Uncovering Early Galaxy Evolution in the ALMA and JWST Era
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Serendipitous discovery of an "ALMA-only" galaxy at $5 < z < 6$ in an ALMA 3-mm survey

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Abstract. We discuss the serendipitous discovery of a dusty high-redshift galaxy in a small (8 arcmin^2) ALMA 3-mm survey Williams *et al.* (2019). The galaxy was previously unknown and is absent from existing multi-wavelength catalogs ("ALMA-only"). Using the ALMA position as prior, we perform forced deblended photometry to constrain its spectral energy distribution. The spectral energy distribution is well described by a massive ($M^* = 10^{10.8}$M$_\odot$) and highly obscured ($A_V \sim 4$) galaxy at redshift $z = 5.5 \pm 1.1$ with star formation rate ∼300 M$_\odot$yr^{-1}. Our small survey area implies an uncertain but large contribution to the cosmic star formation rate density, similar to the contribution from all ultraviolet-selected galaxies combined at this redshift. This galaxy likely traces an abundant population of massive galaxies absent from current samples of infrared-selected or sub-millimeter galaxies, but with larger space densities, higher duty cycles, and significant contribution to the cosmic star-formation rate and stellar mass densities.

Keywords. galaxies: formation, galaxies: evolution, galaxies: high-redshift

1. Introduction

Single dish sub-millimeter surveys have discovered dust-obscured star-forming galaxies (Casey, Narayanan & Cooray *et al.* 2014) that contribute significantly to the cosmic star formation rate density at $1 < z < 3$ (Madau & Dickinson 2014). However, beyond $z > 3$ our view of the dust-obscured Universe is incomplete, with only the brightest and most extreme galaxies identified at $z > 4$ (e.g. Marrone *et al.* 2018). Gravitational lensing has enabled the discovery of some dusty galaxies beyond $z > 5$ (Spilker *et al.* 2016; Zavala *et al.* 2018a), but the lensing correction and selection effects make it difficult to measure how much they contribute to the cosmic star formation rate density. Thus the complete census of star formation in the early Universe including the fraction that is dust obscured is unknown.

Selection at longer wavelengths ($\lambda > 2$ mm) is thought to optimize for the identification of dust-obscured star formation at redshift $z > 4$ (Béthermin *et al.* 2015; Casey *et al.* 2018), which could help select dust-obscured galaxies for census studies. Relatively few surveys at such long wavelength exist compared to the multitude of large and deep surveys at sub-millimeter wavelengths (850μm-1mm). However, ALMA 3-mm surveys to date have so far predominantly identified low redshift sources ($z < 3$; González-López *et al.* 2019; Zavala *et al.* 2018b), similar redshifts to sub-millimeter surveys. Observations with IRAM/GISMO indicate that $\lambda > 2$mm surveys could select higher-redshift sources (Magnelli *et al.* 2019), but counterpart identification to establish redshifts is difficult because of the large beam sizes of single-dish observatories. Nonetheless, relatively few

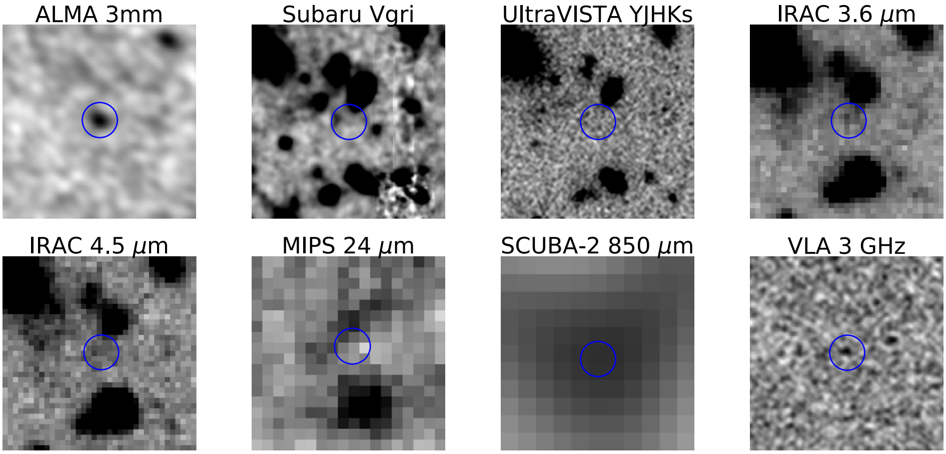

Figure 1. Cutouts (20″x20″) centered at the 3-mm position of the ALMA-only galaxy (blue circle; 3″ diameter). The galaxy is not detected (>3σ) in deep optical and near-IR stacks, or *Spitzer*, *Herschel*, and 850μm. Including the ALMA position as a prior when measuring the photometry results in marginal 2$-$3σ measurements at 3.6+4.5 and 850μm, and a marginal detection at 3GHz (4σ). Figure adapted from (Williams *et al.* 2019).

dust-obscured candidates exist at z > 4. Therefore the amount of dust-obscured star formation in the early universe is still unconstrained.

In a recent ALMA Band 3 survey targeting CO(2-1) molecular gas emission in unrelated quiescent galaxies at $z \sim 1.5$ (Williams *et al.* in prep.), we serendipitously identified two previously unknown galaxies from our ALMA 3-mm imaging (Williams *et al.* 2019). Our survey size (8 arcmin^2) is comparable to deep field campaigns by ASPECS (González-López *et al.* 2019) and therefore represents an opportunity to investigate the prevalence of high-redshift dust-obscured galaxies. In this proceeding, we summarize the SED properties of one of the blindly selected 3-mm sources and the evidence for high-redshift nature, and discuss the implications for our understanding of massive galaxy evolution at $z > 5$ (published in Williams *et al.* 2019).

2. SED properties and modeling

The serendipitously identified galaxy is in the COSMOS field, and has deep coverage at optical-to-radio wavelengths (0.6μm-1.4 GHz), but does not have any counterpart in multi-wavelength catalogs (i.e. "ALMA-only"; see Williams *et al.* 2019 and references therein). Using the ALMA 3-mm position as prior, we perform deblended forced photometry as described in Williams *et al.* (2019). The galaxy is not significantly detected ($< 3\sigma$) from optical to sub-millimeter, with a marginal 4σ detection in the deep 3GHz imaging (Figure 1). The resulting SED is shown in Figure 2. The deep non-detections between $24 - 500\mu$m and the extreme flux ratios between mid- and far-infrared strongly suggest that the peak of the dust emission is at high redshift ($z > 4$). Similar dark sources with extreme flux ratios have also been seen by Cowie *et al.* 2018; Yamaguchi *et al.* 2019.

We use the Bayesian Analysis of Galaxies for Physical Inference and Parameter EStimation (BAGPIPES) code (Carnall *et al.* 2018) to model the SED. We find that the observations are consistent with the SED of a massive $10^{10.8\pm0.4}$M$_\odot$, star forming $SFR = 309^{+241}_{-149}$M$_\odot$/yr, highly obscured $A_V \sim 4^{+1.4}_{-1.0}$ galaxy at very high redshift $z \sim 5.5^{+1.2}_{-1.1}$. The SED fitting results are shown in Figure 2. The Bayesian posterior probability distribution for redshift and the measured infrared luminosity (Log$_{10}$ L$_{IR}$ = 12.6) are well constrained despite the lack of strong detections at any wavelength other than 3-mm.

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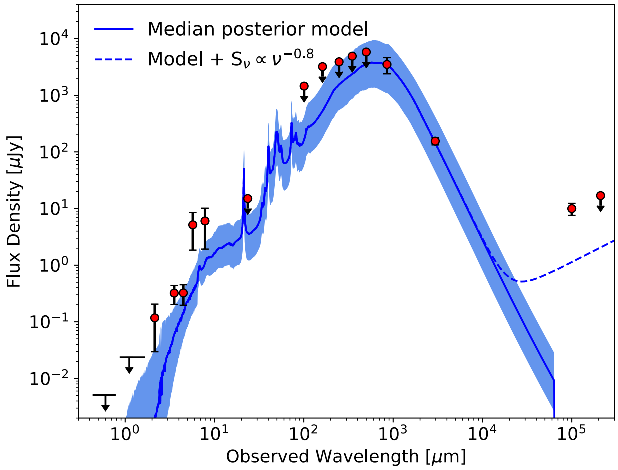

Figure 2. Photometry of the ALMA-only galaxy (red points). Data with signal-to-noise < 1 are shown as upper limits at the 1σ rms value. Photometry with signal-to-noise > 1 is plotted with 1σ uncertainties, but does not necessarily indicate a significant detection. Shown are the median posterior spectrum (dark blue) and 16-84th percentile range (light blue) from BAGPIPES. Dotted line is the radio spectrum predicted from L_{IR} (Tisanić *et al.* 2019), suggesting possible excess radio emission. Figure adapted from (Williams *et al.* 2019).

This result is driven by the deep photometric limits at shorter wavelengths (*Spitzer*/MIPS and *Herschel*/PACS $100-160\mu$m) in combination with the high signal-to-noise ALMA measurement. We also estimate a high molecular gas mass of $M_{gas} \sim 0.5-1.5\times10^{11}$ $M_\odot$, based on the calibration of the sub-millimeter flux density to gas mass (Scoville *et al.* 2016), implying a high inferred gas fraction (∼60%).

3. Contribution to the $z > 4$ galaxy census

This galaxy was identified in a small survey area (8 arcmin^2) which suggests that similar galaxies may be relatively abundant in the early Universe. The implied source density is $0.13^{+0.30}_{-0.10}$ arcmin^{-2}, an order of magnitude higher sub-millimeter galaxies at $z > 4$ which are relatively rare (0.01−0.02 arcmin^{-2}; e.g. Danielson *et al.* 2017; Marrone *et al.* 2018)). Such an abundant population of massive star-forming galaxies would have large impact on our census of star formation rate and stellar mass densities at $z > 4$. Based on our measured star formation rate and the estimated selection volume, we find that the contribution to the cosmic star formation rate density of this one galaxy is ρ_{SFR} $0.9^{+2.0}_{-0.7}\times10^{-2}$ $M_\odot$ yr^{-1} Mpc^{-3} (Figure 3). Bright sub-millimeter galaxies beyond $z > 4$ in comparison contribute about a factor of 10 less (Swinbank *et al.* 2014; Michałowski *et al.* 2017. If this galaxy is representative, similar galaxies could contribute as much to the cosmic star formation rate density as all known ultraviolet-selected galaxies at similar redshifts combined (Williams *et al.* 2019). Dust-obscured star formation could dominate the cosmic star formation history beyond $z > 4$, however, a larger sample is needed for more certain measurements.

The high stellar mass of the galaxy, and its large inferred space density also suggest significant cosmic stellar mass density in similar galaxies at $z \sim 5$: $\rho^* = 1.9^{+4.4}_{-1.5}\times10^6$ $M_\odot$Mpc^{-3} (Williams *et al.* 2019). This is higher than measurements from the rarer, bright ($S_{850} > 4$ mJy) sub-millimeter galaxies ($\approx 0.5\times10^6$ $M_\odot$Mpc^{-3}; Michałowski *et al.* 2017). By comparison, galaxies selected using Hubble Space Telescope contribute $\sim 6.3\times10^6 M_\odot$Mpc^{-3} to the stellar mass density (e.g. Song *et al.* 2016), suggesting

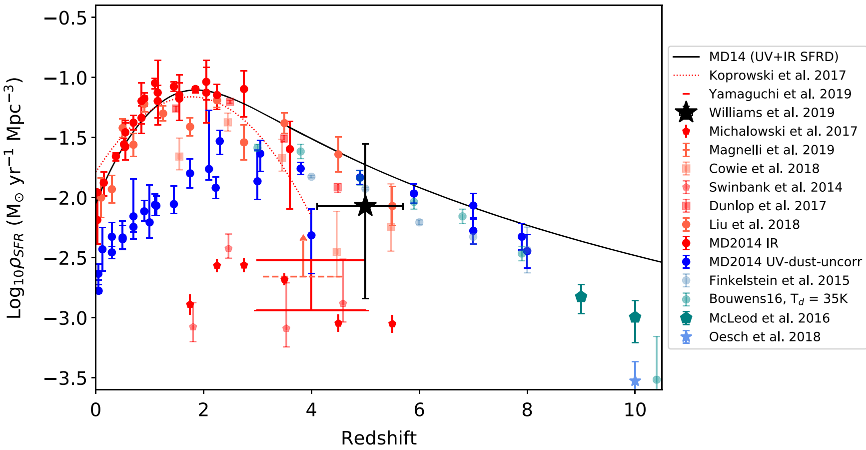

Figure 3. The cosmic star formation history. Blue and green points are measurements based on rest-frame UV (dust un-corrected) and red points are based on star formation rates derived from IR-to-millimeter measurements. In addition to the compilation of Madau & Dickinson (2014; blue circles) we have included later literature measurements $z > 4$ by Finkelstein *et al.* 2015; Bouwens *et al.* 2016; McLeod *et al.* 2016; Oesch *et al.* 2018. We similarly add to the IR compilation of Madau & Dickinson (2014; red circles), with recent constraints at $z > 2$ from Swinbank *et al.* 2014; Koprowski *et al.* 2017; Magnelli *et al.* 2019; Cowie *et al.* 2018; Dunlop *et al.* 2017; Liu *et al.* 2018. The black star indicates the contribution of the “ALMA-only” galaxy Williams *et al.* (2019).

that such galaxies could contribute a significant fraction ($22^{+25}_{-16}\%$) to the total at these redshifts (Williams *et al.* 2019).

Another relevant question is if this galaxy traces a population that could evolve into the earliest known massive quiescent galaxies at $3 < z < 4$ with N$\sim 3 - 5 \times 10^{-5}$ Mpc^{-3} and Log (M/M$_\odot$) $\gtrsim 10.6$ (e.g. Straatman *et al.* 2014). UV-selected galaxies at $z > 4$ are less massive and star forming than necessary to be their progenitors. Similarly, the number densities of bright (> 4 mJy) sub-millimeter galaxies at $z > 4$ are likely too low to be their progenitors ($\sim 0.1 - 3 \times 10^{-6}$ Mpc^{-3} e.g. Michałowski *et al.* 2017). Although sub-millimeter galaxies have large enough star formation rates to rapidly form massive galaxies, their relatively low gas masses indicate very rapid gas depletion timescales ($10 - 100$ Myr; e.g. Aravena *et al.* 2016; Spilker *et al.* 2018). To reconcile rapid gas depletion time with low number density requires large duty cycle corrections. In contrast, the inferred space density of our galaxy is already comparable to the earliest known quiescent galaxies (e.g. Straatman *et al.* 2014). The galaxy has both a large $\sim 10^{11} M_\odot$ gas mass in combination with lower star formation rate, which suggests long depletion timescales compared to sub-millimeter galaxies ($\sim 200 - 500$ Myr). This galaxy may therefore have a longer duty cycle ($\sim 50 - 100\%$; Williams *et al.* 2019). Galaxies such as this one could be evidence for a more gradual path to forming massive galaxies, in contrast to the rapid bursts that are associated with sub-millimeter galaxies (e.g. Pavesi *et al.* 2018; Marrone *et al.* 2018).

Until the *James Webb Space Telescope* (*JWST*) launches, ALMA is the only facility that can study infrared-dark galaxies in detail. Future surveys such as the *JWST* Advanced Deep Extragalactic Survey (JADES) will identify $\sim 15 - 30$ galaxies similar to this galaxy (assuming the measured number densities published in Williams *et al.* 2019; Zavala *et al.* 2018a, for the survey specifications described in Williams *et al.* 2018). In Williams *et al.* 2018, we predicted the number of high-redshift galaxies likely to be identified in *JWST* Cycle 1 from the JADES survey. These predictions are based on the rest-frame UV luminosity functions, which above $z > 4$ is currently the only source of a complete galaxy census. The discovery of infrared-dark galaxies therefore indicates these predicted counts are underestimates, in particular at the massive end of the stellar mass function. With *JWST* it will be possible to fully characterize their stellar population properties and redshifts. *JWST* measurements combined with ALMA observations of star formation, molecular gas, and dust properties will provide powerful constraints on the growth of massive galaxies in the early Universe.

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This proceeding is a summary of work relevant to the symposium previously presented in Williams *et al.* (2018, 2019), to which the reader is referred for further details and the full results. The author acknowledges the important contributions of the co-authors of these publications, without which this proceeding would not be possible.

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