

# Empirical Dust Models: Taking Hydrodynamical Simulations with a Grain of Dust

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## ABSTRACT

We construct a dust empirical model (DEM) framework for applying dust attenuation to simulated galaxies based on handful of sensible assumptions that come from our understanding of dust attenuation. The DEM framework is essentially based on state-of-the-art attenuation curves with a flexible parameterization that allows us to statistically sample them. Applying DEMs to three different hydrodynamic simulations, SIMBA, Illustris TNG, and EAGLE, we are able to produce UV and optical photometry consistent with SDSS observations ( $(G - R) - M_r$  color-magnitude and  $(FUV - NUV) - M_r$  relations). This suggests that there's enough freedom in our current understanding (or lack) of dust for all simulations to reproduce observations. Meanwhile, the DEM provides some insights into dust as well as the subgrid physics that goes into the hydro simulations.

*Keywords:* keyword1 – keyword2 – keyword3

## 1. INTRODUCTION

dust is important because....

assumptions on the attenuation curve can dramatically impact the physical properties inferred from SED fitting (*e.g.* [Kriek & Conroy 2013](#); [?](#); [?](#); [Salim & Narayanan 2020](#)).

motivation for an empirical dust attenuation model

attenuation vs extinction. While extinction curves have been derived from observations and theoretically, it's not easy to map this to attenuation curves. Attenuation curves are a product of complicated empirical processes since it accounts for light that gets scattered and star light that is not obscured

This makes modeling them in a complete physically motivated method expensive. People have done it [Narayanan et al. \(2018\)](#); [Trayford et al. \(2020\)](#). some detail about the radiative transfer method and such. But besides being expensive they have to make a number of assumptions anyway. *e.g.* [Narayanan et al. \(2018\)](#) assumes a fixed extinction curve.

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Moreover, because the radiative transfer method is expensive it's hard to compare many different simulations. Not only that, observables generated from simulations that take into radiative transfer dust models complicates simulation to simulation comparisons. Because you're simultaneously comparing the galaxy formation prescription and all the dust prescription.

emphasize somewhere here that using a prescription trained one sim doesn't translate well to other sims.

Instead, we present a framework using flexible dust empirical models that paints attenuation curves onto galaxies. describe at a high level how we are parameterizing DEMs

emphasize comparisons in observable space (Nelson et al. (2018) talks about importance of color)

talk about the advantages: extremely flexible so it can encompass the wide variety of attenuation curves found in radiative transfer, easy to correlate the attenuation curve with galaxy properties.

Also DEMs make it possible to statistically apply attenuation curves for large galaxy population. Putting this ontop of simulations, we can use them to generate observables and compare them to observations to constrain the DEM. This framework allows us to learn about attenuation curves given a model for galaxy formation.

The other way around also works. If you don't care about dust at all, DEM provides a framework to easily marginalize over dust attenuation and treat dust as a nuisance parameter.

In this paper, we do above for multiple simulations.

Starkenburg et la. in prep will use this framework to marginalize over dust and compare galaxy populations predicted by multiple simulations .

**CH: why do we only do centrals?**

## 2. DATA

### 2.1. SDSS DR7 Central Galaxies

Throughout the paper we compare the simulations and models described below to the observed SDSS central galaxy sample from the Tinker et al. (2011) group catalog. The group catalog, first, selects volume-limited sample of galaxies at  $z \approx 0.04$  with  $M_r < -18$  and complete above  $M_* > 10^{9.4} h^{-2} M_\odot$  from the NYU Value-Added Galaxy Catalog (VAGC; Blanton et al. 2005) of SDSS DR7 (Abazajian et al. 2009). The stellar masses are estimated using the `kcorrect` code (Blanton & Roweis 2007) assuming a Chabrier (2003) initial mass function.

Central galaxies are then identified using a halo-based group finder that uses the abundance matching ansatz to iteratively assign halo masses to groups. Every group contains one central galaxy, which by definition is the most massive, and a group can contain  $\geq 0$  satellites. As with any group finder, galaxies are misassigned due to projection effects and redshift space distortions; however, the central galaxy sample has a purity of  $\sim 90\%$  and completeness of  $\sim 95\%$  (Tinker et al. 2018).

### 2.2. Illustris TNG

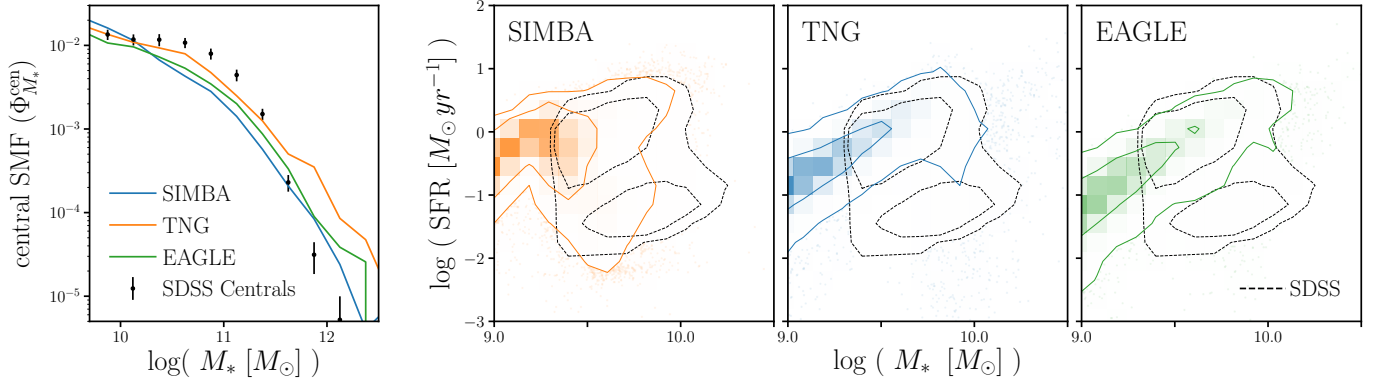
describe what galaxy properties (SFH, ZH, etc) are available

TODO

### 2.3. SIMBA

describe what galaxy properties (SFH, ZH, etc) are available

TODO



**Figure 1.** The stellar mass functions of central galaxies,  $\Phi_{M_*}^{\text{cen}}$ , of the SIMBA (orange) and TNG (blue) simulations compared to the SDSS  $\Phi_{M_*}^{\text{cen}}$ . The uncertainties for the SDSS  $\Phi_{M_*}^{\text{cen}}$  are derived using jackknife resampling and SDSS centrals are identified using a halo-based group finder (Section 2.1). For SIMBA and TNG galaxies, we calculate  $M_*$  as the total stellar mass within the host halo, excluding contributions from any subhalos; centrals are classified based on their individual definition (Section 2.2 and 2.3). *should we include total SMF...?* The simulations and observations have loosely consistent  $\Phi_{M_*}^{\text{cen}}$ . The  $M_* - \text{SFR}$  relation of central galaxies in SIMBA (orange), TNG (blue), and EAGLE (green) simulations and SDSS observations. *CH: describe where the  $M^*$  and SFRs come from for everything.* The differences among the  $M_* - \text{SFR}$  relations demonstrate that the hydro simulations predict galaxy populations with significantly different physical properties.

In Figure ??, we compare the stellar mass function (SMF) of our SDSS central galaxy sample along with central galaxy SMFs of the SIMBA (orange) and TNG (blue) simulations. The uncertainties for the SDSS SMF are derived from jackknife resampling. Although we present the SMFs for reference, we do not use stellar masses throughout the paper since they are inconsistently defined among simulations and observations. Instead, we compare between the simulations and SDSS using luminosity,  $M_r$ , which we consistently forward model and measure in the simulations. In these comparisons, we restrict ourselves to galaxies brighter than  $M_r < -20$ , where our SDSS central galaxy sample is complete.

instantaneous  $\text{SFR}=0$  for  $\sim 11\%$  of SIMBA galaxies,  $\sim 13\%$  for TNG,  $\sim 2\%$  for EAGLE

#### 2.4. Spectral Energy Distributions

describe how the SED is generated using the SFH and ZHs

TODO

#### 2.5. Forward Modeling Optical and UV photometry

Trayford et al. (2015) Figure 1.a. has a comparison without dust that's roughly consistent with what we find for EAGLE

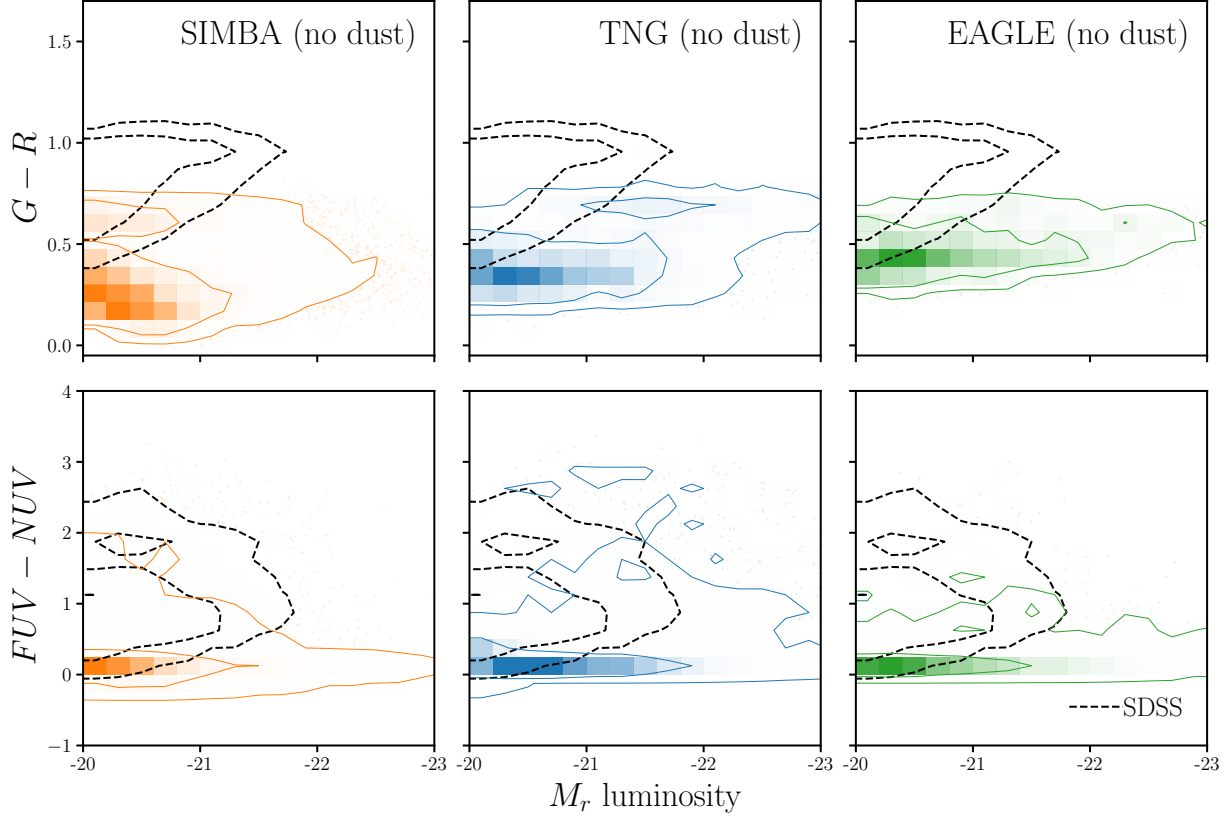
### 3. DUST EMPIRICAL MODELING

#### 3.1. Fiducial DEM

motivation for the DEM model

TODO

Trayford et al. (2015) uses an empirical dust model but doesn't implement an attenuation curve but rather multiplicative factors for the broadband photometry.



**Figure 2.** We present the distributions of the main observables used throughout the paper for SDSS (left), SIMBA (center), and TNG (right) centrals. We do *not* include any prescription for dust for the simulated galaxies. The top panels present the  $G - R$  versus  $M_r$  color magnitude relations while the bottom panels present the  $FUV - NUV$  versus  $M_r$  relations. The observables for the SIMBA and TNG simulated galaxies are derived using forward modeling and are therefore consistent with SDSS measurements (Section 2.5). The contours for SIMBA and TNG do not include galaxies with  $SFR = 0$ , which we mark separately in black. Despite similar SMFs, *the simulations without any dust prescription show stark differences with observations in the color-magnitude observable-space.*

We begin by defining the dust attenuation curve  $A(\lambda)$  as

$$F_o(\lambda) = F_i(\lambda)10^{-0.4A(\lambda)} \quad (1)$$

where  $F_o$  is the observed flux and  $F_i$  is the intrinsic flux. We normalize the attenuation at the  $V$  band,

$$A(\lambda) = A_V \frac{k(\lambda)}{k_V}. \quad (2)$$

For the normalization of the attenuation curve,  $A_V$ , we use the slab model from Somerville & Primack (1999); Somerville et al. (2012). In the slab model the amplitude of attenuation depends on the inclination angle,  $i$ , and the optical depth,  $\tau_V$ :

$$A_V = -2.5 \log \left[ \frac{1 - e^{-\tau_V \sec i}}{\tau_V \sec i} \right] \quad (3)$$

justification of why this is enough. We sample  $i$  uniformly.

Recently, [Salim & Narayanan \(2020\)](#) find significant dependence in  $A_V$  on both  $M_*$  and SFR. We include this dependence through  $\tau_V$ , which we flexibly parameterize as

TODO

$$\tau_V(M_*, \text{SFR}) = m_{\tau,1} \log \left( \frac{M_*}{10^{10} M_\odot} \right) + m_{\tau,2} \log \text{SFR} + c_\tau. \quad (4)$$

Next, for the wavelength dependence of the attenuation curve, we use  $k(\lambda)$  from [Noll et al. \(2009\)](#):

$$k(\lambda) = (k_{\text{Cal}}(\lambda) + D(\lambda)) \left( \frac{\lambda}{\lambda_V} \right)^\delta. \quad (5)$$

Here  $k_{\text{Cal}}(\lambda)$  is the [Calzetti \(2001\)](#) curve:

$$k_{\text{Cal}}(\lambda) = \begin{cases} 2.659(-1.857 + 1.040/\lambda) + R_V, & 6300\text{\AA} \leq \lambda \leq 22000\text{\AA} \\ 2.659(-2.156 + 1.509/\lambda - 0.198/\lambda^2 + 0.011/\lambda^3) + R_V & 1200\text{\AA} \leq \lambda \leq 6300\text{\AA} \end{cases}$$

where  $\lambda_V$  is the  $V$  band wavelength.  $\delta$ , the slope of the attenuation curve, also correlates with galaxy properties. So we parameterize  $\delta$  and

$$\delta(M_*, \text{SFR}) = m_{\delta,2} \log \left( \frac{M_*}{10^{10} M_\odot} \right) + m_{\delta,2} \log \text{SFR} + c_\delta \quad (6)$$

$D(\lambda)$  is the UV dust bump, which we parameter using the standard Lorentzian-like Drude profile:

$$D(\lambda) = \frac{E_b(\lambda \Delta \lambda)^2}{(\lambda^2 - \lambda_0^2)^2 + (\lambda \Delta \lambda)^2} \quad (7)$$

where  $\lambda_0$ ,  $\Delta \lambda$ , and  $E_b$  are the central wavelength, FWHM, and strength of the bump, respectively. In our DEM, we assume fixed  $\lambda_0 = 2175\text{\AA}$  and  $\Delta \lambda = 350\text{\AA}$ .

[Kriek & Conroy \(2013\)](#) and [Tress et al. \(2018\)](#) found evidence that  $E_b$  correlates with the slope of the attenuation curve for star-forming galaxies  $z \sim 2$ . This was dependence was confirmed with simulations in ?.  $E_b$ :

$$E_b = m_E \delta + c_E \quad (8)$$

we fixed this and find our results do not change significantly.

TODO

We also split the attenuation on the star light and nebular emission

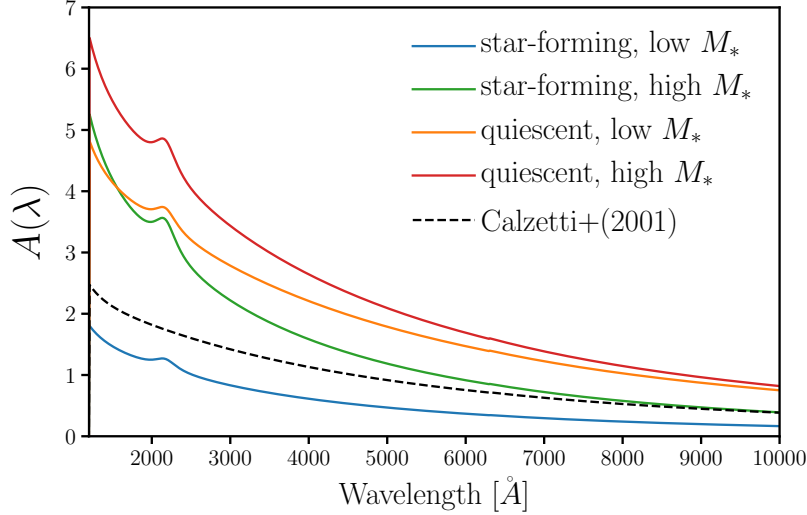
$$F_o(\lambda) = F_i^{\text{star}}(\lambda) 10^{-0.4A(\lambda)} + F_i^{\text{neb}}(\lambda) 10^{-0.4A_{\text{neb}}(\lambda)} \quad (9)$$

where we parameterize

$$A_{\text{neb}}(\lambda) = f_{\text{neb}} A(\lambda) \quad (10)$$

mention of how we treat  $\text{SFR} = 0$  galaxies

TODO



**Figure 3.** Comparison of the attenuation curve for our fiducial dust empirical model (DEM; black) to common attenuation curves in the literature (Calzetti 2001, orange; Salim et al. 2018, blue). We compare the curves for typical star-forming galaxies with  $\text{SFR} = 10^{0.5} M_{\odot}/\text{yr}$  in the left panel and for quiescent galaxies with  $\text{SFR} = 10^{-2} M_{\odot}/\text{yr}$  in the right. For our fiducial DEM, we use parameter values at **the center of the priors listed in Table 1** and include attenuation curves for  $M_{*} = 10^{9.5}$  (dashed) and  $10^{11} M_{\odot}$  (solid). Our fiducial DEM is flexibly parameterized to incorporate both  $M_{*}$  and SFR dependence in the attenuation curve (Section 3.1).

**Table 1.** Parameters of the Dust Empirical Models

Parameter	Definition	prior
$m_{\tau, M_{*}}$	Slope of the $\log M_{*}$ dependence of optical depth, $\tau_V$	flat $[-5., 5.]$
$m_{\tau, \text{SFR}}$	Slope of the $\log \text{SFR}$ dependence of optical depth, $\tau_V$	flat $[-5., 5.]$
$c_{\tau}$	amplitude of the optical depth, $\tau_V$	flat $[0., 6.]$
$m_{\delta, 1}$	Slope of the $\log M_{*}$ dependence of the attenuation curve slope offset, $\delta$	flat $[-4., 4.]$
$m_{\delta, 2}$	Slope of the $\log \text{SFR}$ dependence of the attenuation curve slope offset, $\delta$	flat $[-4., 4.]$
$c_{\delta}$	amplitude of the attenuation curve slope offset, $\delta$	flat $[-4., 4.]$
$f_{\text{neb}}$	fraction of nebular attenuation curve	flat $[1., 4.]$

### 3.2. Likelihood-Free Inference

Approximate Bayesian Computation with Population Monte Carlo Hahn et al. (2017),

To compare the outputs of our DEMs to observations, we first measure the color-magnitude observables ( $G - R$ ,  $FUV - NUV$ , and  $M_r$ ) as described in Section 2.5 consistent with SDSS measurements. Afterwards, we compare the forward modeled observables to SDSS using a L2 norm distance metric:

$$\bar{\rho}(\theta) = \sum_{i=1}^n [X_i^{\text{SDSS}} - X_i^{\text{model}}(\theta)]^2. \quad (11)$$

$X^{\text{SDSS}}$  and  $X^{\text{model}}(\theta)$  are  $n$ -dimensional data vectors of the SDSS and model observables. In our case, we use a 3-dimensional histogram along  $G - R$ ,  $FUV - NUV$ ,

[Ishida et al. \(2015\)](#)

Paragraph on the priors we choose.

- flat priors on everything. We might want to note that this doesn't give flat priors on  $\tau_V$  or  $\mu_{A_V}$  and  $\sigma_{A_V}$  for NT but we're ultimately interested in the dependence.
- priors were chosen to be uninformative and encompass constraints in the literature:
- $m_E$  and  $c_E$  were chosen to be include [Kriek & Conroy \(2013\)](#); [Narayanan et al. \(2018\)](#); [Tress et al. \(2018\)](#)

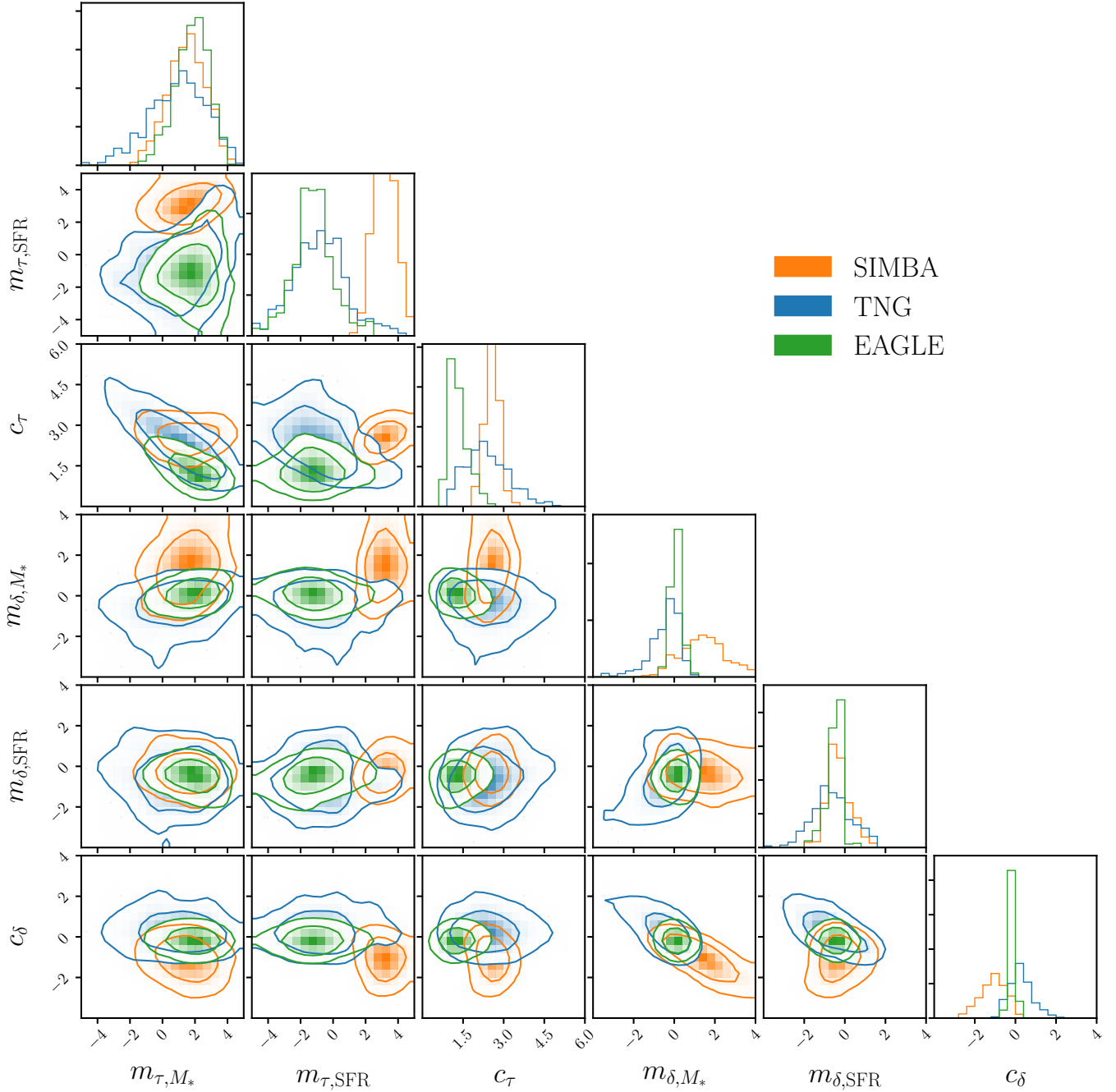
#### 4. RESULTS

We present the posterior distributions of the DEM parameters for the SIMBA (orange), TNG (blue), and EAGLE (green) hydro simulations in Figure 4. The DEM parameters include  $m_{\tau, M_*}$ ,  $m_{\tau, \text{SFR}}$ , and  $c_\tau$ , which parameterize the  $M_*$  dependence, SFR dependence, and amplitude of  $\tau_V$ , the V-band optical depth.  $\tau_V$  dictates the overall strength of the dust attenuation. They also include  $m_{\delta, M_*}$ ,  $m_{\delta, \text{SFR}}$ , and  $c_\delta$ , which parameterize the  $M_*$  dependence, SFR dependence, and amplitude of  $\delta$ , the slope offset of the attenuation curve (Section 3.1 and Table 1). The posteriors are derived using ABC (Section 3.2) and the contours mark the 68% and 95% confidence intervals.

In addition, we present the observables predicted by the DEM with median of the posteriors for the SIMBA (orange), TNG (blue), and EAGLE (green) simulations in Figure 5. We include the SDSS observables for comparison (black dashed; Section 2.1). The top panels present the  $(G - R) - M_r$  color-magnitude relations while the bottom panels present the  $(FUV - NUV) - M_r$  relations. Without any dust prescriptions, we found that simulations predict dramatically different observables than SDSS (Figure 2). **CH: something about clear bimodality with the red sequence and blue cloud** In contrast, *using DEMs we produce  $(G - R) - M_r$  and  $(FUV - NUV) - M_r$  relations consistent with SDSS for all of the simulations.*

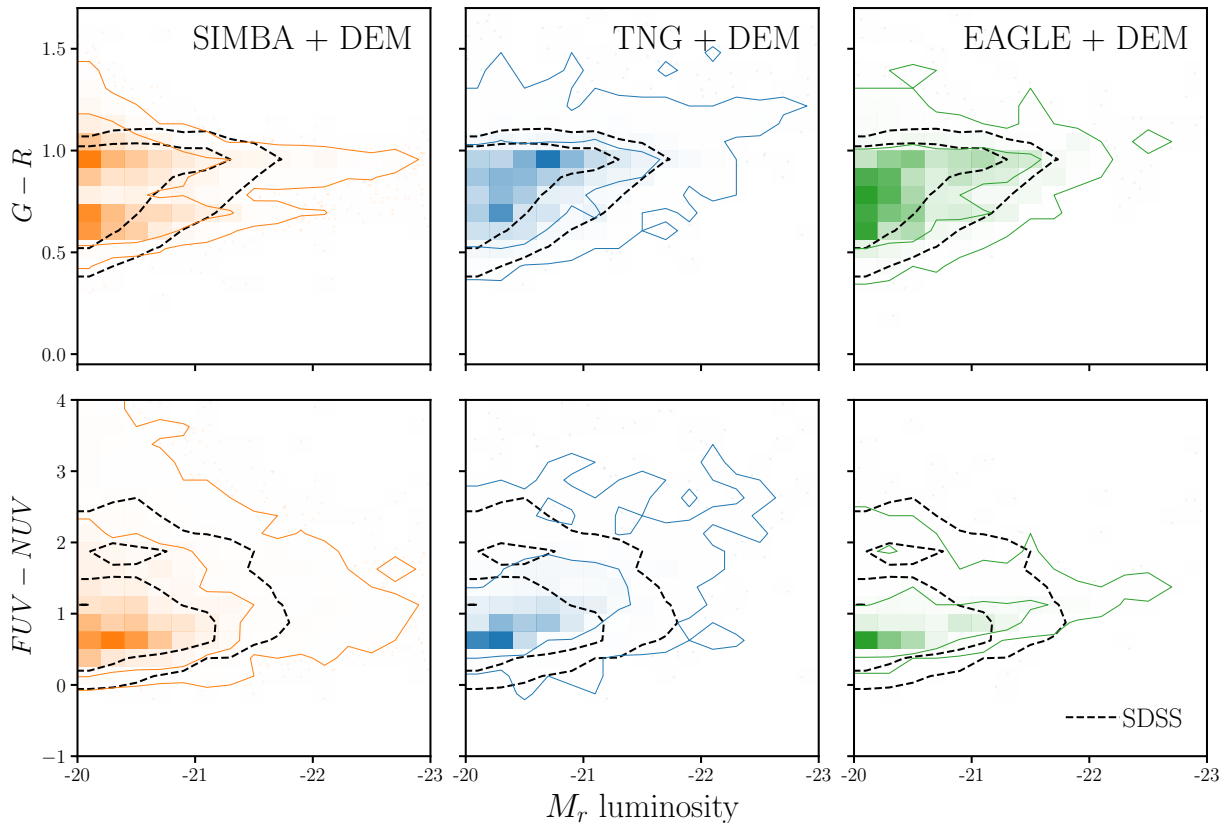
We examine the observables more closely in Figure 6, where we present the  $G - R$  (left) and  $FUV - NUV$  (right) distributions in  $M_r$  bins for the DEM models of the SIMBA (orange), TNG (blue), and EAGLE (green) simulations. The top panels contain galaxies with  $-20 > M_r > -21$  and the bottom panels contain galaxies with  $-21 > M_r > -22.5$ . In each panel we include the SDSS distributions for comparison (grey shaded). These distributions are number densities. The positions of the red sequence and blue cloud in the  $G - R$  distributions for the DEM models are consistent with the SDSS distribution. They also produce  $FUV - NUV$  distributions with peaks consistent with observations. We also find good agreement in the overall normalization (number density), especially for the  $-20 > M_r > -21$  bin.





**Figure 4.** Posterior distributions of our DEM parameters for the SIMBA (orange), TNG (blue), and EAGLE (green) hydro simulations. The contours mark the 68% and 95% confidence intervals. We describe the parameters in Section 3.1 and Table 1 and derive these posteriors using Approximate Bayesian Computation (Section 3.2). In all simulations, dust attenuation increases for higher  $M_*$  galaxies ( $m_{\tau, M_*} \sim 2$ ). The simulations also have consistent optical depth amplitudes ( $c_{\tau}$ ). However, the SFR dependence of  $\tau_V$  is different among the simulations. For TNG and EAGLE, star-forming galaxies have lower  $\tau_V$ ; for SIMBA quiescent galaxies have lower  $\tau_V$ . Meanwhile, for the slope offset of the attenuation curve,  $\delta$ , we find little  $M_*$  and SFR dependence in the simulations and that the amplitude ( $c_{\tau}$ ) is consistent with 0.

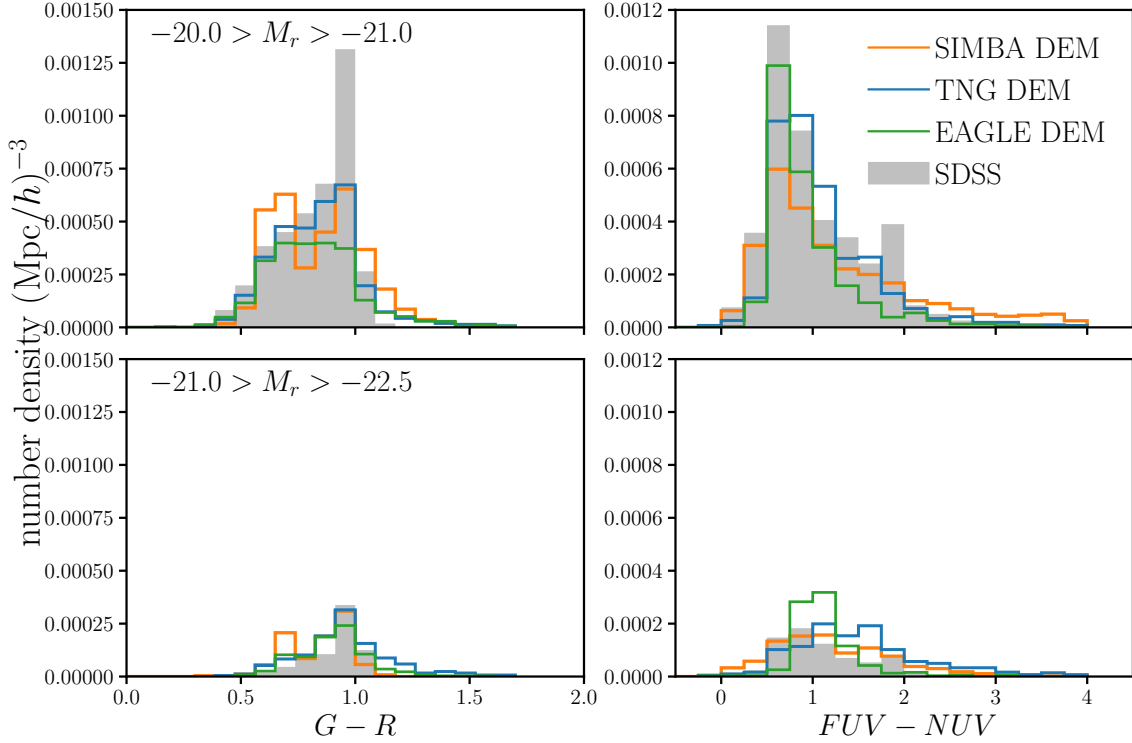




**Figure 5.**  $(G - R) - M_r$  color-magnitude (top panels) and  $(FUV - NUV) - M_r$  (bottom panels) relations predicted by the median DEM posteriors for the SIMBA (orange), TNG (blue), and EAGLE (green) hydro simulations. For comparison, we include the observables for SDSS in the left-most panel (Section 2.1). The median posterior DEMs produce dramatically different observables than when we do not include any dust prescription (Figure 2). Hence, dust must be account for when interpreting and comparing simulations. Moreover, with the DEMs, all three simulations produce observables consistent with SDSS. Since different simulations can produce reproduce observations by varying dust, dust significantly limits our ability to constrain the physical processes that go into galaxy simulations.

There are also a few discrepancies between the DEM models and SDSS observations. First, the red sequence in the observed  $G - R$  distribution has a sharp red color cut-off. In contrast, we do not find as sharp of a  $G - R$  cut off in the DEM models, and find a small fraction of galaxies redder than observations. Furthermore, while the DEM models for TNG and EAGLE agree with SDSS, the DEM model for SIMBA overpredicts blue galaxies. **CH: what do we want to do with SIMBA?** We also find that the TNG and EAGLE DEM models slightly overpredict galaxies in the higher luminosity bin and produce a broader  $G - R$  distribution. Nonetheless, Figure 6 demonstrates that overall the DEM models for SIMBA, TNG, and EAGLE produce observables are in good agreement with SDSS.

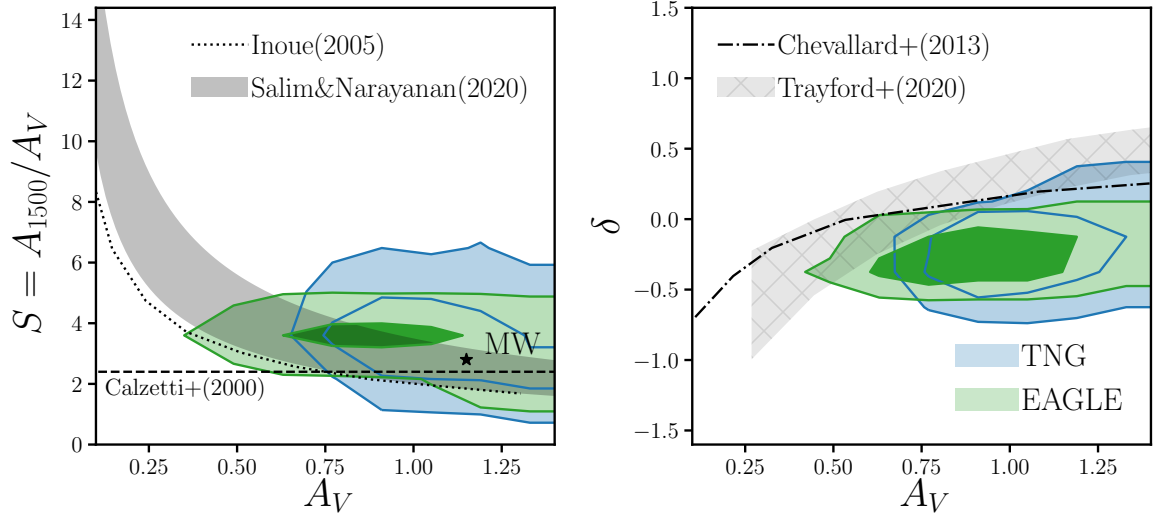
Previous works in the literature have also presented models that predict colors and luminosities for different simulations and dust models and compared them to observations. For instance, Trayford et al. (2015) calculate colors and luminosities for  $z = 0.1$  galaxies using EAGLE with the GALAXEV population synthesis models and a two-component screen model for dust. Compared to GAMA obser-



**Figure 6.**  $G - R$  (left) and  $FUV - NUV$  (right) number density distributions for the DEM models of the SIMBA (orange), TNG (blue), and EAGLE (green) simulations in two  $M_r$  bins:  $-20 > M_r > -21$  (top panels) and  $-21 > M_r > -22.5$  (bottom panels). Each of the DEM models are run using the median posterior parameter values. In comparison to SDSS (grey shaded), the DEM models predict consistent red sequence and blue cloud positions in the  $G - R$  distributions,  $FUV - NUV$  peak positions, and number density. Overall the DEM models for SIMBA, TNG, and EAGLE produce observables are in good agreement with SDSS.

vations, their model produces a bluer red sequence and overpredicts luminous blue galaxies (Trayford et al. 2015, Figure 5). Although a detailed comparison is difficult since they compare all galaxies, not just centrals, we note that the DEM models find good agreement in the positions of the red sequences. Furthermore, for TNG and EAGLE, the DEM models do not overpredict blue galaxies. Even for SIMBA, the DEM model overpredict blue galaxies by a smaller amount.

More recently, Trayford et al. (2017) calculated optical colors for the EAGLE simulation using SKIRT, a Monte Carlo radiative transfer code (Camps & Baes 2015), to model the dust. Trayford et al. (2017) compares all galaxies so again, we do not include a direct comparison. Compared to GAMA, while they find good agreement with observations at intermediate masses,  $10^{10.5} < M_* < 10^{10.8} M_\odot$ , they again find a bluer red-sequence at  $10^{11.2} < M_* < 10^{11.5}$ . While we do not present comparisons in  $M_*$  bins, which compare SED derived  $M_*$  to the predicted  $M_*$  from simulations, we find that the position of the red sequence in the DEM models are in good agreement with SDSS even at  $M_* > 10^{11.2}$ . Our models, however, predict an overall broader color distribution at the high mass end. Using the same Trayford et al. (2017) EAGLE and SKIRT framework, Baes et al. (2019) compared the predicted cosmic spectral energy distributions (CSED) to observations. While this

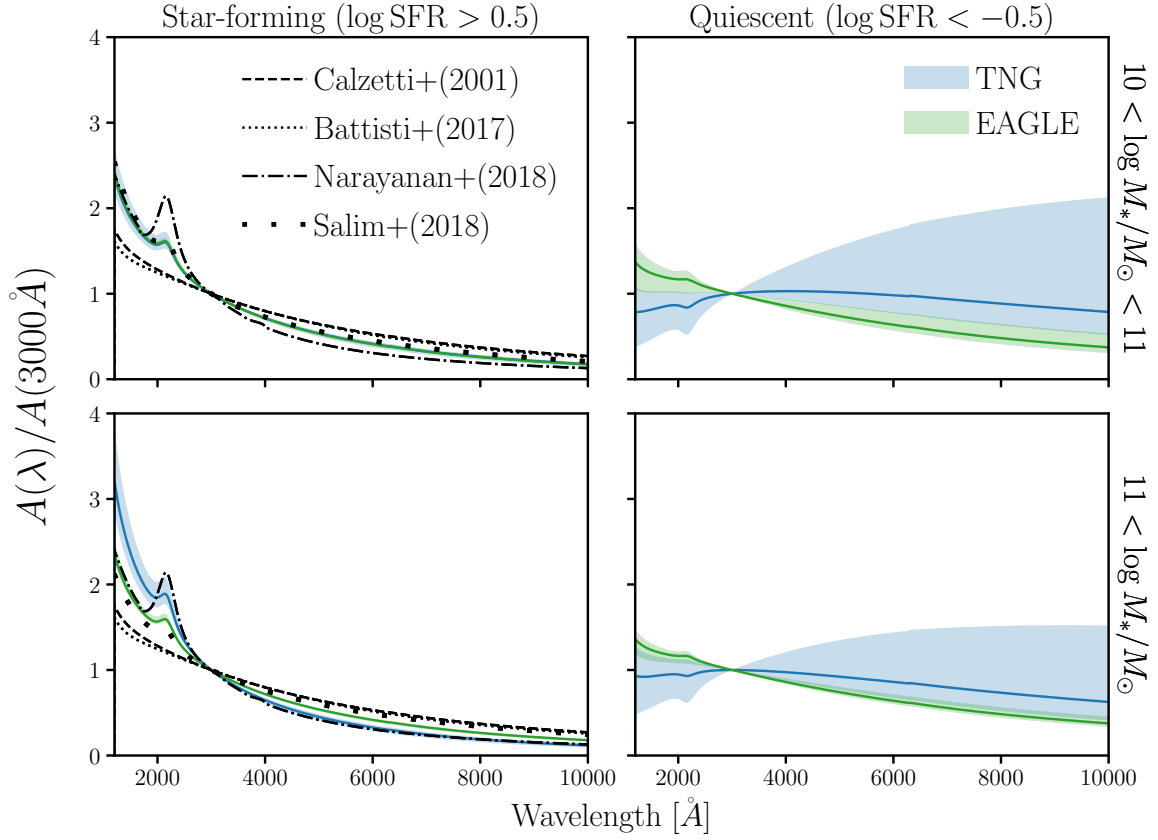


**Figure 7.** The attenuation-slope relation for the TNG (bue) and EAGLE (green) DEM models. We present the relation using two different measurements of slope, commonly used in the literature:  $S = A(1500\text{\AA})/A_V$  (left panel) and the slope offset from the Calzetti (2001) curve,  $\delta$  (right panel). The DEM models predict an attenuation-slope relation, where the slope is steeper at lower attenuation, consistent with both observations and simulation. The DEM models only include massive galaxies, hence, they do not include many galaxies with low attenuation. At  $A_V > 0.5$ , however, the DEM models are in good agreement with observations Salim & Narayanan (2020). In fact, the DEM models match the observed attenuation-slope relation better than radiative transfer simulations, which predict attenuation curves that are too shallow (Chevallard et al. 2013; Trayford et al. 2020)

comparison averages over the galaxy populations, they find the EAGLE-SKIRT CSED overestimates the observed CSED in the UV regime. Moreover, the  $FUV - NUV$  color of their CSED is significantly higher than GAMA  $FUV - NUV$ . The DEM models on the other hand, predict  $FUV - NUV$  in good agreement with observations.

Besides with EAGLE, Nelson et al. (2018) calculated optical colors for the TNG simulations with a dust model that includes attenuation due to dense gas birth clouds surrounding young stellar populations and also attenuation due to simulated distribution of neutral gas and metals. Although they compare the color distribution for all galaxies in bins of  $M_*$ , so we cannot directly compare to the DEM models, compared to SDSS they find bluer red sequence peak position and narrower blue cloud. We find neither of these discrepancies between the DEM models and SDSS. **CH: restatement of how the DEM models have the flexibility to reproduce the optical and UV color-magnitude relationship.**

The simulations with DEMs predict observables in agreement with observations despite the significant differences in the SMFs and  $M_*$ -SFR relations (Figure ??). In other words, the DEM has the flexibility to reproduce observations even when simulations predict galaxy populations with significantly different physical properties. We emphasize that the DEM is based on the standard prescriptions for dust attenuation and, thus, serve as a flexible parameterization within the bounds of our current understanding of dust in galaxies.



**Figure 8.** Attenuation curves of the TNG (blue) and EAGLE (green) DEM models for low (top) and high  $M_*$  (bottom), star-forming (left) and quiescent galaxies (right). The attenuation curves are normalized at  $3000\text{\AA}$ :  $A(\lambda)/A(3000\text{\AA})$ . We mark the  $1\sigma$  standard deviation of the attenuation curves with the shaded region. For comparison, we include measurements of  $A(\lambda)/A(3000\text{\AA})$  from observations (Battisti et al. 2017a; Salim et al. 2018) as well as from simulations (Narayanan et al. 2018). For star-forming galaxies, the Battisti et al. (2017a) attenuation curves are shallower than the DEM attenuation curves; however, this is primarily driven by the differences in  $M_*$  ranges. For Salim et al. (2018), which probe a similar  $M_*$  range as our DEM models, we find good agreement. We also find good agreement with median attenuation curve of Narayanan et al. (2018). With DEM models, we can also constrain the attenuation curves of quiescent galaxies, which are challenging to observationally constrain. Quiescent galaxies, have significantly shallower attenuation curves with larger variations in slope.

Figures 5 and 6 highlights two key points. First, any comparison of simulations must account for dust. Dust entirely changes the predictions of simulations in observables-space. Without dust, we did not find bimodality in the color-magnitude relation. Fortunately, the DEM provides a simple framework for including dust motivated by attenuation laws and correlations with the physical properties of galaxies. Second, the current limitations in our understanding of dust in galaxies significantly impedes our ability to understand galaxy formation from simulations. To robustly interpret any comparison of simulations, we would need to marginalize over dust (*e.g.* DEM parameters). Since DEMs can produce consistent observables for a range of simulations, marginalizing over dust would leave little constraining power on the subgrid prescriptions (*i.e.* galaxy physics) of the simulations.

The DEMs demonstrate that simulations can closely match observations by varying dust attenuation. They therefore illustrate how dust is a major bottleneck for directly interpreting galaxy simulations for insights into galaxy formation. In addition, DEMs also provide some insight into dust. Given our parameterization (Section 3.1), it is especially easy to interpret correlation between dust attenuation and galaxy physical properties. For instance, the posteriors of DEM parameters in Figure 4 reveal a number of consistent trends across the simulations. In all three simulations, we find significant positive  $M_*$  dependence of  $\tau_V$ :  $m_{\tau, M_*} \sim 2$ . Regardless of the underlying hydro simulations, we find that *galaxies with higher  $M_*$  have overall higher dust attenuation*.

This  $M_*$  dependence is consistent with previous works in the literature. The seminal work of Burgarella et al. (2005), for instance, found significant positive  $M_*$  dependence in  $FUV$  attenuation in NUV-selected and FIR-selected samples of Buat et al. (2005) and Iglesias-Páramo et al. (2006). Garn & Best (2010) also find positive  $M_*$  dependence in Balmer decrement-based  $H\alpha$  attenuation in  $\sim 90,000$  SDSS star-forming galaxies. Battisti et al. (2016) similarly find higher Balmer optical depth for higher  $M_*$  in  $\sim 10,000$  star-forming galaxies from GALEX and SDSS. Most recently, Salim et al. (2018) find higher  $V$  and  $FUV$  attenuation for more massive star-forming galaxies in the GALEX-SDSS-WISE Legacy Catalog 2 (GSWLC2). *citation is a bit SDSS heavy. Anything else in the literature?*

TODO

In addition to the  $M_*$  dependence, the DEM posteriors also allow us to examine the correlation between dust attenuation and star formation. For TNG and EAGLE, we infer DEM posteriors with  $m_{\tau, \text{SFR}} \sim -1$  (Figure 4). This means that TNG and EAGLE require higher attenuation for galaxies with lower SFR — *i.e.* quiescent galaxies have higher dust attenuation overall. While previous works that have examined the relationship between dust attenuation and SFR in observations (*e.g.* Garn & Best 2010; ?; Battisti et al. 2016, 2017a), they focus solely on star-forming galaxies. While they find that star-forming galaxies with higher SFR have higher attenuation, much of this trend is driven by the star-forming sequence (more massive star-forming galaxies have higher SFR; Garn & Best 2010; Battisti et al. 2017a). At fixed  $M_*$ , observations find no strong SFR dependence for the SF population.

For SIMBA, unlike for TNG and EAGLE, we infer  $m_{\tau, \text{SFR}} \sim 3$ : galaxies with higher SFR have higher dust attenuation (Figure 4). In fact, the attenuation is so high for star-forming galaxies that they populate the red sequence rather than the blue cloud in the color-magnitude relation. This extreme SFR dependence in the dust attenuation that results in a contradiction of established color-SFR relations, is due to the fact that SIMBA predicts a population of star-forming with exceptionally high SFR, that seemingly lie above the SFS (Figure 1). In a SIMBA DEM model with  $m_{\tau, \text{SFR}} < 0$ , these high SFR galaxies would be high luminosity blue galaxies, not found in observations. *CH: If we impose a  $m_{\tau, \text{SFR}} < 0$  prior for the SIMBA DEM model, we struggle to reproduce observables consistent with SDSS.* The difference in  $m_{\tau, \text{SFR}}$  among the hydro simulations demonstrates that, in addition to insights on dust in galaxies, our DEM approach can also highlight differences and limitations among simulations. Moreover, it further highlights that dust attenuation can be adjusted, within priors set by observations, so that any simulation can match observations. Given this significant discrepancy for SIMBA, we focus the rest of the discussion on TNG and EAGLE. *what subgrid physics is causing*

TODO

### SIMBA to overpredict low mass starbursts compared to TNG and EAGLE?

In addition to the dependence of  $A_V$  on galaxy properties, our results also shed light on the slope of dust attenuation as well as its correlation with galaxy properties. If we measure the slope of the attenuation curve of the DEM models using the quantity  $S = A(3000\text{\AA})/A_V$ , which is easier to constrain observationally, we find that the TNG and EAGLE DEM models both predict slopes within  $2 < S < 5$  and centered around  $S \sim 3.5$  (Figure 7). In comparison, previous observational works that measure dust attenuation in star-forming galaxies also find slopes within the range  $2 < S < 5$  (Burgarella et al. 2005; ?; ?; Battisti et al. 2016, 2017a). ? and Salim et al. (2018) find a broader range of slopes in their galaxy samples,  $2 < S < 15$ . However, their galaxies with steeper slopes,  $S > 6$ , have  $A_V < 0.4$ , which we are not in our sample (we discuss this in further detail below). Excluding those galaxies, we find good agreement. Also for reference, the Small Magellanic Cloud and the Milky Way have attenuation slopes  $S_{SMC} = 4.8$  and  $S_{MW} = 2.8$ . **CH: The dust attenuation curve slopes predicted by the TNG and EAGLE DEM models are in excellent overall agreement with observations.**

In addition to the amplitude, we can also examine the correlation between attenuation curve slopes and galaxy properties. For TNG and EAGLE, we find little  $M_*$  and SFR dependence in  $\delta$ : both  $m_{\delta, M_*}$  and  $m_{\delta, \text{SFR}}$  are consistent with 0. To date most observational works do not examine the correlation between slope and galaxy properties and have been limited to star-forming galaxies. ? recently measured the slope of the attenuation curves of galaxies, some of which are non-star-forming. However, with only 129 galaxies the trends are difficult to meaningfully interpret. More recently, Salim et al. (2018) measured attenuation curves of 23,000 galaxies from the GALEX-SDSS-WISE Legacy Catalog 2 (GSWLC2; ?). While they also mainly focus on star-forming galaxies, Salim et al. (2018) also they find that quiescent galaxies have significantly steeper curves. This is in disagreement with our  $m_{\delta, \text{SFR}} \sim 0$ ; however, we note that Salim et al. (2018) also find significantly steeper curves for the starburst population (galaxies above the SFS). **CH: ? finds the opposite — composite and AGN galaxies have shallower slopes, although with limited statistics (129 galaxies).** Since the DEM model only includes a linear dependence on SFR, it's hard to tell. Furthermore, for star-forming galaxies, Salim et al. (2018) find a significant  $M_*$  dependence on  $\delta$ , unlike our  $m_{\delta, M_*} \sim 0$  constraint. They find, however, this dependence is entirely driven by the underlying fundamental trend between slope and  $A_V$ .

At low attenuation, dust scattering dominates absorption. In this regime, the attenuation curve steepens because red light tends to scatter isotropically while blue light tends to forward scatter, which causes more optical-to-IR light to escape the galaxy than UV light (???). On the other hand, at high attenuation dust absorption is dominant and the attenuation curve is shallower (Chevallard et al. 2013). In Figure 7, we present the  $A_V$  and slope relationship for attenuation curves from the TNG (blue) and EAGLE (green) DEM models. On the left panel we quantify slope using  $S = A(1500\text{\AA})/A_V$ ; on the right panel, we use  $\delta$ . In both panels, the DEM models predict consistent  $A_V$ –slope relations where the slope is steeper at lower attenuation. Furthermore, although the comparison is limited by the  $A_V$  range of the DEM models, we find that the DEM  $A_V$ –slope relations are consistent with the  $A_V$ – $S$  relation of GSWLC2 galaxies (black shaded Salim & Narayanan 2020). They are also



consistent with ?. We also compare our results to theoretical predictions from ??Chevallard et al. (2013). Our DEM models are in good agreement with ?. However, ? and Chevallard et al. (2013) predict shallower attenuation curves than our DEM models. Narayanan et al. (2018), not included in Figure 7, also predict shallower attenuation curves (Salim & Narayanan 2020). Overall, our DEM models better reproduce the  $A_V$ -slope relations of observations than these theoretical predictions.

**CH:** also include Trayford et al. (2020)

The DEM does not explicitly model the complexities of dust-star geometry on a galaxy-by-galaxy basis. However, through the slab model and also the dependence of the attenuation on galaxy properties, it includes significant variation in the attenuation. In Figure 8, we present the normalized attenuation curves of the SIMBA (orange), TNG (blue), and EAGLE (green) DEM models for low (top) and high  $M_*$  (bottom), star-forming (left) and quiescent galaxies (right). The attenuation curves are normalized at  $3000\text{\AA}$ :  $A(\lambda)/A(3000\text{\AA})$ . We represent the variation in the attenuation curves ( $1\sigma$  standard deviation about the median) with the shaded region. For comparison, we include measurements of  $A(\lambda)/A(3000\text{\AA})$  from observations (?Battisti et al. 2017a; Salim et al. 2018) as well as from simulations Narayanan et al. (2018). We note that the ? and Battisti et al. (2017a) attenuation curves are for star-forming galaxies with significantly lower  $M_*$ . The Battisti et al. (2017a) curve, for instance, is derived from  $M_* < 10^{9.9} M_\odot$  star-forming galaxies. Meanwhile, the Salim et al. (2018) curves we include are specifically for  $10^{9.5} < M_* < 10^{10.5} M_\odot$  star-forming galaxies (top left),  $10^{10.5} < M_* M_\odot$  star-forming galaxies (bottom left), and quiescent galaxies (top and bottom right panels).

Focusing first on the attenuation curves of star-forming galaxies (left panels), we find that the ? and ? curves are significantly shallower than the TNG and EAGLE DEM attenuation curves. However, at least part of the discrepancy is driven by differences in  $M_*$ . And, although we do not probe down to low  $M_*$ , the TNG and EAGLE attenuation curves get shallower at lower  $M_*$  so we expect better agreement with ? and ? at the  $M_*$  range they probe. Next, compared to Salim et al. (2018), we find good agreement among the attenuation curves for star-forming galaxies. In addition, the variation we find in the DEM attenuation curves of star-forming galaxies is consistent with the variation Salim et al. (2018) presents in their Figure 9. The DEM attenuation curves are also in excellent agreement with the median attenuation curve of Narayanan et al. (2018) star-forming galaxies. While Narayanan et al. (2018) find larger attenuation curve variation than the DEM models, this is partly due to the fact that their cosmological zoom-in simulations span a broader  $M_*$  range (?). Overall, the DEM models find significant variation in the attenuation curves of star-forming galaxies consistent with both observations and simulations.

In addition to constraining the attenuation curve of star-forming galaxies, the DEM models also shed light on dust attenuation in quiescent galaxies, which is particularly valuable due to the observational challenges of measuring dust attenuation in quiescent galaxies. For instance, MIR emission from active galactic nuclei (AGN) heating nearby dust complicates methods that rely on IR luminosity to measure dust attenuation ?. Even SED fitting methods require accounting for AGN MIR emission (??Salim et al. 2018) in addition to the overall challenge of breaking the degeneracy between SFH and metallicity to fit the continuum of quiescent galaxy SEDs (**CH:** cite?). With DEM models, which take a forward modeling approach with optical and UV data, we do not face these issues and



can constrain the attenuation curves of quiescent galaxies. For both TNG and EAGLE, we find that quiescent galaxies have shallower attenuation curve with large variations in the slopes (Figure 8). We also find that they have higher  $A_V \gtrsim 1.25$ . **CH: explanation for why DEM model does this** In ?, they similar find composite and AGN galaxies to have shallow attenuation curves with higher  $A_V$ ; however, the comparison is limited due to their smaller sample size (129 galaxies). In contrast, Salim et al. (2018) find that quiescent galaxies in GSWLC2 have significantly steeper curves; they, however, focus their analysis mainly on star-forming galaxies.

In our DEM model, we neglect the galaxies with  $\text{SFR}=0$  from simulations by directly sampling the quiescent galaxy observables (Section A). Since galaxies with  $\text{SFR}=0$  predicted by the simulations do not have recent star-formation and also have 0 gas mass@tjitske is this for all sims, we would expect them to also have no dust. However, a DEM model where we do not attenuate  $\text{SFR}=0$  galaxies struggles to reproduce observations. This likely highlights the limitations of hydrodynamical simulations near the mass and temporal resolutions as well as the limitations of subgrid prescriptions for gas. **CH: Uncertainties in the dust destruction timescale may also contribute to the explanation (e.g. ??)**. We emphasize that our prescription for  $\text{SFR}=0$  galaxies ensures that they do not significantly impact the constraints on DEM parameters.

TODO

**CH: fixed UV bump** We fix the UV bump to reduce the number of parameters. But when run our analysis without fixing the UV bump, we find it does not impact our results. We also get no constraints on the UV bump parameters.

**CH: slab model** We rely on the slab model. But nothing changes when we use a more flexible truncated normal distribution in Appendix B. tnorm DEM model allows us to also vary the scatter of the attenuation curve

Chevallard et al. (2013) Trayford et al. (2015) Battisti et al. (2017b) find a trend between inclination and slope... ??

**CH: How about our prior choice?**

**CH: what we learn about in the simulations**

**CH: what we learn about dust** paragraph on restating how we can learn about dust through DEMs based on trends we see across all simulations. summarize main findings again.

**CH: observables unaffected by dust/dem?** Are there observables that hydro sims + DEMs cannot reproduce? What does that say about the hydro sims? What observables are unaffected by DEMs? We should chase those observables.

**CH: don't over-interpret observations** We clearly have to be careful with overinterpreting hydro sims because modifying dust allows us to reproduce whatever we want.

- Should we bother calibrating our empirical and semi-analytic models to hydrodynamic simulations when the hydro sims also require marginalizing over dust parameters? Does this mean that if our goal is to make realistic mocks, we can be relatively careless about

**CH: What are some applications for DEMs?** Realistic mock catalogs that reproduce observations in observable-space rather than physical parameter space. **CH: talk about IQ paper where we use best-fit dust**

## 5. SUMMARY

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### APPENDIX

#### A. RESOLUTION EFFECTS

Figure demonstrating imprint SFR=0 leave on the observable space and how we deal with them so we can ignore them...

#### B. BEYOND THE SLAB DEM

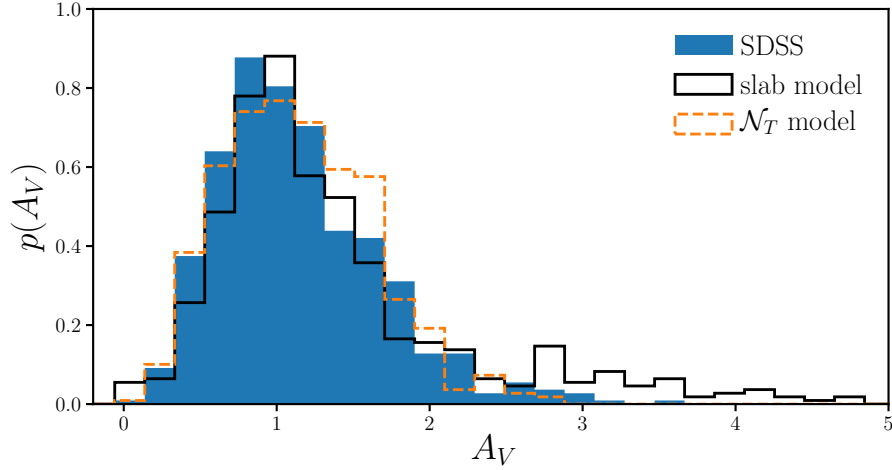
A major assumption of our fiducial DEM is that we sample the amplitude of attenuation from the slab model. The slab model makes the simplifying assumption that dust in galaxies are in a slab-like geometry and illuminated by the stellar radiation source (Somerville & Primack 1999). Then, for a given  $\tau_V$ , the attenuation depends solely on the orientation of the galaxy. This simplification, ignores any complexities in the star-to-dust geometry that impact the shape of the attenuation curve (Witt Gordon 1996, 2000, Seon Drain 2016). TODO

Besides its simplifications, the slab model predicts  $A_V$  distribution with significant differences than the  $A_V$  distributions measured from observations. In Figure 9, we compare the  $A_V$  distribution predicted by the slab model (black) to the  $A_V$  distribution of star-forming galaxies in our SDSS sample (blue). The  $A_V$  values are derived using SED fitting from the ? MPA-JHU catalog and how are the SF galaxies classified. The slab model  $A_V$  values are derived using Eq. 3 and 4 with  $M_*$  and SFRs from the same SDSS sample and the inclinations,  $i$ , are uniformly sampled over the range  $[0, \pi/2]$ . With  $\{m_{\tau,1}, m_{\tau,2}, c_{\tau}\}$  chosen to reproduce the observed  $A_V$  distribution, the slab model can reproduce the overall shape. However, it predicts an extended high  $A_V$  tail not found in observations. TODO

Given these shortcomings of the slab model, we want to ensure that our results do not hinge on the slab model. Modeling the star-to-dust geometries with increased complexities, however, would involve expensive hydrodynamic simulations and dust radiative transfer calculations (*e.g.* Narayanan et al. 2018)jonsson2006, rocha2008, natale2015,hayward smith2015,hou2017,trayford2020. We instead take an empirical approach and implement a flexible model for sampling  $A_V$  based on a truncated normal distribution. TODO

$$A_V \sim \mathcal{N}_T(\mu_{A_V}, \sigma_{A_V}) = \frac{\mathcal{N}(\mu_{A_V}, \sigma_{A_V})}{1 - \Phi\left(-\frac{\mu_{A_V}}{\sigma_{A_V}}\right)}. \quad (\text{B1})$$

Here,  $\mathcal{N}$  is the standard normal distribution and  $\Phi(x) = \frac{1}{2} (1 + \text{erf}(x/\sqrt{2}))$  is the cumulative distribution function of  $\mathcal{N}$ .  $\mu_{A_V}$  and  $\sigma_{A_V}$  are the mean and variance of the truncated normal distribution.



**Figure 9.** Comparison of  $A_V$  distribution of SDSS star-forming galaxies (blue) to predictions from the slab model (Eq. 3; black). **detail on how SDSS SF galaxies are classified.** The slab model assumes that there’s a slab of dust in front of a galaxy. We use  $\tau_V = 2$  for the slab model above. Regardless of  $\tau_V$ , however, the slab model predicts a significantly more asymmetric and peaked  $A_V$  distribution than observations. Given this disagreement, *we include in our analysis a DEM with an empirical prescription for  $A_V$  based on a truncated normal distribution, which better reproduce the observed  $A_V$  distribution* (Section B).

Similar to Eq. 4, we allow  $\mu_{A_V}$  and  $\sigma_{A_V}$  to depend on the physical properties of galaxies:

$$\mu_{A_V} = m_{\mu,1}(\log M_* - 10.) + m_{\mu,2} \log \text{SFR} + c_{\mu} \quad (\text{B2})$$

$$\sigma_{A_V} = m_{\sigma,1}(\log M_* - 10.) + m_{\sigma,2} \log \text{SFR} + c_{\sigma}. \quad (\text{B3})$$

The  $A_V$  distribution from our truncated normal (orange dashed) closely reproduces the observed SDSS  $A_V$  distribution (Figure 5).  $N_T$  is able to reproduce the overall skewness but unlike the slab model, it does not have a long high  $A_V$  tail. With more free parameters and a functional form that closely resembles the observed  $A_V$  distribution, the truncated normal model provides a flexible alternative to the slab model and we include it in our analysis.

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