



## Structural Evolution in Massive Galaxies at $z \sim 2$

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### Abstract

We present 0.2 resolution Atacama Large Millimeter/submillimeter Array (ALMA) observations at 870  $\mu\text{m}$  in a stellar mass–selected sample of 85 massive ( $M_* > 10^{11} M_\odot$ ) star-forming galaxies (SFGs) at  $z = 1.9\text{--}2.6$  in the CANDELS/3D-Hubble Space Telescope fields of UDS and GOODS-S. We measure the effective radius of the rest-frame far-infrared (FIR) emission for 62 massive SFGs. They are distributed over wide ranges of FIR size from  $R_{\text{e,FIR}} = 0.4$  kpc to  $R_{\text{e,FIR}} = 6$  kpc. The effective radius of the FIR emission is smaller by a factor of  $2.3_{-1.0}^{+1.9}$  than the effective radius of the optical emission and is smaller by a factor of  $1.9_{-1.0}^{+1.9}$  than the half-mass radius. Taking into account potential extended components, the FIR size would change only by  $\sim 10\%$ . By combining the spatial distributions of the FIR and optical emission, we investigate how galaxies change the effective radius of the optical emission and the stellar mass within a radius of 1 kpc,  $M_{1\text{kpc}}$ . The compact starburst puts most of the massive SFGs on the mass–size relation for quiescent galaxies (QGs) at  $z \sim 2$  within 300 Myr if the current star formation activity and its spatial distribution are maintained. We also find that within 300 Myr,  $\sim 38\%$  of massive SFGs can reach the central mass of  $M_{1\text{kpc}} = 10^{10.5} M_\odot$ , which is around the boundary between massive SFGs and QGs. These results suggest an outside-in transformation scenario in which a dense core is formed at the center of a more extended disk, likely via dissipative in-disk inflows. Synchronized observations at ALMA 870  $\mu\text{m}$  and James Webb Space Telescope 3–4  $\mu\text{m}$  will explicitly verify this scenario.

*Unified Astronomy Thesaurus concepts:* [High-redshift galaxies \(734\)](#); [Starburst galaxies \(1570\)](#); [Interstellar medium \(847\)](#); [Galaxy structure \(622\)](#); [Galaxy bulges \(578\)](#)

### 1. Introduction

In the current universe, the most massive ( $M_* > 10^{11} M_\odot$ ) galaxies are spheroids or have a prominent bulge in the center (e.g., Conselice 2014) and show little ongoing star formation activity (e.g., Peng et al. 2010). One of the ultimate challenges in galaxy formation and evolution is to understand how massive galaxies obtained a bulge-dominated morphology and stopped forming stars. In this paper, we focus especially on the structural evolution in massive galaxies at  $z \sim 2$ , when the cosmic star formation history peaks (e.g., Madau & Dickinson 2014).

Surface brightness profiles of galaxies are well described by Sérsic models (Sérsic 1963),

$$I(r) \propto \exp\left[-b_n \left(\frac{r}{R_e}\right)^{1/n} - 1\right], \quad (1)$$

where  $R_e$  is the effective radius,  $n$  is the Sérsic index ( $n = 0.5$  for Gaussian,  $n = 1$  for an exponential profile,  $n = 4$  for de

Vaucouleurs profile), and  $b_n$  is an  $n$ -dependent normalization parameter ensuring that  $R_e$  encloses half the light. Typical star-forming galaxies (SFGs) are disk-dominated systems ( $n \sim 1$ ), whereas quiescent galaxies (QGs) are bulge-dominated ( $n \sim 4$ ). The correlation between galaxy structure and star formation activity appears to be established at least out to  $z \sim 2.5$  (e.g., Wuyts et al. 2011b; Whitaker et al. 2015). Furthermore, central stellar mass surface density and bulge-to-total mass ratio are better correlated to specific star formation rate (SFR), color, and fraction of QGs than total stellar mass, suggesting that it is a good predictor of quiescence (Franx et al. 2008; Bell et al. 2012; Lang et al. 2014; van Dokkum et al. 2014). Given the result that massive disk QGs are rare, massive SFGs need to change their morphology from disk-dominated to bulge-dominated at some point and quench star formation around that time or soon thereafter.

However, it is also noted that the observed correlation between galaxy structure and star formation activity does not

necessarily imply physical causation. Lilly & Carollo (2016) demonstrate, using a simple toy model, that the correlation can naturally arise without any such physical role once the evolution of the size–mass relation for SFGs is taken into account (see also van Dokkum et al. 2015). It is important to determine how the structural evolution of the galaxy population proceeds by updating the knowledge about spatial distributions of stars and star formation in massive SFGs.

The effective radius of galaxies is another important parameter for understanding the morphological evolution. Many studies have shown that massive QGs at  $z \sim 2$  are remarkably compact with  $R_e \sim 1$  kpc, which is a factor of 4–5 smaller than the size of local QGs at fixed mass (e.g., Daddi et al. 2005; Trujillo et al. 2006; van Dokkum et al. 2008; van der Wel et al. 2014). Both simulations and observations support that massive compact QGs increase their size through gas-poor minor mergers (Bezanson et al. 2009; Naab et al. 2009; Newman et al. 2012; Williams et al. 2014). Massive compact SFGs have also been discovered at  $z \sim 2$  and are naturally expected to be the direct progenitors of compact QGs (e.g., Barro et al. 2013, 2014; Nelson et al. 2014; Williams et al. 2014; Wisnioski et al. 2018). The evolutionary link from compact SFGs to compact QGs and eventually giant ellipticals has been extensively studied as mentioned above, while the evolutionary fate of extended SFGs has remained relatively less explored.

In the stellar mass range of  $M_* < 10^{11} M_\odot$ , the majority of SFGs at  $z = 2$  have an extended disk with  $R_e = 2\text{--}5$  kpc (e.g., Genzel et al. 2006; Law et al. 2012; van der Wel et al. 2014; Förster Schreiber et al. 2018) and form stars in the more extended disk (Tacchella et al. 2015; van Dokkum et al. 2015; Nelson et al. 2016a; Suzuki et al. 2019; Wilman et al. 2020). This inside-out growth scenario is also supported by a positive slope in the stellar mass–size relation (van der Wel et al. 2014). On the other hand, the inside-out growth alone cannot fully explain the high Sérsic index ( $n \sim 4$ ) in massive QGs or equivalently the formation of a dense core. A combination of the inside-out growth and a declining star formation history can slightly increase the Sérsic index of massive SFGs from  $n = 1$  to  $n = 1.5\text{--}2$  (Lilly & Carollo 2016), but it is not enough. The question is how and when massive SFGs form a dense core and acquire a radial profile with  $n \sim 4$ .

To answer this question, we need to investigate where stars are formed in SFGs with stellar masses above  $\log(M_*/M_\odot) = 11$ , where morphological transformation and quenching are expected to occur (e.g., Bell et al. 2012; Bruce et al. 2012; Lang et al. 2014). The spatial distribution of stellar mass and ongoing star formation has been well studied over the past decade by observations of  $H\alpha$  line and the rest-frame ultraviolet (UV) and optical continuum emission, as mentioned above. However, in this stellar mass range, 99% of the total SFR is obscured by dust, and even  $H\alpha$  emission misses 90%–95% of star formation (van Dokkum et al. 2015; Tadaki et al. 2017a; Whitaker et al. 2017). A radial gradient in dust extinction, furthermore, makes it difficult to study the spatial distribution of the total bolometric star formation in massive SFGs using  $H\alpha$  and UV (Nelson et al. 2016b; Tacchella et al. 2018).

Given that most star formation is obscured by dust, observing the spatially resolved dust continuum is the best approach to determine where stars truly form in massive SFGs. For galaxies at  $z \sim 2.2$ ,  $870 \mu\text{m}$  observations sample the dust

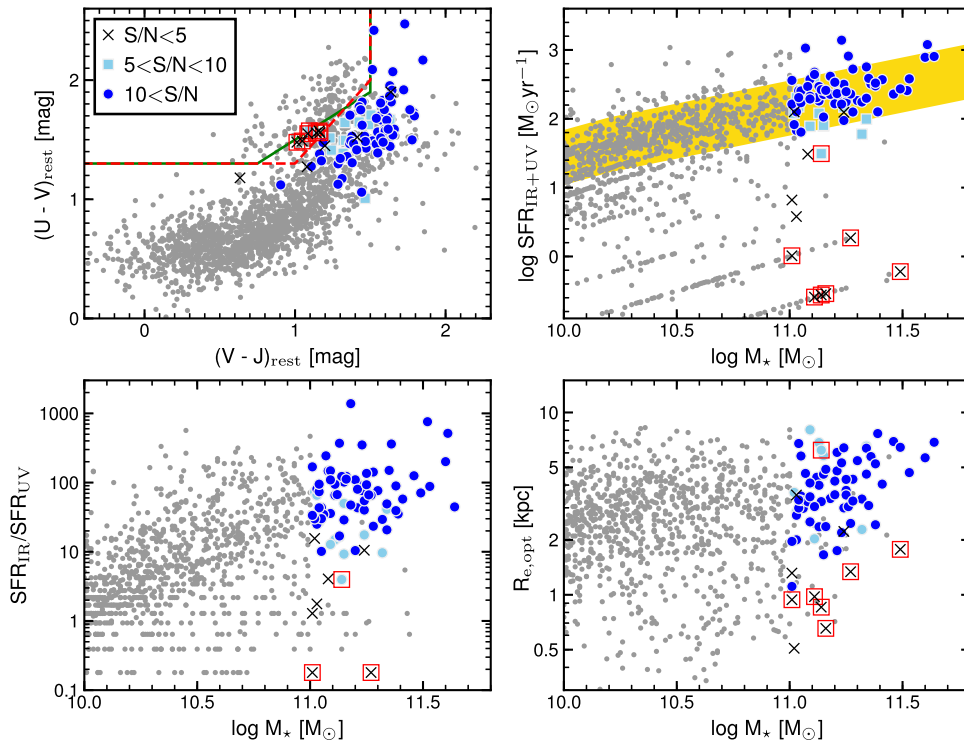
continuum emission in the rest-frame far-infrared (FIR); ( $\sim 270 \mu\text{m}$ ), corresponding to the Rayleigh–Jeans side of modified blackbody radiation with a dust temperature of 25 K. Total  $870 \mu\text{m}$  flux densities are commonly used as a tracer of galaxy-integrated gas mass rather than infrared luminosity and SFR (Scoville et al. 2016), while it is reasonable to use the spatial distribution of  $870 \mu\text{m}$  continuum emission to locate where the dusty star formation happens in galaxies. In this paper, we present Hubble Space Telescope (HST) resolution observations of  $870 \mu\text{m}$  continuum emission with the Atacama Large Millimeter/submillimeter Array (ALMA) to study the spatial distribution of star formation in massive SFGs at  $z = 2$ . In Section 2, we describe the sample selection and ALMA observations. We show the results on detection rates of the  $870 \mu\text{m}$  continuum emission and discuss the sample bias in Section 3. We measure the structural parameters of the dust emission through visibility fitting and compare the effective radius in the rest-frame FIR with the effective radius in the optical in Section 4. Based on the size measurements at both FIR and optical, we discuss structural evolution and quenching in massive galaxies at  $z = 2$  in Section 5. Finally, we give a summary in Section 6. We assume a Chabrier (2003) initial mass function (IMF) and adopt cosmological parameters of  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_M = 0.3$ , and  $\Omega_\Lambda = 0.7$ .

## 2. Sample and Observations

### 2.1. Sample Selection

We use the 3D-HST catalog including multiwavelength photometry from the ultraviolet to near-infrared and grism redshifts (Skelton et al. 2014; Momcheva et al. 2016) for 94,609 galaxies over  $362 \text{ arcmin}^2$  of the UDS and GOODS-S fields in the CANDELS survey (Grogin et al. 2011; Koekemoer et al. 2011). Our sample selection for ALMA observations is as follows.

1. We consider a clean sample of galaxies with reliable photometry including the  $K$ -band (Wuyts et al. 2008; Retzlaff et al. 2010; O. Almaini et al. 2020, in preparation) by adopting a flag of `use_phot = 1` (see Skelton et al. 2014). This flag excludes stars, objects close to a bright star, and galaxies whose photometric redshift is not derived.
2. We select galaxies in the redshift range of  $1.9 < z < 2.6$ . The spectroscopic or grism redshift is used if available, and otherwise the photometric redshift is used.
3. We focus on the most massive galaxies with  $\log(M_*/M_\odot) > 11$  in this work, as this mass range is important for understanding the transformation of galaxy morphology, especially related to bulge formation (e.g., Bell et al. 2012; Bruce et al. 2012; Lang et al. 2014). Using the FAST code (Kriek et al. 2009), we perform spectral energy distribution (SED) fitting with stellar population synthesis models of Bruzual & Charlot (2003) under a Chabrier (2003) IMF and the dust attenuation law of Calzetti et al. (2000) to estimate stellar masses. We adopt exponentially declining star formation histories with reasonable constraints on the  $e$ -folding timescales and stellar ages (see also Wuyts et al. 2011a).
4. We apply the rest-frame  $UVJ$  color–color selection to separate SFGs from QGs (e.g., Wuyts et al. 2007; Whitaker et al. 2011). In total, 86 and 26 galaxies fall in



**Figure 1.** Top left: the rest-frame  $U - V$  vs.  $V - J$  color diagram for our ALMA sample of 85 massive SFGs at  $z = 1.9$ – $2.6$ . Blue circles, light blue squares, and black crosses indicate galaxies that are detected at above  $10\sigma$ , at  $5$ – $10\sigma$ , and not detected in the intermediate-resolution  $870\ \mu\text{m}$  images, respectively. Gray dots show all galaxies in the same redshift range, taken from the 3D-HST catalog (Skelton et al. 2014; Momcheva et al. 2016). A green continuous line shows the criteria to separate between star-forming and quiescent populations, as used in van Dokkum et al. (2015), while a red dashed line indicates our modified criteria, defined by Equation (4). Red open squares show 7 galaxies, which are classified as a quiescent population by the modified  $UVJ$  criteria. Top right: stellar mass vs. SFR. Our ALMA targets are mostly located within  $\pm 0.4$  dex of the star formation main sequence at  $2 < z < 2.5$  (shaded region; a broken power-law model in Whitaker et al. 2014). Bottom left: stellar mass vs. ratio of obscured to unobscured SFR. Bottom right: stellar mass vs. effective radius along the semimajor axis in the rest-frame optical (van der Wel et al. 2014).

the star-forming and the quiescent regime, respectively (Figure 1). Then, we select only  $UVJ$ -based SFGs.

We do not apply further selection criteria based on the SFR or optical morphology to ensure we have an unbiased sample of massive SFGs. One object (U4-5155) lies between two bright galaxies and is elongated with an effective radius of  $5''$  in the HST/F160W-band image (van der Wel et al. 2014). We exclude this galaxy from the sample as it is likely to be magnified by a gravitational lens. The final sample of 85 SFGs is listed in Table 1. In all, 69 and 16 are located in the UDS ( $191\ \text{arcmin}^2$ ) and the GOODS-S field ( $171\ \text{arcmin}^2$ ), respectively. Of the sample, 19 are spectroscopically confirmed with the detection of the  $H\alpha$  emission line in the KMOS<sup>3D</sup> survey (Wisnioski et al. 2015, 2019) or the CO emission line by ALMA observations (Tadaki et al. 2017b). Thirty-two galaxies have accurate redshifts ( $\Delta z = \pm 0.02$ ) based on the HST grism spectra (Momcheva et al. 2016) or  $H\alpha$  narrowband imaging (Tadaki et al. 2013). For the remaining 34 galaxies, we use photometric redshifts. Of these, 12 and 3 targets overlap with the sample of Tadaki et al. (2017a) and Barro et al. (2016), respectively. We note that the 3D-HST catalog uses an HST/F125W+F140W+F160W combined image for detection (Skelton et al. 2014), meaning they are effectively rest-optically selected. While the detection limit is a much lower mass than  $\log(M_*/M_\odot) = 11$ , it is possible that some unknown number of massive galaxies could be optically dark and missed (e.g., Franco et al. 2018; Yamaguchi et al. 2019). Currently, only several optically dark galaxies have been spectroscopically

identified and they are all located at  $z > 3$  (Pavese et al. 2018; Wang et al. 2019; Williams et al. 2019; Umehata et al. 2020). This may be due to the fact that the Balmer break at  $z > 3$  is redshifted to a wavelength longer than the HST/F160W band, leading to a nondetection in the HST images. Therefore, optically dark galaxies at  $z \sim 2$  are likely to have a lesser impact on the completeness of our sample.

## 2.2. Star Formation Activity

We estimate total SFRs by summing the rate of unobscured star formation measured from the rest-frame  $2800\ \text{\AA}$  luminosities, corresponding to UV, and obscured star formation from the total infrared (IR) luminosities following Kennicutt (1998), after conversion to a Chabrier (2003) IMF. We cross-match the 3D-HST, Spitzer/MIPS ( $24\ \mu\text{m}$ ), and Herschel/PACS ( $100$ ,  $160\ \mu\text{m}$ ) catalogs built as described in Lutz et al. (2011) and Magnelli et al. (2013), with a maximum separation of  $1''.5$ . The IR luminosities are derived from the single-band photometry at, in order of priority,  $160\ \mu\text{m}$ ,  $100\ \mu\text{m}$ , and  $24\ \mu\text{m}$  (Wuyts et al. 2011a). Three  $160\ \mu\text{m}$  detected galaxies (U4-4706, U4-7472, and U4-36568) have a companion within  $6''$  in the ALMA  $870\ \mu\text{m}$  images (see Section 2.4). We do not use their PACS photometry with a point-spread function size of  $\text{FWHM} = 12''$ , because it can be contaminated by the emission of the nearby  $870\ \mu\text{m}$  source. Forty-four and 32 galaxies are detected without contamination in the PACS and MIPS band, respectively. For the remaining nine galaxies, we use the SFRs from SED fitting. Typical SFR uncertainties including systematic errors are  $\pm 0.2$  dex for IR-detected galaxies and

**Table 1**  
The Source List of 85 Massive SFGs

ID <sup>a</sup>	R.A. (degree)	Decl. (degree)	$z^b$	$\log M_*$ ( $M_\odot$ )	$\log \text{SFR}$ ( $M_\odot \text{yr}^{-1}$ )	$R_{\text{e,opt}}^c$ (kpc)	$q_{\text{opt}}^c$	S/N <sup>d</sup>	$S_{\text{image}}^e$ (mJy)	$\log M_{\text{gas}}$ ( $M_\odot$ )
U4-190	34.2654	-5.2776	2.06	11.23	3.14	2.2	0.92	80.2	$5.64 \pm 0.14$	11.48
U4-394	34.3965	-5.2768	2.28	11.11	2.68	4.1	0.62	20.0	$1.53 \pm 0.18$	10.92
U4-1620	34.3582	-5.2726	2.3185	11.27	0.27	1.3	0.90	2.4	<0.83	<10.65
U4-1833	34.3766	-5.2713	2.51	11.28	2.72	4.3	0.55	17.7	$1.94 \pm 0.16$	11.02
U4-2166	34.4264	-5.2710	2.11	11.07	3.03	4.6	0.54	29.1	$1.93 \pm 0.18$	11.01
U4-2394	34.5096	-5.2695	2.31	11.11	2.60	2.0	0.51	6.9	$0.61 \pm 0.19$	10.52
U4-4059	34.4374	-5.2642	2.323	11.09	2.57	2.5	0.85	24.2	$1.49 \pm 0.20$	10.91
U4-4499	34.5142	-5.2615	2.1813	11.16	-0.54	0.7	0.54	2.3	<0.74	<10.60
U4-4701	34.2733	-5.2621	2.1065	11.49	-0.22	1.8	0.62	1.9	<0.98	<10.72
U4-4706	34.2882	-5.2626	2.5217	11.24	2.17	...	...	5.2	$0.44 \pm 0.17$	10.38
U4-4915	34.3478	-5.2612	1.907	11.13	2.26	2.4	0.80	15.1	$1.68 \pm 0.25$	10.95
U4-7472	34.4654	-5.2520	2.093	11.52	2.41	...	...	34.4	$3.16 \pm 0.19$	11.23
U4-7516	34.4899	-5.2524	2.080	11.30	2.26	5.4	0.64	25.6	$2.37 \pm 0.24$	11.10
U4-9367	34.3316	-5.2453	2.009	11.25	2.25	3.7	0.42	24.9	$2.01 \pm 0.16$	11.03
U4-12441	34.5847	-5.2348	1.99	11.12	2.31	4.4	0.51	12.5	$1.22 \pm 0.18$	10.81
U4-13526	34.5248	-5.2308	2.49	11.21	2.32	1.7	0.72	13.6	$0.99 \pm 0.21$	10.73
U4-13952	34.3226	-5.2300	2.1830	11.32	2.24	3.4	0.89	30.0	$3.08 \pm 0.18$	11.22
U4-14409	34.3070	-5.2281	2.17	11.21	2.38	4.8	0.36	64.8	$4.33 \pm 0.11$	11.37
U4-14723	34.5298	-5.2277	1.92	11.41	2.57	4.0	0.63	28.5	$2.07 \pm 0.13$	11.04
U4-14996	34.2789	-5.2266	2.082	11.32	1.78	2.3	0.80	6.6	$0.68 \pm 0.13$	10.56
U4-16022	34.5520	-5.2223	2.40	11.34	2.00	6.5	0.19	6.0	$0.46 \pm 0.14$	10.39
U4-16442	34.3367	-5.2211	2.193	11.20	2.22	4.2	0.49	25.2	$1.77 \pm 0.15$	10.98
U4-16504	34.4213	-5.2208	2.530	11.25	2.38	4.3	0.51	35.0	$3.23 \pm 0.19$	11.25
U4-16795	34.4188	-5.2196	2.530	11.18	2.62	...	...	55.0	$4.29 \pm 0.20$	11.37
U4-17264	34.4058	-5.2189	2.2986	11.14	-0.56	0.9	0.95	2.9	<0.87	<10.67
U4-17519	34.3334	-5.2183	2.385	11.60	2.89	5.6	0.57	92.0	$6.92 \pm 0.17$	11.57
U4-19068	34.4233	-5.2129	2.18	11.15	2.35	4.6	0.63	22.2	$1.77 \pm 0.24$	10.98
U4-19126	34.5870	-5.2126	2.03	11.23	2.21	5.3	0.47	12.7	$0.88 \pm 0.16$	10.67
U4-20704	34.2708	-5.2079	2.1915	11.46	2.36	6.9	0.45	21.6	$3.22 \pm 0.21$	11.24
U4-21087	34.2832	-5.2060	2.3168	11.11	-0.59	1.0	0.94	1.8	<0.76	<10.61
U4-21665	34.4902	-5.2040	1.964	11.03	1.83	2.0	0.85	16.9	$0.79 \pm 0.18$	10.62
U4-21998	34.5178	-5.2023	2.11	11.05	1.81	3.5	0.32	10.2	$0.64 \pm 0.15$	10.53
U4-22227	34.4242	-5.2019	2.2896	11.27	2.36	2.5	0.94	42.7	$2.92 \pm 0.15$	11.20
U4-22729	34.4693	-5.2010	2.579	11.34	2.75	6.4	0.31	63.9	$5.03 \pm 0.18$	11.44
U4-23044	34.3857	-5.1990	2.421	11.61	3.08	...	...	76.4	$5.09 \pm 0.20$	11.44
U4-23692	34.3632	-5.1994	2.031	11.64	2.91	6.9	0.79	72.1	$6.11 \pm 0.18$	11.51
U4-26012	34.2653	-5.1895	2.3208	11.06	2.41	3.0	0.72	17.8	$1.25 \pm 0.16$	10.83
U4-26581	34.5491	-5.1877	2.22	11.24	2.50	3.0	0.79	45.1	$3.23 \pm 0.20$	11.24
U4-28087	34.3588	-5.1828	2.113	11.34	2.30	4.6	0.89	17.1	$2.72 \pm 0.15$	11.16
U4-28156	34.4685	-5.1824	1.995	11.36	2.51	5.7	0.81	71.1	$5.44 \pm 0.19$	11.46
U4-28473	34.4224	-5.1810	2.5247	11.35	2.59	3.1	0.62	54.7	$4.36 \pm 0.17$	11.38
U4-28702	34.4775	-5.1800	2.190	11.03	2.10	2.7	0.81	22.9	$1.69 \pm 0.17$	10.96
U4-29179	34.5888	-5.1789	2.006	11.39	2.10	7.7	0.37	15.9	$1.41 \pm 0.19$	10.87
U4-30882	34.2294	-5.1730	2.1057	11.01	0.01	0.9	0.66	1.1	<0.91	<10.69
U4-31189	34.4158	-5.1719	2.294	11.16	2.40	2.4	0.51	10.8	$0.94 \pm 0.19$	10.71
U4-32147	34.3996	-5.1693	2.5294	11.15	1.90	4.5	0.52	8.5	$0.84 \pm 0.16$	10.66
U4-32351	34.3061	-5.1682	2.1800	11.04	2.17	3.4	0.70	9.3	$0.84 \pm 0.18$	10.65
U4-32992	34.4727	-5.1657	2.182	11.01	2.21	2.0	0.74	13.1	$0.96 \pm 0.20$	10.71
U4-34138	34.4086	-5.1631	2.5186	11.05	2.23	5.8	0.84	18.3	$1.90 \pm 0.22$	11.01
U4-34454	34.2867	-5.1615	2.027	11.18	2.36	3.4	0.79	19.4	$1.63 \pm 0.13$	10.94
U4-34617	34.4785	-5.1606	2.530	11.04	2.42	6.8	0.55	17.6	$2.21 \pm 0.18$	11.08
U4-34817	34.2718	-5.1601	2.190	11.21	2.37	6.0	0.69	18.0	$2.02 \pm 0.19$	11.04
U4-36247	34.2817	-5.1548	2.1790	11.04	2.41	3.0	0.89	23.3	$1.80 \pm 0.19$	10.99
U4-36437	34.4852	-5.1542	2.083	11.13	2.47	4.0	0.49	27.2	$2.01 \pm 0.18$	11.03
U4-36568	34.2938	-5.1545	2.1770	11.05	2.40	3.3	0.84	10.9	$1.26 \pm 0.21$	10.83
U4-36685	34.2893	-5.1538	1.95	11.38	2.48	5.2	0.51	19.0	$1.60 \pm 0.17$	10.93
U4-37775	34.5325	-5.1503	1.92	11.49	2.43	6.4	0.36	15.5	$1.46 \pm 0.20$	10.89
U4-38040	34.4687	-5.1481	2.49	11.02	2.08	3.6	0.49	7.6	$0.43 \pm 0.17$	10.37
U4-38640	34.5595	-5.1460	2.42	11.25	2.39	3.5	0.59	21.5	$1.58 \pm 0.21$	10.93
U4-39126	34.5498	-5.1444	2.02	11.13	2.08	6.8	0.31	6.3	$0.54 \pm 0.19$	10.46
U4-39245	34.5539	-5.1438	2.12	11.14	2.42	3.2	0.55	17.3	$1.51 \pm 0.16$	10.91
U4-39537	34.4820	-5.1437	2.0234	11.24	2.09	2.2	0.82	3.7	<0.69	<10.56
U4-40115	34.4408	-5.1411	2.02	11.08	2.47	3.2	0.72	28.6	$2.18 \pm 0.14$	11.06

**Table 1**  
(Continued)

ID <sup>a</sup>	R.A. (degree)	Decl. (degree)	$z^b$	$\log M_*$ ( $M_\odot$ )	$\log \text{SFR}$ ( $M_\odot \text{yr}^{-1}$ )	$R_{e,\text{opt}}^c$ (kpc)	$q_{\text{opt}}^c$	S/N <sup>d</sup>	$S_{\text{image}}^e$ (mJy)	$\log M_{\text{gas}}$ ( $M_\odot$ )
U4-41248	34.3150	-5.1356	1.9210	11.01	0.82	1.3	0.84	2.5	<0.91	<10.68
U4-42529	34.4454	-5.1305	2.39	11.53	2.58	4.7	0.52	26.4	$2.56 \pm 0.18$	11.14
U4-42571	34.4331	-5.1309	2.41	11.38	2.52	2.4	0.82	26.9	$2.10 \pm 0.17$	11.06
U4-42812	34.2675	-5.1296	2.12	11.16	2.41	4.9	0.54	23.0	$1.73 \pm 0.24$	10.97
U4-43123	34.5208	-5.1289	2.03	11.04	2.31	3.3	0.55	12.1	$1.17 \pm 0.14$	10.80
U4-43667	34.2584	-5.1266	2.04	11.15	1.90	5.8	0.68	6.4	$0.92 \pm 0.15$	10.69
GS4-1397	53.1040	-27.9226	2.5552	11.03	0.58	3.5	0.48	3.5	<0.84	<10.66
GS4-1725	53.2049	-27.9179	2.206	11.03	2.31	2.8	0.66	9.0	$0.78 \pm 0.28$	10.62
GS4-2467	53.2112	-27.9072	2.0404	11.08	1.48	...	...	1.1	<0.86	<10.66
GS4-4583	53.1635	-27.8905	2.281	11.11	2.64	3.0	0.58	32.3	$2.23 \pm 0.16$	11.08
GS4-5217	53.1131	-27.8866	2.426	11.02	1.92	...	...	17.7	$1.79 \pm 0.18$	10.99
GS4-11016	53.0773	-27.8596	2.0369	11.24	1.98	6.4	0.58	30.0	$2.19 \pm 0.22$	11.07
GS4-14747	53.0717	-27.8436	1.9560	11.09	2.33	4.1	0.81	42.5	$2.60 \pm 0.17$	11.14
GS4-19348	53.1488	-27.8211	2.5820	11.26	2.91	3.0	0.72	68.7	$4.04 \pm 0.17$	11.34
GS4-22825	53.0940	-27.8041	2.367	11.15	2.03	1.7	0.91	22.1	$1.64 \pm 0.18$	10.95
GS4-30274	53.1311	-27.7731	2.2250	11.20	2.53	3.5	0.44	27.0	$1.78 \pm 0.16$	10.98
GS4-40185	53.0136	-27.7201	2.076	11.14	1.49	6.2	0.74	5.5	$0.46 \pm 0.15$	10.39
GS4-41021	53.1874	-27.7192	2.3135	11.02	2.10	0.5	0.55	-0.1	<0.73	<10.60
GS4-41181	53.1070	-27.7182	2.3001	11.28	2.10	3.3	0.63	27.7	$1.77 \pm 0.16$	10.98
GS4-44065	53.0026	-27.7044	2.59	11.09	2.29	3.4	0.75	12.4	$0.73 \pm 0.15$	10.60
GS4-45068	53.1376	-27.7001	2.4480	11.01	2.56	1.1	0.94	28.7	$1.62 \pm 0.16$	10.94
GS4-45475	53.1737	-27.6981	2.03	11.09	1.89	8.0	0.58	6.4	$0.85 \pm 0.17$	10.65

**Notes.**

<sup>a</sup> Unique identifier in the 3D-HST v4 catalog (Skelton et al. 2014; Momcheva et al. 2016). U4 and GS4 mean objects in the UDS and the GOODS-S field, respectively.

<sup>b</sup> Numbers with 3, 4, and 5 digits mean photometric, grism or narrowband, and spectroscopic redshift, respectively (Section 2.1).

<sup>c</sup> Effective radius along the semimajor axis and the minor-to-major axis ratio from the best-fitting Sérsic profile in the HST/F160W (van der Wel et al. 2012, 2014; Lang et al. 2014).

<sup>d</sup> Signal-to-noise ratio in the ALMA intermediate-resolution images.

<sup>e</sup> 870  $\mu\text{m}$  flux densities measured in the ALMA low-resolution images.

$\pm 0.25$  dex for the others (Wuyts et al. 2011a). In our ALMA sample, the ratio of obscured to unobscured SFR is, on average,  $\text{SFR}_{\text{IR}}/\text{SFR}_{\text{UV}} = 50$ , indicating that the dust emission is a dominant probe of the star formation. Note that our sample is not biased toward a dusty population in the stellar mass range of  $\log(M_*/M_\odot) > 11$ , as shown in Figure 1.

As shown in Figure 1, most of our ALMA targets lie on/around the main sequence of star formation at  $z \sim 2$  (Whitaker et al. 2014). The *UVJ* selection is useful for extracting SFGs without spectroscopic data while it would miss some objects with low-level star formation (e.g., Belli et al. 2017). Five of 26 *UVJ*-selected QGs are detected in the PACS or MIPS band. It is not straightforward to estimate SFRs of QGs from the IR emission because the IR-based SFRs may be overestimated by contributions from evolved stellar populations (Utomo et al. 2014; Leja et al. 2019) or time-averaging effects for recently quenched galaxies (Hayward et al. 2014). The five QGs with an IR detection are located near the bottom of the main sequence even if all the IR emission originates from massive young stars. They are not included in our sample, but they are going to have a minimal impact on our statistical analysis of a representative star-forming population.

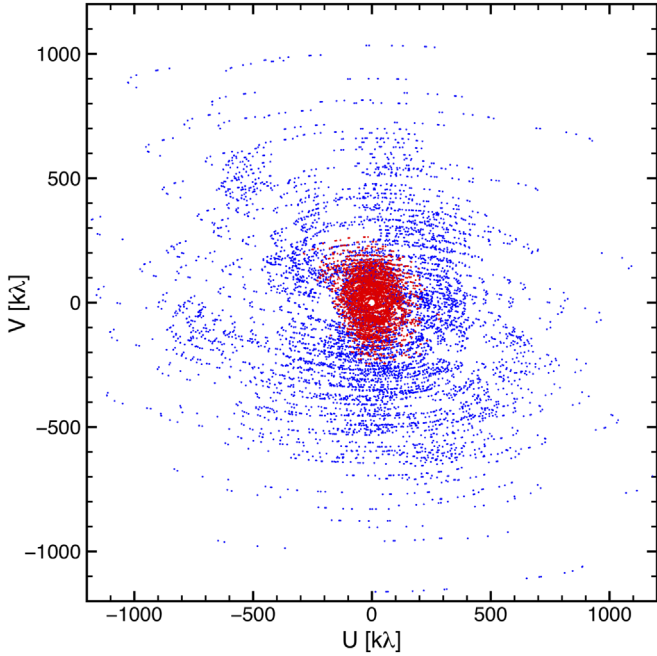
### 2.3. Optical Structure

Deep *HST*/WFC3 imaging data is available for our sample in the CANDELS/3D-HST fields. Fitting of elliptical Sérsic models to the two-dimensional light profiles in the F160W-band image gives the structural parameters of the rest-frame

optical emission:  $R_{e,\text{opt}}$ ,  $n_{\text{opt}}$ , minor-to-major axis ratio  $q_{\text{opt}}$ , and position angle  $PA_{\text{opt}}$  (van der Wel et al. 2012, 2014; Lang et al. 2014). We adopt the effective radius along the semimajor axis to avoid inclination and projection effects, except for Section 5 where the circularized effective radius is used. We do not use six objects (U4-4706, U4-7472, U4-16795, U4-23044, GS4-2467, and GS4-5217) for optical size arguments because the best-fit Sérsic index reaches the constrained limit ( $n = 0.2$  or  $n = 8.0$ ) or the effective radius is unreasonably large with  $R_{e,\text{opt}} > 1''$  ( $\sim 10$  kpc).

### 2.4. ALMA Observations

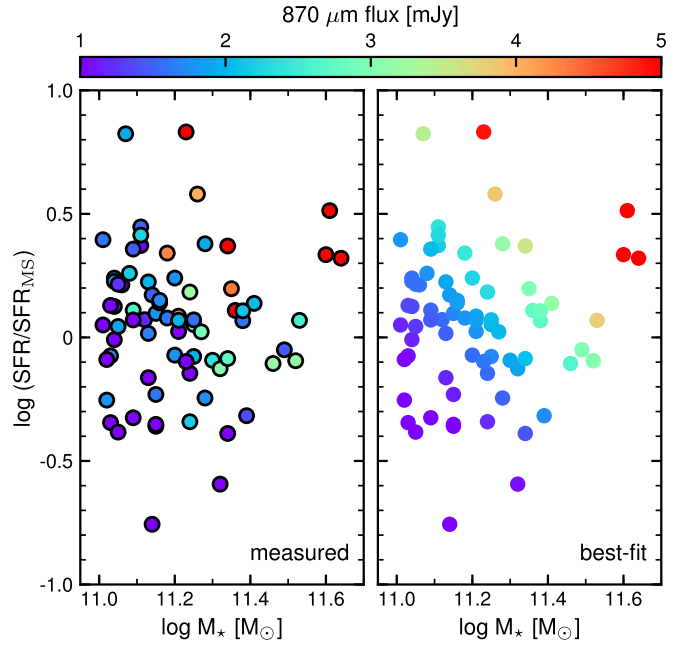
We have carried out ALMA observations of dust continuum emission in the mass-selected sample of SFGs at  $z = 2$ . We use the band 7 receivers with the 64-input correlator in Time Division Mode in a central frequency of 345 GHz ( $\sim 870$   $\mu\text{m}$ ). The frequency range available does not cover intermediate- $J$  ( $J_{\text{up}} < 7$ ) CO lines or atomic carbon lines at  $z = 2$ . We sample a wide range of spatial frequency in the  $uv$  plane by using two array configurations: compact array with baseline lengths of 15–300 m and extended array with 15–1260 m (Figure 2). The extended array data determine the spatial resolution of interferometric images produced through Fourier transforms, while the compact array data are crucial for measuring total fluxes, corresponding to visibility amplitudes in a zero baseline. If short baseline data were not sufficiently sensitive, the size measurements of 870  $\mu\text{m}$  emission would be strongly biased by compact components in galaxies. The maximum recoverable scale of our



**Figure 2.** An example of the  $uv$  coverage in our ALMA observations (U4-190). The extended array data (blue) and the compact one (red) covers the  $uv$  range from 14 to 1398  $k\lambda$  and from 15  $k\lambda$  to 349  $k\lambda$ , respectively.

ALMA observations is  $6''.7$ , corresponding to  $\sim 55$  kpc at  $z = 2$ . We performed new observations of 84 galaxies with the compact array in 2018 May–June and of 66 galaxies with the extended array in 2018 September. The typical on-source time with 43–48 antennas is 4–5 min with the compact array and 7–9 min with the extended array. For the other galaxies in our sample, we use ALMA archival data (2012.1.00245.S, 2012.1.00983.S, 2013.1.00205.S, 2013.1.00566.S, 2013.1.00884.S, 2015.1.00242.S, 2016.1.01079.S) to avoid duplicate observations. We utilize the Common Astronomy Software Application package (CASA; McMullin et al. 2007) for the data calibration.

We create high-, intermediate-, and low-resolution images by changing the weights of visibilities. We clean images down to the  $1.5\sigma$  level in a circular mask with a diameter of  $2''$  ( $4''$  only for low-resolution images) using the `CASA/tclean` task. First, we create high-resolution images by using the compact array data with a  $uv$  distance of  $> 180$   $k\lambda$  and all the extended array data and adopting a Briggs weighting with a `robust` parameter of  $+0.5$ . The spatial resolution and the noise level is  $0''.2\text{--}0''.3$  ( $\sim 2$  kpc) and  $60 \pm 7$   $\mu\text{Jy}$ , respectively. The high-resolution images are used only for visually inspecting the location and the morphology of the dust emission. Next, we create intermediate-resolution images by using all the compact array data and the extended array data with a  $uv$  distance of  $< 180$   $k\lambda$  and adopting `robust` =  $+2.0$ . The spatial resolution and the noise level is  $0''.8\text{--}1''.0$  ( $\sim 7$  kpc) and  $61 \pm 6$   $\mu\text{Jy}$ , respectively. The intermediate-resolution images are useful for defining the signal-to-noise ratios (S/N) of  $870$   $\mu\text{m}$  continuum emission, while they are not sufficient for measuring the total fluxes from the whole galaxies. We therefore create low-resolution images from all the combined data with `uvta-per` =  $4''$  and `robust` =  $2.0$ , resulting in the noise level of  $174 \pm 29$   $\mu\text{Jy}$ . The spatial resolution is  $3''.3\text{--}3''.5$  ( $\sim 28$  kpc), which should cover whole galaxies at  $z = 2$ . Note that we do



**Figure 3.** Flux densities at  $870$   $\mu\text{m}$  for our ALMA sample of 74 galaxies at  $S/N > 5$ , as a function of stellar mass and offset in SFR from the main sequence. Left: the peak flux densities measured in the low-resolution images. Right: the flux densities inferred from the stellar mass and SFR offset using Equation (2).

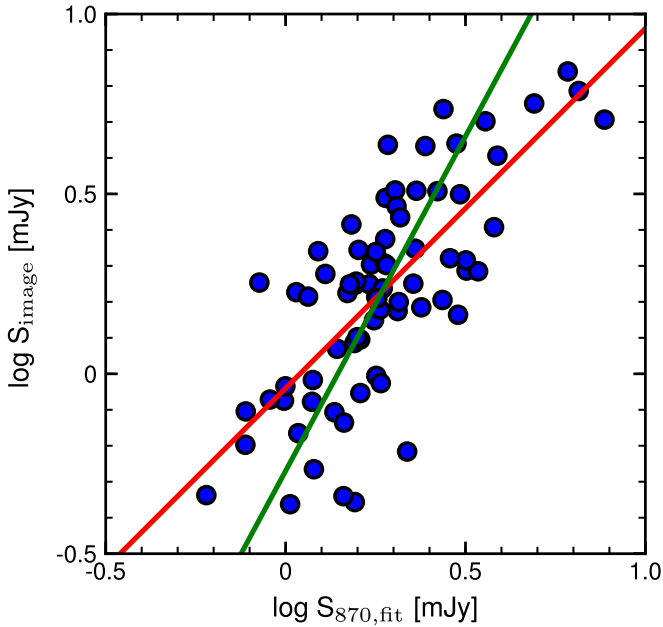
not primarily use these ALMA images for measuring the effective radius of  $870$   $\mu\text{m}$  emission (Section 4.1).

### 3. Results

#### 3.1. Detections of $870$ $\mu\text{m}$ Continuum Emission

We detect the  $870$   $\mu\text{m}$  continuum emission from 74 of 85 galaxies at  $S/N > 5$ , 62 of which have  $S/N > 10$ , in the intermediate-resolution images. For 74 detected objects, we measure the total  $870$   $\mu\text{m}$  flux density from the low-resolution images. As U4-7472 and U4-36568 have a companion  $870$   $\mu\text{m}$  source within a radius of  $1''.5$ , we create low-resolution images after subtracting the companion in the visibility plane to measure the flux densities (Section 4.1). The median flux density is  $S_{\text{image}} = 1.8$  mJy in the range from 0.4 to 6.9 mJy. Dust continuum emission on the Rayleigh–Jeans regime is commonly used as a tracer of gas mass (e.g., Genzel et al. 2015; Scoville et al. 2016; Tacconi et al. 2018). We estimate gas mass in massive SFGs from the  $870$   $\mu\text{m}$  flux density by using the calibration of Scoville et al. (2016). There is a clear trend of increasing flux density in the plane of stellar mass and offset of a galaxy from the star formation main sequence,  $\text{SFR}/\text{SFR}_{\text{MS}}$ , defined by a broken power-law model in Whitaker et al. (2014). More massive, more active SFGs are brighter at  $870$   $\mu\text{m}$  (Figure 3). From a linear fitting in this parameter space, we derive equations to predict an  $870$   $\mu\text{m}$  flux density and a gas mass of SFGs as,

$$\begin{aligned} \log S_{870,\text{fit}} [\text{mJy}] = & (0.95 \pm 0.15) \log M_* \\ & + (0.52 \pm 0.08) \log \left( \frac{\text{SFR}}{\text{SFR}_{\text{MS}}} \right) \\ & - (10.41 \pm 1.7), \end{aligned} \quad (2)$$



**Figure 4.** A comparison between the predicted and the measured flux densities for our ALMA sample of 74 galaxies at  $S/N > 5$ . A red line is the best-fit line ( $S_{\text{image}} = 1.00S_{870,\text{fit}} - 0.04$ ) from a least-squares linear fit when the variable is  $S_{870,\text{fit}}$ . A green line is the best-fit line ( $S_{\text{image}} = 1.86S_{870,\text{fit}} - 0.27$ ) from a least-squares linear fit when the variable is  $S_{\text{image}}$ .

and

$$\begin{aligned} \log M_{\text{gas,fit}} [M_{\odot}] = & (0.95 \pm 0.15) \log M_{\star} \\ & + (0.53 \pm 0.08) \log \left( \frac{\text{SFR}}{\text{SFR}_{\text{MS}}} \right) \\ & + (0.33 \pm 1.7). \end{aligned} \quad (3)$$

The dependence on SFR offset is identical to the general scaling relation covering the wide range of galaxy properties (Tacconi et al. 2018), while the mass dependence is slightly stronger than in the scaling relation (exponent 0.67; Tacconi et al. 2018). The median and the standard deviation of the difference between the actual measurements and the best-fit values is  $\log(S_{\text{image}}/S_{870,\text{fit}}) = -0.03 \pm 0.20$  dex. However, there is a systematic error in the predictions by Equation (2): the flux densities are overestimated at  $S_{\text{image}} < 1$  mJy and underestimated at  $S_{\text{image}} > 3$  mJy (Figure 4). It is possible to correct for the systematics by applying  $S_{870,\text{fit,cor}} = 1.86 S_{870,\text{fit}} - 0.27$ , but the standard deviation of  $\log(S_{\text{image}}/S_{870,\text{fit,cor}})$  increases to 0.27 dex. We also note that this prediction is valid only in the stellar mass range of  $\log(M_{\star}/M_{\odot}) > 11$  and in the redshift range of  $z = 1.9$ – $2.6$ .

In addition to the primary targets of massive SFGs at  $z \sim 2$ , we serendipitously detect 19 dust continuum sources at  $S/N > 5.0$  in the regions within  $13''.6$  of the phase center, where the primary beam correction factor is less than 0.15 (Table 2). The median redshift is  $z = 2.7$  and the  $870 \mu\text{m}$  flux density ranges from 0.4 mJy to 6.8 mJy after the primary beam correction. One source (U4-36568b) does not have an optical counterpart and is likely to be a massive SFG at  $z > 3$  (e.g., Wang et al. 2019). Four of the 19 have a similar redshift to the primary targets with  $|\Delta z| < 0.1$ , suggesting that they are physically associated. In fact, one (GS4-44920 and GS4-45068) of the four pairs has been spectroscopically identified at  $z = 2.448$ – $2.450$  (Kurk et al. 2013), with a projected separation of  $4''$  ( $\sim 32$  kpc).

### 3.2. Nondetected Objects

For 11 nondetected objects, we give the  $5\sigma$  upper limit of the  $870 \mu\text{m}$  flux density from the low-resolution images. Six of them are very close to the boundary of the quiescent regime in the *UVJ* diagram (van Dokkum et al. 2015) and have the lowest SFRs in our sample. Given that they lie about 2 dex below the main sequence at  $z \sim 2$  in the  $M_{\star}$ –SFR diagram (Figure 1), they are no longer representative of the star-forming population. Therefore, we use the modified *UVJ* criteria to define a clean sample of massive SFGs at  $z \sim 2$  as,

$$\begin{aligned} V - J &< 1.5, \\ U - V &> 1.3, \\ U - V &> 1.4(V - J) - 0.1. \end{aligned} \quad (4)$$

The detection rate in the updated SFG sample increases from 87% to 94%, indicating it represents an almost mass-complete sample of SFGs down to  $\log(M_{\star}/M_{\odot}) = 11$ .

For one galaxy (GS4-40185) classified as a QG in the modified criterion, we detect the  $870 \mu\text{m}$  continuum emission at  $S/N = 5.5$ . This galaxy is located below the main sequence with  $\log(\text{SFR}/\text{SFR}_{\text{MS}}) = -0.76$ . The gas mass fraction is  $M_{\text{gas}}/(M_{\star} + M_{\text{gas}}) = 15\%$ . This is more than two times smaller than the median value (37%) in 78 SFGs including five nondetected sources and is comparable to the gas fraction of a post-starburst galaxy at  $z = 0.7$  (Suess et al. 2017). The less active star formation and the small gas fraction suggest that star formation is being quenched. Given that six other galaxies with similar quiescent *UVJ* colors are not detected at  $870 \mu\text{m}$ , GS4-40185 is a good candidate for studying the quenching mechanism that probably works on a short timescale.

## 4. Size Measurements of $870 \mu\text{m}$ Continuum Emission

### 4.1. Visibility Fitting

Size measurements of dust emission usually require high  $S/N$  data. In the analysis of images, the appearance and  $S/N$  depend largely on both the spatial resolution and the spatial extent of the dust emission. The spatial resolution is also coupled to the noise level since interferometers sample the Fourier transform of the intensity distribution within a finite  $uv$  coverage. Figure 5 shows ALMA images of two galaxies with  $S_{870} \sim 3$  mJy, in which one is compact at  $870 \mu\text{m}$  and the other is extended. As the compact object is detected at  $S/N = 29.7$  in the high-resolution image, it is possible to accurately measure the size by fitting Sérsic models to the image (Simpson et al. 2015a; Hodge et al. 2016; Gullberg et al. 2019). In contrast, the extended object is completely missed in the high-resolution image. One easy solution to measure the size is to use the intermediate-resolution image where the emission is detected at  $S/N = 17.1$ , but inhomogeneous measurements lead to systematic uncertainties. The nondetection in the high-resolution image roughly means that the dust emission is extended and allows us to constrain the spatial extent. To fully utilize the information from observations, we measure the size of the  $870 \mu\text{m}$  continuum emission by looking at how the visibility amplitudes change as a function of spatial frequency (Ikarashi et al. 2015; Simpson et al. 2015a; Tadaki et al. 2015). The visibility fitting in the  $uv$  plane provides homogeneous size measurements, regardless of the compact or extended nature of the sources analyzed (right panels of Figure 5).

To derive the structural parameters of the dust emission for 74 massive SFGs with  $S/N > 5$  in our ALMA sample, we fit

**Table 2**  
The Galaxy Properties of 19 Serendipitously Detected Sources

ID	R.A. (degree)	Decl. (degree)	$z^a$	$\log M_*$ ( $M_\odot$ )	$\log \text{SFR}$ ( $M_\odot \text{yr}^{-1}$ )	S/N	$S_{\text{image}}$ (mJy)	Primary source ID <sup>b</sup>	Separation <sup>c</sup> (arcsec)	$ \Delta z ^d$
U4-570	34.3951	-5.2759	2.27	10.87	2.30	12.6	$1.04 \pm 0.24$	U4-394	6.1	0.01
U4-4018	34.3493	-5.2634	2.98	11.37	2.94	8.9	$1.75 \pm 0.61$	U4-4915	9.6	1.07
U4-4303	34.2879	-5.2636	2.454	10.80	1.77	27.2	$2.12 \pm 0.20$	U4-4706	3.8	0.07
U4-4534	34.4388	-5.2636	0.780	10.59	1.66	5.8	$0.86 \pm 0.27$	U4-4059	5.5	1.54
U4-7419	34.4650	-5.2519	2.97	11.24	0.80	29.6	$2.36 \pm 0.19$	U4-7472	1.3	0.88
U4-9997	34.3293	-5.2424	2.77	10.14	2.11	7.3	$4.15 \pm 0.93$	U4-9367	13.3	0.76
U4-14449	34.2775	-5.2281	1.87	10.80	2.24	12.4	$1.58 \pm 0.21$	U4-14996	7.3	0.21
U4-17813	34.5878	-5.2161	4.67	11.69	2.04	8.4	$1.85 \pm 0.87$	U4-19126	13.1	2.64
U4-35673	34.2722	-5.1571	2.190	10.96	2.79	10.0	$3.21 \pm 0.58$	U4-34817	10.7	0.00
U4-36568 <sup>e</sup>	34.2935	-5.1548	...	...	...	18.7	$1.51 \pm 0.21$	U4-36568	1.5	...
U4-39404	34.5505	-5.1433	1.63	10.47	1.63	5.5	$0.46 \pm 0.22$	U4-39126	4.6	0.40
GS4-10771	53.0785	-27.8599	3.6600	11.20	2.80	8.7	$0.70 \pm 0.25$	GS4-11016	3.8	1.62
GS4-11466	53.0779	-27.8582	0.6465	10.62	1.37	6.4	$0.72 \pm 0.29$	GS4-11016	5.4	1.39
GS4-14173	53.0702	-27.8455	3.70	10.34	1.98	18.7	$2.12 \pm 0.31$	GS4-14747	8.3	1.74
GS4-23075	53.0923	-27.8032	2.72	11.02	2.47	25.9	$2.87 \pm 0.27$	GS4-22825	6.6	0.35
GS4-23372	53.0928	-27.8012	2.93	10.65	2.14	18.6	$3.86 \pm 0.58$	GS4-22825	11.2	0.56
GS4-41332	53.1100	-27.7168	3.10	10.20	2.27	10.8	$1.66 \pm 0.50$	GS4-41181	10.8	0.80
GS4-44920	53.1388	-27.7005	2.4495	10.49	1.83	5.4	$0.39 \pm 0.18$	GS4-45068	4.0	0.00
GS4-46181	53.1753	-27.6948	4.79	11.92	3.64	15.1	$6.78 \pm 0.92$	GS4-45475	13.0	2.77

#### Notes.

<sup>a</sup> Redshifts with five digits are based on spectroscopic observations (Szokoly et al. 2004; Popesso et al. 2009; Kurk et al. 2013).

<sup>b</sup> 3D-HST ID of the primary target in ALMA observations.

<sup>c</sup> Projected separation between the serendipitously detected source and the primary target.

<sup>d</sup> Redshift difference between the serendipitously detected source and the primary target.

<sup>e</sup> U4-36568b is not detected in the HST image and is visible only in the ALMA 870  $\mu\text{m}$  image.

elliptical or circular Gaussian models to the observed data by using the UVMULTIFIT (Martí-Vidal et al. 2014). The details of the fitting process are described in Appendix A and the measured structural parameters are listed in Table 3. Only GS4-40185 (S/N = 5.5) shows an extremely small size of FWHM  $< 0''.01$ , but this is probably due to the insufficient sensitivity as mentioned above. We use only 62 massive SFGs with S/N  $> 10$  for discussion of the size measurements at 870  $\mu\text{m}$ .

In the GOODS-S field, we also find that there is a systematic offset of  $\Delta\text{R.A.} = 0''.10$  and  $\Delta\text{decl.} = -0''.24$  in the central positions between HST and ALMA, which is reported in previous studies (Rujopakarn et al. 2016; Franco et al. 2018). In the UDS field, the systematic offset is small,  $\Delta\text{R.A.} = 0''.08$  and  $\Delta\text{decl.} = -0''.06$ . We correct for these offsets when the ALMA images are visually compared to the HST images (Figure A1).

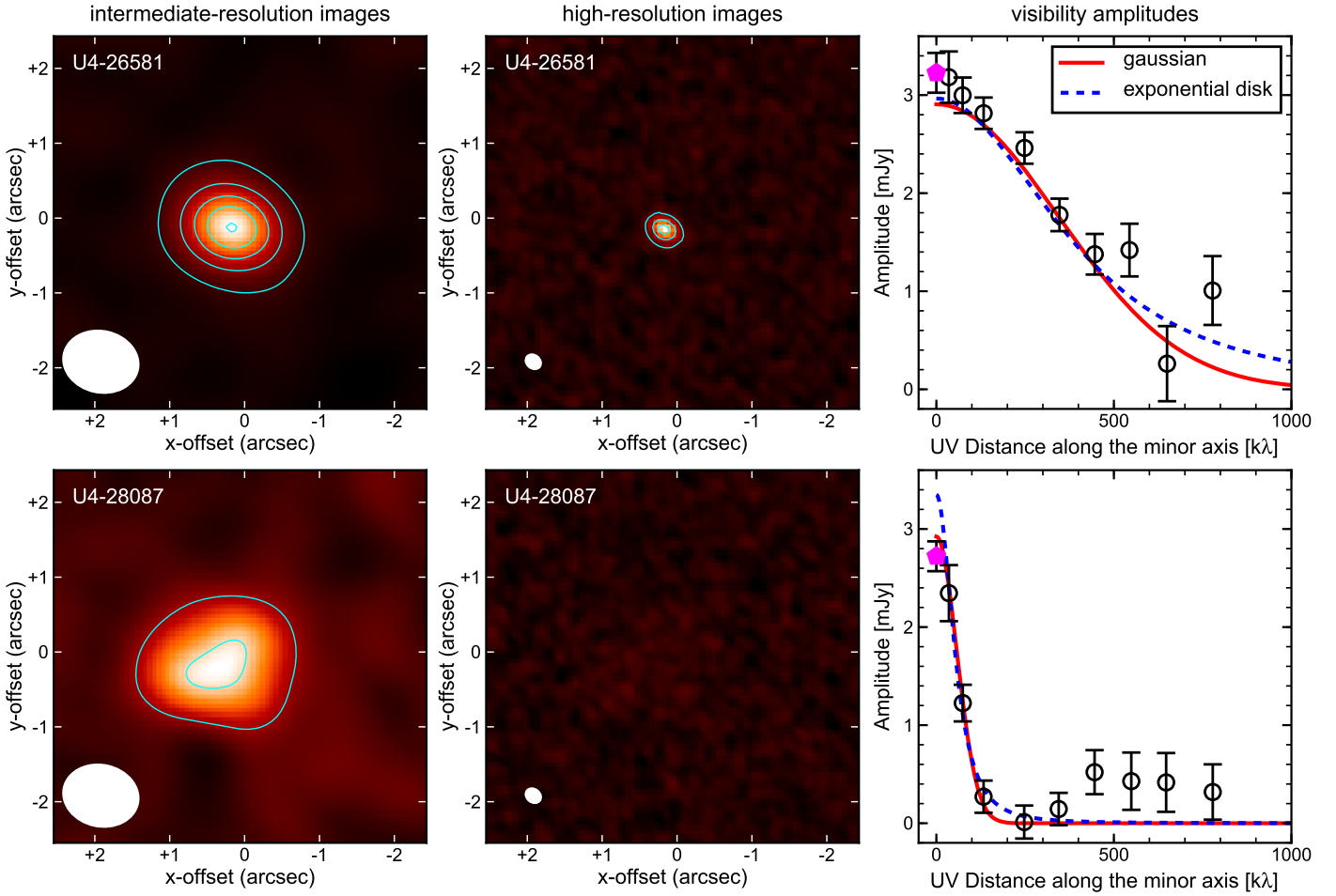
Although most of the visibility data is well fitted by a Gaussian model, several objects show  $> 1\sigma$  excesses over the model amplitude at small  $u'v'$  and/or large  $u'v'$  distances. The excess at both small and large  $u'v'$  suggests a cuspy profile with an extended tail, corresponding to a higher Sérsic index ( $n > 0.5$ ). Surface density profiles of stars and gas in SFGs are often characterized by an exponential function with  $n = 1$  (Wuyts et al. 2011b; Hodge et al. 2016). We fit the visibility data to exponential disk models by fixing the axis ratio and the position angle to the values derived from Gaussian fitting. When adopting an exponential disk model, the measured fluxes and effective radii become on average larger by 5% and 3%, respectively.

#### 4.2. Contributions of Additional Extended Components

The visibility amplitudes at the zero baseline inferred from the best-fit models give a total flux density of galaxies. We compare the visibility-based flux densities for the Gaussian and exponential disk models with the peak flux densities measured in the low-resolution images (Figure 6). For S/N  $> 10$  sources, the ratios of the difference between visibility-based and image-based flux densities are on average  $S_{\text{visibility}}/S_{\text{image}} = 0.93$  in the Gaussian and  $S_{\text{visibility}}/S_{\text{image}} = 0.98$  in the disk model, indicating that the dust emission is better characterized by an exponential profile (Hodge et al. 2016; Gullberg et al. 2019). We therefore use the effective radius from the disk model in the subsequent sections. In the disk model, compact objects with  $R_{\text{e,FIR}} < 0''.125$  show more deficiency of the visibility-based flux densities with  $S_{\text{visibility}}/S_{\text{image}} = 0.88$ . Especially for two compact objects (U4-34138 and U4-34617), the best-fit visibility model includes only 50%–70% of the total flux densities measured in the low-resolution images. They may have additional components such as an extended halo, off-center clumps, or an active galactic nucleus or be building cuspy bulges.

For extended objects with  $R_{\text{e,FIR}} > 0''.125$ , the visibility-based flux densities are in good agreement with the image-based one, with  $S_{\text{visibility}}/S_{\text{image}} = 1.01$ . To evaluate the contributions of additional components, we perform a stacking analysis of the model-subtracted visibilities for subsamples of 13 compact objects (excluding U4-34138 and U4-34617) and 47 extended objects using the STACKER tool (Lindroos et al. 2015). The phase center is individually shifted to the center position of the best-fit model before the stacking. We then





**Figure 5.** ALMA intermediate- and high-resolution images of the  $870\ \mu\text{m}$  continuum emission from U4-26581 (top) and U4-28087 (bottom). The contours are plotted every  $5\sigma$  in all images. Right panels show the visibility amplitudes as a function of  $uv$  distance along the minor axis, corresponding to the major axis in the images. Magenta pentagons show the peak flux density measured in the low-resolution images. Red solid lines and blue dashed lines indicate the best-fitting model for a Gaussian and an exponential profile, respectively. The fit was done to individual visibilities, not to the averaged ones shown by black circles in this figure.

create low-resolution images from the stacked visibility with  $uvtaper = 4''$  and  $robust = 2.0$ , resulting in  $3''.4$  resolution. The tapered images can in principle recover extended emission even with  $R_{e,\text{FIR}} = 0''.5$  (Gullberg et al. 2019). To demonstrate it, we make simulations that add a Gaussian component with a different flux density to the stacked visibilities and measure the peak flux density in the tapered images. The source size is assumed to be  $R_{e,\text{FIR}} = 0''.5$ . Then, we find that one can recover almost 100% of the extended emission in the tapered images.

For our ALMA sample, the residual emission we have detected in the tapered images has  $220 \pm 57\ \mu\text{Jy}$  ( $3.8\sigma$ ) for compact objects and  $80 \pm 26\ \mu\text{Jy}$  ( $3.1\sigma$ ) for extended objects. The mean contribution to the total flux density is 11% (the minimum and maximum values are 4%–21%) for compact objects and 4% (1%–10%) for extended objects. We also numerically calculate the effective radius taking into account the extended component by assuming two component models, which consist of the best-fit disk model and an extended Gaussian with the stacked flux densities. Then, we find that the extended component would change the effective radius by 13% (4%–29%) for compact objects and by 4% (1%–11%) for extended objects. Therefore, the residual emission including an extended component has a smaller impact on the measurements of the effective radius, except for U4-34138 and U4-34617.

### 4.3. Comparison with Submillimeter Bright Galaxies

We compare the  $870\ \mu\text{m}$  properties of massive SFGs at  $z = 2$  with those of submillimeter bright galaxies (SMGs) at  $z = 1$ –4 (Gullberg et al. 2019). The SMG sample is originally detected as 716 single-dish  $850\ \mu\text{m}$  sources with flux densities of  $S_{850} > 3.4\ \text{mJy}$  by the James Clerk Maxwell telescope survey (Geach et al. 2017) and is identified as 706 galaxies by ALMA follow-up observations (AS2UDS; Stach et al. 2019). Of the 706 SMGs, 153 have robust size measurements from ALMA  $0''.18$ -resolution observations (Gullberg et al. 2019). Our mass-selected sample of SFGs has a median flux density of  $1.8\ \text{mJy}$ , which is three times fainter than the flux-limited sample of SMGs. As shown in Figure 7, massive SFGs are distributed over a wide range of the FIR size from  $R_{e,\text{FIR}} = 0''.05$  to  $R_{e,\text{FIR}} = 0''.8$ , while SMGs are mostly compact with  $R_{e,\text{FIR}} < 0''.2$ . An additional 354 objects in the SMG sample are detected in the same ALMA observations, but their size was not measured due to the low S/N of less than 8. The subsample of 153 SMGs is potentially biased to a compact population because the low S/N can be partly caused by extended dust emission as well as faint emission.

However, the observational bias alone is unlikely to be responsible for the size difference between the two samples. Even in our ALMA sample, we find that none of 10 bright sources with  $S_{870} > 3.4\ \text{mJy}$  are extended with  $R_{e,\text{FIR}} > 0''.3$ ,

**Table 3**  
The 870  $\mu\text{m}$  Properties for 74 Massive SFGs

ID	$S_{\text{visibility}} (n = 0.5)$ (mJy)	$R_{\text{e,FIR}} (n = 0.5)$ (kpc)	$q_{\text{FIR}} (n = 0.5)$	$PA_{\text{FIR}} (n = 0.5)$	$S_{\text{visibility}} (n = 1)$ (mJy)	$R_{\text{e,FIR}} (n = 1)$ (kpc)
U4-190	$5.05 \pm 0.09$	$0.9 \pm 0.1$	$0.71 \pm 0.07$	$79 \pm 7$	$5.18 \pm 0.10$	$0.8 \pm 0.0$
U4-394	$1.27 \pm 0.10$	$1.1 \pm 0.2$	$0.78 \pm 0.29$	$152 \pm 42$	$1.35 \pm 0.11$	$1.2 \pm 0.2$
U4-1833	$1.77 \pm 0.16$	$3.8 \pm 0.5$	$0.34 \pm 0.10$	$163 \pm 6$	$1.89 \pm 0.20$	$4.0 \pm 0.6$
U4-2166	$1.81 \pm 0.10$	$1.1 \pm 0.2$	$0.73 \pm 0.20$	$152 \pm 22$	$1.88 \pm 0.11$	$1.1 \pm 0.1$
U4-2394	$0.68 \pm 0.18$	$3.0 \pm 0.9$	...	...	$0.69 \pm 0.22$	$2.9 \pm 1.2$
U4-4059	$1.62 \pm 0.08$	$0.6 \pm 0.1$	$0.67 \pm 0.29$	$145 \pm 27$	$1.65 \pm 0.09$	$0.6 \pm 0.1$
U4-4706	$0.42 \pm 0.15$	$2.3 \pm 1.1$	...	...	$0.27 \pm 0.08$	$0.3 \pm 0.5$
U4-4915	$1.58 \pm 0.19$	$3.3 \pm 0.5$	$0.92 \pm 0.25$	$171 \pm 88$	$1.75 \pm 0.24$	$3.6 \pm 0.6$
U4-7472	$2.50 \pm 0.12$	$2.1 \pm 0.2$	$0.60 \pm 0.11$	$85 \pm 9$	$2.74 \pm 0.15$	$2.3 \pm 0.2$
U4-7516	$2.46 \pm 0.17$	$3.4 \pm 0.3$	$0.60 \pm 0.11$	$6 \pm 9$	$2.69 \pm 0.22$	$3.7 \pm 0.4$
U4-9367	$1.81 \pm 0.12$	$1.9 \pm 0.3$	$0.60 \pm 0.15$	$121 \pm 14$	$1.91 \pm 0.14$	$1.9 \pm 0.3$
U4-12441	$1.19 \pm 0.18$	$4.3 \pm 0.9$	$0.42 \pm 0.16$	$97 \pm 10$	$1.29 \pm 0.22$	$4.6 \pm 1.0$
U4-13526	$0.81 \pm 0.08$	$0.4 \pm 0.2$	$0.68 \pm 0.85$	$98 \pm 80$	$0.81 \pm 0.08$	$0.4 \pm 0.2$
U4-13952	$2.91 \pm 0.17$	$2.7 \pm 0.3$	$0.64 \pm 0.11$	$136 \pm 10$	$3.16 \pm 0.22$	$2.9 \pm 0.3$
U4-14409	$4.02 \pm 0.09$	$1.1 \pm 0.1$	$0.40 \pm 0.06$	$68 \pm 3$	$4.12 \pm 0.10$	$1.1 \pm 0.1$
U4-14723	$2.14 \pm 0.14$	$2.9 \pm 0.3$	$0.48 \pm 0.10$	$55 \pm 7$	$2.26 \pm 0.17$	$2.9 \pm 0.3$
U4-14996	$0.42 \pm 0.09$	$0.7 \pm 0.3$	...	...	$0.44 \pm 0.10$	$0.7 \pm 0.4$
U4-16022	$0.32 \pm 0.08$	$0.3 \pm 0.4$	...	...	$0.32 \pm 0.08$	$0.3 \pm 0.4$
U4-16442	$1.62 \pm 0.10$	$1.7 \pm 0.2$	$0.29 \pm 0.12$	$85 \pm 6$	$1.70 \pm 0.11$	$1.8 \pm 0.3$
U4-16504	$2.83 \pm 0.12$	$1.3 \pm 0.1$	$0.85 \pm 0.14$	$146 \pm 29$	$2.99 \pm 0.14$	$1.3 \pm 0.1$
U4-16795	$4.22 \pm 0.11$	$1.2 \pm 0.1$	$0.53 \pm 0.06$	$126 \pm 5$	$4.39 \pm 0.12$	$1.2 \pm 0.1$
U4-17519	$6.61 \pm 0.12$	$1.6 \pm 0.1$	$0.92 \pm 0.06$	$108 \pm 22$	$6.98 \pm 0.14$	$1.6 \pm 0.1$
U4-19068	$1.87 \pm 0.14$	$2.4 \pm 0.3$	$0.76 \pm 0.18$	$135 \pm 24$	$1.93 \pm 0.17$	$2.3 \pm 0.3$
U4-19126	$0.76 \pm 0.10$	$1.6 \pm 0.5$	$0.64 \pm 0.38$	$65 \pm 35$	$0.79 \pm 0.12$	$1.6 \pm 0.5$
U4-20704	$3.15 \pm 0.24$	$4.9 \pm 0.5$	$0.40 \pm 0.09$	$180 \pm 5$	$3.40 \pm 0.29$	$5.1 \pm 0.6$
U4-21665	$0.96 \pm 0.09$	$1.1 \pm 0.3$	$0.68 \pm 0.34$	$106 \pm 36$	$1.00 \pm 0.11$	$1.1 \pm 0.3$
U4-21998	$0.67 \pm 0.11$	$2.4 \pm 0.8$	$0.23 \pm 0.24$	$82 \pm 11$	$0.69 \pm 0.12$	$2.3 \pm 0.8$
U4-22227	$3.04 \pm 0.12$	$1.7 \pm 0.1$	$0.76 \pm 0.11$	$156 \pm 14$	$3.16 \pm 0.14$	$1.7 \pm 0.1$
U4-22729	$4.53 \pm 0.12$	$2.0 \pm 0.1$	$0.53 \pm 0.05$	$48 \pm 4$	$4.82 \pm 0.14$	$2.1 \pm 0.1$
U4-23044	$5.04 \pm 0.09$	$1.1 \pm 0.1$	$0.99 \pm 0.08$	$0 \pm 2$	$5.22 \pm 0.12$	$1.1 \pm 0.1$
U4-23692	$5.52 \pm 0.14$	$2.1 \pm 0.1$	$0.88 \pm 0.07$	$92 \pm 17$	$5.97 \pm 0.17$	$2.2 \pm 0.1$
U4-26012	$1.16 \pm 0.10$	$1.1 \pm 0.2$	$0.58 \pm 0.26$	$180 \pm 20$	$1.21 \pm 0.11$	$1.2 \pm 0.2$
U4-26581	$2.91 \pm 0.09$	$0.9 \pm 0.1$	$0.62 \pm 0.11$	$63 \pm 10$	$2.96 \pm 0.10$	$0.9 \pm 0.1$
U4-28087	$2.92 \pm 0.27$	$5.6 \pm 0.6$	$0.70 \pm 0.11$	$113 \pm 12$	$3.35 \pm 0.37$	$6.4 \pm 0.7$
U4-28156	$5.33 \pm 0.12$	$2.0 \pm 0.1$	$0.72 \pm 0.06$	$109 \pm 7$	$5.61 \pm 0.15$	$2.0 \pm 0.1$
U4-28473	$4.22 \pm 0.12$	$1.3 \pm 0.1$	$0.44 \pm 0.06$	$24 \pm 4$	$4.35 \pm 0.13$	$1.3 \pm 0.1$
U4-28702	$1.82 \pm 0.12$	$1.3 \pm 0.2$	$0.67 \pm 0.23$	$3 \pm 23$	$1.88 \pm 0.14$	$1.2 \pm 0.2$
U4-29179	$1.24 \pm 0.12$	$2.6 \pm 0.5$	$0.36 \pm 0.14$	$101 \pm 9$	$1.35 \pm 0.15$	$2.9 \pm 0.6$
U4-31189	$0.78 \pm 0.12$	$1.6 \pm 0.4$	...	...	$0.83 \pm 0.15$	$1.7 \pm 0.5$
U4-32147	$0.82 \pm 0.18$	$2.8 \pm 0.7$	...	...	$0.87 \pm 0.22$	$2.7 \pm 0.9$
U4-32351	$0.67 \pm 0.10$	$0.7 \pm 0.2$	...	...	$0.70 \pm 0.11$	$0.7 \pm 0.2$
U4-32992	$1.03 \pm 0.13$	$2.1 \pm 0.5$	$0.67 \pm 0.30$	$166 \pm 29$	$1.08 \pm 0.15$	$2.1 \pm 0.5$
U4-34138	$1.24 \pm 0.10$	$0.7 \pm 0.2$	$0.47 \pm 0.25$	$107 \pm 16$	$1.27 \pm 0.10$	$0.7 \pm 0.1$
U4-34454	$1.78 \pm 0.16$	$3.5 \pm 0.5$	$0.50 \pm 0.13$	$92 \pm 9$	$1.86 \pm 0.19$	$3.5 \pm 0.5$
U4-34617	$1.12 \pm 0.09$	$0.6 \pm 0.1$	$0.27 \pm 0.33$	$60 \pm 12$	$1.15 \pm 0.09$	$0.6 \pm 0.1$
U4-34817	$2.04 \pm 0.21$	$3.5 \pm 0.6$	$0.68 \pm 0.17$	$88 \pm 18$	$2.29 \pm 0.28$	$3.9 \pm 0.6$
U4-36247	$1.59 \pm 0.10$	$0.7 \pm 0.1$	$0.55 \pm 0.20$	$98 \pm 15$	$1.66 \pm 0.10$	$0.7 \pm 0.1$
U4-36437	$1.78 \pm 0.09$	$0.9 \pm 0.1$	$0.59 \pm 0.17$	$36 \pm 16$	$1.82 \pm 0.10$	$0.8 \pm 0.1$
U4-36568	$1.19 \pm 0.20$	$2.6 \pm 0.5$	...	...	$1.30 \pm 0.25$	$2.8 \pm 0.7$
U4-36685	$1.26 \pm 0.11$	$2.1 \pm 0.4$	$0.33 \pm 0.15$	$75 \pm 8$	$1.34 \pm 0.13$	$2.3 \pm 0.4$
U4-37775	$1.50 \pm 0.16$	$3.9 \pm 0.6$	$0.32 \pm 0.12$	$160 \pm 7$	$1.57 \pm 0.19$	$3.9 \pm 0.7$
U4-38040	$0.51 \pm 0.11$	$1.3 \pm 0.5$	...	...	$0.57 \pm 0.14$	$1.5 \pm 0.7$
U4-38640	$1.52 \pm 0.10$	$1.2 \pm 0.2$	$0.68 \pm 0.21$	$78 \pm 20$	$1.57 \pm 0.11$	$1.2 \pm 0.2$
U4-39126	$0.46 \pm 0.12$	$1.4 \pm 0.6$	...	...	$0.49 \pm 0.14$	$1.6 \pm 0.8$
U4-39245	$1.29 \pm 0.12$	$2.0 \pm 0.4$	$0.53 \pm 0.18$	$48 \pm 14$	$1.39 \pm 0.14$	$2.1 \pm 0.4$
U4-40115	$1.75 \pm 0.09$	$0.8 \pm 0.1$	$0.84 \pm 0.25$	$99 \pm 45$	$1.81 \pm 0.10$	$0.8 \pm 0.1$
U4-42529	$2.19 \pm 0.15$	$3.1 \pm 0.3$	$0.39 \pm 0.09$	$153 \pm 6$	$2.37 \pm 0.18$	$3.3 \pm 0.4$
U4-42571	$1.97 \pm 0.12$	$1.7 \pm 0.2$	$0.73 \pm 0.17$	$87 \pm 19$	$2.10 \pm 0.14$	$1.8 \pm 0.2$
U4-42812	$1.80 \pm 0.13$	$2.5 \pm 0.3$	$0.41 \pm 0.11$	$144 \pm 7$	$1.91 \pm 0.16$	$2.6 \pm 0.4$
U4-43123	$1.07 \pm 0.14$	$3.6 \pm 0.8$	$0.21 \pm 0.12$	$110 \pm 6$	$1.11 \pm 0.16$	$3.5 \pm 0.8$
U4-43667	$0.48 \pm 0.13$	$1.8 \pm 0.7$	...	...	$0.51 \pm 0.16$	$1.9 \pm 1.0$
GS4-1725	$1.00 \pm 0.19$	$1.7 \pm 0.4$	...	...	$1.04 \pm 0.23$	$1.7 \pm 0.5$
GS4-4583	$1.71 \pm 0.07$	$0.7 \pm 0.1$	$0.67 \pm 0.18$	$101 \pm 21$	$1.77 \pm 0.08$	$0.7 \pm 0.1$

**Table 3**  
(Continued)

ID	$S_{\text{visibility}} (n = 0.5)$ (mJy)	$R_{\text{e,FIR}} (n = 0.5)$ (kpc)	$q_{\text{FIR}} (n = 0.5)$	$PA_{\text{FIR}} (n = 0.5)$	$S_{\text{visibility}} (n = 1)$ (mJy)	$R_{\text{e,FIR}} (n = 1)$ (kpc)
GS4-5217	$1.50 \pm 0.15$	$2.8 \pm 0.5$	$0.58 \pm 0.19$	$48 \pm 17$	$1.69 \pm 0.19$	$3.2 \pm 0.5$
GS4-11016	$1.86 \pm 0.09$	$1.6 \pm 0.2$	$0.38 \pm 0.10$	$56 \pm 7$	$1.96 \pm 0.11$	$1.7 \pm 0.2$
GS4-14747	$2.24 \pm 0.08$	$0.6 \pm 0.1$	$0.85 \pm 0.17$	$152 \pm 32$	$2.31 \pm 0.08$	$0.6 \pm 0.1$
GS4-19348	$4.07 \pm 0.08$	$0.7 \pm 0.0$	$0.85 \pm 0.06$	$81 \pm 12$	$4.22 \pm 0.08$	$0.7 \pm 0.0$
GS4-22825	$1.34 \pm 0.09$	$1.1 \pm 0.2$	$0.65 \pm 0.16$	$129 \pm 16$	$1.43 \pm 0.10$	$1.2 \pm 0.2$
GS4-30274	$1.62 \pm 0.10$	$1.0 \pm 0.3$	$0.72 \pm 0.40$	$106 \pm 46$	$1.64 \pm 0.11$	$0.9 \pm 0.2$
GS4-40185	$0.36 \pm 0.06$	...	...	...	...	...
GS4-41181	$1.48 \pm 0.07$	$0.5 \pm 0.1$	$0.60 \pm 0.41$	$151 \pm 33$	$1.49 \pm 0.08$	$0.5 \pm 0.1$
GS4-44065	$0.82 \pm 0.11$	$2.2 \pm 0.7$	$0.39 \pm 0.23$	$103 \pm 15$	$0.86 \pm 0.13$	$2.3 \pm 0.7$
GS4-45068	$1.66 \pm 0.08$	$0.7 \pm 0.1$	$0.80 \pm 0.14$	$64 \pm 23$	$1.71 \pm 0.08$	$0.7 \pm 0.1$
GS4-45475	$1.06 \pm 0.24$	$5.0 \pm 1.0$	...	...	$1.13 \pm 0.31$	$5.1 \pm 1.4$

while 33% of the fainter sources are extended. We also evaluate the completeness in our ALMA observations from the CASA simulations. Although some faint and extended emission can be missed in our observations, the incompleteness effect is negligible especially at  $S_{870} > 1$  mJy (a shaded region in Figure 7). This result confirms the previous results that the bright emission in SMGs originates in their compact core with a high surface density of dust, not in a large disk (Gullberg et al. 2019). Some physical mechanism that forces a large amount of gas into the central region of galaxies is likely to be at work, causing the compact starburst.

#### 4.4. Comparison of the Rest-frame Optical and Far-infrared Size

Overlay images illustrate that the dust continuum emission is centrally concentrated while the rest-frame optical emission appears to be extended in the HST/F160W-band images (Figures A1 and A2 in Appendix A). As the HST/F160W band traces emission in the rest-frame wavelength between the  $B$  band and  $V$  band at  $z = 1.9$ – $2.6$ , it is still affected by dust extinction. A heavily obscured region does not become bright in the HST images while it is very bright in the ALMA images. The ALMA images are not sensitive to low-level, unobscured star formation such as off-center blue clumps (e.g., Wuyts et al. 2012). Nevertheless, dust continuum emission can serve as a primary probe of the spatial distribution of the total star formation in massive SFGs because more than 95% of the star formation is obscured by dust in the stellar mass range of  $\log(M_*/M_\odot) > 11$  (Figure 1).

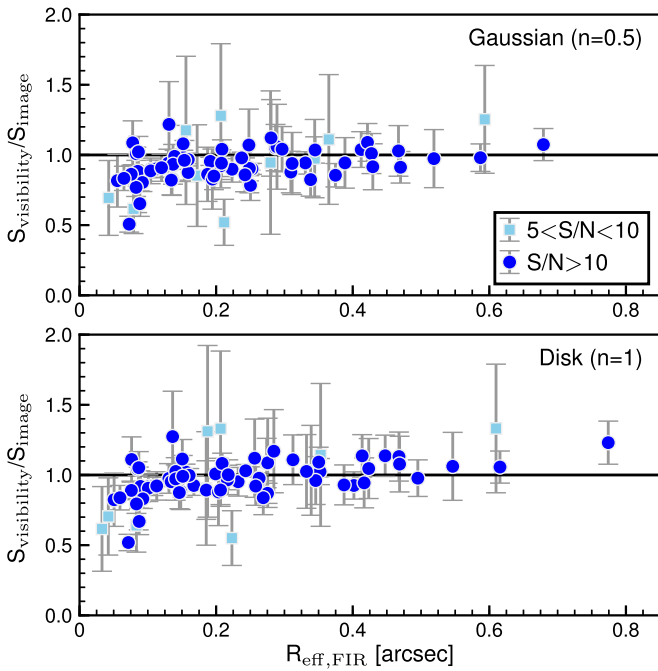
Four of 62 massive SFGs with  $S/N > 10$  do not have robust size measurements in the HST/F160W band (Section 2.3). For the remaining 58 massive SFGs in our ALMA sample, the effective radius in the FIR is smaller by a factor of  $2.3^{+1.9}_{-1.0}$  than that in the optical, placing results from previous studies on a more robust footing (Simpson et al. 2015b; Barro et al. 2016; Rujopakarn et al. 2016; Tadaki et al. 2017a; Calistro Rivera et al. 2018; Elbaz et al. 2018; Fujimoto et al. 2018; Lang et al. 2019; Nelson et al. 2019; Chen et al. 2020). The above range is based on the 16th and 84th percentiles of the optical-to-FIR effective radius ratio. The optical light distribution is commonly used as a probe of the stellar mass distribution. However, the half-light radius is expected to be larger than the half-mass radius, especially for old or dusty galaxies where there is a strong radial dependence

on the mass-to-light ratio (e.g., Mosleh et al. 2017; Price et al. 2017; Suess et al. 2019).

For galaxies in the CANDELS/3D-HST fields, Lang et al. (2014) have constructed a mass-to-light ratio map in the HST/F160W band through the resolved SED modeling with the multiband HST data (Wuyts et al. 2012) and created a stellar mass map from the HST/F160W-band map without decreasing the spatial resolution. Then, they have fitted single Sérsic models to the stellar mass map to derive the half-mass radius. For our sample, 26 of 58 massive SFGs have measurements of the half-mass radius from Lang et al. (2014). The typical uncertainty on the half-mass radius is  $\sim 10\%$  for dusty SFGs (Lang et al. 2019). Other galaxies are excluded because the best-fit Sérsic index reaches the constrained limit ( $n = 0.2$  or  $n = 8.0$ ) or the effective radius is unreasonably small with  $R_{\text{e,mass}} < 0''.05$ . The ratio of the half-mass to the half-light radius is  $R_{\text{e,mass}}/R_{\text{e,opt}} = 0.8^{+0.5}_{-0.3}$ , which can be interpreted as indicating the optical continuum emission is indeed affected by strong dust extinction in the centers of galaxies. However, the effective radius in the FIR is still smaller by a factor of  $1.9^{+1.9}_{-0.9}$  than the half-mass radius (Figure 8). These results suggest that many massive SFGs intensively form stars in a compact central region, which is embedded in a more extended disk probed by the optical continuum emission.

We also compare the FIR size with the  $H\alpha$  size. Eight of 58 massive SFGs have measurements of the effective radius of the  $H\alpha$  emission from the KMOS<sup>3D</sup> survey (Wisnioski et al. 2019; Wilman et al. 2020). The median ratio between the  $H\alpha$  and the FIR effective radius is  $R_{\text{e,H}\alpha}/R_{\text{e,FIR}} = 2.3$  though both trace star formation. The more heavily obscured regions are unlikely to be probed by the rest-frame UV and  $H\alpha$  emission (Chen et al. 2020).

We caution that conversion from  $870 \mu\text{m}$  flux to dust-obscured SFR depends on dust properties such as dust temperature and optical depth. When the dust temperature is higher in a galaxy center, the spatial distribution of the infrared luminosity becomes more compact than that of the dust continuum emission. In contrast, the spatial distribution of the dust mass becomes more extended than that of the dust continuum emission. This can explain the result from previous studies that the effective radius of intermediate- $J$  ( $J_{\text{up}} = 3$  and 4) CO emission is larger than that of dust continuum emission in massive SFGs and SMGs (Chen et al. 2017; Tadaki et al. 2017b, 2019; Calistro Rivera et al. 2018). Simulations also show that the spatial distribution of the dust emission is more compact than the total gas component, but it has a similar

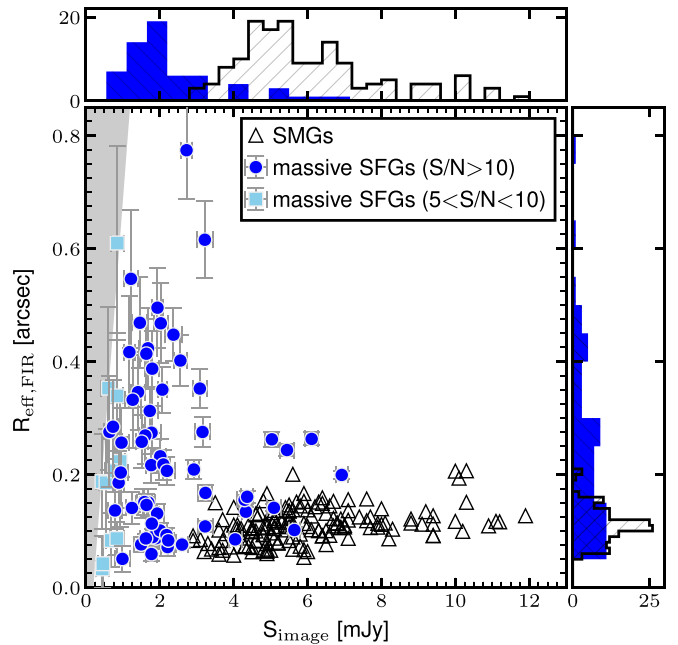


**Figure 6.** Comparisons between visibility-based and image-based flux densities in the low-resolution images as a function of the effective radius of  $870\ \mu\text{m}$  emission. The visibility-based flux densities and sizes are derived from the best-fit model with Gaussian (top) and exponential profile (bottom). Blue circles and light blue squares indicate galaxies that are detected at a level above  $10\sigma$  and  $5\text{--}10\sigma$  in the ALMA intermediate-resolution images, respectively.

spatial distribution to the cold, dense gas (Cochrane et al. 2019). An optical depth effect on dust continuum emission could also lead to a smaller size of the star formation because emission at shorter wavelengths (tracing an infrared luminosity) is preferentially suppressed in a galaxy center. Therefore, the distribution of dust-obscured SFR could be even more compact than is measured from the  $870\ \mu\text{m}$  continuum observations, supporting our result that massive SFGs form stars in a compact region.

#### 4.5. Correlations between the Size Ratio and Other Galaxy Parameters

In the previous section, we found that the effective radius of the FIR emission is smaller than that of the optical emission in massive SFGs. We investigate how the optical-to-FIR effective radius ratio is correlated with other galaxy parameters, including redshift, stellar mass, Sérsic index in the optical, dust extinction  $A_V$ , offset from the star formation main sequence, and gas mass fraction (Figure 9). Then, we compute the Spearman rank correlation coefficient and the  $p$ -value to test for noncorrelation. When the  $p$ -value is very close to 0, we can reject the null hypothesis that the observed correlation is zero. In regard to the redshift, stellar mass, and Sérsic index, there is no significant correlation with the size ratio. The optical-to-FIR effective radius ratio is weakly anticorrelated with the dust extinction, derived from SED fitting to the galaxy-integrated photometry from the rest-frame UV to near-IR, as probed by observed optical to mid-IR fluxes. This is the opposite of what is expected because strong dust extinction in galaxy centers can make the optical effective radius larger. At least, we do not find evidence that the optical-to-FIR effective radius ratio is larger due to dust extinction. Also, the ratio is positively correlated with the gas mass fraction and the offset



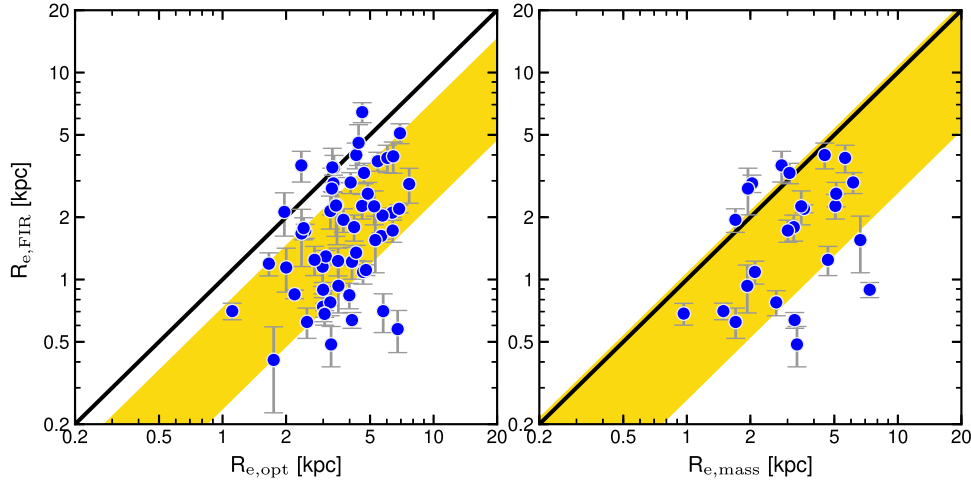
**Figure 7.** Flux densities at  $870\ \mu\text{m}$  and effective radii in massive SFGs at  $z = 2$  (blue circles and light blue squares) and SMGs at  $z = 1\text{--}4$  (open triangles; Gullberg et al. 2019). A gray-shaded region shows faint and extended emission that cannot be detected at above  $5\sigma$  in the simulated observations (Appendix B). The histograms in the top and right panels are the projected distributions of  $870\ \mu\text{m}$  flux densities and effective radii for massive SFGs (filled blue) and SMGs (open black).

from the star formation main sequence. The Spearman rank correlation coefficient and the  $p$ -value is  $\rho_{\text{Spearman}} = 0.46$  and  $p < 0.001$  for the gas mass fraction and  $\rho_{\text{Spearman}} = 0.32$  and  $p = 0.015$  for the main-sequence offset, respectively.

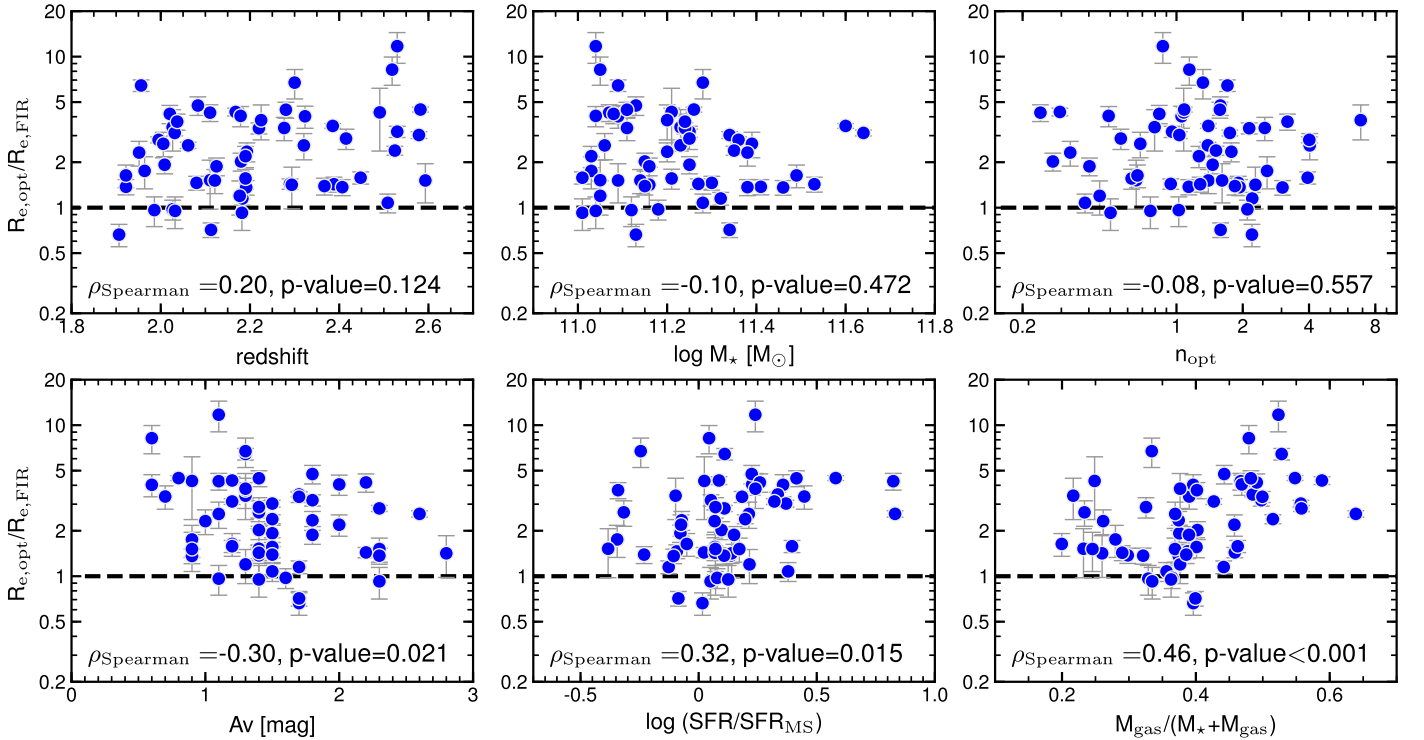
The more central concentration of star formation compared to that of stars indicates that gas is transported from the outer disk into the galaxy center. The fact that more gas-rich, more active SFGs tend to have larger  $R_{e,\text{opt}}/R_{e,\text{FIR}}$  suggests the possibility that the more compact dust emission is related to dissipative processes such as a dissipative concentration of gas (wet compaction). Wet compaction is seen in simulations of gas-rich galaxies at high redshift (e.g., Noguchi 1999; Immeli et al. 2004; Bournaud et al. 2014; Zolotov et al. 2015; Tacchella et al. 2016). Wet compaction is triggered by gas-rich minor/major mergers, counter-rotating streams, and radial gas inflows driven by violent disk instability (e.g., Dekel & Burkert 2014; Forbes et al. 2014). There is also observational evidence of a gas component falling into an SMG with a compact core from a direction perpendicular to the disk rotation (Tadaki et al. 2020). The onset of wet compaction is likely to occur when gas inflows dominate star formation and outflows (Tacchella et al. 2016). It is therefore expected that the incidence of compaction depends on star-forming activity and gas mass fraction in galaxies. When gas falls into the galaxy center to feed a core, it has to lose angular momentum. The extended  $\text{H}\alpha$  disk (Section 4.4) may be formed by the released angular momentum.

## 5. Discussion

Since we derive the spatial distribution of stellar continuum emission from the HST/F160W data and the distribution of dusty star formation from the ALMA data, we combine the two to predict how massive SFGs will change their effective radius and their central stellar mass within a radius of 1 kpc,  $M_{1\text{kpc}}$ , by



**Figure 8.** Size comparisons between the rest-frame FIR, optical, and the stellar mass distribution. Yellow-shaded regions show the 16th and 84th percentiles of the size ratios  $R_{e,opt}/R_{e,FIR} = 2.3^{+1.9}_{-1.0}$  and  $R_{e,mas}/R_{e,FIR} = 1.9^{+1.9}_{-1.0}$ .



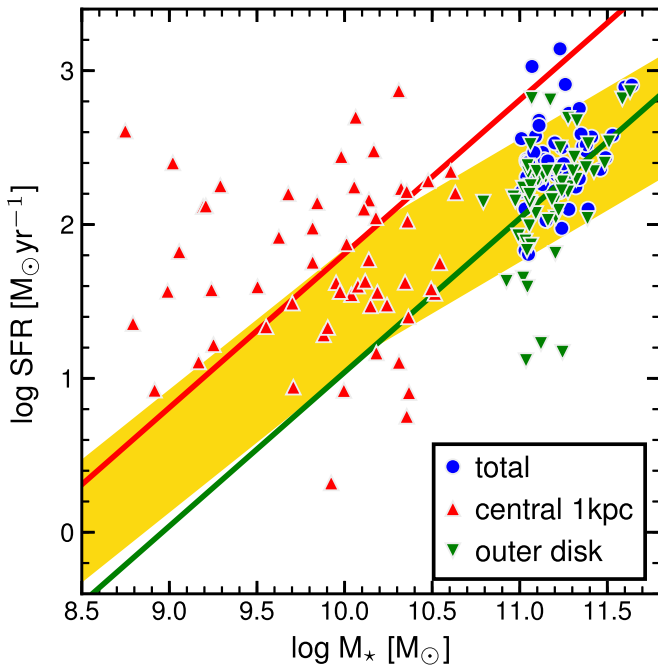
**Figure 9.** Optical-to-FIR effective radius ratio vs. redshift (top left), stellar mass (top center), Sérsic index (top right), dust extinction (bottom left), offset from the star formation main sequence (bottom center), and gas mass fraction (bottom right).

in situ star formation. We discuss the current and future structure for 58 massive SFGs with robust measurements of the structural parameters in both HST/F160W and ALMA data. Unlike the previous sections, we adopt the circularized effective radii of the optical and the FIR emission to treat them fairly since the axis ratios and the position angles are not exactly the same.

### 5.1. Spatially Resolved Stellar Mass and SFR

Before investigating the structural evolution of massive SFGs at  $z \sim 2$ , we look at their spatially resolved stellar mass and SFR at the observed epoch. The surface stellar mass profile

and the surface SFR profile are derived from the best-fitting Sérsic profile in the HST/F160W and ALMA/870  $\mu\text{m}$  data, respectively. Following previous studies (Bezanson et al. 2009; Mowla et al. 2019), we deproject the two-dimensional Sérsic profile using an Abel transform (see also Appendix C). We scale the integral of the inferred three-dimensional profile at HST/F160W to the total stellar mass and that at ALMA 870  $\mu\text{m}$  to the total SFR to compute the central mass ( $M_{1\text{kpc}}$ ) and the central SFR within a radius of 1 kpc ( $\text{SFR}_{1\text{kpc}}$ ). Once the central mass and SFR are given, it is possible to estimate the stellar mass and SFR in the outer disk with  $R > 1$  kpc by subtracting  $M_{1\text{kpc}}$  and  $\text{SFR}_{1\text{kpc}}$  from the total stellar mass and the total SFR.



**Figure 10.** The stellar mass vs. SFR for the central 1 kpc regions (red triangles) and the outer disks (green triangles) of massive SFGs. Red and green lines correspond to the median sSFR for the central 1 kpc regions ( $\log \text{sSFR} [\text{Gyr}^{-1}] = 0.83$ ) and the outer disks ( $\log \text{sSFR} [\text{Gyr}^{-1}] = 0.04$ ), respectively. A yellow-shaded region shows the  $\pm 0.4$  dex range of the star formation main sequence at  $2 < z < 2.5$  (Whitaker et al. 2014). We also show the total stellar mass and total SFR by blue circles.

Figure 10 shows a spatially resolved version of the mass–SFR plane for our ALMA sample. The outer disks are responsible for the total stellar mass, while the SFR in the central 1 kpc regions is comparable to that in the outer disks. This leads to a significant difference in the star formation activity. About half of the central 1 kpc regions are located above the star-forming main sequence defined by galaxy-integrated properties, while the outer disks mostly lie on the main sequence. The median value and the standard deviation of the specific SFRs, defined as  $\text{sSFR} = \text{SFR}/M_*$ , is  $\log \text{sSFR} [\text{Gyr}^{-1}] = 0.83 \pm 0.71$  for the central 1 kpc region and  $\log \text{sSFR} [\text{Gyr}^{-1}] = 0.04 \pm 0.33$  for the outer disk, indicating that the sSFR is higher in the galaxy center than in the outer disk.

The centrally rising sSFR profiles seem to be at odds with previous studies that have applied dust gradient corrections to translate  $\text{H}\alpha$  profiles to SFR profiles, finding that dust-corrected sSFR profiles are centrally dipping in massive SFGs at  $z \sim 2$  (Tacchella et al. 2015, 2018; Suzuki et al. 2019). This difference may be due to underestimates of the central dust extinction and/or the different sample selection. Nelson et al. (2016b) find significant dust attenuation toward centers of massive SFGs through the Balmer decrement. In our ALMA observations, it was difficult to derive the spatial distributions of star formation for less dusty SFGs near the bottom of the star-forming main sequence, corresponding to  $\text{S/N} < 10$  sources. As shown by Tacchella et al. (2018), massive less dusty SFGs are likely to have centrally dipping sSFR profiles. Dust extinction corrections based on the rest-frame UV color, as applied by Tacchella et al. (2018), may be prone to saturation effects in the case of a mixture between obscuring dust clouds and the emitting sources. Also, many of massive SFGs are very faint and fuzzy in the HST/F814W-band

images, making it difficult to determine the rest-frame UV color at  $z \sim 2$  in the first place. Therefore, it would be necessary to use the appropriate indicators, depending on the galaxy properties: submillimeter continuum for massive, dusty SFGs on/around the star-forming main sequence and  $\text{H}\alpha$  line emission for less dusty SFGs.

## 5.2. Structural Evolution in Massive SFGs

Next, we investigate the time evolution of the effective radius and the central mass assuming that the current level of star formation and its spatial distribution are the same for several hundred megayears. The mass of newly formed stars is estimated to be

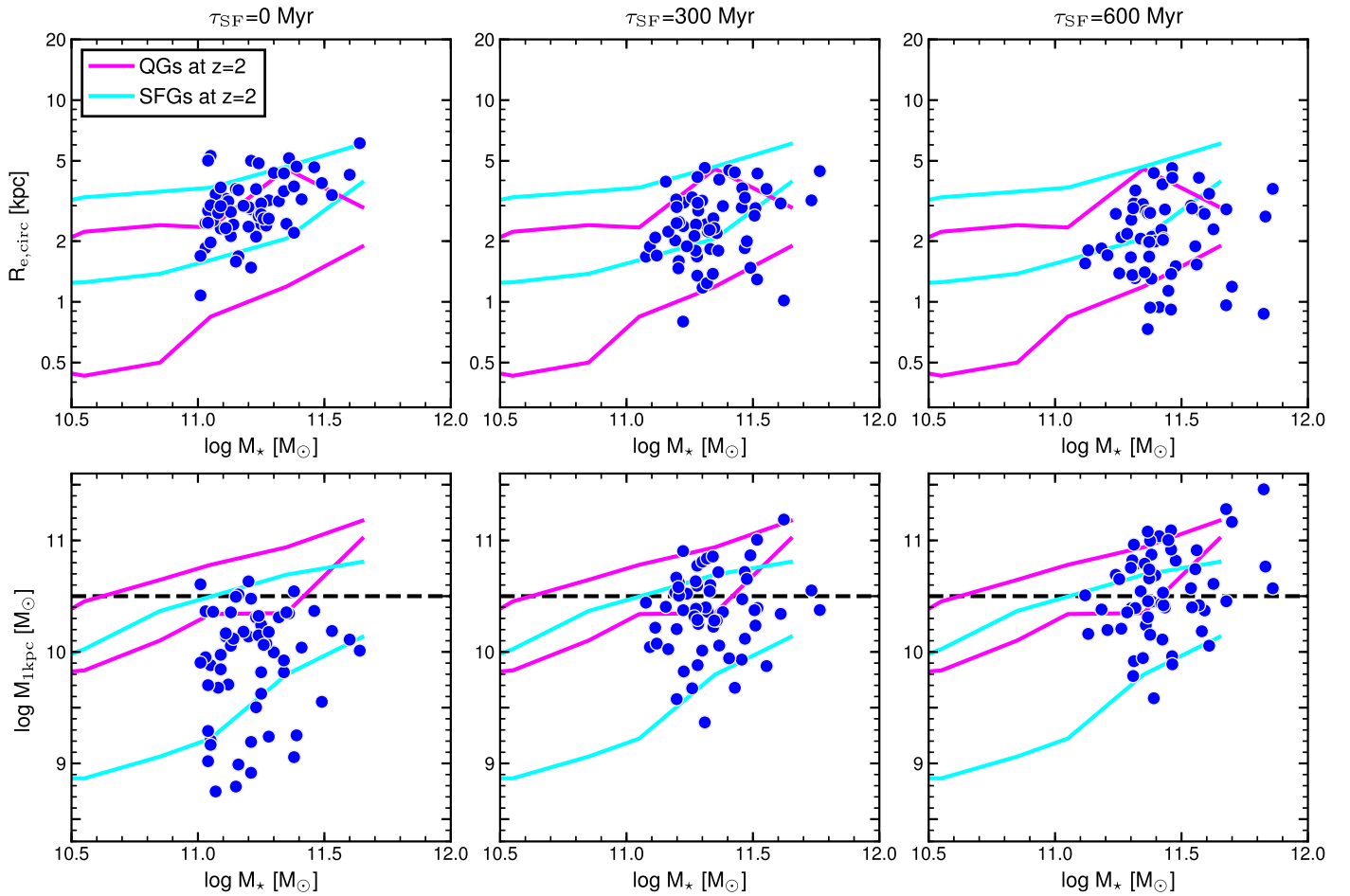
$$M_{*,\text{new}} = \text{SFR} \times \tau_{\text{SF}} \times \beta, \quad (5)$$

where  $\tau_{\text{SF}}$  is the timescale for star formation and  $\beta$  is the mass loss parameter due to supernova explosions and stellar winds. We adopt  $\beta = 0.6$ , appropriate for a Chabrier (2003) IMF. Figure 11 shows the circularized effective radius and the central mass inside a radius of 1 kpc as a function of stellar mass at  $\tau_{\text{SF}} = 0$  Myr, 300 Myr, and 600 Myr. We overplot the 16th and 84th percentiles in each mass bin for SFGs and QGs at  $z = 1.9$ – $2.6$  in the combined sample of the CANDELS/3D-HST survey (Skelton et al. 2014; van der Wel et al. 2014; Momcheva et al. 2016) and the COSMOS-DASH survey (Mowla et al. 2019).

We find that by 300 Myr with the compact starburst, most of massive SFGs lie on the mass–size relation for QGs (Figure 11). This is one of the most important results of this work. In our ALMA sample of 58 massive SFGs, the effective radius is decreased, on average, by 14% in 300 Myr, while the stellar mass is increased by 28%. The averaged evolution in the mass–size plane is approximated by  $\Delta \log R_e = -0.6 \Delta \log M_*$ . The negative slope appears to contradict the context of inside-out growth where galaxies form stars in a more extended disk and gradually increase their size with  $\Delta \log R_e \sim 0.3 \Delta \log M_*$  (van Dokkum et al. 2015). Our result is preferred for explaining the morphological transformation of massive SFGs, at least in terms of effective radius.

We also infer the effective radius of the massive SFGs at higher redshift by putting  $\tau_{\text{SF}} = -300$  Myr in Equation (5). Many of them are found to deviate from the observed mass–size relation and become too large especially in the stellar mass range of  $\log(M_*/M_\odot) < 11$ , suggesting that very little time has passed since the compact starburst occurred. Extended star formation in disks is required to explain the size evolution of SFGs, but it does not transform the morphology of galaxies from disk-dominated to bulge-dominated. The compact starburst naturally produces a cuspy profile, characterized by a high Sérsic index. This outside-in transformation should happen after the inside-out growth of galaxy disks. Observations of massive,  $\log(M_*/M_\odot) > 11$ , early-type galaxies at  $z \sim 0$  show that the mass-weighted age in the galaxy center is younger than that in the outer disks (Goddard et al. 2017), supporting the outside-in transformation.

However, the fact that going 300 Myr back in time brings many galaxies outside the mass–size relation suggests not only that the compact starburst cannot have been going on for a long time, but also that it will not go on for a long time after the current time of the observations, either. As it is implausible to find all observed systems in the first fraction of their compact



**Figure 11.** The effective radius of the optical emission (top) and the central 1 kpc mass (bottom) as a function of stellar mass for 58 massive SFGs in our ALMA sample. We show the observed values at  $\tau_{\text{SF}} = 0$  (left) and the inferred values at  $\tau_{\text{SF}} = 300$  Myr (center) and  $\tau_{\text{SF}} = 600$  Myr (right), which are based on the spatial distribution of the  $870 \mu\text{m}$  continuum emission (Section 5.2). Cyan and magenta lines indicate the 16th and 84th percentiles in each bin of stellar mass for SFGs and QGs at  $z = 1.9\text{--}2.6$  in the combined sample of the CANDELS/3D-HST survey (Skelton et al. 2014; van der Wel et al. 2014; Momcheva et al. 2016) and the COSMOS-DASH survey (Mowla et al. 2019). Black dashed lines indicate  $\log(M_{1\text{kpc}}/M_{\odot}) = 10.5$ , which defines a dense core in this work.

starburst phase, it may not be reasonable to extrapolate the current distributions of star formation into the future beyond 300 Myr. This is also supported by the result that some of massive SFGs become more compact,  $R_e < 1$  kpc, than massive QGs at  $\tau_{\text{SF}} = 600$  Myr.

Based on the current distribution of star formation, we also find that 22 ( $\sim 38\%$ ) of 58 massive SFGs have a dense core with  $\log(M_{1\text{kpc}}/M_{\odot}) > 10.5$  at  $\tau_{\text{SF}} = 300$  Myr and an additional 8 (a total of 30,  $\sim 52\%$ ) reach this threshold at  $\tau_{\text{SF}} = 600$  Myr. Further star formation will allow the remaining SFGs to form a dense core in about 2 Gyr, but it is unlikely to happen as mentioned above. The compact starburst probed by ALMA observations makes  $\sim 40\%$  of massive SFGs form a dense core with  $\log(M_{1\text{kpc}}/M_{\odot}) > 10.5$ , whereas  $\sim 75\%$  of massive QGs with  $\log(M_{\star}/M_{\odot}) > 11$  reach this threshold (Figure 11). Despite the fact that most of our sample has highly compact dust emission, more than half of massive SFGs do not form enough stars in this episode to reach the central mass density of  $\log(M_{1\text{kpc}}/M_{\odot}) > 10.5$ . They need to make their distribution of star formation more compact to form a dense core if galaxies transform their morphology before quenching. An alternative view is that massive SFGs evolve into disk QGs without a dense core, although measurements of the Sérsic index indicate that such cases are infrequent (e.g., Wuyts et al. 2011b; Whitaker et al. 2015). Recent studies have found that three

gravitationally lensed QGs at  $z \sim 2$  are rotationally supported and one of them has a perfect exponential disk with no evidence for a dense core (Toft et al. 2017; Newman et al. 2018a, 2018b). Some massive SFGs may be the immediate progenitors of disk QGs at  $z \sim 2$ , but it could be a minor pathway as indicated by the fact that 75% of massive QGs have a dense core.

## 6. Summary

Using ALMA, we have made high-resolution observations of  $870 \mu\text{m}$  continuum emission for the mass-selected sample of 85 massive,  $\log(M_{\star}/M_{\odot}) > 11$ , SFGs at  $z = 1.9\text{--}2.6$  in the CANDELS/3D-HST fields of UDS and GOODS-S. We have detected the dust continuum emission from 74 galaxies and robustly measured the effective radius for 62 galaxies. In all, 58 of them have robust size measurements in the HST/F160W band. Combining the distribution of star formation from the ALMA data with that of stellar continuum from the HST data, we have investigated the structural evolution in massive SFGs at  $z = 2$ .

1. The  $870 \mu\text{m}$  flux density ranges from 0.4 mJy to 6.9 mJy and increases as a function of stellar mass and offset from the star-forming main sequence. As the gas mass can be estimated from the  $870 \mu\text{m}$  flux density, we confirmed

the trend that more massive, more active SFGs have a larger gas reservoir. Six of 11 nondetected sources are located near the boundary between star-forming and quiescent populations in the  $UVJ$  diagram. Once we adopt the slightly modified boundary, the detection rate is 94% (73/78), indicating that our targets represent a nearly mass-complete sample of SFGs.

2. The effective radius of the 870  $\mu\text{m}$  emission widely ranges from 0.4 kpc to 6 kpc. Many massive SFGs are more extended in the FIR than bright SMGs with  $S_{870} > 3.4$  mJy at  $z = 1-4$ . The significant difference of the FIR size between the mass-selected and the flux-selected sample can be partly caused by observational bias, where high-resolution ALMA images are not sensitive to extended emission. However, there is a lack of bright extended sources with  $S_{870} > 3.4$  mJy and  $R_{\text{c,FIR}} > 0''.3$  even in our ALMA sample of massive SFGs, indicating that the bright submillimeter emission originates not in their large disk but in their compact core.
3. The effective radius in the FIR is smaller by a factor of  $2.3_{-1.0}^{+1.9}$  than the effective radius in the optical and smaller by a factor of  $1.9_{-1.0}^{+1.9}$  than the half-mass radius. The compact dust emission suggests that many massive SFGs intensively form stars in the central 1 kpc region, embedded in a more extended disk probed by the optical continuum emission.
4. We found that the FIR size is weakly anticorrelated with the gas mass fraction: gas-rich galaxies tend to be associated with compact dust emission. This evidence is consistent with the dissipative concentration of gas toward the center of gas-rich galaxies via efficient radial inflows.
5. We derive the stellar masses and the SFRs separately in the central 1 kpc region and in the outer disk by exploiting the best-fit Sérsic profiles in the HST/F160W and ALMA data. The central 1 kpc regions are located above the star formation main sequence and have higher sSFRs than those in the outer disk, indicating the centrally rising sSFR profiles. This result supports an outside-in transformation scenario in which a dense core is formed at the center of a more extended disk, likely via dissipative in-disk inflows.
6. The compact starburst could put most of massive SFGs on the mass-size relation for QGs at  $z \sim 2$  within 300 Myr if the current star formation activity and its spatial distribution are maintained. The averaged evolution in the mass-size plane is approximated by  $\Delta \log R_{\text{e}} = -0.3 \Delta \log M_{\star}$ . We also found that 38% of massive SFGs can form a dense core with  $\log(M_{1\text{kpc}}/M_{\odot}) = 10.5$  within 300 Myr. Some of the remaining ones may need to make their distribution of star formation more compact by further dissipative processes.

The compact dust emission in our ALMA sample appears to be inconsistent with previous results that showed that the  $\text{H}\alpha$  emission is more extended than the stellar continuum emission in less massive, less dusty SFGs at  $z \sim 2$  (Suzuki et al. 2019; Wilman et al. 2020). Note that our targets are all massive SFGs with  $\log(M_{\star}/M_{\odot}) > 11$ , where most star formation is obscured by dust. In the stellar mass range of  $\log(M_{\star}/M_{\odot}) < 11$ , the distribution of dust-obscured star formation is poorly investigated. Deep intermediate ( $0''.5$ ) resolution ALMA observations, rather than high-resolution ones, are the best for confirming if

less massive SFGs form stars in a disk more extended than the spatial extent of previously formed stars and grow from inside out.

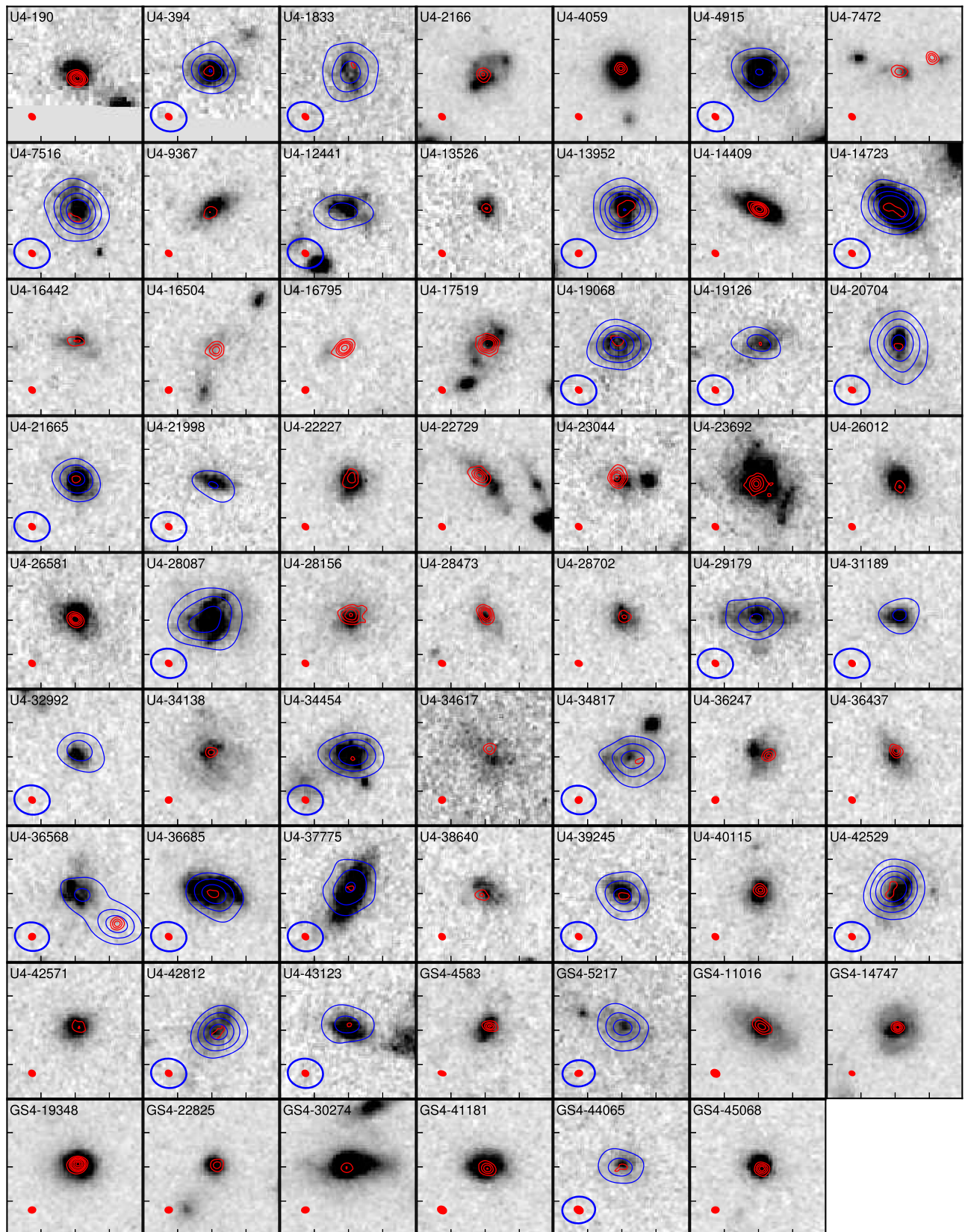
One caveat of our study is that we may overestimate the half-mass radius of massive SFGs due to strong dust extinction in the galaxy centers because the current spatially resolved SED modeling is based on data that does not extend redward of rest-frame 5000 Å, provided by HST/F160W-band observations. If this is true, the half-mass radius could be as compact as the 870  $\mu\text{m}$  emission and the Sérsic index could already reach  $n = 4$ . In that case, massive SFGs do not have to transform their morphology in terms of both size and radial profile (core mass). At this moment, there is no evidence supporting the possibility that the half-mass radius is overestimated by a factor of two. It is definitely important to verify if the stellar mass distribution is surely more extended than the dust in massive SFGs. They are sufficiently bright at 3–4  $\mu\text{m}$ , where the emission is less affected by dust extinction, with an AB magnitude of 20–21. High-resolution 3–4  $\mu\text{m}$  observations with Near Infrared Camera on the James Webb Space Telescope (JWST) will allow us to directly probe the stellar mass distribution. The ALMA–JWST synergetic observations will provide a definitive answer in the structural evolution of massive galaxies at the peak of cosmic star formation history.

We are very grateful to the referee for constructive suggestions to improve the paper. We thank Pieter van Dokkum for comments on the first draft of the paper. This paper makes use of the following ALMA data: ADS/JAO.ALMA#2017.1.01027.S (primary), 2012.1.00245.S, 2012.1.00983.S, 2013.1.00205.S, 2013.1.00566.S, 2013.1.00884.S, 2015.1.00242.S, and 2016.1.01079.S. ALMA is a partnership of ESO (representing its member states), NSF (USA), and NINS (Japan), together with NRC (Canada), NSC, ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO, and NAOJ. K.T. acknowledges support by JSPS KAKENHI grant no. JP20K14526. E.W. acknowledges support by the Australian Research Council Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D), through project number CE170100013. Data analysis was in part carried out on the common-use data analysis computer system at the Astronomy Data Center (ADC) of the National Astronomical Observatory of Japan. This research made use of UVMULTIFIT and stacker, software tools developed by the Nordic ALMA Regional Center. The Nordic ARC node is funded through Swedish Research Council grant no. 2017-00648.

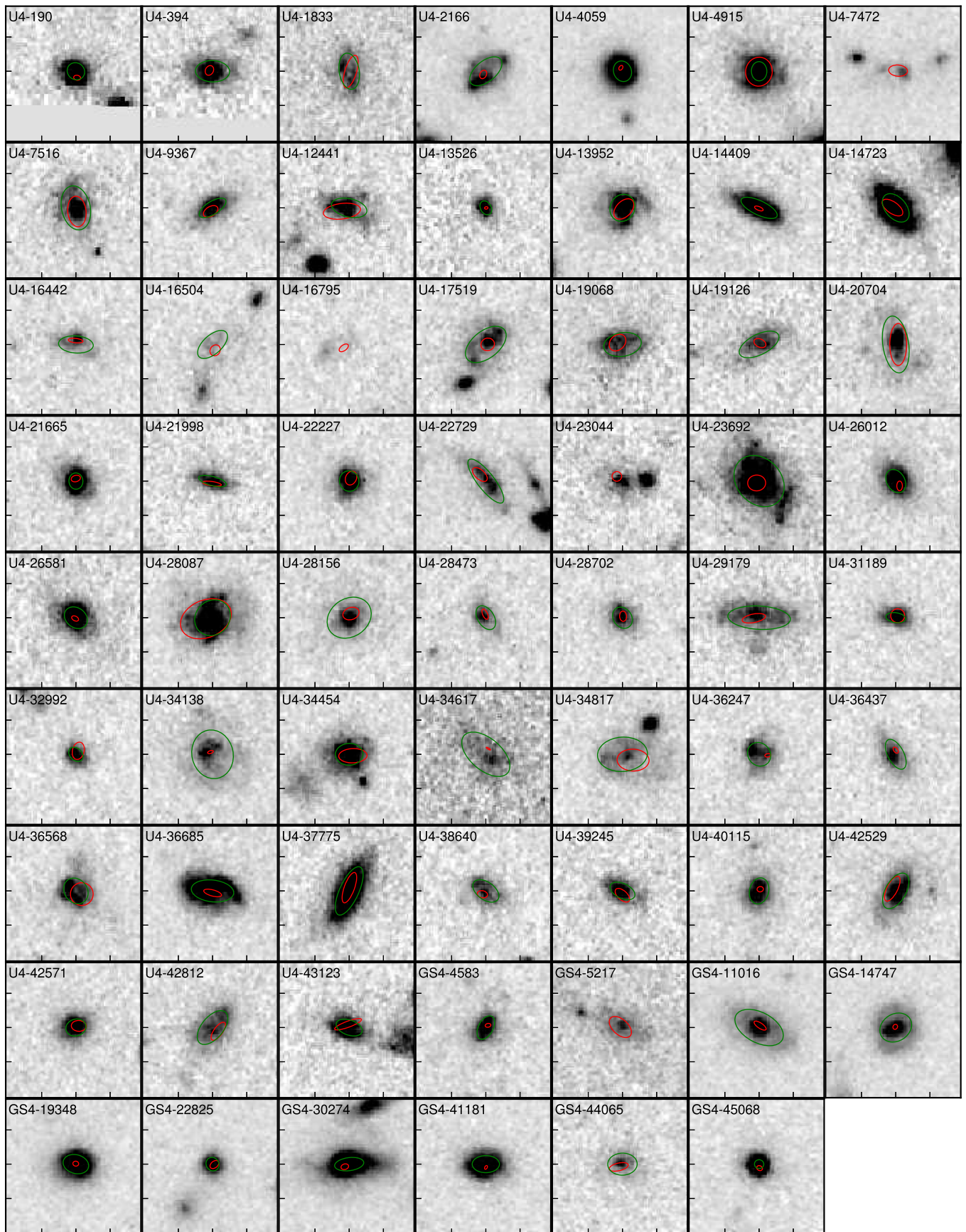
## Appendix A ALMA Images and Catalogs

We present the catalogs for our ALMA sample (Tables 1 and 2). Figure A1 shows the spatial distributions of the 870  $\mu\text{m}$  continuum emission on the HST/F160W-band images for 62 galaxies detected at  $S/N > 10$  in the ALMA intermediate-resolution images. As 27 of them are not detected at  $S/N > 10$  in the high-resolution images, we overlay the contours of the 870  $\mu\text{m}$  emission in the intermediate-resolution images that are sensitive to an extended component. The 870  $\mu\text{m}$  emission is smoothly distributed and does not have multiple components like star-forming clumps in disks (e.g., Hodge et al. 2016; Rujopakarn et al. 2019). The centrally concentrated component is the primary star-forming region in massive SFGs, as most of





**Figure A1.** The HST/F160W-band images ( $4'' \times 4''$ ) for our ALMA sample of 62 massive galaxies. Red contours display the  $870 \mu\text{m}$  flux densities in the ALMA high-resolution images. For galaxies detected at  $S/N < 10$  in the high-resolution images, we overlay blue contours of the  $870 \mu\text{m}$  flux densities in the intermediate-resolution images. Both contours are plotted every  $5\sigma$  to  $20\sigma$  and every  $10\sigma$  from  $20\sigma$ . Red and blue ellipses in the bottom-left corner show the synthesized beams of the high-resolution and the intermediate-resolution images, respectively. The geometric offset between ALMA and HST astrometry was corrected in these images (Section 4.1).



**Figure A2.** The same as Figure A1. Red and green ellipses are based on the structural parameters (centroid, effective radius, minor-to-major axis ratio, and position angle) from the best-fitting Sérsic profile in the ALMA/870  $\mu\text{m}$  and the HST/F160W-band data, respectively.

star formation is obscured by dust. Figure A2 shows the comparison of the effective radius between ALMA/870  $\mu\text{m}$  and HST/F160W band, demonstrating the result that the dust emission is more compact than the optical emission. Table 3 shows the 870  $\mu\text{m}$  properties for 74 massive SFGs.

## Appendix B Measurements of Structural Parameters through Visibility Fitting

Using the CASA Toolkit, we simulate ALMA observations to evaluate the uncertainties of the size measurements through visibility fitting. First, we generate elliptical Gaussian models with six free parameters: centroid position, flux density, FWHM, minor-to-major axis ratio  $q_{\text{FIR}}$ , and position angle  $PA_{\text{FIR}}$ . The position angle is defined as counter-clockwise from north in the images. Next, we add them as a mock source to the observed visibility data for two nondetected objects (U4-17264 and U4-21087). The flux density varies from 0.3 mJy to 2.6 mJy with a step size of 0.1 mJy, the FWHM varies from  $0''.1$  to  $1''.5$  with a step size of  $0''.1$ , and the axis ratio varies from 0.2 to 1.0 with a step size of 0.1, resulting in a total of 6280 mock sources. The centroid position is random within the range from  $-3''$  to  $+3''$  from the phase center and the position angle is random. Then, we create intermediate-resolution images in the same way as in Section 2.4 to derive the S/N of the mock sources. When the mock source is detected at  $S/N > 5$ , we fit elliptical Gaussian models to the visibility data using the UVMULTIFIT. The structural parameters derived from the best-fit model are compared to the input parameters in three bins:  $S/N = 5\text{--}6$ ,  $S/N = 10\text{--}11$ , and  $S/N = 15\text{--}16$  (Figure B1).

The simulations demonstrate the flux measurements work well even at  $S/N = 5$  (Figure B1). The uncertainties in the size measurements are typically  $\Delta\text{FWHM} = \pm 0''.2$  at  $S/N = 5$ ,  $\Delta\text{FWHM} = \pm 0''.1$  at  $S/N = 10$ , and  $\Delta\text{FWHM} = \pm 0''.05$  at  $S/N = 15$ . Only when the measured size is as small as  $\text{FWHM} = 0''.1$  at  $S/N = 5$  is it underestimated by a factor of 4. Measuring the axis ratio requires at least  $S/N = 10$  where the uncertainties are  $\Delta q = \pm 0.15$ . It seems reasonable to adopt circular Gaussian models for measuring the size of the dust emission in  $5 < S/N < 10$  sources. The important thing here is that there are no systematic errors in the measurement of size

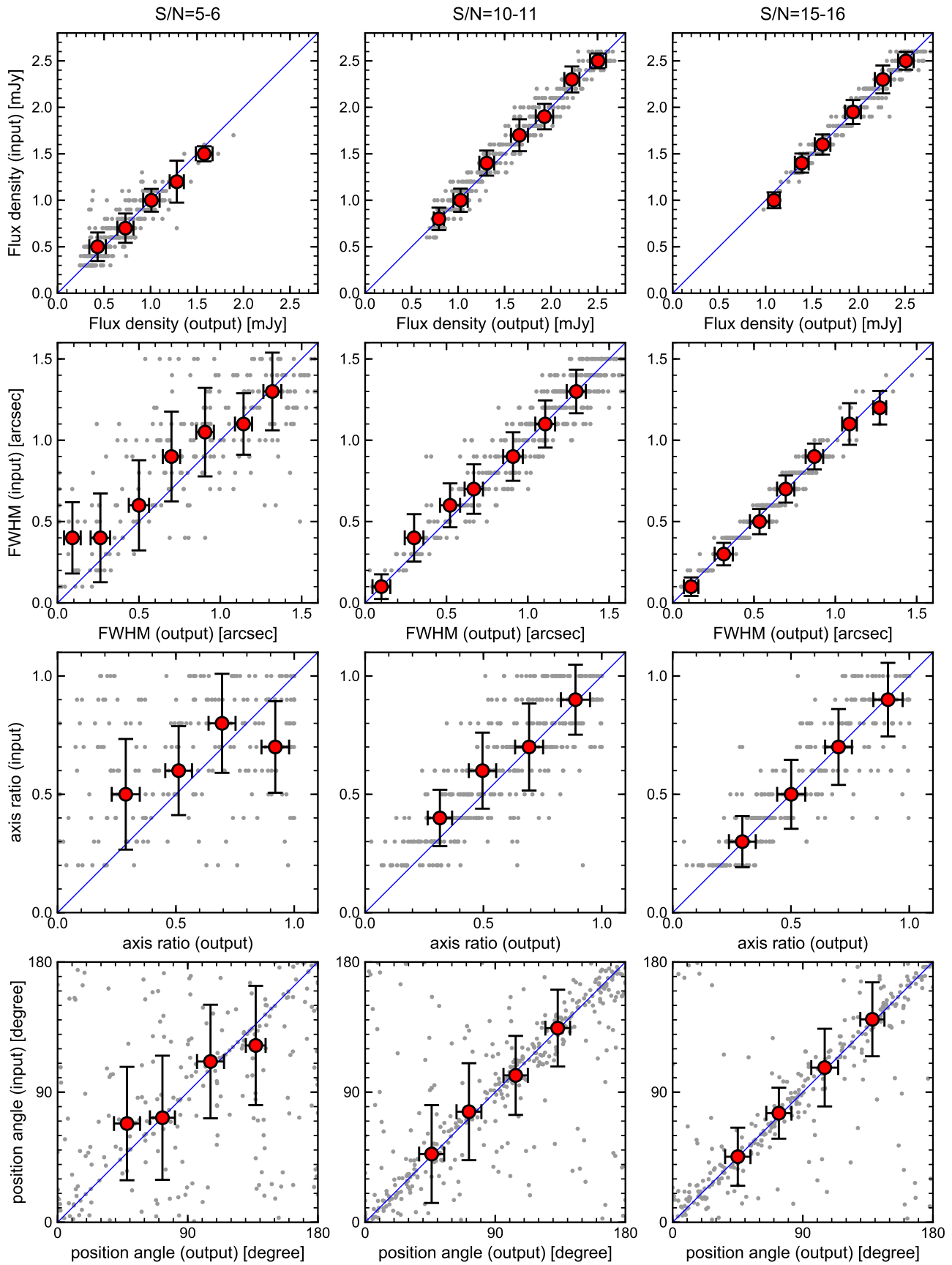
over a wide range from  $\text{FWHM} = 0''.1$  to  $1''.5$  in  $S/N > 10$  conditions. We therefore use only  $S/N > 10$  sources for discussion of the size measurements at 870  $\mu\text{m}$ .

When more than one source is detected in the observed field, we use two- or three-component models for the fitting. We simply assume circular Gaussian models for the second and the third component to reduce the free parameters. Even when taking into account the contribution of additional sources, the measurement results change by only one percent, except for the two cases where a bright companion is located within  $1''.5$  of the primary targets (U4-7472 and U4-36568).

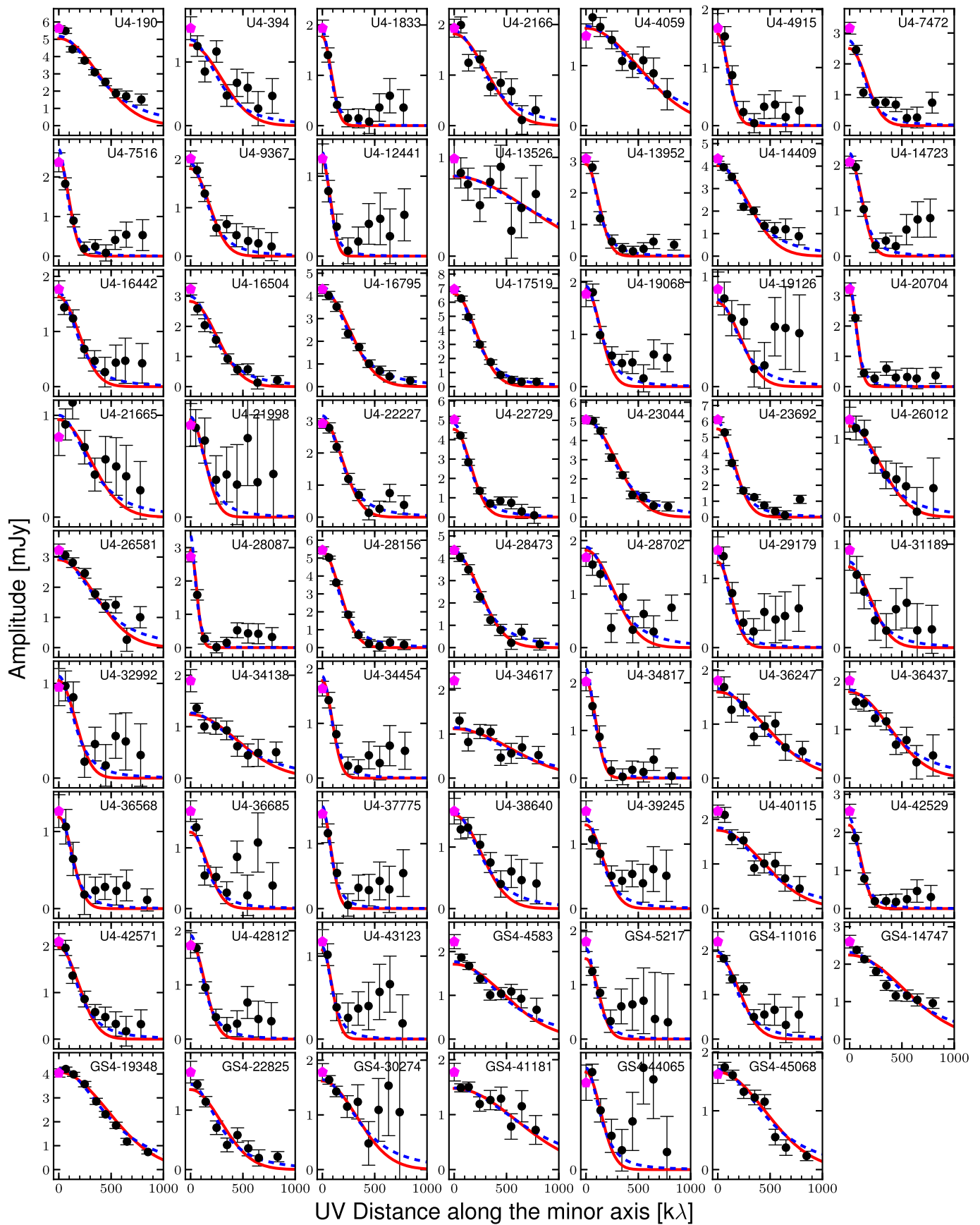
For visualization of the visibility fitting, we compute the  $uv$  distances along the minor axis  $u' v'$  as

$$\begin{aligned} u' &= u \cos \theta - v \sin \theta, \\ v' &= (u \sin \theta + v \cos \theta) \times q_{\text{FIR}}, \text{ and} \\ u'v' &= \sqrt{u'^2 + v'^2}, \end{aligned} \quad (\text{B1})$$

where  $\theta = 90 + PA_{\text{FIR}}$ . The minor axis in the visibility plane corresponds to the major axis in the image. We extract the spatial frequency  $(u, v)$  and the real/imaginary part of individual visibility by using CASA/plotms to derive the  $u' v'$  distance and the amplitudes. The amplitudes are computed as the norm of the visibility vectors, averaged in each  $u' v'$  bin. In the right panels of Figure 5, we show the amplitudes of the visibilities as a function of the  $u' v'$  distance for both cases of compact and extended sources. We note that UVMULTIFIT fits individual visibility data, not the averaged one. In Figure B2, we show the amplitude plots along with the best-fit models for the ALMA sample of 62 galaxies detected at  $S/N > 10$ . They are used only for visually checking the fitting results. The amplitudes of extended sources rapidly decline with  $u' v'$  distance while those of compact sources slowly change. As the Fourier transform of the Gaussian function in the image plane is a Gaussian function in the visibility plane, its spatial extent is derived as  $\text{FWHM}_{\text{image}} [\text{arcsec}] = 182/\text{FWHM}_{\text{visibility}} [k\lambda]$ . Our ALMA observations demonstrate that visibility data at a very high spatial frequency ( $uv > 1000 k\lambda$ ) is inefficient for measuring the size of the dust emission for massive SFGs at  $z \sim 2$  since most of them have  $\text{FWHM}_{\text{image}} > 0''.15$  corresponding to  $uv < 600 k\lambda$ .



**Figure B1.** Comparisons of structural parameters (flux density, FWHM, minor-to-major axis ratio, and position angle) between measurements by fitting to the simulated visibility data (output) and input models in 6280 mock sources. Left, middle, and right panels show the simulation results for sources detected at  $S/N = 5-6$ ,  $S/N = 10-11$ , and  $S/N = 15-16$  in the intermediate-resolution images, respectively. Red circles and the error bars indicate the median and the standard deviation in the bins of output values.



**Figure B2.** Visibility amplitudes vs.  $uv$  distances for our sample of 62 massive SFGs detected at  $S/N > 10$  in the intermediate-resolution images. The symbols are the same as Figure 5.

## Appendix C

### Calculations of the Central Stellar Mass and the Effective Radius

The calculation of the central stellar mass is not straightforward when based on the three-dimensional profile  $\rho$ . Following Bezanson et al. (2009), we deproject the two-dimensional Sérsic profile using an Abel transform:

$$\rho(x) \propto x^{1/n-1} \int_1^\infty \frac{\exp(-b_n x^{1/n} t)}{\sqrt{t^{2n} - 1}} dt \quad (\text{C1})$$







where  $x = r/R_{\text{eff,circ}}$  and  $R_{\text{eff,circ}}$  is given by  $R_{\text{eff}}\sqrt{q}$ . The mass of newly formed stars is given by Equation (5). Then, we numerically compute the central mass as

$$M_{1\text{kpc}} = \int_0^{1\text{kpc}} \rho_{\text{HST}}(x_{\text{HST}}) 4\pi r^2 dr + \int_0^{1\text{kpc}} \rho_{\text{ALMA}}(x_{\text{ALMA}}) 4\pi r^2 dr, \quad (\text{C2})$$

where  $\rho_{\text{HST}}$  and  $\rho_{\text{ALMA}}$  are the three-dimensional mass profiles of already existing and newly formed stars, respectively. The time evolution of the circularized effective radius can be inferred from the two-dimensional mass profiles ( $\Sigma_{\text{HST}}$  and  $\Sigma_{\text{ALMA}}$ ), which are derived from the best-fitting Sérsic profile in the HST and ALMA data, respectively. We numerically compute the circularized effective radius that satisfies

$$\frac{M_* + M_{*,\text{new}}}{2} = \int_0^{R_{\text{eff,circ}}} \Sigma_{\text{HST}}(r) 2\pi r dr + \int_0^{R_{\text{eff,circ}}} \Sigma_{\text{ALMA}}(r) 2\pi r dr. \quad (\text{C3})$$

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### References

Barro, G., Faber, S. M., Pérez-González, P. G., et al. 2013, *ApJ*, 765, 104  
 Barro, G., Faber, S. M., Pérez-González, P. G., et al. 2014, *ApJ*, 791, 52  
 Barro, G., Kriek, M., Pérez-González, P. G., et al. 2016, *ApJL*, 827, L32

Bell, E. F., van der Wel, A., Papovich, C., et al. 2012, *ApJ*, 753, 167  
 Belli, S., Genzel, R., Förster Schreiber, N. M., et al. 2017, *ApJL*, 841, L6  
 Bezanson, R., van Dokkum, P. G., Tal, T., et al. 2009, *ApJ*, 697, 1290  
 Bournaud, F., Perret, V., Renaud, F., et al. 2014, *ApJ*, 780, 57  
 Bruce, V. A., Dunlop, J. S., Cirasuolo, M., et al. 2012, *MNRAS*, 427, 1666  
 Bruzual, G., & Charlot, S. 2003, *MNRAS*, 344, 1000  
 Calistro Rivera, G., Hodge, J. A., Smail, I., et al. 2018, *ApJ*, 863, 56  
 Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, *ApJ*, 533, 682  
 Chabrier, G. 2003, *PASP*, 115, 763  
 Chen, C.-C., Harrison, C. M., Smail, I., et al. 2020, *A&A*, 635, A119  
 Chen, C.-C., Hodge, J. A., Smail, I., et al. 2017, *ApJ*, 846, 108  
 Cochrane, R. K., Hayward, C. C., Anglés-Alcázar, D., et al. 2019, *MNRAS*, 488, 1779  
 Conselice, C. J. 2014, *ARA&A*, 52, 291  
 Daddi, E., Renzini, A., Pirzkal, N., et al. 2005, *ApJ*, 626, 680  
 Dekel, A., & Burkert, A. 2014, *MNRAS*, 438, 1870  
 Elbaz, D., Leiton, R., Nagar, N., et al. 2018, *A&A*, 616, A110  
 Forbes, J. C., Krumholz, M. R., Burkert, A., & Dekel, A. 2014, *MNRAS*, 438, 1552  
 Förster Schreiber, N. M., Renzini, A., Mancini, C., et al. 2018, *ApJS*, 238, 21  
 Franco, M., Elbaz, D., Béthermin, M., et al. 2018, *A&A*, 620, A152  
 Franx, M., van Dokkum, P. G., Förster Schreiber, N. M., et al. 2008, *ApJ*, 688, 770  
 Fujimoto, S., Ouchi, M., Kohno, K., et al. 2018, *ApJ*, 861, 7  
 Geach, J. E., Dunlop, J. S., Halpern, M., et al. 2017, *MNRAS*, 465, 1789  
 Genzel, R., Tacconi, L. J., Eisenhauer, F., et al. 2006, *Natur*, 442, 786  
 Genzel, R., Tacconi, L. J., Lutz, D., et al. 2015, *ApJ*, 800, 20  
 Goddard, D., Thomas, D., Maraston, C., et al. 2017, *MNRAS*, 466, 4731  
 Grogin, N. A., Kocevski, D. D., Faber, S. M., et al. 2011, *ApJS*, 197, 35  
 Gullberg, B., Smail, I., Swinbank, A. M., et al. 2019, *MNRAS*, 490, 4956  
 Hayward, C. C., Lanz, L., Ashby, M. L. N., et al. 2014, *MNRAS*, 445, 1598  
 Hodge, J. A., Swinbank, A. M., Simpson, J. M., et al. 2016, *ApJ*, 833, 103  
 Ikarashi, S., Ivison, R. J., Caputi, K. I., et al. 2015, *ApJ*, 810, 133  
 Immeli, A., Samland, M., Gerhard, O., & Westera, P. 2004, *A&A*, 413, 547  
 Kennicutt, R. C. J. 1998, *ARA&A*, 36, 189  
 Koekemoer, A. M., Faber, S. M., Ferguson, H. C., et al. 2011, *ApJS*, 197, 36  
 Kriek, M., van Dokkum, P. G., Labbé, I., et al. 2009, *ApJ*, 700, 221  
 Kurk, J., Cimatti, A., Daddi, E., et al. 2013, *A&A*, 549, A63  
 Lang, P., Schinnerer, E., Smail, I., et al. 2019, *ApJ*, 879, 54  
 Lang, P., Wuyts, S., Somerville, R. S., et al. 2014, *ApJ*, 788, 11  
 Law, D. R., Steidel, C. C., Shapley, A. E., et al. 2012, *ApJ*, 745, 85  
 Leja, J., Johnson, B. D., Conroy, C., et al. 2019, *ApJ*, 877, 140  
 Lilly, S. J., & Carollo, C. M. 2016, *ApJ*, 833, 1  
 Lindroos, L., Knudsen, K. K., Vlemmings, W., Conway, J., & Martí-Vidal, I. 2015, *MNRAS*, 446, 3502  
 Lutz, D., Poglitsch, A., Altieri, B., et al. 2011, *A&A*, 532, A90  
 Madau, P., & Dickinson, M. 2014, *ARA&A*, 52, 415  
 Magnelli, B., Popesso, P., Berta, S., et al. 2013, *A&A*, 553, A132  
 Martí-Vidal, I., Vlemmings, W. H. T., Muller, S., & Casey, S. 2014, *A&A*, 563, A136  
 McMullin, J. P., Waters, B., Schiebel, D., Young, W., & Golap, K. 2007, in *ASP Conf. Ser. 376, CASA Architecture and Applications*, ed. R. A. Shaw, F. Hill, & D. J. Bell (San Francisco, CA: ASP), 127  
 Momcheva, I. G., Brammer, G. B., van Dokkum, P. G., et al. 2016, *ApJS*, 225, 27  
 Mosleh, M., Tacchella, S., Renzini, A., et al. 2017, *ApJ*, 837, 2  
 Mowla, L. A., van Dokkum, P., Brammer, G. B., et al. 2019, *ApJ*, 880, 57  
 Naab, T., Johansson, P. H., & Ostriker, J. P. 2009, *ApJL*, 699, L178  
 Nelson, E., van Dokkum, P., Franx, M., et al. 2014, *Natur*, 513, 394  
 Nelson, E. J., Tadaki, K.-i., Tacconi, L. J., et al. 2019, *ApJ*, 870, 130  
 Nelson, E. J., van Dokkum, P. G., Förster Schreiber, N. M., et al. 2016a, *ApJ*, 828, 27  
 Nelson, E. J., van Dokkum, P. G., Momcheva, I. G., et al. 2016b, *ApJL*, 817, L9  
 Newman, A. B., Belli, S., Ellis, R. S., & Patel, S. G. 2018a, *ApJ*, 862, 125  
 Newman, A. B., Belli, S., Ellis, R. S., & Patel, S. G. 2018b, *ApJ*, 862, 126  
 Newman, A. B., Ellis, R. S., Bundy, K., & Treu, T. 2012, *ApJ*, 746, 162  
 Noguchi, M. 1999, *ApJ*, 514, 77  
 Pavesi, R., Sharon, C. E., Riechers, D. A., et al. 2018, *ApJ*, 864, 49  
 Peng, Y.-j., Lilly, S. J., Kovač, K., et al. 2010, *ApJ*, 721, 193  
 Popesso, P., Dickinson, M., Nonino, M., et al. 2009, *A&A*, 494, 443  
 Price, S. H., Kriek, M., Feldmann, R., et al. 2017, *ApJL*, 844, L6  
 Retzlaff, J., Rosati, P., Dickinson, M., et al. 2010, *A&A*, 511, A50  
 Rujopakarn, W., Daddi, E., Rieke, G. H., et al. 2019, *ApJ*, 882, 107  
 Rujopakarn, W., Dunlop, J. S., Rieke, G. H., et al. 2016, *ApJ*, 833, 12  
 Scoville, N., Sheth, K., Aussel, H., et al. 2016, *ApJ*, 820, 83

- Sérsic, J. L. 1963, *BAAA*, **6**, 41
- Simpson, J. M., Smail, I., Swinbank, A. M., et al. 2015a, *ApJ*, **807**, 128
- Simpson, J. M., Smail, I., Swinbank, A. M., et al. 2015b, *ApJ*, **799**, 81
- Skelton, R. E., Whitaker, K. E., Momcheva, I. G., et al. 2014, *ApJS*, **214**, 24
- Stach, S. M., Dudzevičiūtė, U., Smail, I., et al. 2019, *MNRAS*, **487**, 4648
- Suess, K. A., Bezanson, R., Spilker, J. S., et al. 2017, *ApJL*, **846**, L14
- Suess, K. A., Kriek, M., Price, S. H., & Barro, G. 2019, *ApJ*, **877**, 103
- Suzuki, T. L., Minowa, Y., Koyama, Y., et al. 2019, *PASJ*, **71**, 69
- Szokoly, G. P., Bergeron, J., Hasinger, G., et al. 2004, *ApJS*, **155**, 271
- Tacchella, S., Carollo, C. M., Förster Schreiber, N. M., et al. 2018, *ApJ*, **859**, 56
- Tacchella, S., Carollo, C. M., Renzini, A., et al. 2015, *Sci*, **348**, 314
- Tacchella, S., Dekel, A., Carollo, C. M., et al. 2016, *MNRAS*, **457**, 2790
- Tacconi, L. J., Genzel, R., Saintonge, A., et al. 2018, *ApJ*, **853**, 179
- Tadaki, K.-i., Genzel, R., Kodama, T., et al. 2017a, *ApJ*, **834**, 135
- Tadaki, K.-i., Iono, D., Hatsukade, B., et al. 2019, *ApJ*, **876**, 1
- Tadaki, K.-i., Iono, D., Yun, M. S., et al. 2020, *ApJ*, **889**, 141
- Tadaki, K.-i., Kodama, T., Nelson, E. J., et al. 2017b, *ApJL*, **841**, L25
- Tadaki, K.-i., Kodama, T., Tanaka, I., et al. 2013, *ApJ*, **778**, 114
- Tadaki, K.-i., Kohno, K., Kodama, T., et al. 2015, *ApJL*, **811**, L3
- Toft, S., Zabl, J., Richard, J., et al. 2017, *Natur*, **546**, 510
- Trujillo, I., Feulner, G., Goranova, Y., et al. 2006, *MNRAS*, **373**, L36
- Umehata, H., Smail, I., Swinbank, A. M., et al. 2020, *A&A*, **640**, 8
- Utomo, D., Kriek, M., Labbé, I., Conroy, C., & Fumagalli, M. 2014, *ApJL*, **783**, L30
- van der Wel, A., Bell, E. F., Häussler, B., et al. 2012, *ApJS*, **203**, 24
- van der Wel, A., Franx, M., van Dokkum, P. G., et al. 2014, *ApJ*, **788**, 28
- van Dokkum, P. G., Bezanson, R., van der Wel, A., et al. 2014, *ApJ*, **791**, 45
- van Dokkum, P. G., Franx, M., Kriek, M., et al. 2008, *ApJL*, **677**, L5
- van Dokkum, P. G., Nelson, E. J., Franx, M., et al. 2015, *ApJ*, **813**, 23
- Wang, T., Schreiber, C., Elbaz, D., et al. 2019, *Natur*, **572**, 211
- Whitaker, K. E., Franx, M., Bezanson, R., et al. 2015, *ApJL*, **811**, L12
- Whitaker, K. E., Franx, M., Leja, J., et al. 2014, *ApJ*, **795**, 104
- Whitaker, K. E., Labbé, I., van Dokkum, P. G., et al. 2011, *ApJ*, **735**, 86
- Whitaker, K. E., Pope, A., Cybulski, R., et al. 2017, *ApJ*, **850**, 208
- Williams, C. C., Giavalisco, M., Cassata, P., et al. 2014, *ApJ*, **780**, 1
- Williams, C. C., Labbe, I., Spilker, J., et al. 2019, *ApJ*, **884**, 154
- Wilman, D. J., Fossati, M., Mendel, J. T., et al. 2020, *ApJ*, **892**, 1
- Wisnioski, E., Förster Schreiber, N. M., Fossati, M., et al. 2019, *ApJ*, **886**, 124
- Wisnioski, E., Förster Schreiber, N. M., Wuyts, S., et al. 2015, *ApJ*, **799**, 209
- Wisnioski, E., Mendel, J. T., Förster Schreiber, N. M., et al. 2018, *ApJ*, **855**, 97
- Wuyts, S., Förster Schreiber, N. M., Genzel, R., et al. 2012, *ApJ*, **753**, 114
- Wuyts, S., Förster Schreiber, N. M., Lutz, D., et al. 2011a, *ApJ*, **738**, 106
- Wuyts, S., Förster Schreiber, N. M., van der Wel, A., et al. 2011b, *ApJ*, **742**, 96
- Wuyts, S., Labbé, I., Förster Schreiber, N. M., et al. 2008, *ApJ*, **682**, 985
- Wuyts, S., Labbé, I., Franx, M., et al. 2007, *ApJ*, **655**, 51
- Yamaguchi, Y., Kohno, K., Hatsukade, B., et al. 2019, *ApJ*, **878**, 73
- Zolotov, A., Dekel, A., Mandelker, N., et al. 2015, *MNRAS*, **450**, 2327