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Galaxy Zoo Hubble: the passive disk fraction decreases from $z = 1.0$ to $z = 0.3$ or maybe increases who even knows

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ABSTRACT

1 INTRODUCTION

Passive, red disks represent an unconventional class of galaxies which do not not adhere to the bimodality of the standard color-morphology relationship. It is well-known that most galaxies exist in one of two populations: blue, late-type disks exhibiting active star formation, and red, early-type ellipticals showing little to no signs of recent star formation (Strateva et al. 2001; Baldry et al. 2004; Correa et al. 2017). This division between the two color populations is particularly apparent when visually represented on a color-magnitude or color-color diagram. Galaxies tend to populate into two distinct regions: the "red sequence" in the upper band, which contains predominently early-type galaxies, and the "blue cloud" in the lower, containing mostly late-type spirals.

The relatively tight correlation suggests an evolutionary link between a galaxy's dynamical history (traced by its morphology) and stellar content (traced by its color). In the simplest interpretation, it could be deduced that galaxies tend to begin their lives as young, star-forming disks, until some mechanism (secular or external) causes star-formation to cease while the galaxy simultaneously undergoes a morphological tranformation from disk to spheroidal. The existence of galaxies which are both passive and exhibiting disk structure, however, insists on more nuanced interpretations of this simple model, perhaps by representing a transition phase in the pathway from the blue cloud to the red sequence.

In an effort to determine the physical processes responsible for producing this unconventional class of galaxies, passive disks have been a subject of interest since their initial discovery. In one of the earliest documented reports of this class, van den Bergh (1976) identified a set of spirals in the Virgo cluster which were forming stars "much less vigorously" than the other galaxies of the same type; these were named "anemic spirals". Evidence of low gas-content in these galaxies suggested that environmental factors may have played some role in stripping the gas required to continue star-formation. The properties of red disks have been since investigated in the local Universe (Couch et al. 1998; Lee et al. 2008; Masters et al. 2010), intermediate redshift (Couch et al. 1998; Dressler et al. 1999; Poggianti et al. 1999; Moran et al. 2006; Bundy et al. 2010), and even out to $z \sim 2.5$ (Stockton et al. 2008). They to be more massive than star-forming spirals (Masters et al. 2010), gas-poor (Hughes & Cortese 2009), and reside preferentially in high-density environments (Goto et al. 2003; Cortese & Hughes 2009; Deng et al. 2009).

Things that still need including:

-better segue into possible quenching mechanisms for creation of red disks, how red disks fit into overall quenching paradigm

something mass dependence - and also give insight into what processes may quench or initiate star-formation without inducing a morphological change, or visa versa.

Maybe: Kevin's theory on different quenching mechanisms for different types

A closer look at the populations within the green valley show that the processes causing galaxies to evolve from the blue cloud to red sequence may be very different. Schawinski et al. (2009) studied the morphological distribution (measured by the GZ1 project) of ∼4000 green-valley galaxies, finding that late-type and early-types likely go through two different evolutionary tracks. For late-types, the quenching process is gradual, and initiated by a cutoff of a gas reservoir. Galaxies quenched recently in this way would populate the green valley at $z = 0$, and those which quenched at an earlier time would be currently identified as red passive disks. Whether these red disks continue to evolve into spheroidals via some process after the initial quenching is unclear from a local Universe analysis. For early-types, the quenching is rapid and probably external and violent, thus triggering the morphological change from disk to spheroidal.

Citations for color-morphology at higher redshift: bimodality does exist out to $z \sim 1$ (Bell et al. 2004; Cirasuolo et al. 2007; Mignoli et al. 2009) and possibly beyond (Giallongo et al. 2005; van Dokkum et al. 2006; Franzetti et al. 2007; Cassata et al. 2008). What requires further study is how exactly the proportions change at different epochs.

2 DATA

The parent sample of galaxies in this paper is drawn from the Galaxy Zoo: Hubble (GZH) catalog (Willett et al. 2016), which provides morphological classifications for galaxies sourced from the HST Legacy Surveys. From the main cata-

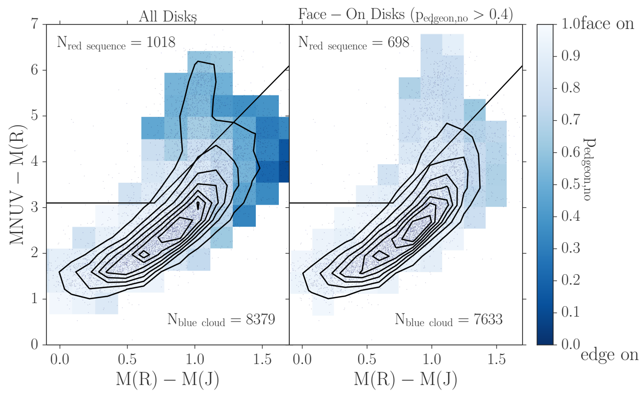

Figure 1.

log we select galaxies with imaging from the Cosmic Evolution Survey (COSMOS, Scoville et al. (2007)) in the redshift range $0 < z < 1$. Rest frame NUV-r and r-J colors are taken from the UltraVISTA catalog (McCracken et al. 2012; Ilbert et al. 2013).

2.1 Selecting passive disk galaxies

We identify a sample of non-clumpy disk galaxies using the morphological classifications provided by GZH. The sample includes subjects which meet the following criteria: $f_{features} > 0.30$ and $f_{clumpy,no} > 0.30$, where f is the debiased vote fraction. We also require at least 20 votes for each question ($N_{smooth\ or\ features} \geqslant 20$ and $N_{clumpy} \geqslant 20$) to reduce uncertainty in the vote fractions.

To classify the galaxies as quiescent or star-forming, a method similar to that described by Ilbert et al. (2013) (hereafter I13) was used, which implements a rest-frame NUV-r^+ versus r^+-J diagnostic. Here are some reasons these colors are great (NUV-r:) (Arnouts et al. 2007; Salim et al. 2005; Wyder et al. 2007),(Martin et al. 2007)

The demarcation line to separate the quiescent and active populations at $z = 1$ is adopted from I13, which defines the quiescent galaxies as those which satisfy: $M_{NUV} - M_{r^+} > 3(M_{r^+} - M_J) + 1$ and $M_{NUV} - M_{r^+} > 3.1$. I13 applies this criteria to all galaxies in a range of $0.2 < z < 3$, although it performs best at separating the two populations in the redshift bin $0.7 < z < 1.2$, where $> 98\%$ of galaxies identified as quiescent exhibited star formation rates less than $log(SFR) = -11$ (see Figure 3 of I13). Therefore this work uses the I13 separation criteria at $z = 1$, and computes the evolution of the demarcation lines as a function of redshift to $z = 0$.

The evolution of $r-J$ and $NUV-r$ colors was measured using a stellar population synthesis model from Bruzual & Charlot (2003). An instantanious-burst model (ssp) was chosen from the Padova1994 track to represent the color evolution of a passively evolving galaxy, with a metallicity $Z = 0.008 = .4Z_{\odot}$, which is the typical metallicity of passive galaxies with mass $9 < log(M_*/M_{\odot}) < 10$ (Peng et al. (2015), Figure 2a), chosen to correspond to the median mass of the sample ($log(M_*/M_{\odot}) = 9.7$). A linear fit was generate for each color within the range $0 < z < 2$, and the slopes for each were used to redefine the demarcation lines in five redshift bins: one with central value $z = 0.007$ (used to classify the SDSS ferengi2 sample), and four with central values z = [0.30,0.50,0.70,0.90] with widths $\Delta z = 0.2$. The quiescent galaxies are thus defined in these bins as those that satisfy:

$$M_{NUV} - M_{r^+} > 3.1 + a_1(z) \quad (1)$$

$$M_{NUV} - M_{r^+} > 3(M_{r^+} - M_J + a_2(z)) + a_1(z) + 1 \quad (2)$$

where $a_1(z) = [0.54, 0.38, 0.27, 0.16, 0.05]$ and $a_2(z) = [0.19, 0.14, 0.10, 0.06, 0.02]$.

3 CORRECTING FOR INCOMPLETENESS IN DISK DETECTION

In this work, we study the growth of the red sequence population by evaluating the fraction of passive disks as a function of redshift, $N_{red\ disks}/(N_{red\ disks} + N_{blue\ disks})$, as well as the fraction of disks occupying the red sequence, $N_{red\ disks}/(N_{red\ disks} + N_{red\ ellipticals})$. To accurately measure these fractions, the number of disks populating each redshift interval must be known with confidence. To identify disk galaxies in our sample, we set a cut of $f_{features} \geqslant 0.3$, such that galaxies meeting this criteria are considered to have distinguishable features or disk structure (additional cuts are also placed to eliminate clumpy, highly inclined, and merging galaxies; see Section 2.1). However, it is known that distinguishing disk structure from spheroidal becomes increasingly challenging at high redshifts (for both experts and novice classifiers alike), where features are less resolved and more difficult to identify. Willett et al. (2016) show using a set of artificially-redshifted simulated galaxy images classified in Galaxy Zoo that vote fractions for the same galaxy can be drastically different measured at $z = 1$ from $z = 0$, often enough to change its morphological classification (we will show the same in Section 3.1). Therefore it is predicted that applying a $f_{features}$ cut to identify disks will increasingly underestimate their true number at increasing redshift intervals. A set of artificially redshifted images was used to quantify and correct for this incompleteness in disk detection, described in the next section.

3.1 FERENGI2 set of artificially redshifted galaxy images

FERENGI2 is a set of simulated galaxy images created using the FERENGI code (Barden et al. 2008). These were created from a parent sample of 936 nearby ($z < 0.01$) SDSS galaxies, all of which had been previously classified in Galaxy Zoo 2 and were cross-matched in 2MASS (Skrutskie et al. 2006) for J magnitudes and GALEX (Martin et al. 2005) for NUV magnitudes, which were necessary to create a color-color separation using a method as similar as possible to that of the COSMOS sample. An evolution factor of $e = -1$ was applied, which brightens each galaxy linearly with redshift: $M' = M + ez$, where M' is the corrected magnitude. This correction is performed to mimic the known physical increase of galaxy magnitude with redshift (Lilly et al. 1998; Loveday et al. 2011), and the value $e = -1$ was chosen

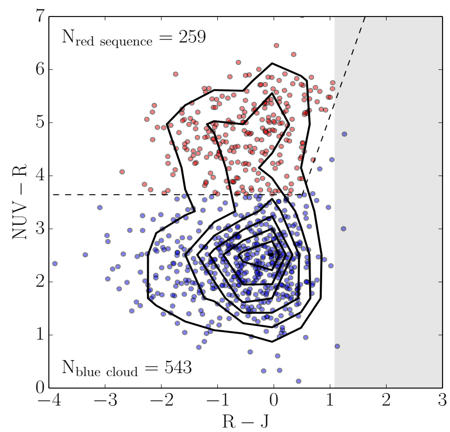

Figure 2. Separation of the quiescent population (red sequence) and active population (blue cloud) of the FERENGI2 sample. The gray shaded region represents the R-J limit of the sample; since FERENGI2 is a subset of GZ2, for which a limit of $r < 17$ was implemented, and the magnitude limit of 2MASS is $J < 15.91$, the FERENGI2 sample is limited to R-J < 1.1.

based on an analysis of spectra template models provided by Brinchmann et al. (2004), which showed that typical galaxies tend to evolve in brightness by one magnitude per redshift. Each galaxy was artificially redshifted 8 times from $z = 0.3$ to $z = 1$ in intervals of $\Delta z = 0.1$ and processed to mimic *HST* imaging parameters, giving a total of 7,488 images (3 examples are shown in Figure 3). The set was then classified in Galaxy Zoo using the same decision tree as used for Galaxy Zoo Hubble. 134 highly inclined disk galaxies were removed from the sample by excluding any with $N_{edgeon} > 20$ and $f_{not\ edge-on} >= 0.6$, using the vote fraction associated with the real galaxy image measured in GZ2. This cut was shown in Galloway et al. (2015) to correlate well with inclination angle $cos(a/b) < 67°$. This was to exclude those which may be mis-classified due to dust-reddening. Using the NUV-J-R selection method described in section 2.1, the remaining sample was divided into a set of red sequence galaxies (259 per redshift bin) and blue cloud (543 per each redshift bin) (see Figure 2).

3.2 Measuring ξ

The FERENGI2 set was used to measure the incompleteness in disk detection, from which a correction factor ξ was derived. This is defined as the number of disks detected divided by the true number of disks expected to exist in a given redshift interval: $\xi(\mathrm{z}) = \mathrm{N_{detected}}/\mathrm{N_{true}}$. Acknowledging that the completeness in disk detection may depend on galaxy color, the corrected fraction of passive disks can then be calculated as:

$$f_{R|D} = \frac{N_{RD} \times \xi_{red}^{-1}}{N_{RD} \times \xi_{red}^{-1} + N_{BD} \times \xi_{blue}^{-1}} \qquad (3)$$

If there is no color bias in disk detection, $\xi_{red} = \xi_{blue}$, and this term cancels out, leaving the fraction unchanged. If there is a bias, however, the ξ terms do not cancel, and the incompleteness in disk detection could have a large effect on the red disk fraction. Therefore a careful measurment of ξ is estimated for both red and blue disk galaxies using the FERENGI2 set of simulated images.

The completness values $\xi_{red}(z)$ and $\xi_{blue}(z)$ were computed in varying bins of redshift for the red sequence and blue cloud galaxies separately. An example calculation of ξ_{blue} in the $z = 0.7$ bin is shown in Figure 4. Each point represents a FERENGI2 galaxy, where the y-axis indicates the value of f_{features} measured in the image redshifted to $z = 0.7$, and the x-axis indicates the value of f_{features} measured in the same galaxy redshifted to $z = 0.3$. Disk galaxies are identified as those for which $f_{\text{features}} \geqslant 0.3$. Since, on average, f_{features} decreases for the same galaxy as it is viewed at higher redshifts, the number of galaxies meeting this threshold is generally fewer at higher redshifts than lower redshifts. This is indicated by the dotted lines: galaxies to the right of the vertical dashed line at $\mathrm{f_{features,z=0.3}} = 0.3$ are identified as disks at $z = 0.3$; their sum is considered the "true" number of disks, $\mathrm{N_{true}}$. Similarly, the galaxies above the horizontal line at $\mathrm{f_{features,z=0.7}} = 0.3$ are identified as disks at $z = 0.7$; their sum is the "detected" number of disks at $z = 0.7$, or $\mathrm{N_{detected}}$. As obvious in the figure, $\mathrm{N_{detected}}$ is in general much lower than $\mathrm{N_{true}}$, emphasizing the increasing difficulty in detecting features at higher redshifts. Their ratio is the completeness ξ; in this example $\xi_{blue}(z = 0.7) = 0.61$, meaning only 61% of disks were detected at this redshift.

It was hypothesized that the completeness in disk detection may be a function of other parameters in addition to redshift. At fixed redshift, for example, it is reasonable to guess that features could be easier to detect galaxies that have higher mass, radius, or surface brightness. To test whether these parameters also impact the number of disks detected, the completeness was measured in fixed redshift bins as a function of surface brightness, effective radius, and mass. The surface brightness was calculated as $\mu = m + 2.5 * \log_{10}(2 \times (b/a) \times \pi R_e^2)$, using SExtractor outputs `MAG_AUTO`, b/a and R_e measured in the I_{814W} band images. The effective radius used was the 50% `FLUX_RADIUS` converted in to kpc, and the masses used were the `MEDIAN` values in the MPA-JHU DR7 catalog (Kauffmann et al. 2003).

Figure 5 shows completeness as a function of redshift and surface brightness, for the red sequence and blue cloud galaxies. 8 redshift bins were further divided into bins of surface brightness with varying widths, where the sizes were chosen to satisfy that $\mathrm{N_{detected}} + \mathrm{N_{true}} \geqslant 10$ in each bin. This was chosen as a comprimise between having a sufficient number of galaxies in each bin to compute the completness fraction $\xi = \mathrm{N_{detected}}/\mathrm{N_{true}}$, and to have enough bins of surface brightness to measure a trend with confidence of completeness as a function of μ. Visual inspection of the data did not suggest any relationship between the two. To be sure, the data were fit to a linear function in each redshift bin. For each fit, a p-value representing a hypothesis test whose null hypothesis is that the slope is zero was computed. Only one reached the criteria $p < 0.05$, but with a low R^2 value of 0.28 which is not considered large enough to represent a good fit. This process was repeated using effective radius and mass as parameters, with the same results. Therefore only redshift was used as a parameter which impacted completeness value with confidence.

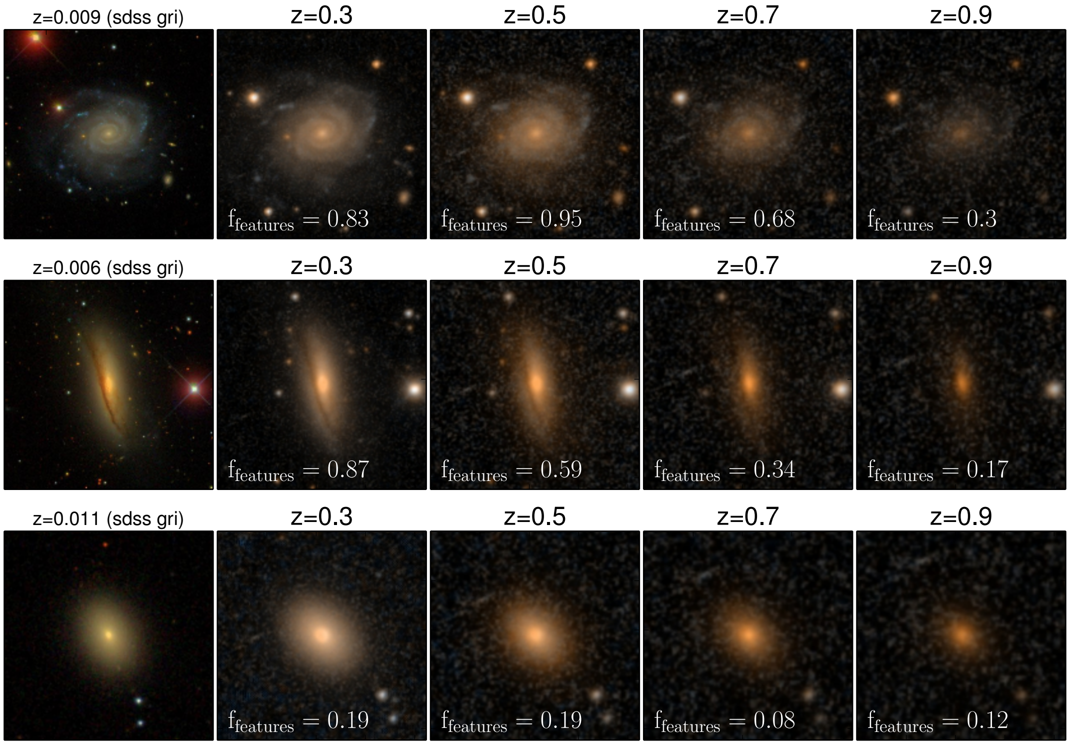

Figure 3. Example images of three galaxies artificially redshifted with the FERENGI code. The left image in each row is a real SDSS gri-composite image; the four to the right are images generated by FERENGI at varying redshifts, processed to mimic *HST/COSMOS* imaging. The $f_{\rm features}$ vote fraction for each simulated image is given; this value tends to decrease for each galaxy as it is processed to be viewed at higher redshifts.

The completeness values $\xi_{\rm red}$ and $\xi_{\rm blue}$ were then measured as a function of redshift for the red sequence and blue cloud FERENGI2 galaxies; results are shown in Figure 6. No significant difference was detected for the two functions, which is apparent from the overlapping $1-\sigma$ errors on the plot. Therefore ξ was computed for all galaxies in bins of redshift between 0.3 and 1.0 with widths $\Delta z = 0.1$; from here a linear relationship for ξ as a function of redshift was derived: $\xi(z) = -0.9 \pm x(z) + 1.2 \pm y$. This correction was used to calculate the fraction of disks on the red sequence:

$$f_{D|R} = \frac{N_{RD} \times \xi^{-1}}{N_{RD} + N_{RE}} \tag{4}$$

4 RESULTS

In this section we present our results of the evolution of disc galaxies from $z = 1$ to $z = 0.2$ in a sample of 27,355 *COSMOS* galaxies morphologically classified in GZH. We will show x, y, and z and talk about it.

4.1 The evolving passive disk fractions: $f_{R|D}$ and $f_{D|R}$

The change in the relative number densities of active/passive disk/elliptical galaxies traces the dominant evolutionary pathways they follow at different mass thresholds. In Figure 7 we measure these using the fractions defined in the previous section, $f_{R|D}$ (left panel) and $f_{D|R}$ (right panel) for four mass bins. We observe significantly different trends in $f_{R|D}$ for the two highest mass bins ($log(M/M_\odot) > 10.7$): for higher-mass galaxies, the fraction of red disks vs. all disks, within error, is either relatively flat or exhibits a small decrease, while the lower-mass galaxies have trends which increase sharply from $z = 1$ to $z = 0.3$. Similarly for the fraction of red disks on the red sequence: the highest mass bin $log(M/M_\odot) > 11.0$ decreases in $f_{D|R}$, while the lowest-mass bin increases sharply from $f_{D|R} \sim 0.05$ to ~ 0.2.

To gain a more intuitive understanding of how the trends of these fractions depend on the different possible evolutionary pathways and their transition rates, it is helpful to rewrite them in a reduced form: $f_{R|D} = (1 + \frac{N_{BD}}{N_{RD}})^{-1}$; $f_{D|R} = (1 + \frac{N_{RE}}{N_{RD}})^{-1}$. Using the former as an example: at zeroth order, it can be seen that if the number of red disks increases at a higher rate than an increase in blue disks in some time interval, the overall fraction $f_{R|D}$ would also increase. For a single mass bin, this scenario would be consistent with a model in which blue galaxies are quenching faster than they are entering the mass bin via star formation. A strong decrease in $f_{R|D}$ would, in constrast, indicate a higher rate of red disks exiting the mass bin than the blue disks; the strength of the decrease would depend on the relative frequencies of blue galaxies quenching to form new red disks and red disks merging to form red ellipticals. The pre-

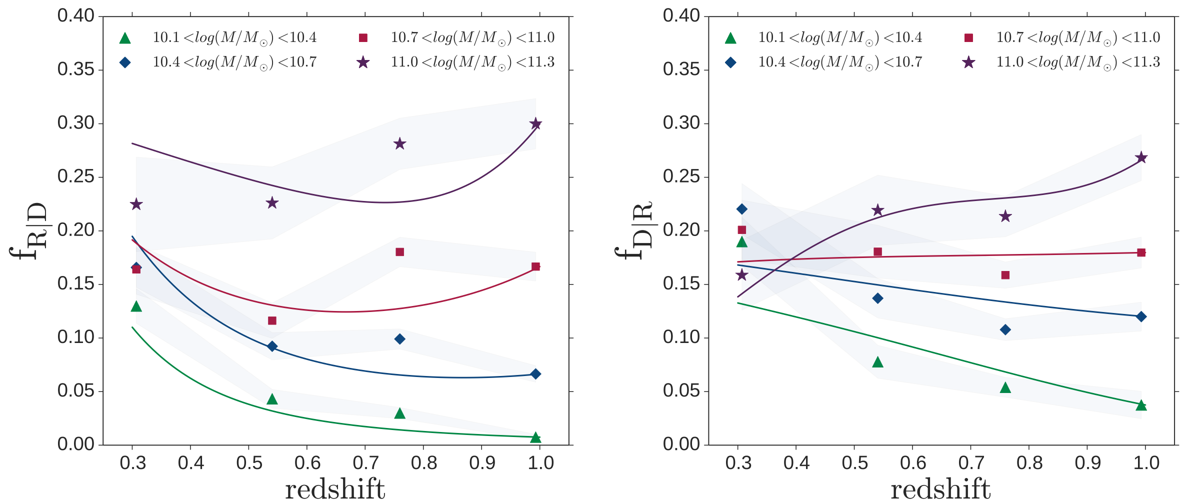

Figure 7. Left: Passive disk fraction ($\mathrm{N_{red\ disks}}/(\mathrm{N_{red\ disks}} + \mathrm{N_{blue\ disks}})$) vs redshift in four mass bins. **Right:** Fraction of disks on the red sequence ($\mathrm{N_{red\ disks}}/(\mathrm{N_{red\ disks}} + \mathrm{N_{red\ ellipticals}})$) vs redshift in four mass bins.

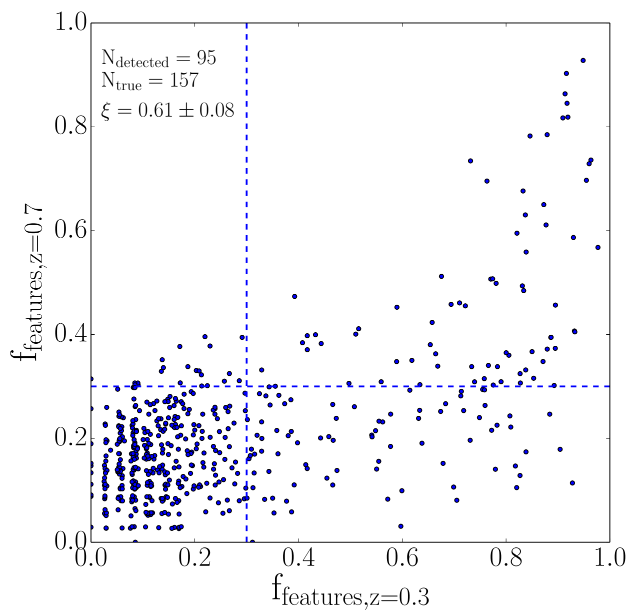

Figure 4. Example calculation of completeness ξ at redshift $z = 0.7$. Points represent FERENGI2 images classified in Galaxy Zoo. The y-axis corresponds to the value of f_{features} measured at the galaxy redshifted to $z = 0.7$, and the x-axis corresponds to the value of f_{features} measured at the galaxy redshifted to $z = 0.3$. On average, the f_{features} is lower at the higher redshift, indicating users on average have more difficulty identifying features in images at higher redshifts. The dotted lines correspond to f_{features}=0.3, the threshold above which a galaxy is considered to have a disk. Galaxies to the right of the vertical dashed line were identified as disks at the lowest redshift $z = 0.3$, the total number defined as $\mathrm{N_{true}}$, the true number of disks. Galaxies above the horizontal dash line were identified as disks at the higher redshift $z = 0.7$, the total number defined as $\mathrm{N_{detected}}$. The ratio $\xi = \mathrm{N_{detected}}/\mathrm{N_{true}}$ is the completeness value; in this example, only 61% of disks were detected at $z = 0.7$.

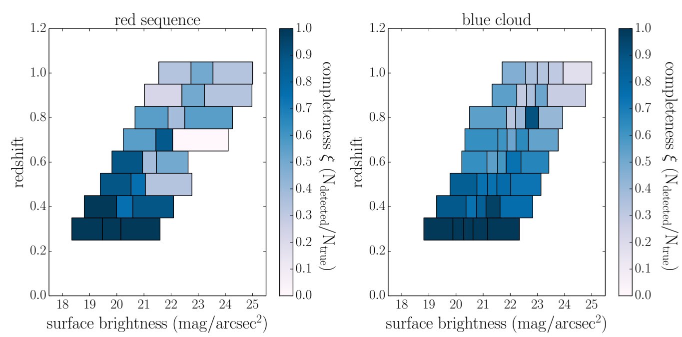

Figure 5. Completeness ξ as a function of redshift and surface brightness for red sequence (left) and blue cloud galaxies (right). In each redshift bin, galaxies were binned by surface brightness in varying widths such that $\mathrm{N_{detected}} + \mathrm{N_{true}} \geqslant 10$ in each bin. The completness ξ was computed in each z, μ bin, represented by the colors. Darker colors represent a completeness of 1, such that all disks were detected, while fainter colors represent a completeness near 0, representing a failure to detect disks. ξ tends to decrease with redshift, but no correlation of ξ with surface brighness is observed at fixed redshift.

cise relative values of these rates cannot be deduced by a simple by-eye analysis of the fraction, however.

We therefore implement a simple toy model to track the change in $f_{R|D}$ and $f_{D|R}$, given a range of parameters representing the quenching and morphological transformation rates for galaxies at fixed stellar mass. We begin by considering the rate of change in the number of blue disks (dN_{BD}/dt), red disks (dN_{RD}/dt), and red ellipticals (dN_{RE}/dt). In a given mass bin, the change in numbers for each population will depend on several parameters, illustrated visually in Figure 8.

4.1.1 Blue Disks

First, galaxies in a blue bin may transition into a red disk bin via a quenching process that does not destroy its disk;

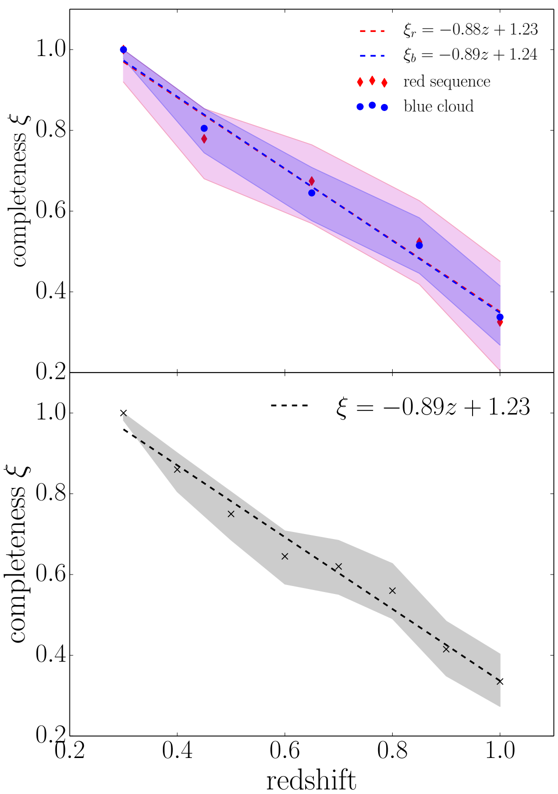

Figure 6. Top: Completeness ξ as a function of redshift for red sequence and blue cloud FERENGI2 galaxies separately. Both populations show a strong dependence on ξ with redshift, but are indistinguishable from each other. **Bottom:** Completeness as a function of redshift for all FERENGI2 galaxies (red and blue combined). The equation representing the linear fit is displayed.

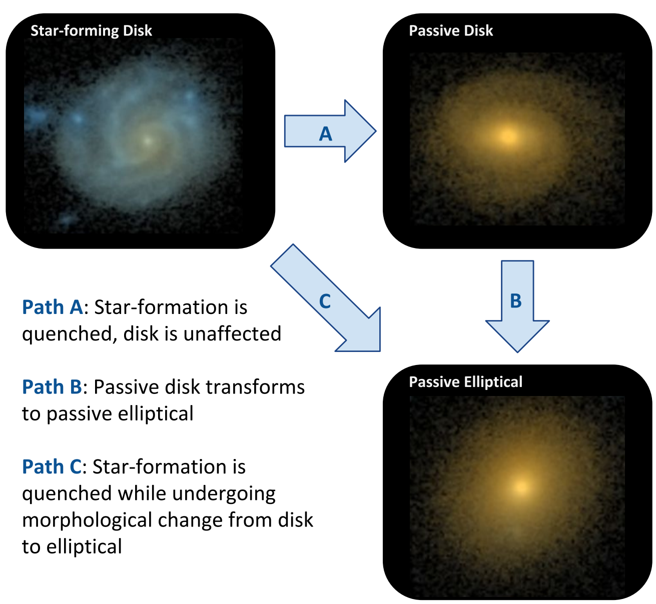

Figure 8. cartoon

we define this rate as $r_{BD \to RD}$, representing the fraction of blue galaxies to transition to red disks per Gyr (path A in Figure 8). Blue galaxies may also exit a bin via a quenching process which *does* destroy the disk; this fraction per Gyr we define as $r_{BD \to RE}$ (path C in Figure 8).

The number of galaxies in a blue disk bin will also change due to star formation, which brings active galaxies from a lower mass bin into the current mass bin. To account for this term we use the formalism outlined by Peng et al. (2010), in which this rate of change is given by $(\alpha + \beta)sSFR$. Here $\alpha = d\phi_{blue}/dm$ is the derivative of the mass function for blue galaxies, which equates to $\alpha = (1 + \alpha_s) - m/M^*$ for a mass function described by the Schechter (1976) function. We use best-fit parameters for blue galaxies measured by Johnpaperetal, which give $\alpha_s = -1.4$ and $M^* = 10.28$ $(log(M/M_\odot))$. Following the method of Peng et al. (2010), we let $\beta = 0$, both for simplicity, and because their conclusions found not to be strongly dependent on β. Last, the specific star-formation rate is given by $sSFR(t) = 2.5(\frac{t}{3.5Gyr})^{-2.2}Gyr^{-1}$ (Peng et al. 2010).

Accounting for all sources and sinks of blue disks entering or exiting a bin of given mass, the rate of change of blue disks can be written fully as:

$$\frac{dN_{BD}}{dt}\bigg|_m = \Big(- r_{BD\to RD} - r_{BD\to RE} - \alpha(m) sSFR(t) \Big) N_{BD} \quad (5)$$

4.1.2 Red Disks

Galaxies exiting a blue bin as they quenched without disrupting their disks enter the pool of red disks, increasing N_{RD} for a given mass bin. Red disks also may undergo a morphological transformation, depleting the pool of red disks as they enter the red elliptical bin (path B in Figure 8). The fraction of galaxies to undergo this pathway per Gyr is denoted as $r_{RD->RE}$. Combining these factors gives the expression:

$$\frac{dN_{RD}}{dt}\bigg|_m = +r_{BD\to RD} N_{BD} - r_{RD\to RE} N_{RD} \quad (6)$$

4.1.3 Red Ellipticals

In this simple model, it is assumed that red, passive ellipticals are the final state in a typical galaxy's evolution. Therefore N_{RE} will always be increasing from the transformation from blue disks and red disks to red ellipticals ($r_{BD\to RE}$, $r_{RD\to RE}$). However, the number of red ellipticals *in a single mass bin* may still decrease due to ellipticals at the given mass merging to enter a bin of red ellipticals at a higher mass. Similarly, their number can increase as ellipticals from a lower mass bin merge to enter the current mass bin. A complete, semi-analytic model would consider this full range of possibilities and couple the resulting equations appropriately amongst all mass bins. For the purposes of this simple model, we opted to represent the total, net rate of change of the number of red ellipticals as a single parameter, κ_{RE}, which we note may be positive or negative, depending on whether more ellipticals are entering or leaving the given mass bin.

$$\frac{dN_{RE}}{dt}\Big|_m = \kappa_{RE} N_{RE} \tag{7}$$

We initialize our model using the observed relative numbers of blue disks, red disks, and red ellipticals measured at $z = 1$, then use the model to compute their evolution to $z = 0.3$ using a range of values for each of the four parameters in four mass bins. For $r_{BD \to RD}, r_{BD \to RE}$, and $r_{RD \to RE}$, we test 25 values between 0 and 1, and 25 values between -1 and 1 for κ_{RE}. We note that a complete model would explore time-varying rates, but for the purposes of simplicity in our toy-model we only experiment with static parameters. For each mass bin, the model was implemented for each permutation of the four rate parameters. The success of each run was evaluated using a χ^2 metric; these results are shown for each mass bin in the corner-plot in Figure 9. The bins are weighted by $1/\chi^2$, such that white regions represent the rate parameters that yield the lowest χ^2, and black representing the largest.

We find a strong mass dependence on the fraction of blue galaxies to quench to red disks ($r_{BD \to RD}$), or Path A in Figure 8. Our observations of $f_{R|D}$ and $f_{D|R}$ are most closely reproduced when $r_{BD \to RD}$ = [0.05, 0.1, 0.15, 0.2] Gyr^{-1} for masses log(M/M$_\odot$) = [10.25,10.55,10.85,11.0]. These values for $r_{BD \to RD}$ correspond to the peaks of the 1-D histograms shown in Figure 9. This increase of $r_{BD \to RD}$ with mass could suggest either: 1) more massive galaxies are more likely to undergo quenching processes which do not destroy their disks, or 2) less massive galaxies simply quench less frequently overall, via any pathway.

Analysis of the next parameter in the low mass bin, $r_{BD \to RE}$, suggests that the former is more likely, given the peak of $r_{BD \to RE}$ at > 0.9 Gyr^{-1}. The high rate of low-mass blue disks quenching to red ellipticals is evidence that they do not quench any less frequently than high mass galaxies, and the increase of $r_{BD \to RD}$ with mass is indeed consistent with quenching processes less likely to destroy the disk of massive galaxies. However, this result is not nearly as constrained, given the broad distribution of likelihoods for this parameter. $r_{BD \to RE}$ is even less constrained for all higher masses. The degeneracies evident in this rate and $r_{RD \to RE}$ make it clear that our model is not sufficient to constrain the relative fequencies of the processes involved in quenching and morphological transformations; a more sophisticated model with the adjustments we have described thus far would be necessary to paint the full picture.

5 DISCUSSION

We have explored the evolution of the passive disk population since $z = 1$ by quantifying their abundances in terms of the fraction of disk galaxies that are red $f_{R|D}$ and the fraction of the red sequence occupied by disks $f_{D|R}$. For both fractions, we observed dependencies on both mass and redshift; this is a strong indication that passive disks play an important role in understanding the processes involved in the quenching and morphological transformation of galaxies. We identified three pathways to describe the evolution of a star-forming disk: $r_{BD \to RD}$ (the rate of blue disks quenching to red disks), $r_{BD \to RE}$ (the rate of blue disks quenching and transforming directly to red ellipticals), and $r_{RD \to RE}$ (the rate of red disks transforming to red ellipticals), and we argue that the relative frequencies of these rates drive the trends in $f_{R|D}$ and $f_{D|R}$. To begin quantifying the occurances of each of the pathways, we developed a toy model to reproduce $f_{R|D}$ and $f_{D|R}$ given some set of rates. Our model was able to constrain $r_{BD \to RD}$ to a reasonable degree of certainty, but the rest would require a more sophisticated model to deduce.

An analysis of $r_{BD \to RD}$ provides an estimate for the fraction of galaxies to go through a passive disk phase. For the most massive galaxies, we find $r_{BD \to RD} = 0.30$ $\pm .1$ Gyr^{-1}, indicating that 30% of massive galaxies become red disks at some point in their lifetime. Whether these 30% tend to stay red disks or tend to evolve to ellipticals is unclear without a more solid constraint on $r_{RD \to RE}$. Using the same logic for the other three mass bins, we can find that [20%, 5%, 5%] of galaxies with masses [10,10,10] become red disks in their lifetimes. These estimates are in agreement with Bundy et al. (2010) (hereafter B10) who estimate an upper limit of 60% of massive galaxies to experience a red disk phase. Their estimation comes from a different approach to ours, via an analysis of the mass function of galaxies with different morphologies and the fractional contribution of disks on the red sequence $f_{D|R}$.

Our estimation of the significance of the passive disk population is in agreement with B10 for the most massive galaxies, as is the downward trend in $f_{D|R}$ with redshift from $z = 1$ to $z = 0.3$. As suggested previously, a downward trend of $f_{D|R}$ represents either a depletion of the total pool of red disks (via a transformation to elliptical), but could also be an indication of an increase in the pool of red ellipticals (which could result from blue or red disks transforming morphology). In contrast, an upward trend is only possible via a pile-up of red disks, which is what we observe for the lower mass bins. Thus far our results are then consistent with a physical scenerio in which 1) more massive galaxies are more likely to become passive disks (given by the increase of $r_{BD \to RD}$ with increasing mass), and 2) less massive galaxies who enter a red disk phase are more likely than massive galaxies to stay in that phase, rather than transform to elliptical (given by the increase of $f_{D|R}$ from $z = 1$ to $z = 0.3$ for low mass bins).

Our first point is in agreement with literature which explores the unimodality of disk galaxies across a CMD (Schawinski et al. 2014; Powell et al. 2017). The smooth transition from the blue cloud to the red sequence in the distribution of low to medium mass disk galaxies is evidence for slow quenching timescales. For higher mass disk galaxies, the unimodality is broken, suggesting a more rapid quenching. This could be due to a higher merger rate for more massive galaxies, or as suggested by Schawinski et al. (2014), evidence for a mass-quenching effect, in which the galaxy's halo reaches a critical mass whereby the gas is inhibited from cooling sufficiently to continue star-formation (Kormendy & Kennicutt 2004; Dekel & Birnboim 2006; Peng et al. 2010). This result is also consistent with B10, who observe the strongest decrease in $f_{D|R}$ from $z = 1$ to $z = 0.3$ for their most massive galaxies.

Our second point is in disagreement with B10, who observe downward trends in $f_{D|R}$ in low mass galaxies. At the lowest redshift bin ($z \sim 0.3$), we measure similar absolute

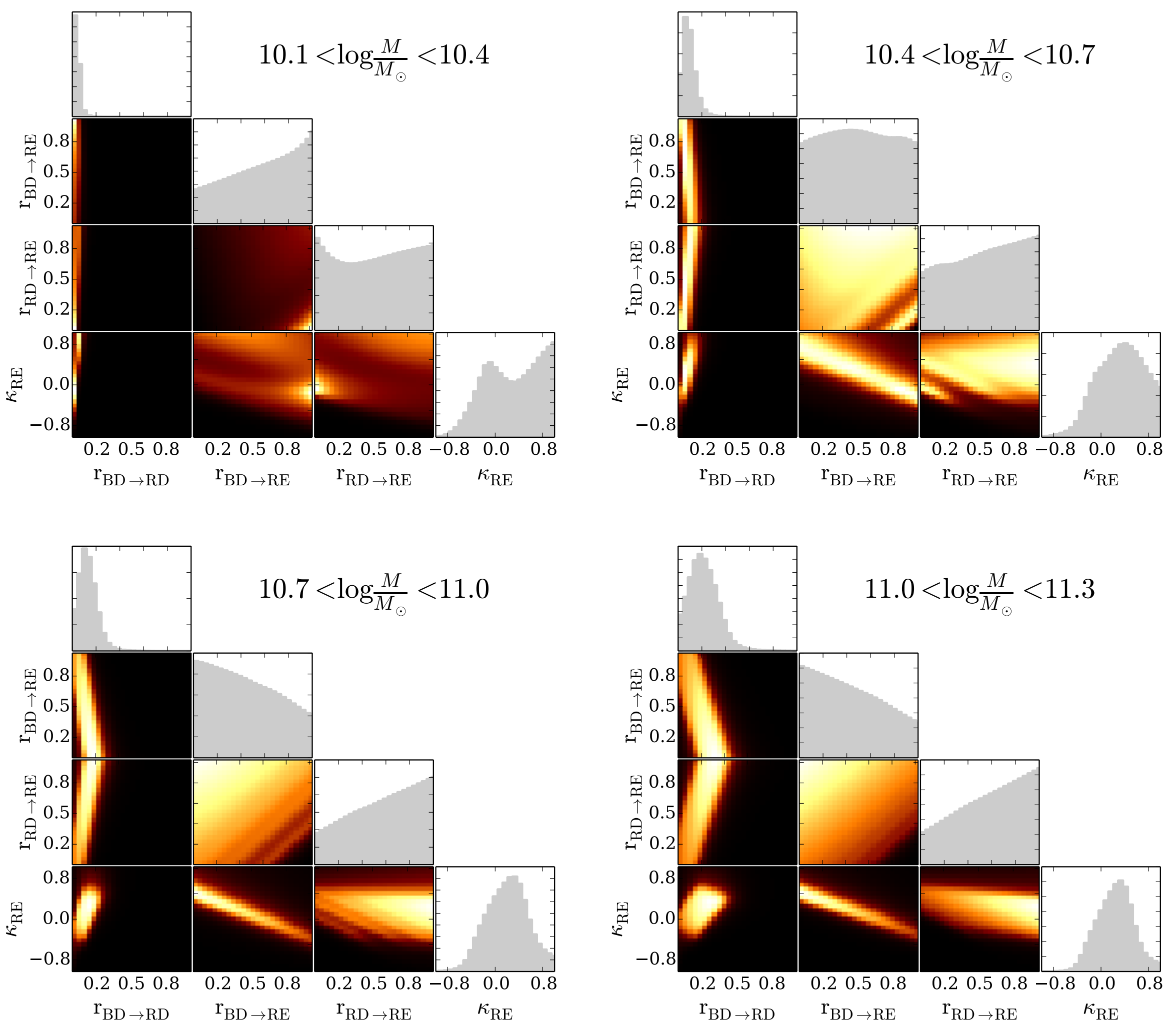

Figure 9. Results of the grid-search for the best-fit rate parameters $r_{BD\to RD}, r_{BD\to RE}, r_{RD\to RE}$, and κ_{RE} for four mass bins. The units for all rate parameters is Gyr^{-1}. 25 equally-spaced values were tested between (0,1) for each parameter, with the exception of κ_{RE} which was tested for 25 values between (-1,1); these are represented by the 25 bins on each axis. Each bin is weighted by $1/\chi^2$, such that white regions correspond to parameters which produced the lowest χ^2, and black representing the highest. There is a strong result in the dependence of $r_{BD\to RD}$ with mass, such that the fraction of blue disks which transition to red disks (ie, quench without disrupting the disk), increases for more massive galaxies. The other parameters are less constrained by this model; therefore a more complex semi-analytic model will be necessary for obtaining the precise values of these rates, and is the subject of future work.

fractions of disks occupying the red sequence for all masses. However, B10 find their contribution to increase at higher lookback time to $z = 1$, while we find a decreasing contribution. The fact that our results agree for the highest mass at all redshifts, but only at the lowest redshift for lower masses, suggests the differences may be attributed in biases in morphological classification. B10 indentifies early and late-type disk galaxies using ZEST (Scarlata et al. 2007) morphologies, which they acknowledge are biased towards disk classification for faint apparent magnitudes, which tend to be attributed to the lowest mass, highest redshift objects. This bias could influence their observed increase in red sequence disks toward $z = 1$ for low masses. On the opposite end, GZ classifications tend to be biased towards elliptical morphologies at fainter magnitudes. We attempted to quantify and correct for this effect as described in Section 3.1, but if our correction was under-estimated, that may have driven the decreasing abundance of disk galaxies observed at increasing redshift for low masses. However, it has been shown in the local Universe that red disk galaxies tend to be more massive, as in Masters et al. (2011). If this is true at all epochs, we would not expect such a significant contribution of red disks for low mass galaxies as found in B10.

6 CONCLUSIONS

We have investigated the influence of the passive disk population by measuring the relative abundances of blue disks, red disks, and red ellipticals since $z = 1$ using morphological classifications from Galaxy Zoo: Hubble and rest-frame colors from UltraVISTA. Using data from artificially-redshifted FERENGI2 images to quantify the known redshift bias in the GZ classifications, we implemented a correction to the incompleteness in the number of disks detected as a function of redshift. The relative numbers were measured in terms of the fraction of disk galaxies that are red $f_{R|D}$ and the fraction of disk galaxies on the red sequence $f_{D|R}$. A simple toy-model was developed to simulate the evolution of these fractions as a function of the rates of three dominant evolutionary pathways: $r_{BD\rightarrow RD}$, the rate of blue disks quenching to red disks, $r_{BD\rightarrow RE}$,the rate of blue disks quenching and transforming directly to red ellipticals, and $r_{RD\rightarrow RE}$,the rate of red disks transforming to red ellipticals. Our main conclusions are as follows:

- $f_{R|D}$ and $f_{D|R}$ decrease from $z = 1$ to $z = 0.3$ for massive galaxies, and increase for the least massive galaxies.
- We estimate as high as 30% (+-error) of massive ($log(M/M_{\odot}) > 11$) galaxies experience a passive disk phase. This fraction decreases with mass, down to 5+- % for galaxies $log(M/M_{\odot}) < 10.4$.
- Low mass galaxies which experience a passive disk phase are more likely than massive galaxies to remain disks, while massive galaxies are more likely to continue thier evolution by transforming to passive ellipticals. To quantify and validate this result would require a more sophisticated model than the simple approached used in this project.

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