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The BlueTides Mock Image Catalogue: Simulated observations of high-redshift galaxies and predictions for JWST imaging surveys

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ABSTRACT

We present a mock image catalogue of ~100,000 $M_{UV} \approx -22.5$ to $-19.6$ mag galaxies at $z = 7$–12 from the BlueTides cosmological simulation. We create mock images of each galaxy with the James Webb (JWST), Hubble, Roman, and Euclid Space Telescopes, as well as Subaru, and VISTA, with a range of near- and mid-infrared filters. We perform photometry on the mock images to estimate the success of these instruments for detecting high-$z$ galaxies. We predict that JWST will have unprecedented power in detecting high-$z$ galaxies, with a 95% completeness limit at least 2.5 magnitudes fainter than VISTA and Subaru, 1.1 magnitudes fainter than Hubble, and 0.9 magnitudes fainter than Roman, for the same wavelength and exposure time. Focusing on JWST, we consider a range of exposure times and filters, and find that the NIRCam F356W and F277W filters will detect the faintest galaxies, with 95% completeness at $m \approx 27.4$ mag in 10ks exposures. We also predict the number of high-$z$ galaxies that will be discovered by upcoming JWST imaging surveys. We predict that the COSMOS-Web survey will detect $\sim 1000$ $M_{1500\AA} < -20.1$ mag galaxies at $6.5 < z < 7.5$, by virtue of its large survey area. JADES-Medium will detect almost 100% of $M_{1500\AA} < -20$ mag galaxies at $z < 8.5$ due to its significant depth, however with its smaller survey area it will detect only $\sim 100$ of these galaxies at $6.5 < z < 7.5$. Cosmic variance results in a large range in the number of predicted galaxies each survey will detect, which is more evident in smaller surveys such as CEERS and the PEARLS NEP and GOODS-S fields.

Key words: galaxies: evolution – galaxies: high-redshift – galaxies: formation.

1 INTRODUCTION

The detection of the most distant, high-redshift galaxies is a key goal for upcoming surveys with new telescopes. To date, the highest-redshift spectroscopically confirmed galaxy was found at $z = 11$ (Oesch et al. 2016; Jiang et al. 2020), with potential candidates recently discovered at $z \sim 13$ (Harikane et al. 2022). Finding these most distant objects, and obtaining a statistical sample of fainter, more typical high-$z$ ($z \geq 7$) galaxies, provides vital insights into galaxy formation and growth in the early Universe. These sources are also expected to be the primary driver of the reionization of the Universe, and so understanding their population provides information on the mechanisms and timelines of cosmic reionization.

The majority of high-$z$ sources so far have been discovered by medium and deep surveys with the Hubble Space Telescope (HST), such as the Hubble Deep Field (Williams et al. 1996), Hubble Ultra Deep Field (HUDF; Beckwith et al. 2006; Koekemoer et al. 2013), Great Observatories Origins Deep Survey (GOODS; Giavalisco et al. 2004), Cosmic Evolution Survey (COSMOS; Scoville et al. 2007; Koekemoer et al. 2007), Wide Field Camera 3 (WFC3) Early Release Science (ERS) program (Windhorst et al. 2011), Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS; Grogin et al. 2011), and untargeted pure-parallel surveys such as HPIIES (Yan et al. 2011) and BoRG (Trenti et al. 2011). One key strategy is to search for magnified high-$z$ galaxies via gravitational lensing from a foreground galaxy cluster, which has resulted in successful detections of a much fainter galaxy population (e.g. Zheng et al. 2014; Ishigaki et al. 2015; Livermore et al. 2017; Coe et al. 2019; Salmon et al. 2020). Ground-based near-infrared telescopes such as the United Kingdom Infrared Telescope Deep Sky Survey (UKIDSS), the Visible and Infrared Survey Telescope for Astronomy (VISTA), and Subaru, have also played a key role (e.g. Kashikawa et al. 2004; McLure et al. 2009; Bowler et al. 2015).

The commencement of science operations with the James Webb Space Telescope (JWST) will launch a new era of high-$z$ galaxy
studies. With highly sensitive imaging capabilities with NIRCam and MIRI from 0.6–5 and 5.6–25.5 microns respectively, JWST will be able to detect and characterize high-z galaxies in the rest-frame UV and optical in unprecedented detail, and discover fainter and more distant objects than currently possible. Its spectroscopic capabilities will allow for secure redshift measurements, and physical insights from key emission lines that cannot be detected from the ground.

One of the key science themes for JWST is the early Universe, studying reionization and the first galaxies. Many large surveys are planned for Cycle 1, the first year of JWST science operations, which will address this goal. One of the largest surveys is the JWST Advanced Deep Extragalactic Survey (JADES), a collaboration between the NIRCam and NIRSpec galaxy assembly Guaranteed Time Observations (GTO) teams (Rieke 2019; Bunker 2021). Two key surveys which will be public to the community immediately are the COSMOS-Web Program (Kartaltepe et al. 2021) and the Cosmic Evolution Early Release Science Survey (CEERS; Finkelstein et al. 2017). Surveys such as the Prime Extragalactic Areas for Reionization and Lensing Science (PEARLS) North Ecliptic Pole (NEP) Time-Domain Field (Windhorst et al. 2017; Jansen & Windhorst 2018) are expected to build up in depth over the lifetime of the mission, due to their importance for studying time-domain phenomena with multiple epochs. Deep observations of cluster lensing fields is also a promising avenue that will be extensively explored (e.g. Willott et al. 2017; Windhorst et al. 2017). Many programs will also target individual high-z sources that have been discovered by other facilities, to provide detailed new information about their physical properties (e.g. Finkelstein et al. 2021; Coe et al. 2021). Overall, this will be a transformative period of new data and discoveries.

Given the importance of these data sets, it is imperative to have a range of theoretical predictions of high-z galaxy properties, to which we can compare the observations. Theoretical predictions are also useful to aid in designing the observing strategies used for future observations, both for future cycles with JWST but also for planning upcoming mission surveys such as with the Euclid and Nancy Grace Roman Space Telescopes.

Previous studies have made estimates for the number of galaxies expected to be found by various JWST surveys. Yung et al. (2018) used the Santa Cruz semi-analytic model to estimate the luminosity function that could be measured by JWST, and showed the expected number of galaxies per volume above two detection limits. Vogelsberger et al. (2020) used the luminosity function from Illustris-TNG, extrapolated to lower magnitudes, to estimate the number of galaxies detected with NIRCam above the JADES-Deep, JADES-Medium and CEERS expected number limits. Wilkins et al. (2022) used the First Light And Reionisation Epoch Simulations (FLARES; Lovell et al. 2020; Vijayan et al. 2021), which contains a large number of high-z galaxies, to predict the number of $z = 10–15$ galaxies that will be detected by various JWST surveys. They used the FLARES luminosity functions and assumed 100% completeness down to the 10σ point-source depths, and predicted that in JWST Cycle 1 approximately 600 galaxies should be identified at $z > 10$.

These studies give useful predictions of the average number of galaxies expected in each survey. However, Steinhardt et al. (2021) considered the effect of cosmic variance on the estimated number counts, using models and observed luminosity functions, and found that this will be the dominant contribution to the uncertainty in high-z galaxy luminosity functions. Behroozi et al. (2020) used the empirical model UniverseMACHINE to produce mock galaxy catalogues and light cones. Based on a simple magnitude cut, they made predictions for $z > 10$ galaxy number counts for a range of JWST surveys, with a total number of $z > 10$ galaxies of 210–972 based on a number of survey realisations. However, the expected number counts from all of these studies are based on the luminosity function and a simple 100% completeness cut at some magnitude limit.

An alternative approach is to create mock images of various JWST surveys, to investigate not only the number of sources above some magnitude in a field, but how many may be extracted and correctly characterized. Williams et al. (2018) created a galaxy catalogue and software for mock image generation based on a phenomenological model, called the JAdes extraGalactic Ultradeep Artificial Realisations (JAGUAR) catalogue. These catalogues take observed UV luminosity and stellar mass functions to create a detailed empirical model of galaxies from $z = 0.2–15$. They made specific simulations of the JADES survey, and predicted that it will discover 1000s of galaxies at $z \geq 6$, and 10s of galaxies at $z \geq 10$, with $m \leq 30$ mag. By extracting sources from detailed mock images created using the JAGUAR extragalactic catalogues, other studies have explored: the impact of the observing strategy and analysis choices on successfully identifying high-z galaxies from low-z interlopers (Hainline et al. 2020); source blending and how accurately galaxy properties can be recovered (Kauffmann et al. 2020); and the effectiveness of medium-band filters for improving galaxy property measurements (Roberts-Borsani et al. 2021).

Yang et al. (2021) simulated very realistic MIRI images of the CEERS survey, and ran a comprehensive photometric pipeline on their images, including mitigating cosmic rays and a variable background subtraction. They used these to determine how well the MIRI imaging can constrain the properties of high-z galaxies. Drakos et al. (2022) presented the Deep Realistic Extragalactic Model (DREAM) for creating synthetic galaxy catalogues, which uses an empirical model to create galaxy catalogues for galaxies up to $z \sim 12$. These catalogues were used to create detailed light cones and mock images of a deep survey with Roman. Drakos et al. (2022) predicted that a 1 degree$^2$ Roman ultra-deep field to $\sim 30$ mag could detect more than $10^6$ $M_{UV} < -17$ mag galaxies, with more than $10^8$ at $z > 7$.

These studies provide comprehensive predictions of the number of galaxies various observing strategies will detect, and how well their physical properties can be extracted from the images. However, these simulations all assume that the galaxies are Sérsic profiles (or point sources for objects unresolved in MIRI in Yang et al. 2021). Realistically, high-z galaxies are generally clumpy (Jiang et al. 2013; Bowler et al. 2017), and so will not follow a simple Sérsic profile. In this work we create mock images of more realistic high-z galaxies from the BlueTides hydrodynamical simulation. We create a catalogue of images of $\sim 100,000$ galaxies in BlueTides at $z = 7–12$, simulating observations with JWST, HST, Roman, Euclid, Subaru and VISTA. As opposed to the detailed models above which create full mock image fields, including galaxies at a range of redshifts and even foreground stars, we image only cut-outs of individual galaxies. These images will be useful for studying the properties of high-z galaxies from the BlueTides simulation, such as their morphologies, as well as making detailed predictions for upcoming surveys. In this work, we focus on predictions of the performance of JWST, investigating the fraction of galaxies detected under a range of exposure times with different NIRCam and MIRI filters. We also make predictions for specific JWST surveys, such as JADES-Medium, COSMOS-Web, CEERS, PEARLS NEP and PEARLS GOODS-S, predicting the number of expected high-z galaxies and considering the effect of cosmic variance.

This paper is structured as follows. In Section 2 we describe our technique for making images with BlueTides, and give an overview of the publicly available mock image catalogue. In Section 3 we perform photometry on a range of mock images. We compare var-
ious telescopes in Section 3.2. Focusing on JWST, we investigate the completeness of observations with different filters and exposure times (Section 3.3), and make specific predictions for the number of high-z galaxies detected in a range of upcoming JWST surveys (Section 3.4). We include a discussion in Section 4, and conclude with a summary in Section 5. The cosmological parameters used throughout are from the nine-year Wilkinson Microwave Anisotropy Probe (WMAP; Hinshaw et al. 2013): Ω_M = 0.2814, Ω_L = 0.7186, Ω_b = 0.0464, σ_8 = 0.820, η_s = 0.971 and h = 0.697.

2 BLUETIDES MOCK IMAGES

Here we give a brief overview of the BLUETIDES simulation (Section 2.1), how galaxy spectral energy distributions (SEDs) are modelled (Section 2.2), and the selection of our galaxy sample (Section 2.3). We then detail how we created the mock images available in the BLUETIDES Mock Image Catalogue in Section 2.4.

2.1 BLUETIDES

BLUETIDES is a large-scale cosmological hydrodynamical simulation, simulating the evolution of galaxies from z = 99 to z = 7 (Feng et al. 2015; Ni et al. 2020). The extreme volume of BLUETIDES, (400/h Mpc)^3, allows for a statistical study of bright galaxies in the early Universe. The simulation contains 2 × 10^7 particles, with dark matter, gas, and star particle initial masses of 1.2 × 10^7/h M_⊙, 2.4 × 10^6/h M_⊙, and 6 × 10^5/h M_⊙ respectively. The gravitational softening length is ε_g = 1.5/h kpc (0.24 kpc at z = 8).

BLUETIDES includes a range of prescriptions to model sub-grid physical processes, for example gas (Katz et al. 1999) and metal line cooling (Vogelsberger et al. 2014), multi-phase star formation (Springel & Hernquist 2003; Vogelsberger et al. 2013) including effects from the formation of molecular hydrogen (Krumholz & Goldreich 2011), supernova feedback (Okamoto et al. 2010), reionization (Battaglia et al. 2013), and black hole growth and active galactic nuclei (AGN) feedback (Springel et al. 2005; Di Matteo et al. 2005; see DeGraf et al. 2012 and DeGraf et al. 2015). For full details, see the original BLUETIDES paper Feng et al. (2015).

For this work, we extract galaxies for imaging analogously to Marshall et al. (2022), with the reader referred there for full details. Galaxy haloes are identified in BLUETIDES using a friends-of-friends (FOF) algorithm. To identify individual halo galaxies, we locate each black hole in the halo, and assume each resides at the centre of a galaxy. Black holes are seeded in dark matter haloes when they reach a threshold mass of M_{Halo, seed} = 5 × 10^10/h M_⊙ at the location of the densest particle (DeGraf et al. 2015).

The BLUETides galaxy properties, such as the star formation density, stellar mass function, and UV luminosity function, have been shown to match current observational constraints at z = 7, 8, 9 and 10 (Feng et al. 2015; Waters et al. 2016; Wilkins et al. 2017; Marshall et al. 2020; Ni et al. 2020).

2.2 Spectral Energy Distribution Modelling

Modelling of the spectral energy distributions (SEDs) of galaxies in BLUETIDES, including the effects of nebular emission and dust attenuation, is described in detail in Wilkins et al. (2016, 2017, 2018, 2020) and Marshall et al. (2022).

Each star particle in a galaxy is assigned an intrinsic stellar SED according to its age and metallicity from the Binary Population and Spectral Synthesis model (BPASS, version 2.2.1; Stanway & Eldridge 2018), assuming a modified Salpeter initial mass function with a high-mass cut-off of 300 M_⊙. Star particles are then associated with a H II region (and nebular continuum and line emission) using the Cloudy photo-ionisation code (Ferland et al. 2017), assuming that the metallicity Z of the H II region is identical to that of the star particle, the hydrogen density is 100 cm^{-3} (Osterbrock & Ferland 2006), and no Lyman-continuum photons escape.

We consider dust attenuation from the interstellar medium (ISM). For each star particle we calculate the line-of-sight density of metals ρ_{metal} and convert this to a dust optical depth:

\[ \tau_{ISM} = \kappa \left( \frac{\lambda}{5500 \text{Å}} \right)^7 \int_{z' = 0}^{z} \rho_{metal}(x, y, z') dz' \]  

(1)

where we assume that γ = -1, i.e. τ_l ∝ λ^{-1}, and use κ = 10^4.6, which is calibrated against the observed galaxy UV luminosity function at redshift z = 7 (Marshall et al. 2020; Ni et al. 2020). For star particles with ages less than 10 Myr, we also assume dust contribution from a birth cloud, with optical depth τ_{BC} = (Z/Z_⊙) \left( \frac{\lambda}{5500 \text{Å}} \right)^7, where we assume γ = -1.

This model assumes a constant dust-to-metal ratio with redshift. We do not model a varying κ with redshift, as there is significant uncertainty in the z ≥ 7 galaxy UV luminosity functions used for the calibration. By calibrating κ at z = 7, we find good agreement with the observed galaxy UV luminosity functions at z = 7–10 (see Figure 1), suggesting that a non-evolving dust-to-metal ratio is a reasonable assumption for this work. However, if the dust is (under) overestimated at higher redshifts, we would expect our predictions to (over) underestimate the number of high-z galaxies that could be detected.

Note that throughout this work we consider only the stellar emission, and do not include the emission from AGN. The core of high-z galaxies can be very dusty, strongly attenuating the AGN (e.g. Bowler et al. 2021), hence justifying this omission (see e.g. Roper et al. 2022). We have also studied the host galaxies of BLUETIDES quasars specifically by creating mock JWST images in Marshall et al. (2021).

2.3 Galaxy Sample

In this work we consider a luminosity-limited galaxy sample, selecting galaxies with dust-attenuated far-UV (FUV) luminosity L_{1500Å} > 10^{28.5} erg/s/Hz or M_{1500Å} < -19.65 mag, as BLUETIDES is incomplete for lower luminosity galaxies due to its resolution. This sample contains 31 galaxies at z = 12, 244 galaxies at z = 11, 1,279 at z = 10, 5,606 at z = 9, 22,144 at z = 8 and 71,052 at z = 7. The UV luminosity function for these galaxies is shown in Figure 1, along with the observations of Bouwens et al. (2015), Atek et al. (2015) and Bouwens et al. (2016). At z = 7 BLUETIDES is complete to M_{1500Å} = -20.1 mag, and at z > 7 it is complete to M_{1500Å} = -19.9 mag, with the luminosity function turning over and decreasing for fainter magnitudes (see Figure 1). Although we do not have a higher resolution BLUETIDES simulation with which to compare, this turnover is a clear indicator of where the simulation would no longer converge due to numerical resolution. Thus, throughout this work we do not consider galaxies below this convergence/completeness limit, to ensure the accuracy of our results.

In Figure 1 we also show the total number density per square degree of BLUETIDES galaxies in a redshift interval z' - 0.5 < z < z' + 0.5. This is calculated by assuming that

\[ N(z' - 0.5 < z < z' + 0.5) = N(z = z') \times \frac{DC(z' - 0.5 \text{ to } z' + 0.5)}{400/h} \]  

(2)

The BlueTides Mock Image Catalogue
where \( \mathcal{N}(z' - 0.5 < z < z' + 0.5) \) and \( \mathcal{N}(z = z') \) are the number of galaxies in the depth \( z' - 0.5 < z < z' + 0.5 \) and in the simulation snapshot at \( z = z' \), respectively. The co-moving radial distance \( D_C \) between \( z = 6.5 \) and 7.5 is 358.3 cMpc, \( z = 7.5 \) and 8.5 is 300.4 cMpc, \( z = 8.5 \) and 9.5 is 256.5 cMpc, \( z = 9.5 \) and 10.5 is 222.32 cMpc, \( z = 10.5 \) and 11.5 is 195.1 cMpc, and \( z = 11.5 \) and 12.5 is 173.0 cMpc. The BlueTides box has a depth of \( 400/h = 573.9 \) cMpc, deeper than one integer redshift window at these high redshifts, and so this conversion results in a reduction of the number of galaxies. This is a coarse estimate that assumes galaxies do not evolve in \( z' - 0.5 < z < z' + 0.5 \), and can be adequately approximated in this interval by the population at \( z = z' \). This assumption is likely accurate at the highest redshifts where the time interval is small, although by \( z = 7 \) this may not be the case.

### 2.4 Mock Images

In Marshall et al. (2022) we created rest-frame images of the \( z \geq 7 \) BlueTides galaxies in standard top-hat filters: FUV (1500Å), 2500Å, \( U, B, V, I, Z, Y, J \) and \( H \), not including instrumental effects such as a point spread function (PSF) or noise. In Marshall et al. (2021) we created mock HST and JWST images, including the PSF, pixel scale, and estimated noise, however we considered only the galaxies which host quasars at \( z = 7 \).

Here we extend these previous studies and create mock images of a large sample of \( \sim 100,000 \) BlueTides galaxies from \( z = 7-12 \) for a range of current and upcoming telescopes. A catalogue of these mock images is publicly available via the Mikulski Archive for Space Telescopes\(^1\). These images consider the instrument PSF and pixel scale, however they are produced without noise so that they can be adapted for each specific use case. Noise (both sky and shot noise) is able to be simply added in post-processing by code which accompanies the catalogue\(^2\): we investigate adding noise in Section 3.

For this work we simulate JWST, HST, Euclid, Roman, VISTA, and Subaru images, with a full list of the instruments and filters given in Table 1 and visualized in Figure A1. We generally consider the filters for each instrument that are red-ward of the Lyman-limit at \( z = 7 \) at 0.73 microns. Filters blue-ward of Lyman-alpha at \( z = 7 \) at 0.97 microns, for example the \( z \)-band, contain very minimal flux, although they are included as they may be of interest for comparisons. We generally consider only the wide-band filters, which are key for finding faint objects; for JWST NIRCam we also simulate F410M, the widest of the medium-band filters, which is popular for high-z galaxy surveys due to its complementarity to F444W.

As in Marshall et al. (2022) our images are of the \( 6 \times 6 \) kpc field of view (FOV) around each galaxy, except for Euclid, VISTA, and Subaru, which have much wider PSFs and so require a larger FOV of \( 10 \times 10 \) kpc to contain the galaxy flux. We bin the image to a pixel scale of 0.5 times the native pixel scale. This assumes that given sufficient dithering in the observations, the final image can sub-sample the original pixel scale by a factor of 2. This is a useful strategy particularly for JWST NIRCam which will under-sample the PSF at some wavelengths. The catalogue images can be re-sampled to a larger pixel scale if required. These image properties are listed in Table 1.

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1. doi:10.17909/ER09-4527
2. github.com/madelinemarshall/BlueTidesMockImageCatalogue
Figure 2. Example $Y$-band images of three $z = 7$ BlueTides galaxies in each of the telescopes. Note that the Euclid, VISTA, and Subaru images cover larger area (10 × 10 pkpc vs 6 × 6 pkpc). These images do not contain noise.

Figure 3. Top: Example spectra for three $z = 7$ galaxies, alongside their photometry in the seven simulated JWST NIRCam filters and two MIRI filters. Bottom: The corresponding mock JWST images, not including any noise.
Table 1. Table of the simulated telescope filters, specifying their pixel scale and field of view (FOV). The pixel scale has a sub-sampling of the native pixel scale by a factor of 2. *Euclid*, VISTA, and Subaru have larger FOVs due to their low resolutions.

| Telescope | Instrument | Filters | Pixel Scale (") | Image FOV (pkpc²) |
|-----------|------------|---------|-----------------|-------------------|
| JWST      | NIRCam (Short Wavelength) | F090W, F115W, F150W, F200W | 0.0155 | 6 × 6 |
|           | NIRCam (Long Wavelength)  | F277W, F356W, F410M, F444W | 0.0315 | 6 × 6 |
|           | MIRI       | F560W, F770W | 0.055 | 6 × 6 |
| HST       | WFC3      | F105W, F125W, F140W, F160W | 0.065 | 6 × 6 |
| Roman     | WFI       | F087, F106, F129, F146, F158, F184 | 0.055 | 6 × 6 |
| Euclid    | NISP       | Y, J, H  | 0.15 | 10 × 10 |
| VISTA     | VIRCam    | Z, Y, J, H, Ks | 0.17 | 10 × 10 |
| Subaru    | HSC       | z, y   | 0.085 | 10 × 10 |
| Spitzer   | IRAC      | Ch1, Ch2 | - | - |

* Note that we provide only the Spitzer fluxes and not the full set of images, as galaxies are unresolved.

3.2. We then make predictions for JWST, considering a range of filters and exposure times in Section 3.3. Finally, we make detailed predictions for detections of high-z galaxies in planned JWST surveys in Section 3.4.

3.1 Photometric Source Extraction

To create our mock telescope images, we add noise based on the expected depth for each exposure time. The noise σ for the mock JWST images is estimated from the predicted 10σ sensitivity of JWST for the corresponding exposure time, from the values provided by STScI (2017a,b). These use a circular photometric aperture 2.58 pixels in radius. These noise estimates assumed 1.2 times the minimum zodiacal light background at RA = 17:26:44, Dec = -73:19:56 on June 19, 2019 (STScI 2017a). For the other telescopes we use their available Exposure Time Calculators (ETCs) to determine σ from the 5σ or 10σ sensitivities at the given exposure time. For each calculation we consider a point source with a flat spectrum in $F_\nu$.

For JWST (STScI ETC Team 2022) we assume an aperture of radius 0′′2, and 4 dither positions. For Subaru (Subaru Telescope 2022) and VISTA (VISTA 2009) we assume an aperture radius of 2′′. As for the PSFs, we assume a seeing of 0′′6 and 0′′66, respectively. For Roman (Pickering et al. 2016) we assume an aperture of radius 0′′286, and a background annuli of 0′′4–0′′5. The readout settings we chose for the 10ks exposure are ‘deep’ with 20 groups and 7 integrations. All other settings in the ETCs are set to their default values. We assume that this noise follows a Gaussian distribution. We also include shot noise from the source flux, following a Poisson distribution.

We use PHOTUTILS (Bradley et al. 2018) to extract the galaxy from each cut-out image, following the procedure outlined in STScI (2022b), particularly the run_detect_sources function. For a detection, we require 5 connected pixels at/above the threshold level of 2σ times the background RMS. NIRCam’s short and long wavelength filters, and MIRI, have different native pixel scales of 0′′031, 0′′063 and 0′′11 respectively. Our images are sub-sampled to a factor of 2, or pixel scales of 0′′0155, 0′′0315 and 0′′055 respectively (Table 1). We find that a re-sampled image with larger pixel scale aids in detection of fainter objects for the shorter wavelength filters. We re-bin the NIRCam detection images by a factor of 4 and 2 to be on a scale of 0′′062 and 0′′063 for the short- and long-wavelength filters respectively, so that these and the MIRI images are on a similar pixel scale.

For the other telescopes, we resample by a factor of 2, reverting to the native pixel scale.

We note that we use only this standardised PHOTUTILS galaxy extraction algorithm throughout this work. High-z galaxy searches may likely consider alternative or additional source detection algorithms, such as Source Extractor (Bertin & Arnouts 1996) or PROFIND.

The SED from each star particle in the FOV is convolved with the instrument filter transmission curve (Figure A1), to determine its flux in the filter. We smooth the light from each star particle adaptively with the smoothing scale (full width at half maximum, FWHM, of the Gaussian) equal to the distance to the 8th nearest neighbour (in 3D). These smoothed fluxes from each star particle within the galaxy are combined to determine the flux in each pixel.

Finally, the resulting image is convolved with the PSF of the instrument. The PSFs are obtained via TinyTim for HST (Krist et al. 2011), and WebPSF for JWST and Roman (Perrin et al. 2015). Euclid NISP is assumed to have a Gaussian PSF with FWHM of 0′′175 in the Y-band, 0′′24 in J, and 0′′28 in H (Seidel 2021). Ground-based Subaru and VISTA are assumed to have Gaussian PSFs with FWHM of 0′′60 and 0′′66 respectively, corresponding to the typical site seeing (Subaru Telescope 2021; ESO 2022). We also include in the catalogue separate images that have not been convolved with the PSF, which could be convolved with the true PSF measured for the instrument as opposed to the models, or used in image simulation software that requires an un-convolved image such as MIRAGE for JWST mock observations (STScI 2022a), for example. Throughout this work, however, we only use the PSF-convolved images.

The effective spatial resolution of BlueTides is the gravitational softening length $\epsilon_{grav} = 1.5/h$ kpckpc, which corresponds to 0.269 pkpc, or 0′′05 at $z = 7$ and 0′′07 at $z = 12$ in this cosmology. The resolution of BlueTides is thus well-matched to JWST, which has a resolution of 0′′05 at 1.5μm, with all other instruments considered here having much lower resolution.

The images of the galaxies are made in the ‘face-on’ direction, as determined by the angular momentum of particles in the galaxy (see Marshall et al. 2020). The quoted luminosity of a galaxy is the total luminosity in the corresponding image. Output images are in ptf/s file type, in units of nJy.

In Figure 2 we show example images of three $z = 7$ BlueTides galaxies in each telescope, in the Y-band or closest equivalent. We also show example mock JWST NIRCam and MIRI images of these three $z = 7$ galaxies, alongside their spectra in Figure 3.

3.2 PREDICTIONS FOR HIGH-Z GALAXY OBSERVATIONS

In this Section we consider a range of observing strategies, and investigate which of the BlueTides galaxies can be successfully detected in the corresponding mock images. To do this, we add background noise expected from different exposure times and specific upcoming surveys, and perform photometric source extraction on the galaxy images, as described in Section 3.1.

We first compare the success of each of the telescopes for observing the same $z = 7$ galaxy sample with the same exposure time (Section 3.2). We then make predictions for JWST, considering a range of filters and exposure times in Section 3.3. Finally, we make detailed predictions for detections of high-z galaxies in planned JWST surveys in Section 3.4.
(Robotham et al. 2018), for example. One could also carefully optimise the parameters in these algorithms to improve the detection of galaxies in specific sets of images. The choice of pixel scale and wavelengths used for the detection images are expected to have an effect on the success of the strategy, and image stacking could also be used to improve the detectability of fainter galaxies. In addition, with more modestly sized galaxy samples from true images, each galaxy candidate could be reasonably visually confirmed, which is not possible for our sample of ~ 100,000 high-z galaxies, which may alter the detection strategy. Our approach also does not consider the difficulty of determining the photometric redshifts of any detected galaxies, which would be necessary for real images. Overall, careful and optimised galaxy extraction techniques may be more successful than expected by the more simplistic, standard predictions here, nonetheless our approach offers useful insights and comparisons.

3.2 Comparison between Telescopes

In this Section we compare each of the telescopes for which we have created mock images in the catalogue. We add noise corresponding to exposure times of 10,000s, in the Y-band or closest equivalent filter: F115W for JWST, F105W for HST, and F106 for Roman. We note that Euclid does not have a General Observer program like the other instruments, instead having a fixed survey strategy with specific exposure depths, and so we do not include Euclid in this comparison.

In Figure 4 we show the fraction of z = 7 galaxies detected in these 10ks Y-band images, for each telescope, as a function of their rest-frame UV magnitude. Note that we consider only galaxies with $M_{1500\text{Å}} < -20.1$ mag at $z = 7$ and $M_{1500\text{Å}} < -19.9$ mag at $z > 7$, the completeness limit of BlueTides. The ground-based telescopes Subaru and VISTA have the brightest completeness limits, becoming 95% complete at $M_{1500\text{Å}} < -22.7$ mag. HST F105W reaches at least 1.5 magnitude deeper, becoming 95% complete at $M_{1500\text{Å}} = -21.3$ mag. Roman F106 has a slightly fainter completeness limit than HST of $M_{1500\text{Å}} = -21.1$ mag. The Roman detection fraction drops more slowly than HST, with 50% detection success at $M_{1500\text{Å}} = -20.3$ mag. 0.6 magnitudes fainter than HST. Finally, JWST will have larger detection fractions than each of these telescopes, becoming 95% complete at $M_{1500\text{Å}} = -20.2$ mag, at least 2.5 magnitudes fainter than VISTA and Subaru, 1.1 magnitudes fainter than HST and 0.9 magnitudes fainter than Roman. This demonstrates the unprecedented power JWST will have in detecting high-z galaxies.

3.3 JWST Predictions for Various Filters and Exposure Times

To further investigate the expected performance of JWST, we create mock images with a range of exposure times: 1, 2, 4, 6, 8, and 10ks, for the full range of simulated filters. We use these standard exposure times, across the full BlueTides area, to investigate how the completeness for observations varies with exposure time and filter choice.

In Figure 5 we show the fraction of galaxies at $z = 7$–11 that are detected in 10ks images, for the various NIRCam and MIRI filters. We consider only galaxies above the completeness limit, with $M_{1500\text{Å}} < -20.1$ mag at $z = 7$ and $M_{1500\text{Å}} < -19.9$ mag at $z > 7$.

The average magnitudes at which these 10ks observations become 95% complete are 26.7, 26.9, 27.1, 27.4, 27.4, 26.9, 27.0, 25.7, and 24.9 mag for F115W, F105W, F200W, F277W, F356W, F410M, F444W, F560W, and F770W, respectively, with a variation of ±0.1 mag between the various redshifts for all filters, except for F115W with ±0.2 mag and ±0.3 mag for F560W. The predicted 10σ point source sensitivities are 28.6, 28.8, 29.0, 28.5, 28.7, 28.0, 27.9, 26.1 and 25.4 mag, respectively (STSci 2017c,b), 1.9 to 0.5 magnitudes fainter than our 95% completeness limits. This a reasonable difference given our galaxies are extended; we have verified this difference through simple testing using the JWST Exposure Time Calculator. The F277W and F356W filters can detect the faintest galaxies in a fixed exposure time, while the MIRI filters are the least sensitive, becoming incomplete at the brightest magnitudes.

In Figure 6 we show the detection fractions as a function of stellar mass, for $z = 7$–11. These 10ks NIRCam exposures can detect > 95% galaxies down to ~ $10^9 M_\odot$ at $z = 7$; the MIRI exposures become incomplete at larger stellar masses, with the F770W filter 95% complete only to $10^{10} / M_\odot$. The mass completeness limit increases at $z > 7$, with galaxies with given mass becoming more difficult to detect at higher-z. Note also that the galaxies redshift out of the F115W band, with Lyman-alpha red-ward of the filter at $z \geq 10$.

In Figure 7 we show the fraction of $z = 9$ galaxies that are detected in images with exposure times ranging from 1–10ks, for each of the NIRCam filters. We chose $z = 9$ as at this redshift the galaxies span the widest range in relevant apparent magnitudes, showing the completeness fraction from $m_{\text{filter}} \approx 25$–29. Increasing the exposure time from 1 to 10ks is expected to improve the detection depth by approximately 1.25–1.6 magnitudes, with a larger increase for the short-wavelength filters.

3.4 Predictions for Planned JWST High-z Galaxy Surveys

In this Section we predict the number of high-z galaxies that will be detected by a range of JWST Cycle 1 surveys.

\footnote{https://jwst.etc.stsci.edu/}
Figure 5. The fraction of galaxies detected as a function of their magnitude in each JWST NIRCam filter, for an exposure time of 10ks, at $z = 7-11$. Bins have a width of 0.25 mag. Only bins containing 5 galaxies or more are shown. We show only galaxies above the BlueTides completeness limit, with $M_{1500\AA} < -20.1$ mag at $z = 7$ and $M_{1500\AA} < -19.9$ mag at $z > 7$.

Figure 6. The fraction of galaxies detected as a function of their stellar mass, for an exposure time of 10ks, at $z = 7-11$. The regions where the BlueTides stellar mass function is incomplete are shaded in grey. Bins have a width of 0.25 mag. Only bins containing 5 galaxies or more are shown. We show only galaxies above the BlueTides completeness limit, with $M_{1500\AA} < -20.1$ mag at $z = 7$ and $M_{1500\AA} < -19.9$ mag at $z > 7$.

Figure 7. The fraction of $z = 9$ galaxies detected as a function of their magnitude in each filter, for a range of exposure times (see legend). Bins have a width of 0.25 mag. Only bins containing 5 galaxies or more are shown.
3.4.1 The JWST Surveys Considered

In this work we consider five extragalactic surveys that will be conducted in JWST Cycle 1. These surveys will implement varying strategies to study high-$z$ galaxies, with a range of survey areas and exposure times. We list the area and exposure times we assume for each survey in Table 2.

JADES (Rieke 2019) is an ambitious imaging and spectroscopic deep-field survey which aims to study the formation and evolution of galaxies from $z \approx 2$ to $z \geq 12$ using a combination of 950 hours of NIRCam, NIRSpec and MIRI data. The NIRCam imaging component will survey two fields, a ‘Medium’ field of area 190 arcmin$^2$ to a 10$\sigma$ point source limit of 28.8 mag, in both GOODS-S and GOODS-N, and a ‘Deep’ survey which will cover a smaller area of 46 arcmin$^2$ to a 10$\sigma$ point source limit of 29.8 mag, centred on the HUDF/GOODS-S. In this work we only consider the JADES-Medium survey, as we find that even with its shallower depth it is capable of detecting ~ 100% of BlueTides galaxies at $z < 8.5$ in our magnitude-limited sample of $M_{1500\lambda} \leq -20$ mag.

CEERS (Finkelstein et al. 2017) will observe a field of 100 arcmin$^2$ in the Extended Groth Strip (EGS) with NIRCam, MIRI, and NIRSpec imaging and spectroscopy, aiming to demonstrate successful survey strategies with JWST. The NIRCam component is designed to detect a large sample of $z \approx 9-13$ galaxies. We note that for CEERS, the depth of each of the 10 NIRCam pointings is not constant, and so we assume the shallowest depth that covers the full 100 arcmin$^2$ area.

The COSMOS-Web Survey (Kartaltepe et al. 2021) is a large-area survey of 0.6 deg$^2$, designed to study bright galaxies in the early Universe and provide a primary extragalactic legacy dataset. This survey has a much shallower depth, but aims to detect ‘an order of magnitude more early Universe galaxies than all other Hubble+Webb surveys combined’ (Kartaltepe et al. 2021), due to its very large survey area.

The PEARLS program (formerly Webb Medium-Deep Fields) contains several surveys of blank fields (Windhorst et al. 2017). Here we consider the PEARLS NEP field (Jansen & Windhorst 2018) and the PEARLS GOOD-S survey. The NEP field is within JWST’s northern continuous viewing zone. The PEARLS NEP program is designed for multi-epoch time-domain observations, and will cover the field with both NIRCam imaging and NIRISS spectroscopy. The imaging is of similar depth to the CEERS field, with 2/3 of the area. The PEARLS GOOD-S survey is a much more modest program of only 5.5 hours, and so may be a more representative example of general Cycle 1 programs.

We note that the BlueTides simulation is incomplete at faint magnitudes $M_{1500\lambda} \geq -20$ mag, due to the resolution of the simulation. As shown below, these medium-depth surveys have very high detection fractions and achieve similar depths as the BlueTides sample. We therefore do not consider deeper surveys such as JADES-Deep, which will discover fainter galaxies. However, these surveys will be important for detecting even the brightest higher-$z$ galaxies ($z \geq 10$), rare objects which can be predicted in greater detail by a larger volume simulation such as FLARES (e.g. Lovell et al. 2020; Wilkins et al. 2022).

3.4.2 Methodology for Survey Predictions

We make predictions for these surveys by adding their expected noise to our mock galaxy images, from their quoted 10$\sigma$ limits or, if unavailable, estimating the noise from the exposure time as described in Section 3.1. As above, we then perform photometry on these mock images, determining whether each high-$z$ galaxy is detected. We require a galaxy to be detected in at least 2 filters within the survey for it to be classified as ‘detected’ in the survey overall. We note that we do not simulate a full mock survey image using a light-cone, and are simply investigating whether the individual galaxies could be detected in a survey image of equivalent depth, ignoring any effects such as foreground contamination. However, when considering the survey areas, we use the true positions of each galaxy from the BlueTides volume in combination with the image cut-out, so in this way we are accurately representing the galaxy distribution at each redshift that could be probed by each survey.

The number of galaxies in each survey area will depend on its placement on the sky relative to the overall galaxy distribution, and particularly galaxy overdensities. To account for such cosmic variance, we consider sub-cubes of the full BlueTides box with volume $V = \text{Survey Width} \times \text{Survey Height} \times D_C(z' - 0.5$ to $z' + 0.5$). The co-moving radial distance gives the appropriate redshift depth corresponding to $z < 0.5$ $< z < z' + 0.5$, as opposed to the full $z = z'$ BlueTides snapshot box which has a depth of 400/h cMpc (see Section 2.3). We consider the number of non-overlapping sub-cubes that can fit in the BlueTides volume, each corresponding to an independent, single realisation of the area covered by the given survey. We note that each of the JWST surveys may have been chosen to cover a specific region of known density, however our calculations assume no preference on targeted environment. Note that we also do not consider the effect of gravitational lensing.

3.4.3 Method Verification with HST

To verify that our mock images and photometry are working as expected, we first make predictions for an existing HST survey. We consider the CANDELS EGS field (Groglin et al. 2011), chosen as it is a medium-depth survey, has easily accessible publicly available catalogues, and has an almost constant depth across the field which allows for a simpler comparison. The EGS field has an area of $\sim 7' \times 26'$, with exposures of 1900s and 3600s in the WFC3 F125W and F160W filters, respectively. This corresponds to approximate 5$\sigma$ point source sensitivities of 27.2 and 27.0 mag (Groglin et al. 2011), which we use in the simulation as our noise estimate. We also resample the images by a factor of 2, to the native pixel scale of 0.13 arcsec.

We search the CANDELS catalogue from Stefanon et al. (2017) for galaxies with $6.5 < z_{\text{phot,median}} < 7.5$. Given the uncertainty in the photometric redshifts, we require each of the various photometric redshift measurements considered in Stefanon et al. (2017) to be $z_{\text{phot}} > 3$, to be confident that the selected galaxies are not low-$z$ interlopers. There are 2 such galaxies in the EGS field that have magnitudes in the BlueTides magnitude range, $24 < M_{1500\lambda} < 26.75$ mag. This is a rough approximation of the number of galaxies in $6.5 < z < 7.5$ in the true HST survey, as these are not spectroscopically-confirmed galaxies.

We run our photometry algorithm on the mock F125W and F160W images. For 178 of the sub-cubes, no galaxies are detected. In 46 sub-cubes one galaxy is detected, 16 sub-cubes contain two detected galaxies, in 6 sub-cubes three galaxies are detected, and one sub-cube contains four detected galaxies. This is broadly consistent with the CANDELS EGS which detected approximately two galaxies. We are therefore confident that our method works as expected and is a reasonable estimate for true observations.
3.4.4 Predictions for JWST

We now show our predictions for the number of high-z galaxies that will be detected in each of the JWST surveys. For the various redshifts and surveys, histograms of the number of detected galaxies in each of the BlueTides sub-cubes with the volume of the survey (i.e. survey realisation), are shown in Figure 8. The mean, median, minimum and maximum number of detected galaxies \( n_{\text{detected}} \) in each set of sub-cubes are listed in Table 3. For a best estimate of the average fraction of galaxies that are successfully detected in each survey, \( n_{\text{detected}}/n_{\text{total}} \), we consider the full sample of galaxies in the BlueTides volume at the redshift snapshot, and not the individual sub-cubes, for the largest possible sample size. These values are also listed in Table 3. Note that we only consider the number of detected galaxies above the completeness limit of BlueTides: \( M_{1500\text{Å}} < -20.1 \) mag for \( z = 7 \) and \( M_{1500\text{Å}} < -19.9 \) mag for \( z > 7 \).

We predict that the COSMOS-Web survey will detect the most high-z galaxies: \( \sim 1000 \) galaxies in \( 6.5 < z < 7.5 \). The detection fraction of this shallow survey of 84% is lower than those for the deeper surveys, however the very large volume of COSMOS-Web still results in the most detected high-z objects.

In Figure 9 we show the luminosity function that would be obtained by each survey, with the points showing the median number density of detected galaxies obtained over the various sub-cubes, and the shaded regions covering the minimum and maximum values. Surveys with a large area such as COSMOS-Web will very precisely measure the true sample luminosity function, with each sub-cube resulting in a similar measurement. This is due to the large area, which covers a wide range of galaxy environments. Surveys with smaller areas...
could measure a wider range of luminosity functions, depending on the region they sample—i.e. due to cosmic variance. The larger area of COSMOS-Web will also allow the detection of bright high-$z$ galaxies that are not statistically expected in the smaller surveys due to their low number densities. However, at higher-$z$ the COSMOS-Web luminosity function will become incomplete at the fainter magnitudes that the deeper surveys will be able to cover.

The large depth of the JADES-Medium survey will result in detections of $\sim 100$ galaxies in $6.5 < z < 7.5$, with detection fractions of almost 100% of the $M_{1500\text{Å}} < -20.1$ mag $6.5 < z < 7.5$ galaxies and $M_{1500\text{Å}} < -19.9$ mag $7.5 < z < 8.5$ galaxies in its field of view. At these redshifts the number of galaxies detected is limited only by the number of objects in the field of view; hence the smaller but deeper JADES-Deep survey would offer no improvements on the detected
number. However, additional depth would improve the higher-\(z\) detection fraction, as well as detecting fainter galaxies that we cannot probe due to the limited resolution of BlueTides. JADES-Medium is likely to result in accurate measurements of the fainter-end of the luminosity function that the shallow depth of COSMOS-Web cannot reach, particularly at \(z > 7\) (Figure 9).

The more modest PEARLS GOODS-S and NEP fields have similar depths, with the NEP covering ~6 times the area. On average we predict that they will detect ~5 and ~35 galaxies in \(6.5 < z < 7.5\) respectively, with \(M_{1500\text{Å}} \approx -20.1\) mag. The CEERS field has an equivalent minimum depth as the NEP field, covering a survey area ~1.5 times larger. This results in predicted galaxy counts that are ~1.5 times larger than that from the NEP, ~51 galaxies in \(6.5 < z < 7.5\). Note, however, that the CEERS program will observe some pointings with larger exposure times, and so our predictions are lower limits for the number of \(M_{1500\text{Å}} \leq -20\) mag galaxies that this survey will detect at \(z \geq 7\).

Due to cosmic variance, there is a large range in expected galaxy counts for these smaller fields (Figure 8). From Figure 9, we see that the PEARLS NEP and CEERS fields are expected to give reasonable estimates of the overall luminosity function from \(M_{1500\text{Å}} \approx -21\) mag to our BlueTides completeness limit of \(M_{1500\text{Å}} \approx -20\) mag, at \(z = 7\) and \(z = 8\). The BlueTides luminosity function drops below the number density corresponding to 1 galaxy/dex being detected in these surveys at \(z = 9\). This occurs at \(z > 7\) for the smaller PEARLS GOODS-S field. In this case, the number of detected galaxies will be highly dependent on the sampled environment. If galaxies are detected, this is likely due to the survey observing an over-dense region, and so the measured luminosity function will be artificially higher than the overall galaxy luminosity function; this is particularly the case for the PEARLS GOODS-S field, as seen from the shaded region in Figure 9. Thus the CEERS and PEARLS NEP surveys are not expected to provide an accurate measure of the \(M_{1500\text{Å}} < -20\) mag luminosity function at \(z > 8\), or \(z > 7\) for PEARLS GOODS-S. Care must be made with smaller volume surveys when interpreting measured luminosity functions, due to cosmic variance.

4 DISCUSSION

4.1 Comparison to Existing Predictions

The FLARES zoom-in simulation suite has larger volume and resolution than BlueTides, containing a large number of very high-\(z\) galaxies and allowing for detailed \(z > 10\) predictions (Wilkins et al. 2022). In FLARES, Wilkins et al. (2022) estimate that in the PEARLS NEP field there will be \(\sim 20\) \(z > 8\) galaxies, with \(\sim 70\) in CEERS and \(\sim 350\) in COSMOS-Web. We predict fewer galaxies in all cases, with a median of \(\sim 11, 18\) and \(174\) galaxies at \(z > 7.5\) in each survey respectively. However, we are limited to \(M_{1500\text{Å}} < -20\) mag, and both FLARES and the observations will have fainter objects that can be detected, so we expect to predict fewer galaxies. We also expect to predict fewer galaxies as we consider a full photometric extraction, as opposed to using the luminosity function and a 100% completeness cut at the point-source magnitude as in Wilkins et al. (2022). It is interesting to note that our predictions are approximately half of those of FLARES for the NEP and COSMOS-Web, but we predict almost 4 times fewer galaxies in CEERS; this may be because we assume the shallower depth which covers the full CEERS field, not considering that some pointings have longer exposure times.

Behroozi et al. (2020) use the UniverseMachine model to provide an estimate of the number of galaxies per square arcminute above \(M_{1500\text{Å}} < -20\) mag, in an integer redshift range. Using this and the areas of the five surveys from Table 2, and assuming a 100% detection fraction, we convert these to predictions for JADES-Medium, COSMOS-Web, CEERS, PEARLS NEP and PEARLS GOODS-S of 76, 864, 39, 26 and 4 galaxies at \(z = 7\), respectively. These predictions are consistent with our expected range as estimated from the various survey sub-cubes (Table 3). At \(z = 10\), the Behroozi et al. (2020) model corresponds to predictions of 5, 54, 2.4, 1.6 and 0.2 galaxies in the five surveys. We note that these are significantly more than our predictions, which all have a mean of < 1 and with a maximum of 5 \(z = 10\) galaxies detected in any of the survey realisations. However, to account for the fact that these Behroozi et al. (2020) predictions assume that every galaxy above \(M_{1500\text{Å}} < -20\) mag is detected, we multiply these predictions by our detection fractions from Table 3. We find that, as high-\(z\) galaxies are difficult to recover from the photometry, the Behroozi et al. (2020) predictions are reduced to only 2,
3, 0.4, 0.3 and 0.03 galaxies in the five surveys at \( z = 10 \); these are consistent with our \textsc{BlueTides} predictions.

Similarly, using the galaxy number density from the Illustris-TNG simulation (figure 16, Vogelsberger et al. 2020), the survey areas, and assuming a 100% detection fraction, we predict that CEERS, JADES-Medium, and COSMOS-Web will detect \( \sim 13, 26 \) and \( 301 \) galaxies at \( z = 8 \) with \( M_{1500\AA} < -19.9 \) mag, and \( \sim 30, 59 \) and 673 galaxies at \( z = 7 \) with \( M_{1500\AA} < -20.1 \) mag, respectively. These are broadly consistent with our estimates and generally lie within our expectations due to cosmic variance. However, this predicts only \( \sim 70\% \) of the number of \( z = 7 \) galaxies we expect in COSMOS-Web from \textsc{BlueTides}, yet approximately twice as many as \( z = 8 \). These predictions assume 100% detectability above the magnitude threshold; if we multiply by our detection fractions in Table 3, Vogelsberger et al. (2020) would predict that COSMOS-Web will detect \( \sim 113 \) galaxies at \( z = 8 \) with \( M_{1500\AA} < -19.9 \) mag, and \( \sim 566 \) galaxies at \( z = 7 \) with \( M_{1500\AA} < -20.1 \) mag; \( \sim 70\% \) and \( \sim 50\% \) of our predictions, which is more consistent.

\section{4.2 Limitations}

Our approach to creating mock telescope images to predict the number of detectable high-\( z \) galaxies includes several limitations.

For \textit{JWST}, our noise estimates all assumed a background of \( 1.2 \) times the minimum zodiacal light background at \( \text{RA} = 17:26:44, \text{Dec} = -73:19:56 \) on June 19, 2019, as predicted by pre-flight data (STScI 2017a). The true depth of an image will depend on the position of the pointing on the sky, the date of observation, and the readout mode. For a specific example, the PEARLS NEP field is in a dark region of sky, and so our assumed background is likely to be higher than the observed background. In addition, the \textit{JWST} science instrument commissioning has predicted significantly better \( \sigma \) sensitivities than the pre-launch values used throughout this work (Rigby et al. 2022), which would cause our predictions to be underestimates of the completeness and expected number of detectable galaxies.

Our images are cut-outs of individual galaxies at specific redshift snapshots. We do not make light-cones of galaxies across a range of redshifts, simulating a true survey image as in Williams et al. (2018) and Drakos et al. (2022), for example. Thus, we cannot consider the effects of blending, with nearby foreground galaxies or stars complicating the detection of high-\( z \) galaxies. In addition, our method implicitly assumes that all of the galaxies that are successfully detected are indeed at the specified redshift. With true observations, contaminating low-\( z \) objects may be misidentified as high-\( z \) galaxies, or alternatively true high-\( z \) galaxies may be misclassified. We do not consider this potential contamination, which was investigated for \textit{JWST} in detail in Hainline et al. (2020), for example. Instead, with our approach we simply study whether high-\( z \) galaxies could be successfully detected in a specific image, assuming that they are isolated in the image and are correctly identified.

A key limitation of this work is that we are restricted to studying only galaxies with \( M_{1500\AA} \leq -20 \) mag, due to the resolution of the simulation. Unfortunately this limits our predictions to the brightest high-\( z \) galaxies, while one of the key features of \textit{JWST} is its exquisite sensitivity, which will allow it to discover faint objects in the early Universe. However, the large volume of \textsc{BlueTides} makes it an ideal simulation for studying bright, rare, high-\( z \) galaxies. This work has thus provided detailed predictions for these bright galaxies that are limited in smaller simulations. In addition, the large volume of \textsc{BlueTides} allows us to study the effects of cosmic variance on the predicted galaxy number counts.

\section{5 CONCLUSIONS}

In this work we introduce the \textsc{BlueTides} Mock Image Catalogue, a publicly available catalogue of mock images of \( \sim 100,000 \) \( M_{UV} \approx -22.5 \) to \( -19.6 \) mag galaxies in the \textsc{BlueTides} hydrodynamical simulation at \( z = 7–12 \). We create mock images with the James Webb, Hubble, Euclid and Roman Space Telescopes, as well as VISTA and Subaru.

These images are created from the stellar particle distribution of \textsc{BlueTides} galaxies, as determined through the detailed hydrodynamics of the cosmological simulation. Each star particle is assigned an SED based on its age and metallicity, and nebular continuum, line emission, and dust attenuation from the ISM and a birth cloud are also modelled. Images are created with the pixel scales of the various instruments, with fluxes taken from a convolution of the SEDs with the various filter transmission curves (see Appendix A). These images are convolved with model PSFs, to produce realistic estimates of what true images with these telescopes would look like. The available images are \( 6 \times 6 \) and \( 10 \times 10 \) kpc snapshots around each galaxy, and not a full mock light-cone or instrument field of view. We note that the images available in the catalogue have no noise, so that they can be adapted for specific use cases.

We use these mock images to make detailed predictions for photometric surveys with the various telescopes. To do this we add appropriate noise to the images, and then run a \textsc{photutils} photometric source extraction algorithm to determine whether the galaxies would be successfully detected in the given exposures.

To compare the various telescopes we perform photometry on mock 10ks \( F \)-band images of \( z = 7 \) galaxies from VISTA, Subaru, \textit{HST}, \textit{JWST} and \textit{Roman}. We predict the highest detection fractions from \textit{JWST}, which becomes 95% complete at \( M_{1500\AA} = -20.2 \) mag, at least 2.5 magnitudes fainter than VISTA and Subaru, 1.1 magnitudes fainter than \textit{HST}, and 0.9 magnitudes fainter than \textit{Roman}. This highlights the remarkable capabilities of \textit{JWST} for detecting high-\( z \) galaxies.

We then consider various observing strategies with \textit{JWST}, adding noise corresponding to a range of exposure times, for each of the simulated NIRCam and MIRI filters. We find that 10ks observations become 95% complete at an average of \( 26.7, 26.9, 27.1, 27.4, 27.4, 26.9, 27.0, 25.7, \) and 24.9 mag for \( F115W, F150W, F200W, F277W, F356W, F410M, F444W, F560W, \) and \( F770W \), respectively, with a variation of \( \pm 0.1 \) mag between the various redshifts for most filters. The \( F277W \) and \( F356W \) filters can detect the faintest galaxies in a fixed exposure time, with the MIRI filters the least sensitive. Our 95% completeness limits are 1.9 to 0.5 magnitudes brighter than the predicted 10\( \sigma \) point source sensitivities, as our galaxies are extended and have realistic structures. We also find that increasing the exposure time from 1 to 10ks is expected to improve the \textit{NIRCam} detection depth by approximately 1.25–1.6 magnitudes.

We then make predictions for five upcoming \textit{JWST} Cycle 1 surveys: JADES-Medium, COSMOS-Web, CEERS, PEARLS NEP and PEARLS GOODS-S. We add realistic noise estimates based on the survey depths in each filter, and require a galaxy to be detected in at least two of the filters for it to be classified as successfully detected. To consider the effects of cosmic variance, we bin the full \textsc{BlueTides} cube into sub-cubes with volume equal to the survey volume, with each sub-cube corresponding to an independent realisation of the survey.

We predict that the COSMOS-Web survey will detect the most high-\( z \) \( M_{1500\AA} < -20 \) mag galaxies, with an average of \( \sim 1000 \) galaxies expected in \( 6.5 < z < 7.5 \). With its large survey area, COSMOS-Web will detect bright high-\( z \) galaxies that are too rare to
be found in smaller surveys, and will precisely measure the bright end of the galaxy luminosity function as the large area reduces the effects of cosmic variance. We predict that JADES-Medium will detect \( M_{\lambda=1500\text{Å}} \leq -20\) mag galaxies with \( \sim 100\% \) success rates at \( z < 8.5 \), detecting \( \sim 100 \) galaxies with \( M_{\lambda=1500\text{Å}} \leq -20.1 \) mag in \( 6.5 < z < 7.5 \). This deeper survey will obtain accurate measurements of the fainter-end of the luminosity function that the shallow depth of COSMOS-Web cannot reach. We predict that the PEARLS GOODS-S and NEP fields will detect \( \sim 5 \) and \( \sim 35 \) \( M_{\lambda=1500\text{Å}} \leq -20 \) mag galaxies in \( 6.5 < z < 7.5 \) respectively, with CEERS detecting \( \sim 50 \) such galaxies. These smaller volume surveys are highly subject to cosmic variance, with a wide range in expected number counts and measured luminosity functions depending on the region they sample.

BlueTides is an ideal simulation for studying bright, rare galaxies in the early Universe. Due to the resolution of the simulation however, we are limited to only studying galaxies above the completeness limit of \( M_{\lambda=1500\text{Å}} = -20.1 \) mag at \( z = 7 \), and \( M_{\lambda=1500\text{Å}} = -19.9 \) mag at \( z > 7 \). We have therefore focused only on shallower surveys and made predictions for these bright galaxies. Overall, JWST is expected to discover many fainter and higher-z galaxies that this simulation cannot accurately capture.

Our approach of applying photometry to mock images of these BlueTides galaxies gives us detailed predictions for realistic galaxies, as opposed to the common approaches of using a luminosity function and magnitude cut, or applying photometry to modelled galaxies with Sérsic profiles. As well as our JWST investigation, this approach using the BlueTides Mock Image Catalogue can be used in future work for Roman and Euclid survey predictions, for example. The images can also be used for studying the physical properties of galaxies within the BlueTides simulation, such as their sizes and morphologies, and determining how successfully these properties can be measured with various instruments. Overall, this publicly available BlueTides Mock Image Catalogue will be a useful tool for the community.

**DATA AVAILABILITY**

The BlueTides Mock Image Catalogue is publicly available as a High Level Science Product (HLSP) via the Mikulski Archive for Space Telescopes (MAST) archive at [https://doi.org/10.17909/er09-4527](https://doi.org/10.17909/er09-4527). Example codes for using this catalogue can be found at [https://github.com/madelinemarshall/BlueTidesMockImageCatalogue](https://github.com/madelinemarshall/BlueTidesMockImageCatalogue). Data of the BlueTides simulation is available at [http://bluetides.psc.edu](http://bluetides.psc.edu). Other data generated in this work will be shared on reasonable request to the corresponding author.

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**REFERENCES**

Astropy Collaboration et al., 2013, A&A, 558, A33
Atek H., et al., 2015, ApJ, 800, 18
Battaglia N., Trac H., Cen R., Loeb A., 2013, ApJ, 776, 81
Beckwith S. V. W., et al., 2006, AJ, 132, 1729
Behroozi P., et al., 2020, MNRAS, 499, 3702
Bertin E., Arnouts S., 1996, A&AS, 117, 393
Bouwens R. J., et al., 2015, ApJ, 803, 34
Bouwens R. J., et al., 2016, ApJ, 830, 67
Bowler R. A. A., et al., 2015, MNRAS, 452, 1817
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., 2021, MNRAS, 510, 5088
Bradley L., et al., 2018, astrophyphotutils:v0.5, doi:10.5281/zenodo.1340699, [https://doi.org/10.5281/zenodo.1340699](https://doi.org/10.5281/zenodo.1340699)
Bunker A. J., 2021, Proc. Int. Astron. Union, 352, 342
Coe D., et al., 2019, ApJ, 884, 85
Coe D., et al., 2021, Physical Properties of the Triply-Lensed z = 11 Galaxy, JWST Proposal. Cycle 1, ID. #1433, [https://ui.adsabs.harvard.edu/abs/2021jwst.prop.1433C](https://ui.adsabs.harvard.edu/abs/2021jwst.prop.1433C)
DeGraf C., Matteo T. D., Khandai N., Croft R., 2012, ApJ, 755, L8
DeGraf C., Matteo T. D., Treu T., Fong Y., Woo J.-H., Park D., 2015, MNRAS, 454, 913
Di Matteo T., Springel V., Hernquist L., 2005, Nature, 433, 604
Dracos N. E., et al., 2022, ApJ, 926, 194
ESO 2022, Paranal Site Information, [https://www.eso.org/sci/facilities/paranal/astroclimate/site.html](https://www.eso.org/sci/facilities/paranal/astroclimate/site.html)
Feng Y., Di-Matteo T., Croft R. A., Bird S., Battaglia N., Wilkins S., 2015, MNRAS, 455, 2778
Feng Y., Bird S., Francois Lanusse 2017, Rainwoodman/Bigfile 0.1.39, doi:10.5281/ZENODO.1051251
Ferland G. J., et al., 2017, Revista Mexicana de Astronomía y Astrofísica, 53, 385
Finkelstein S. L., et al., 2017, The Cosmic Evolution Early Release Science (CEERS) Survey, JWST Proposal ID 1345, Cycle 0 Early Release Science, [https://ui.adsabs.harvard.edu/abs/2017jwst.prop.1345F](https://ui.adsabs.harvard.edu/abs/2017jwst.prop.1345F)
Finkelstein S. L., et al., 2021, Confirming a Potential Ultra-Massive Galaxy at z=10.57, JWST Proposal. Cycle 1, ID. #1758, [https://ui.adsabs.harvard.edu/abs/2021jwst.prop.1758F](https://ui.adsabs.harvard.edu/abs/2021jwst.prop.1758F)
Giavalisco M., et al., 2004, ApJ, 600, L93
Giavalisco M., et al., 2004, ApJ, 197, 35
Hainline K. N., et al., 2020, ApJ, 892, 125
Harikane Y., et al., 2022, ApJ, 929, 1
Hinshaw G., et al., 2013, ApJS, 208, 19
Figure A1. The filter transmission curves used in the simulations for each telescope. Note that we provide only the Spitzer fluxes and not images, as galaxies are unresolved.

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