

DESI Survey Validation Spectra Reveal an Increasing Fraction of Recently Quenched Galaxies at $z \sim 1$

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ABSTRACT

We utilize ~ 17000 bright Luminous Red Galaxies (LRGs) from the novel Dark Energy Spectroscopic Instrument Survey Validation spectroscopic sample, leveraging its deep (~ 2.5 hour/galaxy exposure time) spectra to characterize the contribution of recently quenched galaxies to the massive galaxy population at $0.4 < z < 1.3$. We use **Prospector** to infer non-parametric star formation histories and identify a significant population of post-starburst galaxies that have joined the quiescent population within the past ~ 1 Gyr. Among our sample of recently quenched galaxies, 277 at $z > 1$, which represents the largest spectroscopic sample of post-starburst galaxies at that epoch. At $0.4 < z < 0.8$, we measure the number density of quiescent LRGs, finding that recently quenched galaxies constitute a growing fraction of the massive galaxy population with increasing lookback time. Finally, we quantify the importance of this population amongst massive ($\log(M_*/M_\odot) > 11.2$) LRGs by measuring the fraction of stellar mass each galaxy formed in the Gyr before observation, $f_{1\text{Gyr}}$. Although galaxies with $f_{1\text{Gyr}} > 0.1$ are rare at $z \sim 0.4$ ($\lesssim 0.5\%$ of the population), by $z \sim 0.8$ they constitute $\sim 3\%$ of massive galaxies. Relaxing this threshold, we find that galaxies with $f_{1\text{Gyr}} > 5\%$ constitute $\sim 10\%$ of the massive galaxy population at $z \sim 0.8$. We also identify a small but significant sample of galaxies at $z = 1.1 - 1.3$ that formed with $f_{1\text{Gyr}} > 50\%$, implying that they may be analogues to high-redshift quiescent galaxies that formed on similar timescales. Future analysis of this unprecedented sample promises to illuminate the physical mechanisms that drive the quenching of massive galaxies after cosmic noon.

Keywords: Post-starburst galaxies (2176), Galaxy quenching (2040), Galaxy evolution (594), Quenched galaxies (2016), Galaxies (573)

1. INTRODUCTION

In the local Universe, the vast majority of massive ($\log(M_*/M_\odot) \gtrsim 11$) galaxies are completely quiescent and have been so for 5–10 Gyr (e.g., Muzzin et al. 2013; Donnari et al. 2019; Leja et al. 2021). There is a growing consensus that two distinct pathways to quiescence are at play, with a rapid path dominating the buildup of quiescent galaxies at high redshifts and a slower channel that populates the “green valley” at low redshift (e.g., Schawinski et al. 2014; Wu et al. 2018; Maltby et al. 2018; Belli et al. 2019; Suess et al. 2021). The precise details of how the quiescent population grows from the rapid quenching pathway as a function of cosmic time remain very uncertain. Some studies have characterized the rates of rapid quenching as a function of cosmic time using either photometric (Whitaker et al. 2012; Wild et al. 2016; Belli et al. 2019; Park et al. 2022) or shallow spectroscopic (Rowlands et al. 2018) samples and have found that recently quenched galaxies, otherwise known as post-starburst galaxies, stopped contributing significantly to the quiescent population by $z \gtrsim 0.5$. However, photometric studies yield weak constraints on timescales. Thus, our picture of precisely when galaxies shut off their star formation and the contribution of late-time star formation remains poorly constrained.

Ideally, one would study the assembly of the red sequence by modeling the star-formation histories of complete samples of massive galaxies and studying how the incidence and characteristics of the population vary as a function of cosmic time. However, measuring the high-order moments of a star-formation history, such as timescales and burst fractions, requires high signal-to-noise continuum spectroscopy (Suess et al. 2022a). The limiting factor in performing such modeling has been the availability of sufficiently deep spectra beyond $z \gtrsim 0.5$. The largest existing spectroscopic samples have not prioritized observing the gamut of quiescent galaxies; the SDSS LRG (Eisenstein et al. 2001) and BOSS (Dawson et al. 2013) surveys targeted the reddest quiescent galaxies, prioritizing pure, uniform samples at the expense of younger, bluer galaxies, and the EBOSS (Dawson et al. 2016) survey poorly sampled the quiescent population in favor of more accessible emission line sources. Deeper, more targeted surveys such as LEGA-C (van der Wel et al. 2021; Wu et al. 2018) and VANDELS (McLure et al. 2018; Carnall et al. 2019) have identified samples of ~ 1000 s of massive quiescent galaxies at $z \gtrsim 0.5$, re-

quiring significant investments on deep fields to reveal spectroscopic information for small samples.

The next generation of large spectroscopic surveys will revolutionize the availability of continuum spectroscopy of massive galaxies. Here, we utilize the Dark Energy Spectroscopic Instrument (DESI), a robotic, fiber-fed, highly multiplexed spectroscopic surveyor that operates on the Mayall 4-meter telescope at Kitt Peak National Observatory (DESI Collaboration et al. 2016a). DESI, which can obtain simultaneous spectra of almost 5000 objects over a $\sim 3^\circ$ field (DESI Collaboration et al. 2016b; Silber et al. 2022, Miller et al. in preparation), is currently over a year into a five-year survey of approximately one-third of the sky (DESI Collaboration et al. 2016a), and has already observed more galaxies than the entire Sloan Digital Sky Survey. Here we show that even the relatively small (~ 20000 galaxies) but deep Survey Validation (SV) sample of Luminous Red Galaxies (LRGs) within the DESI Survey can be leveraged to identify new and exciting samples of recently quenched galaxies that push well beyond what previous surveys have been capable of (Zhou et al. 2022).

In this letter, we infer non-parametric star formation histories of LRGs in the DESI SV sample (Dawson et al. in preparation) and use them to study the growth of the red sequence from recently quenched galaxies. In Section 2, we describe the parent sample and demonstrate the use of non-parametric star formation histories to fit the spectrophotometric data with *Prospector* (Johnson & Leja 2017; Leja et al. 2017; Johnson et al. 2021). In Section 3, we use the results of this fitting to identify recently quenched galaxies and characterize their evolving number densities as a function of cosmic time. Finally, in Section 4, we discuss the implications of these findings on our understanding of the physical mechanisms that are driving the production of massive, quiescent galaxies through the rapid quenching channel.

Throughout this letter, we use the terms “recently quenched galaxy” and “post-starburst galaxy” interchangeably to refer to galaxies which have recently and rapidly shut off their star formation. We assume a concordance Λ CDM cosmology with $\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$ and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, and quote AB magnitudes.

2. DATA

2.1. The DESI LRG SV Sample

In order to characterize the growth of the population of quiescent galaxies at intermediate redshifts, this work

relies on the large program of deep spectra that were taken as a part of the DESI SV LRG sample (Zhou et al. 2020, 2022, Dawson et al. in preparation). The primary objective of DESI is to determine the nature of dark energy with precise cosmological measurements (Levi et al. 2013), but the wealth of spectroscopy provides an excellent sample for studies of galaxy evolution. The data volume of the DESI requires multiple supporting software pipelines and products used in this work. Target selection and photometry was performed on imaging from the DESI Legacy Surveys (Zou et al. 2017; Dey et al. 2019, Schlegel et al. in preparation). Fiber assignments, tiling, and target selection were performed with the algorithms outlined in Raichoor et al., Schlafly et al., and Myers et al. (in preparation) respectively. All redshifts were determined with the Redrock pipeline (Bailey et al. in preparation). All spectroscopy used was reduced using the “Fuji” internal spectroscopic data release which will be identical to the DESI Early Data Release (Guy et al. 2022, EDR, tentatively expected in early 2023).

While the SV sample included fainter targets, we restrict this study to the brightest SV LRGs with an observed fiber z magnitude $z_{\text{fiber}} < 21.6$ cut similar to the one that is used in the full LRG sample. There are three primary reasons for this choice. First, the SV selection is more inclusive than subsequent Survey Validation samples and the main DESI sample, which removes any potential bias against observing young, recently quenched LRGs. Second, the SV observations were an order of magnitude deeper than the observations for the main survey, with ~ 2.5 hours of integration per spectrum, resulting in the high signal-to-noise measurements of the continuum.

We select all tiles that were observed under the dark time observing conditions in SV. We then select all galaxies which meet the LRG SV cuts outlined in Zhou et al. (2022) with an additional $z_{\text{fiber}} < 21.6$ magnitude constraint, a cut at $z > 0.4$ (above which the SV LRG sample begins to be mass complete), and a cut at $z < 1.3$ (at which point the age-sensitive H_δ absorption feature is no longer covered by DESI spectroscopy). We remove galaxies with poor redshift measurements by applying a cut of $\text{ZWARN} == 0$ to the DESI catalog. We then remove the 580/17797 galaxies that did not reach target depth (exposure time $t_{\text{exp}} > 1$ hour). The median exposure time of this final sample is 2.4 hours, with 16th and 84th percentile exposure times of 1.5 and 4.1 hours respectively. This selection results in a total sample of 17217 galaxies.

2.2. Inferring Star Formation Histories with Prospector

We model the DESI spectra and photometry using non-parametric star formation histories with the SED fitting code **Prospector** (Johnson & Leja 2017; Leja et al. 2017; Johnson et al. 2021) to infer the detailed stellar populations of the sample. Non-parametric star formation histories (SFHs) are particularly useful for fitting post-starburst galaxies because they do not impose an analytic form on the shape of the SFH, which allows for multiple rises and falls over the course of a galaxy’s lifetime. We adopt a flexible bin model that is optimized to model recently quenching galaxies (Suess et al. 2022a). The model utilizes 3 fixed time bins at early times ($t_{\text{lookback}} > 2$ Gyr), 5 flexible bins that each form the same amount of total stellar mass (allowing for greater resolution near periods of intense star formation), and a final flexible bin that allows a galaxy to remain quenched after star formation is finished. This scheme was extensively tested and is well designed to recover quenching timescales and burst mass fractions (Suess et al. 2022a,b).

We use the **dynesty** dynamic nested sampling package (Speagle 2020), the Flexible Stellar Population Synthesis (FSPS) stellar population synthesis models (Conroy et al. 2009; Conroy & Gunn 2010), the MILES spectral library (Sánchez-Blázquez et al. 2006; Falcón-Barroso et al. 2011), and the MIST isochrones (Choi et al. 2016; Dotter 2016). We assume a Chabrier (2003) Initial Mass Function and fix the model redshift to the spectroscopic redshift. In contrast with the Suess et al. (2022b) prescription for fitting post-starburst galaxies, we elect to fit nebular emission non-physically by marginalizing over Gaussian lines at the locations of emission features in the spectrum. The massive LRG sample likely hosts many active galactic nuclei (AGN) which can contribute strongly to a galaxy’s emission line strength (especially the recently quenched galaxies, e.g., Greene et al. 2020). Additionally, the LRG selection allows for the targeting of a small fraction of dusty star-forming galaxies with strong emission lines; we want to be completely agnostic to the source of emission when fitting star formation histories to these galaxies. This procedure subtracts out the emission from the spectrum at each step in the fitting before calculating the likelihood, which allows the fits to utilize continuum information (e.g. $H\beta$ absorption) despite the existence of emission that our models do not generate using information about the current SFR.

We use the mass-metallicity prior described in Leja et al. (2019). We utilize the **PolySpecModel** procedure which accounts for deviations between the shape of the photometry and the spectrum by dividing out a poly-

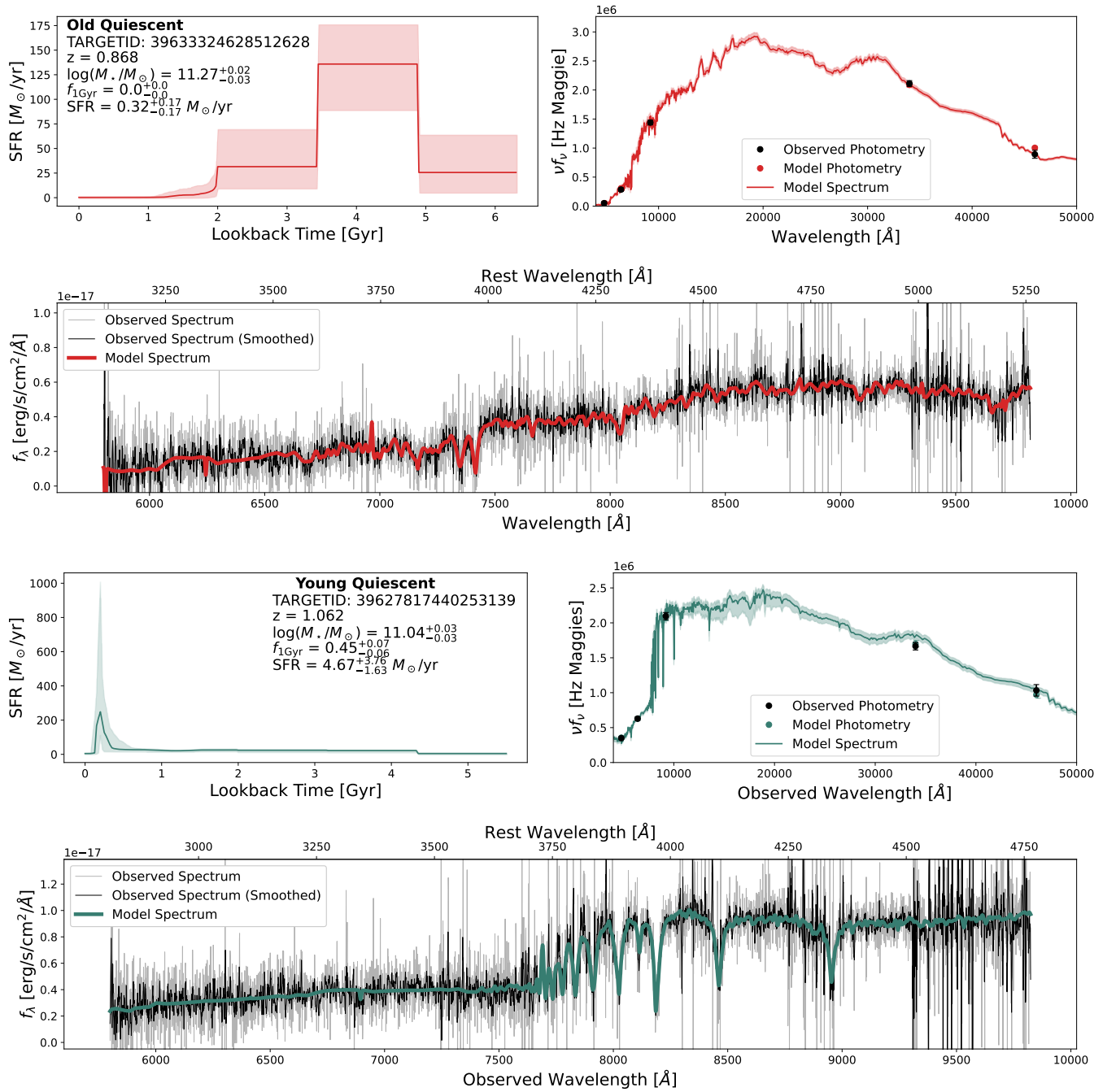


Figure 1. Example old (top, TARGETID=3963332462851262) and recently quenched (bottom, TARGETID=39627817440253139) galaxies from the DESI SV LRG Sample with *Prospector* fits using the star-formation history model from [Suess et al. \(2022a\)](#). For each galaxy, we show the median and 68% confidence interval star-formation history (top left) with selected galaxy properties. We also show the best fitting models (color) to the observed photometry (*g/r/z/W1/W2*, black) (top right). Finally, we show the DESI spectrum (observed, grey; 5 pixel boxcar smoothed, black) along with the best fitting model (color) (bottom). From this modeling, we identify quiescent LRGs and infer the dominance of recent star formation and the timescale of quenching.

mial from the observed and model spectra during fitting. We assume the [Kriek & Conroy \(2013\)](#) dust law with a free A_v and dust index. Additionally, following [Wild et al. \(2020\)](#), we assume that the attenuation is doubled around young ($< 10^7$ yr) stars. We fix the shape of the IR SED following the [Draine et al. \(2007\)](#) dust emission templates, with $U_{\min} = 1.0$, $\gamma_e = 0.01$, and $q_{\text{PAH}} = 2.0$. Finally, we include both a spectroscopic jitter term to account for the possibility of underestimated noise and the **Prospector** pixel outlier model. We center priors on the SFH such that they follow the predicted SFH of a massive quiescent galaxy from the **UNIVERSEMACHINE** catalog ([Behroozi et al. 2019](#)); this weakly prefers solutions with early-time star formation in the star formation histories we fit to ensure that outshining of a young stellar population is treated conservatively. The fidelity of this star formation history at recovering mock parameters is illustrated in [Suess et al. \(2022a\)](#). Of principle importance to this work, the burst fraction is well recovered when $< 50\%$ of a galaxy’s stellar mass is formed in a burst. For greater burst fractions the fits are very poorly constrained, and because of the prior they saturate at $\sim 50\%$ burst fractions; thus, burst fractions measured in this work can be thought of as strong lower limits when they are high.

We fit all 17217 galaxies in the DESI SV LRG sample ($z_{\text{fiber}} < 21.6$) with this procedure, providing the Milky Way extinction corrected $g/r/z/W1/W2$ photometry (using the extinction maps from [Schlegel et al. 1998](#)) and the galaxy spectrum. Because the signal in the redshift range of interest is concentrated at the red end of the spectrograph, we elect to only fit the spectra from the R and Z arms of the spectrograph ($5800\text{\AA} < \lambda_{\text{obs}} < 9824\text{\AA}$) to save on computation time and to avoid any issues with the flux calibration at the fainter end of the spectra. We note that the fits failed for 52/17217 galaxies (0.3% of the total sample). Visual inspection of the spectra of these failed fits suggests that they broadly fall into four categories: extremely low signal-to-noise galaxies, spectra with large masked regions, galaxies with incorrect redshift assignment, and broad-line AGN/QSOs (which our models are not equipped to characterize). As such, we omit the unmodeled galaxies and perform all analysis on the 17703 successfully fit galaxies.

Example fits to quiescent (top, red) and recently quenched (bottom, green) galaxies are shown in Figure 1. The quiescent galaxy that is representative of the majority of the DESI LRG sample is fit entirely with early star formation, consistent with a very old stellar population, and as such, all the mass was formed in the three fixed-width early-time bins. In contrast,

Table 1. Selected Fit Quantities and Errors

z	$\log(M_*/M_\odot)$	SFR [M_\odot/yr]	ΔSFR	$f_{1\text{Gyr}}$
0.5568	$11.23^{+0.01}_{-0.01}$	$2.31^{+0.47}_{-0.35}$	$-1.16^{+0.08}_{-0.07}$	$0.11^{+0.01}_{-0.01}$
0.6701	$11.22^{+0.01}_{-0.01}$	$1.17^{+0.14}_{-0.14}$	$-1.52^{+0.05}_{-0.06}$	$0.0^{+0.0}_{-0.0}$
0.8976	$11.23^{+0.02}_{-0.1}$	$0.92^{+0.84}_{-0.31}$	$-1.76^{+0.39}_{-0.18}$	$0.0^{+0.07}_{-0.0}$
0.5396	$11.36^{+0.01}_{-0.01}$	$2.98^{+0.4}_{-0.34}$	$-1.16^{+0.06}_{-0.06}$	$0.05^{+0.01}_{-0.02}$
0.4364	$11.12^{+0.01}_{-0.01}$	$2.85^{+0.27}_{-0.24}$	$-0.9^{+0.05}_{-0.04}$	$0.01^{+0.0}_{-0.0}$
0.8807	$11.34^{+0.03}_{-0.03}$	$0.08^{+0.28}_{-0.08}$	$-2.86^{+0.62}_{-1.51}$	$0.0^{+0.0}_{-0.0}$
0.6999	$10.8^{+0.03}_{-0.04}$	$19.39^{+2.56}_{-2.4}$	$0.08^{+0.07}_{-0.09}$	$0.22^{+0.05}_{-0.04}$
0.5415	$11.11^{+0.04}_{-0.03}$	$0.09^{+0.05}_{-0.04}$	$-2.45^{+0.19}_{-0.28}$	$0.01^{+0.01}_{-0.0}$
0.5166	$11.2^{+0.02}_{-0.03}$	$21.25^{+2.17}_{-3.02}$	$-0.15^{+0.06}_{-0.08}$	$0.1^{+0.02}_{-0.02}$
1.0623	$11.04^{+0.03}_{-0.03}$	$4.67^{+3.76}_{-1.63}$	$-0.94^{+0.26}_{-0.18}$	$0.45^{+0.07}_{-0.06}$

NOTE—Selected median and 68% confidence values of relevant parameters derived from the posteriors of the **Prospector** fits to DESI SV LRGs for a random sample of galaxies.

the recently quenched galaxy is clearly fit with a post-starburst SED shape with strong Balmer absorption features and a characteristic lack of emission line infill. This indicates that the post-starburst galaxy has quenched after a period of intense star formation, and the star formation history reflects this. We infer that the galaxy began rapidly forming stars ~ 500 Myr before observation, and quenched ~ 150 Myr ago.

From the posteriors on the star formation histories, we derive a number of model parameters, many of which we directly use to select and characterize the properties of post-starburst galaxies. Stellar masses are calculated accounting for mass loss and have typical 1σ uncertainties of 0.025 dex, and rest absolute magnitudes are calculated directly from the spectra generated from the posterior. We measure the star-formation rate in all galaxies as the star-formation rate in the closest bin to the epoch of observation in the non-parametric star formation history. Above $\sim 1M_\odot/\text{yr}$, these star-formation rates have been shown to reliably recover the instantaneous star-formation rate of mock galaxies, and our measurements have typical uncertainties of $\sim 15\%$. Below this, they are effectively upper limits ([Suess et al. 2022a](#)). Additionally, quantify the offset from the star-forming sequence, ΔSFR , as:

$$\Delta\text{SFR} = \log(\text{SFR}) - \log(\text{SFR}_{\text{SFS}}(z)) \quad (1)$$

where $\text{SFR}_{\text{SFS}}(z)$ is the inferred star formation rate from the star-forming sequence at the observed redshift of the galaxy defined in [Leja et al. \(2021\)](#), which is also measured using **Prospector** SED fits. We set a fiducial threshold for quiescence at $\Delta\text{SFR} = -0.6$, $\sim 2\sigma$ below the main sequence at a given redshift. Near the fiducial value, the typical uncertainty in ΔSFR is ~ 0.1 dex. As with the star formation rate, this value is significantly more uncertain for measured values. Finally, we

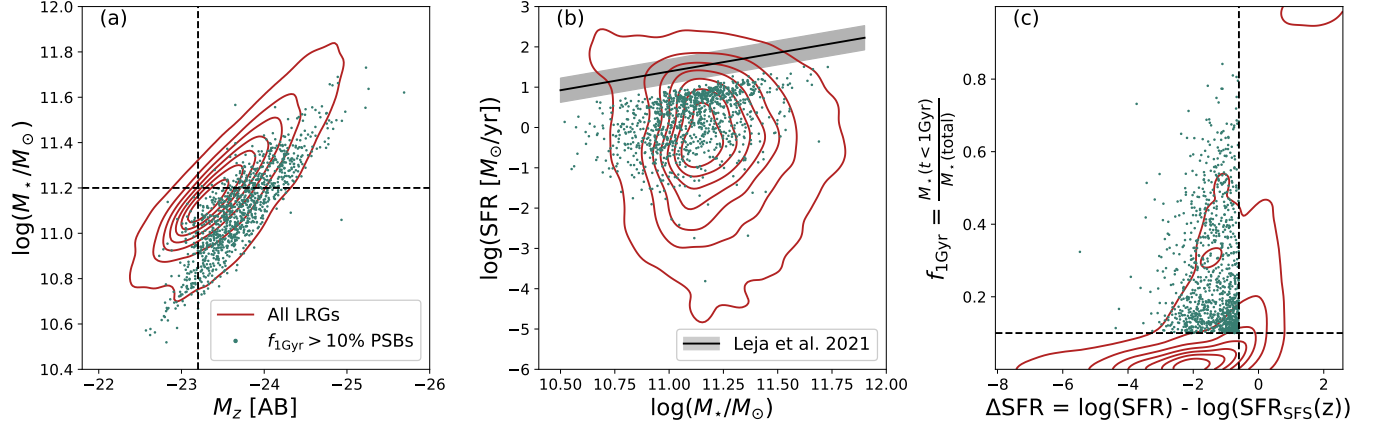


Figure 2. Properties of the full LRG sample (red contours) and a subset of post-starburst galaxies that recently quenched a significant episode of star formation using our fiducial selection ($f_{1\text{Gyr}} > 0.1$, $\Delta\text{SFR} < -0.6$, green points). All plotted points are the median values from the posterior of the *Prospector* fits. In panel (a), we show the stellar mass versus the absolute magnitude (M_z) along with the magnitude limited threshold ($M_z < -23.2$) and the mass complete threshold ($\log(M_*/M_\odot) > 11.2$) discussed in Section 2.3. In panel (b), we show the star-formation rate versus stellar mass, with the star-forming sequence at $z = 0.7$, the median redshift of our sample, shown as a black line with characteristic ~ 0.3 dex 1σ scatter (Leja et al. 2021). In panel (c), we show the post-starburst selection plane, $f_{1\text{Gyr}}$ versus ΔSFR , with the fiducial selection cuts illustrated as dashed lines. The post-starburst sample is significantly brighter than the parent sample at fixed stellar mass and occupies a unique part of parameter space by having formed a significant amount of recent stellar mass despite being fully quenched.

measure the fraction of the total stellar mass formed in the Gyr before observation, $f_{1\text{Gyr}}$. Galaxies with small $f_{1\text{Gyr}}$ are very well constrained to be small, and for galaxies which formed 10 – 70% of their stellar mass in the past Gyr, typical uncertainties are 15 – 30%. A sample table of constraints on parameters shown in Table 1.

We show some of the observed and derived characteristics of the full LRG sample as red contours in Figure 2. In the first panel, we show the stellar mass versus the rest frame absolute magnitude, M_z , illustrating the tight correlation between the two parameters. We additionally show lines which correspond to the cuts we make in the two parameters to construct the volume limited samples described in Section 2.3. In the next panel, we show the star formation rate versus the stellar mass along with the “star forming sequence” at $z = 0.7$ with 0.3 dex scatter from Leja et al. (2021) to illustrate that the sample is largely quiescent. Finally, we show the sample in the post-starburst selection plane of $f_{1\text{Gyr}}$ versus ΔSFR discussed in Section 3.1 with our fiducial cuts to select recently quenched galaxies. In all 3 planes, we show the fiducial sample of post-starburst galaxies as green points.

2.3. Selecting Volume Limited Samples

Because the choices made in spectroscopic targeting significantly impact the observed sample, it is necessary to select a volume limited sample to fairly compare galaxies across redshift bins. This is especially

true because the $z_{\text{fiber}} < 21.6$ cut in observed magnitude would observe a faint galaxy at low-redshift but not high-redshift. We use the fits to the spectrophotometric data to select samples which we can use to infer number densities. Throughout this letter, we utilize three relevant samples: the full LRG sample, the rest absolute Z-magnitude selected “magnitude limited” sample, and the “mass complete” sample to select recently quenched galaxies.

By virtue of being the youngest and brightest galaxies in any given quiescent sample, post-starburst galaxies have the lowest M_*/L ratios at fixed stellar mass and therefore are relatively bright compared to the majority of LRGs. As such, in order to get large, complete samples of post-starburst galaxies to study as a function of redshift, a luminosity cut will maximize the sample size. We define a magnitude limited sample with rest-frame $M_z < -23.2$, at which the entirety of the reddest (in rest $g - z$ color, which should map to the highest M_*/L ratios) 2.5% of the LRG sample is selected at $z = 0.8$. This selection results in the largest volume limited sample we can obtain where we expect to have observed all bright post-starburst galaxies in DESI out to $z \sim 0.8$, yielding a total of 8683 galaxies.

While a magnitude limited sample selects the bulk of the post-starburst galaxies in the SV sample, in order to characterize the growth of the post-starburst population relative to the fainter (at fixed stellar mass) old quiescent population, we also require a mass complete sample. In the redshift range $0.4 < z < 0.8$, the DESI

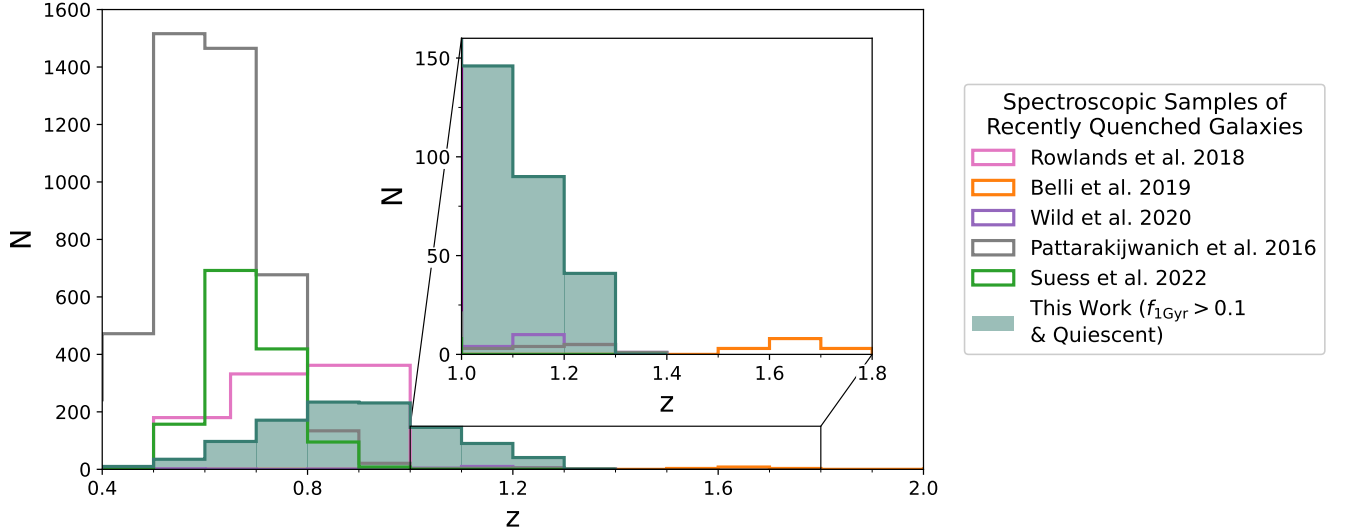


Figure 3. Redshift distributions of spectroscopic samples of recently quenched galaxies from $0.4 < z < 2.0$, with an inset focusing on $z > 1$ where the improvement in sample size from this work is most significant. Our fiducial post-starburst sample ($f_{1\text{Gyr}} > 0.1$, $\Delta\text{SFR} < -0.6$) is shown as a filled green histogram. Other samples shown include PCA-identified post-starburst galaxies from Rowlands et al. (2018) and Wild et al. (2020), galaxies with $t_{50} < 1.5$ Gyr from Belli et al. (2019), galaxies selected with K+A template fitting from the SDSS Pattarakijwanich et al. (2016), and galaxies selected using rest UBV filters from the SQuIGGLE sample also selected from the SDSS (Suess et al. 2022b).

LRG targeting only selects a sample which is $\gtrsim 80\%$ mass complete for very massive galaxies ($\log(M_*/M_\odot) \gtrsim 11.2$ —accounting for systematic differences between the stellar masses we measure and those in Zhou et al. 2022). As such, in situations where we wish to compare to the quiescent population as a whole, we elect to use only galaxies above this stellar mass. This sample is significantly smaller than the magnitude limited sample, with only 5375 galaxies above the stellar mass cut at $z < 0.8$.

We show these cuts in Figure 2a, illustrating that the stellar mass cut is significantly more restrictive than the luminosity cut, which lets through post-starburst galaxies at masses as low as $10^{10.8} M_\odot$. At fixed stellar mass, the fiducial post-starburst sample (see Section 3.1) is significantly brighter than a typical LRG (red contours), and we therefore maximize our ability to constrain the number density of recently quenched galaxies as a population by instituting a cut on the absolute magnitude.

3. ANALYSIS

3.1. Selecting Recently Quenched Galaxies

There are a number of ways of selecting post-starburst galaxies, all of which share the common goal of selecting galaxies that recently quenched after a period of significant star formation (French 2021). Historically, these galaxies have been selected using a combination of emission line cuts (to select against current star formation) and Balmer absorption depth (to select for a

stellar population dominated by A type stars) (Dressler & Gunn 1983; Zabludoff et al. 1996; Balogh et al. 1999). Here, we leverage the tightly constrained star formation histories to select a physically motivated sample of recently quenched galaxies. First, we focus on selecting a pure quiescent sample. In Figure 2b+c, it is clear that some galaxies that are dusty and star-forming have been selected due to their red colors and exist in the LRG parent sample. To remove these, we perform a conservative cut in ΔSFR , classifying galaxies as quiescent only if their median ΔSFR is $\sim 2\sigma$ (0.6 dex) below the star-forming sequence at their redshift from Leja et al. (2021). This selection, which is highlighted in Figure 2c, removes 2622 galaxies ($\sim 15\%$ of the total sample). All qualitative results in this work are insensitive to the exact definition of quiescence that we adopt, though exact sample sizes and number densities will by definition differ slightly.

Secondly, we are interested in separating the quiescent galaxy population physically into recent additions to the red sequence and older galaxies. In this work, our definition of recently quenched does not require a burst, as we are interested in classifying all galaxies which rapidly formed a significant amount of stellar mass before quenching as post-starburst galaxies. To select such a sample, we leverage the inferred star formation histories to measure the fraction of the stellar mass formed within the last Gyr ($f_{1\text{Gyr}}$) for all galaxies (see also Webb et al. 2020). In combination with the cut for

quiescence, selecting galaxies with high $f_{1\text{Gyr}}$ identifies a sample that must have rapidly truncated its star formation in order to have formed a large amount of its stellar mass while also reaching quiescence within 1 Gyr. We adopt $f_{1\text{Gyr}} > 0.1$ (also shown in Figure 2c) for our fiducial post-starburst selection and explore the impact of different thresholds in Section 4. The fiducial selection identifies 1089 post-starburst galaxies from the 15012 quiescent LRGs using the fiducial $f_{1\text{Gyr}} > 0.1$ selection.

This sample of post-starburst galaxies is unparalleled in size beyond $z \gtrsim 1$. In Figure 3, we show the redshift distributions of this sample compared to other large spectroscopic samples of post-starburst galaxies at intermediate redshift. This sample of 100s of post-starburst galaxies at $z < 0.8$ is smaller than other samples which select galaxies from the full Sloan Digital Sky Survey (Pattarakijwanich et al. 2016; Suess et al. 2022b) or VIPERS Survey (Rowlands et al. 2018). However, at $z > 1$ (shown in the inset), we find that this sample dramatically increases the number of spectroscopically confirmed post-starburst galaxies at the tail end of cosmic noon.

While our selection of post-starburst galaxies relies on our inferred star formation histories, there are many other selections that use empirical measures of spectroscopic features to select post-starburst galaxies (French 2021). We choose a few common post-starburst identification methods and compare the resulting number densities with our fiducial model (see Section 3.2). For all literature comparisons, we use the same $\Delta\text{SFR} \leq -0.6$ criterion for quiescence rather than relying on common empirical metrics like EW H_α , which falls out of our spectral window for most of the sample, or EW [OII], which is an uncertain tracer of SFR due to potential contribution from AGN/LINERs. We note that while exact definitions of H_δ spectral indices vary in the literature (e.g., Alatalo et al. (2016) uses H_δ , French et al. (2015) uses $H_{\delta,A}$, and Baron et al. (2022) $H_{\delta,F}$), these differences are subtle. We adopt $H_{\delta,A}$ as our preferred definition, as it is optimized for features from A-type stars (Worthey & Ottaviani 1997). The three selections we compare to our fiducial selection ($f_{1\text{Gyr}} > 0.1$ and $\Delta\text{SFR} < -0.6$) are as follows:

1. $H_{\delta,A} > 4 \text{ \AA}$: After applying the quiescence criteria, we select 1727 galaxies with $H_{\delta,A} > 4 \text{ \AA}$ following e.g., French et al. (2015, 2018); Wu et al. (2018); Yesuf (2022).
2. $H_{\delta,A} > 5 \text{ \AA}$: We impose a more stringent cut, $H_{\delta,A} > 5 \text{ \AA}$, following e.g., Alatalo et al. (2016); Baron et al. (2022), selecting 1035 post-starburst galaxies.

3. SQuIGGLE Selection: Finally, after applying the quiescence criteria, we use medium band synthetic rest-frame UBV filters to identify post-starburst galaxies with $U - B > 0.975$ and $-0.25 < B - V < 0.45$ following the procedure for selecting galaxies with SEDs dominated by A-type stellar populations (Suess et al. 2022b). We apply these cuts to the median best-fit models because the spectral coverage is not red enough to consistently overlap with the synthetic V filter. This selection finds only 324 post-starburst galaxies.

3.2. The number density of recently quenched galaxies

The DESI SV LRG selection is designed to have a uniform comoving number density of galaxies at $0.4 < z < 0.8$, which enables robust determination of number densities of subsets of the spectroscopic sample (Zhou et al. 2022). For this selection, we use the target density of 1439 deg^{-2} to calculate the number density in bins of $\Delta z = 0.1$ in redshift from $z = 0.4$ to $z = 1.3$ by measuring the density of targets for a given selection criterion and dividing by the volume of the bin. We measure the number densities only for the magnitude limited or mass complete samples. We utilize jackknife resampling of the 31 SV pointings to calculate the errors on the measured number densities. The errors do not account for catastrophic redshift errors, but those should be very rare ($\leq 0.5\%$, see Zhou et al. 2022) and subdominant relative to cosmic variance and Poisson errors.

The comoving number density of each post-starburst sample as a function of redshift is shown in Figure 4. The raw number density of the DESI LRG SV sample ($z_{\text{fiber}} < 21.6$) is shown in grey. We show the number density of the rest-frame magnitude limited ($M_z < -23.2$) sample with the fiducial quiescence cut ($\Delta\text{SFR} < -0.6$) in red. We then apply the post-starburst selections outlined in Section 3.1 to the magnitude limited sample. The number densities are shown for $H_{\delta,A} > 4 \text{ \AA}$ (light blue), for $H_{\delta,A} > 5 \text{ \AA}$ (dark blue), SQuIGGLE-like (light green), and our fiducial $f_{1\text{Gyr}} > 0.1$ selection (dark green). In all cases, the number density of post-starburst galaxies rises as a function of redshift in the range of redshifts where the parent LRG sample is complete ($z < 0.8$). Above this, we illustrate that our measurements are lower limits.

In the second panel of Figure 4, we compare our fiducial sample of post-starburst galaxies to several measurements from the literature. We find qualitative agreement with previous studies (Wild et al. 2016; Rowlands et al. 2018; Belli et al. 2019). Additionally, the number density of the post-starburst galaxies that we measure is

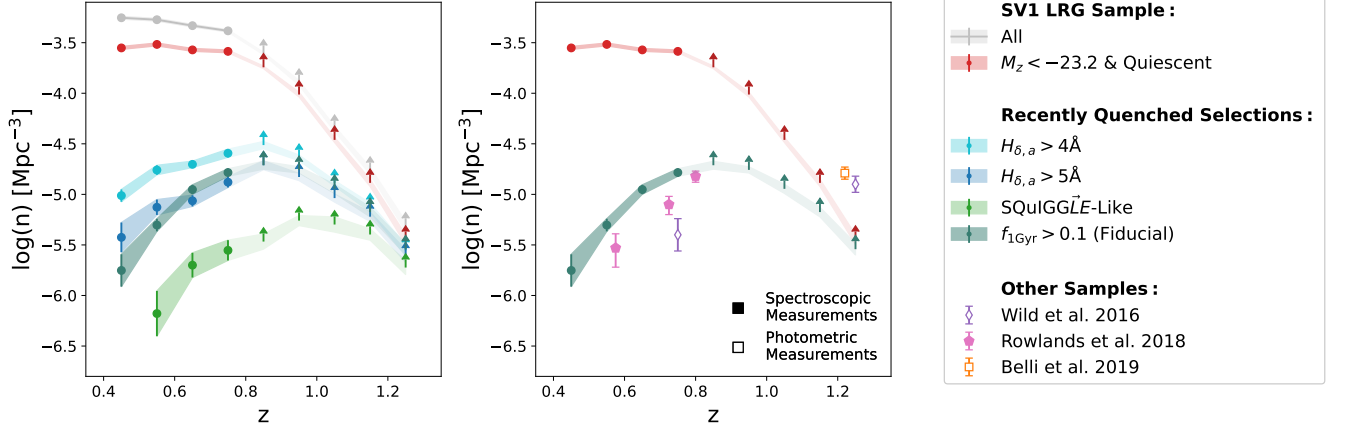


Figure 4. (Left): Number densities within the DESI SV LRG sample (full sample, gray; luminosity-complete and quiescent, red) and a variety of post-starburst selections from the luminosity-complete quiescent sample ($H_{\delta,a} > 4$, light blue; $H_{\delta,a} > 5$, dark blue; SQuIGGLE SED selection, light green; and $f_{1\text{Gyr}} > 0.1$, green). Beyond $z \sim 0.8$, we indicate that the measured number densities are lower limits by plotting as upward facing arrows. All post-starburst selections show an increasing number density over the redshift range in which we are complete, with varying normalization resulting from the relative restrictiveness of the post-starburst criteria. (Right): The same magnitude limited LRG and $f_{1\text{Gyr}} > 0.1$ samples as the previous panel in addition to literature measurements (photometric: open symbols; spectroscopic: filled symbols). All three of the Wild et al. (2016) ($M_* > 10^{10.8} M_\odot$), Rowlands et al. (2018) ($M_* > 10^{11} M_\odot$), and Belli et al. (2019) ($M_* > 10^{10.8} M_\odot$) samples show a trend of increasing number density with redshift, but the normalization differs between the different samples as a result of differing stellar mass limits and selection techniques.

very similar to that of compact star forming galaxies at $z=0.5$, adding credence to the argument that such galaxies may be progenitors to local post-starburst galaxies (Tremonti et al. 2007; Diamond-Stanic et al. 2021; Whalen et al. 2022). However, in detail, this comparison is limited by systematic effects; our sample is systematically more massive than other post-starburst samples, and is selected using a magnitude (not mass) limit. Additionally, as shown in the first panel of Figure 4, differing identification techniques can significantly impact the measured number density of post-starburst galaxies. Still, a clear consensus emerges from this comparison that recently quenched galaxies were increasingly common at greater lookback time.

3.3. Exploring the Growth of the Red Sequence by Rapidly Quenched Galaxies

In the previous section, we studied the number density of a magnitude limited sample of post-starburst galaxies to maximize our sample size. Here, we attempt to quantify explicitly fraction of massive galaxies that have recently quenched and joined the red sequence as a function of cosmic time. To do so, we utilize the mass complete ($\log(M_*/M_\odot) > 11.2$) subset of the LRG sample, which we show in the first panel of Figure 5 (red) along with the corresponding stellar mass function from Leja et al. (2020). This measurement over-predicts the stellar mass function by ~ 0.2 dex at $z \sim 0.4$ while matching well at $z \sim 0.7$. This may be due to systematic dif-

ferences in the stellar mass estimates (e.g., differences in modeled star formation histories, unmodeled contributions from AGN, or spectrophotometric modeling in our fits versus broadband multiwavelength SEDs), and the mismatch in redshift evolution may a result of the targeting incompleteness. As such, we adopt the number densities from the stellar mass function as the total abundance of massive ($\log(M_*/M_\odot) < 11.2$) galaxies and note that the fractions we measure may be systematically lower than reported by ~ 0.2 dex. Above $z = 0.8$ where LRG targeting is known to be incomplete, we inflate the upper error bar on the measured lower limits by assuming that every galaxy we have not targeted (quantified by the deviation between the measured number density and the stellar mass function) to capture the possibility that every galaxy we did not measure is a recently quenched galaxy. Since this is unlikely due to the lower M_*/L ratio of post-starburst galaxies, this conservative estimates captures the full range of possibility in the number density of galaxies in a given selection at $z > 0.8$.

We show the number densities of four different selections of recently quenched galaxies: $f_{1\text{Gyr}} > 0.05$ (light green), $f_{1\text{Gyr}} > 0.1$ (green), $f_{1\text{Gyr}} > 0.2$ (dark green), and $f_{1\text{Gyr}} > 0.5$ (black). Points that do not appear indicate that the redshift bin contained zero galaxies that met the selection criteria. All four sets of recently quenched galaxies show increasing number densities with redshift, but at $z \sim 0.8$, galaxies which formed

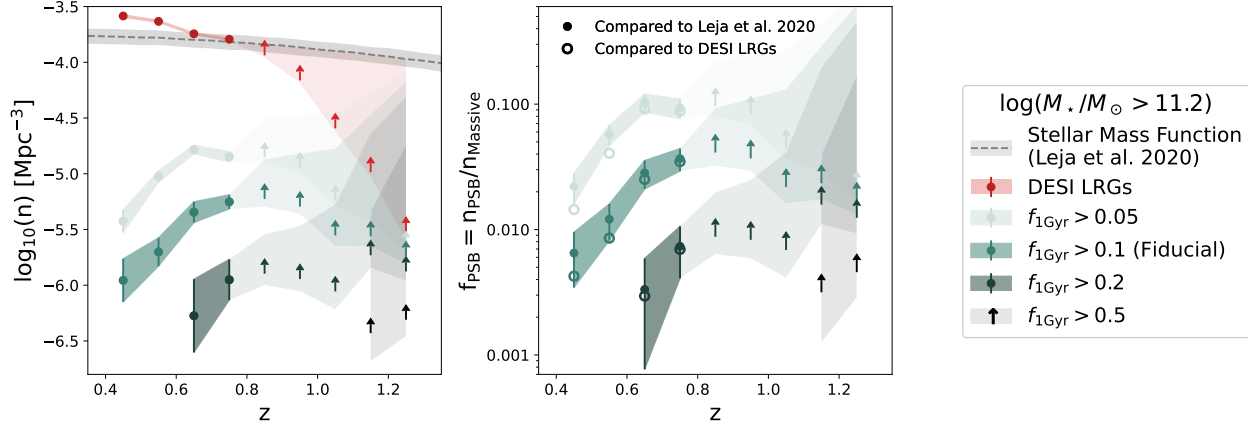


Figure 5. The number densities (left) and fractions (right) of recently quenched massive ($\log(M_*/M_\odot) > 11.2$) galaxies. The dashed line and grey band (left) represent the stellar mass function of similarly mass galaxies (Leja et al. 2020), and the red points show the number density of all LRGs above the mass limit. The light green, green, dark green, and black points represent the number densities and fractions of recently quenched galaxies with $f_{1\text{Gyr}}$ greater than 0.05, 0.1, 0.2, and 0.5 respectively, as compared to the stellar mass function from Leja et al. (2020). On the right panel, the open points of the same colors show the fraction of post-starburst galaxies as compared to our own massive galaxy number density measurements. Above $z = 0.8$, measurements are indicated as lower limits with errors inflated to encapsulate the possibility that all galaxies which were not targeted by DESI meet the selection criterion.

a large fraction of their stellar mass in the past Gyr are very rare. For example, at $z = 0.8$, galaxies that formed $> 20\%$ of their stellar mass in the past Gyr were significantly (> 1 dex) rarer than those which formed 5% of their stellar mass. However, we find that the number density of the $f_{1\text{Gyr}} > 20\%$ population cannot decrease with lookback time, and in fact, at $z \sim 1.2$ the lower limit number density of this population is higher than the number density at $z=0.8$. The rarity of such objects at intermediate- z is extremely consistent with the rarity of “late bloomers,” galaxies that formed the majority of their stellar mass in the 2 Gyr before quenching (Dressler et al. 2018). Additionally, we identify a very small population of galaxies which rapidly formed $\geq 50\%$ of their stellar mass in the Gyr before observation at $z = 1.1 - 1.3$, with lower limits that indicating a number density of at least $\log_{10}(n) > -6.5 \text{ Mpc}^{-3}$. Similar extreme post-starburst galaxies have been found in photometric samples with comparably low number densities and could represent analogs to the formation of massive quiescent galaxies at high- z (Park et al. 2022).

In the right panel of Figure 5, we show the same post-starburst samples as fractions of the total massive galaxy population (shown with solid points using the stellar mass function from Leja et al. (2020) as the denominator and empty points using our own measurements of the LRG number density). We find that galaxies which formed $> 20\%$ of their stellar mass represent $\sim 0.5\%$ of the total galaxy population at $z=0.8$, but by $z \sim 1.2$ must be at least 1%, with an upper limit that extends to them being the entirety of the quiescent population.

In contrast, galaxies with $f_{1\text{Gyr}} > 5\%$ and $> 10\%$ are significant even at $z=0.4$, representing $\sim 1.5\%$ and 0.5% of the massive galaxy population, and by $z = 0.8$ they are $\sim 10\%$ and 3% of the total population. The general rarity of extreme post-starburst galaxies in this massive sample is consistent with findings that the formation redshift of $\log(M_*/M_\odot) = 11.2$ galaxies is $z_{\text{form}} \sim 2 - 3$ (Gallazzi et al. 2014; Pacifici et al. 2016; Fumagalli et al. 2016; Carnall et al. 2019; Estrada-Carpenter et al. 2019; Díaz-García et al. 2019; Webb et al. 2020; Khullar et al. 2022); at the epochs we are probing, the average massive quiescent galaxy quenched long in the past. However, we find that a significant number of massive galaxies are still quenching well after cosmic noon ($z \sim 2$), and expect that with a more complete sample, at higher redshift the population dominated by recent star formation would become the norm.

4. DISCUSSION AND CONCLUSIONS

Using the DESI SV sample, we measure non-parametric star formation histories for a novel sample of Luminous Red Galaxies. We select physically motivated samples of post-starburst galaxies and leverage the well characterized parent sample to characterize the increasing number density of recently quenched galaxies with lookback time. We find the following:

1. The sample of quiescent galaxies which formed $> 10\%$ of its stellar mass in the past Gyr represents a novel spectroscopic sample. The 277 galaxies we

- identify at $z > 1$ are an order of magnitude larger than previous samples (see Figure 3).
2. The number density of post-starburst galaxies rises steadily with redshift from $z = 0.4$ – 0.8 based on our model selection and empirical identification methods; post-starburst galaxies were more common at earlier cosmic time (see Figure 4).
 3. The fraction of massive ($\log(M_*/M_\odot) > 11.2$) galaxies which have recently quenched their star formation and which formed $> 10\%$ of their stellar mass in the past Gyr rises in this redshift range from $\lesssim 0.5\%$ at $z=0.4$ to $\sim 3\%$ in at $z=0.8$ (see Figure 5). Furthermore, at $z > 1$, we find a significant emerging population that formed $> 20\%$ and $> 50\%$ of its stellar mass in the past Gyr.

Using these findings, we now discuss possible physical mechanisms that are driving the rapid quenching in this sample of galaxies. One of the most compelling fast processes that could shut off star formation and produce post-starburst galaxies is major mergers (e.g., Hopkins et al. 2008). After cosmic noon, simulations have found that many massive galaxies that quench do so via major mergers (e.g., Wellons et al. 2015), which funnel gas inward and induce a burst of star formation that rapidly shuts off. Indeed, many studies of post-starburst galaxies have found that merger features are more common in post-starburst systems (e.g., Pawlik et al. 2016; Sazonova et al. 2021; Ellison et al. 2022, Verrico et al. 2022 in preparation).

We estimate the relative frequency of major mergers using the UNIVERSEMACHINE (Behroozi et al. 2019) and find that 15% and 20% of $\log(M_*/M_\odot) > 11.2$ galaxies, at $z = 0.4$ and $z = 0.8$ respectively, experienced a major merger ($M_{*,2}/M_{*,1} > 25\%$ in the progenitor galaxies in the merger tree) in the past Gyr. This rate is significantly higher than the 0.5% and 3% fractions we find for our fiducial sample of recently quenched galaxies, and the merger fraction increases more slowly than the post-starburst fraction. Some of this difference may be driven by gas-poor major mergers between already quiescent systems or gas rich mergers that do not quench, and we conclude that it is plausible that every very massive galaxy that rapidly quenches between $0.4 < z < 0.8$ does so as a result of a major merger. However, at high- z , our measured lower limits fall short of placing strong constraints.

Still, the high- z tail of our distribution promises to be a very powerful tool for studying rapid quenching. Prior to DESI, only a small number of spectroscopic continuum observations from surveys could be mined for post-starburst galaxies above $z \gtrsim 1$ (Wild et al. 2020), and

often samples can only be obtained through targeted followup of photometrically identified sources (e.g., Belli et al. 2019). Even in the smallest (but highest signal-to-noise) subset of DESI LRG spectra, we have identified an order of magnitude more spectroscopically confirmed post-starburst galaxies than had been measured previously. Future work will leverage these star formation histories further to study trends using parameters such as the time since quenching (Suess et al. 2022b), which has been used in post-starburst populations to constrain the evolution of AGN incidence (Greene et al. 2020), sizes (Setton et al. 2022), molecular gas contents (Bezanson et al. 2022), and merger fractions (Verrico et al. submitted). Using the combination of the unique spectroscopically derived moments of the star formation history and ancillary data, we hope to place strong constraints on the mechanisms that drive the quenching of massive galaxies as close to cosmic noon as is currently possible. Future surveys, such as PFS (Greene et al. 2022) and MOONRISE (Maiolino et al. 2020) will extend wavelength coverage into the NIR, pushing farther in redshift to cosmic noon. In conjunction with this sample, comprehensive studies of the properties of post-starburst galaxies from $z = 0$ to $z = 2$ will paint a cohesive picture of the rapid quenching process and its role in producing the present-day quiescent population.

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tain with particular significance to the Tohono O’odham Nation. We direct readers to Astrobite’s coverage of the Tohono O’odham People and Kitt Peak National Observatory, as part of their series on the interactions between predominantly western astrophysics observatories and Indigenous communities: <https://astrobites.org/2019/08/16/a-tale-of-two-observatories>.

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