Abstract

Recent simulation studies suggest that the compaction of star-forming galaxies (SFGs) at high redshift might be a critical process, during which the central bulge is being rapidly built, followed by quenching of the star formation. To explore dust properties of SFGs with compact morphology, we investigate the dependence of dust temperature, $T_{\text{dust}}$, on their size and star formation activity, using a sample of massive SFGs with log$(M_\text{h}/M_\odot) > 10$ at $1 < z < 3$, drawn from the 3D-HST/CANDELS database in combination with deep Herschel observations. $T_{\text{dust}}$ is derived via fitting the mid-to-far-infrared photometry with a mid-infrared power law and a far-infrared modified blackbody. We find that both extended and compact SFGs generally follow a similar $T_{\text{dust}} - z$ evolutionary track as that of the main-sequence galaxies. The compact SFGs seem to share similar dust temperature with extended SFGs. Despite the frequent occurrence of active galactic nuclei (AGNs) in compact SFGs, we do not observe any effect on dust caused by the presence of AGNs in these galaxies during the compaction. Our results disfavor different ISM properties between compact and extended SFGs, suggesting that a rapid and violent compaction process might be not necessary for the formation of compact SFGs.

1. Introduction

The presence of massive quiescent galaxies (QGs) and star-forming galaxies (SFGs) with extremely small sizes in both observations and simulations (so-called red and blue “nuggets,” respectively; van Dokkum et al. 2008; Damjanov et al. 2009; Barro et al. 2013; Dekel & Burkert 2014; Zolotov et al. 2015; Tacchella et al. 2016a, 2016b) has spurred extensive discussion about a possible “compaction and quenching” evolutionary scenario. During the compaction process, galaxies acquire a significant amount of central stellar mass in a short timescale, followed by the cessation of star formation. Evidence of such a two-step quenching mode have been found in local and distant galaxies (Barro et al. 2013, 2017; Fang et al. 2013, 2015; Wang et al. 2018; Woo & Ellison 2018). Possible mechanisms accounting for the compaction include mergers orviolent disk instabilities, inducing gas inflows and resulting in active star formation in the central region (Hopkins et al. 2008; Dekel & Burkert 2014; Zolotov et al. 2015; Tacchella et al. 2016b). When the compact center of a galaxy is being rapidly built, the galaxy enters a starburst phase associated with a short gas depletion timescale (230±90 Myr; Barro et al. 2016) as well as the triggering of active galactic nuclei (AGN)/stellar feedback that initialize the quenching process of the galaxy (Cai et al. 2013; Zolotov et al. 2015). Therefore, in massive SFGs where gas replenishment is usually suppressed (Tacchella et al. 2016b), the compaction will end up with the formation of QGs (Tacchella et al. 2016b; Barro et al. 2017).

Nevertheless, it remains to be explored which mechanisms drive the compaction. Recent studies reveal a dust-obscured nature for the compact star-forming galaxies (cSFGs; e.g., Barro et al. 2014), which would be the first step of the proposed “compaction and quenching” scenario. These galaxies appear to be dusty according to their locations on the popular $UVJ$ diagram with many of them being detected by Herschel. Furthermore, a much larger AGN fraction is found in cSFGs than in extended star-forming galaxies (eSFGs) and QGs along the “compaction and quenching” sequence, suggesting that AGNs might play a role during the compaction and quenching process (Barro et al. 2014; Kocevski et al. 2017). But how AGNs help to shape the physical properties and fueling process of their hosting cSFGs still remains to be fully explored (Kocevski et al. 2017).

The infrared (IR) emission of active SFGs primarily traces the dust-obscured star formation. Dust properties (e.g., the dust mass and temperature), as usually constrained by a modified blackbody fitting to the FIR spectral energy distribution (SED), are linked to the physical conditions within which star formation occurs. Thus, dust in the interstellar medium (ISM) provides a unique perspective to study properties of host galaxies such as gas content and star formation efficiency (Magnelli et al. 2014; Schreiber et al. 2016, 2018; Liang et al. 2019; Ma et al. 2019). Besides star formation, AGN activity may also contribute to dust heating. A harder radiation field may lead to more efficient dust heating and thus higher dust temperature. This is particularly relevant for cSFGs that have a frequent occurrence of AGN (Barro et al. 2014; Kocevski et al. 2017). Therefore, the AGN effect may be uncovered through the analysis of dust content.

By investigating dust properties of cSFGs and eSFGs as well as the potential effect of AGNs on those, the work presented here is an attempt to gain new insights into the physical mechanisms involved in the compaction process. Based on the wealth of multiwavelength photometry collected from the Hubble Space Telescope (HST), Spitzer, and Herschel observations in the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey fields (CANDELS; Grogin et al.
2. Data and Sample

Four of the CANDELS fields are selected to conduct this work, where both robust rest-frame optical size measurements and deep mid-IR (MIR) to far-IR (FIR) photometries are available, i.e., the Great Observatories Origins Survey (GOODS) Northern and Southern fields (GOODS-N and GOODS-S), the Cosmic Evolution Survey field (COSMOS), and the All-wavelength Extended Groth Strip International Survey fields (AEGIS). These valuable size measurements and infrared observations ensure a census of dust temperature variation during the compaction process of SFGs at the peak of the cosmic star formation history.

2.1. 3D-HST Survey

Our sample is primarily based on data products from the 3D-HST spectroscopic survey (Brammer et al. 2012) in combination with the CANDELS program (Grogin et al. 2011; Koekemoer et al. 2011).

We use the astrometry and photometry from the 3D-HST Release v4.1 (Skelton et al. 2014) but adopt the updated physical parameters from the Data Release v4.1.5 (Momcheva et al. 2016) to select massive galaxies with [log(M/M_☉) > 10] at 1 < z < 3. Only those with use_phot = 1 in the 3D-HST catalogs are considered, i.e., galaxies with reliable photometric measurements. We adopt the “best” galaxy redshift, z_3D, created by Momcheva et al. (2016). This z_3D is determined by combing the grism redshift, if robust, with the spectroscopic and photometric redshifts compiled by Skelton et al. (2014).

Using z_3D, Momcheva et al. (2016) re-derive other auxiliary stellar population parameters, rest-frame colors, and SFRs from spectral energy modeling with FAST (Kriek et al. 2009).

Furthermore, the circularized radius, r_e, is derived using r_e = R_e × √g, where R_e is the effective radius along the major axis and q is the axis ratio, as measured by van der Wel et al. (2014) from CANDELS HST/WFC3 imaging mosaics with GALFIT (Peng et al. 2002). We correct them to the rest-frame optical size at 5000 Å using Equation (2) in van der Wel et al. (2014) to achieve a uniform measurement. We exclude galaxies with inaccurate or no size measurement, i.e., with Flag = 2 or 3 in the catalog of van der Wel et al. (2014).

In total, 6303 galaxies satisfy our mass and redshift cuts as well as use_phot = 1, 5700 of which have robust size measurements and would be further considered in the next section.

2.2. MIR to FIR Photometry and X-Ray Data

The four CANDELS fields used here are all covered by the PACS Evolutionary Probe (PEP; Elbaz et al. 2011; Lutz et al. 2011; Magnelli et al. 2013) survey at 100 and 160 μm (and 70 μm in GOODS-S) and by the Herschel Multi-tiered Extragalactic Survey (HerMES; Roseboom et al. 2010, 2012; Oliver et al. 2012) at 250, 350, and 500 μm. Our MIR to FIR photometry is retrieved from the PEP and HerMES catalogs, which were extracted at the positions of the Spitzer/MIPS 24 μm sources.

To identify AGNs in our sample, we use X-ray observations from the Chandra X-ray Observatory (Chandra; Weisskopf et al. 2000). The X-ray source catalogs for 2 Ms exposure of the Chandra Deep Field-North (Xue et al. 2016) and 7 Ms exposure of the Chandra Deep Field-South (Luo et al. 2017) are adopted for the GOODS-N and GOODS-S fields, respectively. In these two catalogs, AGNs are already identified via several X-ray-based criteria (Xue et al. 2016; Luo et al. 2017). For the COSMOS and AEGIS fields, we use the X-ray source catalogs from the Chandra COSMOS Legacy survey (Civano et al. 2016; Marchesi et al. 2016) and the AEGIS-X Deep survey (Brightman et al. 2014; Nandra et al. 2015), respectively.

AGNs in these two fields are identified by either an intrinsic X-ray luminosity of L_0.5–7 keV ≥ 3 × 10^{42} erg s^{-1} or an intrinsic photon index of Γ ≤ 1.0 (obscured AGNs), which are consistent with the criteria adopted by Xue et al. (2016) and Luo et al. (2017) in the GOODS-N and GOODS-S fields, respectively. Because L_0.5–7 keV is not given in the catalogs of the COSMOS and AEGIS fields, we converse the provided L_2–10 keV to L_0.5–7 keV via

\[ L_{0.5–7 \text{ keV}} = L_{2–10 \text{ keV}} / 0.72, \]

assuming an intrinsic photon index of Γ = 1.8.

For each field, we use the PEP catalog as the reference one, and subsequently cross-match it with the 3D-HST catalog, the HerMES catalog, and the X-ray source catalog utilizing the method described below. Briefly, for every source in the reference catalog (i.e., the PEP catalog), we search for the nearest counterpart within an optimized matching radius. Here, we consider a range of matching radii from 0.1 to 5.0 with a step of 0.1, among which the optimized one is set to the largest radius satisfying the following two criteria: (1) the fake matched fraction, defined as the ratio of the fake matched number (see below) to the successful matched number, is smaller than 5%; (2) the differential successful matched number, i.e., the new successful matched number with increasing matching radius, is larger than the differential fake matched number. To estimate the fake matched number given two catalogs, we shift one of them by 30 pixels in random directions 16 times and take the average of the 16 “successful” matched numbers as the fake matched number. Clearly, the optimized matching radius depends on the number densities of the matched catalogs, and thus varies between catalogs even for the same field. However, we note that most of the resulting optimized matching radii are smaller than 1.5 pixels.

Since both the 3D-HST catalogs and the X-ray source catalogs provide redshift information, we require that z_3D from the 3D-HST catalogs and 2X (redshifts of optical counterparts of X-ray sources) from the X-ray source catalogs should be in agreement.

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5 http://3dhst.research.yale.edu/Data.html

6 http://www.mpe.mpg.de/ir/Research/PEP/DR1

7 http://hedam.lam.fr/HerMES
good agreement, i.e., $|z_{\text{best}} - z_{X}|/z_{\text{best}} \leq 0.2$ (only one source was excluded by this criterion). In total, the cross-match yields a sample of 2403 galaxies with at least one Herschel measurement and a robust HST/size measurement.

Furthermore, to ensure an accurate measurement of dust temperature, we remove sources with less than three detections at rest-frame wavelength longer than 50 μm. After these selections, we obtain an MIR-to-FIR catalog including 521 galaxies, 109 of which have AGN counterparts.

### 2.3. Sample Selection

We use the $UVJ$ criteria of Williams et al. (2009) to select SFGs among our catalog of 521 galaxies, resulting in 488 FIR-detected massive SFGs with $\log(M_\star/M_\odot) > 10$ at $1 < z < 3$. To ensure a robust analysis of dust temperature, sources with catastrophic MIR-to-FIR SED fitting (see Section 3.1) are also removed from our final sample. We end up with a sample of 495 SFGs within which 95 galaxies are identified as X-ray AGN hosts. Note that approximately 64% of these galaxies have spectroscopic or grism redshift, which is key for accurate dust temperature measurements.

Finally, to identify cSFG from eSFGs, we use the compactness criteria defined by Barro et al. (2013), i.e., $\Sigma_{1.5} = \log(M_\star c_{1.5}/M_\odot \text{kpc}^{-1.5})$. Since the mass–size relation of SFGs evolves with redshift (van der Wel et al. 2014), cSFGs are identified as $\Sigma_{1.5} \geq 10.3$ at $1 < z \leq 2$ (Barro et al. 2013) and $\Sigma_{1.5} \geq 10.45$ at $2 < z < 3$ (Barro et al. 2014), respectively. In total, there are 61 cSFGs.

Figure 1 shows the distributions on the $UVJ$ and the mass–size diagrams for our final sample. We observe a higher occurrence of X-ray AGNs in cSFG than in eSFGs, i.e., 37% versus 18%, respectively. This finding is consistent with the ubiquitous AGNs in cSFGs reported by Barro et al. (2016) and Kocevski et al. (2017). More than 80% of our SFGs have $V - J$ colors redder than 1.2, a criterion used for selecting dusty SFGs in Spitler et al. (2014). Such red $V - J$ colors of our sample indicate that they are dust-obscured, which agrees with their Herschel detections.

### 3. Dust Temperature and Star Formation Rate

#### 3.1. Dust Temperature

Following Casey (2012) and using the corresponding IDL code cmcirdes, we model the MIR to FIR (i.e., 24 to 500 μm) SED of our SFGs, with an MIR power law plus an FIR graybody with a single dust temperature, $T_{\text{dust}}$. The power-law component accounts for the MIR emission of small clumps associated with hot dust or for AGN radiation, while the graybody accounts for the cold dust component emission (Casey 2012; Casey et al. 2014). For galaxies lacking sufficient FIR detection, the peak of the graybody emission will be poorly constrained, resulting in an unreliable estimate on $T_{\text{dust}}$.

To reduce such an effect, only galaxies with more than three data points at $\lambda_{\text{rest}} > 50 \mu$m (i.e., where the graybody emission dominates) are included in our analysis (see Section 2.2). This extra selection criteria effectively translates into having for most of our galaxies more than four bands covering their MIR to FIR emission (76% have $\geq 5$ bands), providing us with a very accurate description of their infrared emission.

We fix the dust emissivity to a standard reference value of 1.5 (Chapman et al. 2005; Casey et al. 2009), leaving the power-law slope ($0.5 < \alpha < 5.5$) as a free parameter (Casey 2012). We first perform an automatic fitting process assuming an optically thin dust model. Then we visually inspect the best-fit SEDs for individual sources in order to ensure acceptable best-fit results. For a few cases in which the model fails to fit the data, we rerun the fit by manually adjusting (and fixing) $\alpha$ values. For 25 galaxies, we are able to better constrain $T_{\text{dust}}$ with manual fitting, and the new best-fit results are adopted. However, there are still 29 of the original 488 FIR-detected massive SFGs that fail to achieve an acceptable fit even though manual fitting process is implemented, due to either insufficient wavelength coverage that leads the peak emission unconstrained, or the fact that the data apparently deviate a lot from the assumption of MIR power law plus FIR graybody. These galaxies with failed determination of $T_{\text{dust}}$ are already excluded from our final sample (see Section 2.3).
While dust temperature can be defined in different ways, such as mass-weighted or light-weighted, the light-weighted dust temperature derived as here using the FIR peak emission is what can be best constrained observationally (Casey et al. 2014; Liang et al. 2019). These light-weighted dust temperatures reflect the condition of the ISM surrounding massive and thus luminous star-forming regions. They are also less dependent on the assumed underlying templates and allow for a direct comparison with previous works.

### 3.2. Star Formation Rate

The SFRs in the 3D-HST catalogs are derived using rest-frame UV luminosity, $L_{UV}$, in combination with the Spitzer/ MIPs 24 μm based total IR luminosities, $L_{IR}$, as described in Whitaker et al. (2014):

$$SFR = SFR_{UV} + SFR_{IR},$$

$$= 1.09 \times 10^{-10} (2.2L_{UV} + L_{IR}).$$

We only keep the UV-based SFRs but recalculate $SFR_{IR}$ based on our MIR to FIR photometries. We make use of the total IR luminosity, $L_{IR}$, integrating the SED output by cmcirsed from the rest-frame 8 to 1000 μm, and correct AGN contribution, $L_{IR,AGN}$, with the method presented in Dai et al. (2018). Briefly, we convert the 2–10 keV luminosity of our X-ray AGNs to AGN emission at 6 μm using the well calibrated X-ray to MIR relation of Stern (2015)

$$\log(L_{2-10keV}/[\text{erg s}^{-1}]) = 40.981 + 1.024x - 0.047x^2,$$

where $x = \log(\nu L_\nu(6 \text{ μm})/[10^{41} \text{ erg s}^{-1}])$. $L_{IR,AGN}$ is then extrapolated by multiplying $\nu L_\nu(6 \text{ μm})$ by a factor of 2.5, derived from the AGN template of Dai et al. (2012). We find generally small corrections for AGN contribution in our sample with a median value of $L_{IR,AGN}/L_{IR} \approx 9\%$. Note that for galaxies without X-ray AGN detection, the median of $L_{IR}$ based on our FIR SED fitting is only larger by 0.07 dex than, and therefore broadly consistent with, that derived by Whitaker et al. (2014).

The SFR–$M_*$ distributions for our SFGs are shown in Figure 2 along with the main sequence of SFGs from Whitaker et al. (2014). Compared to the main-sequence of SFGs, a significant number of our SFGs have enhanced star formation activity, especially in the high-redshift bin.

### 4. Results

#### 4.1. Dust Temperature for Extended and Compact Galaxies

Dust temperature of SFGs is known to evolve with redshift in the sense that typical SFGs exhibit hotter dust temperature at high redshift than in the local universe, possibly due to a higher star formation efficiency or lower metallicity (Magnelli et al. 2014; Schreiber et al. 2018; Liang et al. 2019). Such an evolution cannot be neglected especially for our sample spanning a large redshift range. Therefore, Figure 3 shows the dust temperature versus redshift for both eSFGs and cSFGs compared to that of main-sequence galaxies inferred by Magnelli et al. (2014). The median dust temperatures of eSFGs and cSFGs are also summarized in Table 1. We found that the number of cSFGs relatively to the number of eSFGs significantly decreases between $z \sim 2.5$ and $z \sim 1.5$ (upper panel of Figure 3). This is consistent with Barro et al. (2013) in which the decrease is explained by the fact that cSFGs are continuously formed at a redshift of 2–3 and gradually fade into QGs at later times.

It is clear that both eSFGs and cSFGs generally follow the $T_{dust} - z$ evolutionary track defined by the main-sequence SFGs presented in Magnelli et al. (2014), especially for galaxies at $z \lesssim 2$. From $z \sim 2.5$ to $\sim 1.5$, the dust temperature of cSFGs drops by 7.0 ± 3.4 K. In the same redshift range, the dust temperature of eSFGs drops by 6.7 ± 2.0 K. The redshift evolution of dust temperatures for cSFGs and eSFGs are thus fully consistent within the uncertainties.

In the higher redshift bin, $T_{dust}$ of both cSFGs and eSFGs are about 5 K higher than that inferred by Magnelli et al. (2014). This trend can, however, be explained by their higher SFRs as revealed in Figure 2.

Similarly, $T_{dust}$ for AGN-hosting SFGs are also uniformly distributed around the $T_{dust} - z$ track of main-sequence SFGs (see the open circle in Figure 3 and Table 1). No AGN effect on the temperature of the cold dust is observed for our sample.
Figure 3. Top: normalized number distribution (i.e., the total area under the histogram is 1) of compact SFGs (red line) and extended ones (blue line), together with the fraction of compact SFGs at different redshifts (black dashed line). Bottom: evolution of the dust temperature, $T_{\text{dust}}$, with redshift for our extended SFGs (blue points) and compact SFGs (red points), compared to the overall redshift evolution of $T_{\text{dust}}$ for the main-sequence galaxies (Magnelli et al. 2014; thick magenta dashed line). The SFGs associated with X-ray-detected AGNs are marked with black circles. The typical error of $\sim5.5$ K for our sample is illustrated by the green error bar. Generally, the evolution of $T_{\text{dust}}$ with redshift for both our extended and compact SFGs is similar to that of the main-sequence galaxies.

### Table 1

| Sample       | $N$   | $T_{\text{dust}}/K$ | $\log(M_{\text{dust}}/M_{\odot})$ |
|--------------|-------|---------------------|-----------------------------------|
| $1 < z < 2$  |       |                     |                                   |
| eSFGs        | 337   | $31.6 \pm 0.5$      | $8.1 \pm 0.1$                     |
| cSFGs        | 34    | $31.8 \pm 1.8$      | $8.4 \pm 0.1$                     |
| AGNs         | 67    | $33.3 \pm 1.2$      | $8.3 \pm 0.1$                     |
| $2 < z < 3$  |       |                     |                                   |
| eSFGs        | 62    | $38.3 \pm 1.9$      | $8.5 \pm 0.1$                     |
| cSFGs        | 26    | $38.8 \pm 2.9$      | $8.7 \pm 0.1$                     |
| AGNs         | 28    | $38.7 \pm 2.4$      | $8.7 \pm 0.1$                     |

Note. For $T_{\text{dust}}$ and $M_{\text{dust}}$, the median is provided, together with uncertainties estimated via the bootstrapping method.

However, further interpretation is limited by both the small sample size and the large uncertainty involved during the $T_{\text{dust}}$ calculation.

Based on our FIR SED fits, we also infer dust masses ($M_{\text{dust}}$) by extrapolating the rest-frame 850 μm emission of our galaxies and assuming a dust absorption coefficient of $k_{\text{SFG}} = 0.15 \text{ m}^2\text{ kg}^{-1}$ (Casey 2012). The resulting $M_{\text{dust}}$ is given in Table 1. It can be seen that a huge amount of dust is enclosed in our SFGs, which is expected from their FIR detections. Though cSFGs might have more dust compared to eSFGs, it should be treated with caution since the reliability of $M_{\text{dust}}$ measurement is limited by the lack of data at longer wavelengths. Our measurement is consistent with those of high-redshift dusty SFGs or submillimeter galaxies with $T_{\text{dust}} \approx 20-50$ K and $\log(M_{\text{dust}}/M_{\odot}) \approx 8-9.3$ (Kovács et al. 2006; Casey 2012; Casey et al. 2014). Furthermore, the huge amount of dust in cSFGs also directly confirms the observations of Barro et al. (2014) that SFGs become more compact before they lose their gas and dust.

To reveal the role of compactness in dust heating, we plot the $\Sigma_{1.5-T_{\text{dust}}}$ relation, color-coded by specific star formation rates (sSFR $\equiv$ SFR/$M_{\odot}$), in Figure 4. Obviously, there is no significant trend between $\Sigma_{1.5}$ and $T_{\text{dust}}$ in both redshift bins, while the Pearson linear (or Spearman rank) correlation coefficients are close to zero for both subsamples. This result suggests a similar dust temperature for cSFGs and eSFGs, which is consistent with Gómez-Guijarro et al. (2019) in which the authors found that the ISM properties of cSFGs are similar to those of eSFGs located slightly above the main sequence. Moreover, no significant feature of sSFR on the $\Sigma_{1.5-T_{\text{dust}}}$ plane is observed in both redshift bins, although we will show in Section 4.2 that cSFGs tend to have smaller sSFR compared to eSFGs at $2 < z < 3$.

### 4.2. Connection with Star Formation

In this section, we focus on the effect of star formation activities on dust, with both the sSFRs and the SFR surface densities ($\Sigma_{\text{sSFR}} = \text{SFR}/2\pi r_e^2$).\(^8\)

Dust temperature has been found to correlate with sSFR, better than other quantities like SFRs or $L_{\text{IR}}$ (Magnelli et al. 2014). In Figure 5 we show the relation between $T_{\text{dust}}$ and sSFR, color-coded by their compactness ($\Sigma_{1.5}$). The whole sample is divided into two redshift bins ($1 < z < 2$ and $2 < z < 3$). The running medians of $T_{\text{dust}}$ for two subsamples are shown with green solid lines, while the uncertainties of the running medians estimated via the bootstrapping method (green hatched shadows) and the running standard deviations (yellow shadows) are also plotted in Figure 5.

In each redshift bin, $T_{\text{dust}}$ of our sample is roughly consistent with that of the main-sequence galaxies at similar redshift (magenta dashed line; Magnelli et al. 2014) within the large scatter. At $1 < z \lesssim 2$, a weak positive correlation with a linear correlation coefficient of $r = 0.34 \pm 0.06$ between sSFR and $T_{\text{dust}}$ is found, which supports that active star formation heats dust intensively. However, at $2 < z < 3$, due to the lack of small-$T_{\text{dust}}$ SFGs in the low-sSFR regime, such a relation is more ambiguous, and $T_{\text{dust}}$ seems to show no correlation with sSFR ($r = 0.16 \pm 0.09$). The lack of small-$T_{\text{dust}}$ SFGs with relatively low sSFR at $2 < z < 3$ might be due to the selection effect, i.e., our FIR selection bias to galaxies with more intense star formation compared to the main-sequence SFGs at similar redshift (Whitaker et al. 2014), as suggested by the right panel of Figure 2 and the large void region below the Magnelli et al. (2014) relation at $z \sim 2.5$ in Figure 3.

In the low-redshift bin, SFGs with different compactness are well mixed, which is supported by the similar distributions of sSFR for eSFGs and cSFGs given in Figure 5. However, both the distribution of individual galaxies and the comparison of

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\(^8\) Note that $\Sigma_{\text{sSFR}}$ used in this work is defined by rest-frame optical size $r_e$, the star formation-related size, however, is found to be smaller than the optical stellar size for SFGs at this redshift (e.g., Elbaz et al. 2018; Fujimoto et al. 2018; Puglisi et al. 2019; Chen et al. 2020). Given the lack of the measurement of star formation-related sizes of these galaxies, we will use $\Sigma_{\text{sSFR}}$ defined by optical size to describe the concentration of star formation, but one should keep in mind that the derived values might be the lower limits of the true ones.
the sSFR distributions between the eSFG and cSFG subsamples imply that more compact SFGs (redder color in Figure 5) seem to possess lower sSFR at $2 < z < 3$, which might be a signature of suppression of star formation. However, as shown in the right panel of Figure 2, our FIR selected galaxies form an SFR detection limit of $\sim 100 M_\odot \text{yr}^{-1}$, which bias our sample to more star-bursting galaxies at low-$M_*$ end. Given that eSFGs in this subsample tend to be less massive than cSFGs, eSFGs thus might be more star-bursting (higher sSFR) than cSFGs. In other words, the observed lower sSFR of cSFGs at $2 < z < 3$ might result from the FIR selection combining with the lack of cSFGs at the low-$M_*$ end. Further $M_*$-controlled comparison reveals that cSFGs and eSFGs have similar sSFR within the same $M_*$ bins, supporting that the apparently lower sSFR of cSFGs might be just a selection effect.

High-redshift cSFGs also seem to have slightly hotter dust than that predicted by the main-sequence SFGs (Magnelli et al. 2014). This might suggest differences in the ISM conditions of these compact objects with respect to typical SFGs with similar sSFR. However, considering the low number statistic and the aforementioned selection effect, this result should be treated with caution.

Similar plots for the $T_{\text{dust}}-\Sigma_{\text{SFR}}$ relation are also shown in Figure 5. SFGs with greater compactness (gray to red points) have significantly larger $\Sigma_{\text{SFR}}$ than eSFGs, suggesting that size shrinkage is more dramatic than SFR changes. The linear correlation coefficients between $T_{\text{dust}}$ and $\Sigma_{\text{SFR}}$ are $0.30 \pm 0.06$ and $0.24 \pm 0.08$ for the $1 < z \leq 2$ and $2 < z < 3$ subsamples, respectively, indicating a weak relation in both redshift bins.

From Figures 5, we find that AGN hosts are distributed in a similar way as those without AGNs. The two populations share the same dependence of $T_{\text{dust}}$ on star formation activities, in terms of sSFR and $\Sigma_{\text{SFR}}$. Star formation thus might be the main heating source of dust in these galaxies.

In short, at $1 < z \leq 2$, cSFGs seem to be indistinguishable from eSFGs except for their compact stellar morphology, while an apparent suppression of star formation is observed for cSFGs at $2 < z < 3$; however, this might be a selection effect.

4.3. Role of cSFGs

Given the current data, we only observed an apparent suppression of star formation for our selected cSFGs compared to eSFGs at $2 < z < 3$. The role of these cSFGs in the picture of galaxy evolution is still unclear.

Elbaz et al. (2018) compiled a sample of $z \sim 2$ Herschel-selected galaxies, which resemble the massive end ($M_* \gtrsim 10^{10} M_\odot$) of our high-redshift subsample, and found that galaxies located within the scatter of the main sequence tend to have compact star formation and short depletion timescales. The authors argued that these galaxies could be at the last step of star formation. Although we do not have measurement of star formation-related size for our sample, the most massive galaxies at $2 < z < 3$ located within the scatter of the main sequence also tend to have compact stellar morphology (see Figure 2), possibly suggesting similar properties to those galaxies hidden in the main sequence in the Elbaz et al. (2018) sample.

Furthermore, based on observations of galaxies at $0.5 < z < 3$, Gómez-Guijarro et al. (2019) reported that cSFGs and eSFGs exhibit similar star formation efficiencies, while the ISM properties (e.g., CO excitation and local physical conditions of the neutral gas) of cSFGs are also similar to those of eSFGs located slightly above the main sequence. Besides the above ISM properties, our results (i.e., Table 1 and Figure 4) provide the further supplement related to dust that no significant differences in $T_{\text{dust}}$ and $M_{\text{dust}}$ are observed between cSFGs and eSFGs for both redshift subsamples.

9 Figure 2 clearly shows that fewer cSFGs are observed at the low-$M_*$ ends in both redshift bins. In fact, our FIR selection should bias our sample to more compact galaxies due to their compact morphology and thus possibly higher IR surface brightness. Therefore, given an IR detection limit and a fixed SFR, cSFGs should be much easier to detect, which conflicts with our observations. The physical reason for this conflict is still unknown and might be worth further study.

10 Note that seven out of eight Herschel-selected galaxies in Elbaz et al. (2018) have redshifts of $\gtrsim 2$.6
Therefore, for cSFGs in both redshift bins, because of their similarity to eSFGs, it is possible that these galaxies form their compact stellar cores via slow secular evolution rather than a rapid compaction process, as suggested by Gómez-Guijarro \textit{et al.} (2019).

5. Summary

In this work, we investigate how dust temperature depends on the compactness and the star formation activity, using a sample of massive high-redshift SFGs with FIR observations from Herschel in four 3D-HST/CANDELS fields. Our findings are summarized as follows.

1. Dust temperature of both eSFGs and cSFGs agree, within the uncertainties, with the $T_{\text{dust}} - z$ evolutionary track of the main-sequence SFGs found by Magnelli \textit{et al.} (2014).

2. No significant difference in dust temperature is found between cSFGs and eSFGs.

3. While similar sSFR is found for eSFGs and cSFGs at $1 < z \leq 2$, cSFGs tend to show smaller sSFR at $2 < z < 3$, which results from our FIR selection and the lack of low-$M_*$ cSFGs. Compared to eSFGs, cSFGs are observed to have larger $\Sigma_{\text{SFR}}$, which is consistent with their remarkable size shrinkage.

4. $T_{\text{dust}}$ seems to slightly correlate in a positive way with sSFR at $1 < z \leq 2$, but such trends disappear at $2 < z < 3$, which might be caused by FIR selection effects.

5. No difference of dust temperature is observed whether or not AGN activities are ignited; though AGNs have higher occurrence in cSFGs, which is consistent with the literature (Barro \textit{et al.} 2013; Fang \textit{et al.} 2015; Kocevski \textit{et al.} 2017).
6. Our findings, together with other ISM studies in the literature, suggest similar ISM properties between eSFGs and cSFGs, which implies that a rapid and violent compaction process might not be necessary for the formation of eSFGs.

The intense star formation in the central bulge and strong AGN feedback may lead to extreme properties of the ISM in the compact phase. However, our results disfavor different ISM properties in cSFGs compared to eSFGs, questioning the existence of a rapid compaction process to form such compact galaxies. Our sample size is limited by both precise size measurement and the need for multwavlength Herschel galaxies. Our sample size is limited by both precise size measurement and the need for multwavlength Herschel galaxies. Our sample size...