Effects of self-consistent rest-ultraviolet colours in semi-empirical galaxy formation models

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18 May 2020

ABSTRACT

Connecting the observed rest-ultraviolet (UV) luminosities of high-z galaxies to their intrinsic luminosities (and thus star formation rates) requires correcting for the presence of dust. We bypass a common dust-correction approach that uses empirical relationships between infrared (IR) emission and UV colours, and instead augment a semi-empirical model for galaxy formation with a simple – but self-consistent – dust model and use it to jointly fit high-z rest-UV luminosity functions (LFs) and colour-magnitude relations ($M_{UV}$-$\beta$). In doing so, we find that UV colours evolve with redshift (at fixed UV magnitude), as suggested by observations, even in cases without underlying evolution in dust production, destruction, absorption, or geometry. The observed evolution in our model arises due to the reduction in the mean stellar age and rise in specific star formation rates with increasing $z$. The UV extinction, $A_{UV}$, evolves similarly with redshift, though we find a systematically shallower relation between $A_{UV}$ and $M_{UV}$ than that predicted by IRX-$\beta$ relationships derived from $z \sim 3$ galaxy samples. Finally, assuming that high 1600Å transmission ($\gtrsim 0.6$) is a reliable LAE indicator, modest scatter in the effective dust surface density of galaxies can explain the evolution both in $M_{UV}$-$\beta$ and LAE fractions. These predictions are readily testable by deep surveys with the James Webb Space Telescope.

Key words: galaxies: high-redshift – galaxies: luminosity function, mass function.

1 INTRODUCTION

Current constraints on galaxy formation are based largely on the rest ultraviolet (UV) properties of redshift $z \gtrsim 4$ galaxies, e.g., luminosity functions (LFs; Bouwens et al., 2015; Finkelstein et al., 2015) and UV colour-magnitude relations (CMDs, $M_{UV}$-$\beta$; Bouwens et al., 2009; Finkelstein et al., 2012; Bouwens et al., 2014; Dunlop et al., 2013). Such observations probe the star formation rate (SFR) of high-z galaxies, given that the rest-UV emission is dominated by massive young stars, and have thus allowed astronomers to begin piecing together the cosmic star formation rate density (SFRD) in the early Universe (see Madau & Dickinson, 2014, for a review). UV colours, generally quantified by a power-law spectral slope $\beta$ (defined by $f_{\lambda} \propto \lambda^\beta$), are critical to this inference as they are modulated by dust extinction in a characteristic wavelength-dependent manner, allowing one to “dust correct” UV magnitude measurements, so long as multi-band photometry covering the rest UV continuum ($1300 \lesssim \lambda/\text{Å} \lesssim 2600$) is available.

Unfortunately, the link between $\beta$ and UV extinction, $A_{UV}$, is potentially complicated. One common approach is to assume that thermal radiation emitted from dust grains (in the infrared; IR) is a reliable tracer of the energy lost in the UV. In low redshift star-forming galaxies, for which there is both rest-UV and rest-IR coverage, there is indeed a relationship between $A_{UV}$ and $M_{UV}$ than that predicted by IRX-$\beta$ relationships derived from $z \sim 3$ galaxy samples. Finally, assuming that high 1600Å transmission ($\gtrsim 0.6$) is a reliable LAE indicator, modest scatter in the effective dust surface density of galaxies can explain the evolution both in $M_{UV}$-$\beta$ and LAE fractions. These predictions are readily testable by deep surveys with the James Webb Space Telescope.

Key words: galaxies: high-redshift – galaxies: luminosity function, mass function.
els (SAMs), which may not model dust explicitly. There are several ways this approach may break down. For example, the origin of the IRX-β relation is an active area of research, both observationally (e.g., Overzier et al., 2011; Casey et al., 2014; Reddy et al., 2018) and theoretically (e.g., Narayanan et al., 2018; Salim & Boquien, 2019; Ma et al., 2019; Schulz et al., 2020), so it may be premature to apply it at arbitrarily high redshift, where the properties of stars and dust may differ from low-z samples. Inferences based on IRX-β arguments could be biased for a less interesting reason, which is that the assumptions underlying the M99 relation are often not made in SAMs. For example, adopting a different stellar population synthesis (SPS) model can change the input stellar spectrum, as can changes in the star formation histories (SFHs) of individual galaxies, thus posing a self-consistency issue when invoking empirical IRX-β relations. For example, model galaxies generally have rapidly rising star formation histories (SFHs), and are thus intrinsically bluer than the assumed input β adopted in M99 (see, e.g., Finlator et al., 2011; Wilkins et al., 2013), which is based on the assumption of a constant star formation rate (SFR).

In this work we take a different approach that avoids self-consistency issues by using a simple dust model in lieu of an IRX-β assumption. This approach allows us to compute self-consistent solutions for the spectra of objects in our model, assess the circumstances in which evolution in the properties of dust is required by current measurements, and make physically-motivated predictions for upcoming β measurements to be conducted with the James Webb Space Telescope (JWST).

In Section 2 we detail our dust model and the underlying assumptions about star formation in early galaxies. We detail our main results in Section 3 and discuss them in a broader context in Section 4. In Section 5 we summarize our findings.

We adopt AB magnitudes throughout (Oke & Gunn, 1983), i.e.,

$$M_\lambda = -2.5 \log_{10} \left( \frac{f_\lambda}{3631 \, \text{Jy}} \right)$$

(1)

and use a Planck 2015 cosmology (Planck Collaboration et al., 2016).

2 MODEL

Our model is similar to other semi-empirical models that have appeared in the literature in recent years. We outline our model for star formation in galaxies in §2.1, our approach to dust in §2.2, and our method for generating synthetic spectra and estimating UV colours in §2.3. Much of this has been described previously (Mirocha et al., 2017; Mirocha & Furlanetto, 2019), and is publicly available within the ares code.

2.1 Star Formation

We assume the SFR is proportional to the baryonic mass accretion (MAR) onto dark matter (DM) halos (as in, e.g.;

$$M_\star(M_z, z) = f_\star(M_z, z) \dot{M}_b(z, M_z)$$

(2)

where \( f_\star \) is the efficiency of star formation. The baryonic MAR is well approximated by a power-law in mass and redshift (e.g., McBride et al., 2009; Dekel et al., 2013), however, rather than adopting a parametric form for the MAR calibrated by simulations, we derive it directly from the halo mass function (HMF; see Appendix A of Furlanetto et al., 2017, for more details). We adopt the Tinker et al. (2010) HMF in this work, generated by the HMF code\(^2\) (Murray et al., 2013).

We assume that the star formation efficiency (SFE) is a double power-law (DPL) in \( M_b \), i.e.,

$$f_\star(M_z) = \frac{f_{\star,10}}{\left( \frac{M_z}{10^{12} M_\odot} \right)^{-\alpha_{\star,lo}} + \left( \frac{M_z}{10^{12} M_\odot} \right)^{-\alpha_{\star,hi}}}$$

(3)

where \( f_{\star,10} \) is the SFE at \( 10^{12} M_\odot, M_z \) is the mass at which \( f_\star \) peaks, and \( \alpha_{\star,hi} \) and \( \alpha_{\star,lo} \) describe the power-law index at masses above and below the peak, respectively. The additional constant \( C_{10} \equiv (10^{10}/M_\odot)^{-\alpha_{\star,lo}} + (10^{10}/M_\odot)^{-\alpha_{\star,hi}} \) is introduced to re-normalize the standard DPL formula to \( 10^{12} M_\odot \), rather than the peak mass. This model predicts \( z > 6 \) UVLFs in good agreement with observations when calibrating only to measurements at \( z \sim 6 \) (Mirocha et al., 2017; Furlanetto et al., 2017), in agreement with the results of other similar models from recent studies (e.g., Trenti et al., 2010; Behroozi et al., 2013a; Mason et al., 2015; Mashian et al., 2016; Sun & Furlanetto, 2016; Tacchella et al., 2018; Behroozi et al., 2019).

In this work, we extend our models to \( z \sim 4 \) to more adequately address issues of time evolution in the \( M_{UV-\beta} \) relationship and UVLFs. Furthermore, we include log-normal scatter in the SFR of halos at fixed halo mass\(^3\) (\( \sigma_{\delta_{b\star} SFR} = 0.3 \)), and synthetize the spectra of all galaxies in the model, rather than assuming a constant steady-state value for the relationship between UV luminosity and SFR. In other words, for each halo in our model, with index \( i \), we determine the intrinsic spectrum at redshift \( z_{\text{obs}} \) by integrating over the past star formation history, i.e.,

$$L_{\lambda,i}(z_{\text{obs}}) = \int_{z_{\text{obs}}}^{z_{\text{form}}} M_{\star,i}(z') L_{\lambda}(\Delta t') \frac{dt'}{dz'} dz'$$

(4)

where \( L_{\lambda}(\Delta t') \) is the luminosity of a simple stellar population of age \( \Delta t = t(z_{\text{obs}}) - t(z') \). This luminosity is then reddened by an optical depth \( \tau_{\lambda,i} \), yielding the observed luminosity

$$L'_{\lambda,i} = L_{\lambda,i}(z_{\text{obs}}) e^{-\tau_{\lambda,i}}$$

(5)

We adopt the BPASS version 1.0 (Eldridge & Stanway, 2009) single-star models\(^4\) throughout when modeling \( L_{\lambda}(\Delta t') \) with an intermediate stellar metallicity of \( Z_\odot/5 \). These choices largely affect the inferred normalization of the SFE and dust

\(^2\) https://hmf.readthedocs.io/en/latest/

\(^3\) We take this to represent scatter in halo accretion rates, but such scatter will also resemble the dispersion in halo assembly times (e.g., Ren et al., 2018).

\(^4\) We neglect nebular emission in this work for simplicity. Though the inclusion of nebular continuum emission can substantially reden the UV colours of very young objects, this effect is small for galaxies with near-continuous, rapidly-rising star formation rates.
opacity. As a result, any change to the stellar model will largely be absorbed by normalization parameters, leaving constraints on the shape of the SFE and dust scale length relatively unaffected.

2.2 Dust Obscuration

For each galaxy in our model we track the build-up of metals by assuming a fixed metal yield per unit SFR, i.e., \( \dot{M}_Z = f_Z M_* \), where the metal production efficiency \( f_Z \) is set to 0.1 in our fiducial case. We further assume that a fraction \( f_d = 0.4 \) of these metals reside in dust grains (Dwek, 1998). This “instantaneous recycling” approximation is reasonable, at least in the \( z \gtrsim 6 \) limit, as the Universe is too young for asymptotic giant branch (AGB) stars to have become a non-negligible source of dust production (e.g., Dwek et al., 2007).

To redden galaxy spectra, we must also make an assumption about the geometry of the dust distribution and the opacity of dust (per unit mass). For simplicity, we adopt a simple spherically-symmetric dust screen model, where the dust optical depth along obscured lines of sight is given by

\[
\tau_d = \int_0^R r \rho_d(r) \kappa_d dr.
\]

We take the absorption coefficient \( \kappa \) to be a power-law as we only explore a relatively narrow range in wavelength in this study,

\[
\kappa = \kappa_{1000} \left( \frac{\lambda}{10^3 \text{Å}} \right)^{\gamma_\kappa}.
\]

where \( \kappa_{1000} = \kappa(\lambda = 10^3 \text{Å}) \approx 10^5 \text{cm}^2 \text{g}^{-1} \approx 20 \text{pc} M_\odot^{-1} \) and \( \gamma_\kappa = -1 \) in our fiducial model. These choices are consistent with an SMC-like dust law in the rest-UV (Weingartner & Draine, 2001), though more complex models may be warranted, e.g., to accommodate the 2175Å “bump” present in some galaxies (for a recent review of the dust attenuation law, see Salim & Narayanan, 2020).

In this framework, sources at the center of spherically-symmetric, uniform density dust clouds, are obscured by an optical depth given by

\[
\tau_c = \kappa_\lambda N_d = \kappa_\lambda \frac{3M_d}{4\pi R_d^2}
\]

i.e., the characteristic scale \( R_d \) determines both the dust density and the length of sightlines passing through the dust envelope. To start, we model \( R_d \) generically as a power-law in mass\(^5\),

\[
R_d = R_0 \left( \frac{M}{10^{10} M_\odot} \right)^{\alpha_{d,lo}} \text{kpc},
\]

where \( R_0 \) normalizes the scale length at \( M_h = 10^{10} M_\odot \) and \( \alpha_{d,lo} \) controls the dependence of \( R_d \) on \( M_h \). We will show in §3 that a more complicated function is likely warranted. Note that the virial radii of dark matter halos evolve as \( R_{\text{vir}} \propto M_h^{1/3}(1+z)^{-1} \), while \( R_d \propto M_h^{1/2} \) implies dust column densities that are proportional to \( M_d/M_h \) (see Eq. 8).

Note that we make no effort to model dust emission in this work—an any link to the IRX-\( \beta \) relation would require modeling of dust temperatures. Imara et al. (2018) present a very similar approach to ours, but focus instead on the implications at longer wavelengths. We expect that our predictions for dust emission would be similar to those of Imara et al. (2018) were we to make the same assumptions for how stellar radiation is reprocessed by dust. As we will discuss in §4, UV extinction is a prediction of our model, rather than an input, as is effectively the case for IRX-\( \beta \)-based models.

2.3 Synthetic Observations

In order to fairly compare with constraints on the \( M_{\text{UV}}-\beta \) relation at high-\( z \), we “observe” our model galaxies using the same magnitude definition and photometric filters as in Bouwens et al. (2014) (hereafter B14). The filters\(^6\) employed vary with redshift as follows:

- \( z \sim 4 \): \( i_{814}, z_{850}, (Y_{105}), J_{125} \)
- \( z \sim 5 \): \( z_{850}, Y_{105}, (J_{125}), H_{160} \)
- \( z \sim 6 \): \( Y_{105}, (J_{125}), H_{160} \)
- \( z \sim 7 \): \( J_{125}, H_{160} \)

B14 employed the filters listed above in the ERS (Windhorst et al., 2011) and CANDELS (Koekemoer et al., 2011; Grogin et al., 2011) fields, but in the deeper XDF (Illingworth et al., 2013), and HUDF09 (Bouwens et al., 2011) fields, filters enclosed in parentheses were not used. The Y_{098} filter was used when available. The UV magnitude in B14 is defined as the geometric mean of the photometric measurements for each galaxy, which we indicate with angular brackets, \( \langle M_{\text{UV}} \rangle \).

We make no effort in this study to conduct mock surveys and perform sample selection self-consistently, and therefore have no basis on which to use different combinations of filters for objects at the same redshift. For consistency, we adopt the ERS/CANDELS filters for all objects, and only use the \( Y_{098} \) filter at \( 4 \lesssim z \lesssim 6 \). We expect this to be a reasonable approach given that most of the information about dust is in the brightest, reddest objects, which are captured best by the wider field surveys.

As pointed out in Finkelstein et al. (2012), photometric estimates of \( \beta \) can bias estimates of dust attenuation. We also find that photometrically-estimated UV slopes are biased relative to intrinsic, spectroscopically-estimated (in C94 windows) UV slopes. The effect is generally of order \( \Delta \beta \sim +0.1 \) for objects with intrinsic slopes \( \beta \sim -2.4 \), particularly at \( z \gtrsim 6 \) (for both HST and JWST), i.e., measured slopes are biased red. However, larger biases can occur if one is forced to use sub-optimal filter combinations. We illustrate these effects thoroughly in §3 and Appendix A, where we also provide a full listing of the HST filters and the redshifts at which they are used (Table A1; shown graphically in Figure A3) along with the NIRCAM wide and medium filters that

\(^5\) Similar approaches have been taken in previous work, e.g., Somerville et al. (2012) adopt \( R_d = R_{\text{gas}} \), where the radius of the cold gas disk \( R_{\text{gas}} \) is assumed to be a constant fraction of the stellar scale length. We discuss our choice the \( R_d \) parameterization further in §3.3 and §4.2.

\(^6\) WFC: http://www.stsci.edu/hst/acs/analysis/throughputs/tables

\(^7\) WFC3: http://www.stsci.edu/hst/wfc3/ins_performance/throughputs/Throughput_Tables
lie within the range of the Calzetti et al. (1994) windows. Unless indicated otherwise, these are the filters used for β estimation throughout this paper.

3 RESULTS

3.1 Basic Trends

In Figure 1, we show how the relationship between dust scale length, $R_d$, and halo mass, $M_h$, influences UVLFs and the $M_{UV} - \beta$ relation. We show scenarios spanning the range from $R_d \propto M_h^{3/4}$ to $R_d \propto M_h^{2/3}$.

For illustrative purposes, we fix $f_{\ast, 10} = 0.03$, $M_{\ast, peak} = 2 \times 10^{11} M_\odot$, $\alpha_{\ast, lo} = 2/3$, $\alpha_{\ast, hi} = 0$, and $R_{d, 10} = 1.1$ kpc. In this case, the production of dust continues even as star formation slows at high mass, resulting in monotonically rising $\beta$. The B14 measurements prefer $\alpha_d \approx 0.5$. The UV colors are extremely sensitive to $\alpha_d$: the $M_{UV} - \beta$ relation becomes too steep for $\alpha_d = 1/3$ (dashed), and much too shallow for $\alpha_d = 2/3$ (dotted). In the former case, while reducing the normalization length scale, $R_{d, 10}$, can help (equivalent to decrease in dust yield), the shape of the UVLF and $M_{UV} - \beta$ remain problematic (dash-dotted). The shaded region for $z \sim 4$ models shows how changing the wavelength-dependence of the dust opacity (Eq. 7) between $\kappa_d \propto \lambda^{-1.3}$ and $\kappa_d \propto \lambda^{-0.7}$ affects the UVLFs and CMDs.

We explore the impact of high-mass SFE variations in Figure 2 for three different high-mass SFE slopes. For a strong decline, $\alpha_{\ast, hi} = -0.8$, predictions for the bright-end of the $z \sim 4$ UVLF are in much better agreement with B14 measurements, though come at the cost of imparting a turn-over in $M_{UV} - \beta$ (dotted lines). This sharp decline in the SFE also has implications for galaxy stellar mass functions (SMFs), which we explore further in §3.3.

3.2 Effects of Scatter in Dust Column Density

The models shown thus far assume a 1:1 mapping between halo mass and dust scale length. Some scatter in the dust column density, $N_d$, at fixed $M_h$ still arises due to scatter in the SFR of galaxies (and thus dust production rate), but this is likely overly conservative. To explore the impact of scatter further we explore scenarios with lognormal scatter in $N_d$, $\sigma_{\log_{10} N_d}$, at fixed halo mass. In what follows, we also force the dust scale length to be a shallow function of halo mass, $R_d \propto M_h^{1/3}$, for reasons that will become apparent momentarily.

The introduction of $N_d$ scatter has an interesting impact on $M_{UV} - \beta$. Consider a faint galaxy, $M_{UV} \sim -17$, with the average amount of dust attenuation, so that $\beta \sim -2.4$. Now, if we subject this galaxy to a strong negative fluctuation in $N_d$, it will become brighter and bluer, and thus enter an $M_{UV}$ bin occupied (generally) by galaxies that reside in more massive, slightly more rare, halos. The opposite case of a positive $N_d$ spike will lead our galaxy to migrate in the opposite direction in the $M_{UV} - \beta$ plane, where it will occupy an $M_{UV}$ bin with galaxies that live in smaller, more common halos. As a result, there will be a net blueward bias in $\beta$ at fixed $M_{UV}$: galaxies scattering toward smaller $M_{UV}$ will always be outnumbered by unscattered objects in the same magnitude bin, while galaxies scattering to brighter $M_{UV}$ will always outnumber the “typical” galaxy in that bin.

We show this effect in Figure 3. Due to the net bias toward bluer colors, models with more $N_d$ scatter can accommodate shallower relationships between $R_d$ and $M_h$, hence our adoption of the $R_d \propto M_h^{1/3}$ limit for each model in Figure 3. Without scatter, $\beta(M_{UV})$ is much too sharp, as shown also in the dashed lines of Figure 1, but non-zero scatter curbs this behavior. There is tension between UVLFs and $M_{UV} - \beta$, which varies as a function of redshift, though this tension can be alleviated by slightly generalizing the $R_d$ parameterization and calibrating the model properly via multi-dimensional fitting, as we describe in the next sub-section.

3.3 Model Calibration

In order to properly calibrate the model and quantify degeneracies between star formation and dust parameters, we perform a multi-dimensional Markov Chain Monte-Carlo (MCMC) fit to the $z \sim 4.6$, and 8 UVLFs from Bouwens et al. (2015) and $z \sim 4$ and 6 $M_{UV} - \beta$ relations from Bouwens et al. (2014) using emcee11 (Foreman-Mackey et al., 2013).

We note before moving on to the results of this calibration that fitting to the B14 empirical $\beta$ fits is more efficient computationally than, e.g., fitting to the Finkelstein et al. (2012) UV slopes determined via SED fitting. In order to compare fairly with the Finkelstein et al. (2012) measurements one needs higher wavelength resolution in order to adequately sample the spectra of objects within the Calzetti et al. (1994) spectral windows, of which there are 10, in contrast to the usual $\sim 2 - 5$ HST filters used in the B14 analysis. Our approach scales as the number of wavelengths over which to perform spectral synthesis, making the empirical approach a more efficient option. We compare our best-fitting models to the Finkelstein et al. (2012) (hereafter F12) results shortly.

The simplest model we explore has a total of six free parameters: the typical four parameters needed to describe $^9$ We explore the impact of $N_d$ scatter on the intrinsic scatter of the $M_{UV} - \beta$ relation in §3.4.

$^{10}$ Note that scatter in the SFR at fixed halo mass will also affect UV colours, though the effect is relatively small (see Figure 11).

$^{11}$ https://emcee.readthedocs.io/en/stable/
the steepness of the star formation and dust production, the decline in the SFE above the peak, and differences caused by stellar metallicity for dust-free models (between $Z = 0.001$ and $Z = Z_{⊙} = 0.02$; horizontal bands). Data shown include UVLFs from Bouwens et al. (2015) (4 $\leq z \leq 8$) and Oesch et al. (2018) ($z \sim 10$), and $M_{U_0}$ measurements from B14. A dust-free model is also shown for reference at $z \sim 4$. Note that these models are for illustrative purposes (i.e., they are not the result of fits; see §3.4 for MCMC results).

Figure 1. Effects of variations in the relationship between dust scale length, $R_d$, and halo mass, $M_h$. Left: SFE (black) and dust column density (blue; right axis) as a function of $M_h$ for four different $R_d(M_h)$ models. Note that the dot-dashed curve is systematically shifted, but keeps the same power-law as the dashed curve. Right: Corresponding UVLFs (left) and CMDs (right) at a series of redshifts. Models in which $R_d \propto M_h^{0.2}$ (solid) are in good agreement with measurements. Shallower slopes are too steep (dashed), even if the normalization of $R_d$ is adjusted to systematically reduce dust reddening (dot-dashed). The shaded regions for $z \sim 4$ models represent mild, changes in the wavelength-dependence of the dust opacity (top-most bands), and differences caused by $\alpha$, $\alpha_d$, and halo mass, $M_h$, $R_d$, hi, $M_{1600}$). Note that these models are for illustrative purposes (i.e., they are not the result of fits; see §3.4 for MCMC results).

Figure 2. Effects of variations in the efficiency of star formation in high-mass halos. Same as Figure 1, except line styles indicate a change in the slope of the SFE above the peak, $\alpha_{s\, hi}$. Because dust production is directly proportional to galaxy SFR in our model, a downturn in the SFE can cause galaxies to become bluer as they grow more massive (dotted lines). Solutions to this issue are discussed in §3.3.

a double power-law SFE ($f_s, M_{\text{peak}}, \alpha_{s\, hi}$), and two parameters for the dust scale length ($R_{d\, 10}, \alpha_d$). We do not allow any of these parameters to evolve with cosmic time.

This simple, redshift-independent but halo mass-dependent model for star formation and dust obscuration agrees reasonably well with observations as shown in Figure 4 (dotted lines). However, due to the tight link between star formation and dust production, the decline in the SFE at high-mass needed to match the steepness of the $z \sim 4$ UVLF has two unfortunate side-effects: (i) a turn-over in the $M_{U_0}$-$\beta$ relation, and (ii) and decline in the bright-end of the SMF much steeper than suggested by constraints from Song et al. (2016) and Stefanon et al. (2017) (see dotted lines in bottom row in Fig. 4).

We employ two strategies to remedy this problem in all that follows. First, we impose a prior requiring $\beta$ to be a monontonic function of $M_{U_0}$ over the range of magnitudes probed by observations (including UVLFs and CMDs), which either eliminates a turn-over in $M_{U_0}$ entirely or pushes it to slightly brighter objects, helping to reduce the disagreement between the bright-end of the UVLF and SMF$^{12}$. Second, we introduce an additional degree of free-

$^{12}$ From Figure 4, it is clear that none of our models predict a
Figure 3. Effects of scatter in dust column density at fixed halo mass. Same as Figure 1, except linestyles indicate the amount of log-normal scatter, with $\sigma_{\log N_d} = 0.1, 0.2, \text{ and } 0.3$. We assume an intermediate case for high-mass SFE, $f_{\ast, \text{hi}} \propto M_h^{-0.4}$, and a shallow limit for the dust scale length, $R_d \propto M_h^{1/3}$. The overall effect is a net blueward bias, as objects up-scattered into brighter magnitude bins always outnumber the typical object in that bin.

Figure 4. Evolution of UVLF, SMF, and CMDs. Top: Rest UV information only, including UVLFs at $z \sim 4, 6, \text{ and } 8$ (left), $z \sim 5, 7, \text{ and } 10$ (center), and $M_{\ast, \text{UV}} - \beta$ relation from $4 \leq z \leq 7$. Data shown include UVLFs from Bouwens et al. (2015) ($4 \leq z \leq 8$) and Oesch et al. (2018) ($z \sim 10$), and $M_{\ast, \text{UV}} - \beta$ from B14 (right). Bottom: Predictions in terms of stellar masses, rather than $M_{\ast, \text{UV}}$, including SMFs at $z \sim 4, 6, \text{ and } 8$ (left), $z \sim 5, 7, \text{ and } 10$ (center), and $M_{\ast} - \beta$ relations at $4 \leq z \leq 7$ (right). Data shown include SMFs from Song et al. (2016) (circles), Stefanon et al. (2017) (squares), and Duncan et al. (2014) (pentagons), and $M_{\ast} - \beta$ from Finkelestein et al. (2012). Note that the Stefanon et al. (2017) and Duncan et al. (2014) stellar masses have been shifted by 0.25 dex to convert from a Chabrier to Salpeter IMF, and the $z \sim 4$ UV colours are repeated in each panel.
dom in our parameterization of $R_d$, allowing it to be a double
power-law in $M_h$ rather than a single unbroken power-law. With this parameterization, as the SFE declines at high-
mass to match the steepness of the UVLF, the dust scale
length can become shallower to ensure that $\beta$ continues to
rise. This solution is amenable to shallower SFE curves at
high-mass, resulting in better agreement with SMFs at the
bright-end as well. Along with the standard four para-
ters for the SFE, this results in a total of 9 free parameters,
which we calibrate via fitting to the B14 $M_{UV} - \beta$ relation
at $z = 4$ and 6, and UVLFs from B15 at $z \sim 4, 6$ and 8.
Best-fitting values of the model parameters and their un-
certainties are summarized in Table 1, with a subset of the
posterior distributions shown in Figure 6.

In Figure 4, we show the rest UV calibration of this
final model (top) and its predictions for the SMF as $M_{UV} - \beta$
relation (bottom) at all $4 \lesssim z \lesssim 10$ (solid lines). The top
row of Fig. 4 is not terribly surprising, as much of the data
shown is used in the calibration. Most noteworthy in this
context is the evolution in the $M_{UV} - \beta$ relation, which arises
despite the assumption that the production rate, opacity,
and scale length of dust are constant in time. This evolution
arises due to evolution in the typical stellar age, but also
because specific star formation rates rise rapidly with
redshift, which is a generic prediction of most models (e.g.,
Behroozi et al., 2013b; Dayal et al., 2013). In other words,
part of the evolution in $M_{UV} - \beta$ is due to evolution in $M_{UV}$
(at fixed stellar or halo mass) alone, with the rest arising
due to the bluer colors typical of increasingly young stellar
populations at high redshift (see §4.2 for more discussion).

In Figure 5, we show the key ingredients of our model
as recovered via MCMC fitting. First, in the top panel we
show the SFE (filled gray contours) compared to a dust-free
solution (dotted) and a solution obtained via the M99+B14
approach (dashed). As expected, the treatment of dust
affects both the normalization and shape of the SFE as a
function of $M_h$, with offsets of a factor of $\sim 2-3$ near the
peak. The posterior distribution for the component param-
eters, as well as the reconstructed SFRD, are included in
Appendix B. In the bottom panel, we show the recovered
dust scale length with pure power-laws included to guide
the eye. The departure from a pure power-law is subtle – at
high-mass, $M_h \gtrsim 10^{11} M_\odot$, our solution roughly tracks the
$R_d \propto R_{vir} \propto M_h^{1/3}$ solution, while at lower mass a steeper
slope at high-mass, $\alpha \sim 1$, and shallower slope at low-
mass, $\alpha \sim 0.7$, with a change in slope occurring at $10^{11} \lesssim M_{d,peak}/M_\odot \lesssim 10^{12}$ (panel b). There is of course
a mild degeneracy between the dust scale length and high-
mass SFE slope (panel c), with $\alpha \sim 0.5$. The dust scale
length and scatter have no significant degeneracy (panel d).
Finally, in panel (e), we see that the halo mass of the break
in the dust scale length is poorly constrained, and though
relation is preferred. The blue line shows the corresponding
dust column density for the best-fit model only (right axis).

Finally, in Figure 6, we show a subset of the posterior
distribution. From the left-most panel, we see the degener-
cy between components of the double power-law $R_d$ model.
Solutions favoring a single, unbroken power-law would track
the dotted line, but clearly such solutions are not preferred
by our fits. The maximum likelihood model has a steep
slope at high-mass, $\alpha_{d,hi} \sim 0.1$, and shallower slope at
low-mass, $\alpha_{d,lo} \sim 0.7$, with a change in slope occurring at
$10^{11} \lesssim M_{d,peak}/M_\odot \lesssim 10^{12}$ (panel b). There is of course
a mild degeneracy between the dust scale length and high-
mass SFE slope (panel c), with $\alpha_{s,hi} \sim 0.5$. The dust scale
length and scatter have no significant degeneracy (panel d).

Finally, in panel (e), we see that the halo mass of the break
in the dust scale length is poorly constrained, and though

![Figure 5. Reconstructed star formation efficiency and dust scale length.](image-url)
the Stefanon et al. (2017) constraints. Predictions for the


tional constraints. Our predictions are closer to the Duncan

SMF at low-mass is in considerable tension with observa-

et al. (2012).

are in good agreement with the constraints from Finkelstein

models (e.g., Tacchella et al., 2018), the slope of the

ment is reasonably good, though, as is the case for many

The bottom row of Figure 4 shows our model’s predictions

do not recover the “true” UV colour evolution (computed

by LAE, with the critical opacity left as a free

paradox in solving for the UV luminosity and colors of

is preferred, the 68% contours are consis-

The first block of four parameters are those

parameters describe the dust scale length and scatter in dust column

density (see §2.2). Fits were performed using broad uninformative

priors on each parameter, as listed in the final column.


\[
M_{d,\text{peak}} > M_{*,\text{peak}}
\] is preferred, the 68% contours are consist-

ent with occurring at \(M_{d,\text{peak}} = M_{*,\text{peak}}\). A triangle plot

of the SFE parameters is included in Appendix B compared to

the results of simpler models published in previous studies.

### 3.4 Model Predictions

The bottom row of Figure 4 shows our model’s predictions for the galaxy SMF and relation between \(M_\bullet\) and \(\beta\). Agreement is reasonably good, though, as is the case for many models (e.g., Tacchella et al., 2018), the slope of the \(z \sim 4 - 5\) SMF at low-mass is in considerable tension with observational constraints. Our predictions are closer to the Duncan et al. (2014) SMF measurements than Song et al. (2016), while at the bright end, our predictions agree well with the Stefanon et al. (2017) constraints. Predictions for \(M_\bullet - \beta\) are in good agreement with the constraints from Finkelstein et al. (2012).

In Figure 7, we zoom-in on our predictions for the \(z \sim 8\) and 9 UVLFs, given the continued progress in finding bright galaxies at these redshifts (e.g., Bowler et al., 2020; Morishita et al., 2018; Stefanon et al., 2019; McLeod et al., 2016; Livermore et al., 2018; Rojas-Ruiz et al., 2020). We show our predictions both for the observed UVLF (solid) and the intrinsic UVLF (dotted), i.e., the UVLF uncorrected for dust. We find that \(z \sim 8 - 9\) galaxies are still reddened considerably at the bright end, by \(\sim 1\) magnitude (at, e.g., \(M_{UV,\text{obs}} = -23\)), though the bright-end still declines slowly, in agreement with the recent Bowler et al. (2020) results. As a result, departures from the Schechter form of the UVLF at the bright-end may not be an indicator of reduced dust contents in bright high-\(z\) galaxies.

Because our model is fundamentally anchored to the evolution of dark matter halos, it is straightforward to make predictions for future UV colour measurements with JWST. We show these predictions in Figure 8, including evolution in \(\beta\) at various \(M_{UV}\) (left) and \(M_\bullet\) (right). We expect the mild trend in \(\beta(z; M_{UV})\) observed thus far at \(4 \lesssim z \lesssim 7\) to con-
tinue to higher redshift (top-left panel), as has been shown in other empirically-calibrated models (e.g., Williams et al., 2018). However, photometric measurements of \(\beta\) generally do not recover the “true” UV colour evolution (computed using C94 windows; black lines). For example, evolution in \(\beta\) as computed with NIRCAM wide filters (magenta) exhibits sharp features at redshifts where two-filter coverage requires excursions outside the C94 range (see Figure A3).

The NIRCAM medium filters probe the underlying evolution more faithfully, at least at \(z \gtrsim 7\), with only a slight redward bias, \(\beta \lesssim 0.1\). Further investigation into the evolution in the shape of the \(M_{UV} - \beta\) and \(M_\bullet - \beta\) relation (bottom row) seems potentially informative, as our models do not reflect the trends observed in B14 and F12 in detail—in fact, we predict little to no evolution in the \(\beta\) gradients with respect to \(M_{UV}\) (bottom left) or \(M_\bullet\) (bottom right). However, measurement uncertainties are large, so we have not investigated potential sources of this disagreement in detail at this stage.

A key advantage of our approach is that we do not invoke an IRX-\(\beta\) relationship to correct for dust, instead self-consistently solving for the UV luminosity and colors of high-\(z\) galaxies with a semi-empirical dust model. As a re-

sult, the relationship between \(A_{UV}\) and \(M_{UV}\) is a prediction of our model, rather than an input. We show our recovered \(A_{UV}(M_{UV})\) curves in Figure 9 compared to the results obtained when assuming a Meurer et al. (1999) relation and the B14 fits to \(M_{UV} - \beta\). Our predicted \(A_{UV}\) values are system-

tically lower than the M99+B14 approach for bright galaxies (dashed lines).

Finally, an interesting question in high-\(z\) galaxy evo-

lution is whether or not redshift evolution in \(M_{UV} - \beta\) and Lyman-\(\alpha\) emitter (LAE) fractions are related to the same underlying phenomenon. Evolution in both colors (e.g., Finkelstein et al., 2012; Bouwens et al., 2014) and Ly-\(\alpha\) emission (e.g., Shapley et al., 2003; Pentericci et al., 2009; Verhamme et al., 2008; Stark et al., 2010; Hayes et al., 2011; Yang et al., 2017; Oyarzún et al., 2017) has been attributed to evolution in dust, but to our knowledge there has been no effort to connect these phenomena explicitly in a physical model. To explore this potential link, we make the simplifying assumption that any object with sufficiently low dust opac-

ity will be a LAE, with the critical opacity left as a free parameter to be determined.

In a model with a 1:1 relationship between halo mass and dust column density, there will be a characteristic mass (or \(M_{UV}\)) at which galaxies become LAEs (assuming some equivalent width cut) – this mass is set simply by the dust column density for which \(t_{dust} \sim 1\). Scatter in dust column density has an interesting side-effect in this context: the transition from objects that are optically thick to dust \(1600\)A is no longer a sharp function of halo mass and/or \(M_{UV}\). In our framework, scatter in dust column density is degenerate with the dust scale length: an intrinsically shallow \(R_d(M_h)\) relationship (and thus steep \(M_{UV} - \beta\) relation) can be counteracted by scatter, and vice-versa (see §3.2). So, though we cannot self-consistently predict the LAE fraction, we can explore different regions of the posterior distribution to see if the preferred values of \(\sigma_{\log_{10} N_d}\) are preferred also by LAE measurements.

As shown in Figure 10, the fraction of objects with high \(1600\)A transmission \((e^{-1600}\gtrsim 0.6 \pm 0.025}) looks remarkably similar to the LAE fraction, \(x_{LAE}\), at \(3.5 \lesssim z \lesssim 4.5\) as measured by Stark et al. (2010), at least for \(\sigma_{\log_{10} N_d} \gtrsim 0.12\) (solid lines). With less scatter, the fraction of objects with high UV transmission transitions more abruptly between zero and one (dotted curves). The redshift evolution of

| parameter | recovery | prior range |
|-----------|----------|-------------|
| \(\log_{10}(f_{*,10})\) | \(-1.27^{+0.043}_{-0.032}\) | (-3, 0) |
| \(\log_{10}(M_{*,\text{peak}}/M_\odot)\) | \(11.20^{+0.002}_{-0.290}\) | (9, 13) |
| \(\alpha_{*,\text{lo}}\) | \(0.79^{+0.035}_{-0.030}\) | (0, 1.5) |
| \(\alpha_{*,\text{hi}}\) | \(-5.2^{+0.239}_{-0.030}\) | (-1, 0.5) |

| \(R_d,10/\text{kpc}\) | \(1.08^{+0.069}_{-0.103}\) | (0.01, 10) |
| \(\alpha_{d,\text{lo}}\) | \(0.09^{+0.027}_{-0.194}\) | (0, 2) |
| \(\alpha_{d,\text{hi}}\) | \(0.72^{+0.185}_{-0.021}\) | (-1, 2) |
| \(\log_{10}(M_{d,\text{peak}}/M_\odot)\) | \(11.84^{+0.124}_{-0.978}\) | (9, 13) |
| \(\sigma_{\log_{10} N_d}\) | \(0.02^{+0.069}_{-0.013}\) | (0, 0.6) |

Table 1. Marginalized constraints on the parameters of our fiducial model. The first block of four parameters are those describing the SFE (see Eq. 3 and §2.1), while the next five parameters describe the dust scale length and scatter in dust column density (see §2.2). Fits were performed using broad uninformative priors on each parameter, as listed in the final column.

\(M_{d,\text{peak}} > M_{*,\text{peak}}\) is preferred, the 68% contours are consistent with occurring at \(M_{d,\text{peak}} = M_{*,\text{peak}}\). A triangle plot of the SFE parameters is included in Appendix B compared to the results of simpler models published in previous studies.
f_{halo}(>e^{-\tau_{1600}})$ in coarse $M_{UV}$ bins also agrees reasonably well with the redshift evolution measured by Stark et al. (2011). Agreement with the more recent Kusakabe et al. (2020) measurements is less clear, at least as a function of $M_{UV}$ (left panel), though our predictions for $x_{LAE}(z)$ for faint objects (filled triangles; right panel) tracks the Kusakabe et al. (2020) points more closely, at least before the effects of an increasingly neutral IGM at $z \gtrsim 6$ become important. Of course, the caveat here is that our fits prefer very little scatter, and the critical value of $e^{-\tau_{1600}} \geq 0.6 \pm 0.025$ was tuned by-eye until the normalization of models and measurements matched. But, it is at least intriguing that $\sigma_{\log_{10} N_d}$ values permitted by $M_{UV}-\beta$ measurements generate reasonable LAE populations, and that relatively little scatter, $\sigma_{\log_{10} N_d} \approx 0.1$, is needed to do so.

Because the $M_{UV}$-$\beta$-LAE connection is largely an issue of scatter in dust column in our framework, we show also our model’s predictions for the intrinsic scatter in $\beta$ at fixed $M_{UV}$, $\Delta \beta$. A larger amount of scatter in $N_d$ of course results in more scatter also in $\beta$, as we see in the top row of Fig. 11. In order to ensure that variations in $\sigma_{\log_{10} N_d}$ would not worsen agreement with measured UVLFs and CMDs, we draw points directly from the posterior (indicated in bottom row of Fig. 11), except for values $\sigma_{\log_{10} N_d} > 0.1$, for which there are none. With $\sigma_{\log_{10} N_d} \sim 0.12$, our predictions get close to the empirical findings of Rogers et al. (2014), who found evidence of steadily rising intrinsic scatter with increasing galaxy luminosity. The scatter in $\beta$ in our models is well-approximated as a Gaussian, in line with the assumptions of Rogers et al. (2014) and empirical findings of (Castellano et al., 2012).

4 DISCUSSION

Our model, though simple, remedies potential inconsistencies in IRX-$\beta$ approaches while making testable predictions for upcoming observations. In this section we discuss the implications of the model, and assess the degree to which it is a useful conceptual framework for thinking about dust reddening in high-$z$ galaxies.

4.1 Physical Interpration of the Model

Taken at face value, our model predicts the UV luminosity and reddening of galaxies under the assumption that dust within galaxies is distributed uniformly in a sphere and is a source of attenuation only (i.e., no scattering), while star formation is centrally-concentrated (see Eq. 8). Only in this limit does the dust scale length uniquely determine both the dust density and the path length through dust to stellar sources. In reality, the distribution of dust in galaxies is unlikely to be so ideal, so we do not adhere strongly to this geometrical interpretation. Instead, we think of this model as a simple way to connect dust reddening to halo properties. In other words, we caution against over-interpreting the dust scale lengths we infer, and instead emphasize bulk properties like the dust mass, column density, UV luminosity, and colours. Because of this, it is perhaps more reasonable to refer to an effective dust scale length or column density, i.e., that which is representative of the reddening over an entire galaxy, composed of many distinct star-forming regions and dust columns.

A key input to our model, aside from the dust scale length described above, is of course the dust production efficiency. We assume a constant dust yield $f_d = 0.4$ (Dwek, 1998), which fixes the dust-to-metal ratio (DTMR) in each
Figure 8. Predictions for redshift evolution in UV colours at fixed $M_{UV}$ (left column; compared to B14) and fixed $M_*$ (right column; compared to F12). The top row shows evolution of the normalization at a particular $M_{UV}$ (left) and $M_*$ (right; different plot symbols correspond to three different mass bins), while the bottom row illustrates evolution in the shape of $\beta$ with respect to $M_{UV}$ (left) and $M_*$ (right). Continued evolution in $\beta$ at fixed $M_{UV}$ should be detected by JWST, with the most accurate recovery enabled by coverage in the NIRCAM medium filters (cyan). Pure wide-band photometry requires sampling the rest-UV spectrum outside the C94 windows, resulting in a bias in $\beta$ estimates (magenta). Evolution in the normalization with respect to $M_*$ is expected (top right), while little evolution in the $M_{UV} - \beta$ or $M_* - \beta$ relations are expected at fixed $M_{UV}$ (bottom left) and $M_*$ (bottom right), respectively. Note that the F12 $M_* - \beta$ measurements are fit over $7.5 \leq \log_{10}(M_*/M_\odot) \leq 9.5$ (red circles, bottom right panel), whereas we report the slope at three different $M_*$ values (solid, dashed, dotted, see annotations in top-right panel). Results in right column use $\beta$ as measured in the C94 spectral windows, while $\beta$ values in left-column are computed using HST photometry (blue), NIRCAM wide (magenta) and medium (cyan) filters, and C94 windows (black). Refer to §2.3 and Appendix A for more information about filter choices.

of our model galaxies. Because we also assume a constant metal production efficiency, and instantaneous return model in which $\dot{M}_Z \propto \dot{M}_*$, the dust masses of galaxies in our model will always be a constant fraction of the stellar mass. In reality, the situation is likely more complicated. For example, the DTMR likely scales with halo mass in a non-trivial way depending on the interplay between dust production, destruction, and grain growth in the ISM. However, semi-analytic models including simple treatments of these processes generally predict variations over $7 \lesssim \log_{10}(M_*/M_\odot) \lesssim 12$ of only a factor of $\sim 2 - 3$, and perhaps $\sim 10$ in extreme cases (Popping et al., 2017). Given this rather shallow modulation of dust content with stellar mass, we do not expect our results to dramatically change upon generalizing the model.
4.2 Evolving Dust?

Given that our model adopts a fixed dust yield and a time-independent dust opacity and scale length, all evolution in UV colours (at fixed $M_{UV}$) arises from evolution in components of the model unrelated to dust. As a result, any observed evolution in $\beta$ at fixed $M_{UV}$ need not be due to evolution in the properties of dust, at least in the limit in which the SFE and $R_d$ are universal. Evolution in UV colours occurs naturally in our model due to two independent effects: (i) objects of fixed $M_{UV}$ are hosted by smaller halos at higher redshift and thus have less dust than objects of the same $M_{UV}$ at lower redshift (sSFR grows rapidly with z; see §2.1), and (ii) the mean stellar age is simply younger at high redshift.

There is a significant body of work suggesting the need for evolution in the properties of dust with cosmic time, some of which are largely empirical\footnote{These inferences still require assumptions about, e.g., the temperature of dust, evolution of which could masquerade as evolution in dust content. Furthermore, dust may be multi-phase, complicating procedures based on a single temperature (Liang et al., 2019).} (Reddy et al., 2010; Capak et al., 2015), while others invoke evolving dust properties to reconcile galaxy formation models with observational constraints (Guo & White, 2009; Somerville et al., 2012; Yung et al., 2019; Qiu et al., 2019). The latter admit to being ad hoc: time-independent dust properties result in dramatic under-prediction of bright galaxies at high redshifts (e.g., Somerville et al., 2012; Yung et al., 2019).

The results of numerical simulations are varied. Illustris prefers redshift evolution in the dust opacity (Vogelsberger et al., 2020), while the FIRE and CRIC simulations introduce no such evolution (Ma et al., 2019; Khakhaleva-Li & Gnedin, 2016), but still obtain luminosity functions that are roughly in agreement with observations. Ma et al. (2019) concluded that their simulations are consistent with evolution in dust properties, though such evolution would have to be geometrical in nature given their assumption of a constant dust-to-metal (DTM) ratio.

In this work, we find that evolution in UV colours and UV extinction (at fixed $M_{UV}$), which are often interpreted as signatures of evolving dust, arise naturally even for scenarios in which no dust (or even metallicity) evolution is allowed. We suspect that the general need for evolving dust in some theoretical models is due to the shrinking sizes of high-$z$ galaxies at fixed mass. For example, many SAMs connect the dust scale length to the scale length of galaxy disks (Somerville et al., 2012; Qiu et al., 2019), which shrink rapidly in concert with the virial radii of their host dark matter halos. $R_{UV} \propto M_h^{1/3} (1+z)^{-1}$. We are able to reproduce this effect: for example, if we force the relationship between dust scale length and halo masses to look like the relation between halo virial radii and mass ($R_{halo} \propto M_h^{1/3}$, neglecting the redshift dependence), our $M_{UV}$-$\beta$ relations and UVLFs are much too steep (see dashed and dash-dotted curves in Fig. 1). However, because our model can adjust the scale length as a free parameter, and appeal to scatter in dust column densities to shallow out intrinsically steep $M_{UV}$-$\beta$ relations, we are able to avoid redshift-dependent dust optical depths. The implicit prediction here is that if the scale length of dust does not perfectly track the scale length of gas in galaxy disks, the intrinsic properties of dust in galaxies need not evolve with time. This prediction is in principle testable, now that spatially resolved dust continuum maps can be obtained for high-$z$ galaxies using ALMA (e.g., Gullberg et al., 2018).

We note before moving on that there are other potential sources of mild evolution in the UV colours of galaxies that we have not included, such as metallicity evolution (e.g.,...
Wilkins et al., 2016), which will of course affect the intrinsic spectrum of galaxies and potentially amplify the effects of scatter in dust column density. Furthermore, below $z \sim 6$, AGB stars become a relevant source of dust production that we have effectively neglected by assuming an instantaneous dust return model. We defer a detailed discussion of these effects to future work.

### 4.3 Scatter in Dust Column

In simulations and some semi-analytic models, scatter in the dust column density will inevitably arise due to viewing angle effects (Yung et al., 2019). It is unclear if our treatment of $\sigma_{\text{log} N_d}$ as a free parameter is acting to mimic these effects. Our model predicts scatter in $\beta$ (at fixed $M_{UV}$) at the level of $\sigma_\beta \sim 0.2$ at $M_{UV} \gtrsim -19$ (see Fig. 11). This is comparable, though slightly lower, than the observed Rogers et al. (2014) trend and predictions from Yung et al. (2019). Given the importance of scatter in potentially setting both the shape of $M_{UV}-\beta$ and LAE fractions, future constraints on $\Delta \beta$ – including its distribution function – may serve as an important discriminator between models, and help determine if the $M_{UV}-\beta$/LAE connection explored here is at work in real galaxies.

In this case, “strong” means equivalent widths of $\geq 55$Å, so as to compare directly with the measurements of Stark et al. (2010).

This binary model for the LAE fraction is much simpler than others in the literature. A common approach is to model the intrinsic Ly-$\alpha$ equivalent width (EW), which requires assumptions about the SFR, escape fraction, and kinematics of galaxies, and then apply an EW cut in order to compare with observations (e.g., Dayal et al., 2008). Our results suggest that, to zeroth order, the abundance of LAEs could be set by the dust column density PDF of galaxies, and that this PDF is also responsible (in part) for the shape of the $M_{UV}-\beta$ relation.

Though the potential connection between patchiness and Ly-$\alpha$ emission we explore in Fig. 10 has been considered before (e.g., Neufeld, 1991; Hansen & Oh, 2006; Finkelstein et al., 2008, 2009), to our knowledge, there have been no attempts to draw an explicit connection between the $M_{UV}$-$\beta$ and $M_{UV}$-xLAE in a forward model, despite the fact that both are often attributed to dust. The viability of scatter in $N_d(M_h)$ as the mechanism responsible for each trend is in principle testable, perhaps most clearly via measurements of the intrinsic scatter in $M_{UV}$-$\beta$ (see §4.3).

### 4.4 Connection with LAE fraction

We find that the $M_{UV}$-$\beta$ $M_{UV}$-xLAE relations can be explained by scatter in dust column density at fixed halo mass, $\sigma_{\text{log} N_d} \gtrsim 0.1$, assuming that 1600Å transmission is a reliable predictor of whether or not galaxies are strong LAEs.

### 4.5 Color Selection Criteria

Given that the scatter we invoke is log-normal, it is possible that galaxies in our model will experience fluctuations in dust column substantial enough to migrate outside the typ-
Rest UV colours of high-z galaxies

4.6 Implications for JWST

Our model will be readily testable with constraints on high-z galaxy counts and colors from JWST. The most noticeable tensions in the model is at the low-mass end of the 4 ≤ z ≤ 6 stellar mass function, where current measurements diverge (Song et al., 2016; Stefanon et al., 2017; Duncan et al., 2014). Such measurements should improve considerably with JWST given the substantial expansion of coverage in the infrared, which will much more fully probe the rest-optical emission of high-z galaxies. Improved colour constraints, particularly for massive galaxies, would also improve the model calibration. However, given the small field of view of NIRCAM, such constraints may only be possible for shallow, wide area surveys.

The redshift evolution in β(M_UV) predicted by our model is also readily testable with JWST. In principle, using the medium NIRCAM filters, rest-UV colours can be measured out to z ≈ 15, provided there are galaxies bright enough to detect at such high redshifts. We find only minimal evolution in the shape of β(M_UV) and β(M_L). The medium filters are key to all future z ≥ 8 colour constraints, as the wide filters are cannot cleanly isolate the rest UV continuum generally used for estimating β (see Fig. A3).

Finally, testing the hypothesis that the scatter in dust column density drives both M_UV-β and M_UV-σ_21 will require improved constraints on the intrinsic scatter in β(M_UV). We compare favorably, to the Rogers et al. (2014) estimates of scatter in β(M_UV), in that the scatter rises monotonically for increasingly bright galaxies, and for σ_0.1 the scatter is typically close to 0.2 at M_UV ≈ −21, in agreement with Rogers et al. (2014) (though slightly lower). Larger values of σ_0.1, likely closer to 0.2 would improve agreement, though our fits clearly prefer σ_0.1 ≤ 0.1. This could simply be a limitation of the model – perhaps alternate parameterizations or additional flexibility would permit larger σ_0.1 values. We leave this as an avenue to pursue in future work.

4.7 Implications for Cosmic SFRD & Reionization

Assumptions about dust necessarily impact the inferred cosmic star formation rate density (SFRD), and thus predictions for reionization. Naively, one might expect dust-free models to provide a floor in predictions for the SFRD, since any increase in the dust content of galaxies will require enhancements to the SFE in order to preserve agreement with observed UVLFs. However, the presence of dust can also modulate the inferred shape of the SFRD (see Fig. 5). As a result, the introduction of dust will shift the SFRD upward at late times, z ≲ 10, but potentially result in little overall change in the SFRD at earlier times, when fainter halos (which form stars less efficiently) become the dominant source population. Indeed, we find a steeper slope f_σ ∝ M_h^β (or steeper) here compared to the f_σ ∝ M_h^β scaling reported in Mirocha et al. (2017), the latter of which neglected dust (see Appendix B). As a result, systematic uncertainties in modeling dust – at least in the framework presented here – are unlikely to cause a substantially earlier start to reionization or reheating. Any evidence for efficient star formation at z ≥ 10 from, e.g., kinetic Sunyaev-Zeldovich constraints from the CMB (e.g., Miranda et al., 2017) or global 21-cm signal measurements (Bowman et al., 2018), is most likely indicative of star formation in halos below the atomic cooling threshold (Mirocha & Furlanetto, 2019; Mebane et al., 2020). This statement may be subject to change in models in which the SFE of galaxies grows with redshift or changes shape in non-trivial ways, a possibility which we defer to future work.

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16 We use the Madau (1995) model for IGM absorption, which is necessary in order to accurately predict colors indicative of the Lyman break.
4.8 Implications for IRX-β

A common approach to dust-correcting rest-UV measurement of high-
\( z \) galaxies is to invoke empirical correlations between infrared excesses and \( \beta \) (Meurer et al., 1999). The IR excess can be related to UV attenuation under the assumption of a known intrinsic UV slope and dust opacity, making it possible to convert the observed \( M_{UV} \) to an intrinsic UV magnitude, and thus SFR. The standard M99 approach assumes \( \beta_0 = -2.23 \), appropriate for constant star formation in the STARBURST99 models. Our models use the BPASS models (Eldridge & Stanway, 2009) and assume galaxy star formation histories are rising rapidly and have scatter, which modulates the input \( \beta_0 \) for each galaxy. The effects of breaking the assumptions made in M99 has been pointed out previously also by other authors (e.g., Wilkins et al., 2013).

Our forward model generally predicts less UV attenuation at fixed \( M_{UV} \) than the M99 relation, at least at the bright end, \( M_{UV} \lessapprox -18 \). This is likely a byproduct of our joint inference approach, as the \( M_{UV}-\beta \) relation and UVLFs have competing requirements (see §3.1 and Fig. 2). For the faint, \( M_{UV} \gtrsim -18 \) dust-poor galaxies, our model predicts more attenuation than M99, which makes sense given that our model galaxies are intrinsically bluer than \( \beta_0 \approx -2.23 \).

5 CONCLUSIONS

Our main conclusions are as follows:

- Models without redshift-dependent dust properties still predict evolution in \( M_{UV}-\beta \) given that stellar ages are declining and specific SFRs are rising with redshift. In other words, much of the evolution in \( M_{UV}-\beta \) reflects evolution in the typical halo (or stellar) mass of galaxies in our model, and thus their integrated dust production. This result is conservative given our neglect of metallicity evolution, which is also expected to result in UV colour evolution at fixed stellar mass (see §4.2; Figures 4 and 8).
- This lack of evolution is at odds with other models in the literature, which require \textit{ad hoc} redshift evolution in the dust opacity in order to prevent excessive reddening in high-\( z \) galaxies. This need may be real: if the dust scale length is related to the scale length of galaxy disks, and thus dark matter halo virial radii, it will contract rapidly in both halo mass and redshift and cause reddening to increase as well. Our model assumes no redshift evolution in the dust scale length (at fixed \( M_h \)) and so avoids this effect. Observationally, constraining the effective dust scale length may be difficult, so guidance from simulations may offer important insights in this context (see §4.1).
- Scatter in the relationship between dust column density and halo mass can help accommodate dust scale lengths that track halo virial radii (see Fig. 3). Furthermore, for values of the log-normal scatter in effective dust column density at fixed halos mass, \( \sigma_{\text{Dust}} \approx 0.1 \), the evolution in the abundance of galaxies with 1600 Å \( \gtrsim 0.6 \) resembles the evolution in the LAE population from \( 3 \lesssim z \lesssim 6 \) (see Fig. 10). This could be an indicator that the shape of \( M_{UV}-\beta \) and \( M_{UV}-\text{X}_{\text{LAE}} \) are driven by the same phenomenon.
- Measurements of the intrinsic scatter, \( \Delta \beta \), provide important constraints on this aspect of the model. An increased scatter in the dust column density increases the scatter in \( \beta \) as well, with scatter continuing to grow in even brighter objects (see Fig. 11).
- UV colours are expected to continue to evolve smoothly with redshift at fixed \( M_{UV} \), and are in principle measurable with JWST out to \( z \approx 15 \) at all \( M_{UV} \lesssim -17 \) (see Fig. 8). We predict little to no redshift evolution in the shape of the \( M_{UV}-\beta \) and \( M_{UV}-M_h \) relations.

The aforementioned results depend on the assumption of a time-independent SFE, which is common in the recent literature, but also on a universal \( R_d(M_h) \) relation. Both assumptions are subject to change in simple models, which predict evolution in the SFE and \( R_d(M_h) \), if indeed \( R_d \propto R_{\text{vir}} \). We explore the consequences of these assumptions in a forthcoming paper (Mirocha et al., in prep).

J.M. acknowledges stimulating conversations with Chris Willott, Nissim Kanekar, Louis Abramson, Adrian Liu, Alan Heavens, James Rhoads, Tracy Webb, and Steve Finkelstein, and support through a CITA National Fellowship. C.M. acknowledges support through the NASA Hubble Fellowship grant HST-HF2-51413.001-A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA, under contract NAS5-26555. Computations were made on the supercomputers Cedar (from Simon Fraser University and managed by Compute Canada) and Mammouth (from the Université de Sherbrooke and managed by Calcul Québec and Compute Canada). The operation of these supercomputers is funded by the Canada Foundation for Innovation (CFI), the ministère de l’Économie, de la science et de l’innovation du Québec (MESI) and the Fonds de recherche du Québec - Nature et technologies (FRQ-NT).

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APPENDIX A: PHOTOMETRIC ESTIMATES OF UV SLOPES

It is important to extract $M_{UV}$ and $\beta$ from theoretical models in an observationally-motivated way, given that biases (in $\beta$ especially) comparable to observed trends can arise if using an idealized approach.

In Figure A1, we illustrate the difference between spectroscopic and photometric estimates of UV magnitudes and colours. In the former case, we assume $M_{UV} = M_{1600}$, measure $\beta$ as a power-law fit to intrinsic galaxy spectra through the C949 windows. Our photometric estimates follow B14, who compute $M_{UV}$ as the geometric mean of all photometry, which we indicate with angular brackets, $(M_{UV})$. Similarly, $\beta$ is computed as a power-law fit through available photometry. In Figure A2, we show $\Delta \beta \simeq 0.05 - 0.2$ biases in the UV colours estimated with HST photometry (open symbols), similar to what was found in Finkelstein et al. (2012) (see their Fig. 4), particularly at $z \gtrsim 6$. These biases will persist, even with JWST (see filled symbols in lower right panel of Fig. A2).

From Figure A3 it is clear that at $z \gtrsim 6$, the rest $1268 \lesssim \lambda \lesssim 2580$ range is sampled more sparsely than at $z \lesssim 6$. This is particularly noticeable at $z \sim 7-8$ for HST, with coverage heavily weighted to the bluest part of the rest UV spectrum. Coverage at $9 \lesssim z \lesssim 11$ for JWST is also weighted to the bluest part of the rest-UV spectrum, which has many absorption features, hence the redward bias (bottom right panel of Fig. A2).
A2). Clearly, use of the NIRCAM medium filters will be required in order to get accurate colours at $z \gtrsim 8$. One could in principle use the wide filters at $z > 8$ also, though their increasing spectral width with wavelength corresponds to an increase in contamination from emission outside the C94 spectral range (see unfilled boxes).

We include a full listing of the filters used as a function of redshift both for HST and the JWST wide and medium filters in Table A1.

### APPENDIX B: UPDATED SFE CONSTRAINTS

For completeness, here we present our new constraints on the SFRD and SFE parameters, and compare directly to two other common approaches: (i) use of the IRX-$\beta$ method of dust correction, or (ii) neglect of dust attenuation entirely.

First, in Figure B1, we show the SFRD reconstructed from our fits compared to a dust-free model calibrated to $z \sim 6$ UVLFs from B15 (gray contours), and a model calibrated to $z \sim 4$ and 6 UVLFs from B15 using the common M99+B14 IRX-$\beta$-based approach (black contours). Our new models (blue) agree with the IRX-$\beta$ approach at $z \sim 6$, predicting $\rho_* \simeq 4 \times 10^{-2} M_{\odot} \text{yr}^{-1} \text{cMpc}^{-3}$. At higher redshifts, the new models tend toward the dust-free $z \sim 6$ calibration because, while the inclusion of dust biases the normalization of the SFE high, it also biases the shape of the SFE toward steeper slopes. As a result, our new estimates of the $z \gtrsim 10$ SFRD are largely unchanged compared to previous work (Mirocha et al., 2017).

In Figure B2, we show the posterior distribution of the SFE parameters. Following the same color scheme as in Figure B1, we can quickly see that there are systematic differences when neglecting dust, particularly in the normalization of the SFE, which here we anchor to $10^{10} M_{\odot}$ halos (first column; $f_{*, 10}$). Our new approach, while qualitatively similar to the M99+B14 contours, does exhibit some important differences. For example, the new models prefer shallower SFE slopes at low mass (third column; $\alpha_{*,10}$), which result in slightly higher SFRDs at $z \gtrsim 8$, as described above and shown in Figure B1.
Table A1. Filters used to estimate UV slope as a function of redshift. First 8 rows indicate HST filters used by Bouwens et al. (2014) to estimate $\beta$, while bottom two sets of filters demarcated by horizontal lines are the JWST NIRCAM wide and medium filters within the wavelength range of the Calzetti et al. (1994) windows. Note that at $z \sim 4$ and 7 only one NIRCAM wide filter lies within the C94 window. As a result, in Figure 8, predictions using the wide filters only require broadening the rest-frame interval to $\lambda > 2580 \, \text{Å}$ in order to estimate $\beta$. At these redshifts, we adopt the next bluest available filter.

| Filter | Name  | $z \sim 4$ | $z \sim 5$ | $z \sim 6$ | $z \sim 7$ | $z \sim 8$ | $z \sim 9$ | $z \sim 10$ | $z \sim 11$ | $z \sim 12$ |
|--------|-------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| F775W  | i775  | ✓          |            |            |            |            |            |            |            |            |
| F814W  | i814  | ✓          |            |            |            |            |            |            |            |            |
| F850LP | s850  | ✓          | ✓          |            |            |            |            |            |            |            |
| F098M  | Y098  | ✓          | ✓          | ✓          | ✓          | ✓          |            |            |            |            |
| F105W  | Y105  | ✓          | ✓          | ✓          | ✓          |            |            |            |            |            |
| F125W  | J125  | ✓          | ✓          | ✓          |            |            |            |            |            |            |
| F140W  | JH140 |            |            |            |            |            | ✓          | ✓          | ✓          |            |
| F160W  | H160  | ✓          | ✓          | ✓          | ✓          | ✓          | ✓          |            |            |            |
| F090W  | n/a   | ✓          | ✓          |            |            |            |            |            |            |            |
| F115W  | n/a   | ✓          |            |            |            |            |            |            |            |            |
| F150W  | n/a   | ✓          | ✓          | ✓          | ✓          | ✓          |            |            |            |            |
| F200W  | n/a   | ✓          | ✓          | ✓          | ✓          | ✓          | ✓          |            |            |            |
| F140M  | n/a   | ✓          | ✓          | ✓          | ✓          | ✓          |            |            |            |            |
| F162M  | n/a   | ✓          | ✓          | ✓          |            |            |            |            |            |            |
| F182M  | n/a   | ✓          | ✓          | ✓          |            |            |            |            |            |            |
| F210M  | n/a   | ✓          | ✓          | ✓          |            |            |            |            |            |            |
| F250M  | n/a   | ✓          | ✓          |            |            |            |            |            |            |            |
| F300M  | n/a   | ✓          |            |            |            |            |            |            |            |            |

Figure A3. Filter placement vs. galaxy redshift. Blue boxes show filters used in HST analyses of B14, while filled magenta and cyan boxes show the NIRCAM wide (W) and medium (M) filters that lie completely within the C94 windows. Open boxes are added to supplement the NIRCAM filter set at redshifts for which only one filter lies within C94 windows. For reference, we show the observed wavelength of Ly-α (solid), the Calzetti et al. (1994) spectral range often used to compute $\beta$ (dashed, dotted), and 1600Å, where magnitudes are often reported. See Table A1 for full filter listing. Note that boxes are offset horizontally for clarity, but placement is determined using integer redshifts only.

Figure B1. Star formation rate density at high-z predicted by our models. Blue contours show 68% and 95% credibility regions for our new models presented in this work, while gray and black contours show the 68% confidence regions obtained when neglecting dust and employing an IRX-$\beta$-based approach (described in text), respectively.
Figure B2. Posterior distribution of SFE parameters for three different approaches to rest-UV inference. Results using the new model presented in this work are shown in blue, while the dust-free and M99+B14 results are shown in gray and black, respectively. In each case, inner contours represent 68% confidence regions, while outer contours indicate 95%. Best fits and 1-σ error-bars are presented in Table 1.