sample consists of 12 galaxies that were selected from *HST* imaging of the field by Bouwens et al. (2015). The names of objects are taken from Bouwens et al. (2015). Photometry and photometric redshifts are from updated NIRCcam imaging.

| Name | RA | Dec. | z_{phot} | F150W (mag) | F200W (mag) | F356W (mag) | F410M (mag) |
|-----------------|------------|-----------|------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| EGSI-9136950177 | 214.806959 | 52.838203 | $5.26^{+0.01}_{-0.01}$ | $24.94^{+0.01}_{-0.01}$ | $24.88^{+0.01}_{-0.01}$ | $24.68^{+0.01}_{-0.01}$ | $24.36^{+0.01}_{-0.01}$ |
| EGSZ-9338153359 | 214.890898 | 52.893217 | $6.12^{+0.23}_{-0.20}$ | $26.63^{+0.04}_{-0.04}$ | $26.37^{+0.02}_{-0.02}$ | $25.64^{+0.01}_{-0.01}$ | $26.89^{+0.09}_{-0.08}$ |
| EGSZ-9314453285 | 214.881001 | 52.891207 | $6.54^{+0.04}_{-0.09}$ | $26.38^{+0.04}_{-0.04}$ | $26.09^{+0.03}_{-0.03}$ | $25.57^{+0.01}_{-0.01}$ | $26.35^{+0.06}_{-0.05}$ |
| EGSI-9179549499 | 214.824915 | 52.830484 | $6.56^{+0.04}_{-0.10}$ | $25.95^{+0.03}_{-0.03}$ | $25.76^{+0.03}_{-0.03}$ | $25.53^{+0.01}_{-0.01}$ | $26.20^{+0.04}_{-0.04}$ |
| EGSZ-9271353221 | 214.863024 | 52.889431 | $6.59^{+0.03}_{-0.04}$ | $26.10^{+0.03}_{-0.03}$ | $25.93^{+0.02}_{-0.02}$ | $25.44^{+0.02}_{-0.02}$ | $26.39^{+0.08}_{-0.08}$ |
| EGSZ-9419055074 | 214.924558 | 52.918690 | $6.66^{+0.01}_{-0.01}$ | $26.04^{+0.05}_{-0.05}$ | $25.72^{+0.02}_{-0.02}$ | $24.51^{+0.01}_{-0.01}$ | $25.42^{+0.03}_{-0.02}$ |
| EGSZ-9350655307 | 214.896097 | 52.925157 | $6.69^{+0.02}_{-0.02}$ | $25.96^{+0.03}_{-0.03}$ | $25.97^{+0.02}_{-0.02}$ | $25.26^{+0.01}_{-0.01}$ | $25.57^{+0.03}_{-0.03}$ |
| EGSI-0020500266 | 215.008510 | 53.007336 | $6.74^{+0.04}_{-0.03}$ | $26.48^{+0.03}_{-0.03}$ | $26.44^{+0.03}_{-0.03}$ | $25.65^{+0.01}_{-0.01}$ | $25.68^{+0.02}_{-0.02}$ |
| EGSZ-9135048459 | 214.806240 | 52.812713 | $6.74^{+0.01}_{-0.01}$ | $26.88^{+0.05}_{-0.05}$ | $27.25^{+0.05}_{-0.05}$ | $27.27^{+0.05}_{-0.05}$ | $27.40^{+0.10}_{-0.09}$ |
| EGSZ-9262051131 | 214.859155 | 52.853586 | $7.25^{+0.11}_{-0.11}$ | $26.24^{+0.04}_{-0.04}$ | $26.23^{+0.05}_{-0.05}$ | $26.23^{+0.03}_{-0.03}$ | $25.22^{+0.02}_{-0.02}$ |
| EGSY-9105550297 | 214.793938 | 52.841534 | $7.32^{+0.23}_{-0.09}$ | $25.60^{+0.02}_{-0.02}$ | $25.77^{+0.02}_{-0.02}$ | $25.58^{+0.01}_{-0.01}$ | $25.02^{+0.02}_{-0.02}$ |
| EGSY-9587400281 | 214.994754 | 53.007741 | $7.54^{+0.03}_{-0.04}$ | $26.24^{+0.03}_{-0.03}$ | $26.08^{+0.02}_{-0.02}$ | $26.01^{+0.02}_{-0.02}$ | $25.23^{+0.02}_{-0.02}$ |

the world coordinate system of this grid is the same for all filters.

We also use *HST*/ACS imaging in the EGS field for constraining the physical properties of the galaxies analysed in this work. The ACS mosaics utilized here were produced as part of the CHArGE project (Kokorev, in preparation) and are matched to the *Gaia* astrometric frame with a pixel scale of $40 \text{ mas pixel}^{-1}$. These CHArGE mosaics include data in the F435W, F606W, and F814W bands as part of the following surveys: the All-Wavelength Extended Groth Strip International Survey (Davis et al. 2007), the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS; Grogin et al. 2011; Koekemoer et al. 2011), and the Ultraviolet Imaging of the CANDELS (UVCANDELS⁷; PI: Teplitz).

The *HST* and *JWST* imaging introduced above span nearly a factor of four in angular resolution from a point spread function (PSF) FWHM of $\approx 0.045 \text{ arcsec}$ in ACS/F435W to $\approx 0.18 \text{ arcsec}$ in WFC3/F160W. To ensure robust colour calculations, we must therefore account for variations in the PSF across different images. At the same time, we aim to preserve as much signal to noise as possible, particularly in the shorter wavelength filters, which probe the Lyman-alpha break. We have thus opted to homogenize the PSFs of all the NIRCcam LW mosaics (as well as the WFC3 mosaics used by our companion papers) to that of WFC3/F160W, while the ACS and NIRCcam SW mosaics are homogenized to the PSF of ACS/F814W.⁸ Our algorithm for performing the PSF homogenization largely follows that of Endsley et al. (2021) where we construct the PSF of each mosaic by stacking cutouts of unsaturated isolated stars (oversampling to a resolution of 3 mas pixel^{-1} for this step) and then derive PSF convolution kernels using the PYTHON PHOTUTILS package (Bradley et al. 2021). The PSF encircled energy distributions after convolution are found to agree with the targeted PSF (i.e. ACS/F814W or

WFC3/F160W) to within 1–2 per cent at radii $> 0.1 \text{ arcsec}$ in all bands.

2.2 Sample selection and galaxy properties

The goal for this study is to provide a resolved view of the brightest galaxies in the reionization era. Our sample is based on the galaxies previously identified in existing *HST* imaging of the EGS field (Bouwens et al. 2015; Bouwens et al. 2016, 2019; Roberts-Borsani et al. 2016; Leonova et al. 2022). We limit our selection to those systems that fall into the CEERS/NIRCcam footprint observed on 2022 June 29. Our current study is focused on 12 galaxies with photometric redshifts between $6 < z < 8$ with H-band magnitudes brighter than $H = 26.6 \text{ mag}$ to ensure that we are able to resolve enough pixels at the required signal-to-noise ratio with the NIRCcam data. However, we note that in a future paper, we will investigate the resolved properties of the more general population of high- z galaxies with a well-selected sample directly from the NIRCcam imaging. We list the 12 *HST*-selected bright galaxies in Table 1, and adopted the source names from the original literature sources. Colour postage stamp images based on the NIRCcam SW imaging are also presented in Fig. 1.

The NIRCcam photometry in the seven filters for our sample are extracted with custom elliptical apertures. In this process, we ensure the aperture includes the total galaxy flux as indicated by PHOTUTILS (Bradley et al. 2021) segmentation maps in all filters, while also avoiding light from neighbouring contaminants. These contaminants are identified by their detections in the *HST*/ACS optical filters, suggesting they lie at lower redshifts than our galaxies. Photometry uncertainties are estimated by placing the same aperture in the surrounding $10 \times 10 \text{ arcsec}^2$ regions with all the sources being masked. The photometry is then corrected for aperture loss, which is estimated by centring the aperture at the corresponding PSF. We list the NIRCcam photometry in four of the filters (F150W and F200W sampling the rest-UV, and F356W and F444W sampling the rest-optical) in Table 1. In the same manner, we also extract the *HST*/ACS short-wavelength filters (F435W, F606W, and F814W) photometry,

⁷<https://archive.stsci.edu/hlsp/uvcanfels>

⁸The ACS/F814W and WFC3/F160W mosaics have slightly larger FWHM relative to that of NIRCcam/F200W and NIRCcam/F444W, respectively, given the smaller mirror size of *HST*.

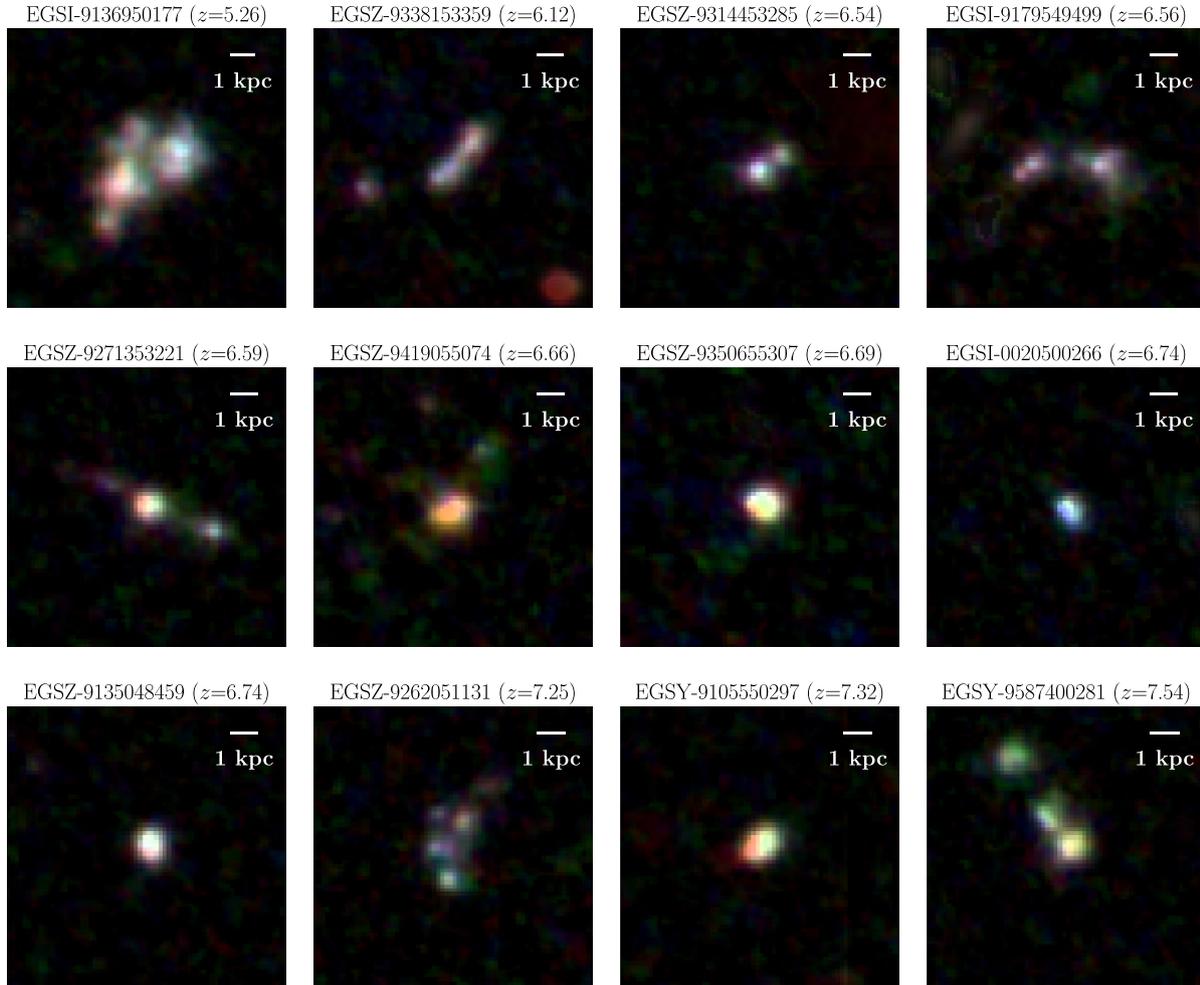


Figure 1. *JWST*/NIRCam colour images of the 12 $z \simeq 6\text{--}8$ galaxies analysed in this paper. *Blue*: NIRCcam/F115W, *green*: NIRCcam/F150W, and *red*: NIRCcam/F200W. The images span a scale of $2 \times 2 \text{ arcsec}^2$. The nearby foreground objects in each image (identified with clear detections in the *HST* optical filters) have been masked. These galaxies were selected in the *HST* imaging of the EGS and are among the brightest star-forming galaxies ($F200W=24.8\text{--}26.6$) in the CEERS footprint at $z \gtrsim 6$. The filters correspond to the rest-frame UV. The light is dominated by a number of clumpy star-forming complexes, with sizes ranging from unresolved ($<150 \text{ pc}$) to 480 pc .

which will be used for constraining the photometric redshift when deriving galaxy properties.

Following the procedure described in Whitler et al. (2022a), we fit the *HST*+NIRcam photometry with Bayesian Analysis of GaLaxy sEds (BEAGLE v0.20.4; Chevillard & Charlot 2016), providing constraints on the physical properties of our galaxies. The Gutkin, Charlot & Bruzual (2016) models are adopted, which self-consistently combine the latest version of Bruzual & Charlot (2003) stellar population models underpinned by the PARSEC isochrones (Bressan et al. 2012; Chen et al. 2015) and the nebular emission computed by CLOUDY (Ferland et al. 2013). We place uniform prior on redshift from $5 \leq z \leq 10$, which allows us to obtain updated constraints on the photometric redshifts with the inclusion of NIRCam photometry. A constant star formation history (CSFH) is assumed for our fiducial models, with the total stellar mass allowed to vary from $5 \leq \log(M_*/M_\odot) \leq 12$ and the star formation period from 1 Myr to the age of the Universe at the corresponding redshift. We note that CSFH models can underpredict the stellar mass and age of galaxies dominated by very young light-weighted ages (e.g. Tacchella et al. 2022; Tang, Stark & Ellis 2022; Whitler et al. 2022a), and we thus also consider more flexible star formation histories in our

analysis later in this paper. We adopt the Chabrier (2003) initial mass function with the upper-mass cutoff of $300 M_\odot$. Narrow log-normal priors are used on stellar metallicity (centre $\mu_{\log(Z/Z_\odot)} = -0.7$, standard deviation $\sigma_{\log(Z/Z_\odot)} = 0.15$) and ionization parameter ($\mu_{\log U} = -2.5$, $\sigma_{\log U} = 0.25$), as motivated by spectroscopic observations of the high-ionization emission lines at $z = 7\text{--}9$ (e.g. Stark et al. 2017; Hutchison et al. 2019). The nebular metallicity (including dust and gas-phase) is kept the same as the stellar metallicity, with a fixed dust-to-metal mass ratio of $\xi_d = 0.3$. Future investigation will investigate the impact of alpha enhancement, but we note that the effects of depletion do decouple the gas and stellar metallicity in our models. Finally, we assume the Small Magellanic Cloud (SMC) dust attenuation curve (Pei 1992) with V-band optical depth varying from $-3.0 \leq \log(\tau_V) \leq 0.7$, and adopt the Inoue et al. (2014) model for the intergalactic medium attenuation.

The SED fits are shown in Fig. 2. The resulting constraints on the integrated properties, such as absolute UV magnitude (M_{UV}), stellar mass (M_*), and the sSFRs, are summarized in Table 2. The updated photometric redshifts derived from the new NIRCam photometry (together with *HST*/ACS constraints) place our galaxies at $5.26 \leq z \leq 7.54$. The M_{UV} varies from -19.86 to -21.60 , with the

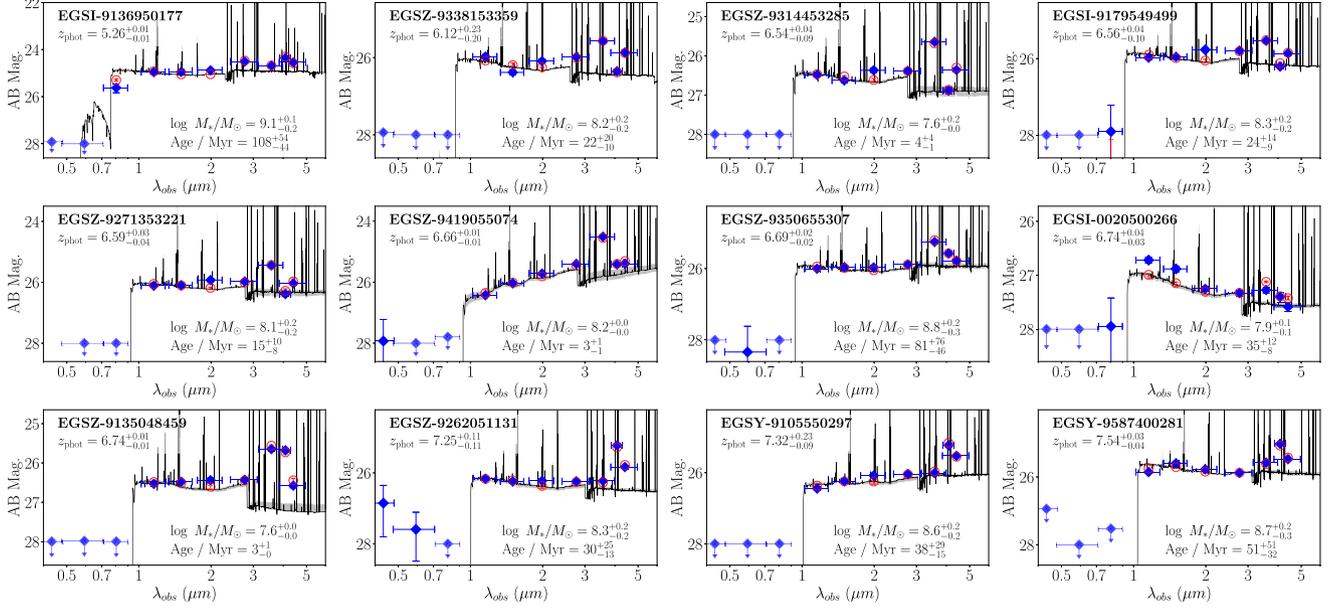


Figure 2. The BEAGLE SED fits to the 12 $z \simeq 6-8$ UV-bright galaxies analysed in this paper. The optical data from *HST*/ACS and near-infrared measurements from *JWST*/NIRCam are marked with blue diamonds, and we show 2σ upper limits shown in cases of non-detections. Overlaid on the data are the fitted median (black line) and 68 per cent credible interval SEDs (grey shaded regions) from BEAGLE. The corresponding model photometry is also shown in red circles. The stellar mass and CSFH age are shown for each object. The objects have light-weighted ages that range between 3 and 183 Myr, with stellar masses between $4 \times 10^7 M_{\odot}$ and $2 \times 10^9 M_{\odot}$.

Table 2. Physical properties inferred from BEAGLE by SED-fitting of *HST*/ACS+*JWST*/NIRCam photometry. We have adopted a CSFH. The fitted photometric redshifts have been presented in Table 1. Here, we report the absolute rest-UV magnitude, the stellar mass, the sSFRs, and the stellar population ages (defined as the time since star formation starts). We also list their *V*-band optical depth and the [O III]+H β emission line equivalent widths. The reported values are the median of the posterior with the 16th and 84th percentiles as uncertainties.

| Name | M_{UV} (mag) | $\log(M_*/M_{\odot})$ | sSFR (Gyr^{-1}) | Age (Myr) | τ_V | EW [O III]+H β (\AA) |
|-----------------|--------------------------|------------------------|-------------------------------|-------------------|------------------------|--|
| EGS1-9136950177 | $-21.60^{+0.06}_{-0.03}$ | $9.13^{+0.12}_{-0.17}$ | 9^{+6}_{-2} | 108^{+54}_{-44} | $0.01^{+0.02}_{-0.01}$ | 773^{+223}_{-31} |
| EGSZ-9338153359 | $-20.31^{+0.07}_{-0.03}$ | $7.60^{+0.18}_{-0.04}$ | 44^{+35}_{-21} | 4^{+4}_{-1} | $0.01^{+0.02}_{-0.01}$ | 2554^{+195}_{-193} |
| EGSZ-9314453285 | $-20.67^{+0.08}_{-0.02}$ | $8.18^{+0.23}_{-0.21}$ | 236^{+65}_{-111} | 22^{+20}_{-10} | $0.01^{+0.01}_{-0.00}$ | 1387^{+199}_{-116} |
| EGS1-9179549499 | $-20.95^{+0.06}_{-0.04}$ | $8.30^{+0.16}_{-0.16}$ | 41^{+24}_{-15} | 24^{+14}_{-9} | $0.01^{+0.02}_{-0.01}$ | 990^{+90}_{-95} |
| EGSZ-9271353221 | $-20.78^{+0.04}_{-0.02}$ | $8.11^{+0.18}_{-0.25}$ | 66^{+76}_{-26} | 15^{+10}_{-8} | $0.01^{+0.02}_{-0.01}$ | 1613^{+209}_{-318} |
| EGSZ-9419055074 | $-20.40^{+0.02}_{-0.03}$ | $8.20^{+0.05}_{-0.03}$ | 337^{+79}_{-88} | 3^{+1}_{-1} | $0.31^{+0.03}_{-0.03}$ | 2130^{+386}_{-226} |
| EGSZ-9350655307 | $-20.91^{+0.07}_{-0.04}$ | $8.81^{+0.19}_{-0.26}$ | 12^{+14}_{-6} | 81^{+76}_{-46} | $0.05^{+0.03}_{-0.04}$ | 772^{+261}_{-158} |
| EGSZ-9135048459 | $-19.86^{+0.06}_{-0.07}$ | $7.93^{+0.09}_{-0.09}$ | 361^{+55}_{-58} | 35^{+12}_{-8} | $0.00^{+0.00}_{-0.00}$ | 456^{+121}_{-52} |
| EGS1-0020500266 | $-20.40^{+0.03}_{-0.03}$ | $7.57^{+0.02}_{-0.02}$ | 28^{+8}_{-7} | 3^{+1}_{-0} | $0.01^{+0.01}_{-0.01}$ | 3436^{+356}_{-645} |
| EGSZ-9262051131 | $-20.84^{+0.09}_{-0.05}$ | $8.35^{+0.20}_{-0.19}$ | 31^{+23}_{-13} | 30^{+25}_{-13} | $0.01^{+0.01}_{-0.00}$ | 1037^{+21}_{-200} |
| EGSY-9105550297 | $-21.36^{+0.05}_{-0.02}$ | $8.72^{+0.23}_{-0.30}$ | 26^{+18}_{-11} | 51^{+51}_{-32} | $0.01^{+0.02}_{-0.01}$ | 841^{+73}_{-114} |
| EGSY-9587400281 | $-20.72^{+0.05}_{-0.04}$ | $8.59^{+0.18}_{-0.17}$ | 19^{+31}_{-9} | 38^{+29}_{-15} | $0.14^{+0.02}_{-0.03}$ | 590^{+64}_{-52} |

median absolute magnitude (-20.8) near M_{UV}^* , assuming the $z \simeq 7$ luminosity function of Bowler et al. 2017. The galaxies in our sample have moderate stellar masses that range from $3.7 \times 10^7 M_{\odot}$ to $1.3 \times 10^9 M_{\odot}$. Adoption of more flexible star formation histories can increase these masses by a factor of several for the systems with the youngest light-weighted ages (see Topping et al. 2022; Whittler et al. 2022a). The galaxies are found to span a range of sSFRs (9–361 Gyr^{-1}) and light-weighted stellar population ages (3–107 Myr), both derived assuming CSFH. The youngest among them are likely

experiencing a recent upturn or burst of star formation, powering high [O III]+H β equivalent widths (456–3436 \AA). These emission lines can heavily contaminate the NIRCam filters, allowing us to map the spatial distribution of these lines in the following sections.

2.3 Spatially resolved analysis of NIRCam images

We produce spatially resolved continuum maps in the rest-frame UV and optical using the NIRCam images. We use the F200W

images to probe the UV continuum powered by the recently formed stars. This bandpass covers rest-frame 2000–3000 Å at the redshifts of our sample. Two versions of the UV maps are created, one at original resolution in our fiducial reduction and the other matched to the same resolution of the F444W images. The first version shows the morphology at its highest resolution, while the latter is used to uniformly extract the NIRCcam SEDs in subregions of the galaxy. The NIRCcam images also allow for a view of the resolved morphology in the optical, which was inaccessible with the earlier *HST* imaging. The optical continuum is sensitive to light from older stellar populations as well as the nebular continuum powered by young stars. We carefully identify filters that are least impacted by strong emission lines (in particular, $H\beta$, [O III], and $H\alpha$), based on their photometric redshifts and the BEAGLE SEDs. The F356W images are used for four galaxies, F410M for another five galaxies, and F444W for the remaining three sources. These filters sample the continuum emission at rest-frame wavelengths of 4000–5300 Å.

As already mentioned in Section 3.1, the galaxies in our sample power prominent rest-optical emission lines ([O III]+ $H\beta$), which can heavily contaminate one or more NIRCcam filters (F356W, F410M, or F444W). This leads to large flux excesses in the contaminated filters as compared to adjacent continuum-dominated filters (e.g. F356W–F444W < -1 for EGSZ-9314453285 as shown in Table 1). At the redshifts of our sample, the [O III]+ $H\beta$ emission lines fall in the F356W filter for 8, and the F410M for four galaxies. We estimate the continuum from the adjacent filters that are least contaminated by emission lines, which is then subtracted from the image of line-dominated filter. The resulting maps correspond to the distribution of the [O III]+ $H\beta$ emission lines, which we will compare with the UV continuum morphology.

The high-resolution NIRCcam images also allow us to characterize the structural properties for our sample, which are often resolved into multiple components. We visually identify the UV clumps associated with each of galaxy from the NIRCcam F115W, F150W, and F200W images, treating those with a single component as one clump. Following the procedures in Matthee et al. (2017), we constrain the deconvolved half-light radius (r_e) in both UV and optical for individual clumps by fitting 2D asymmetric exponential profile with the IMFIT software (Erwin 2015). We use the PSF constructed by stacking the star images in Section 2.1 for model convolution and estimate the size uncertainties via bootstrap resampling of 100 iterations. For galaxies with multiple clumps, we first fit all clumps together with multicomponent models to constrain their sizes. When a satisfactory multicomponent fit is not possible, we separate and fit the relatively fainter clumps alone, and refit the remaining clumps with multicomponent models. Objects with $r_e < 1$ pixel in the rest-UV filters and 2 pixels in the rest-optical (roughly 1/2 FWHM of the corresponding PSF) are taken as unresolved, and we only list their sizes as upper limits. The rest-UV images have a factor 2 higher resolution than the optical images, leading some of closely separated components resolved in the UV to be blended together on the optical images. We thus place upper limits for their optical size based on the FWHM measured from the radial profile. The resulting measurements are reported in Table 3, with the clumps ordered and labelled by their F200W magnitudes (see the next section).

2.4 Stellar population modelling

The spatial resolution and wide wavelength coverage (from rest-UV to optical) of NIRCcam enables us to constrain the stellar population properties of the individual structures within each galaxy. In particular, the relative strength of rest-UV and optical continuum

and the flux excess due to emission lines place much-improved constraints on the light-weighted stellar population ages and the dust content than was possible with UV data on its own. We derive the stellar population properties for the UV-selected clumps by fitting stellar population models to the PSF-matched NIRCcam photometry. We will also consider the stellar population properties of the lower surface brightness emission that surrounds the clumps, testing whether the clumps are embedded in an older component of the galaxy.

The photometry for clumps and the surrounding medium have been extracted from PSF-homogenized NIRCcam images, with all filters convolved to the same resolution of F444W. The clump photometry is measured with a fixed 6-pixel (0.18 arcsec) diameter aperture, which, at the typical UV sizes of these structures, is large enough to capture the emission from the central region but avoids contamination from the surrounding medium. The aperture loss is taken into account based on the PSF-convolved models from our exponential profile fitting on the F200W images. We also estimate the photometric errors with blank apertures, taking the standard deviation from at least 500 apertures randomly put on the 10×10 arcsec² source-masked images. The photometry for the lower surface brightness medium between the clumps is calculated by masking all pixels within 4 pixels from any clumps to reduce their contamination. To define the outer extent of this inter-clump medium, we use the galaxy segmentation maps produced with PHOTUTILS, including the pixels that are 2σ above the background. The uncertainties are derived from the standard deviation of the background pixels in the same 10×10 arcsec² region.

The NIRCcam photometry is then fit with BEAGLE to derive constraints on the stellar population and dust properties in the different components. The redshifts for each clump and the surrounding medium are fixed to those fitted with the integrated galaxy photometry (see Table 1), allowing us to focus on the SED differences induced by the variations of the stellar population ages or the dust content. We adopt the same models and settings as those for constraining the integrated properties (see Section 2.2), also assuming a CSFH. We report the inferred absolute UV magnitudes, stellar masses, light-weighted stellar population ages, V-band optical depths, and the rest-frame EW [O III]+ $H\beta$ for each of the components in Table 3.

3 RESULTS AND DISCUSSION

In this section, we present our results on the spatially resolved properties of $z \sim 6$ –8 galaxies based on the *JWST*/NIRCcam imaging. We begin by investigating the rest-UV structures in our galaxies (Section 3.1), focusing on the spatially resolved properties of the star-forming clumps revealed in individual galaxies. We then investigate the light distributions of both optical continuum and emission lines, and compare them with the location of the UV clumps (Section 3.2). Lastly, we discuss the nature of the star-forming clumps and their implications for mass assembly in $z > 6$ galaxies (Section 3.3).

3.1 Star-forming clumps in $z \sim 6$ –8 galaxies

Previous studies of $z \sim 7$ galaxies have characterized the resolved structure in early galaxies using *HST*/WFC3 imaging (e.g. Ouchi et al. 2013; Sobral et al. 2015; Bowler et al. 2017; Matthee et al. 2017), revealing important insights into the clumpy nature of luminous star-forming systems. In the following, we take advantage of the higher spatial resolution, improved sensitivity, and additional filters of *JWST*/NIRCcam to build on these studies investigating the internal properties in $z > 6$ galaxies.

Table 3. The physical properties of the individual clumps in each galaxy. Clumps within the same galaxy are labelled and ordered by decreasing apparent F200W magnitudes. The rest-optical sizes are left blank when the long-wavelength NIRCcam resolution does not allow us to resolve two smaller structures identified in the UV.

| Name | M_{UV} (mag) | $r_{e, UV}$ (pc) | $r_{e, opt}$ (pc) | $\log(M_*/M_\odot)$ | Age (Myr) | τ_V | EW [O III]+H β (Å) |
|---------|--------------------------|---------------------|----------------------|------------------------|-------------------|------------------------|-----------------------------|
| 9136-C1 | $-20.17^{+0.02}_{-0.02}$ | <367 | <735 | $8.74^{+0.12}_{-0.16}$ | 173^{+88}_{-71} | $0.02^{+0.03}_{-0.01}$ | 817^{+182}_{-18} |
| 9136-C2 | $-20.05^{+0.06}_{-0.04}$ | <367 | <735 | $8.17^{+0.10}_{-0.10}$ | 48^{+17}_{-12} | $0.00^{+0.00}_{-0.00}$ | 1003^{+162}_{-114} |
| 9136-C3 | $-19.42^{+0.05}_{-0.02}$ | <367 | – | $8.23^{+0.13}_{-0.20}$ | 101^{+53}_{-46} | $0.01^{+0.02}_{-0.00}$ | 949^{+88}_{-87} |
| 9136-C4 | $-18.89^{+0.05}_{-0.09}$ | <367 | <367 | $8.15^{+0.23}_{-0.28}$ | 89^{+110}_{-51} | $0.09^{+0.03}_{-0.04}$ | 1063^{+101}_{-266} |
| 9338-C1 | $-19.65^{+0.05}_{-0.04}$ | 387 ± 39 | 356 ± 13 | $8.66^{+0.09}_{-0.11}$ | 260^{+85}_{-92} | $0.01^{+0.04}_{-0.01}$ | 505^{+16}_{-21} |
| 9338-C2 | $-19.45^{+0.08}_{-0.06}$ | <169 | – | $7.78^{+0.14}_{-0.14}$ | 32^{+18}_{-11} | $0.00^{+0.01}_{-0.00}$ | 1000^{+159}_{-128} |
| 9338-C3 | $-19.27^{+0.08}_{-0.02}$ | <169 | – | $7.61^{+0.11}_{-0.10}$ | 25^{+10}_{-6} | $0.00^{+0.00}_{-0.00}$ | 1129^{+91}_{-119} |
| 9338-C4 | $-18.80^{+0.11}_{-0.06}$ | 409 ± 45 | <339 | $6.94^{+0.02}_{-0.02}$ | 2^{+0}_{-0} | $0.00^{+0.01}_{-0.00}$ | 3841^{+422}_{-166} |
| 9314-C1 | $-19.96^{+0.02}_{-0.03}$ | 285 ± 13 | 416 ± 22 | $7.38^{+0.42}_{-0.02}$ | 2^{+15}_{-0} | $0.00^{+0.00}_{-0.00}$ | 1611^{+631}_{-173} |
| 9314-C2 | $-19.41^{+0.04}_{-0.03}$ | 194 ± 14 | <326 | $7.29^{+0.05}_{-0.03}$ | 3^{+1}_{-1} | $0.06^{+0.03}_{-0.03}$ | 2971^{+242}_{-381} |
| 9179-C1 | $-19.86^{+0.03}_{-0.06}$ | 391 ± 92 | 627 ± 84 | $8.12^{+0.11}_{-0.12}$ | 54^{+22}_{-16} | $0.00^{+0.01}_{-0.00}$ | 735^{+66}_{-143} |
| 9179-C2 | $-19.63^{+0.01}_{-0.01}$ | 330 ± 52 | <325 | $7.60^{+0.20}_{-0.20}$ | 14^{+10}_{-6} | $0.01^{+0.01}_{-0.00}$ | 1504^{+173}_{-111} |
| 9179-C3 | $-19.09^{+0.08}_{-0.06}$ | <162 | – | $7.17^{+0.26}_{-0.06}$ | 5^{+6}_{-2} | $0.04^{+0.03}_{-0.03}$ | 2023^{+44}_{-34} |
| 9271-C1 | $-20.15^{+0.10}_{-0.02}$ | 256 ± 16 | 365 ± 25 | $7.60^{+0.04}_{-0.03}$ | 3^{+1}_{-0} | $0.09^{+0.02}_{-0.03}$ | 2635^{+343}_{-283} |
| 9271-C2 | $-19.11^{+0.03}_{-0.03}$ | 350 ± 32 | 399 ± 29 | $7.69^{+0.10}_{-0.10}$ | 39^{+14}_{-10} | $0.00^{+0.00}_{-0.00}$ | 762^{+94}_{-194} |
| 9271-C3 | $-18.66^{+0.06}_{-0.02}$ | 271 ± 48 | <324 | $7.57^{+0.32}_{-0.29}$ | 39^{+55}_{-23} | $0.01^{+0.03}_{-0.01}$ | 1125^{+98}_{-304} |
| 9419-C1 | $-20.05^{+0.06}_{-0.02}$ | 479 ± 51 | 541 ± 67 | $8.05^{+0.05}_{-0.02}$ | 4^{+2}_{-1} | $0.31^{+0.02}_{-0.02}$ | 2272^{+66}_{-476} |
| 9419-C2 | $-18.32^{+0.02}_{-0.05}$ | 222 ± 35 | <323 | $7.82^{+0.18}_{-0.23}$ | 115^{+86}_{-58} | $0.01^{+0.02}_{-0.00}$ | 658^{+203}_{-219} |
| 9350-C1 | $-20.67^{+0.04}_{-0.03}$ | 251 ± 25 | <322 | $8.74^{+0.17}_{-0.18}$ | 73^{+57}_{-33} | $0.10^{+0.03}_{-0.03}$ | 873^{+90}_{-133} |
| 0020-C1 | $-19.84^{+0.01}_{-0.01}$ | <160 | <320 | $7.87^{+0.08}_{-0.08}$ | 32^{+8}_{-7} | $0.00^{+0.00}_{-0.00}$ | 319^{+72}_{-23} |
| 9135-C1 | $-20.32^{+0.01}_{-0.02}$ | <160 | <320 | $7.57^{+0.04}_{-0.03}$ | 2^{+0}_{-1} | $0.00^{+0.01}_{-0.00}$ | 3777^{+448}_{-307} |
| 9262-C1 | $-19.38^{+0.03}_{-0.04}$ | <153 | <307 | $8.22^{+0.18}_{-0.23}$ | 95^{+77}_{-49} | $0.05^{+0.03}_{-0.04}$ | 680^{+51}_{-132} |
| 9262-C2 | $-19.46^{+0.07}_{-0.05}$ | <153 | <307 | $7.83^{+0.14}_{-0.13}$ | 42^{+21}_{-13} | $0.00^{+0.00}_{-0.00}$ | 539^{+227}_{-88} |
| 9262-C3 | $-19.42^{+0.07}_{-0.04}$ | <153 | <307 | $7.69^{+0.13}_{-0.11}$ | 24^{+11}_{-7} | $0.00^{+0.00}_{-0.00}$ | 1277^{+31}_{-112} |
| 9262-C4 | $-18.89^{+0.01}_{-0.03}$ | <153 | – | $7.57^{+0.25}_{-0.25}$ | 27^{+27}_{-14} | $0.01^{+0.02}_{-0.01}$ | 1232^{+315}_{-364} |
| 9105-C1 | $-20.50^{+0.01}_{-0.01}$ | 248 ± 7 | 364 ± 35 | $8.56^{+0.15}_{-0.16}$ | 51^{+33}_{-20} | $0.12^{+0.02}_{-0.03}$ | 552^{+134}_{-95} |
| 9587-C1 | $-20.59^{+0.01}_{-0.03}$ | 377 ± 14 | 587 ± 23 | $8.36^{+0.20}_{-0.23}$ | 42^{+37}_{-21} | $0.03^{+0.02}_{-0.02}$ | 576^{+64}_{-144} |
| 9587-C2 | $-19.93^{+0.05}_{-0.00}$ | <149 | – | $7.91^{+0.15}_{-0.12}$ | 33^{+16}_{-10} | $0.00^{+0.00}_{-0.00}$ | 527^{+146}_{-13} |
| 9587-C3 | $-19.76^{+0.00}_{-0.02}$ | 374 ± 22 | 506 ± 23 | $8.27^{+0.18}_{-0.20}$ | 91^{+68}_{-43} | $0.01^{+0.01}_{-0.00}$ | 564^{+133}_{-130} |
| 9587-C4 | $-19.66^{+0.08}_{-0.04}$ | <149 | – | $7.81^{+0.13}_{-0.11}$ | 31^{+15}_{-8} | $0.00^{+0.00}_{-0.00}$ | 665^{+163}_{-18} |

The NIRCcam rest-UV images reveal a range of structures in our galaxies (Fig. 1). The majority (8/12) of the samples are resolved into 2–4 clumps, with four of these galaxies showing four clumps. For the eight galaxies, the clumps are separated by ≈ 0.3 –4.3 kpc, with the closest separations found in EGSZ-9338153359 (0.6 kpc), EGSI-9179549499 (0.6 kpc), and EGSY-9587400281 (0.3 kpc). The rest of the sample is well described by a single component. These basic properties are broadly similar to the previous findings derived from *HST* imaging (e.g. Ouchi et al. 2013; Sobral et al. 2015; Bowler

et al. 2017; Matthee et al. 2017). The individual clumps can be quite luminous, with M_{UV} spanning from -18.66 to -20.67 . The clumps often dominate the total UV light of each galaxy, contributing at least 76 per cent of the total F200W flux. The most luminous galaxies ($M_{UV} < -20.7$) appear more likely to contain 3–4 clumps, while the fainter ($M_{UV} > -20.7$) systems tend to show only one single clump. This suggests a multicomponent structure is common in the most luminous galaxies with single clumps being common at lower luminosities, in agreement with previous studies (e.g. Bowler et al.

2017; Bouwens et al. 2022a). These high surface brightness UV structures are sites of vigorous star formation (e.g. Dekel & Burkert 2014; Guo et al. 2015; Vanzella et al. 2017a, 2019).

While these UV structures are often marginally resolved with the WFC3 images, the higher-resolution NIRCcam data allow for improved constraints on their sizes. The UV half-light radius ($r_{e,UV}$) of each clump has been constrained by profile-fitting with 2D exponential models. The derived values range from <149 pc up to 480 pc. The small sizes are comparable to those of complexes of star clusters found at high redshift (e.g. Vanzella et al. 2017a, 2020; Bouwens et al. 2022a), which we will discuss later. The profile fits show that the UV structures are not always symmetric, with ellipticities ranging from 0.0 to 0.7 when resolved. The asymmetric morphology is clear in the images and can be a signature of interactions among the clumps or suggests that these structures are unresolved conglomerations of smaller unrelaxed structures. This is also consistent with the close separations among the clumps found in some systems, where two peaks are found at a distance of just ≈ 2 pixels (≈ 300 pc) with both being very compact unresolved systems (e.g. EGSZ-9338153359 and EGSY-9587400281). Given their close separation, such clumps are likely interacting and will presumably merge together.

Prior to the *JWST* era, our interpretation of these clumpy structures was stunted by the absence of rest-optical imaging at comparable spatial resolution as provided by *HST*. The longer wavelength emission is critical for assessing the age of the clumpy structures, while also allowing dusty or old red structures (that may dominate the galaxy mass while being faint in the UV) to be identified. NIRCcam provides access to the rest-optical emission with some of its LW filters. As described in Section 2.4, we have fit the SEDs of all clumps identified in the images of our galaxy samples using the BAGLE tool. The modelling shows that the stellar masses for the clumps vary from $8.6 \times 10^6 M_{\odot}$ to $5.6 \times 10^8 M_{\odot}$ (assuming CSFH). When combined with the estimated sizes of the clumps, this corresponds to a stellar mass surface density of 8 to $\approx 1117 M_{\odot} \text{pc}^{-2}$. The SED fits also reveal variations of dust content across individual galaxies with multiple components, with the optical depths varying from negligible values up to 0.1–0.3 (e.g. EGSZ-9136950177, EGSZ-9271353221, and EGSZ-9419055074), consistent with gradients identified in ALMA far-IR continuum observations (e.g. Bowler et al. 2022). The variation in UV colour in different clumps is clear in Fig. 1, with some star-forming complexes being much redder in the UV than the others (e.g. those in EGSZ-9136950177 and EGSZ-9271353221).

The ages of the clumpy star-forming complexes give some insight into their nature. The inferred light-weighted ages (assuming a CSFH) are fairly young, with a median age of 36 Myr. This is in general younger than the star-forming clumps uncovered at lower redshifts (e.g. Guo et al. 2015). However, a wide range of ages can also be found within seven of the galaxies. In the case of EGSZ-9338153359, the youngest clump is dominated by an extremely young (2 Myr) stellar population, while another clump 2 kpc away appears much older (>200 Myr). It is clear that at least in the most luminous star-forming galaxies at $z > 6$, the integrated SED is comprised of the sum of several distinctly different stellar populations with varying light-weighted ages and dust content.

However, as recently shown by Whitler et al. (2022a), even galaxies with light dominated by extremely young massive stars, a significant number of old stars can still be hidden. By adopting the same approach as Whitler et al. (2022a), we fit the SEDs of the youngest star-forming clumps with non-parametric SFH, using the PROSPECTOR (Johnson et al. 2021) code (also see Whitler et al. 2022b). We adopt the continuity prior with a fixed redshift $z_{\text{form}} = 20$

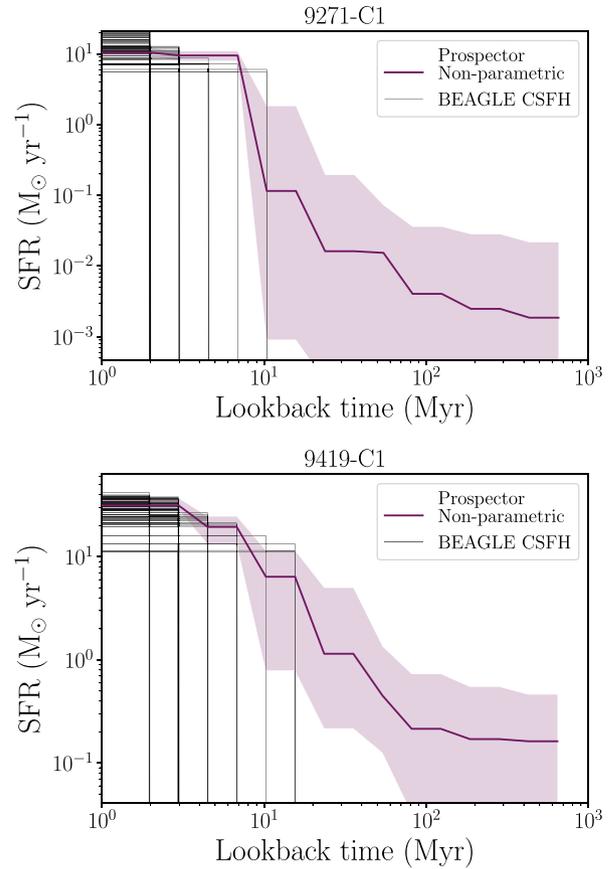


Figure 3. Non-parametric SFH fits with PROSPECTOR (magenta) to two extremely young clumps, 9271-C1 and 9419-C1, following methodology of Whitler et al. (2022a). Also shown in black are their BEAGLE CSFH fits (black), which favours extremely young light-weighted ages (< 5 Myr). However, with the non-parametric SFH fits, it is clear that old stars with age > 50 Myr could still be hidden in these systems, leading to a total stellar mass increasing by a factor of ~ 5 . Longer wavelength imaging from MIRI will help clarify the presence of these older stars.

at which the star formation starts. In doing so, we allow for significant amount of star formation at earlier epochs than CSFH models in cases where the galaxy has experienced a recent burst. In Fig. 3, we present the resulting constraints on the past star formation with PROSPECTOR for two of the clumps, i.e. 9419-C1 and 9135-C1. The results suggest that stars older than 50 Myr could still contribute up to 25 per cent of the total stellar mass of the star-forming complexes that have light-weighted CSFH ages younger than 5 Myr, increasing the derived stellar mass by a factor of a few times. In this case, the clumps (> 150 pc in scale) identified in NIRCcam would potentially be dominated by the light from very young recently formed star clusters (< 10 pc in scale and unresolved in our imaging), but would also contain fainter older clusters or field stars from previous generations of star formation. Such old stars are seen in nearby complexes with very young star clusters (e.g. Grebel & Chu 2000; Aloisi et al. 2007; Corbin et al. 2008).

3.2 Spatially resolved maps of optical continuum and [O III]+H β emission

To understand the variations of the clump properties in more detail, we make spatially resolved maps of the rest-optical continuum,

comparing them against the UV maps. Based on the redshifts and the BEAGLE SED fits to the integrated photometry, we are able to identify filters that are least impacted by nebular lines and thus are dominated by the continuum emission from the nebular gas and older stellar populations. We present the optical continuum morphology in Fig. 4. In general, the optical morphology appears to also be clumpy, resembling the structures seen in the UV. We do not find evidence for very red clumps dominated by extremely old stellar population or obscured star formation that were previously hidden in the UV. Such reddened nuclear structures may appear at later epochs or in higher mass reionization-era galaxies. The overall very similar rest-UV and rest-optical morphology for $z \gtrsim 6$ galaxies is also consistent with the recent findings with the NIRCcam imaging in the GLASS-JWST program (Treu et al. 2022; Yang et al. 2022). For the systems in this sample, the rest-optical emission peaks where the UV clumps are located. For each clump, the offsets between the optical and UV peaks ($\lesssim 0.03$ arcsec) are found to be within the astrometric uncertainties (0.015–0.025 arcsec). It is apparent in Fig. 4 that the ratio of UV to optical luminosity varies from clump to clump, with some of UV-bright regions significantly fainter at longer wavelengths (e.g. 9271-C2), reflecting the variations in age and attenuation discussed above. This also leads to observable offsets between the integrated barycentre of the two maps (i.e. the first-moment flux weighted centre; see Bowler et al. 2017), with the largest offset found in EGSZ-9338153359 at 0.16 arcsec.

The strength of [O III]+H β emission lines tracks the locations of H II regions. The equivalent width has been shown to strongly correlate with the age of the stellar population (and gas conditions) in the extreme emission line galaxy regime that is common at $z > 6$ (e.g. De Barros et al. 2019; Tang et al. 2019; Endsley et al. 2021). Much more prominent line emission is seen in very young stellar populations with weak underlying optical continuum. Taking advantage of the NIRCcam LW filters that are heavily contaminated by these lines, we map the [O III]+H β emission to provide additional insights into the distribution of the H II regions and the age variations among clumps. We carefully isolate these filters by their clear flux excess relative to the continuum filters in the BEAGLE SEDs at the inferred redshift, and then subtract the underlying optical continuum emission (which we described above). In Fig. 5, we present the emission line maps for four galaxies with large inferred variations of clump ages from our SED fits. It is clear that the youngest UV structures (e.g. 9338-C2, and 9271-C1) are found where the line emission is strongest relative to the continuum. The brightest clumps in the UV do not always power large flux excess in the line-dominated filters. We find that this in particular occurs towards clumps with older stellar population ages (e.g. 95–260 Myr for 9338-C1 and 9262-C1 assuming a CSFH). Because we find significant age variations in clumps across individual galaxies, we also find varying EW of the [O III]+H β emission lines. This is also consistent with the recently studies that have reported variations of the FIR [O III] 88 μ m emission line properties that also traces the ionized gas in $z \simeq 7$ galaxies (Akins et al. 2022; Witstok et al. 2022; Wong et al. 2022). Measurements of the emission line EWs in the NIRCcam photometry help to break the degeneracy between age and dust, improving constraints on both. For example, in EGSZ-941905574, the brightest clump (9419-C1) has clearly red UV colours (F150W-F200W = 0.33 mag), but powers a prominent knot on the [O III]+H β map. The BEAGLE modelling favours a younger stellar population age (4^{+2}_{-1} Myr) than the clump in this system with bluer UV colours but negligible emission line excesses (115^{+86}_{-58} Myr). Many spectral properties (i.e. the [O III]/[O II] ratio) correlate with the [O III]+H β EW (e.g. Tang et al. 2019; Du

et al. 2020; Tang et al. 2021). The variations in [O III]+H β EW across individual galaxies in our sample suggest that there are likely to be strong gradients in line ratios across different clumps in a given galaxy. Care must be taken to interpret future NIRSpc/MSA observations that may only be sensitive to one of several clumps in an individual galaxy. The measured line ratios may not be representative for all bright star-forming complexes within the galaxy.

While many clumps in our galaxies show very young light-weighted ages ($\lesssim 25$ Myr), it is conceivable that they may be embedded in an older stellar population that is more smoothly distributed. To test this, we constrain the stellar population properties of the lower surface brightness interclump medium by fitting its NIRCcam SEDs with BEAGLE in the same way as that for the clumps. As described in Section 2, the photometry for this region is extracted by summing the flux at 2σ above the background, but masking the pixels (distance < 4 pixels) close to the location of any clumps. We also consider different choices of masking radius (5 and 6 pixels), but we find consistent results on the inferred stellar population ages for the medium. This suggests that our results are unlikely to be biased by contamination from the clump flux. In Fig. 6, we present an example of resulting fits (EGSZ-9271353221), along with the apertures used to extract the photometry. In this galaxy, the interclump region also shows a flux excess in the F356W filter compared to the adjacent continuum-dominated filter, with strength in between the three clumps. While slightly older than the brightest clump (9271-C1, at 3^{+1}_0 Myr), it has a clearly smaller light-weighted age (10^{+7}_{-7} Myr) than the other two clumps (≈ 33 Myr, all assuming a CSFH). The light-weighted ages for the interclump medium still fall in the age range spanned by the clumps when we use different masking radius (15–20 Myr with masking radius 5–6 pixels). When considering the full sample, our results suggest that the interclump medium is not always older than all of the clumps, with inferred ages spanning 2–83 Myr. When the lower surface brightness regions are found to be older than 50 Myr, clumps with comparable ages can also be seen in the same system. It is conceivable that such extended and diffuse structures consist of stars stripped off from the clumps of similar ages during their interactions.

3.3 The nature of compact star-forming clumps

The clumpy star-forming complexes identified in this paper resemble compact structures previously uncovered at $z \gtrsim 6$, leveraging the magnification provided by gravitational lensing (e.g. Kawamata et al. 2018; Bouwens et al. 2021, 2022a; Meštrić et al. 2022). In Fig. 7 (left-hand panel), we show the position of these clumps in the plane of rest-UV size and UV luminosity. For reference, we compare to magnification-corrected measurements of the gravitationally lensed galaxies identified in the *Hubble* Frontier Fields from Bouwens et al. (2022a). Both the lensed and unlensed clumps follow a similar relationship between the luminosity and size, with the sources presented in this paper mostly probing the luminous end (given the absence of magnification). The star-forming clumps are not surprisingly (on average) smaller than individual Lyman Break Galaxies (LBGs) at these redshifts (adopting the Bouwens et al. 2022a linear fit of the luminosity–size relation for the Shibuya et al. 2015 LBGs), occupying a region more similar to the star cluster complexes found at lower redshifts (e.g. Bastian et al. 2006; Livermore et al. 2015; Messa et al. 2019; Zanella et al. 2019). The resolution limit of NIRCcam at these redshift prevents us from identifying substructures within the ≈ 150 pc scales spanned by many of our clumps. It is likely that several young star clusters (≈ 10 pc in size) are dominating the light from our clumps. Characterizing such smaller structures requires

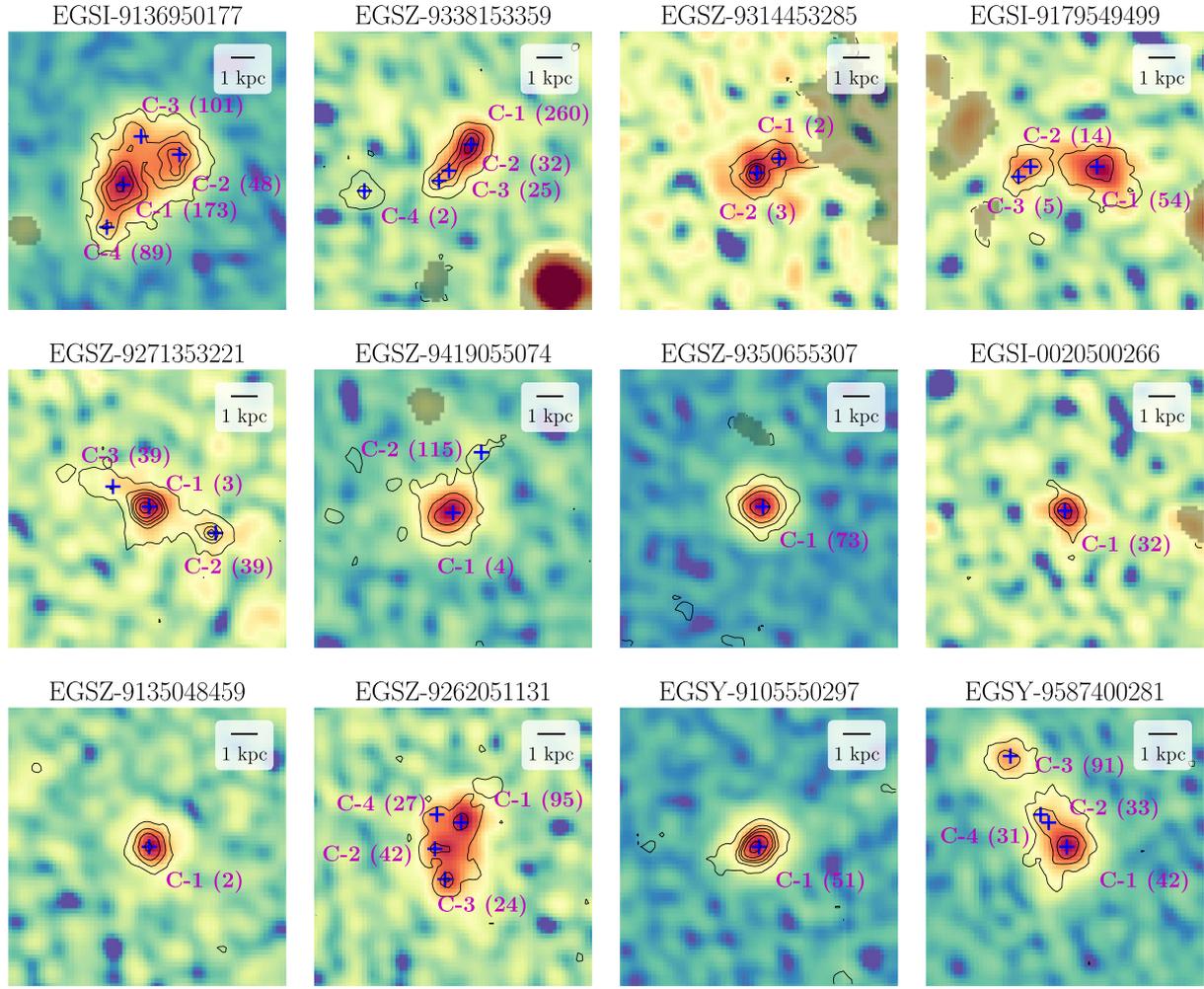


Figure 4. Comparison of the rest-optical continuum with the rest-frame UV continuum in 12 galaxies at $6 < z < 8$, constraining the relative distribution of old and young stars in reionization era galaxies. The rest-optical continuum is shown in colour (with red denoting bright optical continuum), with rest-UV overlaid as contours. The locations of the clumps identified in the short-wavelength NIRCcam photometry are marked with a blue cross, and the clump ID is also shown in magenta. We also note the stellar population age (assuming CSFH) in Myr for each clump in brackets right after the clump ID. Nearby contaminants have been shaded in grey. The rest-optical continuum is as clumpy as the rest-UV, with emission peaking in the young star-forming complexes. The images do not reveal optically bright clumps that are not seen in the UV, consistent with the majority of mass being contained in the star-forming complexes.

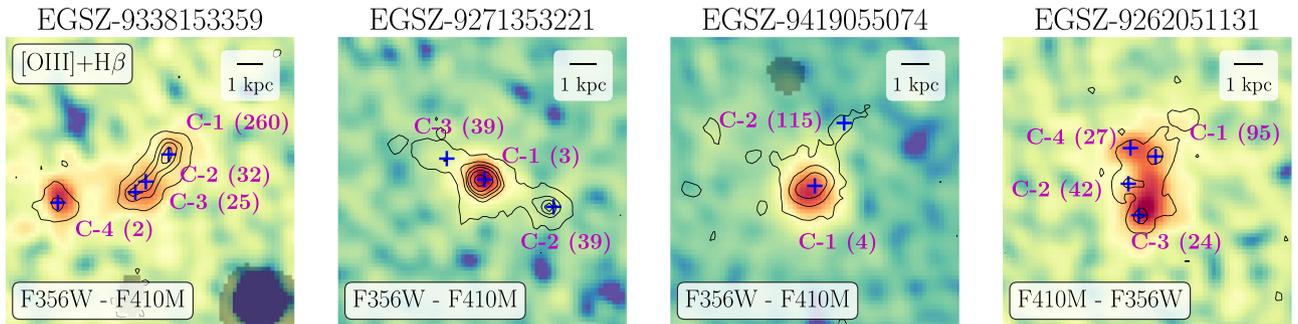


Figure 5. Spatial maps of $[O III]+H\beta$ emission for four objects in our sample. UV continuum contours are overlaid. Similar to Fig. 4, the locations of individual UV clumps are marked with a cross with the ID shown in magenta and the stellar population age (in Myr, assuming CSFH) in brackets. To create line maps, we use filters (denoted in bottom-left of each panel) that are dominated by strong emission lines (see Fig. 2), and subtract the underlying optical continuum using adjacent filters with minimal line contributions (the second filter listed in the bottom-left). The $[O III]+H\beta$ emission is found to vary considerably across 1 kpc scales in $z \gtrsim 6$ galaxies.

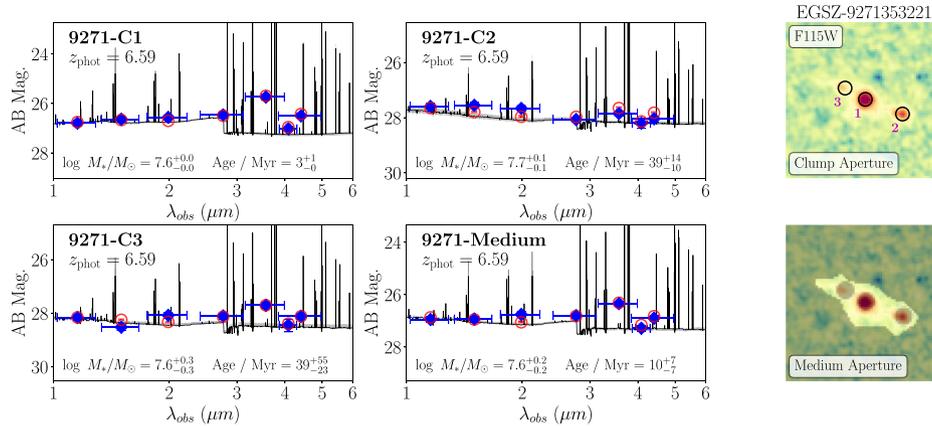


Figure 6. Resolved NIRCcam SED fitting of individual clumps within a $z \simeq 6.59$ galaxy in our sample. The four left-hand panels show the SEDs and BEAGLE model-fits, while the right-hand panel shows the apertures used for the clumps and the inter-clump medium. The SEDs reveal clear light-weighted age differences in the different star complexes, clearly indicated by varying emission line excesses across the galaxy.

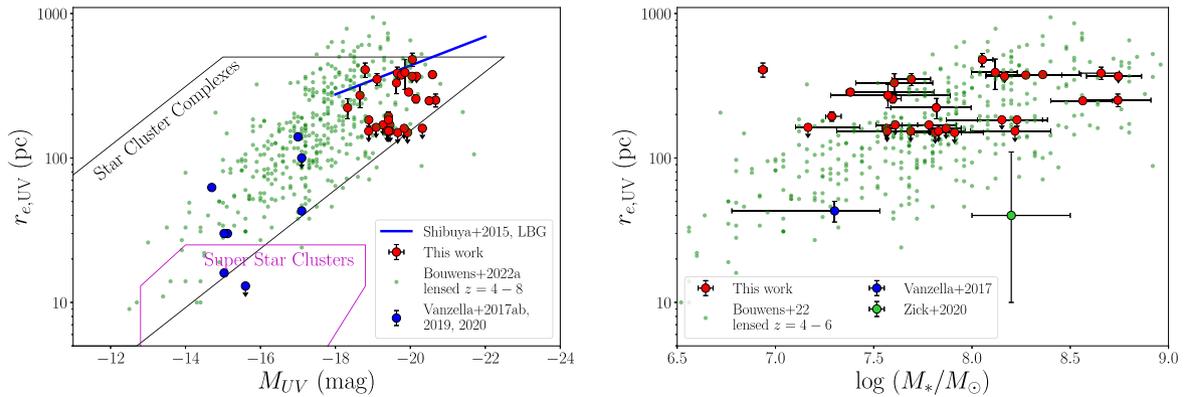


Figure 7. Relationship between size and UV luminosity (left-hand panel) and size and stellar mass (right-hand panel). The star-forming complexes identified in this work are denoted as red circles, with upper limits marking systems that are unresolved. Following Bouwens et al. 2021, we also show in the left-hand panel the regions occupied by star cluster complexes and super star clusters with polygons. The luminosity and size ranges spanned by these polygons match observations of star clusters at lower redshifts (e.g. Bastian et al. 2006; Livermore et al. 2015; Messa et al. 2019; Zanella et al. 2019). The clumps in the $6 < z < 8$ galaxies of this paper are consistent with the relation between size and luminosity derived from gravitationally lensed galaxies in the *Hubble* Frontier Fields, occupying the larger end of the relation (Bouwens et al. 2022a). These clumps correspond to star-forming complexes, likely powered by multiple smaller super star clusters that are below our resolution limit. We also show the sizes previously inferred for highly magnified stellar clumps in $z = 2-6$ gravitationally lensed galaxies that are thought to be candidates for proto globular clusters (e.g. Vanzella et al. 2017a, b; Zick et al. 2018; Vanzella et al. 2019, 2020). It is clear that surveys using gravitational lensing with higher spatial resolution will be required to characterize these cluster-scale components.

gravitational lensing (e.g. Vanzella et al. 2017a, b, 2019, 2020). NIRCcam imaging of massive galaxy clusters will allow many such star clusters to be identified, complementing the characterization of larger clump complexes that is possible in the field.

The internal structure of $z \gtrsim 6$ galaxies, with most of the stellar mass locked in bright star-forming complexes, points to a rapid phase of mass assembly, consistent with the large sSFR expected at these high redshifts (e.g. Leethochawalit et al. 2022; Stefanon et al. 2022; Topping et al. 2022). The presence of multiple clumpy components separated by $< 1-4$ kpc (and asymmetric single components) suggests merger activity may be common, as suggested by pair counts (Duncan et al. 2019). In the right-hand panel of Fig. 7, we show the mass–size relationship of the star-forming complexes, as compared to the faint lensed galaxies from Bouwens et al. (2022a). We note that the lensed galaxies do not have rest-optical measurements, so the stellar masses have been converted assuming a fixed stellar age, consistent with what has been adopted in (Bouwens et al. 2022a; also see Kikuchi et al. 2020). The position of the UV-bright clumps on the size–stellar

mass plane implies large stellar mass surface densities, ranging from 8 to $1117 M_{\odot} \text{pc}^{-2}$. The largest values approach those measured for the most compact star-forming complexes uncovered with lensing (e.g. Vanzella et al. 2017a; Zick et al. 2018), and are potentially sites of proto-globular clusters in formation (e.g. D’Ercole et al. 2008). The assembly and merging of these dense structures may dominate the mass growth of the galaxy (e.g. Ouchi et al. 2013; Conselice 2014), helping eventually to build early bulge-like structures at high redshifts.

4 SUMMARY

We characterize the internal structure of 12 star-forming galaxies at $z \simeq 6-8$ using *JWST*/NIRCcam imaging of the EGS field. The galaxies are bright ($F200W = 24.9-26.6$) and were selected in *HST* imaging of the EGS field. The NIRCcam images sample the SEDs from the rest-frame UV to optical with up to 150 pc resolution, enabling maps to

be made of the relative distribution of young star-forming regions and old stellar populations. We also create maps of [O III]+H β emission using filters dominated by strong emission lines, tracking the locations of the H II regions. We characterize the size distribution and SED-based properties of the subcomponents identified in each galaxy. We summarize our primary conclusions below.

1. The $z \gtrsim 6$ galaxies generally appear clumpy in the rest-UV, with the light dominated by star-forming complexes (or ‘clumps’) with stellar masses of $9 \times 10^6 M_{\odot}$ – $7 \times 10^8 M_{\odot}$. The UV-detected clumps are generally very compact in the NIRC*am* images with median effective radii of 236 pc (ranging from <150 to 480 pc). Most of the galaxies in our sample (8 of 12) are comprised of multiple bright clumps with typical separations of 0.3–4.3 kpc, similar to what has been seen in UV-luminous galaxies at $z \simeq 7$ (e.g. Bowler et al. 2017; Matthee et al. 2017). The bright star-forming complexes are embedded in a more diffuse (‘interclump’) UV-emitting stellar population. In our sample, we find that the clumps comprise on average at least 76 per cent of the UV luminosity. The star-forming complexes vary significantly in their UV continuum colours, with variations seen within individual galaxies (as also seen at *HST* resolution by Bowler et al. 2022).

2. We characterize the ages of the star-forming complexes using the SEDs of the clumps identified in the NIRC*am* images. The light-weighted ages of the clumps in $z \gtrsim 6$ galaxies tend to be young, with a median of 36 Myr (here assuming CSFH), much younger than the clumps seen in galaxies at $z \simeq 2$. Within a given galaxy, the clumps can vary significantly in age, with some complexes extremely young (<5 Myr) and others several kpc away showing much older stellar populations (>100 Myr). When we adopt more flexible star formation histories, we find that the youngest clumps ($\lesssim 5$ Myr) can be fit with non-negligible contributions from older stellar populations (e.g. Whitler et al. 2022a, b; Tacchella et al. 2022). It is plausible that these very young clumps ($\simeq 150$ pc in size) are dominated by the light from a small recently formed super star cluster that outshines the light of older stars in its vicinity.

3. The longer wavelength NIRC*am* imaging (2–5 μm) allows us to test whether the young UV-emitting star-forming complexes surround a central nuclear structure with older stars that dominates the mass. In the 12 $z \gtrsim 6$ galaxies considered in this paper, we find that the distribution of rest-optical continuum closely matches that seen in the rest-UV, with emission peaking in the bright star-forming complexes. We find no evidence in the rest-optical for old and red central clumps, which are undetected (or faint) in the rest-frame UV. Such old nuclear structures may not yet be present in the brightest reionization-era galaxies. Instead, a significant fraction of the galaxy mass appears to be situated in the clumpy star-forming complexes.

4. We characterize the properties of the regions between the clumps, testing whether the star-forming complexes are embedded in an older and more smoothly distributed stellar population. In some cases, we do find that the interclump medium is dominated by an old ($\gtrsim 100$ Myr) stellar population, which contributes a significant amount of mass to the galaxy. However, in these galaxies, there is nearly always at least one UV-bright clump with a similarly old age as the more diffuse lower surface brightness population. The data, therefore, do not suggest the UV-bright clumps are situated in a uniformly older population of stars.

5. We create maps of [O III]+H β emission using (continuum-subtracted) line-dominated filters in the LW NIRC*am* channels, enabling the distribution of H II regions to be mapped across the galaxies. We find significant gradients in the [O III]+H β strength across individual galaxies, with some star-forming complexes powering much stronger line emission (for similar optical continuum

strength) than other complexes located $\simeq 1$ kpc away. These variations are likely driven in part by the differences in the stellar population ages of the underlying star-forming components. Given the correlation between rest-optical spectral properties and [O III] EW (e.g. Tang et al. 2019), we expect significant variations in line ratios across UV-bright reionization era galaxies. Care must be taken in interpreting results from NIRS*pec* MSA observations, which may only probe a small sub-region within these systems.

6. The UV sizes and luminosities of the star-forming complexes in our sample are consistent with the relationship between effective radii and M_{UV} derived for faint gravitationally lensed galaxies in the Hubble Frontier Fields (Bouwens et al. 2022a), sampling the higher mass end probed by the lensing fields. The light from the clumps are likely powered by one or more super star clusters below our $\simeq 150$ pc resolution limit, perhaps providing signposts of protoglobular clusters in formation.

With most of their stellar mass found to be in luminous star-forming complexes $\simeq 150$ –480 pc in size, reionization-era galaxies are clearly in a phase of rapid assembly. These structures may eventually merge together (e.g. Ouchi et al. 2013; Conselice 2014), building denser nuclear structures. Future observations with *JWST* will soon build on this picture. NIRS*pec* integral field spectroscopy targeting bright $z \gtrsim 6$ galaxies will soon reveal the kinematics and dynamical mass of the individual star-forming components, while longer wavelength imaging with MIRI will help clarify the contribution of old stellar populations to the youngest star-forming complexes. Subparsec resolution cosmological simulations will also complement our understanding of the conditions for forming such star-forming complexes in early galaxies (e.g. Calura et al. 2022). Collectively, these studies will help establish the origin of the bright star-forming complexes in $z \gtrsim 6$ galaxies and their role in the build-up of early galaxy structures.

ACKNOWLEDGEMENTS

The authors thank the anonymous referee for their helpful comments that improved and strengthened this paper. DPS acknowledges support from the National Science Foundation through the grant AST-2109066. RE acknowledges funding from NASA *JWST*/NIRC*am* contract to the University of Arizona, NAS5-02015. LW acknowledges support from the National Science Foundation Graduate Research Fellowship under grant no. DGE-2137419.

The authors thank Jacopo Chevallard for the use of the BEAGLE tool used for much of our SED fitting analysis. We thank Gabe Brammer for providing the optical imaging of the EGS as part of CHARGE program. This material is based in part upon High Performance Computing (HPC) resources supported by the University of Arizona TRIF, UITS, and Research, Innovation, and Impact (RII) and maintained by the UArizona Research Technologies department.

DATA AVAILABILITY

The *JWST* and *HST* imaging data used in this work are available through the MAST Portal (<https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html>). The photometry and analysis code used in this work will be shared upon reasonable request to the corresponding author.

REFERENCES

- Akins H. B. et al., 2022, *ApJ*, 934, 64
 Aloisi A. et al., 2007, *ApJ*, 667, L151
 Bagley M. B. et al., 2022, preprint ([arXiv:2211.02495](https://arxiv.org/abs/2211.02495))

- Bastian N., Emsellem E., Kissler-Patig M., Maraston C., 2006, *A&A*, 445, 471
- Bouwens R. J. et al., 2015, *ApJ*, 803, 34
- Bouwens R. J. et al., 2016, *ApJ*, 830, 67
- Bouwens R. J., Stefanon M., Oesch P. A., Illingworth G. D., Nanayakkara T., Roberts-Borsani G., Labbé I., Smit R., 2019, *ApJ*, 880, 25
- Bouwens R. J., Illingworth G. D., van Dokkum P. G., Ribeiro B., Oesch P. A., Stefanon M., 2021, *AJ*, 162, 255
- Bouwens R. J., Illingworth G. D., van Dokkum P. G., Oesch P. A., Stefanon M., Ribeiro B., 2022a, *ApJ*, 927, 81
- Bouwens R. J., Illingworth G., Ellis R. S., Oesch P., Paulino-Afonso A., Ribeiro B., Stefanon M., 2022b, *ApJ*, 931, 81
- Bouwens R. J. et al., 2022c, *ApJ*, 931, 160
- Bowler R. A. A., Dunlop J. S., McLure R. J., McLeod D. J., 2017, *MNRAS*, 466, 3612
- Bowler R. A. A., Cullen F., McLure R. J., Dunlop J. S., Avison A., 2022, *MNRAS*, 510, 5088
- Bradley L. et al., 2021, astropy/photutils: 1.3.0, Zenodo, available at <https://doi.org/10.5281/zenodo.5796924>
- Bressan A., Marigo P., Girardi L., Salasnich B., Dal Cero C., Rubele S., Nanni A., 2012, *MNRAS*, 427, 127
- Bruzual G., Charlot S., 2003, *MNRAS*, 344, 1000
- Calura F. et al., 2022, *MNRAS*, 516, 5914
- Chabrier G., 2003, *PASP*, 115, 763
- Chen Y., Bressan A., Girardi L., Marigo P., Kong X., Lanza A., 2015, *MNRAS*, 452, 1068
- Chevallard J., Charlot S., 2016, *MNRAS*, 462, 1415
- Conselice C. J., 2014, *ARA&A*, 52, 291
- Corbin M. R., Kim H., Jansen R. A., Windhorst R. A., Cid Fernandes R., 2008, *ApJ*, 675, 194
- D’Ercole A., Vesperini E., D’Antona F., McMillan S. L. W., Recchi S., 2008, *MNRAS*, 391, 825
- Davis M. et al., 2007, *ApJ*, 660, L1
- De Barros S., Oesch P. A., Labbé I., Stefanon M., González V., Smit R., Bouwens R. J., Illingworth G. D., 2019, *MNRAS*, 489, 2355
- Dekel A., Burkert A., 2014, *MNRAS*, 438, 1870
- Du X., Shapley A. E., Tang M., Stark D. P., Martin C. L., Mobasher B., Topping M. W., Chevallard J., 2020, *ApJ*, 890, 65
- Duncan K. et al., 2019, *ApJ*, 876, 110
- Endsley R., Stark D. P., Chevallard J., Charlot S., 2021, *MNRAS*, 500, 5229
- Endsley R., Stark D. P., Whitler L., Topping M. W., Chen Z., Plat A., Chisholm J., Charlot S., 2022, preprint ([arXiv:2208.14999](https://arxiv.org/abs/2208.14999))
- Erwin P., 2015, *ApJ*, 799, 226
- Ferland G. J. et al., 2013, *Rev. Mex. Astron. Astrofis.*, 49, 137
- Finkelstein S. L. et al., 2015, *ApJ*, 810, 71
- Finkelstein S. L. et al., 2017, The Cosmic Evolution Early Release Science (CEERS) Survey, JWST Proposal ID 1345. Cycle 0 Early Release Science
- Grebel E. K., Chu Y.-H., 2000, *AJ*, 119, 787
- Grogin N. A. et al., 2011, *ApJS*, 197, 35
- Guo Y. et al., 2015, *ApJ*, 800, 39
- Gutkin J., Charlot S., Bruzual G., 2016, *MNRAS*, 462, 1757
- Hashimoto T. et al., 2018, *Nature*, 557, 392
- Hutchison T. A. et al., 2019, *ApJ*, 879, 70
- Inoue A. K., Shimizu I., Iwata I., Tanaka M., 2014, *MNRAS*, 442, 1805
- Johnson B. D., Leja J., Conroy C., Speagle J. S., 2021, *ApJS*, 254, 22
- Kawamata R., Ishigaki M., Shimasaku K., Oguri M., Ouchi M., 2015, *ApJ*, 804, 103
- Kawamata R., Ishigaki M., Shimasaku K., Oguri M., Ouchi M., Tanigawa S., 2018, *ApJ*, 855, 4
- Kikuchihara S. et al., 2020, *ApJ*, 893, 60
- Koekemoer A. M. et al., 2011, *ApJS*, 197, 36
- Laporte N., Meyer R. A., Ellis R. S., Robertson B. E., Chisholm J., Roberts-Borsani G. W., 2021, *MNRAS*, 505, 3336
- Lee B. et al., 2013, *ApJ*, 774, 47
- Leethochawalit N. et al., 2022, preprint ([arXiv:2207.11135](https://arxiv.org/abs/2207.11135))
- Leonova E. et al., 2022, *MNRAS*, 515, 5790
- Livermore R. C. et al., 2015, *MNRAS*, 450, 1812
- Marrone D. P. et al., 2018, *Nature*, 553, 51
- Matthee J. et al., 2017, *ApJ*, 851, 145
- Matthee J. et al., 2019, *ApJ*, 881, 124
- McLeod D. J., McLure R. J., Dunlop J. S., 2016, *MNRAS*, 459, 3812
- Messa M., Adamo A., Östlin G., Melinder J., Hayes M., Bridge J. S., Cannon J., 2019, *MNRAS*, 487, 4238
- Meštrić U. et al., 2022, *MNRAS*, 516, 3532
- Oke J. B., Gunn J. E., 1983, *ApJ*, 266, 713
- Ouchi M. et al., 2013, *ApJ*, 778, 102
- Pei Y. C., 1992, *ApJ*, 395, 130
- Roberts-Borsani G. W. et al., 2016, *ApJ*, 823, 143
- Robertson B. E., 2022, *ARA&A*, 60, 121
- Shibuya T., Ouchi M., Harikane Y., 2015, *ApJS*, 219, 15
- Smit R. et al., 2018, *Nature*, 553, 178
- Sobral D., Matthee J., Darvish B., Schaerer D., Mobasher B., Röttgering H. J. A., Santos S., Hemmati S., 2015, *ApJ*, 808, 139
- Stark D. P. et al., 2017, *MNRAS*, 464, 469
- Stark D. P., 2016, *ARA&A*, 54, 761
- Stefanon M., Bouwens R. J., Illingworth G. D., Labbé I., Oesch P. A., Gonzalez V., 2022, *ApJ*, 935, 94
- Tacchella S. et al., 2022, *ApJ*, 927, 170
- Tang M., Stark D. P., Chevallard J., Charlot S., 2019, *MNRAS*, 489, 2572
- Tang M., Stark D. P., Chevallard J., Charlot S., Endsley R., Congiu E., 2021, *MNRAS*, 501, 3238
- Tang M., Stark D. P., Ellis R. S., 2022, *MNRAS*, 513, 5211
- Topping M. W. et al., 2022, *MNRAS*, 516, 975
- Treu T. et al., 2022, preprint ([arXiv:2207.13527](https://arxiv.org/abs/2207.13527))
- Vanzella E. et al., 2017a, *MNRAS*, 467, 4304
- Vanzella E. et al., 2017b, *ApJ*, 842, 47
- Vanzella E. et al., 2019, *MNRAS*, 483, 3618
- Vanzella E. et al., 2020, *MNRAS*, 494, L81
- Whitler L., Stark D. P., Endsley R., Leja J., Charlot S., Chevallard J., 2022a, preprint ([arXiv:2206.05315](https://arxiv.org/abs/2206.05315))
- Whitler L., Endsley R., Stark D. P., Topping M., Chen Z., Charlot S., 2022b, preprint ([arXiv:2208.01599](https://arxiv.org/abs/2208.01599))
- Witstok J. et al., 2022, *MNRAS*, 515, 1751
- Wong Y. H. V. et al., 2022, *ApJ*, 929, 161
- Wuyts S. et al., 2012, *ApJ*, 753, 114
- Yang L. et al., 2022, *ApJL*, 938, L17
- Zanella A. et al., 2019, *MNRAS*, 489, 2792
- Zick T. O., Weisz D. R., Boylan-Kolchin M., 2018, *MNRAS*, 477, 480

This paper has been typeset from a $\text{\TeX}/\text{\LaTeX}$ file prepared by the author.