It is well established that (1) star-forming galaxies follow a relation between their star formation rate (SFR) and stellar mass ($M_*$), the “star formation sequence,” and (2) the SFRs of galaxies correlate with their structure, where star-forming galaxies are less concentrated than quiescent galaxies at fixed mass. Here, we consider whether the scatter and slope of the star formation sequence is correlated with systematic variations in the Sérsic indices, $n$, of galaxies across the SFR–$M_*$ plane. We use a mass-complete sample of 23,848 galaxies at $0.5 < z < 2.5$ selected from the 3D-HST photometric catalogs. Galaxy light profiles parameterized by $n$ are based on Hubble Space Telescope Cosmic Assembly Near-IR Deep Extragalactic Legacy Survey near-infrared imaging. We use a single SFR indicator empirically calibrated from stacks of Spitzer/MIPS 24 µm imaging, adding the unobscured and obscured star formation. We find that the scatter of the star formation sequence is related in part to galaxy structure; the scatter due to variations in $n$ at fixed mass for star-forming galaxies ranges from $0.14 \pm 0.02$ dex at $z \sim 2$ to $0.30 \pm 0.04$ dex at $z < 1$. While the slope of the log SFR–log $M_*$ relation is of order unity for disk-like galaxies, galaxies with $n > 2$ (implying more dominant bulges) have significantly lower SFR/$M_*$ than the main rigdeline of the star formation sequence. These results suggest that bulges in massive $z \sim 2$ galaxies are actively building up, where the stars in the central concentration are relatively young. At $z < 1$, the presence of older bulges within star-forming galaxies lowers global SFR/$M_*$, decreasing the slope and contributing significantly to the scatter of the star formation sequence.

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

1. INTRODUCTION

One of the outstanding problems in galaxy formation is understanding the causal relationship between the morphologies and star formation histories of galaxies. There is increasing evidence that galaxies with quiescent stellar populations have significantly smaller sizes and more concentrated light profiles than actively star-forming galaxies at fixed stellar mass out to $z = 2.5$ (Kriek et al. 2009; Williams et al. 2010; Wuyts et al. 2011b; van der Wel et al. 2014). We know that quenching occurs, causing one population to migrate to the other. However, the process(es) that are primarily responsible for the shutdown of star formation are not well understood. It is yet unclear if the well-defined correlation between stellar mass and star formation rate (SFR; e.g., Brinchmann et al. 2004; Noeske et al. 2007; Whitaker et al. 2014; Schreiber et al. 2015, and numerous others) is driven by galaxy mass alone, or if some other parameter, such as surface density (Franx et al. 2008) or bulge mass (Lang et al. 2014), comes into play.

In the nearby universe, Abramson et al. (2014) find that increasing the galaxy bulge mass-fraction lowers the global specific SFR ($\epsilon_{\text{SFR}} \equiv \text{SFR}/M_*$). Their working assumption is that star formation occurs in disks (Kennicutt 1998), and bulges are composed primarily of older stars. While the bulge contributes to the total stellar mass of the galaxy, it does not significantly contribute to the global star formation, thereby depressing the sSFR. This naturally predicts a flattening of the galaxy log SFR–log $M_*$ relation at the massive end where galaxies are bulge-dominated. Whitaker et al. (2014) measure a strong evolution in the slope of the star formation sequence at the massive end, consistent with a flat slope at $z < 0.5$ and a slope close to unity at $z > 2.5$. In other words, even at $z \sim 2$ we are seeing a depression in the global specific SFRs among massive galaxies.

Lang et al. (2014) decomposed the bulges and disks of massive high-redshift galaxies out to $z = 2.5$. They speculate that significant bulge growth precedes the departure from the star formation sequence. Lang et al. further demonstrate that the bulge mass is a more reliable predictor of quiescence than the total stellar mass (see also Bell et al. 2012). To understand the regulation and quenching of star formation in galaxies across cosmic time, we must take these analyses one step further and connect the structural evolution of quiescent and star-forming galaxies with their sSFRs.

Before we can understand the details of how galaxies quench their star formation, we must first synthesize the properties of massive galaxies in a self-consistent manner. Such an analysis...
requires a robust quantification of the rest-frame optical galaxy structural properties and a single indicator for the total obscured and unobscured star formation in galaxies for the entire population. In this Letter, we combine Sérsic index measurements derived from Cosmic Assembly Near-Infrared Deep Extragalactic Legacy Survey (CANDELS)/WFC3 imaging with total UV + IR SFRs, using *Spitzer*/MIPS 24 μm photometry, extending the 24 μm stacking technique presented in Whitaker et al. (2014) to probe a range in structural parameters. We present the trends between galaxy $M_*$, total sSFR, and $n$ at $0.5 < z < 2.5$, exploring the dependence of the slope and scatter of the star formation sequence on galaxy concentration.

In this Letter, we use a Chabrier (2003) initial mass function and assume a ΛCDM cosmology with $Ω_m = 0.3$, $Ω_{Λ} = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. All magnitudes are given in the AB system.

2. DATA AND SAMPLE SELECTION

2.1. Stellar Masses, Redshifts, and Rest-frame Colors

We take advantage of the Hubble Space Telescope (HST)/WFC3 and ACS photometric and spectroscopic datasets in five well-studied extragalactic fields through the CANDELS; (Grogin et al. 2011; Koekemoer et al. 2011) and the 3D-HST survey (Brammer et al. 2012). Using stellar masses, redshifts, and rest-frame colors from the 3D-HST 0.3–8 μm photometric catalogs (see Skelton et al. 2014), we select samples of 9400, 8278, and 6170 galaxies greater than stellar masses of log $M_*/M_☉ =$ 8.8, 9.0, and 9.6 in three redshift intervals of $0.5 < z < 1.0$, $1.0 < z < 1.5$, and $1.5 < z < 2.5$. The galaxies are split into star-forming and quiescent sub-samples based on their rest-frame $U - V$ and $V - J$ colors, following a modified definition of Whitaker et al. (2012a). We have used the *Spitzer*/IRAC color selections presented in Donley et al. (2012) to identify and remove luminous active galactic nuclei (AGNs); 3% of the sample were removed as AGN candidates. We note that the results of this Letter do not depend on this step. The final sample comprises 23,848 galaxies at $0.5 < z < 2.5$.

We indicate the stellar mass limits for which the majority of objects in the sample have $H_{F160W} < 23.5$ (see Section 2.2). These limits are well above the mass-completeness limits presented in Tal et al. (2014), which are determined by comparing object detection in CANDELS/deep with a recombined subset of exposures reaching the CANDELS/wide depth. The stellar masses of star-forming galaxies have been corrected for contamination of the broadband fluxes from emission lines using the values presented in Appendix A of Whitaker et al. (2014). These corrections only become significant at log $M_*/M_☉ < 9.5$ and $z > 1.5$. For example, Whitaker et al. (2014) find that stellar masses of log $M_*/M_☉ =$ 9.5 are overestimated by 0.06 (0.2) dex at $1.5 < z < 2.0(2.0 < z < 2.5)$ because of emission line fluxes.

Where available, we combine the spectral energy distributions with low-resolution HST/WFC3 G141 grism spectroscopy to derive grism redshifts with $Δz/(1 + z) = 0.3\%$ accuracy (Brammer et al. 2012). We select the “best” redshift to be the spectroscopic redshift, grism redshift or the photometric redshift, in this ranked order depending on availability. Photometric redshifts comprise 62% (79%) of the

$0.5 < z < 1.5$ (1.5 < z < 2.5) sample, while 26% (19%) have grism redshifts and 12% (2%) spectroscopic redshifts.

2.2. Morphology

The Sérsic (1968) index is a measure of the shape of the surface brightness profile of a galaxy, indicating the concentration of the light; it has been shown to correlate with quiescence (e.g., de Vaucouleurs 1948; Caon et al. 1993). At $1 < z < 3$, Bruce et al. (2014) demonstrate that $n = 4$ corresponds to a bulge-to-disk ratio of about four in massive galaxies, where ~80% of the light is in the bulge. Exponential disks have $n = 1$ and bulge-to-disk ratios of about a quarter, with 20% of the light in the bulge. The transition from bulge-dominated to disk-dominated occurs around $n = 2$. We caution that we are not directly measuring the bulge mass-fractions, rather adopting $n$ as a proxy for bulge dominance. Furthermore, it is not clear whether this interpretation of $n$ holds at $z ≥ 1$.

$n$ is measured from HST/WFC3 $F_{125W}$ at $0.5 < z < 1.5$ and $H_{F160W}$ at $1.5 < z < 2.5$ (van der Wel et al. 2012). Simulations by van der Wel et al. (2012) show that the systematic errors in $n$ for all galaxy types are <10% for $H_{F160W} < 23.5$, thus motivating our mass limits. It is complicated to correct for the wavelength dependence of $n$ within the redshift bins, we do not correct for this effect but note that $n$ increases by ~10% from 4500 to 8000 Å.

2.3. Total SFRs

Total star formation rates are derived from stacking analyses of *Spitzer*/MIPS 24 μm photometry, following the procedure detailed in Whitaker et al. (2014). The *Spitzer*/MIPS 24 μm images in the AEGIS field are provided by the Far-Infrared Deep Extragalactic Legacy (FIDEL) survey (Dickinson & FIDEL Team 2007), COSMOS from the S-COSMOS survey (Sanders et al. 2007), GOODS-N and GOODS-S from Dickinson et al. (2003), and UDS from the *Spitzer* UKIDSS Ultra Deep Survey14 (SpUDS; PI: J. Dunlop). The analysis code uses a high-resolution $J_{F125W} + H_{F160W} + H_{F160W}$ detection image as a prior to model the contributions from neighboring blended sources in the lower resolution MIPS 24 μm image (Labbé et al. 2010). All galaxies are “cleaned” of the contaminating flux of the neighboring sources before stacking. We refer the reader to Section 3 of Whitaker et al. (2014) for the full details of the MIPS 24 μm stacking analyses. The SFRs derived for quiescent galaxies herein are upper limits, as the 24 μm technique overestimates the SFRs for galaxies with log $sSFR < -$10 yr$^{-1}$, but remains robust above this limit (Hayward et al. 2014; Utomo et al. 2014). For this reason, identifying star-forming galaxies from 24 μm-based sSFRs results in a significant fraction of interloping quiescent galaxies.

3. RESULTS

If increasing bulge mass-fractions result in a flattening of the star formation sequence at the massive end (Abrahamson et al. 2014), we should see a correlation between the $n$, $M_*$, and sSFR. In Figure 1, we show the Sérsic indices of galaxies as a function of their stellar mass, color-coded by the UV + IR sSFRs for all galaxies (left), star-forming only (middle), and

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12 We no longer require $V - J < 1.5$, similar to van der Wel et al. (2014), as this is a false upper limit imposed on the quiescent population. This effects <1% of galaxies.

14 http://irsa.ipac.caltech.edu/data/SPITZER/SpUDS/
quiescent only (right). Indeed, we find a decrease in the sSFRs for galaxies with high $n$ at $\log M_*/M_\odot > 10$. There does not appear to be any dependence of $n$ on the average sSFR for low-mass galaxies with $\log M_*/M_\odot < 10$.

Quiescent galaxies with $\log (M_*/M_\odot) > 10$ tend to have $n > 2$, consistent with bulge-dominated light profiles. Although this finding is not new, we do show for the first time that the analogous star-forming sub-population with similar $n$-values also have depressed sSFRs relative to the bulk of the star-forming population. We also see a low-mass quiescent population at $0.5 < z < 1.0$ with similar (disk-like) Sérsic indices in Figure 1, albeit these galaxies lie close to or below the mass limit. This may suggest that lower-mass galaxies quench their star formation at later times through a more

Figure 1. Sérsic indices of galaxies as a function of stellar mass, color-coded by the sSFRs derived from UV+IR stacking analyses in 0.2 dex bins of $\log M_*/M_\odot$ and 0.5 width bins of $n$. The vertical dashed lines correspond to the stellar mass limits down to which $n$ is robust for color-selected star-forming (blue) and quiescent (red) populations. At fixed stellar mass, galaxies with higher $n$ (implying prominent bulges) and $\log (M_*/M_\odot) > 10$ have lower sSFRs, suggesting that the bulge formation is linked to quiescence. The size of the symbol depends on the number of galaxies, and the underlying grayscale demarcates the opposite population (e.g., star-forming galaxies in the quiescent panels).
The aim of this Letter is to connect rest-frame optical measurements of the $n$–$M_*$ relation for galaxies by log(sSFR) $> -10$ yr$^{-1}$. Whitaker et al. (2012b) demonstrated that a steeper slope of the star formation sequence is measured when selecting blue star-forming galaxies (e.g., Peng et al. 2010). Here, we show explicitly that by selecting galaxies with prominent disks (which often have blue rest-frame optical colors), we measure a slope close to unity across the full range in stellar mass and redshift. We confirm similar results by Wuyts et al. (2011b), and emphasize the critical importance of understanding selection biases.

4. DISCUSSION

The correlation is not statistically significant above $n > 1$. Shifting the UVJ selection redward increasingly weakens the trend. Perhaps the larger photometric errors of quiescent galaxies at high-$z$ scatter some into the intermediate parameter space, which get removed by this test. The $n > 2$ star-forming galaxies well separated from the UVJ line show a similar range of colors to $n < 2$ star-forming galaxies (compare...
Panels D and G, Figure 4). They may also have similar sSFRs, although $n > 3$ star-forming galaxies are not prevalent at the highest masses. Disk-dominated star-forming galaxies are neither preferentially dusty or dust-free; their range in colors in Figure 4 likely reflects the inclination angle through which we view the disk (Patel et al. 2012). The process of forming a significantly massive bulge at $z > 1$ appears to be connected to a transformation in the rest-frame optical galaxy structure and color before the decrease of the global sSFR of galaxies. Panel D in Figure 4 demonstrates that the galaxy morphology is in place at $z \sim 2$ before the reddening of the rest-frame colors associated with passive evolution.

The observation that the correlation between the slope of the star formation sequence and $n$ is weaker among star-forming galaxies at $z > 1$ may tell us something about bulge formation. Traditional bulges may already be in place at $z < 1$. For example, van Dokkum et al. (2014) find little growth in the centers of massive galaxies below $z < 0.8$, but at higher redshifts there is growth at all radii. Furthermore, Nelson et al. (2012) demonstrate that (new) star formation at $z \sim 1$ occurs at all radii in exponential disks. In other words, bulges at $z \lesssim 1$ may already be composed of older stars. The picture is less clear at higher redshifts; it may be that massive galaxies are actively building up their bulges. From Figures 1–3, we see that bulge-dominated galaxies at high-$z$ exist, but do not seem to have a significantly lower global sSFR. If the bulges of massive $z \sim 2$ galaxies are actively forming, the stars will still be young and there should not yet be a strong depression in global sSFRs. Choi et al. (2014) derived stellar ages for a large sample of quiescent galaxies at $0.1 < z < 0.7$ that are consistent with an equivalent single-burst star formation epoch of $z \sim 1.5$, supporting the idea that $z \sim 2$ is an important epoch for the bulge formation for massive galaxies. This does not however tell us anything about how bulges grow. We cannot tell if clumps of stars form in situ and migrate to the bulge due to disk instabilities (e.g., Noguchi 1999; Elmegreen et al. 2008), or some other mechanism.

The best way to decompose the star formation histories of $z \sim 2$ galaxies will be with future spatially resolved studies. For example, Nelson et al. (2015) find that the radial $H\alpha$ profiles of galaxies above the ridge of the star formation sequence are enhanced at all radii, whereas galaxies below have suppressed star formation at all radii. Their results suggests that a global process regulates gas accretion, and the scatter in the star formation sequence is real. It is however unclear why the amount of gas accretion depends on disk mass instead of total mass. In this work, we demonstrate that this scatter may be related in part to $n$. In Figure 2, the scatter of the SFRs between $10 < \log(M/M_\odot) < 11$ for all galaxies ranges from $0.34 \pm 0.09$ dex at $1.5 < z < 2.5$, to $0.43 \pm 0.05$ dex at $1.0 < z < 1.5$, and $0.48 \pm 0.02$ dex at $0.5 < z < 1.0$. When considering UVJ-selected star-forming

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**Figure 3.** Best-fit linear slope $\alpha$ of the log SFR–log $M_*$ relation above the star-forming mass limits depends strongly on $n$ when both star-forming and quiescent galaxies are considered. This trend is weaker for star-forming galaxies only, and may signify active bulge-formation among the most massive galaxies at $z \sim 2$, where the stars in the central concentration are younger. The symbol size represents the number of galaxies $N$. Dotted lines are the best-fit relation from the opposite panel for reference.

**Table 1**

<table>
<thead>
<tr>
<th>Redshift Range</th>
<th>$a$</th>
<th>$b$</th>
<th>$a$</th>
<th>$b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.5 &lt; z &lt; 1.0$</td>
<td>$1.01 \pm 0.03$</td>
<td>$-0.14 \pm 0.01$</td>
<td>$0.93 \pm 0.03$</td>
<td>$-0.08 \pm 0.01$</td>
</tr>
<tr>
<td>$1.0 &lt; z &lt; 1.5$</td>
<td>$1.06 \pm 0.03$</td>
<td>$-0.15 \pm 0.01$</td>
<td>$0.96 \pm 0.03$</td>
<td>$-0.05 \pm 0.02$</td>
</tr>
<tr>
<td>$2.5 &lt; z &lt; 2.5$</td>
<td>$0.95 \pm 0.03$</td>
<td>$-0.15 \pm 0.01$</td>
<td>$0.90 \pm 0.03$</td>
<td>$-0.04 \pm 0.01$</td>
</tr>
</tbody>
</table>

**Note.** Linear fit coefficients parameterizing the evolution of the slope, $\alpha$, of the log SFR–log $M_*$ relation as a function of Sérsic index, $n$, where $\alpha = a + bn$. 

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Figure 3. Best-fit linear slope $\alpha$ of the log SFR–log $M_*$ relation above the star-forming mass limits depends strongly on $n$ when both star-forming and quiescent galaxies are considered. This trend is weaker for star-forming galaxies only, and may signify active bulge-formation among the most massive galaxies at $z \sim 2$, where the stars in the central concentration are younger. The symbol size represents the number of galaxies $N$. Dotted lines are the best-fit relation from the opposite panel for reference.
and note that the 24 contributions of intrinsic and systematic scatter at present, galaxies. However, we are unable to decompose the relative remaining scatter is correlated with variations in \( n \).net al. 2012b introduce \( \sim SFR \) within the redshift bins \( \sim \) \( n \). Connected to the roughly constant 0.34 dex observed scatter of the star formation sequence (Whitaker et al. 2012b), we show that this scatter is driven in part by real differences in \( n \). Random errors will introduce \( \sim 0.05 \) dex scatter, and evolution of the average SFR within the redshift bins \( \sim 0.11–0.14 \) dex (Whitaker et al. 2012b). It may be that a significant portion of the remaining scatter is correlated with variations in \( n \) among galaxies. However, we are unable to decompose the relative contributions of intrinsic and systematic scatter at present, and note that the 24 \( \mu m-L_\text{IR} \) conversion itself could introduce as much 0.25 dex of scatter (Wuyts et al. 2011a).

These results support the claim that we are witnessing the rapid build-up of bulges at \( z \sim 2 \) in massive galaxies. A prominent bulge may be an important condition for quenching to occur (e.g., Bell et al. 2012), at least in massive galaxies. Franx et al. (2008) demonstrated that surface density and inferred velocity dispersion are better correlated with sSFR and color than stellar mass. We will explore these dependencies in an upcoming paper (K. Whitaker et al. 2015, in preparation).

We thank the anonymous referee for a highly constructive report. This work is based on observations taken by the 3D-

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**Figure 4.** Rest-frame \( U - V \) and \( V - J \) colors also reflect a bimodality in the Sérsic index (panel (a)), with bulge-dominated galaxies predominately inhabiting the quiescent region and disk-dominated galaxies in the star-forming region. There do not exist strong trends within the quiescent and star-forming populations. The notable exception is the cross-over region between these two populations, where galaxies tend to be bulge-dominated, matching the quiescent population, while still residing in the star-forming color–color parameter space at \( z < 1 \) (panel (b)). Conversely, at \( z > 1.5 \), star-forming galaxies with high Sérsic indices cover the full color–color parameter space (panel (d)).