Rapid early coeval star formation and assembly of the most-massive galaxies in the universe

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1 INTRODUCTION

Galaxy clusters are at the peak of the mass-assembly hierarchy in the ΛCDM paradigm and share a common feature of hosting a distinct population of galaxies aptly referred to as the brightest cluster galaxies (BCGs) (Peebles 1968; Sandage 1976; Tremaine & Richstone 1977). The BCGs are ultra-luminous (with \( \sim 10L_{\odot} \)) where \( L_{\odot} \) is the characteristic luminosity of the general galaxy population), morphologically spheroidal, have a large spatial extent, and exhibit core stellar velocity dispersions of order \( 300 - 400 \) km s\(^{-1}\) (Lin & Mohr 2004; Pipino et al. 2011; Loubser et al. 2018). The BCGs are in fact the brightest and the most-massive galaxies in the present-day Universe. Many of the observed characteristics of the BCGs seem to scale with the properties of the hosting cluster halo (Brough et al. 2008; Lidman et al. 2012; Kravtsov et al. 2014; Lavoie et al. 2016) and they are frequently found close to, and typically have relatively small velocity offsets with respect to, the potential centres of the cluster halo (Lidman et al. 2013; Lauer et al. 2014). This is commonly interpreted as an indication that the formation and evolution of the BCGs and their host clusters are intimately linked, and that studying the former will provide clues about the formation and evolution of the latter. However, pinning down the assembly and growth histories of these gigantic galaxies is proving to be a challenge.

There are several pathways that could explain the origin of the BCGs: (i) extended in-situ star formation (e.g. via cooling flows); (ii) rapid star formation and early assembly; and (iii) early star formation in separate galaxies but relatively recent assembly via a sequence of late-time mergers. The key idea underlying the first proposal is that radiative cooling drives the hot intracluster medium to concentrate at the clusters’ potential centre where it then forms stars at relatively high rates (Cowie & Binney 1977; Fabian & Nulsen 1977). However, observations show that not only are the bulk of the BCG stars old (Whiley et al. 2008), but...
heating from the central active galactic nucleus (AGN) also strongly suppresses the cooling of the intracluster medium (Tabor & Binney 1993; Ciotti & Ostriker 1997; Silk & Rees 1998). The second proposal suggests that massive elliptical galaxies, including the BCGs, form via essentially monolithic collapse of a mass density peak (Eggen et al. 1962), with the galaxies’ stellar mass building up rapidly in the process. One difficulty with this model is that BCGs show evidence of significant growth in their sizes over cosmic time (Daddi et al. 2005; van der Wel et al. 2008; Shankar et al. 2015). Once a leading theory, this scenario has fallen out of favour due to the emergence of the hierarchical assembly paradigm for cosmic structure formation. According to this paradigm, the third proposal, galaxies form via a series of mergers of lower-mass systems – implying that the low mass systems first, and over time build-up the more-massive systems (Aragon-Salamanca et al. 1998; Dubinski 1998).

Numerical studies investigating the formation and evolution of BCGs in the presently favoured hierarchical ΛCDM model find that the majority of stars that end up in the present-day BCGs typically form at $z \gtrsim 4$ in distinct progenitor galaxies (De Lucia et al. 2006). These galaxies then eventually merge to assemble the BCGs we observe today. As for the timing of this assembly, until recently, the theoretical consensus was that present-day BCGs are assembled late via dissipative mergers (Aragon-Salamanca et al. 1998; Dubinski 1998). The second proposal suggests that massive elliptical galaxies, including the BCGs, form via essentially monolithic collapse of a mass density peak (Eggen et al. 1962), with the galaxies’ stellar mass building up rapidly in the process. One difficulty with this model is that BCGs show evidence of significant growth in their sizes over cosmic time (Daddi et al. 2005; van der Wel et al. 2008; Shankar et al. 2015). Once a leading theory, this scenario has fallen out of favour due to the emergence of the hierarchical assembly paradigm for cosmic structure formation. According to this paradigm, the third proposal, galaxies form via a series of mergers of lower-mass systems – implying that the low mass systems form first, and over time build-up the more-massive systems (Aragon-Salamanca et al. 1998; Dubinski 1998).

Recent observations, however, suggest that the late-assembly picture may not be as concrete as once thought, and that early assembly may play a major role in the evolution of the BCGs. Several BCGs have been discovered at $z \sim 1$–1.5 that have stellar masses comparable to the most-massive galaxies in the universe (Collins et al. 2009). If these BCGs were to grow at the rates theoretically expected via late-time hierarchical assembly, they would greatly exceed the predicted masses of those theoretical models. There is also evidence that the luminosities and sizes of the BCGs, as a population, do not evolve much past $z \sim 1$ (White et al. 2008; Stott et al. 2011), indicating that little growth through the hierarchical scenario is possible. The absence of observed evolution past $z \sim 1$ implies that these massive galaxies must grow via a combination of in-situ star formation and early assembly. With respect to the former, Webb et al. (2015) analyse a set of BCGs in the Spitzer Adaptation of the Red-Sequence Cluster Survey (SpARCS; see Muzzin et al. 2009; Wilson et al. 2009) and find that a large contribution to the overall growth of the BCGs must be due to in-situ star formation based on the estimated star formation rates of hundreds of BCGs (in the range $0.8 < z < 1.8$), and also find an increasing star formation rate with increasing redshift. As to the latter, there is growing evidence of highly over-dense protocluster cores (e.g. Ishigaki et al. 2016; Higuchi et al. 2018; Miller et al. 2018; Jiang et al. 2018; Wang et al., in prep.; also see Ito et al. 2019, and Overzier 2016 for a broad census review) at high redshifts ($z \gtrsim 4$). As we demonstrate in Section 2, protocluster cores with a high density of galaxies are the birthplaces of BCGs, and highly-over-dense systems should collapse rapidly in the ΛCDM theory – casting into doubt whether the theoretical consensus of late assembly is valid for the entire population of BCGs.

In this paper, we investigate the above tension between the current theoretical picture and accumulation of observational results in order to gain insight into the evolution of the BCG population. Specifically, we use a bespoke non-cosmological simulation based on the observed parameters of the SPT2349-56 protocluster (Miller et al. 2018) to track its forward evolution. Our interest lies in determining the future evolution of the protocluster core – including the fate of the observed galaxies – and the timescale of its evolution. We then use the MultiDark Planck 2 Bolshoi simulation (Riebe et al. 2013; Klypin et al. 2016) a large-volume non-baryonic simulation, to estimate the frequency of similar events in the universe. While dark-matter simulations exist that provide ample resolution and population statistics (through their large volumes) for discovering over-dense protoclusters at high redshift, simulating the equivalent volumes in tandem with the hydrodynamical equations of motion and galactic-baryonic physical processes is, at present, not feasible due to computational constraints. These constraints force us to study the forward evolution of SPT2349-56 in the bespoke simulation. In Section 2 we describe our setup and initial conditions for the SPT2349-56 simulation. In Section 3, we discuss the assembly and growth of the system. In Section 4, we analyse a large volume dark-matter-only simulation in order to determine how frequent such highly over-dense events may be. Lastly, we synthesise our findings and present a revised paradigm for the formation and the evolution of the BCGs in Section 5.

2 METHODOLOGY

We start by constructing a bespoke simulation of the SPT2349-56 system in order to specifically study its forward evolution. Observations indicate that the 14 galaxies that comprise the core of the protocluster are within a 130 kpc (physical) projected region on the sky, and we show the observed physical properties of each of the 14 galaxies in
leftmost two columns of Table 1. The observed line-of-sight velocity distribution was found to approximate a Gaussian distribution with $\sigma_{v_{\text{LOS}}} \approx 408 \text{ km s}^{-1}$ (Miller et al. 2018).

In order to simulate the forward evolution of the system, we use a modified version of GIZMO (Hopkins 2015), a publicly available gravity plus hydrodynamics simulation program, that is equipped with an implementation of the meshfree finite mass method (Lanson & Vila 2008a,b; Gaburov & Nitadori 2011).

We simulate the protocluster in isolation with vacuum boundary conditions. The simulation is non-cosmological, and evolves the equations of motion for 1 Gyr. Gas and star particles in the simulation have an initial mass of $M_{\text{gas}} = M_s = 10^6 M_\odot$. Gas properties are calculated using the cubic spline kernel with $\epsilon = 32$ and evolves the equations of motion for vacuum boundary conditions. The simulation is non-cosmological, that is equipped with an implementation of the mesh-free finite mass method (Lanson & Vila 2008a,b; Gaburov & Nitadori 2011).

We simulate the protocluster in isolation with vacuum boundary conditions. The simulation is non-cosmological, and evolves the equations of motion for 1 Gyr. Gas and star particles in the simulation have an initial mass of $M_{\text{gas}} = M_s = 10^6 M_\odot$. Gas properties are calculated using the cubic spline kernel with 32 neighbouring particles in our simulations. The dark matter particle mass is $M_{\text{DM}} = 5 \times 10^5 M_\odot$. Additionally, we seed each galaxy with a black hole of mass $M_{\text{BH}} = 10^7 M_\odot$. We use adaptive gravitational softening for all gravitationally interacting particles (Hopkins et al., 2018), which requires minimum softening parameters. Baryonic particles have a minimum softening of $\epsilon_{\text{b, min}} = 50 \text{ pc}$ and, for dark matter, we use a minimum softening of $\epsilon_{\text{dark, min}} = 200 \text{ pc}$.

2.1 Initial conditions

We assume a Planck Collaboration XVI (2014) cosmology throughout the following procedure, and generate initial conditions using the MakeGalaxy software (Hernquist 1993; Springel & White 1999; Springel 2000; Springel et al. 2005). Each galaxy in our synthetic SPT2349-56 system consists of a dark matter halo, gas disc and stellar disc, with no stellar bulge or surrounding gaseous circumgalactic medium. MakeGalaxy employs the methods of Springel et al. (2005) to create stable spiral galaxies, which we summarise here. We model the dark matter distribution in each galaxy with a Hernquist (1990) profile where the scalelength is related to the corresponding NFW concentration $c_{\text{vir}}$ of the halo (Navarro et al. 1997). We model the gas and stellar discs with exponentially declining surface densities with the scalelength $H$ related to the angular momentum (through the spin parameter $J$) of the system. We follow Robertson et al. (2006) and use $J = 0.033$, which is the mode of the spin distribution from cosmological simulations (Vitvitska et al. 2002). The combined gas+stellar disc is also under the condition that the total disc mass is a fixed fraction of the total mass of the system, i.e. $M_{\text{disc}} = m_d M_{\text{tot}}$. To ensure disc stability we choose $m_d = 0.03$ for each disc as values between $0.03 \lesssim m_d \lesssim 0.05$ lead to stable discs in the $\Lambda$CDM cosmology (Mo et al. 1998). The vertical structure of the stellar disc is that of an isothermal sheet with a radially constant scaleheight $z_0$ given as a free parameter proportional to the scalelength of the disc, which we assume to be $z_0 = 0.1H$. For the vertical structure in the gas disc, we set the scaleheight such that hydrostatic equilibrium is enforced. We tested each galaxy in isolation to ensure that the system is physically and numerically stable, and find an average star formation rate of $\approx 75 M_\odot \text{ yr}^{-1}$ over 1 Gyr, with a peak of $\approx 140 M_\odot \text{ yr}^{-1}$, for the most-massive galaxy.

In order to setup each galaxy, we require estimates of their dark matter halo, stellar, and gas masses as well as the concentrations of the dark matter halos. We base our following calculations on the observed total galactic gas mass, $M_{\text{gas, gal}}$, shown in Table 1. We prepare and simulate three separate realisations of the SPT2349-56 system.

2.1.1 Masses

We estimate the dark matter halo mass of an individual galaxy in the protocluster core by first assuming a reasonable gas fraction $f_{\text{gas, gal}}$, computing the corresponding galactic stellar mass $M_{\text{gal}}$, and then estimating the halo virial mass $M_{\text{vir}}$ from $M_{\text{gal}}$. We define the gas fraction as,

$$f_{\text{gas, gal}} \equiv \frac{M_{\text{gas, gal}}}{M_{\text{gas, gal}} + M_{\text{gal}}}.$$  \hfill (1)

Therefore, the stellar mass is

$$M_{\text{gal}} = \left( \frac{1}{f_{\text{gas, gal}}} - 1 \right) M_{\text{gas, gal}}.$$  \hfill (2)

We assume all of our galaxies have the same gas fraction, $f_{\text{gas, gal}} = 0.7$, estimated from the results in Narayanan et al. (2012) and Tadaki et al. (2019). This assumption is reasonable for high-redshift galaxies, where gas fractions $f_{\text{gas}} > 0.4$ are routinely inferred, with a large spread above this value (Carilli et al. 2010; Daddi et al. 2010; Tacconi et al. 2010, 2013). As for relating $M_{\text{vir}}$ and $M_{\text{gal}}$, Behroozi et al. (2013b) show that the stellar-to-halo mass fraction is $M_{\text{gal}}/M_{\text{vir}} \approx 0.01$, within a factor of two for a wide range of halo masses at $z = 4 - 5$. Using these observational results we estimate $M_{\text{gal}} \approx 0.428 M_{\text{gas, gal}}$ and $M_{\text{vir}} \approx 42.8 M_{\text{gas, gal}}$ to within a factor of two. We show the results of our calculations in Table 1.

2.1.2 Halo properties

Having an estimate of the virial mass of each system allows us to calculate the halo concentrations and virial velocities. Using the universal halo concentration model from Bullock et al. (2001), the concentration parameter is

$$C_{\text{vir}}(M_{\text{vir}}, z) = 9 \left( \frac{M_{\text{vir}}}{M_{\text{coll, 0}}} \right)^{-0.13} (1 + z)^{-1},$$  \hfill (3)

where $M_{\text{coll, 0}} = 1.18 \times 10^{13} M_\odot$. Diemer & Kravtsov (2015) show that, for halo masses in our regime of interest ($M_{\text{vir}} \lesssim 4.42 \times 10^{12} M_\odot$), equation (3) is an excellent approximation to their more general models. The virial velocity follows from the virial mass as,

$$V_{\text{vir}} \approx \left( 10 G M_{\text{vir}} H(z) \right)^{1/3},$$  \hfill (4)

where $H(z) = H_0 \sqrt{\Omega_{\text{m, 0}}(1 + z)^3 + \Omega_{\Lambda, 0}}$. We show the results of equations (3) and (4), applied to each halo, in Table 1.

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1 http://www.tapir.caltech.edu/~phopkins/Site/GIZMO.html
centres of each galaxy to lay within a sphere of radius 65 kpc after the initial condition. We constrain the mass-weighted Myr each stellar particle with an arbitrary logarithmic scaling at 1 then sample 14 new velocity components for each spatial distribution in Table 1 provides the initial velocities of our synthetic SPT2349-56 system. The observed velocity distribution of each galaxy in one of the realisations of our modelled galaxies. We fit a Gaussian to the distribution and positioning of each galaxy in one of the realisations of our synthetic SPT2349-56 system. We bin the observed objects. Fig. 1 shows a qualitative view of the observed line-of-sight offset velocities (ΔVLOS) and cold gas masses (Mgas,gal) to estimate the remaining physical parameters in this table. M∗,gal is the estimated galactic stellar mass, Cvir is the estimated NFW halo concentration, and Vvir is the estimated virial mass of the galaxy’s host halo.

| Label | ∆VLOS (km s⁻¹) | Mgas,gal (10¹⁰ Msun) | M∗,gal (10¹⁰ Msun) | Mvir (10¹⁰ Msun) | Cvir | Vvir (km s⁻¹) |
|-------|----------------|----------------------|-------------------|-----------------|------|-------------|
| A     | -90            | 12.0                 | 5.14              | 514             | 1.67 | 537         |
| B     | -124           | 11.2                 | 4.79              | 479             | 1.69 | 524         |
| C     | 603            | 6.7                  | 2.87              | 287             | 1.81 | 442         |
| D     | -33            | 8.4                  | 3.6               | 360             | 1.75 | 477         |
| E     | 84             | 4.8                  | 2.05              | 205             | 1.89 | 395         |
| F     | 395            | 3.4                  | 1.46              | 146             | 1.97 | 353         |
| G     | 308            | 1.6                  | 0.685             | 68.5            | 2.18 | 274         |
| H     | -719           | 4.4                  | 1.88              | 188             | 1.91 | 384         |
| I     | 310            | 2.2                  | 0.942             | 94.2            | 2.09 | 305         |
| J     | 481            | 2.2                  | 0.942             | 94.2            | 2.09 | 305         |
| K     | 631            | 3.1                  | 1.33              | 133             | 2.00 | 342         |
| L     | -379           | 3.3                  | 1.41              | 141             | 1.98 | 348         |
| M     | 34             | 1.2                  | 0.514             | 51.4            | 2.26 | 249         |
| N     | 90             | 1.0                  | 0.428             | 42.8            | 2.31 | 234         |

Figure 1. A schematic view of one of the realisations of our synthetic SPT2349-56 system. We bin the xy-plane positions of each stellar particle with an arbitrary logarithmic scaling at 1 Myr after the initial condition. We constrain the mass-weighted centres of each galaxy to lay within a sphere of radius 65 kpc (physical) based on the observed projected separations.

2.1.3 System dynamics

For the dynamical evolution of the entire system we require the initial positions randomly within a sphere of physical radius 65 kpc (the observed maximal separation) for each galaxy with no dependence on the true separations between the observed objects. Fig. 1 shows a qualitative view of the positioning of each galaxy in one of the realisations of our synthetic SPT2349-56 system. The observed velocity distribution in Table 1 provides the initial velocities of our simulated galaxies. We fit a Gaussian to the distribution and then sample 14 new velocity components for each spatial direction. We randomly select the orientation of the spin axes for each galaxy.

2.2 Galactic Physics

Our sub-grid physics models are the same as those described in Rennehan et al. (2019) (based on the model in Davé et al. 2016), except that we now include a model for supermassive black hole (SMBH) growth and feedback. We briefly describe the models below and point the reader to the aforementioned reference for more information.

2.2.1 Cooling and Star Formation

For radiative cooling, we calculate the cooling rates in the presence a UV background (Faucher-Giguère et al. 2009) using the GRACLE-3.1 cooling library² (Smith et al. 2017).

Our star formation implementation follows that in the MUFASA simulations (Davé et al. 2016, 2017). We determine the conversion rate of gas into stars based on the estimated fraction of molecular hydrogen (fH₂) in the gas based on the approximations in Krumholz et al. (2009). We convert gas at densities above the threshold n_{crit} = 0.2 cm⁻³ into stars at a rate dρ_*/dt = ϵ_*, fH₂, P_{gas}/t_{dyn} where ρ_* is the stellar density, ϵ_* = 0.02 is star formation efficiency (Kennicutt 1998), and t_{dyn} = (G P_{gas}⁻¹)⁺¹⁄² is the local dynamical time. We also force gas onto an artificial equation of state, T_{eqS} = 10^4 (n_{gas}/n_{crit})¹⁄³ K, where n_{gas} is the gas hydrogen number density, above the star formation critical density (n_{gas} > n_{crit}) to suppress numerical fragmentation (Teyssier et al. 2011; Davé et al. 2016).

2.2.2 Stellar Feedback

We include energetic feedback from supernova types Ia and II (SNIa and SNII, respectively), stellar radiation, and stellar winds from asymptotic giant branch (AGB) stars based

² https://grackle.readthedocs.io
on the MUFASA cosmological simulation model. We also include mass injection from SNIa, SNII, and AGB stars, which is important for enriching the gas in the simulation (Davé et al. 2016; Liang et al. 2016). We account for the effects of both prompt and delayed SNIa (Scannapieco & Bildsten 2005).

Metals are vital in determining the balance of gas cooling and heating in astrophysical gas, and therefore we include their production and account for their role in cooling. We consider metal production by SNIa, SNII as well as AGB stars (Iwamoto et al. 1999; Nomoto et al. 2006; Oppenheimer & Davé 2008). For details, we refer the reader to Liang et al. (2016), Davé et al. (2016), and Rennehan et al. (2019). We consider metal production by SNIa, SNII as well as AGB stars (Iwamoto et al. 1999; Nomoto et al. 2006; Oppenheimer & Davé 2008). We account for the effects of both prompt and delayed SNIa (Scannapieco & Bildsten 2005).

2.2.3 Active Galactic Nuclei

High luminosity galaxies often host active galactic nuclei (AGN) concurrently with intense starburst episodes in the local universe (Nardini et al. 2008), and at early epochs (Alexander et al. 2005). Therefore, we also include the effects of AGN feedback into our investigation. AGN are important in determining the correct estimate of stellar mass growth. Our model is that of Springel et al. (2005), which we briefly describe below.

We initially place black holes of mass $10^5 M_\odot$ in the centres of each galaxy, and allow them to grow via Eddington-limited Bondi accretion. We use the unboosted Bondi model because the mesh-free finite mass method can resolve higher densities at the same mass resolution, compared to the common smoothed particle hydrodynamics implementations (Hopkins 2015). We also include energetic feedback, and assume that each AGN generates energy in the gas at a rate $E = \epsilon_c c^2 \rho_{\text{gas}}/\rho_{\text{gas}} c_s^2$, where $\epsilon_c = 0.1$ is the radiative efficiency; $\epsilon_c = 0.05$ is the coupling fraction to the gas, and $c$ is the speed of light. The accretion rate $\dot{M}_{\text{BH}} = 4\pi G^2 M_{\text{BH}}^2 \rho_{\text{gas}}/(\epsilon_c c^2 + \rho_{\text{gas}} c_s^2)^{3/2}$ is the Bondi accretion rate onto the black hole, where $c_s$ is the surrounding gas sound speed, $v_{\text{rel}}$ is the relative velocity of the SMBH with respect to the gas, and $\rho_{\text{gas}}$ is the surrounding gas density. The gas properties—density, sound speed, and relative velocity—are calculated over the nearest 128 neighbouring gas particles. The energy is deposited to the surrounding gas in a kernel-weighted manner, over the same nearest 128 neighbouring particles. To follow the dynamical evolution of the SMBHs, we use the model from Tremmel et al. (2015) in which the dynamical friction force is calculated by using the approximation from Chandrasekhar (1943).

3 STELLAR ASSEMBLY AND GROWTH

To gain a qualitative understanding of the protocluster assembly, we examine one realisation of the system visually in Fig. 2. We bin the positions of each star particle in the simulated $xyz$-plane at three times: $t = 0.12$, 0.5, and 1 Gyr, from top to bottom, respectively.

In the top panel of Fig. 2, there are several stellar streams protruding through the system as the galaxies undergo the initial collapse after $\sim 120$ Myr. These streams are due to tidal stripping from the companion galaxies as the initial velocity dispersion of the system, combined with

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{A particle view of the assembly of one of the realisations of our synthetic SPT2349-56. We bin the positions of the stellar particles in the simulation in the $xy$-plane ($150$ kpc $\times$ $150$ kpc) using an arbitrary logarithmic scaling. These panels represent $t = 0.12$, 0.5, and 1 Gyr from the initial condition, from top to bottom, respectively. There are obvious shell-like structures and stellar streams throughout the short assembly period, until the system resembles a massive elliptical galaxy at $\sim 500$ Myr.}
\end{figure}
the close proximity of galaxies, is unable to prevent im-
minent merging. At maximum distance, the tidal tails extend approximately 90 kpc.

In the middle panel, 500 Myr after the start of the sim-
ulation, several streams are visible in addition to shell-like
structures surrounding the core of the galaxy. It is difficult
to distinguish any of the original structure as the stellar
populations begin to mix. At this point during the simu-
lation, many of the stellar particles are launched out to ≈ 75 kpc from the centre-of-mass of the system, building up the
diffuse stellar envelope and intracluster light.

At 1 Gyr in the bottom panel of Fig. 2, the system
resembles a massive elliptical galaxy. Many of the stars from
the initial galaxies, as well as those formed in-situ, were
kicked out and formed an extended diffuse stellar halo. There
is no longer any visible structure in this halo. Using radiative
transfer we are able to further investigate the evolution of
the system.

Fig. 3 shows colour-composite mock James Webb Space
Telescope (JWST) observations of one of our synthetic
SPT2349-56 realisations. We generated these observations
using the SKIRT radiative transfer code (Baes et al. 2011;
Camps & Baes 2015; Baes & Camps 2015) and an adapted
version of the observational reality suite described in Bot-
trell et al. (2017a,b). To produce these images, we first as-
signed star particles spectral templates based on the STAR-
burst99 (Leitherer et al. 1999) spectral energy distribu-
tion set for old stellar populations and Groves et al. (2008)
templates, which include emission from HII and photodisso-
ciation regions, for young (< 10 Myr-old) star particles. We
use a multi-component dust model (Zubko et al. 2004) with
a constant dust-to-metal ratio of 0.3 and do not limit dust
to star-forming gas particles. SKIRT produced rest-frame optical
data cubes that we processed into noiseless, idealised
photometric images in the JWST NIRCam F150W, F200W, F277W, F356W band passes3 at redshifts corresponding to
the simulation snapshots. In the right column of Fig. 3, we
show idealised images. The idealised images are noiseless and
are neither rebinned down to the NIRCam angular resolu-
tion nor convolved with the NIRCam point-spread function.
At each of the redshifts we consider z ∈ {4, 3.3, 3.2, 3.1, 3.0, 2.9, 2.8, 2.7, 2.6, 2.5, 2.4, 2.3, 2.2, 2.1, 2.0, 1.9, 1.8, 1.7, 1.6, 1.5, 1.4, 1.3, 1.2, 1.1, 1.0, 0.9, 0.8, 0.7, 0.6, 0.5, 0.4, 0.3, 0.2, 0.1, 0.0, 0, 0, 0}, Gyr, at least three of these filters
are the densest structures in the protocluster’s redshifted rest frame optical
domain.

We assigned the filtered light at the smallest wave-
lengths to the blue values, the mid-range wavelengths to the
green, and the longest to the red to construct a qualitative,
visual representation of the system from t = 1 Gyr to t = 1
Gyr (from top to bottom in Fig. 3, respectively)4.

In the top-right panel of Fig. 3, we show t = 120 Myr
after the initial condition. Already by this point in the sys-
tem’s evolution, we see the long stellar streams from the top
panel of Fig. 2 as a spatially-extended low-surface brightness
web surrounding the remnant cores of each initial galaxy.
Several bright star-forming cores remain visible in blue and
white. Initial gravitational torques cause the fragmentation

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3 https://jwst-docs.stsci.edu/display/JTI/NIRCam+Filters

4 Specifically, we use the NIRCam filters {F200W, F277W, F356W} at 120 Myr, and {F150W, F200W, F277W} at both 500
Myr and 1 Gyr.
Figure 3. (left) James Webb Space Telescope mock observations of the forward evolution of SPT2349-56. Redshifts are $z \sim 4$, 3.3, and 2.7, from top to bottom, respectively. (right) Synthetic false colour images made from three of the James Webb Space Telescope NIRCam filters without the CCD angular scale or noise. The snapshots correspond to the redshift labels in the left column, for each row.
reaching stellar masses of $\sim 10^{12} \, M_\odot$ to $\sim 10^{13} \, M_\odot$ in the low-growth and high-growth scenarios, respectively. However, since they grow rapidly to a large mass, the dynamical friction timescale for lower-mass satellites to merge into the system becomes large, which could hamper late-time growth.

In the top panel in Fig. 4, we show the forward-evolution of the star formation rate of our synthetic SPT2349-56 system as a function of time, averaged over our three realisations, up to 1 Gyr ($z \approx 2.7$) after the observation ($z = 4.3$). The star formation rate (SFR) peaks at $\sim 3000 \, M_\odot \, yr^{-1}$ approximately 5 Myr after the initial condition and decays exponentially to $\sim 40 \, M_\odot \, yr^{-1}$ at 1 Gyr. Our simulated SFR is comparable to the observed results of Miller et al. (2018) who find a total star formation rate of $\sim 6500 \, M_\odot \, yr^{-1}$ for the 14 galaxies in the SPT2349-56 system. We use a non-linear least squares fitting method to fit an exponential curve to the SFR, and find that the decay time is $\tau \sim 200$ Myr. Initially, the SFR peaks due to high compression from the proximity of each individual galaxy, and the fact that they are rapidly collapsing under their mutual gravity. Additionally, strong fluctuations in SFR occur as the discs undergo tidal interactions. Stellar feedback is the main cause of the declining SFR, as the black holes provide little feedback past the initial $\sim 50$ Myr due to their low accretion rates. They are unable to accrete because of their high velocities relative to the medium – which suppresses accretion. On the other hand, stellar feedback is most powerful when the star formation rate is the highest, as the system coalesces, and the supernovae and stellar winds begin to excavate the gas out of the original galaxies.

The balance of stellar feedback and star formation causes a smooth decline in star formation rate, and consequently a smooth increase in average total stellar mass across our three realisations, as we show in the bottom panel in Fig. 4. In this panel, the total stellar mass is given as the solid line and we label the combined initial and final (at 1 Gyr) stellar masses, $M_{\text{initial}} = 2.81 \times 10^{11} \, M_\odot$ and $M_{\text{final}} = 8.14 \times 10^{11} \, M_\odot$, respectively. The horizontal dashed line shows the assembly mass, which we define as 90% of the final mass ($M_{\text{assembly}} = 7.33 \times 10^{11} \, M_\odot$). The vertical dotted line shows the time at which assembly occurs, $\tau_{\text{assembly}} \sim 370$ Myr. Assembly occurs rapidly in the system, and our results show that the system nearly quadruples size within a gigayear. We also show the observed masses of brightest cluster galaxies (BCGs) in Burke et al. (2015) from the Cluster Lensing and Supernova survey with Hubble (CLASH) survey with × symbols at 1 Gyr. These BCGs belong to clusters with masses $\gtrsim 10^{15} \, M_\odot$, and range in redshift from $0.187 < z < 0.890$. Although our system is at $z \approx 2.7$ after 1 Gyr, it is already more massive than most of the BCGs from the CLASH survey.

We posit that recently discovered systems similar to SPT2349-56 (e.g. Ishigaki et al. 2016; Higuchi et al. 2018; Jiang et al. 2018) are the proto-cores of the massive galaxy clusters. The speed of assembly and growth of stellar mass in our simulated realisations of SPT2349-56 is obvious from Figs. 2, 3, & 4. The star formation rate declines exponentially with an $\epsilon$-folding time of $\sim 200$ Myr while simultaneously, an object that qualitatively looks like many observed BCGs forms by 500 Myr. From these results, we predict that the observed high-redshift over-dense protoclusters (Ishigaki et al. 2016; Miller et al. 2018; Jiang et al. 2018; Wang et al., in prep.) will undergo a similar evolution and therefore form massive BCGs as early as $z \approx 4$. As we demonstrated, the JWST will be able to clearly see the massive BCGs out to redshift of $z \approx 3$, and their progenitors out to $z \approx 4.3$, opening up a new frontier for exploration, especially in collaboration with survey telescopes such as the Wide-Field Infrared Survey Telescope (WFIRST).

In terms of redshift, our simulation began at $z = 4.3$ and ended 1 Gyr later at $z = 2.7$, assuming a Planck Collaboration XVI (2014) cosmology.

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Figure 4. Growth and assembly history of the simulated protocluster system, averaged over three independent realisations. (top) Average star formation rate over the first gigayear of evolution. We used a non-linear least squares method to fit a decaying exponential and found a decay timescale of $\tau = 200$ Myr. (bottom) The total average stellar mass evolution. The horizontal dashed line shows 90% of the final mass, and the dotted vertical line shows the time at which the system reaches 90% of the final mass. We show the observed masses of brightest cluster galaxies from the CLASH survey as × symbols at 1 Gyr which were measured within a 50 kpc aperture. After 1 Gyr ($z = 2.7$), the average stellar mass across the three realisations is more massive than most of the lower-redshift CLASH brightest cluster galaxies.
4 IMPLICATIONS FOR GALAXY CLUSTERS

In the hierarchical structure formation scenario, galaxy clusters are the youngest and most-massive objects in the universe. In this theory, the more massive the cluster, the younger and rarer the system. Hence, the most-massive clusters should continue to assemble the bulk of their mass until late times. What we have demonstrated in the previous section is the possibility of a downsizing effect (Bower et al. 2006; Cimatti et al. 2006; Neistein et al. 2006; Fontanot et al. 2009; Oser et al. 2010) on the cluster scale, where the cores of these massive clusters could be much older than the cores of less-massive clusters, beginning to assemble at redshifts \( z \gtrsim 2 \) at the minimum. Our results on the rapid assembly of the brightest cluster galaxy (BCG) are then not unexpected as these high-redshift protocluster cores would be the strongest relative overdensities in the early universe. This begs the question: why has the theoretical community not predicted high-redshift fully-assembled BCGs?

One of the issues is that the main tools of contemporary theoretical astrophysicists are numerical simulations. These are necessary because of the strong non-linearity of the structure formation process after the linear perturbation theory breaks down. However, a lack of computational power limits the spatio-temporal dynamic range of the numerical simulations. We are therefore forced into a compromise. We can model a small comoving volume of the universe and resolve the galaxies in this volume (e.g. Schaye et al. 2015; Pillepich et al. 2018; Dave et al. 2019) but such volumes generally do not contain the rare massive clusters we would expect to host an object such as SPT2349-56. Or, we can sacrifice resolution in favour of large volumes but then galaxy formation must be introduced in an ad hoc fashion (Ruszkowski & Springel 2009), which can introduce biases. Despite these difficulties, we do expect that these protoclusters are present in the largest dark-matter-only simulations, such as the MultiDark Bolshoi (Klypin et al. 2011) and Millennium XXL (Angulo et al. 2012) simulations.

To test our theory of early, rapid assembly of the cores of the most-massive clusters with regards to the general population of galaxy clusters, we investigate their assembly history in the MultiDark Planck 2 (MDPL2) simulation (Riebe et al. 2013; Klypin et al. 2016) – a child of the MultiDark Bolshoi suite of simulations. The MDPL2 simulation consists of 3840\(^3\) particles within a simulation volume of side-length 1 cGpc\(^{-1}\), and has a mass resolution of 1.51 \(\times\) 10\(^9\) M\(_\odot\)\(\, h^{-1}\). Given that our estimated mass of dark matter in the SPT2349-56 system is \(\sim 1.9 \times 10^{13}\) M\(_\odot\)\(\, h^{-1}\) (within a factor of two), MDPL2 provides ample resolution to find the substructures (dark matter halos) associated with the observed protocluster. All of the halo data is publicly available online\(^6\) and we specifically use the MDPL2. Rockstar database in the following analysis. This database contains halo properties that were determined using the ROCKSTAR halo finder (Behroozi et al. 2013a), and includes the substructure trees for each host halo.

First, we require a set of criteria for the occurrence of highly over-dense massive collapse events at high redshift. We analysed the formation histories of all galaxy clusters that had final masses\(^7\) of \(M_{\text{vir}} \geq 5 \times 10^{14}\) M\(_\odot\) at \(z = 0\), and narrowed our search to those with a large number of relatively massive halos entering their progenitor’s virial radius across cosmic time. Specifically, we define an over-dense collapse event to be when \(N \geq 5\) halos of individual mass \(M_{\text{vir}} \geq 2 \times 10^{11}\) M\(_\odot\) (the substructures) enter the virial radius of a halo that is no more than 20 times more massive than each substructure. The latter condition considers only those events in which the substructures have a chance of merging within a Hubble time (at their respective redshift). We

\(^6\) https://www.cosmosim.org

\(^7\) Henceforth we assume a Planck Collaboration XVI (2014) cosmology for \(h\) in our quoted masses and distances.
determine the first redshift at which an over-dense event occurs for each of the galaxy clusters above our mass limit. The least massive events we find are a factor of \( \sim 10 \) less massive than our estimated mass for SPT2349-56 and, therefore, ought to rapidly (if found above \( z \gtrsim 4 \)) collapse into elliptical galaxies of mass \( M_\ast \gtrsim 10^{11} \, M_\odot \) based on our estimates in Section 3.

In the top panel of Fig. 5, we present a two-dimensional histogram that encodes the occurrence of high-density collapse regions for a cluster of a given final mass at \( z = 0 \). Specifically, we count the number of first occurrences of an over-dense event in a grid of redshift and final cluster mass coordinates. We normalise to the total number of events in each mass bin, so that the colouring shows the probability of finding the first event for that final cluster mass at a given redshift, compared to all other events that occur. We do not include non-events in the top panel but this does not affect our approximate probability estimate in logarithmic space as the number of clusters that have a non-event is a small overall fraction of the total number in each mass bin.

There is a clear trend showing that the mode redshift increases from \( z \approx 2.5 \) for \( M_{\text{vir}} = 5 \times 10^{14} \, M_\odot \) to \( z = 4 \) for \( M_{\text{vir}} = 2 \times 10^{15} \, M_\odot \). Additionally, lower-mass clusters at \( z = 0 \) are less likely to have a high-density collapse at redshifts \( z \gtrsim 4 \) (above the dashed line in Fig. 5) compared to clusters with masses \( M_{\text{vir}} \gtrsim 10^{15} \, M_\odot \). There are, however, clusters that did not experience an over-dense collapse at any redshift – those we show in the bottom panel of Fig. 5. Except for the anomaly at \( M_{\text{vir}} \approx 10^{15.1} \, M_\odot \), there is a clear power-law trend where the fraction of non-events increases with decreasing final mass of the clusters.

For the present purposes, our interest lies in the objects that collapse in the range \( z \gtrsim 4 \) since these would end up as the most-massive, blue, elliptical galaxies at \( z \approx 2.5 \) by our predictions. We find that 11.6% of clusters with final masses \( M_{\text{vir}} > 10^{15} \, M_\odot \) have an over-dense collapse event occur above \( z = 4 \), and 7.6% of clusters with final masses \( 5 \times 10^{14} \, M_\odot \leq M_{\text{vir}} < 10^{15} \, M_\odot \). In total, we find 147 high-density collapse events at \( z > 4 \). Given the volume of the simulation, \( V \approx 3.2 \, \text{cMpc}^3 \), we expect a comoving number density of corresponding massive, blue, elliptical cluster BCGs at redshifts \( z \gtrsim 3 \) to be \( n \approx 46 \, \text{cMpc}^{-3} \) (or \( n \approx 4.6 \times 10^{-8} \, \text{cMpc}^{-3} \)).

In Fig. 6, we examine the spatial, mass, and velocity distribution (from top to bottom, respectively) of an example cluster proto-core in the MDPL2 simulation\(^8\). This proto-cluster is the most-massive progenitor (MMP) at \( z = 4.266 \) (the approximate redshift of SPT2349-56) of the second-most-massive cluster at \( z = 0 \).

In the top panel of Fig. 6, we show the spatial distribution of the substructure entering the virial region of the MMP. The dotted line shows the observed extent of the SPT2349-56 object for comparison. Each halo is marked with a triangle that we colour based on the logarithmic mass distribution (from top to bottom, respectively) of an example. The virial radius of the MMP is \( R_{\text{vir}} \approx 120 \, \text{kpc} \) and we see that most of the massive substructure is within the SPT2349-56 sphere.

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\(^8\) Specifically, we examine the halo with rockstarId=923730455 in the MDPL2.Rockstar table.

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**Figure 6.** An example of one of the many high-redshift, over-dense regions we found in the Multi-Dark Planck 2 simulation. This system is the progenitor of the second-most-massive galaxy cluster at \( z = 0 \), and is approximately an order of magnitude less in mass than our estimation of SPT2349-56. (top) Spatial (physical) positions of substructure within a more-massive halo \( (M_{\text{vir}} \sim 10^{15} \, M_\odot) \). The physical projection of the observed SPT2349-56 region is overlaid with a dotted line. (middle) Virial mass histogram of substructure compared with the estimated virial masses of the dark matter halos in SPT2349-56. We consider only those masses that lay within the dotted line. (bottom) Kernel density estimate of the substructure velocities along the line of sight. We show the SPT2349-56 observed values as a comparison. As above, we only consider substructure within the dotted circle in the top panel for the velocity distribution.
or approximately half of the virial radius of the MMP. In this particular system, there are eight halos with masses $M_{\text{vir, sub}} > 10^{11} M_{\odot}$, and we assume that they will merge on timescales shorter than the dynamical friction timescale taken at the virial radius of the host (Mo et al. 2010),

$$t_{\text{ff}} \approx \frac{1.17}{\ln(M_{\text{vir}}/M_{\text{vir, sub}})} \left( \frac{M_{\text{vir}}}{M_{\text{vir, sub}}} \right)^{1/2} 10 H(z),$$

where $M_{\text{vir}}$ is the virial mass of the host system, $M_{\text{vir, sub}}$ is the virial mass of the substructure, and $H(z) = H_0(\Omega_m(1+z)^3 + \Omega_{\Lambda}0)$. Each substructure component is within a factor of $\sim 10$ of the host, therefore $t_{\text{ff}} \approx \eta t_1/2$ where $t_1 = 1/H(z)$ is the Hubble time. At $z = 4.266$ the Hubble time is $t_1 \approx 1.43$ Gyr assuming a Planck Collaboration XVI (2014) cosmology and, therefore, $t_{\text{ff}} \approx 0.72$ Gyr. Of course, this is an upper limit since the substructure is within half of the virial radius of the host. Evidently, over-dense systems such as the example in the top panel assemble rapidly in the early universe. However, will they go on to form objects as massive and bright as our synthetic SPT2349-56?

To address this question, we show the mass distribution of our cluster proto-core in the middle panel of Fig. 6. As we mention above, there are eight objects above $M_{\text{vir, sub}} > 10^{11} M_{\odot}$, and we first assume that each of these halos host a galaxy. Using the same methodology as in Section 2.1.1, we estimate that each halo should host a galaxy with stellar mass that is 1% of the halo mass. Therefore, each galaxy in the system should contain, on average, a stellar mass $M_\ast \approx 7 \times 10^{10} M_{\odot}$. If we use a conservative estimate of mass doubling within 1 Gyr of evolution based on Section 3, we would expect this object to become an elliptical galaxy with stellar mass $M_\ast \sim 5 \times 10^{10} M_{\odot}$. We expect these BCGs to preferentially exist in those clusters. In this study, through our use of the MDPL2 simulation, we use the Planck Collaboration XVI (2014) value of $\sigma_8$ which is higher than those derived from cluster counts. As it is, events such as SPT2349-56 are rare in this cosmology and ought to be rarer still if $\sigma_8$ were even slightly lower. A combination of surveying with the Wide-Field Infrared Survey Telescope (WFIRST) and follow-up confirmation with the JWST would provide a lower-bound on the number density, hence providing an additional constraint on $\sigma_8$ that could settle the issue. While we provide only an approximate estimate of the number density of massive BCGs, a more detailed study could provide an exact constraint on the value.

One major caveat is that for the BCGs to be highly star-forming, they must not exhaust their gas supply, and they must not have their star formation halted by active galactic nuclei feedback. However, given that the regions we discovered at $z \geq 3$ are highly over-dense, they undergo what could be considered an effectively monolithic formation scenario where the substructure gives rise to galaxies that are gas rich, which then rapidly merge to form the BCG. And only afterwards, after the newly formed BCG’s gas content depletes due to feedback and consumption, would star formation quench and the galaxy age passively.

5 CONCLUSIONS

The cores of galaxy clusters are home to the most luminous galaxies in the universe – the brightest cluster galaxies (BCGs). These galaxies have unique properties, such as their velocity dispersion and luminosity profiles, that set them apart from other galaxies at the high-end of the galaxy luminosity function. The contemporary picture of their formation...
and growth scenario is that their stars are old and formed at high redshift \((z \gtrsim 4)\) in separate individual galaxies that, at late times \((z \lesssim 1)\), hierarchically assemble to form the massive galaxies we observe today. There are, however, recent observations of highly-overdense protoclusters at \(z \gtrsim 4\) (Ishigaki et al. 2016; Miller et al. 2018; Jiang et al. 2018) that muddle this simple picture, since we expect these to go on to form the BCGs (Ito et al. 2019).

The hierarchical assembly picture of structure formation predicts the gradual build-up of objects through successive mergers of small objects. Under this theory, we expect the most-massive galaxies to be the youngest in terms of their assembly time. However, observations of massive ellipticals show a downsizing effect whereby the mass of the systems and the stellar ages are anti-correlated (Cimatti et al. 2006; Bower et al. 2006; Fontanot et al. 2009). In other words, the most-massive systems appear to have the oldest stellar populations. We propose a new paradigm wherein a similar downsizing effect occurs on the scale of galaxy clusters themselves. In our proposal, the cores of the most-massive clusters – the BCGs – assemble earlier than the cores of lower-mass clusters, on average. A subset of cluster-cores are assembled at very high redshift \((z \gtrsim 3)\), with the probability of high-redshift assembly decreasing as a function of decreasing mass \((at z = 0)\) of the clusters.

In order to determine the rapidity of assembly and growth of the BCGs, we studied the forward-evolution of a recently discovered, highly over-dense protocluster at \(z = 4.3\), SPT2349-56 (Miller et al. 2018). We found that the star formation peaks at \(\sim 3000 \text{ M}_\odot \text{yr}^{-1}\) very early in our simulation, and decays exponentially with a timescale of \(\tau \sim 200 \text{ Myr}\). By 1 Gyr, we found that the system remains at a stable star formation rate of \(\sim 40 \text{ M}_\odot \text{yr}^{-1}\). We found that the system assembles 90% of its mass at \(t_{\text{assembly}} \sim 370 \text{ Myr}\) after the initial condition and has a SDSS rest-frame \(g - r\) colour of \(g - r \approx 0.13\). In terms of redshift, 370 Myr corresponds to \(z \sim 3.3\) and implies that fully formed, highly star-forming, blue BCGs should exist at redshifts \(z \gtrsim 3.3\), given that there are observations of systems similar to SPT2349-56 above \(z \gtrsim 4.3\) (Ishigaki et al. 2016; Jiang et al. 2018). We demonstrated that new observational tools such as the James Webb Space Telescope will be able to easily image such systems, given that we estimated their absolute magnitudes to be \(M_{AB,F277W} \sim -28.7\) in the F277W NIRCam band.

We expect that systems such as SPT2349-56 go on to form the cores of the most-massive clusters in the universe. We used the Multi-Dark Planck 2 simulation\(^{10}\) – a child of the Multi-Dark Bolshoi simulations – to investigate the occurrence of highly over-dense assembly events in the early universe for all clusters with \(z = 0\) mass \(M_{\text{vir}} \gtrsim 5 \times 10^{14} \text{ M}_\odot\). Our analysis revealed that there is a clear trend of less-massive clusters having over-dense events occur at lower redshifts (compared to more-massive clusters), indicating that there is a downsizing effect. We also determined that \(~8\% of all the clusters we investigated begin to assemble their cores rapidly at high redshift, with a higher percentage of \(11.6\%\) for clusters with final masses above \(M_{\text{vir}} \gtrsim 10^{15} \text{ M}_\odot\). Based on these estimates, we predict that there is a population of bright, blue BCGs above \(z \gtrsim 3\) with a comoving number density of \(n \approx 46 \text{ cGpc}^{-3}\). Additionally, we predict that there is a similar star-forming BCG population that extends down to \(z \sim 1.5\) – although they will be up to an order-of-magnitude less massive than their high-redshift counterparts, given the downsizing trend. At redshifts lower than \(z \sim 1.5\), there is insufficient gas to support high star formation rates and those BCGs that begin assembling late will assemble through dry mergers, in keeping with the conventional picture. We emphasise the distinction between core assembly and assembly of the rest of the cluster, and that our results do not suggest that the entire cluster assembles at high-redshift. We expect protocluster cores to be embedded in an extended lower density (compared to the proto-core) galaxy distribution, with these galaxies eventually forming the satellite population of the assembling cluster.

Given that extraordinary infrared observational tools such as Wide-Field Infrared Space Telescope (WFIRST) and the JWST will launch in the upcoming decade, we expect the census of interesting astronomical objects to broaden significantly. Based on our arguments in this paper, we anticipate that some of those high-redshift objects will be the cores of the most-massive clusters in the universe – the BCGs. Not only are these interesting objects in their own right but their discovery and census would also help to constrain the tension in the measurements of the cosmological parameter \(\sigma_8\), given their rarity and association with the most-massive clusters.

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Our analysis was performed using the Python program-
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APPENDIX A: JWST OBSERVING STRATEGY

To generate mock NIRCam images, we select an optimal observing strategy for our synthetic SPT2349-56 system assuming 10 ks of observing time. We used the MUTLIACCUM MEDIUM 8 observing read-mode using Module B, in which each 10×1ks integration is divided non-destructively into 10×100s groups with 8×10s frames/group and 2×10s drop frames/group. This MULTIACCUM "up-the-ramp" observing strategy enables cosmic ray rejection, reduces the readout noise (roughly by the square root of the total number of frames) and increases the dynamic range by preventing saturation by bright sources. We generate point spread function (PSF) images for this observing strategy in each band pass using pynrc and the WebbPSF package (Perrin et al. 2012, 2014) and convolve with the idealised image. The 1σ AB surface brightness sensitivities determined by pynrc for the NIRCam detector with this observing strategy were $m_{\text{AB, band}} = 27.38, 27.62, 28.52, 28.65$ AB mag arcsec$^{-2}$ for F150W, F200W, F277W, F356W. These sensitivity estimates are based on characterization data for the detectors including readout and 1/f noise, dark current, and background levels equal to 1.2 times the minimum zodiacal light background. The current development version of pynrc does not allow us to convert between calibrated and non-calibrated images (i.e., AB zero points, effective gain and exposure time), so we do not incorporate Poisson shot noise from the source light. For now, we naively model the total noise contributions as a single Gaussian process with standard deviation equal to the reported sensitivity in each band pass using our observing strategy.

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