

# The Star-Forming Sequence in a Hierarchical Universe

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## ABSTRACT

**sentence on the questions of SF galaxies.** Star-forming galaxies are observed to have a tight relationship between their star formation rates and stellar masses. This so-called “star-forming sequence” (SFS) characterizes both the star formation histories and stellar mass growth of star-forming galaxies. Meanwhile, observed constraints on the stellar-to-halo mass relation (SHMR) connect the stellar mass growth of galaxies to their host halo accretion history. Combining these observed trends with a high-resolution cosmological  $N$ -body simulation, we present a model that tracks the star formation, stellar mass, and host halo accretion histories of star-forming central galaxies over  $z < 1$ . By comparing this model to the observed stellar mass function and SFS of central galaxies in the SDSS Data Release 7, we find that star formation variability on timescales  $\lesssim 0.5$  Gyr is *necessary* to produce tighter scatter in the SHMR,  $\sigma_{\log M_*}$ , at  $M_h = 10^{12} M_\odot$  comparable to observations. However, to conservatively reproduce the observed  $\sigma_{\log M_*} \sim 0.2$  dex, the star formation histories must also correlate strongly with halo accretion history with a correlation coefficient  $r > 0.5$  — *i.e.* exhibit strong assembly bias. The timescale of star formation variability and the correlation between star formation and halo accretion history we infer, provide key constraints on the star formation history and the evolution of star-forming central galaxies.

*Keywords:* methods: numerical – galaxies: clusters: general – galaxies: groups: general – galaxies: evolution – galaxies: haloes – galaxies: star formation – cosmology: observations.

## 1. INTRODUCTION

Observations from surveys such as the Sloan Digital Sky Survey (SDSS; ?), Cosmic Evolution Survey (COSMOS; Scoville et al. 2007), and the PRISM Multi-object Survey (PRIMUS; Coil et al. 2011; Cool et al. 2013) have provided statistically meaningful samples of galaxies, which have been

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critical for establishing the global trends of galaxies in the local universe. Broadly speaking, galaxies fall into two categories: quiescent and star-forming galaxies. Quiescent galaxies have little to no star formation, are red in color, and have elliptical morphologies. Meanwhile, star-forming galaxies have significant star formation, are blue in color, and have disk-like morphologies (Baldry et al. 2006; Moustakas et al. 2013; see Blanton & Moustakas 2009 and references therein).

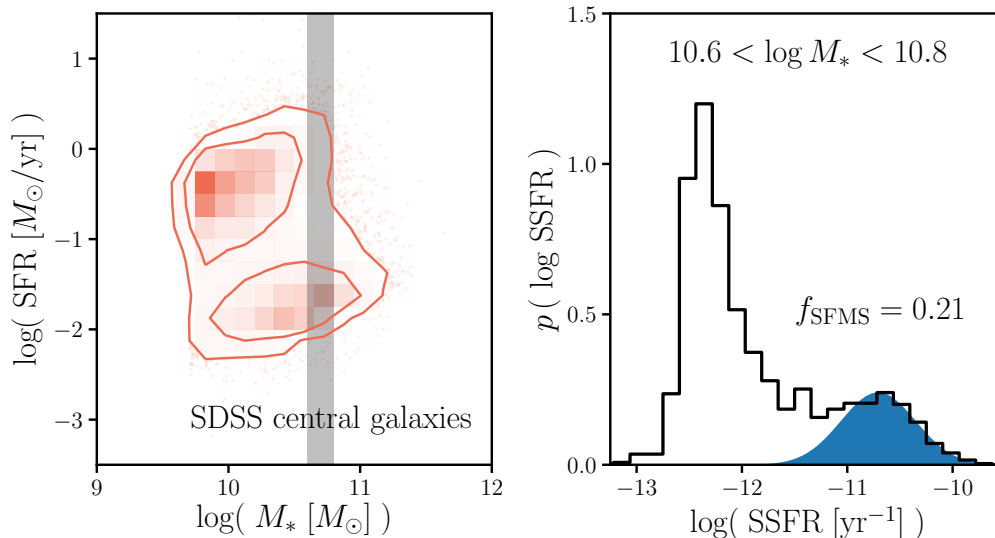
Star-forming galaxies, furthermore, are found on the so-called “star-forming sequence” (hereafter SFS), a tight relationship between their star formation rates (SFR) and stellar masses (Noeske et al. 2007; Daddi et al. 2007; Salim et al. 2007; Speagle et al. 2014; Lee et al. 2015, see also Figure 1). This sequence, which is observed out to  $z > 2$  (??), plays a crucial role in characterizing galaxy evolution over the past  $\sim 10$  Gyr. The significant fraction of star-forming galaxies that quench their star formation and migrate off of the SFS reflects the significant growth in the fraction of quiescent galaxies (Moustakas et al. 2013). Meanwhile, the decline of star formation in the entire SFS (Lee et al. 2015; ?) over time reflects the decline in overall cosmic star formation (??). The SFS and its evolution also connects star formation history and stellar mass growth of star-forming galaxies.

**CH:** some blanket statements about connection between galaxy-halo connection For instance, the stellar-to-halo mass relation (SHMR) is constrained from **papers that look at SHMR or sigma of that from high redshift** (Mandelbaum et al. 2006; Conroy et al. 2007; More et al. 2011; Leauthaud et al. 2012; Tinker et al. 2013; Velandier et al. 2014; Han et al. 2015; Zu & Mandelbaum 2015; Gu et al. 2016) Constraints on the SHMR at  $z \sim 1$  from observations find Remarkably, at  $z \sim 0$ , observational constraints find little evolution in the scatter in the SHMR. These observational constraints suggest that stellar mass growth of galaxies are closely linked to the hierarchical growth of their host dark matter halos.

Despite our understanding of the evolving galaxy population in a hierarchical universe, we face a number of challenges when it comes to understanding their detailed star formation histories (SFH). For instance, SFHs at lookback times longer than 200 Myr do not contribute to SFR indicators such as  $H\alpha$  or  $FUV$  fluxes. Measuring SFHs from fitting photometry or spectroscopy typically assume a specific functional form of the SFH, such as exponentially declining or lognormal, that do not include short timescale variability (*e.g.* Wilkinson et al. 2017; Carnall et al. 2018). Even methods that recover non-parametric SFHs from high signal-to-noise observations can only retrieve SFHs in coarse temporal resolutions (*e.g.* Tojeiro et al. 2009; Leja et al. 2018). While simulations provide another means for understanding SFHs, are also subject to their specific time and mass resolutions that suppress the variability of their star formation, especially in analytic models, semi-analytic models, and large-volume cosmological simulations (?). These challenges make difficult to constrain certain things like the timescale of star formation variability.

**CH:** paragraph on assembly bias and how we’ve look at it w.r.t. quenching and stuff but it’s still unclear at a sfh level.

In this paper, we take advantage of this connection between SFH and the underlying dark matter to constrain the SFH of star-forming central galaxies. We focus on central galaxies since the SFHs of satellites are likely influenced by environmentally-driven external mechanisms such as ram pressure stripping (Gunn & Gott 1972; Bekki 2009), strangulation (Larson et al. 1980; Balogh et al. 2000),



**Figure 1.** The SFR– $M_*$  relation of the central galaxies in SDSS DR7 mark the bimodal distribution of the star-forming and quiescent populations (left panel). *Star-forming centrals*, based on the correlation between their SFR and  $M_*$ , lie on the so-called “star-forming sequence”. On the right, we present the SSFR distribution,  $p(\log \text{SSFR})$ , of SDSS centrals with  $10.6 < \log M_* < 10.8$ . Based on the SFS component from the [Hahn et al. \(2018\)](#) GMM fit to the SFR– $M_*$  relation (shaded in blue), galaxies in the SFS account for  $f_{\text{SFS}} = 0.21$  of the centrals in the stellar mass bin.

or harassment (Moore et al. 1998). Moreover, centrals constitute the majority of massive galaxies ( $M_* > 10^{9.5} M_\odot$ ) at  $z \sim 0$  ([Wetzel et al. 2013](#)). Using a similar approach as [Wetzel et al. \(2013\)](#); [?](#), we present a model that combines a high resolution cosmological  $N$ -body simulation with observed evolutionary trends of the SFS. Our model statistically tracks the star formation, stellar mass, and host halo mass histories of star-forming central galaxies over  $z \sim 1$  to 0. By comparing predictions of this empirical model to observations, we constrain the timescale of star formation variability and also the correlation between SFH and host halo history. **sentence on implication**

In Section 2 we describe the  $z \approx 0$  central galaxy sample that we construct from SDSS Data Release 7. Then in Section 3, we describe the  $N$ -body simulation and how we evolve the SFR and stellar masses of the star-forming central galaxies in our model. We compare predictions from our model to observations and present the resulting constraints in Section 4. Finally, we conclude and summarize the results in Section 5.

## 2. CENTRAL GALAXIES OF SDSS DR7

We construct our galaxy sample following the sample selection of [Tinker et al. \(2011\)](#). We select a volume-limited sample of galaxies at  $z \approx 0.04$  with  $M_r - 5 \log(h) < -18$  and complete above  $M_* > 10^{9.4} M_\odot$  from the NYU Value-Added Galaxy Catalog (VAGC; [Blanton et al. 2005](#)) of the Sloan Digital Sky Survey Data Release 7 (SDSS DR7; [Abazajian et al. 2009](#)). The stellar masses of these galaxies are estimated using the `kcorrect` code ([Blanton & Roweis 2007](#)) assuming a [Chabrier \(2003\)](#) initial mass function. For their specific star formation rates (SSFR) we use measurements

from the current release of the MPA-JHU spectral reductions<sup>1</sup> (Brinchmann et al. 2004). Generally,  $\text{SSFR} > 10^{-11} \text{yr}^{-1}$  are derived from  $\text{H}\alpha$  emission,  $10^{-11} > \text{SSFR} > 10^{-12} \text{yr}^{-1}$  are derived from a combination of emission lines, and  $\text{SSFR} < 10^{-12} \text{yr}^{-1}$  are based on  $D_n4000$  (see discussion in Wetzel et al. 2013). We emphasize that  $\text{SSFR} < 10^{-12} \text{yr}^{-1}$  should only be considered upper limits to the actual galaxy SSFR (Salim et al. 2007).

From this galaxy sample, we identify central galaxies using the Tinker et al. (2011) group finder, a halo-based algorithm that uses the abundance matching ansatz to iteratively assign halo masses to groups. It initially assigns a tentative halo mass to each galaxy by matching their abundances. Then starting with the most massive galaxy, nearby lower mass galaxies are assigned a probability of being a satellite. Once all the galaxies are assigned to a group, the halo masses of the central galaxies are updated by abundance matching with the total stellar mass in the groups. This entire process is repeated until convergence. Every group contains one central galaxy, which by definition is the most massive, and a group can contain zero, one, or many satellites. As with any group finder, galaxies are misassigned due to projection effects and redshift space distortions. Our central galaxy sample has a purity of  $\sim 90\%$  and completeness of  $\sim 95\%$  (?). Moreover, as illustrated in Campbell et al. (2015), the Tinker et al. (2011) group finder robustly identifies red and blue centrals as a function of stellar mass, which is highly relevant to our analysis. We present the  $\text{SFR}-M_*$  relation of the SDSS DR7 central galaxies, described above, in the left panel of Figure 1. The contours of the relation clearly illustrate the bimodality in the galaxy sample with the star-forming centrals lying on the so-call “star-forming sequence” (SFS).

### 3. MODEL: SIMULATED CENTRAL GALAXIES

We’re interesting in constructing a model that tracks central galaxies and their star formation within the heirarchical growth of their host halos. This requires a cosmological  $N$ -body simulation that accounts for the complex dynamical processes that govern the host halos of galaxies. In this paper we use the high resolution  $N$ -body simulation from Wetzel et al. (2013) generated using the White (2002) TreePM code with flat  $\Lambda$ CDM cosmology ( $\Omega_m = 0.274$ ,  $\Omega_b = 0.0457$ ,  $h = 0.7$ ,  $n = 0.95$ , and  $\sigma_8 = 0.8$ ). From initial conditions at  $z = 150$ , generated from second-order Lagrangian Perturbation Theory, 2048<sup>3</sup> particles with mass of  $1.98 \times 10^8 M_\odot$  are evolved in a 250 Mpc/ $h$  box with a Plummer equivalent smoothing of 2.5 kpc/ $h$  (Wetzel et al. 2013, 2014). ‘Host halos’ are then identified using the Friends-of-Friends algorithm (FoF; Davis et al. 1985) with linking length of  $b=0.168$  times the mean inter-particle spacing. Within these host halos, Wetzel et al. (2013) identifies ‘subhalos’ as overdensities in phase space through a six-dimensional FoF algorithm (FoF6D; White et al. 2010). The host halos and subhalos are then tracked across the simulation outputs from  $z = 10$  to 0 to build merger trees (Wetzel et al. 2009; Wetzel & White 2010). The most massive subhalos in newly-formed host halos at a given simulation output are defined as the ‘central’ subhalo. A central subhalo retains its ‘central’ definition until it falls into a more massive host halo, at which point it becomes a ‘satellite’ subhalo.

<sup>1</sup> <http://wwwmpa.mpa-garching.mpg.de/SDSS/DR7/>

Throughout its 45 snapshot outs, **TreePM** simulation tracks the evolution of subhalos back to  $z \sim 10$ . We restrict ourselves to 15 snapshots from  $z = 1.08$  to  $0.05$ , where we have the most statistically meaningful observations. Furthermore, since we’re interested in centrals we only keep subhalos that are classified as centrals throughout the redshift range. This criterion removes “black splash” or “ejected” satellite galaxies (*e.g.* Mamon et al. 2004; Wetzel et al. 2014) misclassified as centrals. Next, we describe how we select and initialize the star-forming central galaxies from the central subhalos of the **TreePM** simulation in our model.

### 3.1. Selecting Star-Forming Centrals

To construct a model that tracks the SFR and stellar mass evolution of star-forming central galaxies, we first need to select them from the central galaxies/subhalos in the **TreePM** simulation. Since we want our model to reproduce observations, our selection is based on  $f_{\text{SFS}}^{\text{cen}}(M_*)$ , the fraction of central galaxies within the SFS measured from the SDSS DR7 VAGC (Section 2). Below, we describe how we derive  $f_{\text{SFS}}^{\text{cen}}(M_*)$  and use it to select star-forming central galaxies in our model. Afterwards we describe how we initialize the SFRs and  $M_*$  of these galaxies.

Often in the literature, an empirical color-color or SFR– $M_*$  cut that separates the two main modes (red/blue or star-forming/quiescent) in the distribution is chosen to classify galaxies (*e.g.* Baldry et al. 2006; Blanton & Moustakas 2009; Drory et al. 2009; Peng et al. 2010; Moustakas et al. 2013; Hahn et al. 2015). The red/quiescent or blue/star-forming fractions derived from this sort of classification, by construction, depend on the choice of cut and neglect galaxy subpopulations such as transitioning galaxies *i.e.* galaxies in the “green valley”. Instead, for our  $f_{\text{SFS}}^{\text{cen}}(M_*)$ , we use the SFS identified from the Hahn et al. (2018) method. Hahn et al. (2018) uses Gaussian Mixture Models and the Bayesian Information Criteria in order to fit the SFR– $M_*$  relation of a galaxy population and identify its SFS. This data-driven approach relaxes many of the assumptions and hard cuts that go into other methods. Furthermore, Hahn et al. (2018) demonstrate its method can be flexibly applied to a wide range of SFRs and  $M_*$ s and for multiple simulations. The weight of the SFS GMM component from the method provides an estimate of  $f_{\text{SFS}}^{\text{cen}}$ . In the right panel of Figure 1, we present the SSFR distribution,  $p(\log \text{SSFR})$ , of the SDSS DR7 central galaxies within  $10.6 < \log M_* < 10.8$  with the SFS GMM component shaded in blue. The SFS constitutes  $f_{\text{SFS}}^{\text{cen}} = 0.21$  of the SDSS central galaxies in this stellar mass bin. Using the  $f_{\text{SFS}}^{\text{cen}}$  estimates, we fit  $f_{\text{SFS}}^{\text{cen}}$  as a linear function of  $\log M_*$  similar to Wetzel et al. (2013); Hahn et al. (2017a):

$$f_{\text{SFS, bestfit}}^{\text{cen}}(M_*) = -0.627 (\log M_* - 10.5) + 0.354. \quad (1)$$

We note that this is in good agreement with the  $f_Q^{\text{cen}}(M_*; z \sim 0)$  fit from Hahn et al. (2017a).

For each central subhalo in our simulation, we assign a probability of it being on the SFS, using Eq. 1 with  $M_*$  at  $z \sim 0$  assigned through subhalo abundance matching (SHAM) to  $M_{\text{peak}}$ , the maximum host halo mass that it ever had as a central subhalo (Conroy et al. 2006; Vale & Ostriker 2006; Yang et al. 2009; Wetzel et al. 2012; Leja et al. 2013; Wetzel et al. 2013, 2014; Hahn et al. 2017a). SHAM, in its simplest form, assumes a one-to-one mapping between subhalo  $M_{\text{peak}}$  and galaxy stellar mass,  $M_*$ , that preserves rank order:  $n(>M_{\text{peak}}) > n(>M_*)$ . In practice, we apply a

0.2 dex log-normal scatter in  $M_*$  at fixed  $M_{\text{peak}}$  based on the observed SHMR. For  $n(>M_*)$ , we use observed stellar mass function (SMF) from Li & White (2009), which is based on the same SDSS NYU-VAGC sample as our group catalog. Based on the probabilities from Eq. 1 and SHAM  $M_*$ , we randomly identify centrals from our simulation as SF at  $z \sim 0$ . Tinker et al. (2017, 2018) found that quenching is independent of halo growth rate and therefore we randomly select SF subhalos. In our model, we assume that once a SF galaxy quenches its star formation, it remains quiescent. Without any quiescent galaxies rejuvenating their star formation, galaxies on the SFS at  $z \sim 0$  are also on the SFS at  $z > 0$ . Using this assumption the SF centrals we select at  $z \sim 0$  are also on the SFS at the initial redshift of our model:  $z \sim 1$ .

We next initialize the SF centrals at  $z \sim 1$  using the observed SFR- $M_*$  relation of the SFS with  $M_*$  assigned using SHAM with a SMF interpolated between the Li & White (2009) SMF and the SMF from Marchesini et al. (2009) at  $z = 1.6$ . We choose the Marchesini et al. (2009) SMF, among others, because it produces interpolated SMFs that monotonically increase at  $z < 1$ . As noted in Hahn et al. (2017a), at  $z \approx 1$ , the SMF interpolated between the Li & White (2009) and Marchesini et al. (2009) SMFs is consistent with more recent measurements from Muzzin et al. (2013) and Ilbert et al. (2013). Observations in the literature at  $z \sim 1$ , however, not only use galaxy properties derived differently from the SDSS VAGC but they also find SFS with significant discrepancies from one another. Speagle et al. (2014) compiles the SFR- $M_*$  relation of the SFS from 25 studies in the literature, each with different methods of deriving galaxy properties. Even *after* their calibration, for a fixed  $M_* = 10^{10.5} M_\odot$ , the SFRs of the SFSs at  $z \sim 1$  vary by more than a factor of 2 (see Figure 2 of Speagle et al. 2014). With little consensus on the SFS at  $z \sim 1$ , and consequently its redshift evolution, we flexibly parameterize the SFS SFR,  $\log \text{SFR}_{\text{SFS}}(M_*, z)$ , with free parameters  $m_{M_*}^{\text{low}}$ ,  $m_{M_*}^{\text{high}}$ , and  $m_z$ . These parameters characterize the stellar mass dependence of the SFS below and above  $10^{10} M_\odot$  and its redshift dependence, respectively.

We parameterize the log SFR of the SFS as,

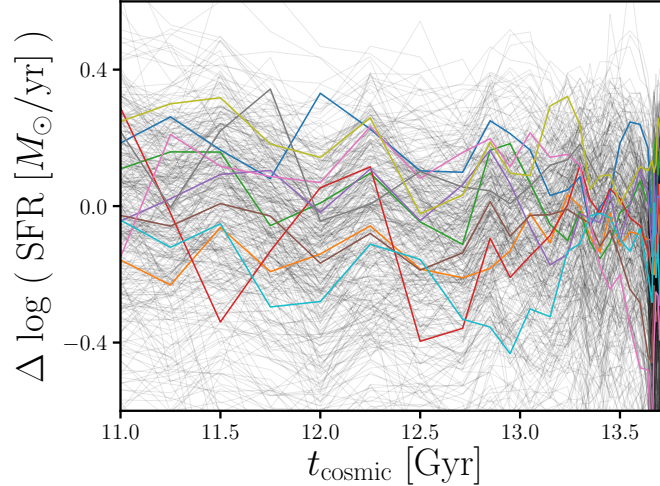
$$\log \text{SFR}(M_*, z) = \begin{cases} m_{M_*}^{\text{low}} (\log M_* - 10.) & \text{for } M_* < 10^{10} M_\odot \\ m_{M_*}^{\text{high}} (\log M_* - 10.) & \text{for } M_* \geq 10^{10} M_\odot. \end{cases} + m_z(z - 0.05) - 0.19. \quad (2)$$

We assign SFRs to our SF centrals at  $z \sim 1$  by sampling a log-normal distribution centered about  $\log \text{SFR}_{\text{MS}}(M_*, z = 1)$  with a constant scatter of 0.3 dex, motivated from observations (Daddi et al. 2007; Noeske et al. 2007; Magdis et al. 2012; Whitaker et al. 2012). Later when comparing to observations, we choose conservative priors for the parameters  $m_{M_*}^{\text{low}}$ ,  $m_{M_*}^{\text{high}}$  and  $m_z$  that encompass the best-fit SFS from Speagle et al. (2014) and measurements from Moustakas et al. (2013) and Lee et al. (2015). With our SF centrals initialized at  $z \sim 1$ , next, we describe how we evolve their SFR and  $M_*$ .

### 3.2. Evolving along the Star Formation Sequence

The tight correlation between the SFRs and stellar masses of star-forming galaxies on the SFS has been observed spanning over four orders of magnitude in stellar mass, with a roughly constant scatter of  $\sim 0.3$  dex, and out to  $z > 2$  (e.g. Noeske et al. 2007; Daddi et al. 2007; Elbaz et al. 2007; Salim et al. 2007; Santini et al. 2009; Karim et al. 2011; Whitaker et al. 2012; Moustakas et al. 2013;





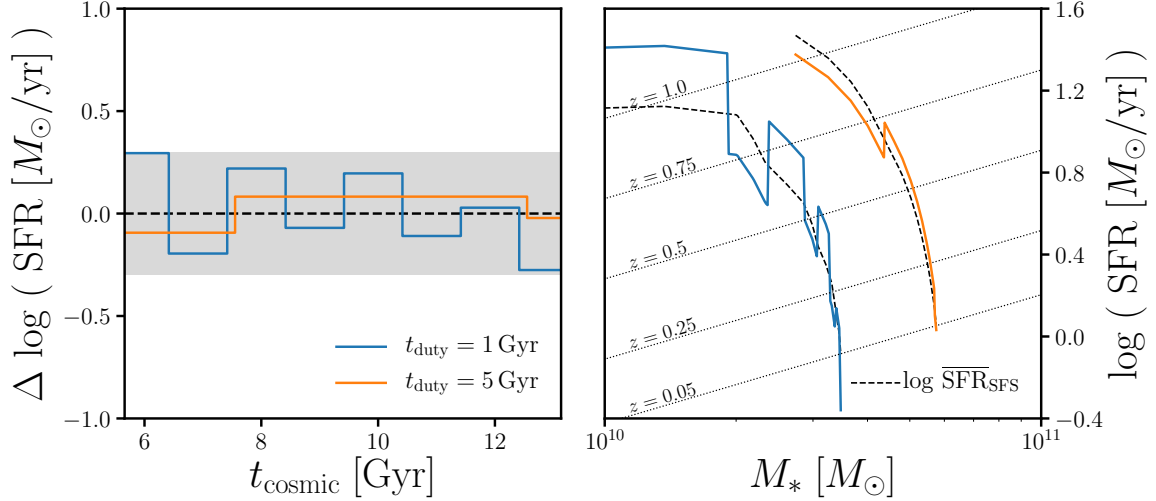
**Figure 2.** Galaxies in the Illustris simulation have SFHs that evolve along the SFS, with their SFRs stochastically fluctuating about the  $\log \text{SFR}$  of the SFS. We highlight  $\Delta \log \text{SFR}$ , SFR with respect to  $\log \text{SFR}_{\text{SFS}}$  (Eq. 3), for a handful of galaxies with  $10^{10.5} < M_* < 10^{10.6} M_\odot$  at  $z \sim 0$ . We calculate  $\Delta \log \text{SFR}$  with  $\log \text{SFR}_{\text{SFS}}$  identified using the Hahn et al. (2018) method, same as in Section 3.1. The implementation of SFR variability in the SFHs of star-forming centrals in our model (Section 3.2) is motivated by the SFHs of Illustris galaxies above.

Lee et al. 2015; see also references in Speagle et al. 2014). This correlation is also predicted by modern galaxy formation models (Somerville & Davé 2015, see Hahn et al. 2018 and references therein). The SFS naturally presents itself as an anchoring relationship to characterize the star formation and  $M_*$  growth histories of SF galaxies throughout  $z < 1$ . More specifically, *we characterize the SFH of each star-forming central with respect to the  $\log \text{SFR}$  of the SFS* (Eq. 2):

$$\log \text{SFR}_i(M_*, t) = \log \text{SFR}_{\text{SFS}}(M_*, t) + \Delta \log \text{SFR}_i(t). \quad (3)$$

Since SFHs determine the  $M_*$  growth of galaxies, in this prescription,  $\Delta \log \text{SFR}_i(t)$  dictates the SFH and  $M_*$  evolution a star-forming central. Next, we describe our prescription for  $\Delta \log \text{SFR}$ .

One simple prescription for  $\Delta \log \text{SFR}(t)$  would be to keep  $\Delta \log \text{SFR}$  fixed throughout  $z < 1$  to the offsets from the  $\log \text{SFR}_{\text{SFS}}$  in the initial SFRs of our SF centrals at  $z \sim 1$  similar to simple analytic models such as Mitra et al. (2015). Galaxies with higher than average initial SFRs continue evolving above the average SFS, while SF centrals with lower than average initial SFRs continue evolving below the average SFS. In addition to not being able to reproduce observations, which we later demonstrate, we also do not find such SFHs in SF galaxies of hydrodynamic simulations such as Illustris (Vogelsberger et al. 2014; Genel et al. 2014). In Figure 2, we plot  $\Delta \log \text{SFR}_i$  of star-forming galaxies in the Illustris simulation as a function of cosmic time. These galaxies have stellar masses within  $10^{10.5} - 10^{10.6} M_\odot$  at  $z = 0$ . At each simulation output, we calculate  $\Delta \log \text{SFR}$  using Eq. 3 with  $\log \text{SFR}_{\text{SFS}}$  derived from the SFS identified using the same Hahn et al. (2018) method as in Section 3.1. As the highlighted  $\Delta \log \text{SFR}_i$  illustrate, star-forming galaxies in Illustris evolve along the SFS, with their SFRs fluctuating about  $\log \text{SFR}_{\text{SFS}}$ .

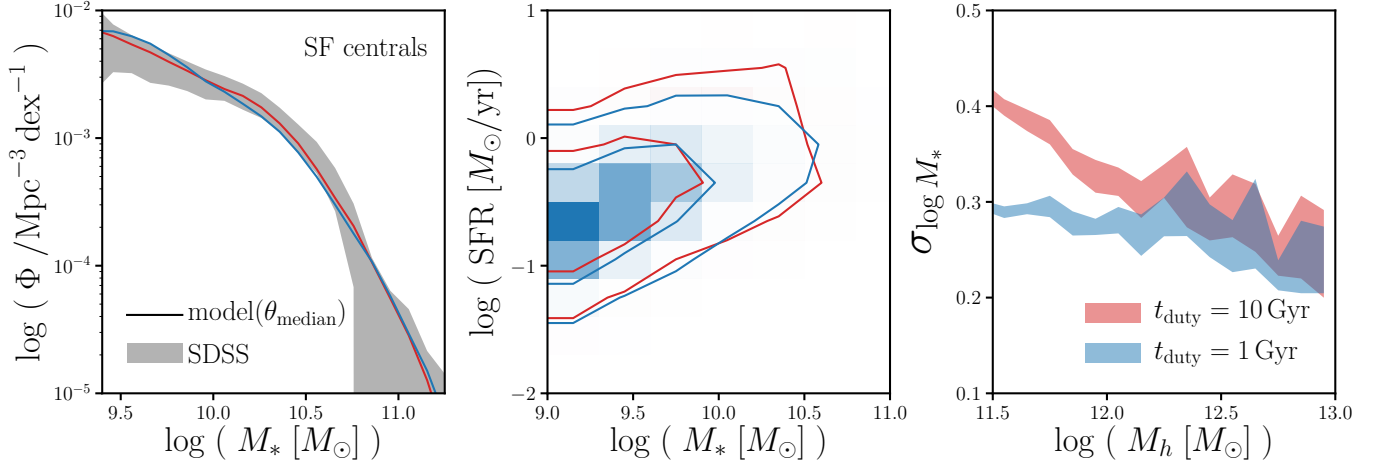


**Figure 3.** We incorporate star formation variability in our model using a “star formation duty cycle” where the SFRs of SF centrals fluctuate about the  $\log \text{SFR}_{\text{SFS}}$  on some timescale  $t_{\text{duty}}$ . In our fiducial prescription, we randomly sample  $\Delta \log \text{SFR}_i(t)$  from a log-normal distribution with 0.3 dex scatter at each timestep. We illustrate  $\Delta \log \text{SFR}_i(t)$  of two SF centrals with star formation duty cycles on  $t_{\text{duty}} = 1 \text{ Gyr}$  (blue) and 5 Gyr (orange) timescales in the left panel.  $\Delta \log \text{SFR}(t)$  determines the SFH and hence the  $M_*$  growth of the SF central galaxies (Eq. 4). On the right, we illustrate the SFR and  $M_*$  evolutions of the corresponding SF centrals. For reference, we include  $\log \text{SFR}_{\text{SFS}}(M_*, i(t), t)$  that the galaxies’ SFR and  $M_*$  evolve along (black solid). We also include  $\log \text{SFR}_{\text{SFS}}(M_*)$  at various redshifts between  $z = 1$  to 0.05 (dotted lines). *The star-forming centrals in our model evolve their SFRs and  $M_*$  along the SFS with their SFRs fluctuate about  $\log \text{SFR}_{\text{SFS}}$ .*

Motivated by the SFHs of Illustris SF galaxies, we introduce variability to the SFHs of our SF centrals in the form of a “*star formation duty cycle*”. Within the Eq. 3 SFH, we parameterize  $\Delta \log \text{SFR}_i$  to fluctuate about the  $\log \text{SFR}_{\text{SFS}}$  on timescale,  $t_{\text{duty}}$ , with amplitude sampled to reproduce the observed log-normal distribution with 0.3 dex scatter at every timestep. For our fiducial star formation duty cycle prescription, we randomly sample  $\Delta \log \text{SFR}_i$  from a log-normal distribution with  $\sigma = 0.3 \text{ dex}$ . We illustrate  $\Delta \log \text{SFR}_i(t)$  of SF centrals with our star formation duty cycle prescription on  $t_{\text{duty}} = 1 \text{ Gyr}$  (blue) and 5 Gyr (orange) timescales in the left panel of Figure 3. The shaded region represents the observed 0.3 dex  $1\sigma$  scatter of  $\log \text{SFR}$  in the SFS. This  $\Delta \log \text{SFR}$  prescription by construction reproduces the observed log-normal SFR distribution of the SFS at any point in the model. Although, we do not expect this simplified prescription to reflect the individual SFHs of SF centrals, we seek to statistically capture the stochasticity from gas accretion, star-bursts, and feedback mechanisms for the entire SF population. Measuring  $t_{\text{duty}}$  in the duty cycle parameterization provides us with an estimate of the timescale of such star formation variabilities and thus provide additional useful constraints on the physics of galaxy formation.

Using our fiducial SFH prescription, we evolve both the SFR and  $M_*$  of our SF centrals along the SFS. Based on Eq. 3, the SFRs of our SF centrals are functions of  $M_*$ . Meanwhile,  $M_*$  is the integral





**Figure 4.** Our models with different star formation duty cycle timescales (blue:  $t_{\text{duty}}=1$  Gyr; red:  $t_{\text{duty}}=10$  Gyr) run with median values of their ABC posterior distribution have SMFs and SFSs consistent with observations (left and middle). *They however produce significantly different scatter in  $\log M_*$  at fixed  $\log M_{\text{halo}}$  — scatter in the SHMR (right).* By comparing the scatter in SHMR of our models to observational constraints on the SHMR, we constrain the timescale of the star formation duty cycle and thereby the SFHs of star forming galaxies.

of the SFR over time:

$$M_*(t) = f_{\text{retain}} \int_{t_0}^t \text{SFR}(M_*, t) dt + M_0. \quad (4)$$

$t_0$  and  $M_0$  are the initial cosmic time and stellar mass at  $z \sim 1$ , respectively.  $f_{\text{retain}}$  here is the fraction of stellar mass that is retained after supernovae and stellar winds; we use  $f_{\text{retain}} = 0.6$  (Wetzel et al. 2013). We can now evolve the SFR and  $M_*$  of our star-forming centrals until the final  $z = 0.05$  snapshot by solving the differential equation of Eqs. 3 and 4. On the right panel of Figure 3, we present the SFR and  $M_*$  evolutions of two SF centrals with  $t_{\text{duty}} = 1$  Gyr (blue) and 5 Gyr (orange), same as the left panel. For reference, we include the mean  $\log \text{SFR}$  of the SFS that the galaxies' SFR and  $M_*$  evolve along,  $\log \text{SFR}_{\text{SFS}}(M_{*,i}(t), t)$  (black solid). We also include  $\log \text{SFR}_{\text{SFS}}(M_*)$  (dotted lines) at various redshifts between  $z = 1$  to 0.05. Based on the SFH prescription in our model, star-forming centrals evolve their SFRs and  $M_*$  along the SFS with their SFRs fluctuate about  $\log \text{SFR}_{\text{SFS}}$ .

With the evolved SFRs and  $M_*$  of SF centrals, we can compare our model to observed galaxy population statistics such as the quiescent fraction and SMF to constrain its free parameters. Our model, run with these inferred parameters, then reproduces observations of galaxy properties and has host halo properties from the **TreePM**  $N$ -body simulation. This allows us to compare our models to observations of the galaxy-halo connection such as the SHMR. In the following section, we present this comparison and the constraints we derive on the role and timescale of star formation variability in SF central galaxies.

#### 4. RESULTS

Our model takes **TreePM** central subhalos and tracks their SFR and  $M_*$  evolution using a flexible parameterization of the SFS and SFHs that incorporate variability through a star formation duty cycle. At  $z = 0.05$ , its final timestep, our model predicts properties such as SFR,  $M_*$ , and host halo mass,  $M_h$ , of central galaxies it classifies as star-forming. We now use these resulting properties to compare our model to observations and constrain its free parameters—the SFS parameters of Eq. 2. Since the focus of our model and this paper is SF centrals, the main observable we use is the SMF of SF centrals in SDSS, which we estimate as

$$\Phi_{\text{SF, cen}}^{\text{SDSS}} = f_{\text{SFS}}^{\text{cen}} \times f_{\text{cen}} \times \Phi^{\text{Li\&White(2009)}}. \quad (5)$$

$f_{\text{SFS}}^{\text{cen}}$  is the fraction of central galaxies on the SFS, which we fit in Eq. 1.  $f_{\text{cen}}$  is the central galaxy fraction from [Wetzel et al. \(2013\)](#) and  $\Phi^{\text{Li\&White(2009)}}$  is the SMF of the SDSS from [Li & White \(2009\)](#). If our model reproduces the observed  $\Phi_{\text{SF, cen}}^{\text{SDSS}}$ , by construction it reproduces the observed quiescent fraction.

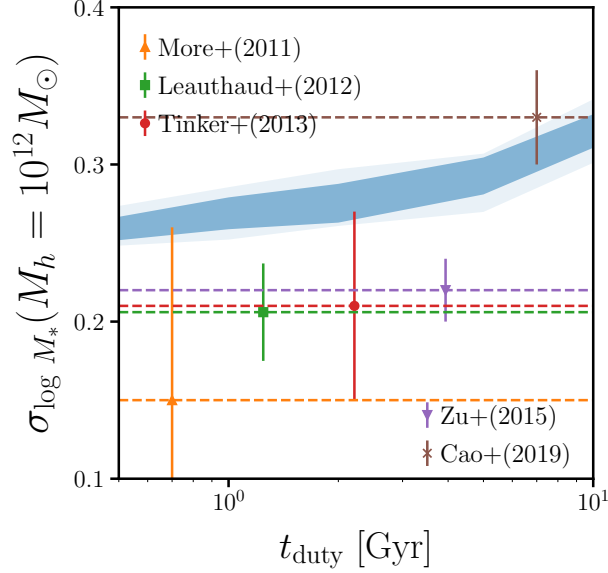
For the comparison between our model to observation, we use the parameter estimation framework of Approximate Bayesian Computation (ABC). ABC has the advantage over standard approaches to parameter inference in that it does not require evaluating the likelihood. It relies only on a simulation of the observed data and a distance metric to quantify the “closeness” between the observed data and simulation. Many variations of ABC has been used in astronomy and cosmology (*e.g.* [Cameron & Pettitt 2012](#); [Weyant et al. 2013](#); [Ishida et al. 2015](#); [Alsing et al. 2018](#)). We use ABC in conjunction with the efficient Population Monte Carlo (PMC) importance sampling as in ([Hahn et al. 2017a,b](#)). For initial sampling of our ABC particles, *i.e.* the priors of our parameters  $m_{M_*}^{\text{low}}$ ,  $m_{M_*}^{\text{high}}$ , and  $m_z$ , we use uniform distributions over the ranges  $[0.0, 0.8]$ ,  $[0.0, 0.8]$ , and  $[0.5, 2.]$ , respectively. As we mention earlier in Section 3.1, the range of the prior were conservatively chosen to encompass the best-fit SFS from [Speagle et al. \(2014\)](#) and measurements from [Moustakas et al. \(2013\)](#) and [Lee et al. \(2015\)](#) at  $z \sim 1$ . Finally, for our distance metric we use the following distance between the SMF of the star-forming centrals in our model to the observed  $\Phi_{\text{SF, cen}}^{\text{SDSS}}$ :

$$\rho_{\Phi} = \sum_M \left( \frac{\Phi^{\text{sim}} - \Phi_{\text{SF, cen}}^{\text{SDSS}}}{\sigma'_{\Phi}} \right)^2. \quad (6)$$

$\Phi^{\text{sim}}(M)$  above is the SMF of the SF centrals in our model and  $\sigma'_{\Phi}(M)$  is the uncertainty of  $\Phi_{\text{SF, cen}}^{\text{SDSS}}$ , which we derive by scaling the [Li & White \(2009\)](#) uncertainty of  $\Phi^{\text{SDSS}}$  derived from mock catalogs. For the rest of our ABC-PMC implementation, we strictly follow the implementation of [Hahn et al. \(2017b\)](#) and [Hahn et al. \(2017a\)](#). We refer reader to those papers for further details.

##### 4.1. Timescale of the Star Formation Duty Cycle

We present the SMFs (left), SFSs (center), and the scatter in  $\log M_*$  at a given  $\log M_h$ ,  $\sigma_{\log M_*}$ , (right) of our model run using SFHs with two different duty cycle timescales,  $t_{\text{duty}} = 10 \text{ Gyr}$  (red) and  $1 \text{ Gyr}$  (blue), in Figure 4. For each  $t_{\text{duty}}$ , we evaluate our model at the median parameter values



**Figure 5.** With shorter star formation duty cycle timescales,  $t_{\text{duty}}$ , our model produces smaller scatter in  $\log M_*$  at  $M_h = 10^{12} M_\odot$ ,  $\sigma_{\log M_*}$ . For  $t_{\text{duty}}$  ranging from 10 to 0.5 Gyr,  $\sigma_{\log M_*}$  ranges from **CH:  $0.32^{+0.019}_{-0.021}$  to  $0.26^{+0.010}_{-0.012}$** . For comparison, we include observational  $\sigma_{\log M_*}$  constraints from Yang et al. (2009); More et al. (2011); Leauthaud et al. (2012); Tinker et al. (2013); Zu & Mandelbaum (2015) (see Section 4.1). Star formation variability on short timescales is necessary to produce a tight SHMR roughly consistent with constraints from observations.

of the respective posterior distributions derived using ABC. For both  $t_{\text{duty}}$ , our model successfully produces SMFs,  $\Phi_{\text{SF, cen}}^{\text{SDSS}}$ , and SFSs consistent with observations, as expected (left and center panels). Despite their consistency with observations, however, different  $t_{\text{duty}}$  of the models predict significantly different  $\sigma_{\log M_*}$ , particularly below  $M_h < 10^{12.5} M_\odot$ . We further illustrate the sensitivity of  $\sigma_{\log M_*}$  of our model to  $t_{\text{duty}}$  in Figure 5, where we present  $\sigma_{\log M_*}$  at fixed halo mass  $M_h = 10^{12} M_\odot$  as a function of  $t_{\text{duty}}$ . As in Figure 4,  $\sigma_{\log M_*}$  at each  $t_{\text{duty}}$  is predicted from our model run with  $t_{\text{duty}}$  and  $\theta$  from the corresponding ABC posterior distribution. The shaded width represents the 68% and 95% confidence intervals. For  $t_{\text{duty}}$  ranging from 10 to 0.5 Gyr,  $\sigma_{\log M_*}$  ranges from  **$0.32^{+0.019}_{-0.021}$  to  $0.26^{+0.010}_{-0.012}$**  — a shorter star formation duty cycle timescale produces significantly smaller scatter in the SHMR. Hence, *observational constraints on the SHMR can be used to constrain the timescale of star formation variability and SFH of SF central galaxies.*

We compare  $\sigma_{\log M_*}$  predicted from our model to observational constraints in the literature. These constraints are mainly derived from fitting some sort of halo occupation based models to observations of galaxy clustering, SMF, satellite kinematics, or galaxy-galaxy weak lensing. In Figure 5, we include  $\sigma_{\log M_*}$  constraints from More et al. (2011); Leauthaud et al. (2012); Tinker et al. (2013); Zu & Mandelbaum (2015) and Cao et al. (in preparation). More et al. (2011) and Zu & Mandelbaum (2015) use SDSS VAGC to fit satellite kinematics and galaxy clustering and galaxy-galaxy lensing measurements, respectively. Meanwhile, Leauthaud et al. (2012); Tinker et al. (2013) use COSMOS to fit the SMF, galaxy clustering, and galaxy-galaxy lensing. Finally, Cao et al. (in preparation)

uses the kurtosis of the line-of-sight pairwise velocity dispersion between central galaxies and all neighboring galaxies to constrain the scatter in SHMR at low halo masses. We note that [Leauthaud et al. \(2012\)](#); [Zu & Mandelbaum \(2015\)](#) measure  $\sigma_{\log M_*}$  for all central galaxies, not only star-forming. At  $M_h \sim 10^{12} M_\odot$ , however, [More et al. \(2011\)](#); [Tinker et al. \(2013\)](#) find only a  $< 1\sigma$  difference in  $\sigma_{\log M_*}$  between SF and quiescent centrals, so we include their measurements in our comparison.

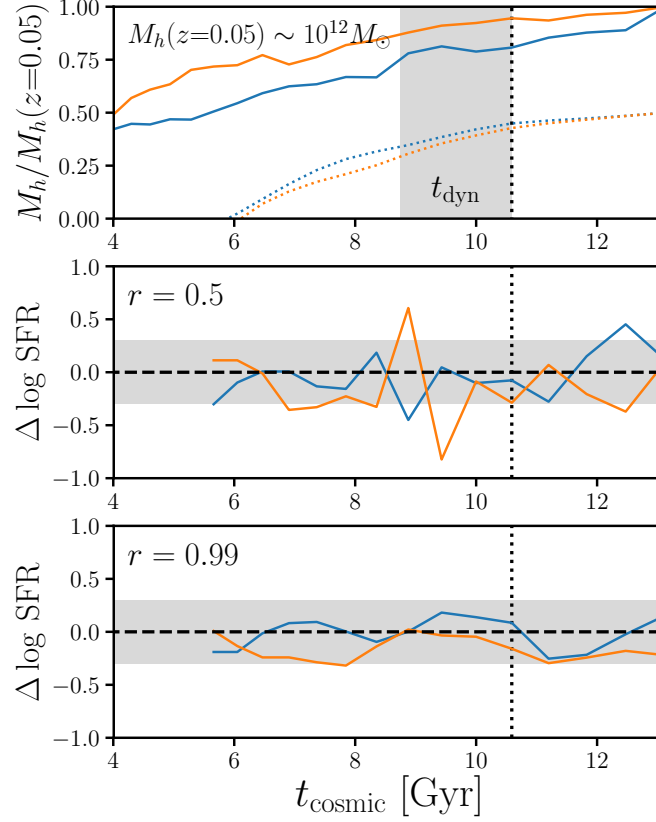
Besides [Cao et al. \(in preparation\)](#), the  $\sigma_{\log M_*}$  constraints in the literature are relatively consistent:  $\sigma_{\log M_*} \lesssim 0.2$ . However, it's important to note that these constraints are derived using halo models that fix  $\sigma_{\log M_*}$ , independent of  $M_h$ . As constraining power comes from a wide range of halo masses, such analyses are not ideal measurements of  $\sigma_{\log M_*}$  at a specific  $M_h \sim 10^{12} M_\odot$ . **CH: something on the discrepancy.** These constraints are likely overestimates of the intrinsic  $\sigma_{\log M_*}$ , since observational constraints measure the quadratic sum of the intrinsic scatter and measurement scatter. Hence, a longer duty cycle timescale predicts  $\sigma_{\log M_*}$  in tension with observations. *A short duty cycle timescale—  $t_{\text{duty}} \lesssim 0.5$  Gyr— is necessary for our model to ameliorate the tension with  $\sigma_{\log M_*}$  constraints in the literature.* This  $t_{\text{duty}}$  constraint implies that SFRs of star-forming galaxies have variations on  $\lesssim 0.5$  Gyr timescales. However, even with the shortest duty cycle timescale we probe ( $\sigma_{\log M_*} = 0.26^{+0.010}_{-0.012}$ ) our model predicts  $\sigma_{\log M_*}$  larger than in observations.

#### 4.2. The Need for Assembly Bias?

A shorter star formation duty cycle timescale produces smaller scatter in the SHMR of our model. This dependence on the duty cycle timescale, allows us to compare our model with measurements of  $\sigma_{\log M_*}$  and  $\sigma_{\log M_h}$  to constrain  $t_{\text{duty}}$ , which reflect the star formation variability timescale. Such comparisons in the previous section, demonstrate that  $t_{\text{duty}} \lesssim 0.5$  Gyr is necessary to reduce tensions with observed constraints. Yet a short duty cycle timescale alone is not enough to conservatively reproduce observed  $\sigma_{\log M_*}$  constraints. In our fiducial model, the SFR and  $M_*$  evolution of star-forming centrals are independent from the evolution of host halo properties. However, as the lack of evolution in the observed SHMR scatter and comparison from the previous section suggest, the SFR and  $M_*$  evolution of star-forming centrals in our model is likely correlated with the accretion histories of their host halos. Therefore, in this section, we introduce *assembly bias* into the SFH prescription of our model.

Assembly bias, most commonly in the literature, refers to the dependence of the spatial distribution of dark matter halos on halo properties besides mass ([Gao et al. 2005](#); [Wechsler et al. 2006](#); [Gao & White 2007](#); [Wetzel et al. 2007](#); [Li et al. 2008](#); [Sunayama et al. 2016](#)). At low halo mass, older and more concentrated halos form in high density environments. While at high halo mass, the effect is the opposite — younger, less concentrated halos form in high-density regions. Furthermore, as predicted by semi-analytic models ([Croton et al. 2007](#)) and found using galaxy group catalogs ([Yang et al. 2006](#); [Wang et al. 2008](#); [Tinker et al. 2011](#); [?](#); [Lacerna et al. 2014](#); [?](#); [Tinker et al. 2017, 2018](#)), this assembly bias propagates beyond spatial clustering to galaxy properties such as formation histories and star formation properties. For our model, we incorporate assembly bias by correlating the SFHs of our star-forming central galaxies and their host halo accretion histories with a correlation coefficient  $r$ .

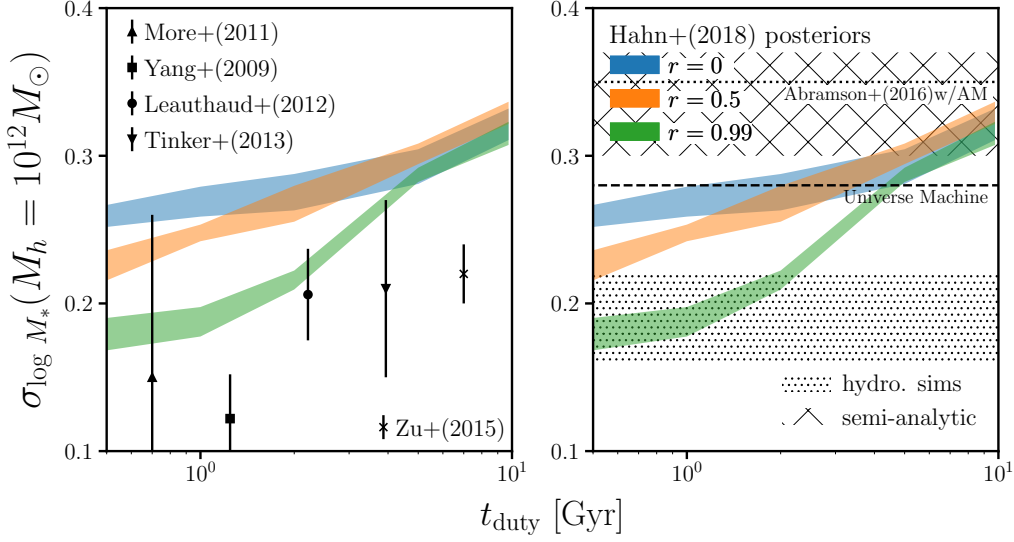
More specifically, we correlate a galaxy's SFR with respect to the mean SFS SFR (*i.e.*  $\Delta \log \text{SFR}$  in Eq. 3) to the halo mass accretion over dynamical time. At every  $t_{\text{duty}}$  timestep,  $t$ ,  $\Delta \log \text{SFR}(t)$  is



**Figure 6.** We incorporate assembly bias into the SF centrals of our model by correlating host halo accretion history with the SFH with respect to the SFS SFR. We plot the relative halo accretion history,  $M_h(t)/M_h(z=0.05)$  for two arbitrarily chosen SF centrals with  $M_h(z=0.05) \sim 10^{12} M_\odot$ , in the top panel. In the two panels below we present  $\Delta \log \text{SFR}$ , SFH with respect to the SFS, of these galaxies for our model with correlation coefficients  $r = 0.5$  and  $0.99$  (middle and bottom). At some  $t$  (dotted),  $\Delta \log \text{SFR}(t)$  is correlated with halo accretion over the range  $t - t_{\text{dyn}}$  to  $t_{\text{dyn}}$  (shaded top panel). The SFHs illustrate how  $\Delta \log \text{SFR}(t)$  correlates with  $\Delta M_h = M_h(t) - M_h(t - t_{\text{dyn}})$  and with stronger correlations for larger  $r$ .

assigned based on  $\Delta M_h(t) = M_h(t) - M_h(t - t_{\text{dyn}}(t))$  in  $M_{\text{max}}$  bins with a correlation coefficient  $r$ , a parameter added to our model. Our prescription for track halo mass accretion over dynamical time is similar to the ?? empirical models. In Figure 6 we illustrate how we incorporate assembly bias into our star-forming centrals by correlating the host halo accretion history with the SFH with respect to the SFS SFR. We plot the relative halo accretion histories  $M_h(t)/M_h(z=0.05)$  of two arbitrarily chosen SF centrals with  $M_h(z=0.05) \sim 10^{12} M_\odot$  in the top panel. Below, we plot  $\Delta \log \text{SFR}$ , SFH with respect to the SFS, of these galaxies for our model with correlation coefficients  $r = 0.5$  and  $0.99$  (middle and bottom). At some  $t$ , we choose a random TreePM snapshot (dotted), we can see that  $\Delta \log \text{SFR}(t)$  is correlated with halo accretion over the period  $[t, t - t_{\text{dyn}}]$  (shaded top panel). The SFHs illustrate the correlation between  $\Delta \log \text{SFR}(t)$  and  $\Delta M_h = M_h(t) - M_h(t - t_{\text{dyn}})$  and how  $\Delta \log \text{SFR}(t)$  correlates more strongly with  $\Delta M_h(t)$  for higher  $r$  within the range 0 to 1 (Figure 6).





**Figure 7.** When we incorporate assembly bias,  $\sigma_{\log M_*}$  of our model spans the various observational constraints and predictions from galaxy formation models. We plot  $\sigma_{\log M_*}(M_h = 10^{12} M_\odot)$  as a function of the star formation duty cycle timescale,  $t_{\text{duty}}$ , for our best-fit model with no assembly bias (blue) and with correlation coefficients between host halo accretion history and SFH of  $r=0.5$  (orange) and  $0.99$  (green). Stronger assembly bias at  $t_{\text{duty}} < 5$  Gyr significantly reduces the scatter in SHMR,  $\sigma_{\log M_*}$ . In the left panel, we include observational constraints from Figure 5; in the right, we include predictions from hydrodynamical simulations (dotted region), semi-analytic models (hatched), and the UNIVERSEMACHINE (?) (dashed). We also include on the right  $\sigma_{\log M_*}$  derived from matching Abramson et al. (2016) SFHs to halos via abundance matching. With strong assembly bias and  $t_{\text{duty}} < 1$  Gyr, our model conservatively agrees with  $\sigma_{\log M_*}$  observational constraints and predictions from hydrodynamic simulations.

Next, using our implementation of assembly bias, we compare the model with different values of  $r$  to observations using ABC-PMC (see Section 4.1). From the resulting posterior estimates, we examine the scatter in the SHMR ( $\sigma_{\log M_*}$ ) given our model with  $r = 0$  (no assembly bias; blue),  $0.5$  (orange), and  $0.99$  (green) as a function of  $t_{\text{duty}}$  in Figure 7. We again emphasize that for all values of  $r$  our model, run on the posterior distributions of its parameters, reproduce the observed SMF of SF centrals and SFS. At  $t_{\text{duty}} \geq 5$  Gyr we find no significant difference in  $\sigma_{\log M_*}$ , regardless of  $r$ . Below  $t_{\text{duty}} < 5$  Gyr, however,  $\sigma_{\log M_*}$  of our model decreases significantly with stronger assembly bias in our model. For  $t_{\text{duty}} = 0.5$  Gyr, we find  $\sigma_{\log M_*} = 0.26^{+0.010}_{-0.012}$ ,  $0.22^{+0.013}_{-0.005}$ , and  $0.17^{+0.007}_{-0.015}$  for  $r=0.0, 0.5$ , and  $0.99$ , respectively. Comparing our updated model to the constraints included in Figure 5, we find that incorporating assembly bias significantly reduces the tensions with observations (right panel). In fact, *with a short star formation duty cycle ( $t_{\text{duty}} \leq 1$  Gyr) and strong assembly bias, our model conservatively reproduces  $\sigma_{\log M_*}$  constraints from the literature.*

In addition to the observational constraints, we also compare the SHMR scatters predicted by our models to  $\sigma_{\log M_*}$  from modern galaxy formation models on the right panel: hydrodynamic simulations (dot filled), semi-analytic models (hatched), and an empirical model (dashed line). For the hydrodynamic simulations, the dotted region encompasses constraints from EAGLE (McAlpine et al.

2016), Massive Black II (?), and Illustris TNG (?), see Figure 8 of Wechsler & Tinker (2018). For the semi-analytic models, the hatched region includes Lu et al. (2014); Somerville et al. (2012), and the SAGE model<sup>2</sup>. Finally, we include the empirical model from ?, the UNIVERSEMACHINE. By varying  $r$  and  $t_{\text{duty}}$ ,  $\sigma_{\log M_*}$  of our model encompasses all of the constraints from galaxy formation models. However, as discussed in Wechsler & Tinker (2018), only the hydrodynamic simulations are in agreement with observations while semi-analytic models and UNIVERSEMACHINE predict SHMR scatters that are too high. Meanwhile, our model, with short  $t_{\text{duty}}$  and high  $r$ ,  $\sigma_{\log M_*}$ , is in good agreement with observations.

A key element of our model is the SFH prescription for SF central galaxies where the SFH evolves about the SFS. Contrary to our SFH prescription, Kelson (2014), for example, argue that the SFS is a simple consequence of central limit theorem and can be reproduced even if *in situ* stellar mass growth is modeled as a stochastic process like a random walk. Gladders et al. (2013); Abramson et al. (2015, 2016), similarly argue that  $\sim 2000$  loosely constrained log-normal SFHs can reproduce observations such as the SMF at  $z \leq 8$  and the SFS at  $z \leq 6$ . These works, however, focus on reproducing observations of galaxy properties and do not examine the galaxy-halo connection such as the SHMR. In order to test whether log-normal SFHs can also produce realistic SHMRs, we take the SFHs,  $\text{SFR}(t)$  and  $M_*(t)$ , from Abramson et al. (2016) and assign them to halos by abundance matching their  $M_*$  to  $M_h$  at  $z \sim 1$ . We then restrict the SFHs to those that would be classified as star-forming based on a rough  $\log \text{SSFR} > -11$ . cut. Afterwards we measure  $\sigma_{\log M_*}$  at the lowest  $M_h$  where it can be reliably measured given the Abramson et al. (2016) sample's  $M_* > 10^{10} M_\odot$  limit. Based on our abundance matching prescription, we find Abramson et al. (2016) predicts a scatter of  $\sigma_{\log M_*}(M_h = 10^{12.4}) = 0.33 \pm 0.04$  (dotted line in Figure 7). Despite the Abramson et al. (2016) SFHs can reproduce a number of galaxy observations,  $\sigma_{\log M_*}$  derived from the SFHs and abundance matching predict SHMR scatters too high compared to constraints from observations and predictions from hydrodynamic simulations. This estimate is, however, derived from a simple abundance matching scheme. As Diemer et al. (2017) find from their log-normal fits to the SFHs of Illustris galaxies, halo formation history correlates with the fits. Incorporating such assembly bias into our abundance matching may reduce  $\sigma_{\log M_*}$ .

In this section, we demonstrate that incorporating assembly bias into our model by correlating  $\Delta \log \text{SFR}$  to  $\Delta M_h$  reduces the tension with the SHMR scatter in observations. With assembly bias added, our model can produce the range of  $\sigma_{\log M_*}$  constraints from observations as well as modern galaxy formation models. However, even with assembly bias a short duty cycle is *necessary* to produce tight scatter in the SHMR. This further confirms our conclusion from the previous section that the SFRs of star-forming central galaxies have variations on  $\lesssim 0.5$  Gyr timescales. Furthermore, with a short star formation duty cycle timescale and strong assembly bias  $r > 0.5$ , our model conservatively agrees with observational constraints and produces tight scatter in the SHMR, unlike predictions from semi-analytic models and UNIVERSEMACHINE. Our comparison not only provides constraints

<sup>2</sup> <https://tao.asvo.org.au/tao/>

on the timescale of star formation variability, but it also confirms the role of assembly bias in the SFH of star-forming galaxies.

## 5. SUMMARY AND CONCLUSION

### some brief intro paragraph consistent with the intro

We combine the high-resolution cosmological  $N$ -body **TreePM** simulation with SFHs that evolve the SF central galaxies along the SFS and present a model that tracks the SFR,  $M_*$ , and host halo accretion histories of SF centrals from  $z \sim 1$  to  $z = 0.05$ . More specifically, we characterize the SFHs to evolve with respect to the mean log SFR of the SFS with a “star formation duty cycle” that introduces variability on some specific timescale,  $t_{\text{duty}}$ . Besides  $t_{\text{duty}}$ , we parameterize the SFS using **parameters**, free parameters that dictate the low  $M_*$  and high  $M_*$  slopes and redshift evolution. With priors for these parameters set to only produce SFS within observed range, we use ABC-PMC to infer a model that reproduce the observed SMF of the SF centrals in the SDSS DR7 group catalog. When we examine the SHMR of this model we find:

- A shorter star formation duty cycle in our model produces significantly tighter scatter in the SHMR both for fixed  $M_h = 10^{12} M_\odot$  and  $M_* = 10^{10} M_\odot$ . As  $t_{\text{duty}}$  ranges from 10 to 0.5 Gyr,  $\sigma_{\log M_*} = 0.32^{+0.019}_{-0.021}$  to  $0.26^{+0.010}_{-0.012}$  and  $\sigma_{\log M_h} = 0.30^{+0.005}_{-0.006}$  to  $0.19^{+0.008}_{-0.006}$ . The dependence of  $\sigma_{\log M_*}$  and  $\sigma_{\log M_h}$  on  $t_{\text{duty}}$  demonstrates that the scatter in SHMR provides some constraint on  $t_{\text{duty}}$  and the timescale of star formation variability.
- We compare the  $\sigma_{\log M_*}$  and  $\sigma_{\log M_h}$  predicted by our model to constraints from halo occupation modeling of galaxy clustering, SMF, satellite kinematics, and galaxy-galaxy weak lensing observations. The  $\sigma_{\log M_h}$  comparison does not significantly constrain  $t_{\text{duty}}$ . However, from the  $\sigma_{\log M_*}$  comparison, we find that a duty cycle with  $t_{\text{duty}} \lesssim 0.5$  Gyr is necessary to reduce the tension with observations.
- We next incorporate assembly bias into our model by allowing the star formation histories to correlate with halo accretion histories by a correlation coefficient,  $r$ . With assembly bias, our model can predict  $\sigma_{\log M_*} = 0.17$  to  $0.33$ , which spans the predictions from modern galaxy formation models. However, to conservatively reproduce  $\sigma_{\log M_*}$  predictions from hydrodynamic simulations and constraints from observations, a short duty cycle and  $r > 0.5$ — *i.e.* strong assembly bias— is required.

### Paragraph about implications of our results

### Paragraph about future with DESI BGS.

## ACKNOWLEDGEMENTS

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## REFERENCES

- Abazajian, K. N., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2009, *The Astrophysical Journal Supplement Series*, 182, 543, doi: [10.1088/0067-0049/182/2/543](https://doi.org/10.1088/0067-0049/182/2/543)
- Abramson, L. E., Gladders, M. D., Dressler, A., et al. 2016, *The Astrophysical Journal*, 832, 7, doi: [10.3847/0004-637X/832/1/7](https://doi.org/10.3847/0004-637X/832/1/7)
- . 2015, *The Astrophysical Journal Letters*, 801, L12, doi: [10.1088/2041-8205/801/1/L12](https://doi.org/10.1088/2041-8205/801/1/L12)
- Alsing, J., Wandelt, B., & Feeney, S. 2018, arXiv:1801.01497 [astro-ph]. <https://arxiv.org/abs/1801.01497>
- Baldry, I. K., Balogh, M. L., Bower, R. G., et al. 2006, *Monthly Notices of the Royal Astronomical Society*, 373, 469, doi: [10.1111/j.1365-2966.2006.11081.x](https://doi.org/10.1111/j.1365-2966.2006.11081.x)
- Blanton, M. R., & Moustakas, J. 2009, *Annual Review of Astronomy and Astrophysics*, 47, 159, doi: [10.1146/annurev-astro-082708-101734](https://doi.org/10.1146/annurev-astro-082708-101734)
- Blanton, M. R., & Roweis, S. 2007, *The Astronomical Journal*, 133, 734, doi: [10.1086/510127](https://doi.org/10.1086/510127)
- Blanton, M. R., Schlegel, D. J., Strauss, M. A., et al. 2005, *The Astronomical Journal*, 129, 2562, doi: [10.1086/429803](https://doi.org/10.1086/429803)
- Brinchmann, J., Charlot, S., White, S. D. M., et al. 2004, *Monthly Notices of the Royal Astronomical Society*, 351, 1151, doi: [10.1111/j.1365-2966.2004.07881.x](https://doi.org/10.1111/j.1365-2966.2004.07881.x)
- Cameron, E., & Pettitt, A. N. 2012, *Monthly Notices of the Royal Astronomical Society*, 425, 44, doi: [10.1111/j.1365-2966.2012.21371.x](https://doi.org/10.1111/j.1365-2966.2012.21371.x)
- Campbell, D., van den Bosch, F. C., Hearin, A., et al. 2015, *Monthly Notices of the Royal Astronomical Society*, 452, 444, doi: [10.1093/mnras/stv1091](https://doi.org/10.1093/mnras/stv1091)
- Carnall, A. C., Leja, J., Johnson, B. D., et al. 2018, arXiv:1811.03635 [astro-ph]. <https://arxiv.org/abs/1811.03635>
- Chabrier, G. 2003, *Publications of the Astronomical Society of the Pacific*, 115, 763, doi: [10.1086/376392](https://doi.org/10.1086/376392)
- Coil, A. L., Blanton, M. R., Burles, S. M., et al. 2011, *The Astrophysical Journal*, 741, 8, doi: [10.1088/0004-637X/741/1/8](https://doi.org/10.1088/0004-637X/741/1/8)
- Conroy, C., Wechsler, R. H., & Kravtsov, A. V. 2006, *The Astrophysical Journal*, 647, 201, doi: [10.1086/503602](https://doi.org/10.1086/503602)
- Conroy, C., Prada, F., Newman, J. A., et al. 2007, *The Astrophysical Journal*, 654, 153, doi: [10.1086/509632](https://doi.org/10.1086/509632)
- Cool, R. J., Moustakas, J., Blanton, M. R., et al. 2013, *The Astrophysical Journal*, 767, 118, doi: [10.1088/0004-637X/767/2/118](https://doi.org/10.1088/0004-637X/767/2/118)
- Croton, D. J., Gao, L., & White, S. D. M. 2007, *Monthly Notices of the Royal Astronomical Society*, 374, 1303, doi: [10.1111/j.1365-2966.2006.11230.x](https://doi.org/10.1111/j.1365-2966.2006.11230.x)
- Daddi, E., Dickinson, M., Morrison, G., et al. 2007, *The Astrophysical Journal*, 670, 156, doi: [10.1086/521818](https://doi.org/10.1086/521818)
- Davis, M., Efstathiou, G., Frenk, C. S., & White, S. D. M. 1985, *The Astrophysical Journal*, 292, 371, doi: [10.1086/163168](https://doi.org/10.1086/163168)
- Diemer, B., Sparre, M., Abramson, L. E., & Torrey, P. 2017, *The Astrophysical Journal*, 839, 26, doi: [10.3847/1538-4357/aa68e5](https://doi.org/10.3847/1538-4357/aa68e5)
- Drory, N., Bundy, K., Leauthaud, A., et al. 2009, *The Astrophysical Journal*, 707, 1595, doi: [10.1088/0004-637X/707/2/1595](https://doi.org/10.1088/0004-637X/707/2/1595)
- Elbaz, D., Daddi, E., Le Borgne, D., et al. 2007, *Astronomy and Astrophysics*, 468, 33, doi: [10.1051/0004-6361:20077525](https://doi.org/10.1051/0004-6361:20077525)
- Gao, L., Springel, V., & White, S. D. M. 2005, *Monthly Notices of the Royal Astronomical Society*, 363, L66, doi: [10.1111/j.1745-3933.2005.00084.x](https://doi.org/10.1111/j.1745-3933.2005.00084.x)
- Gao, L., & White, S. D. M. 2007, *Monthly Notices of the Royal Astronomical Society*, 377, L5, doi: [10.1111/j.1745-3933.2007.00292.x](https://doi.org/10.1111/j.1745-3933.2007.00292.x)
- Genel, S., Vogelsberger, M., Springel, V., et al. 2014, *Monthly Notices of the Royal Astronomical Society*, 445, 175, doi: [10.1093/mnras/stu1654](https://doi.org/10.1093/mnras/stu1654)
- Gladders, M. D., Oemler, A., Dressler, A., et al. 2013, *The Astrophysical Journal*, 770, 64, doi: [10.1088/0004-637X/770/1/64](https://doi.org/10.1088/0004-637X/770/1/64)
- Gu, M., Conroy, C., & Behroozi, P. 2016, *The Astrophysical Journal*, 833, 2, doi: [10.3847/0004-637X/833/1/2](https://doi.org/10.3847/0004-637X/833/1/2)
- Hahn, C., Tinker, J. L., & Wetzel, A. R. 2017a, *The Astrophysical Journal*, 841, 6, doi: [10.3847/1538-4357/aa6d6b](https://doi.org/10.3847/1538-4357/aa6d6b)
- Hahn, C., Vakili, M., Walsh, K., et al. 2017b, *Monthly Notices of the Royal Astronomical Society*, 469, 2791, doi: [10.1093/mnras/stx894](https://doi.org/10.1093/mnras/stx894)

- Hahn, C., Blanton, M. R., Moustakas, J., et al. 2015, *The Astrophysical Journal*, 806, 162, doi: [10.1088/0004-637X/806/2/162](https://doi.org/10.1088/0004-637X/806/2/162)
- Hahn, C., Starkenburg, T. K., Choi, E., et al. 2018
- Han, J., Eke, V. R., Frenk, C. S., et al. 2015, *Monthly Notices of the Royal Astronomical Society*, 446, 1356, doi: [10.1093/mnras/stu2178](https://doi.org/10.1093/mnras/stu2178)
- Ilbert, O., McCracken, H. J., Le Fèvre, O., et al. 2013, *Astronomy and Astrophysics*, 556, A55, doi: [10.1051/0004-6361/201321100](https://doi.org/10.1051/0004-6361/201321100)
- Ishida, E. E. O., Vitenti, S. D. P., Penna-Lima, M., et al. 2015, *Astronomy and Computing*, 13, 1, doi: [10.1016/j.ascom.2015.09.001](https://doi.org/10.1016/j.ascom.2015.09.001)
- Karim, A., Schinnerer, E., Martínez-Sansigre, A., et al. 2011, *The Astrophysical Journal*, 730, 61, doi: [10.1088/0004-637X/730/2/61](https://doi.org/10.1088/0004-637X/730/2/61)
- Kelson, D. D. 2014, arXiv:1406.5191 [astro-ph]. <https://arxiv.org/abs/1406.5191>
- Lacerna, I., Padilla, N., & Stasyszyn, F. 2014, *Monthly Notices of the Royal Astronomical Society*, 443, 3107, doi: [10.1093/mnras/stu1318](https://doi.org/10.1093/mnras/stu1318)
- Leauthaud, A., Tinker, J., Bundy, K., et al. 2012, *The Astrophysical Journal*, 744, 159, doi: [10.1088/0004-637X/744/2/159](https://doi.org/10.1088/0004-637X/744/2/159)
- Lee, N., Sanders, D. B., Casey, C. M., et al. 2015, *The Astrophysical Journal*, 801, 80, doi: [10.1088/0004-637X/801/2/80](https://doi.org/10.1088/0004-637X/801/2/80)
- Leja, J., Carnall, A. C., Johnson, B. D., Conroy, C., & Speagle, J. S. 2018, arXiv:1811.03637 [astro-ph]. <https://arxiv.org/abs/1811.03637>
- Leja, J., van Dokkum, P., & Franx, M. 2013, *The Astrophysical Journal*, 766, doi: [10.1088/0004-637X/766/1/33](https://doi.org/10.1088/0004-637X/766/1/33)
- Li, C., & White, S. D. M. 2009, *Monthly Notices of the Royal Astronomical Society*, 398, 2177, doi: [10.1111/j.1365-2966.2009.15268.x](https://doi.org/10.1111/j.1365-2966.2009.15268.x)
- Li, Y., Mo, H. J., & Gao, L. 2008, *Monthly Notices of the Royal Astronomical Society*, 389, 1419, doi: [10.1111/j.1365-2966.2008.13667.x](https://doi.org/10.1111/j.1365-2966.2008.13667.x)
- Lu, Y., Wechsler, R. H., Somerville, R. S., et al. 2014, *The Astrophysical Journal*, 795, 123, doi: [10.1088/0004-637X/795/2/123](https://doi.org/10.1088/0004-637X/795/2/123)
- Magdis, G. E., Daddi, E., Béthermin, M., et al. 2012, *The Astrophysical Journal*, 760, 6, doi: [10.1088/0004-637X/760/1/6](https://doi.org/10.1088/0004-637X/760/1/6)
- Mamon, G. A., Sanchis, T., Salvador-Solé, E., & Solanes, J. M. 2004, *Astronomy and Astrophysics*, 414, 445, doi: [10.1051/0004-6361:20034155](https://doi.org/10.1051/0004-6361:20034155)
- Mandelbaum, R., Seljak, U., Kauffmann, G., Hirata, C. M., & Brinkmann, J. 2006, *Monthly Notices of the Royal Astronomical Society*, 368, 715, doi: [10.1111/j.1365-2966.2006.10156.x](https://doi.org/10.1111/j.1365-2966.2006.10156.x)
- Marchesini, D., van Dokkum, P. G., Förster Schreiber, N. M., et al. 2009, *The Astrophysical Journal*, 701, 1765, doi: [10.1088/0004-637X/701/2/1765](https://doi.org/10.1088/0004-637X/701/2/1765)
- McAlpine, S., Helly, J. C., Schaller, M., et al. 2016, *Astronomy and Computing*, 15, 72, doi: [10.1016/j.ascom.2016.02.004](https://doi.org/10.1016/j.ascom.2016.02.004)
- Mitra, S., Davé, R., & Finlator, K. 2015, *Monthly Notices of the Royal Astronomical Society*, 452, 1184, doi: [10.1093/mnras/stv1387](https://doi.org/10.1093/mnras/stv1387)
- More, S., van den Bosch, F. C., Cacciato, M., et al. 2011, *Monthly Notices of the Royal Astronomical Society*, 410, 210, doi: [10.1111/j.1365-2966.2010.17436.x](https://doi.org/10.1111/j.1365-2966.2010.17436.x)
- Moustakas, J., Coil, A. L., Aird, J., et al. 2013, *The Astrophysical Journal*, 767, 50, doi: [10.1088/0004-637X/767/1/50](https://doi.org/10.1088/0004-637X/767/1/50)
- Muzzin, A., Marchesini, D., Stefanon, M., et al. 2013, *The Astrophysical Journal*, 777, 18, doi: [10.1088/0004-637X/777/1/18](https://doi.org/10.1088/0004-637X/777/1/18)
- Noeske, K. G., Weiner, B. J., Faber, S. M., et al. 2007, *The Astrophysical Journal Letters*, 660, L43, doi: [10.1086/517926](https://doi.org/10.1086/517926)
- Peng, Y.-j., Lilly, S. J., Kovač, K., et al. 2010, *The Astrophysical Journal*, 721, 193, doi: [10.1088/0004-637X/721/1/193](https://doi.org/10.1088/0004-637X/721/1/193)
- Salim, S., Rich, R. M., Charlot, S., et al. 2007, *The Astrophysical Journal Supplement Series*, 173, 267, doi: [10.1086/519218](https://doi.org/10.1086/519218)
- Santini, P., Fontana, A., Grazian, A., et al. 2009, *Astronomy and Astrophysics*, 504, 751, doi: [10.1051/0004-6361/200811434](https://doi.org/10.1051/0004-6361/200811434)
- Scoville, N., Aussel, H., Brusa, M., et al. 2007, *The Astrophysical Journal Supplement Series*, 172, 1, doi: [10.1086/516585](https://doi.org/10.1086/516585)
- Somerville, R. S., & Davé, R. 2015, *Annual Review of Astronomy and Astrophysics*, 53, 51, doi: [10.1146/annurev-astro-082812-140951](https://doi.org/10.1146/annurev-astro-082812-140951)
- Somerville, R. S., Gilmore, R. C., Primack, J. R., & Domínguez, A. 2012, *Monthly Notices of the Royal Astronomical Society*, 423, 1992, doi: [10.1111/j.1365-2966.2012.20490.x](https://doi.org/10.1111/j.1365-2966.2012.20490.x)
- Speagle, J. S., Steinhardt, C. L., Capak, P. L., & Silverman, J. D. 2014, *The Astrophysical Journal Supplement Series*, 214, 15, doi: [10.1088/0067-0049/214/2/15](https://doi.org/10.1088/0067-0049/214/2/15)



- Sunayama, T., Hearin, A. P., Padmanabhan, N., & Leauthaud, A. 2016, *Monthly Notices of the Royal Astronomical Society*, 458, 1510, doi: [10.1093/mnras/stw332](https://doi.org/10.1093/mnras/stw332)
- Tinker, J., Wetzel, A., & Conroy, C. 2011, *ArXiv e-prints*, 1107, arXiv:1107.5046
- Tinker, J. L., Hahn, C., Mao, Y.-Y., Wetzel, A. R., & Conroy, C. 2018, *Monthly Notices of the Royal Astronomical Society*, 477, 935, doi: [10.1093/mnras/sty666](https://doi.org/10.1093/mnras/sty666)
- Tinker, J. L., Leauthaud, A., Bundy, K., et al. 2013, *The Astrophysical Journal*, 778, 93, doi: [10.1088/0004-637X/778/2/93](https://doi.org/10.1088/0004-637X/778/2/93)
- Tinker, J. L., Wetzel, A. R., Conroy, C., & Mao, Y.-Y. 2017, *Monthly Notices of the Royal Astronomical Society*, 472, 2504, doi: [10.1093/mnras/stx2066](https://doi.org/10.1093/mnras/stx2066)
- Tojeiro, R., Wilkins, S., Heavens, A. F., Panter, B., & Jimenez, R. 2009, *The Astrophysical Journal Supplement Series*, 185, 1, doi: [10.1088/0067-0049/185/1/1](https://doi.org/10.1088/0067-0049/185/1/1)
- Vale, A., & Ostriker, J. P. 2006, *Monthly Notices of the Royal Astronomical Society*, 371, 1173, doi: [10.1111/j.1365-2966.2006.10605.x](https://doi.org/10.1111/j.1365-2966.2006.10605.x)
- Velander, M., van Uitert, E., Hoekstra, H., et al. 2014, *Monthly Notices of the Royal Astronomical Society*, 437, 2111, doi: [10.1093/mnras/stt2013](https://doi.org/10.1093/mnras/stt2013)
- Vogelsberger, M., Genel, S., Springel, V., et al. 2014, *Monthly Notices of the Royal Astronomical Society*, 444, 1518, doi: [10.1093/mnras/stu1536](https://doi.org/10.1093/mnras/stu1536)
- Wang, Y., Yang, X., Mo, H. J., et al. 2008, *The Astrophysical Journal*, 687, 919, doi: [10.1086/591836](https://doi.org/10.1086/591836)
- Wechsler, R. H., & Tinker, J. L. 2018, *ArXiv e-prints*, 1804, arXiv:1804.03097
- Wechsler, R. H., Zentner, A. R., Bullock, J. S., Kravtsov, A. V., & Allgood, B. 2006, *The Astrophysical Journal*, 652, 71, doi: [10.1086/507120](https://doi.org/10.1086/507120)
- Wetzel, A. R., Cohn, J. D., & White, M. 2009, *Monthly Notices of the Royal Astronomical Society*, 395, 1376, doi: [10.1111/j.1365-2966.2009.14424.x](https://doi.org/10.1111/j.1365-2966.2009.14424.x)
- Wetzel, A. R., Cohn, J. D., White, M., Holz, D. E., & Warren, M. S. 2007, *The Astrophysical Journal*, 656, 139, doi: [10.1086/510444](https://doi.org/10.1086/510444)
- Wetzel, A. R., Tinker, J. L., & Conroy, C. 2012, *Monthly Notices of the Royal Astronomical Society*, 424, 232, doi: [10.1111/j.1365-2966.2012.21188.x](https://doi.org/10.1111/j.1365-2966.2012.21188.x)
- Wetzel, A. R., Tinker, J. L., Conroy, C., & van den Bosch, F. C. 2013, *Monthly Notices of the Royal Astronomical Society*, 432, 336, doi: [10.1093/mnras/stt469](https://doi.org/10.1093/mnras/stt469)
- . 2014, *Monthly Notices of the Royal Astronomical Society*, 439, 2687, doi: [10.1093/mnras/stu122](https://doi.org/10.1093/mnras/stu122)
- Wetzel, A. R., & White, M. 2010, *Monthly Notices of the Royal Astronomical Society*, 403, 1072, doi: [10.1111/j.1365-2966.2009.16191.x](https://doi.org/10.1111/j.1365-2966.2009.16191.x)
- Weyant, A., Schafer, C., & Wood-Vasey, W. M. 2013, *The Astrophysical Journal*, 764, 116, doi: [10.1088/0004-637X/764/2/116](https://doi.org/10.1088/0004-637X/764/2/116)
- Whitaker, K. E., van Dokkum, P. G., Brammer, G., & Franx, M. 2012, *The Astrophysical Journal Letters*, 754, L29, doi: [10.1088/2041-8205/754/2/L29](https://doi.org/10.1088/2041-8205/754/2/L29)
- White, M. 2002, *The Astrophysical Journal Supplement Series*, 143, 241, doi: [10.1086/342752](https://doi.org/10.1086/342752)
- White, M., Cohn, J. D., & Smit, R. 2010, *Monthly Notices of the Royal Astronomical Society*, 408, 1818, doi: [10.1111/j.1365-2966.2010.17248.x](https://doi.org/10.1111/j.1365-2966.2010.17248.x)
- Wilkinson, D. M., Maraston, C., Goddard, D., Thomas, D., & Parikh, T. 2017, *arXiv:1711.00865 [astro-ph]*. <https://arxiv.org/abs/1711.00865>
- Yang, X., Mo, H. J., & van den Bosch, F. C. 2006, *The Astrophysical Journal Letters*, 638, L55, doi: [10.1086/501069](https://doi.org/10.1086/501069)
- . 2009, *The Astrophysical Journal*, 695, 900, doi: [10.1088/0004-637X/695/2/900](https://doi.org/10.1088/0004-637X/695/2/900)
- Zu, Y., & Mandelbaum, R. 2015, *Monthly Notices of the Royal Astronomical Society*, 454, 1161, doi: [10.1093/mnras/stv2062](https://doi.org/10.1093/mnras/stv2062)