Optical and near-infrared observations of the SPT2349-56 proto-cluster core at z = 4.3

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ABSTRACT

We present Gemini-S and Spitzer-IRAC optical-through-near-IR observations in the field of the SPT2349-56 proto-cluster at z = 4.3. We detect optical/IR counterparts for only nine of the 14 submillimetre galaxies (SMGs) previously identified by ALMA in the core of SPT2349-56. In addition, we detect four z ~ 4 Lyman-break galaxies (LBGs) in the 30 arcsec diameter region surrounding this proto-cluster core. Three of the four LBGs are new systems, while one appears to be a counterpart of one of the nine observed SMGs. We identify a candidate brightest cluster galaxy (BCG) with a stellar mass of (3.2 ± 2.5) × 10^11 M⊙. The stellar masses of the eight other SMGs place them on, above, and below the main sequence of star formation at z ≈ 4.5. The cumulative stellar mass for the SPT2349-56 core is at least (1.1 ± 2.9) × 10^11 M⊙, a sizeable fraction of the stellar mass in local BCGs, and close to the universal baryon fraction (0.16) relative to the virial mass of the core (10^13 M⊙). As all 14 of these SMGs are destined to quickly merge, we conclude that the proto-cluster core has already developed a significant stellar mass at this early stage, comparable to z = 1 BCGs. Importantly, we also find that the SPT2349-56 core structure would be difficult to uncover in optical surveys, with none of the ALMA sources being easily identifiable or constrained through g, r, and i colour-selection in deep optical surveys and only a modest overdensity of LBGs over the extended core structure. SPT2349-56 therefore represents a truly dust-obscured phase of a massive cluster core under formation.

Key words: submillimetre: galaxies – galaxies: high-redshift – galaxies: evolution – galaxies: star formation

1 INTRODUCTION

Submillimetre galaxies (SMGs), which are forming stars at prodigious rates, even sometimes exceeding 1,000 M⊙ yr⁻¹
SMGs have recently been directly identified as an important star-formation mode in overdense proto-clusters of galaxies in the early Universe (e.g. Casey 2016; Umehata et al. 2019; Chapman et al. 2009; Oteo et al. 2018; Miller et al. 2018). SMGs can be sites of intense star formation often long before the height of galaxy assembly (e.g. Casey et al. 2014) when a much larger fraction of star formation was occurring in overdense, collapsing proto-clusters of galaxies (Chiang et al. 2017). Observing massive SMGs at the highest redshifts is therefore crucial for understanding the evolution of large-scale structures. Additionally, galaxy proto-clusters are interesting laboratories in which the mass budget of galaxies in dense environments can be studied. Identifying differences between field SMGs and those growing within overdensities, such as in proto-cluster cores, can help elucidate aspects of galaxy evolution that lead to the vastly different properties of galaxies found between clusters and in the field at the present epoch. SMGs growing in the dense environments of proto-clusters are expected to have formed earlier, be more massive, and undergo major mergers more frequently than their field galaxy counterparts (Overzier 2016; Rennehan et al. 2020). Furthermore, the enormous early build-up of mass in galaxy proto-clusters makes them critical when investigating large-scale structures in the Universe and can potentially help constrain cosmological parameters (e.g. Wen & Han 2011).

The South Pole Telescope (SPT) uncovered a population of dusty, thermal sources selected at millimetre wavelengths (Vieira et al. 2010; Mocanu et al. 2013; Everett et al. 2020), which were predominantly identified through Atacama Large Millimeter/submillimeter Array (ALMA) imaging and spectroscopy to be gravitationally lensed SMGs at $z > 3$ (Vieira et al. 2013). However, detailed lens modeling of the population revealed several examples that appeared to not have significant lensing magnification (Spilker et al. 2016) as well as lack bright foreground lensing galaxies even in deep imaging (Rotermund in prep.). These unlensed sources are candidate proto-cluster cores (Chapman in prep., Wang in prep.), of which the now well-studied $z = 4.3$ SPT2349-56 (Miller et al. 2018; Hill et al. 2020) represents the brightest example in this SPT proto-cluster (SPT-PC) survey. High-redshift proto-cluster candidates have also been identified in Herschel surveys (Lewis et al. 2018); one $z = 4$ candidate has been followed up with ALMA and confirmed as a massive proto-cluster core by Oteo et al. (2018), with a followup study of the member galaxies presented in Long et al. (2020) and Ivison et al. (2020).

SPT2349-56 was detected as a thermal dust source, slightly resolved even by the 1 arcmin SPT beam. At 1.4 mm, one of the three SPT bands, it has a peak flux density of $S_{1.4\,\text{mm}} = 23.3\,\text{mJy}$ (Miller et al. 2018), comparable to the median flux density of the SPT-SMG sample of 24 mJy (Reuter in prep.). Follow-up observations were initially conducted at 870 μm with the Large APEX Bolometer Camera (LABOCA, Siringo et al. 2009) on the Atacama Pathfinder Experiment (APEX) telescope in order to obtain a more precise location on the sky. At LABOCA’s 19-arcsec resolution, SPT2349-56 was resolved into two elongated sources, in contrast to the majority of the SPT sample, which continue to appear as unresolved sources at this resolution, singling it out as a possible extended structure of galaxies. The bright southern source was found to have a flux density of $S_{870\,\mu\text{m}} \approx 77\,\text{mJy}$ (Miller et al. 2018) and is clearly the locus of activity and centre-of-mass of the proto-cluster system (Hill et al. 2020). Surrounding structures include a bright northern source with $S_{870\,\mu\text{m}} \approx 25\,\text{mJy}$ and a connecting bridge with $S_{870\,\mu\text{m}} \approx 7\,\text{mJy}$ (Miller et al. 2018), as well as an offset satellite halo located 1.5 Mpc from the core (Hill et al. 2020). The redshift of two bright sources within the southern core were first constrained to lie at $4.300 \pm 0.002$ through $^{13}$CO lines from a blind ALMA 3-mm spectral scan (Strandet et al. 2016). Deeper follow-up ALMA observations began in Cycles 3 and 4 and initial results highlighted a core region of 14 SMGs (Miller et al. 2018). Recently the extended structure has been mapped by ALMA in Cycles 5 and 6 (Hill et al. 2020).

This paper presents optical-through-near-IR photometry of SPT2349-56, with the aim of searching for additional optically-selected cluster members and to study the bright SMGs in the SPT2349-56 proto-cluster core. Section 2 describes the optical and near-IR data, while section 3 presents the analysis and results of our study. We discuss our results in section 4 and conclude in section 5. A Hubble constant $H_0 \approx 70\,\text{km\,s}^{-1}\,\text{Mpc}^{-1}$ and density parameters $\Omega_{\Lambda} = 0.7$ and $\Omega_m = 0.3$ are assumed throughout.

## 2 OBSERVATIONS

### 2.1 Gemini imaging

Imaging and spectroscopy of SPT2349-56 were obtained under programme ID GS-2017B-Q-7 (PI Chapman). Deep Gemini imaging in the $g, r, i$ and $K_s$-bands were obtained using GMOS (optical; Hook et al. 2004) and FLAMINGOS-2 (near-IR; Eikenberry et al. 2004) at the Gemini-South Observatory in Cerro-Pachon, Chile. The observations were performed in service mode under near photometric conditions on 2016 October 6 and 2016 November 23, with standard observing strategies. Data reduction followed Gemini-IRAP reduction scripts and standard parameters for the optical data. The $g, r,$ and $i$-band fluxes were calibrated against DSS imaging.

For the $K_s$ observations, the data were reduced using the python-based FLAMINGOS-2 Data Pipeline, FATBOY, created by the Astronomy Department at the University of Florida. Briefly, a calibration dark was subtracted from the data set, a flatfield image and a bad pixel map were created, and the flatfield was divided through the data. Sky
subtraction was performed to remove small-scale structure with a subsequent low-order correction for the large-scale structure. Finally, the data were aligned and stacked. The mosaiced image was calibrated to the astrometry and photometry of 2MASS catalogues. The seeing, as derived from the FWHM size of stars in each frame, ranged from 0.6 to 0.8 arcsec.

**SEXTRACTOR** (Bertin & Arnouts 1996) was used to extract catalogues of sources in all bands. The 3σ AB magnitude depths achieved were $g = 27.4$, $r = 26.8$, $i = 26.1$, and $K = 24.5$.

### 2.2 IRAC imaging

The SPT2349-56 field was twice observed at 3.6 and 4.5 μm with the Infrared Array Camera (IRAC; Fazio et al. 2004) on board the Spitzer Space Telescope (Werner et al. 2004). It was first observed in 2009 August as part of a large programme to obtain follow-up imaging of a large sample of SPT-selected SMG sources (PID 60194; PI Vieira). The observing scheme used was to obtain 36 dithered 100-sec integrations at 3.6 μm and, separately, a much shallower 12×30-sec integration at 4.5 μm. Later, in Cycle 8, the field was covered serendipitously as part of the Spitzer-SPT Deep Field survey (PID 80032; PI Stanford, Ashby et al. 2013). This surveyed 92 deg² uniformly in both IRAC passbands with an integration of 4×30 sec. Using established techniques, we combined all exposures covering the SPT target from PID 60194 and 80032 at 3.6 and 4.5 μm to obtain the best possible S/N in our final mosaics, which were pixelated to 0.6 arcsec. The maps were shown in Miller et al. (2018) to illustrate possible identifications of ALMA sources, but the IRAC photometry was not extracted or tabulated. Here we compile faint ($≈3σ$) catalogues by running SEXTRACTOR on the combined maps. A variety of parameters were adjusted to attempt to obtain as complete a catalogue as possible in the very crowded central region of SPT2349-56. Eight of the 14 sources identified by ALMA are detected in the IRAC bands at $>3σ$ in at least one of the 3.6 or 4.5 μm channels, as shown in Fig. 1. These are listed with 4 arcsec aperture magnitudes (corrected to total flux using point spread function curve of growth) in Table 1.

The brightest SMGs in the core are labelled $A$ through $N$, as ordered by their 850 μm flux density (Miller et al. 2018). The central region of the proto-cluster is marked by three (possibly interacting) luminous ALMA sources ($B$, $C$, and $G$) spanning a 2-arcsec diameter region. These three galaxies are highly dominated by a bright, possibly extended source whose centroid lies close to source $C$. The $K$-band data, with $≈0.6$ arcsec seeing, easily resolves this trio, but only significantly detects $C$ as a $K_{AB} = 22.2$ isolated source. The $K$-band flux ratio implied by the non-detections of $B$ and $G$ allows us to place limits on the IRAC flux that may be attributed to $B$ and $G$. This value is comparable to the 3σ RMS limit of the IRAC data in uncrowded regions of the map and we adopt this same limit as for the other IRAC-undetected sources (listed in Table 1).

### 2.3 VLT spectroscopy

We also observed SPT2349-56 with the X-shooter echelon spectrograph (Vernet et al. 2011) on the ESO Very Large Telescope (VLT)-UT2, Kueyen, as part of programme 092.A-0503(A) (PI Chapman). X-shooter is capable of near-continuous spectroscopy from 0.3 to 2.48 μm, with a slit width and length of 1.2 and 11 arcsec, respectively. We observed two positions centred on the optical/near-IR identifications of ALMA components $A$ and $C$, dithering the observations in an ABBA sequence at positions $+3$ arcsec and $−3$ arcsec along the slit axis every 600 sec. We set the position angle to best match any other relevant features nearby. We first peaked up on a nearby star in a field within 1 arcmin of the target position, then did a blind offset.

Observations were taken on the nights of UT 2013 October 16 and November 12, with total integrations of 5,400 sec for each source. Seeing conditions were similar throughout these observations with values around 0.8 arcsec and taken with a low average airmass of 1.2.

We used the ESO pipeline (Modigliani et al. 2010) to reduce our data. This pipeline applies spatial and spectral rectification to the spectra using the two-dimensional arc spectra. The data were flatfielded and cosmic rays were identified and masked. The two dither positions were subtracted to remove the sky to first order, and the different echelle orders were combined together into a continuous spectrum. Flux calibration was achieved through observations of standard stars LTT3218, GD-71 and Feige 110.

### 2.4 ALMA observations

Deep ALMA observations covering SPT2349-56 were presented in Miller et al. (2018) and Hill et al. (2020). In this work we make use of the Band 7 maps covering the redshifted $[\text{C} \, \text{II}] 158\mu \text{m}$ fine structure line ($ν_{\text{obs}} = 358.4\,\text{GHz}$ at the median cluster redshift). Data reductions and processing are described in these works. The maps reach an average depth of 0.1 mJy RMS at this frequency, corresponding to a $3σ$ limit on SFR $< 10\,\text{M}_\odot\,\text{yr}^{-1}$.

### 3 RESULTS

#### 3.1 Rest-frame ultraviolet properties

We first assess the $g$, $r$, and $i$-band properties of SPT2349-56, which are at rest-frame ultraviolet wavelengths at $z = 4.3$. Five ALMA sources ($A$, $C$, $E$, $J$, and $M$) appear to have significant counterparts in the Gemini-S optical imaging (see Fig. 1 and Table 1). However, two of the identifications are offset from their respective ALMA sources: $A$ (0.4 arcsec) and $J$ (0.8 arcsec). This was assessed by aligning the optical images to the $K_s$ and IRAC astrometric frames using many bright stars in the field. The $K_s$ and IRAC images were aligned to the 2MASS astrometric frame, which was verified to provide a good match to the ALMA frame — several near-IR identifications of ALMA sources are all well centred (specifically, $C$, $E$, $K$, and $M$ all show agreement within 0.2 arcsec with the ALMA centroids). Four of the ALMA sources detected in the optical drop out in the $g$ band, consistent with $z = 4.3$ galaxies. The optical identification for source $A$, however, is bright in the $g$ band; while the ALMA source $A$ is confirmed.
Figure 1. Optical and near-IR imaging (22 × 22 arcsec² cutouts). Top row: Gemini-S GMOS g, r, and i-band (0.47, 0.63, 0.84 µm); Bottom row: Gemini-S FLAMINGOS-2 Ks-band (2.16 µm), Spitzer IRAC 3.6 µm, and Spitzer IRAC 4.5 µm. The green contours are drawn at 4σ, 10σ, and 30σ and show the ALMA 358-GHz continuum data. The purple contours are drawn at 3σ and 4σ and show the average ALMA Band 7 channel map covering the [C ii] emission in sources M and N. The z ≃ 4 LBGs identified in this work (‘LBG1–4’) are shown with cyan squares.

Table 1. Optical and Near-IR Photometry of SPT2349-56 SMGs.

| ID | g [AB] | r [AB] | i [AB] | Ks [AB] | 3.6 µm [AB] | 4.5 µm [AB] |
|----|--------|--------|--------|---------|-------------|-------------|
| A  | 25.81±0.03 | 25.91±0.03 | 24.69±0.03 | – | 21.93±0.02 | 21.84±0.02 |
| B  | – | – | – | – | – | – |
| C  | 26.52±0.07 | 25.84±0.07 | 22.21±0.08 | 20.83±0.01 | 20.79±0.01 | – |
| D  | – | – | – | – | 22.82±0.22 | – |
| E  | 26.68±0.14 | 26.14±0.14 | 24.03±0.12 | 21.73±0.02 | 21.68±0.01 | – |
| F  | – | – | – | – | – | – |
| G  | – | – | – | – | – | – |
| H  | – | – | – | 24.31±0.15 | – | – |
| I  | – | – | – | 23.54±0.10 | 22.23±0.02 | 22.12±0.02 |
| J  | – | – | – | 22.78±0.08 | 22.67±0.24 | – |
| K  | – | – | – | 22.68±0.15 | 22.68±0.08 | – |
| L  | – | – | – | 22.68±0.08 | – | – |
| M  | 25.64±0.04 | 25.11±0.04 | 23.82±0.11 | 22.67±0.08 | 22.10±0.13 | – |
| N  | – | – | – | 24.29±0.15 | – | – |

Note: For sources without entries the 3σ limits are g = 27.4, r = 26.8, i = 26.1, Ks = 24.5, 3.6 µm = 22.1, and 4.5 µm = 22.1.
to be at \( z = 4.3 \), the optical source was identified spectroscopically to be a foreground \( z = 2.54 \) galaxy, as described in Sect. 3.1.1.

We also use the optical imaging to search for Lyman-break galaxies (LBGs) using the \( g \)-band dropout technique of Steidel et al. (1999) (specifically \( g - R > 2.0, g - R > 2(R - I) + 1.5, \) and \( R - I < 1.2 \)) to select galaxies in the \( \sim 3.8 - 4.5 \) range. There are four LBGs with \( i < 26 \) identified within this core structure (labelled LBG1-4), two of which lie near ALMA sources J and M. ALMA sources C and E are also undetected in the \( g \) band, however, their \( r - i \) colours are too red to satisfy the LBG criteria above. While LBG1 lies 0.2 arcsec from the ALMA centroid of source \( M \) and is likely the same galaxy, LBG2 and the ALMA centroid for source \( J \) are offset by about 0.8 arcsec (see Fig. 1) and we therefore treat LBG2 as a separate galaxy in this work. Deep spectroscopic follow-up may ascertain whether or not this second LBG is close in velocity to ALMA source \( J \).

The third and fourth LBGs lie 5 arcsec south and 15 arcsec north (respectively) of the bright central source C. There is no (sub-)\( \mu \)m continuum detected at these positions in the deep ALMA maps reaching \( S_{50\mu \text{m}} < 0.3 \) mJy, 3\( \sigma \) (Hill et al. 2020). For LBG3 there is a candidate 6.8\( \sigma \) \([C \text{ II}] \) \( 158 \mu \text{m} \) line detection at 359.4 GHz (\( z = 4.288 \)), a significance that places it just below the cutoff adopted in the catalogue of Hill et al. (2020). It has a line flux of 0.46±0.07 Jy km s\(^{-1}\) and a FWHM of 204±35 km s\(^{-1}\). The rest-UV SFR estimate (calculated as described in Table 2) is 26 M\(_{\odot}\) yr\(^{-1}\), which agrees reasonably well with the \([C \text{ II}] \) line strength for typical \( z \sim 4 \) galaxies (Schaerer et al. 2020). The \([C \text{ II}] \) emission is shown in Fig. 2. In contrast, LBG4 shows no evidence of a \([C \text{ II}] \) line. However, it is identified as the brightest Ly\( \alpha \) emitter in the MUSE survey of Apostolovski (in prep.) and is clearly a member of the proto-cluster, with a Ly\( \alpha \) redshift of 4.308. Neither of these LBGs are detected at \( K_s \) or IRAC wavebands.

### 3.1.1 Foreground source of SMG A

Source A stands out in the rest-UV images (\( g, r, \) and \( i \) bands), as it is brighter than any other SPT2349-56 source and it is the only one detected in the \( g \) band. An X-shooter spectrum of source A (see Fig. 3) does not show any emission features expected from a \( z = 4.3 \) galaxy, but does reveal a foreground \( z = 2.54 \), star-forming galaxy that likely dominates the \( g \)-band photometry and contributes to the \( r \) and \( i \)-band fluxes. The optical band centroids are significantly offset by 0.4 arcsec from the ALMA and IRAC emission centroids. The foreground source is unlikely to be very massive given the blue colours, an \( r \)-band magnitude of \( z = 26 \), and an \( \text{O III} \lambda 5007 \) line FWHM of 53 km s\(^{-1}\). The linewidth suggests an upper limit to a dynamical mass enclosed within a 2 kpc radius of \( M_{\text{dyn}} = 1.56 \times R_{1/2} \sigma^2 < 1.6 \times 10^9 \text{ M}_\odot \) (see Erb et al. 2006). For \( z = 2.5 \) LBGs of this luminosity, typical stellar masses of \(< 10^9 \text{ M}_\odot \) are in agreement with our dynamical estimate (Shapley et al. 2005). It is difficult to directly ascertain the stellar mass of this galaxy, but it is clearly undetected in the \( K_s \)-band down to 24.5 magnitudes. Due to the offset relative to the IRAC source we ascribe the faint IRAC flux to the \( z = 4.3 \) ALMA source A and not to the foreground UV-luminous galaxy.

This configuration does not provide a significant gravitational lensing boost to source A, even assuming a lensing mass reflective of the high end of our dynamical mass estimate. Using a simple lens model (Spilker et al. 2016) we set the Einstein lensing mass to 2.5\( \times 10^9 \text{ M}_\odot \) (a generous assumption) and adjust the background source offset until the apparent image is 0.5 arcsec from the lens position to match our configuration. We find a magnification factor of \( \mu = 1.15 \) for a circular lens, or ranging from 1.09 to 1.24 for a highly elliptical lens (\( e = 0.6 \)), depending on the position angle.

### 3.2 Rest-frame optical properties

We consider next the observed \( K_s \), IRAC 3.6\( \mu \)m, and IRAC 4.5\( \mu \)m properties of the SPT2349-56 sources with an aim of constraining stellar mass. As noted in Sect. 2, we detect eight sources in one or both IRAC bands (namely \( A, C, D, E, J, K, M, \) and \( N \)). Five of these are detected in \( K_s \) (\( C, E, J, M, \) and \( N \)), three of which are also detected in \( i \) and \( r \) (\( C, E, \) and \( M \)). In addition, source \( H \) is detected in just the \( K_s \) band. Such generally incomplete or low SNR photometry

| ID | RA   | Dec | \( r \) | \( i \) | SFR |
|----|------|-----|-------|------|-----|
| 1\(^a\) | 23:49:43.406 | \(-56:38:20.93\) | 25.64 | 25.11 | 36±4 |
| 2\(^b\) | 23:49:43.340 | \(-56:38:29.90\) | 26.22 | 26.00 | 16±4 |
| 3 | 23:49:42.703 | \(-56:38:28.97\) | 26.18 | 25.48 | 26±4 |
| 4\(^c\) | 23:49:42.198 | \(-56:38:10.28\) | 26.38 | 26.08 | 15±4 |

Note: Photometry errors range from 0.12 for the brightest detections to 0.31 for the faintest, as listed in Appendix B. None of these four LBGs are significantly detected in the \( g \) band. SFRs are calculated as \( 1.4 \times 10^{-28} L_{\odot}(1.5, 500 \text{ A}) \text{ M}_\odot \) yr\(^{-1}\), with extinction estimated from \( r - i \) colour.

\(^a\) This LBG is well aligned with ALMA source \( M \) and we treat it as such above. We duplicate its properties here for completeness.

\(^b\) This LBG lies 0.8 arcsec offset from ALMA source \( J \). We treat this LBG as a distinct galaxy since the \( K_s \) and IRAC fluxes are well aligned with source \( J \).

\(^c\) LBG4 is identified as the brightest \( z = 4.3 \) Ly\( \alpha \) emitter in Apostolovski (in prep.).
limits the constraints possible from SED fitting (the exceptional source C is discussed separately below).

We estimate the stellar masses by modelling the multi-wavelength spectral energy distributions (SEDs) using the software Code Investigating GALaxy Emission (cigale; Noll et al. 2009; Serra et al. 2011; Boquien et al. 2019). cigale adopts an energy balance principle between the UV-optical and FIR-mm regimes – the energy absorbed by dust in the UV-optical is proportional to the thermal radiation emitted by dust in the FIR.

We first consider the six sources detected in both IRAC bands, which also generally have supporting detections in other bands. To model the sources we have assumed a delayed star-formation history with a single exponential decrease. The e-folding time (τ) and age of the stellar population are kept as free parameters while a solar metallicity and α-Chabrier initial mass function (IMF; Chabrier 2003) are assumed. It has been found in the literature (Michałowski et al. 2012) that stellar mass estimates using a single-exponential decay SFH can be a factor of about 2 different than double-exponential or a bursty-type SFH. Typically the single exponential decay SFH provides the lowest stellar mass, our estimates are therefore relatively conservative. Nebular emission is included in the fitting using templates from Inoue (2011). The dust attenuation is modelled using a Calzetti et al. (2000) attenuation curve with a power law slope of 0. The stellar mass estimates are consistent within the errors even when the slope is allowed to vary.

Table 3. Properties of SPT2349-56 SMGs.

| ID | AV | Age [Gyrs] | τ [Gyrs] | log (M*/M⊙) | fgas |
|----|----|-----------|---------|--------------|------|
| A  | 2.4±1.1 | 0.9±0.4 | 1.8±2.4 | 11.35±0.31 | 0.35 |
| B  | – | – | – | <10.71 | <0.69 |
| C  | 1.7±0.3 | 0.9±0.4 | 2.7±2.5 | 11.54±0.25 | 0.17 |
| D* | – | – | – | 10.85±0.42 | 0.54 |
| E  | 2.0±0.7 | 0.9±0.5 | 2.4±2.5 | 11.17±0.27 | 0.25 |
| F  | – | – | – | <10.71 | <0.40 |
| G  | – | – | – | <10.71 | <0.37 |
| H* | – | – | – | 10.78±0.37 | 0.42 |
| I  | – | – | – | <10.71 | <0.31 |
| J  | 0.8±0.7 | 1.1±0.4 | 1.1±1.9 | 10.94±0.17 | 0.20 |
| K  | 1.7±1.1 | 0.9±0.4 | 1.7±2.3 | 10.84±0.29 | 0.31 |
| L  | – | – | – | <10.71 | <0.40 |
| M  | 0.8±0.4 | 0.9±0.4 | 2.2±2.4 | 10.54±0.22 | 0.26 |
| N* | – | – | – | 11.12±0.27 | 0.07 |

Note: The first four columns are best-fitting parameters from cigale.

a cigale fits are performed on these sources with the age of the main population fixed, as photometry is faint and sparse in wavelength coverage.

b Exponentially declining star formation histories, SFH ∝ e^−t/τ.

c Gas fraction, fgas = Mgas/(Mgas + Mr); Gas masses were determined from the 12CO line luminosities ([C ii] when 12CO was not available) from Miller et al. (2018) using the standard conversion of Bothwell et al. (2013) with αCO = 0.8 and a 1.36X correction factor to include helium.

The stellar masses for the sources are estimated using the 'pdf analysis' module in cigale. Mock catalogues are generated and analyzed to check the reliability of these estimates within the parameter space explored. SED fitting using cigale works optimally if the data ranges from UV to mm wavelengths. However, the dust peak in the FIR is unconstrained with our (sub)-mm photometry, and the SED fitting for the sources was primarily conducted across the optical/near-IR region. In this case, zero contribution was assumed from an AGN component. Fitting using only optical/near-IR photometry can give rise to systematic uncertainties in estimations of various physical properties (Ciesla et al. 2015) – up to about 20 per cent for stellar mass estimates. Results are shown in Appendix A.

We next estimate the stellar masses for those sources with more limited photometry: D, H and N. Here we constrain the SED fits, allowing the age of the stellar population to lie between 0.7–1.25 Gyrs, consistent with that of the brighter sources in the proto-cluster. For sources H and N the results of the mock catalogue analysis are consistent within error of the best fit. However, mock catalogue analysis for source D showed the stellar mass estimate to not be as certain as for the others (as can be expected for fitting with a single-band detection) – the limits at our other wavelengths did not provide strong enough constraints. Best-fitting cigale results for these three sources are also shown in Appendix A.

The remaining five sources are undetected in all observed bands, and may actually have very low stellar masses. However, their large 12CO luminosities (Miller et al. 2018) suggest sizable gas masses, often comparable to the other sources, and correlating reasonably with their SFRs.
large $^{12}$CO line widths (Miller et al. 2018) also suggest sizable dynamical masses. Very high gas fraction galaxies are possible, since at such an early epoch it is reasonable that this star formation episode represents the first major stellar growth phase in these galaxies, stimulated by the dense environment (Rennehan et al. 2020). However, we do not discount the possibility that some of these five SMGs have extreme dust extinction levels, as seen in some field SMGs (e.g. Simpson et al. 2015) and that their stellar masses are sizable, implying similar gas fractions to the other SMGs.

For the nine sources constrained by SED fits, we determine the stellar mass to lie in the range $(0.3–3.3) \times 10^{11} M_\odot$, with a median $M^*$ of $(0.88 \pm 0.07) \times 10^{11} M_\odot$, where the error is the standard deviation. Stellar mass estimates are presented in Table 3. Source C is discussed in detail below. The cumulative stellar mass for the SPT2349-56 core is $(11.5 \pm 2.9) \times 10^{11} M_\odot$, which is a lower limit as we have only included nine of the 14 sources.

For these remaining five sources, which lack any optical/near-IR detections, we estimate an upper limit on $M^*$ as below. The majority of the stellar mass in a galaxy manifests itself as a rest-frame near-IR bump in the SED whose emission peaks at approximately 1.6 $\mu$m. For SPT2349-56 at $z = 4.3$, this peak in stellar light is redshifted to 0.5 $\mu$m. Our closest observed photometry comes from IRAC’s 4.5–$\mu$m band. We use the average mass-to-light ratio for the nine detected sources, ($M^*/L_{4.5 \mu m}$) = 0.98 $M_\odot$/L$_{\odot}$, to constrain the stellar mass in those five sources not robustly detected, shown as upper limits in Table 3.

We also list the gas fractions (calculated as described in the notes of Table 3), showing an average $f_{\text{gas}} = 0.3$ for the nine near-IR detected sources, and a limit of $f_{\text{gas}} = 0.4$ for the 5 undetected. Thus, the estimates of the $M^*$ limits above are in reasonable agreement with the $M^*$ values one would infer from their $M_{\text{gas}}$, even if extreme extinction is responsible for their non-detections.

3.2.1 A large stellar mass for source C

As noted, source C stands out with an exceptionally large rest-optical luminosity for $z \sim 4.3$, especially compared to all other ALMA sources in the proto-cluster core ($\approx 2.5$ times brighter than the next most luminous sources, $E$ and $A$). It lies near the centre-of-mass of the structure, and is embedded in a dense region of ALMA sources, possibly the core of a forming brightest cluster galaxy (BCG). The X-shooter spectrum of the source detects a very faint continuum through the H and K$_s$ bands, but does not detect any emission lines. Specifically at the wavelengths of the redshifted [O ii] $\lambda 3727$ Å and [Mg ii] $\lambda 2800$ Å lines, there is no obvious excess, however the observed wavelengths do lie within relatively noisy sky-line regions. The line flux limit in these regions is similar, at $\lesssim 1 \times 10^{-10}$ ergs s$^{-1}$ cm$^{-2}$. Since the continuum is so poorly detected, there are no useful constraints on the line equivalent widths.

The stellar size of C is constrained at high SNR in K$-$band, with an unresolved Gaussian FWHM fit of $(0.59 \times 0.53)$ arcsec$^2$, implying a $< 2$ kpc half-light radial size. For a massive galaxy at early epochs this is not particularly unusual (Damjanov et al. 2011), however, as an early BCG galaxy this is tiny. By $z \approx 1$, half-light radii for BCGs in massive clusters range from 14 to 53 kpc, with an average determined from stacking of $32.1 \pm 2.5$ kpc for $z = 1$ (Stott et al. 2011). We discuss SPT2349-56 relative to $z = 1$ clusters below. This is only 30 per cent smaller than the size in low-redshift comparison samples with $43.2 \pm 1.0$ kpc. Thus the SPT2349-56 progenitor BCG must grow in size dramatically over the subsequent $\approx 2$ Gyrs, for example through dry mergers (Cooke et al. 2019).

In addition to the stellar mass fitting for source C, we attempted full SED fitting of UV-through-mm wavelengths. Dust emission is modelled using the updated empirical templates from Draine et al. (2014) (originally from Draine & Li 2007). Limits from Herschel-SPIRE are adopted at 250–500 $\mu$m (Miller et al. 2018), effectively restricting the range of templates possible. The best fit has the following parameters: a stellar mass of $(3.2^{+1.2}_{-1.0}) \times 10^{11} M_\odot$; a SFH age of the main population of $(500 \pm 350)$ Myrs; and an AGN fraction of 0.0 with an upper limit of 0.4. The best-fitting SED is shown in Fig. 4.

We attempted to constrain the AGN contribution using templates from Fritz et al. (2006). However, the only mid-IR constraint is from WISE at $22 \mu$m, with supplemental SPIRE limits, which were not sufficiently deep to quantify the fractional AGN contribution. During the fitting, we allowed the AGN fraction to vary from 0.0 to 0.9 in increments of 0.1 and let the AGN be either type-1 or type-2. A fractional contribution of close to 0.0 is preferred based on the probability distribution function and the reduced $\chi^2$, but as evident from Fig. 4, higher AGN fractions are also possible and more data are required to further constrain this.

In contrast, source C does have some properties suggestive of an AGN at other wavelengths. It has a much narrower [C ii] line profile than all other similarly bright sources in the proto-cluster, and accordingly one of the lowest [C ii]/$L_{\text{FIR}}$ ratios found in the structure (Miller et al. 2018; Hill et al. 2020), typical of an AGN (Stacey et al. 2010). It has a large CO(16–15) luminosity with a CO excitation more consistent with AGN-dominated galaxies (Canning in prep.). However, our SED fitting appears consistent with a large stellar mass, and does not obviously require an AGN component from a hot dust torus (e.g. Hainline et al. 2011). Further, the 3.6-$\mu$m excess is well modeled with a strong Hα line component, which JWST observations will be able to confirm.

4 DISCUSSION

4.1 Implications for optical proto-cluster identification

We have demonstrated that the SPT2349-56 proto-cluster core is difficult to study in either its rest-UV or rest-optical properties, due to the extreme faintness of most of its members. A parallel study with the VLT/MUSE integral field spectrograph has also demonstrated that these ALMA sources are not detected in Lyα, although there appears to be an overdensity of Lyman emitters in the surrounding $\approx 1$ arcmin field (Apostolovski in prep.).

It is of interest to determine whether this proto-cluster would be detected in a large optical survey using the same g-band dropout selection criteria we used to identify LBGs within SPT2349-56. The mean LBG density around redshift
clusters across a 121 deg
as strong overdensities in the photometric LBG selection. A blunt tool to identify overdensities without spectroscopic
g-comparable depth in the
per Suprime-Cam (Toshikawa et al. 2018), which reached
g-of the
computing the number of these LBGs within 1.8 arcmin-
adopted here, and searched for proto-cluster candidates by
S data. Toshikawa et al. (2018) selected galaxies around
z
is not surprising, given the broad redshift range
overdense region appears to be quite compact. This in itself
in the surrounding region, with a constant density out to
pears to fall off to the field density of around 1 per arcmin
forces the likelihood that all four of these LBGs lie in the
time within a circular area of about 0.2 arcmin
2
even one LBG at this depth is only expected 10 per cent of
This corresponds to an overdensity of about 20 times the
of SPT2349 and encircling the 14 ALMA sources in its core.
This result can be compared to a recent search for proto-
crossed the ALMA core. Moreover, our imaging of these 14 SMGs
quasars/AGN candidates are found in the region from optical
colour selection. Finally, our imaging of these 14 SMGs
do not reveal any obvious signs of AGN contribution, even in the
bright SMG C. Finally, the foreground galaxy at z = 2.54
along the line-of-sight to ALMA source A illustrates the
importance of multi-wavelength analysis and spectroscopic
follow-up in such deep observations of crowded structures.

4.2 Main sequence of star formation
Having estimated the stellar masses, we can assess the relation
between the SFR and stellar mass for the SPT2349-56
SMGs, adopting SFRs based on ALMA photometry from
Hill et al. (2020), and compare them to the coeval field population.
For a given redshift, the majority of star-forming field galaxies are observed to exhibit a correlation between
these two properties (e.g. Noeske et al. 2007; Speagle et al.
2014; Santini et al. 2017). Santini et al. (2017) suggest that
the tightness of the correlation, defined as the main sequence
(MS), is due to similarities in the gas accretion histories.
For galaxies along the MS it is expected that the dominant
mechanism for growth is a smooth accretion of gas from the
intra-galactic medium over long timescales. Bright SMGs
have been proposed to lie significantly above these correlations (e.g. Hainline et al. 2011; Michałowski et al. 2012),
possibly due to major mergers triggering intense SFRs (e.g.
Engel et al. 2010). The empirically defined MS is typically
parameterized as a power law,
\[
\log \left( \frac{\text{SFR}}{M_\odot \text{yr}^{-1}} \right) = \alpha \log \left( \frac{M^*}{M_\odot} \right) + \gamma
\]
where \(\alpha\) is the slope of the log SFR – log \(M^*\) relation, and \(\gamma\) is the MS normalization. While the normalization is clearly
observed to increase with redshift, the slope is still
debated. Generally it is believed that the slope is predominately unevolving, and approximately linear in power-law

\[
\begin{align*}
\text{Figure 4.} \quad \text{cigale fit to source C, the brightest at rest-optical wavelengths and the only ALMA source with high significance detection in the} \ K_s \ \text{band. The best fit includes a negligible AGN} \\
\text{fraction, with an excess in } 3.6 \mu m \ \text{potentially driven by strong } H\alpha \ \text{emission. Higher AGN fraction fits are shown to} \\
\text{demonstrate that the available mid-IR data cannot constrain the AGN contribution in this source.}
\end{align*}
\]

4 to \(i_{AB} < 26.5\) is roughly 1 arcmin\(^{-2}\) (Steidel et al. 1999; Toshikawa et al. 2018), and we have found four LBGs within a 30 arcsec diameter region surrounding the center-of-mass of SPT2349 and encircling the 14 ALMA sources in its core. This corresponds to an overdensity of about 20 times the background, with a large sensitivity to the enclosed region chosen (taking the smallest possible circle that encloses the four LBGs results in a overdensity of 30 times). The fact that even one LBG at this depth is only expected 10 per cent of
the time within a circular area of about 0.2 arcmin\(^2\) reinforces the likelihood that all four of these LBGs lie in the
SPT2349-56 structure. Furthermore, the LBG density appears to fall off to the field density of around 1 per arcmin\(^2\)
in the surrounding region, with a constant density out to
~ 2 arcmin radius (the limit of our optical imaging). Thus, while SPT2349-56 contains a large overdensity of LBGs, the
overdense region appears to be quite compact. This in itself
is not surprising, given the broad redshift range \(z = 3.8-4.5\) of the g-band dropout selection, which makes it a relatively
blunt tool to identify overdensities without spectroscopic
follow-up (e.g. Steidel et al. 1996) – even relatively strong
spikes in redshift distributions characteristic of large over-
densities (e.g. Steidel et al. 2000) do not manifest themselves
as strong overdensities in the photometric LBG selection.

This result can be compared to a recent search for proto-
clusters across a 121 deg\(^2\) optical survey using Subaru’s Hy-
per Suprime-Cam (Toshikawa et al. 2018), which reached
comparable depth in the g.r. and i bands as our Gemini-
S data. Toshikawa et al. (2018) selected galaxies around
\(z \approx 4\) using a similar g-band dropout technique as the one
adopted here, and searched for proto-cluster candidates by
computing the number of these LBGs within 1.8 arcmin-
radius apertures (about 0.75 proper Mpc). They found that
the mean number of LBGs within such an aperture is 6.4,
with a standard deviation of 3.2. By adopting a 4σ overdens-
ity threshold, a large number of proto-cluster candidates
were found. However, since SPT2349-56 is so compact, such
a large aperture would entirely wash-out the overdensity sig-
nal needed to reach the adopted 4σ threshold. These conclu-
sions would apply equally to LSST surveys which will reach
similar depths over large areas (Robertson et al. 2019).

On the other hand, simple arguments demonstrate that
in large optical surveys for \(z \sim 4\) dropout-galaxies (e.g.
Toshikawa et al. 2018), the four central LBGs in SPT2349-56
are not unusual. In the absence of clustering, even a 1 deg\(^2\)
survey has a > 50 per cent chance to find four \(z \sim 4\) LBGs
in a 30 arcsec diameter circle (0.2 arcmin\(^2\)). Thus we con-
clude that optical surveys are typically blind to structures
like SPT2349-56. Nevertheless, SPT2349-56 clearly repre-
sents an early phase of one of the most massive structures in
the Universe, a truly dust obscured phase of a massive
cluster core under formation.

While optically identifiable sources are found in the
proto-cluster, distinct from the ALMA-identified sources, our
analysis reinforces the notion that this incredibly mas-
sive and active structure is most easily identifiable in mm-
wave surveys like that of SPT. AGN are important in the
evolution of clusters and BCGs, providing feedback and reg-
ulation to the star formation evolution. However, no bright
quasars/AGN candidates are found in the region from optical
colour selection. Moreover, our imaging of these 14 SMGs
do not reveal any obvious signs of AGN contribution, even in the
bright SMG C. Finally, the foreground galaxy at \(z = 2.54\)
along the line-of-sight to ALMA source A illustrates the
importance of multi-wavelength analysis and spectroscopic
follow-up in such deep observations of crowded structures.
Figure 5. Assessing the SPT2349-56 sources relative to the main sequence (MS) of star-forming galaxies. SPT2349-56 SMGs are shown with $M^*$ values derived from cigale best fits (blue diamonds – open symbols have additional constraints on the fits as described in text). Constraints on $M^*$ for those lacking optical/nearIR detections (blue double-sided limits) are shown at the scaled IRAC limits as described in text. However the non-detections may be driven by extreme extinction since their dynamical and gas masses are generally comparable to the SMGs detected by IRAC, and thus we show right-sided limits as well to reflect this. LBGs are shown as 3σ IRAC limits scaled as described in text. The SFRs for the SMGs are scaled from integrated $L_{FIR}$ estimates (Hill et al. 2020). SFRs for the LBGs are estimated from their rest-UV luminosities. The $z > 3.5$ SMGs (da Cunha et al. 2015) from the ALESS survey (Simpson et al. 2015) are shown as purple circles. The MS at $z = 4.3$ determined by Speagle et al. (2014) is shown in green, where the scatter (shaded green) is ±0.2 dex. The MS power law in the $4 \leq z < 5$ range from Santini et al. (2017) is also shown (grey dashed line).

near unity. For the $4 \leq z < 5$ range, Santini et al. (2017) find $\alpha = 0.94 \pm 0.06$ and $\gamma = 1.37 \pm 0.05$. Speagle et al. (2014), through a literature review in which 25 studies were considered, determined a MS best fit with $\alpha = 0.80 \pm 0.02$ and $\gamma = 6.4 \pm 0.2$ when the age of the Universe is set to 1.35 Gyrs ($z = 4.3$), with a scatter of ±0.2 dex. While Speagle et al. (2014) did not include data from the first and last 2 Gyrs of the Universe in their fitting, they find their MS relation to provide a reasonable fit to the data even out to $z \sim 5$ and that the parameters of the MS are only marginally affected when including high-$z$ data.

Figure 5 shows the relation between SFR and $M^*$. The MS from Speagle et al. (2014) is shown for a redshift of 4.3, as well as the Santini et al. (2017) MS at $4 \leq z < 5$. Five of the eight IRAC-detected sources ($A, C, D, E, J$) as well as the $K_s$-detected source $H$ appear to lie within the scatter of the MS of Speagle et al. (2014). This assessment is unchanged if the Santini et al. (2017) MS relation is instead adopted. Several of the five IRAC-undetected sources (especially $B$ and $F$) could lie above the MS if their inferred stellar masses are truly as low as the flux limits suggest, but extreme extinction may be driving the faintness rather than a low $M^*$. Indeed, their dynamical and gas masses (from $^{12}$CO line widths and $^{12}$CO luminosities, respectively) are generally as large as those sources detected by IRAC, which would imply their stellar masses are similarly large, unless they have very high gas fractions relative to stars. Our gas fraction analysis above does suggest that the stellar masses may well be as large or even larger than the location of our IRAC limits would imply (see Table 3). We thus show these five SMGs as double-sided limits to reflect this possibility.

We further compare the SPT2349-56 SMGs in Fig. 5 to a sub-sample of the da Cunha et al. (2015) isolated SMGs from the blank field ALESS survey (Simpson et al. 2015), where we have restricted the redshift range to $z > 3.5$ (a mix of spectroscopic and photometric redshifts). The $M^*$ values in the 10 SPT2349-56 sources with higher SFRs (SFR $> 100 \, M_\odot \, \text{yr}^{-1}$, comparable to those in ALESS) likely have a similar median stellar mass to those of ALESS, $0.9 \times 10^{11} \, M_\odot$. Because four of these 10 SPT2349-56 SMGs only have limits, we cannot probe this comparison further.

Interestingly, the four SPT2349-56 SMGs with SFRs below the detection limit of ALESS have similar $M^*$ values to the much higher SFR ALESS galaxies, suggesting they either have atypically high stellar masses or have SFRs well below the MS given their stellar mass. At least three ($K, M$
and N) and plausibly all four (given that L is a limit) lie significantly below the MS. While quenched galaxies at \( z > 4 \) are exceedingly rare (e.g. Speagle et al. 2014), environmental factors in the dense proto-cluster core may have accelerated the quenching of these galaxies.

In our comparison with the \( z = 4-5 \) main sequence of star formation, we find evidence for SMGs at three potentially different stages of evolution. The fact that many of these SMGs are all apparently well situated along the MS reveals that even in the most extreme environment ever found at \( z > 4 \), star-forming galaxies are not clearly offset from the scaling relations of coeval field galaxies. Indeed, Speagle et al. (2014) find the mode of star formation at a given mass to be independent of the density of the environment. SMGs lying above the MS may be gas-rich galaxies at early evolutionary stages, which are driven to high SFRs through the dense merger environment of the core. However, in the simulation conducted by Rennehan et al. (2020) of the evolution of the 14 SMGs in the proto-cluster core, the intense star formation and resulting stellar feedback together dramatically reduce the gas in the merger system resulting in rapid decline in star formation. The SMGs below the MS may represent quenched galaxies whose star formation has been truncated through feedback in this environment. The LBGs identified in SPT2349-56, distinct from SMG identifications, are not obviously very massive galaxies. They may require much deeper near-IR observations to better constrain their stellar masses. The considerable diversity of these sources in their evolutionary phases is no doubt a result of the extreme merger environment of these 14 SMGs, which are contained within a 130 kpc region, no larger than the dark halo of the Milky Way!

### 4.3 Stellar growth of the BCG

Source C stands out in Fig. 5, with an inferred \( M^* \) as massive as any SMGs seen in the literature at any redshift. SED fitting is consistent with \( M^* = (2-6) \times 10^{11} \text{M}_\odot \) (from the width of the cigale probability distribution) and the gas-rich merging complex seen in sources B, C, and G may represent the accumulated stellar population of a forming BCG in the core of a massive galaxy cluster. The cumulative stellar mass for all the SMGs in the SPT2349-56 core is at least \((11.5 \pm 2.9) \times 10^{11} \text{M}_\odot \) (considering only nine of the 14 SMGs are included), which is comparable to the gas mass of the 14 SMGs derived in Miller et al. (2018), 6.7 \( \times 10^{11} \) (\( \alpha_{\text{CO}}/0.8 \text{M}_\odot \)). This gas mass is normalized to the conservative CO-luminosity-to-gas-mass conversion factor typically adopted for very luminous galaxies (e.g. Tacconi et al. 2010). A more likely estimate would scale \( \alpha_{\text{CO}} \) continuously towards \( \alpha_{\text{CO}} = 4 \) for the lowest SFR (and mass) galaxies (Narayanan et al. 2010), yielding \( \sim 10^{12} \text{M}_\odot \). Since Rennehan et al. (2020) have estimated that all 14 galaxies will completely merge in around 500 Myrs and that the stellar mass will increase in this time due to the partial (50 per cent) consumption of this gas, we can infer that by a redshift of only 3.3 the stellar mass of this assembling BCG could be in excess of \( 1.5 \times 10^{12} \text{M}_\odot \).

In Fig. 6, we show the assembling BCG stellar mass of SPT2349-56 compared to a sample of \( z \approx 1 \) galaxy cluster data from van der Burg et al. (2013), and \( z = 0.3-0.8 \) clusters from Hilton et al. (2013). The summed \( M^* \) of the nine detected SPT2349-56 SMGs is already comparable to that of BCGs of the most massive \( z = 1 \) clusters (\( > 10^{13} \text{M}_\odot \) halo mass), and strongly suggests an inside out collapse of a very massive structure (van der Burg et al. 2015), with such an accelerated growth of the core mass relative to \( z = 1 \) clusters.

We show the summed \( M^* \) of the nine detected SPT2349-56 SMGs and the predicted increase of \( M^* \) in 500 Myrs to \( z = 3.3 \) from Rennehan et al. (2020). A growth in \( M_{200} \) of 3\( \times \) is expected from \( z = 4.3 \) to \( z = 3.3 \) (the predicted 500 Myrs depletion time of \( M_{\text{gas}} \) mentioned above) and 70\( \times \) from \( z = 4.3 \) to \( z = 1 \) (Chiang et al. 2013). Starting from the virial mass of the SPT2349-56 core (Miller et al. 2018), this provides a rough evolutionary track for SPT2349-56 leading to \( z = 1 \), assuming no additional growth in \( M^* \). In hierarchical \( \Lambda \text{CDM} \) modelling, Ragone-Figueroa et al. (2018) find that on average the stellar mass of the BCG and the extended stellar halo grows from \( z = 2 \) to \( z = 1 \) by a factor of about 1.6 with an additional factor of 1.5 from \( z = 1 \) to \( z = 0 \). Even without accounting for the stochastic growth associated with merging satellites as in the Ragone-Figueroa et al. (2018) simulations, SPT2349-56 ends up at \( 8 \times 10^{14} \text{M}_\odot \) in \( M_{200} \) by \( z = 1 \), with a significant excess in BCG mass, relative to the comparison cluster samples (although not a vastly unusual outlier given the dispersion). The fact that SPT2349-56 already appears to have an excess of stellar mass at \( z = 4.3 \), and that further rapid BCG growth is necessitated by the merger and enormous gas mass present in these galaxies, suggest it may well be an outlier in the BCG / \( M_{200} \) relation by \( z = 1 \).

### 4.4 Baryon budget of SPT2349

Next, we turn to an assessment of the baryon budget of SPT2349-56 at \( z = 4.3 \) and explore whether some of the SPT2349-56 baryons may already be in the form of a diffuse, hot gas filling the space between the galaxies – the intra-cluster medium (ICM) that is characteristic of massive virialized galaxy clusters at \( z < 1.5 \). The virial mass of these 14 SMGs is estimated as \( 1.13 \times 10^{13} \text{M}_\odot \) in Miller et al. (2018). Hill et al. (2020) find a slightly lower \( M_{\text{vir}} \), but that further rapid BCG growth is necessitated by the merger and enormous gas mass present in these galaxies, suggest it may well be an outlier in the BCG / \( M_{200} \) relation by \( z = 1 \).
Figure 6. The assembling BCG stellar mass of SPT2349-56 compared to a sample of $z = 1$ galaxy cluster data from van der Burg et al. (2013) (purple circles), and $z = 0.3-0.8$ clusters from Hilton et al. (2013) (orange squares). We show the summed $M^*$ of the nine detected SPT2349-56 SMGs (blue filled star) and the predicted increase of $M^*$ of the SPT2349-56 BCG (dashed blue star). The dashed black line is a fit to the joint cluster datasets.

5 CONCLUSIONS

We have studied SPT2349-56 at optical and near-IR observed-frame wavelengths with imaging from Gemini-S and Spitzer-IRAC. Arguably the most important conclusion from this work is that despite the incredibly total SFR and density of SPT2349-56, it would be exceedingly difficult to identify in large surveys through optical overdensity selection techniques, and the structure is faint or undetected even at near-IR through IRAC wavelengths. This emphasizes the importance of searching for early formative structures at millimetre wavelengths. Also of importance for cluster formation, we find the likely BCG associated with ALMA source C. This is significant, as it coincides with where most of the [C II] and CO(4-3) emitters are spatially located, and significant stellar growth has already occurred near the center-of-mass of the cluster core. Our conclusions are as follows.

- We detect four plausible counterparts to SPT2349-56 SMGs in the $g$, $r$, and $i$ bands, although one is revealed to be an interloper $z = 2.54$ galaxy along the line-of-sight to SMG A. We estimate a possible resulting gravitational lensing magnification of ALMA source A to be $< 1.2$.

- Using the Steidel et al. (1999) $z < 4$ dropout selection criteria at our $i_{AB} < 26.5$ depth, we find four LBGs that are likely new members of an already highly overdense region: one is unambiguously the counterpart of an ALMA SMG ($M^*$); one is only 0.8 arcsec offset from another ALMA SMG ($J$); one is detected in Ly$\alpha$ by VLT/MUSE (Apostolovski in prep.); and the final one has a candidate [C II] line detection in our deep ALMA data. While this represents a substantial local overdensity (perhaps 20 times the background level within a 30 arcsec diameter region), the small number of galaxies would not be a statistically significant overdensity in a large survey.

- For the nine SMGs detected by IRAC or in $K_s$, we use their multi-band imaging to study their properties and estimate the stellar masses using CIGALE fitting, finding $M^*$ to range between $(0.3-3.3) \times 10^{11} M_{\odot}$.

- Source C appears to be brighter and to have a substantially larger stellar mass than any of the other SPT2349-56 sources, and is amongst the most massive $z > 3.5$ SMGs from the ALESS field survey. It may be the stellar seed of a rapidly forming BCG galaxy.

- The highest SFR SMGs in SPT2349-56 have a similar range of $M^*$ to the ALESS SMGs at $z > 3.5$, and lie within the scatter of the main sequence of star formation at these redshifts. However, our lowest SFR SMGs have stellar masses consistent with the high $M^*$ values of the other SPT2349-56 sources as well as the ALESS SMGs and may represent rapid build-up of stellar mass and a subsequent early quenching of massive galaxies in the dense proto-cluster core.

- The cumulative stellar mass for the SPT2349-56 core is at least $(1.5 \pm 2.9) \times 10^{11} M_{\odot}$. Since these galaxies appear destined to merge on a short timescale (Rennehan et al. 2020), this stellar mass is already comparable to that of a BCG in a $> 10^{15} M_{\odot}$ galaxy cluster at $z < 1$. The combined stars and gas in the SPT2349-56 core represent a large fraction (more than ~ 18 per cent) of the virial mass estimate, and this may suggest that there is not yet an established hot ICM at this early epoch.

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APPENDIX A

In the following section we include the SED fits from cigale for the six sources detected in both IRAC bands, followed by those detected in only one IRAC band or in $K_s$.

APPENDIX B

In this section we list all g-band dropouts in the 6 arcmin diameter field surrounding SPT2349-56. Those LBGs selected by Steidel et al. (1999) colour criteria, to $i < 26.5$, are highlighted, while a broader set extending the $r-i$ colour to 1.2 mag are included as presented in Steidel et al. (1999).

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Figure 1. Best fitting SED from \textsc{cigale} for SMGs detected at both IRAC bands.
**Figure 2.** Best fitting SED from cigale for SMGs with single band near-IR constraints. While source $N$ is detected at 3.6$\mu$m and $K_s$, $D$ is only detected at 4.5$\mu$m and $H$ only at $K_s$.

**Table 1.** Properties of all candidate LBGs in SPT2349-56 to 2 arcmin diameter.

| ID    | RA      | Dec     | $i$   | $r$   | $g$   | $r-i$ | $g-r$ |
|-------|---------|---------|-------|-------|-------|-------|-------|
|       | [AB]    | [AB]    | [AB]  | [AB]  | [AB]  |
| 2087a | 23:49:57.182 | -56:37:28.70 | 22.30 | 23.14 | 26.45 | 0.84  | 3.32  |
| 489   | 23:49:59.732 | -56:39:50.03 | 22.49 | 22.83 | 25.83 | 0.35  | 3.00  |
| 2973  | 23:49:56.196 | -56:37:13.00 | 22.65 | 23.20 | 26.17 | 0.55  | 2.97  |
| 2704  | 23:49:56.689 | -56:37:20.64 | 22.72 | 24.54 | –     | 1.82  | –     |
| 2352  | 23:49:57.760 | -56:37:38.87 | 22.82 | 24.36 | –     | 1.54  | –     |

* Full table included in electronic edition.