The dust content of galaxies from $z = 0$ to $z = 9$

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ABSTRACT

We study the dust content of galaxies from $z = 0$ to $z = 9$ in semi-analytic models of galaxy formation that include new recipes to track the production and destruction of dust. We include condensation of dust in stellar ejecta, the growth of dust in the interstellar medium (ISM), the destruction of dust by supernovae and in the hot halo, and dusty winds and inflows. The rate of dust growth in the ISM depends on the metallicity and density of molecular clouds. Our fiducial model reproduces the relation between dust mass and stellar mass from $z = 0$ to $z = 7$, the dust-to-gas ratio of local galaxies as a function of stellar mass, the double power law trend between dust-to-gas ratio and gas-phase metallicity, the number density of galaxies with dust masses less than $10^8 M_\odot$, and the cosmic density of dust at $z = 0$. The dominant mode of dust formation is dust growth in the ISM, except for galaxies with $M_\star < 10^7 M_\odot$, where condensation of dust in supernova ejecta dominates. The dust-to-metal ratio of galaxies evolves as a function of gas-phase metallicity, unlike what is typically assumed in cosmological simulations. Model variants including higher condensation efficiencies, a fixed timescale for dust growth in the ISM, or no growth at all reproduce some of the observed constraints, but fail to reproduce the shape of dust scaling relations and the dust mass of high-redshift galaxies simultaneously.

Key words: galaxies: formation – galaxies: evolution – galaxies: ISM – ISM: dust, extinction – methods: numerical

1 INTRODUCTION

Dust is a key ingredient in interstellar medium (ISM) and galaxy physics. For example, dust influences interstellar chemistry via surface reactions and acts as a catalyst for the formation of molecules (Hollenbach & Salpeter 1971; Mathis 1990; Li & Draine 2001; Draine 2003). Dust depletes metals from the gas phase ISM (Calzetti, Kinney & Storchi-Bergmann 1994; Calzetti et al. 2000; Netzer et al. 2007; Spoon et al. 2007; Melbourne et al. 2012). Dust grains absorb stellar radiation in the ultraviolet (UV) and re-emit this radiation in the infrared (IR, Spitzer 1978; Draine & Lee 1984; Mathis 1990; Tielens 2005). Dust contributes significantly to the metals in the circumgalactic medium (CGM) and can be an additional cooling channel for gas (e.g., Ostriker & Silk 1973; Ménard et al. 2010; Peeples et al. 2014; Peek, Ménard & Corrales 2015).

Interstellar dust is produced in the ejecta of asymptotic giant branch (AGB) stars and supernovae (SNe; Gehrz 1989; Todini & Ferrara 2001; Nozawa et al. 2003; Ferrarotti & Gail 2006; Nozawa et al. 2007; Zhukovska, Gail & Tielens 2008; Nanni et al. 2013). After the initial formation, dust growth can occur in the dense ISM via accretion of metals onto dust particles (Draine 1990; Dominik & Tielens 1997; Dwek 1998; Draine 2009; Hirashita & Kuo 2011; Zhukovska 2014). The exact contribution to the dust mass of a galaxy by the different dust formation channels is still unknown, although several authors have suggested that dust growth via accretion in the ISM plays an important role (e.g., Dwek, Galliano & Jones 2007; Zhukovska 2013; Michalowski 2015; Schneider, Hunt & Valiante 2016). Dust can be destroyed via thermal sputtering, collisions with other dust grains, and SN shocks (Draine & Salpeter 1979a; McKee 1989; Jones, Tielens & Hollenbach 1996).

The dust content of galaxies at low and high redshifts has intensely been studied over the past decades. Such studies provide additional constraints for galaxy formation models and the baryonic physics that regulates the dust and gas content of galaxies. These observational constraints include for instance the relation between dust mass and stellar mass (Corbelli et al. 2012; Santini et al. 2014), the gas fraction of galaxies and dust mass (Cortese et al. 2012), dust mass and...
star-formation rate (SFR; da Cunha et al. 2010; Casey 2012; Santini et al. 2014), and the dust mass function of galaxies (Dunne, Eales & Edmunds 2003 [Valiante, Dunne & Eales 2009; Dunne et al. 2011; Eales et al. 2009; Clemens et al. 2013]). Two particularly interesting scaling relations are the ratio between dust mass and gas mass in the ISM (dust-to-gas ratio), or the ratio between dust mass and the total mass in metals (dust-to-metal ratio) as a function of metallicity or galaxy stellar mass (Issa, MacLaren & Woldendale 1990; Lisenfeld & Ferrara 1998 [Hirashita, Tajiri & Kamaya 2002; James et al. 2002; Hunt, Bianchi & Maiolino 2005; Draine et al. 2007; Engelbracht et al. 2008; Galametz et al. 2011; Magrini et al. 2011; Rémy-Ruyer et al. 2014a, 2014b, 2014c; Rémy-Ruyer et al. 2014a demonstrated that dust-to-gas ratio in galaxies cannot be described by a single power-law as a function of metallicity, but is better represented by a double power-law with a break around a metallicity of 0.1 Z⊙ (Edmunds 2001).

Absorption line studies using gamma ray burst have suggested that the dust-to-metal ratio in galaxies at redshifts z = 0.1 to z = 6.3 is surprisingly similar to the dust-to-metal ratio in the local group (Zafar & Watson 2013; Sparre et al. 2014; Wiseman et al. 2016; De Cia et al. 2013) and De Cia et al. (2016) also find dust-to-metal ratios similar to the local group in damped Lyman-alpha absorbers from z = 1 to z = 3. The authors furthermore show that the dust-to-metal ratios may drop at metallicities lower than 0.05 Z⊙. These results demonstrate that high-redshift absorbers can already be significantly enriched with dust but also that the dust production efficiency can vary significantly between different environments.

Far-infrared (FIR) and submillimeter observations have shown that even at the highest redshifts (z > 4) galaxies can have significant reservoirs of dust (10^7 M⊙) or even greater, Bertoldi et al. (2003; Hughes, Dunlop & Rawlings 1997; Valiante et al. 2009; Venemans et al. 2012; Casey, Narayanan & Cooray 2014; Krichers et al. 2014). Watson et al. (2015) found a galaxy at z = 7.5 ± 0.2 with a dust mass of 4 × 10^7 M⊙ and a dust-to-gas ratio half of the Milky Way value. Although these dusty examples may not be representative of typical high-redshift galaxies, they set strong constraints on our understanding of dust formation and growth in galaxies and in the early Universe. The Atacama Large sub/Millimeter Array (ALMA) and the James Webb Space Telescope (JWST) are expected to further revolutionise our understanding of dust physics in the low- and high-redshift Universe.

Despite the observational prospects and theoretical importance, cosmological models of galaxy formation typically do not include self-consistent tracking of the production and destruction of dust nor dust chemistry. Traditionally, a linear scaling between dust and metal abundance is assumed (e.g., Silva et al. 1998; Granato et al. 2000; Baugh et al. 2005; Lacey et al. 2008; Fontanot & Somerville 2011; Nemi et al. 2012; Somerville et al. 2012; Hayward et al. 2013b; Cowley et al. 2016). A few groups have started to include self-consistent tracking of dust in hydrodynamic simulations (Bekki 2013, 2015; McKinnon, Torrey & Vogelsberger 2016), but these studies used zoom-simulations of individual objects and didn’t focus on trends between global galaxy properties and dust mass covering a large range of parameter space and cosmic time. Recently, McKinnon et al. (2016) used a hydrodynamic model to make predictions for the dust content of galaxies in cosmological volumes, focusing on the redshift regime z < 2.5. Mancini et al. (2016) looked into the dust-to-gas ratio and dust absorption properties of galaxies at redshifts z > 5.

Most advances in dust chemistry in galaxy formation were made using specialised models (e.g., Dwek 1998; Hirashita, Tajiri & Kamaya 2002; Inoue 2003; Morgan & Edmunds 2003; Zhukovska, Gall & Trieloff 2008; Valiante et al. 2009; Asano et al. 2013; Zhukovska 2014; Feldmann 2015). These models have been essential for developing our understanding of the relevance of the individual channels of dust formation to the dust content of galaxies. Unfortunately, these models are often idealised to reproduce specific objects and are not placed within a cosmological context. Furthermore, they generally do not include all physical processes thought to be relevant for galaxy formation.

Semi-analytic models (SAMs) offer a good alternative approach for self-consistently tracking the production and destruction of dust in galaxies within the framework of a Λ-cold dark matter cosmology. Simplified but physically motivated recipes are used to track physical processes such as the cooling of hot gas into galaxies, star formation, the energy input from supernovae and active galactic nuclei into the ISM, the sizes of galaxy discs, and the enrichment of the ISM by supernovae ejecta and stellar winds (see Somerville & Dave 2015 for a recent review). The low computational cost of SAMs makes them a powerful tool to model a broad range of galaxy masses probing large volumes, provide predictions for future studies, and explore different recipes for physical processes in galaxies.

In this paper, we include tracking of dust production and destruction in the most recent version of the Santa Cruz semi-analytic model (Popping, Somerville & Trager 2014; Somerville, Popping & Trager 2015). We explore how the dust content of galaxies and our Universe evolves over time and how this is affected by different implementations of the processes that produce dust. We extend the Arrigoni et al. (2010) galactic chemical evolution (GCE) model to include the condensation of dust in stellar ejecta, the growth of dust in the dense ISM, the destruction of dust through thermal sputtering by supernovae (SNe), dusty winds from star-forming regions, dust destruction in the hot halos, and the infall of dust from the CGM. We present the evolution of dust masses in galaxies, the evolution of dust-to-gas and dust-to-metal ratios, and the cosmic density of dust in different components. We make predictions for the mass of dust in the hot halo of galaxies and the mass of dust ejected out of galaxies. We also discuss what mode of dust formation (condensation in stellar ejecta and dust produced through accretion in the ISM) dominates in different types of galaxies at different cosmic epochs and explore the relevance of metal depletion onto dust grains. In this work we only focus on the evolution of dust masses and the different dust formation channels, leaving the rest of the underlying galaxy properties unchanged from the models published in Popping, Somerville & Trager (2014) and Somerville, Popping & Trager (2015). In a future work we will extend this model by including a self-consistent treatment of the impact of dust on the galaxy formation physics (i.e., cooling of hot gas through dust channels, H2 formation reactions based
on the dust abundance, and dust absorption based on the actual dust abundance).

This paper is structured as follows. In Section 2 we present the galaxy formation model and GCE used in this work. We present the newly implemented dust chemistry in Section 2.2. We briefly summarise how observations of dust masses in galaxies are typically carried out and their uncertainties in Section 3. In Section 4 we present our predictions for the dust scaling relations in galaxies and how these evolve with cosmic time. We discuss our finding in Section 5 and summarise our work in Section 6. Throughout this paper we adopt a flat ΛCDM cosmology with Ω₀ = 0.28, ΩΛ = 0.72, h = H₀/(100 km s⁻¹ Mpc⁻¹) = 0.7, σ₈ = 0.812, and a cosmic baryon fraction of f_b = 0.1658 (Komatsu et al. 2009).

2 GALAXY FORMATION MODEL

In this section we present the galaxy formation model on top of which the tracking of dust production and destruction is included. We provide a general introduction to the semi-analytic model employed in this work and will focus in more detail on some elements of the code relevant for the tracking of dust (Section 2.1). We then discuss the GCE model (Section 2.2), relevant for the condensation of dust in stellar ejecta. We adopt a flat ΛCDM cosmology with Ω₀ = 0.28, ΩΛ = 0.72, h = H₀/(100 km s⁻¹ Mpc⁻¹) = 0.7, σ₈ = 0.812, and a cosmic baryon fraction of f_b = 0.1658 (Komatsu et al. 2009). Unless stated otherwise we leave the free parameters associated with the galaxy-formation model fixed to the values given in Somerville, Popping & Trager (2015).

2.1 Semi-analytic model framework

The galaxy formation model was originally presented in Somerville & Primack (1999) and Somerville,Primack & Faber (2001). Significant updates to this model are described in Somerville et al. (2008b, S08), Somerville et al. (2012), Popping, Somerville & Trager (2014, PST14), Porter et al. (2014), and Somerville, Popping & Trager (2015, SPT15). The model tracks the hierarchical clustering of dark matter haloes, shock heating and radiative cooling of gas, SN feedback, star formation, active galactic nuclei (AGN) feedback (by quasars and radio jets), metal enrichment of the interstellar and intracluster medium, mergers of galaxies, starbursts, and the evolution of stellar populations. The PST14 and SPT15 models include new recipes that track the abundance of ionised, atomic, and molecular hydrogen and a molecule-based star-formation recipe. These models have been fairly successful in reproducing the local properties of galaxies such as the stellar mass function, gas fractions, gas mass function, SFRs, and stellar metallicities, as well as the evolution of the galaxy sizes, quenched fractions, stellar mass functions, and luminosity functions. Somerville et al. (2008b, S08), Porter et al. (2014), Popping et al. (2014), Brennan et al. (2015, PST14, SPT15).

Fundamentally, semi-analytic models track the flows of material between different reservoirs. In our models, all galaxies form within a dark matter halo. The reservoirs for gas include the “hot” gas that is assumed to be in a quasi-hydrostatic spherical configuration throughout the virial radius of the halo, the “cold” gas in the galaxy, assumed to be in a thin disk, and “ejected” gas which is gas that has been heated and ejected from the halo by stellar winds. We can schematically think of the cold disk gas as corresponding to the ISM, and the hot halo gas as corresponding to the circumgalactic, intra-group, or intra-cluster medium. The interpretation of the “ejected” gas is less clear, but presumably it corresponds either to the circumgalactic or intergalactic medium or some combination of the two. Gas moves between these reservoirs as follows. As dark matter halos grow in mass, pristine gas is accreted from the intergalactic medium into the hot halo. In addition, a simple cooling model is used to estimate the rate at which gas accretes from the hot halo into the cold gas reservoir, where it becomes available to form stars. Gas is removed from the cold gas reservoir as it becomes locked up in stars, and also by stellar and AGN-driven winds. Part of the gas that is ejected by stellar winds is returned to the hot halo, and the rest is deposited in the “ejected” reservoir. Gas “re-accretes” from the ejected reservoir back into the hot halo according to a parameterized timescale (see S08 for the details of all of these recipes). In the present work, we add new “dust” reservoirs corresponding to all of these gas reservoirs. We track the production and destruction of dust within the relevant reservoirs, as well as the movement of dust between reservoirs, as will be described a bit later.

The galaxy that initially forms at the center of each halo is called the “central” galaxy. When dark matter halos merge, the central galaxies in the smaller halos become “satellite” galaxies and orbit within the larger halo until their orbit decays and they merge with the central galaxy, or until they are tidally destroyed.

Here we briefly summarise the recipes employed to compute the size of galaxy discs and to track the molecular hydrogen abundance. These play an important role in modelling the growth of dust by accretion in the ISM (see Section 5.2). We point the reader to Somerville et al. (2008b, S08), Somerville et al. (2012, PST14, and SPT15 for a more detailed description of the model.

The sizes of the galaxy discs are important as they set the surface densities for our H₂ partitioning recipe and growth rate of dust by accretion in the ISM. When gas cools onto a galaxy, we assume it initially collapses to form a rotationally supported disc. The scale radius of the disc is computed based on the initial angular momentum of the gas and the halo profile, assuming that angular momentum is conserved and that the self-gravity of the collapsing baryons causes contraction of the matter in the inner part of the halo (Blumenthal et al. 1986, Flores et al. 1993, Mo, Mao & White 1998). This approach successfully reproduces the evolution of the size-stellar mass relation of disc-dominated galaxies from z ~ 2 to z = 0 (Somerville et al. 2008a). The sizes of H I discs in the local Universe and the observed sizes of CO discs in local and high-redshift galaxies (PST14).

To compute the H₂ fraction of the cold gas we use an approach based on the work by Gnedin & Kravtsov (2011). The authors performed high-resolution ‘zoom-in’ cosmological simulations with the Adaptive Refinement Tree (ART) code (Kravtsov 1999), including gravity, hydrodynamics, non-equilibrium chemistry, and simplified 3D on-the-fly radiative transfer (Gnedin & Kravtsov 2011). The authors present a fitting formula for the H₂ fraction of cold gas
based on the dust-to-gas ratio relative to solar, $D_{\text{MW}}$, the ionising background radiation field, $U_{\text{UV}}$, and the surface density of the cold gas (see PST14, SPT15). We assume that the local UV background scales with the SFR relative to the Milky Way value, $U_{\text{MW}} = SFR/SFR_{\text{MW}}$, where we choose $SFR_{\text{MW}} = 1.0 \, M_\odot \, \text{yr}^{-1}$ (Murray & Rahman 2010). As in PST14 and SPT15, we assume that the dust-to-gas ratio is proportional to the metallicity of the gas in solar units $D_{\text{MW}} = Z_{\text{gas}}/Z_\odot$ (where in this case the metallicity is given by all the available metals in the ISM). As discussed above, this assumption is known to be incorrect in detail. In a future paper we will make our models self-consistent by instead using the modeled dust mass to estimate the molecular hydrogen fraction. However, initially we prefer to leave the underlying galaxy formation model unchanged and explore how successful our simple model is at reproducing fundamental observations of dust content.

We considered other recipes for the partitioning of H I and H$_2$ in PST14 and SPT15. We found that metallicity based recipes that do not include a dependence on the UV background predict less efficient formation of H$_2$, less star formation, and less metal enrichment at early times in low-mass haloes ($M_\text{h} < 10^{10.5} \, M_\odot$). PST14 also considered a pressure-based recipe (Bigiel & Rosolowsky 2006), but found that the pressure-based version of the model is less successful in reproducing the H I density of our Universe at $z > 0$.

The SF in the SAM is modelled based on an empirical relationship between the surface density of molecular hydrogen and the surface density of star-formation (Bigiel et al. 2008; Genzel et al. 2010; Bigiel & Blitz 2012a). Observations of high-density environments (especially in starbursts and high-redshift objects) have indicated that above some critical surface density, the relation between molecular hydrogen surface density and SFR surface density steepens (Sharon et al. 2013; Hodge et al. 2015). To account for this steepening we use the following expression to model star formation

$$\Sigma_{\text{SFR}} = A_{\text{SF}} \frac{\Sigma_{\text{H}_2}/(10 \, M_\odot \, \text{pc}^{-2})}{(1 + \frac{\Sigma_{\text{H}_2}}{\Sigma_{\text{H}_2,\text{crit}}})^{N_{\text{SF}}}},$$

where $\Sigma_{\text{H}_2}$ is the surface density of molecular hydrogen and with $A_{\text{SF}} = 5.98 \times 10^{-3} M_\odot \text{yr}^{-1} \text{pc}^{-2}$, $\Sigma_{\text{H}_2,\text{crit}} = 70 M_\odot \text{pc}^{-2}$, and $N_{\text{SF}} = 1$.

Following PST14 and SPT15, we adopt a metallicity floor of $Z = 10^{-3} Z_\odot$ and a floor for the fraction of molecular hydrogen of $f_{\text{mol}} = 10^{-4}$. These floors represent the enrichment of the ISM by Pop III stars and the formation of molecular hydrogen through other channels than on dust grains (Haiman, Rees & Loeb 1996; Bromm & Larson 2004).

### 2.2 Galactic Chemical Evolution

We use the Galactic Chemical Evolution (GCE) model presented in Arrigoni et al. (2010) to track the abundance of individual elements. Arrigoni et al. (2010) extended the Somerville et al. semi-analytic model to include the detailed metal enrichment by type Ia and type II supernovae and long-lived stars. With this extension our model tracks the abundances of 19 individual elements, as well as the rate of SNIa and SNII. We refer the reader to Arrigoni et al. (2010) for a detailed description of the GCE and its ingredients. In this paper we will discuss several updates to the Arrigoni model adopted here, including modified stellar yields and the delay time distribution formulation for SNIa. We assume a Chabrier (Chabrier 2003) initial stellar mass function with a slope of $x = -1.35$ in the mass range 0.1–100 $M_\odot$. This yields better agreement with the observed mass metallicity and alpha-to-iron ratio of galaxies (Arrigoni et al. 2010; Fontanot et al. 2010). We adopt the solar abundances from Asplund et al. (2009).

#### 2.2.2 Delay time distribution for SN Ia

The delay time distribution (DTD) describes the SN rate after a burst of star-formation. Here we adopt the DTD from Maoz, Mannucci & Brandt (2012), where

$$\text{SNR}(t)_{\text{Ia}} = 4 \times 10^{13} \text{yr}^{-1} m_*(\frac{t}{1 \text{Gyr}})^{-1},$$

is the rate of SNIa produced by a stellar population with mass $m_*$ that was formed at $t = 0$. Walcher et al. (2016) showed that a GCE adopting a power law DTD such as in Maoz, Mannucci & Brandt (2012) reproduces the age and alpha-element abundances of early-type galaxies better than the more classical single or double Gaussian shaped DTD.
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3 DUST CHEMISTRY MODEL

There are a number of physical processes that contribute to the formation, destruction, and removal of dust from the ISM of galaxies. The net rate of change in the mass of dust is described as

$$\dot{M}_{\text{dust}} = \dot{M}_{\text{dust, produced}} + \dot{M}_{\text{dust, growth}} - \dot{M}_{\text{dust, destruct}} - M_{\text{dust, SF}} + \dot{M}_{\text{dust, infall}} - \dot{M}_{\text{dust, ISM}}. \quad (3)$$

where $\dot{M}_{\text{dust, produced}}$ is the condensation rate of dust in the ejecta of long-lived stars and SNe, $M_{\text{dust, growth}}$ the growth rate of dust in the ISM, $\dot{M}_{\text{dust, destruct}}$ the destruction rate of dust in the ISM due to SNe, $M_{\text{dust, SF}}$ the dust locked up in stars during SF, $\dot{M}_{\text{dust, infall}}$ the mass of dust accreting onto the galaxy from the CGM, and $\dot{M}_{\text{dust, ISM}}$ the decrease in the dust mass due to outflows and heating. An equation similar to Equation (3) can be constructed for the gas-phase metallicity, where every time dust condenses the same amount of metals is removed from the cold gas reservoir, and every time dust is destroyed the same amount of metals are added back to the gas reservoirs.

The individual recipes for the dust-related processes are described below in separate subsections. The model tracks the dust evolution of the refractory elements C, Mg, Si, S, Ca, Ti, Fe, and O. We summarise the physical parameters adopted in the various recipes in Table 1 and describe them in further detail in sub-section 3.1.

### 3.1 Dust production

Some of the metals returned to the ISM by long-lived stars and supernovae may condense into dust. To model the condensation of dust we follow the approach presented in Dwek (1998), with updated condensation efficiencies based on recent theoretical and observational work. In the following $m_{\text{C,E}}$ is the mass of the $j$th element (C, Mg, Si, S, Ca, Ti, Fe, and O) returned by the $k$th stellar process (SNIa, SNII, or AGB stars), whereas $M_{\text{dust, J,E}}$ marks the mass of dust of the $j$th element from the $k$th type of process.

The amount of dust produced by AGB stars with a carbon-to-oxygen ratio $C/O > 1$ in their returned mass is described as

$$m_{\text{dust, AGB}} = \left\{ \begin{array}{ll} \delta_{\text{C,AGB}} m_{\text{C,AGB}} - 0.75 m_{\text{O,AGB}} \quad & \text{if } j = C, \\ 0 & \text{else,} \end{array} \right. \quad (4)$$

where $\delta_{j,\text{AGB}}$ is the condensation efficiency of element $j$ for AGB stars. When the carbon-to-oxygen ratio of the AGB mass return is less than 1 ($C/O < 1$), the mass of dust produced can be described as

$$m_{\text{dust, AGB}} = \left\{ \begin{array}{ll} \delta_{\text{C,AGB}} m_{\text{C,AGB}} / \mu_j \quad & \text{if } j = O, \\ 0 & \text{else,} \end{array} \right. \quad (5)$$

where $\mu_j$ is the mass of element $j$ in atomic mass units.

The mass of dust produced via the ejecta of SNIa is

$$m_{\text{dust, SNIa}} = \left\{ \begin{array}{ll} \delta_{\text{SNIa, C,SNII}} m_{\text{C,SNII}} / \mu_j \quad & \text{if } j = C, \\ 0 & \text{else,} \end{array} \right. \quad (6)$$

where $\delta_{\text{SNIa, C,SNII}}$ is the dust condensation efficiency of element $j$ for SNIa. The same approach is used for the dust condensation in the ejecta of SNII, where the condensation efficiency for SNIa $\delta_{\text{SNIa}}$ is replaced by the condensation efficiency for SNII $\delta_{\text{SNII}}$.

The total mass of dust condensation in the ejecta of long-lived stars in then given by

$$\dot{M}_{\text{dust, J,E}} = \frac{\dot{m}_{\text{dust, AGB}}}{dt} + \frac{\dot{m}_{\text{dust, SNIa}}}{dt} + \frac{\dot{m}_{\text{dust, SNII}}}{dt}. \quad (7)$$

### 3.2 Growth of dust by accretion in the ISM

Collisions between gas-phase elements and existing dust grains can lead to the growth of the dust mass in galaxies (Draine 1990, Dwek 1998, Draine 2009). To model this process we follow the prescription in Zhukovska, Gail & Tröster (2008) and Zhukovska (2014). Our model makes the explicit assumption that dust can only grow in the dense regions of the ISM, within our model associated with molecular hydrogen. Not all the ISM resides in such states. We can define an “effective” exchange time $\tau_{\text{exch, eff}}$, over which all the ISM in a galaxy is cycled through molecular clouds (Zhukovska 2014). This exchange time is given by

$$\tau_{\text{exch, eff}} = \tau_{\text{exch}} \frac{1 - \frac{\dot{f}_{\text{mol}}}{f_{\text{mol}}}}{f_{\text{mol}}}. \quad (8)$$

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**Table 1. Summary of the dust-related model parameters in our fiducial model**

| Parameter | Description | Section defined | value |
|-----------|-------------|-----------------|-------|
| $\delta_{\text{AGB}}$ | Condensation efficiency in AGB ejecta | 3.1 | 0.2 |
| $\delta_{\text{SNIa}}$ | Condensation efficiency in SNIa ejecta | 3.1 | 0.15 |
| $\delta_{\text{SNII}}$ | Condensation efficiency in SNII ejecta | 3.1 | 0.15 |
| $\tau_{\text{acc,0}}$ | Time scale of dust growth | 3.2 | 15 Myr |
| $\dot{f}_{\text{SN}}$ | Supernova efficiency | 3.3 | 0.36 |
| $M_{\text{cleared, carbonaceous}}$ | Gas mass cleared of carbonaceous dust by one SN event | 3.3 | 600 M$_{\odot}$ |
| $M_{\text{cleared, silicates}}$ | Gas mass cleared of silicate dust by one SN event | 3.3 | 980 M$_{\odot}$ |
where $\tau_{\text{exch}} = 20$ Myr (Murray & Rahman 2010) is the lifetime of molecular clouds and the timescale for exchange from the dense to the diffuse ISM. $f_{\text{mol}}$ is the molecular fraction of the cold gas, computed as described in section 2.1.

The growth rate of element $j$ on dust grains $M_{j,\text{dust}}^{\text{growth}}$ can be expressed as \cite{Zhukovska2014}:

$$ M_{j,\text{dust}}^{\text{growth}} = \frac{1}{\tau_{\text{exch,eff}}} \left( f_{j,\text{cond}} M_{j,\text{metal}} - M_{j,\text{dust}} \right), \quad (9) $$

where $f_{j,\text{cond}}$ is the condensation degree of species $j$ after cloud dispersal. This is the mass fraction of metal species $j$ in a molecular cloud condensed into dust at the end of the molecular cloud lifetime. $M_{\text{metal},j}$ is the total mass of element $j$ either locked up in dust or cold gas.

We adopt an approximation from \cite{Zhukovska2014} to describe $f_{j,\text{cond}}$:

$$ f_{j,\text{cond}} = \left( \frac{f_{j,0} (1 + \tau_{\text{exch}} / \tau_{\text{acc}})}{1 + \tau_{\text{exch}} / \tau_{\text{acc}}} \right)^{-2/3} + 1, \quad (10) $$

where $f_{j,0}$ is the initial degree of condensation for dust species $j$. $\tau_{\text{acc}}$ is the timescale for dust growth.

We adopt an expression for the timescale for dust growth that has been used in many previous works \cite{Hirashita2006, Inoue2003, Asano2013, deBennassuti2014, Schneider2016} to describe $\tau_{\text{acc}}$:

$$ \tau_{\text{acc}} = \tau_{\text{acc},0} \times \left( \frac{n_{\text{mol}}}{100 \text{ cm}^{-3}} \right)^{-1} \left( \frac{T_{\text{cl}}}{50 \text{ K}} \right)^{-1/2} \left( \frac{Z_j}{Z_{\odot}} \right)^{-1}. \quad (11) $$

$\tau_{\text{acc},0}$ is the timescale for dust growth in Milky Way molecular clouds and treated as a free parameter. $T_{\text{cl}}$ is the temperature in molecular clouds which we assume to be 50 K (Wilson, Walker & Thornley 1997). $n_{\text{mol}}$ is the number density of molecular clouds and $Z_j$ is the gas-phase abundance of species $j$ with respect to the solar abundance. We will discuss our choice for $\tau_{\text{acc},0}$ in Section 3.6.

Equation (11) is derived from the expression for dust mass growth rate in clouds \cite{Hirashita2006, Inoue2003}:

$$ M_{j,\text{dust}}^{\text{growth}} = f_{\text{mol}} N \pi (a^2) \alpha \rho_{\text{g}}^{\text{gas}}(v), \quad (12) $$

where $N$ is the number of dust grains, $(a^2)$ is the 2nd moment of a grain size $a$, $\alpha$ is the mean sticking coefficient of metals, $\rho_{\text{g}}^{\text{gas}}$ is the mass density of gaseous metals that are not contained in dust, and $v$ is the mean velocity of metals in gas phase. This derivation is presented in detail in \cite{Asano2013}, and implicitly assumes spherical dust grains, a sticking coefficient $\alpha = 1$ and that the solid matter in dust grains has a fixed mass density of 3 g cm$^{-3}$. This approach furthermore assumes a fixed mean grain radius of $\alpha = 0.1 \mu$m. The grain sizes for dust grains produced by SNe are expected to be larger than 0.01$\mu$m \cite{Bianchi2007, Nozawa2007} and the grain size distribution of dust produced by AGB stars is thought to peak near 0.1$\mu$m \cite{Groenewegen1997, Winters1997, Yasuda2012, Asano2013}.

SAMs do not provide volume densities of individual clouds. To overcome this we express the SFR surface density in terms of the volume density dependent free-fall time of the molecular gas,

$$ \Sigma_{\text{SFR}} = \epsilon \frac{\Sigma_{\text{H}_2}}{t_{\text{ff}}}, \quad (13) $$

where $\epsilon$ is the efficiency of star-formation. Observations constrain this efficiency to $\sim 1\%$ \cite{Krumholz2007, Krumholz2012, Krumholz2014}. The free-fall time is given by

$$ t_{\text{ff}} = \sqrt{\frac{3 \pi}{32 G n_{\text{mol}}}}, \quad (14) $$

with $G$ the gravitational constant. In Equation 1 we presented a recipe that relates SFR surface density to molecular hydrogen surface density. By combining Equation 14 with Equation 13 we can write a new expression for the free-fall time

$$ t_{\text{ff}} = \epsilon \left[ A_{\text{SF}} (10 M_{\odot} \text{pc}^{-2}) \left( 1 + \frac{\Sigma_{\text{H}_2}}{\Sigma_{\text{H}_2,\text{crit}}} \right)^{N_{\text{SF}}} \right]^{-1}. \quad (15) $$

We can now simply solve for $n_{\text{mol}}$ by combining Equations 13 and 15.

To illustrate this recipe we plot the accretion time scale of dust as a function of molecular hydrogen surface density and metallicity in Figure 1. We find that below the critical surface density of 70 $M_{\odot}$ pc$^{-2}$, the accretion time scale is only a function of metallicity. At higher surface densities star-formation becomes more efficient, which results in higher volume densities and shorter time scales for accretion.

The gas surface density and molecular hydrogen fraction are important physical parameters when calculating the growth-rate of dust due to metal accretion. These parameters are not fixed throughout a galaxy, but vary with radius. We assume that the cold gas is distributed in an exponential disc with scale radius $r_{\text{gas}}$ and a central gas surface density of $M_{\text{cold, gas}}/(2\pi r_{\text{gas}})$, where $M_{\text{cold, gas}}$ is the mass of all cold gas in the disc. Bigiel & Blitz (2012b) find that this is a good approximation for nearby spiral galaxies. We divide the gas disc into radial annuli and compute the fraction of molecular gas and the growth rate of dust in each annulus as described above. The total growth-rate of dust in the galaxy at each time step is then calculated using a fifth order Runge-Kutta integration scheme.

![Figure 1](image_url)
3.3 Dust destruction

There are a number of processes that can destroy dust in the ISM. SN blast waves in particular efficiently destroy dust grains through inertial and thermal sputtering (e.g., McKee 1989; Jones et al. [1994]; Jones, Tielens & Hollenbach 1996). The time scale over which dust grains in the ISM are destroyed due to SN blast waves is given by (McKee 1989)

$$\tau_{\text{destruction}} = \frac{M_{\text{HI+HI}}}{M_{\text{cleared}} f_{\text{SN}} R_{\text{SN}}}.$$  \hspace{1cm} (16)

where $M_{\text{HI+HI}}$ is the mass of diffuse gas (ionised and atomic) in the galaxy, $M_{\text{cleared}}$ is the mass of gas cleared from dust by one supernova event (which is different for carbonaceous and silicate grains, Section 3.6), $f_{\text{SN}}$ accounts for the effects of correlated SNe and SNe out of the plane of the galaxy, and $R_{\text{SN}}$ is the supernova rate of supernova type I and type II combined. We note that we assume here that destruction in the dense cold ISM is inefficient, because shock velocities are lower, and that destruction only works in the warm ISM (in our case H1 and HII) [Jones, Tielens & Hollenbach 1996].

The supernova rate is calculated as a part of the GCE presented in Section 2.2. The destruction rate of the dust is then given by

$$\dot{M}_{\text{dust}} = \frac{M_{\text{dust}}}{\tau_{\text{destruction}}} \cdot M_{\odot} \cdot \text{yr}^{-1}.$$  \hspace{1cm} (17)

3.4 SF, Infall, outflow, and mergers

There are a number of physical processes that act on the dust in the ISM that we have not discussed yet in detail. These are processes that affect the ISM as a whole, and therefore also the dust within it. Our model includes the following additional dust-related processes.

- When stars are formed out of the ISM the dust that is locked up in these stars is assumed to be destroyed and added to the metal content of the stars. The rate at which dust is locked up in stars is proportional to the SFR of the galaxy and equals $\dot{M}_{\text{sputtering}} = D_j SFR$, where $D_j$ marks the dust-to-gas ratio for element $j$.
- SN and AGN can heat up and expel gas and dust from the ISM into the halo or even further out. We assume that the dust-to-gas ratio of the heated ISM and outflows equals the average dust-to-gas ratio of the ISM. The rate $\dot{M}_{\text{dust}}$ at which dust is removed from the galaxy is therefore directly proportional to the total ISM mass heated up or blown out by AGN and SNe through $D_j$. Similar to the metals, dust can also be ejected out from and reaccreted onto the halo.
- The rate at which dust accretes onto the galaxy is proportional to the cooling rate of the gas through $D_j$, the dust abundance of the dust of element $j$ in the hot gas.
- Whenever a central and a satellite galaxy merge, the dust undergoes exactly the same processes as the cold gas, scaled by the dust-to-gas ratio $D_j$ for element $j$. A detailed description of the processes acting on the cold gas during mergers is given in S08.

3.5 Dust in the hot halo

Once dust is ejected into the hot halo of a galaxy, it can be destroyed by thermal sputtering and grain-grain collisions (Draine & Salpeter 1979). We follow the work by Tsai & Mathews [1995]; Hirashita et al. (2015), and McKinnon et al. (2016) to include the effects of thermal sputtering. The sputtering rate for a grain of radius $a$ in gas with a density of $\rho$ and temperature $T$ is

$$\frac{da}{dt} = -(3.2 \times 10^{-18} \text{cm}^2 \cdot \text{s}^{-1}) \left( \frac{\rho}{m_p} \right) \left[ \left( \frac{T_0}{T} \right)^{\omega} - 1 \right]^{-1},$$ \hspace{1cm} (18)

where $m_p$ is the proton mass, $T_0 = 2 \times 10^6 \text{K}$ is the temperature above which the sputtering rate flattens, and $\omega = 2.5$ controls the low-temperature scaling of the sputtering rate. The associated sputtering time-scale for the grain is (Tsai & Mathews 1995)

$$\tau_{\text{sputtering}} = 0.17 \text{Gyr} \left( \frac{a_{-1}}{\rho_{-27}} \right) \left[ \left( \frac{T_0}{T} \right)^\omega + 1 \right],$$ \hspace{1cm} (19)

where $a_{-1}$ is the grain size in units of $0.1 \mu\text{m}$ and $\rho_{-27}$ is the gas density in units of $10^{-27} \text{g} \cdot \text{cm}^{-3}$. For the temperature $T$ we take the virial temperature of the halo. Following McKinnon et al. (2016) we now estimate the destruction rate of dust species $j$ in the hot halo due to thermal sputtering as

$$\dot{M}_{\text{sputtering}} = - \frac{M_{\text{dust, hot}}}{\tau_{\text{sputtering}}^3}.$$  \hspace{1cm} (20)

The dust that is destroyed by thermal sputtering is added to the metals in the hot halo.

We do not self-consistently include dust cooling channels in our models in the present work (Ostriker & Silk 1973; Cantalupo 2010; Gnedin & Hollon 2012). Rather, we treat the dust as ‘normal metals’ when calculating the cooling rate of the hot gas (i.e., the cooling rates are based on the temperature and the sum of the metals and dust in the hot gas). We will include a self-consistent treatment of the dust cooling physics in a future work.

3.6 Physical parameters

We chose the values of the main physical parameters in this work either based on theoretical work or by tuning our model to observations in the local Universe. The parameters and their respective values are all listed in Table 1. In our fiducial model, we take a fixed condensation efficiency for AGB stars of $\delta_{\text{AGB}} = 0.2$. This number is in decent agreement with the dust-condensation efficiencies calculated in Ferrarotti & Gail (2006) for the majority of combinations of initial stellar mass and metallicity. Previous works employing the Ferrarotti & Gail (2006) condensation-efficiencies have successfully reproduced the dust-properties of the Large Magellanic Cloud and our own Milky Way (Zhukovska, Gail & Trieloff 2008; Zhukovska & Henning 2013), as well as the UV luminosity function of $z > 5$ galaxies (Mancini et al. 2016). Theoretical models have begun to explore the dust-condensation efficiency as a function of a star’s mass and metallicity, and found variations from $\delta_{\text{AGB}} = 0.2$ (e.g., Ferrarotti & Gail 2006; Zhukovska, Gail & Trieloff 2008). While not included in our model, we acknowledge that varying condensation efficiencies depending on the stellar type may be more realistic, especially in

1 though see Temim et al. (2015) who find $\tau_{\text{destruction}}$ is only weakly dependent on density.
very low-metallicity regimes. We note that the adopted dust-condensation efficiency for AGB stars is significantly lower than the numbers used in Dwek (1998) and other recent works that assume \( \delta^{\text{AGB}}_{\text{carbon}} = 1.0 \) (e.g., Bekki 2013; McKinnon, Torrey & Vogelsberger 2016; McKinnon et al. 2016).

The dust-condensation efficiency we adopt for SNe corresponds to the condensed dust that survives the passage of the reverse SN shock. Observational work on the condensation of dust in SN ejecta typically probes condensation before the passage of the reverse shock. A direct comparison between the different condensation efficiencies should therefore be treated with caution. Theoretical work by Bianchi & Schneider (2007) suggests dust-condensation efficiencies of \( \sim 40-100 \) percent before the reverse SN shock. Only \( \sim 2-20 \) percent of the initial dust mass survives the reverse shock, corresponding to a condensation efficiency \( \delta^{\text{SN}}_{\text{reverse}} \) of \( \sim 1-20 \)\%.

The content of low-mass and low-metallicity galaxies is fully determined by the condensation efficiency of SNe (and the destruction rate of the dust). These objects are too young for AGB stars to contribute significantly to the dust mass and the growth of dust in their ISM is not yet efficient (Zhukovska et al. 2014). We choose a SN dust-condensation efficiency of \( \delta^{\text{SN}}_{\text{reverse}} = 0.15 \), which yields good agreement with the dust mass in low mass galaxies at \( z = 0 \) (Figure 1).

We calibrate the normalisation of the time-scale for dust growth \( \tau^{\text{acc}}_{0} \) (Eqn. 11) using the observational constraints on dust mass in massive galaxies (Ciesla et al. 2014; Rémy-Ruyer et al. 2014b). We find a time scale of \( \tau^{\text{acc}}_{0} = 15 \) Myr, consistent with values adopted in earlier simulations using a similar approach for dust accretion in the ISM (e.g., Hirashita 2000b; Asano et al. 2013; de Bennassuti et al. 2014; Feldmann et al. 2015; Schneider, Hunt & Valiante 2016).

The adopted values for the physical parameters that describe the destruction of dust by SN blast waves are based on work by Slavin, Dwek & Jones (2015). The authors estimate the gas mass cleared of dust by a SN event (\( M^{\text{clear}} \)) based on new calculations of grain destruction in evolving, radiative SN remnants. A distinction has to be made between carbonaceous grains (constituted of carbon) and silicates (constituted of the other refractory elements tracked in our model). Slavin, Dwek & Jones (2015) find \( M^{\text{clear, carbonaceous}} = 600 M_{\odot} \) and \( M^{\text{clear, silicate}} = 980 M_{\odot} \) for carbonaceous and silicate grains, respectively. These numbers are about a factor of 1.5 lower than estimates for the LMC (Zhukovska, Gail & Trieloff 2008). The parameter that accounts for the correlated nature of supernova events and supernovae occurring outside of the plane of galaxies is set to \( f_{\text{SN}} = 0.36 \). Observations have found similar estimates for \( f_{\text{SN}} \) in the Milky Way and LMC (McKee 1989; Zhukovska & Henning 2013).

### 3.7 Model variants

We consider four different variants of our model. These variants are chosen to illustrate different scenarios for dust formation, and to provide a comparison with other models and simulations in the literature. We summarise the model variants in Table 2.

The first variant is our fiducial model. This variant adopts the free parameters as discussed in the previous section and listed in Table 1.

The second model variant, ‘no-acc’, is motivated by recent work by Ferrara, Viti & Ceccherelli (2016). These authors suggested that the contribution of dust growth on grains to the dust mass of galaxies is negligible. They argue that accretion does take place in dense environments, but the accreted materials are locked up in icy water mantles, which photo-desorb quickly after the grains return to the diffuse ISM. To mimic this process, we completely turn off the growth of dust through accretion onto grains. To ensure that enough dust is formed to reproduce local- and high-redshift observations, the efficiency of dust condensation in stellar ejecta must then be much higher than in our fiducial model.

We therefore test the extreme case where the condensation efficiency is 100\% for AGB ejecta and SN ejecta in order to reproduce the dust content of local galaxies (Figure 2).

The third variant, ‘fix-tau’, assumes a fixed timescale for dust accretion in the ISM. Cosmological simulations of galaxy formation that include dust chemistry have so far often assumed a fixed timescale for the accretion of dust, independent of gas density and/or gas phase metallicity (Bekki 2013; McKinnon, Torrey & Vogelsberger 2016). We choose a value of \( \tau^{\text{acc}} = 100 \) Myr, in agreement with the accretion time scales adopted in Bekki (2013) and McKinnon, Torrey & Vogelsberger (2016). For clarity, we plot the accretion timescale \( \tau^{\text{acc}} \) as a function of gas surface density and metallicity in Figure 1 and mark the fixed timescale of 100 Myr as a dashed horizontal line. This figure immediately shows that the differences between a fixed and a metallicity and density dependent accretion timescale can be very significant. We will refer to this figure to explain some of the differences between the model variant predictions.

The fourth variant, ‘high-cond’, assumes a much higher condensation efficiency for dust in stellar ejecta, as adopted in the fiducial models of Bekki (2013), McKinnon, Torrey & Vogelsberger (2016), and McKinnon et al. (2016). We take \( \delta^{\text{SN}}_{\text{other}} = 0.8 \) for the other

### Table 2. Summary of the three model variants. Unless listed in the changed parameters column, all parameters are as listed in Table 1.

| Name       | Changed Parameters                                                                 |
|------------|-----------------------------------------------------------------------------------|
| fiducial   |                                                                                   |
| no-acc     | \( \delta^{\text{AGB}}_{\text{carbon}} = 1.0, \delta^{\text{AGB}}_{\text{other}} = 1.0, \delta^{\text{SN}}_{\text{carbon}} = 1.0, \delta^{\text{SN}}_{\text{other}} = 1.0 \) |
| fix-tau    | \( \tau^{\text{acc}} = 100 \) Myr                                               |
| high-cond  | \( \delta^{\text{AGB}}_{\text{carbon}} = 1.0, \delta^{\text{AGB}}_{\text{other}} = 0.8, \delta^{\text{SN}}_{\text{carbon}} = 1.0, \delta^{\text{SN}}_{\text{other}} = 0.8 \) |
elements. Similarly, we assume $\delta^\text{SN}_{j} = 1.0$ for carbon and $\delta^\text{SN} = 0.8$ for the other elements. The condensation efficiencies are also close to the values adopted in Dwek (1998). In this variant the timescale for dust accretion is a function of gas density and gas-phase metallicity, as in our fiducial model.

4 MEASURING DUST MASSES

In this work we compare with a wide range of observational estimates of the dust content of galaxies. These estimates are obtained in several different ways. Here we summarize the main existing approaches for obtaining observational estimates of the dust mass in galaxies.

The infrared emission of galaxies is widely used to estimate their dust content. The modelling of their IR spectral energy distribution (SED) has been especially improved within the past 10-20 years with the arrival of far-IR (Spitzer, Herschel) and sub-mm (Herschel, Submillimetre Common-User Bolometer Array (SCUBA), Balloon-borne Large Aperture Submillimeter Telescope (BLAST), and ALMA ground instrumentation and space telescopes, adding much better constraints on the cold dust regime.

Assuming that galaxies behave as optically thin single or double temperature sources, the SEDs of local and high redshift galaxies have been (and still are) widely modeled using 1 or 2 modified blackbody (MBB; with $L = A\nu(\nu)^{\beta}$) fitting techniques. This is the case for half of the observably derived dust masses we will be quoting in this paper. Observations with Herschel and Planck have shown that in the diffuse ISM, $A\nu$ estimates from the Draine et al. (2007) model are a factor of 3 larger than $A\nu$ derived from optical estimates from quasi-stellar objects (QSOs) observed in the Sloan survey (Planck Collaboration et al. 2014). These new results indicate that part of the physical assumptions on the dust opacity that feed the current SED models should probably be revised.

For high-redshift galaxies, the contribution of a cold dust component ($T < 20K$) is still not well constrained but submm/mm observations using ALMA now enable us to extend the SED coverage toward the cold regime, lowering the uncertainties we have on the dust mass of these objects. In our study, we will use ALMA-based dust estimates from da Cunha et al. (2015) and Mancini et al. (2015).

Finally, the dust-to-metal ratio can be measured indirectly via optical/UV absorption-line spectroscopy, for instance the Fe or Zn lines. Abundance ratios of elements that strongly deplete onto dust grains and elements that hardly deplete provide an estimate for the dust-to-metal ratio. Our paper will be using the dust-to-metal estimates obtained by De Cia et al. (2013, 2015) and Wiseman et al. (2016).

5 RESULTS

In this section we present our predictions for the evolution of the dust content of galaxies over a redshift range from $z = 0$ to $z = 9$. The simulations were run on a grid of haloes with virial masses ranging from $5 \times 10^{7}$ to $5 \times 10^{14}$ $M_\odot$ and a mass resolution of $5 \times 10^{6}$ $M_\odot$. Unless stated otherwise, we restrict our analysis to central star forming galaxies, selected using the criterion sSFR > 1/(3$\Omega_{\text{M}}(z)$), where sSFR is the galaxy specific star-formation rate and $t_H(z)$ the Hubble time at the galaxy’s redshift. This approach selects galaxies in a similar manner to commonly used observational methods for selecting star-forming galaxies, such as color-color cuts (e.g., Lang et al. 2014).

5.1 Dust masses in galaxies

In Figure 2 we present the dust mass of galaxies as a function of their stellar mass from $z = 0$ to $z = 9$. We find good agreement between the predictions by our fiducial model and the observed dust masses at $z = 0$ over the entire mass range probed. Our predictions are $\sim 0.5$ dex lower than the observations by Ciesla et al. (2014) at $M_{*} < 10^9$ $M_\odot$, but in
Figure 2. The dust mass of galaxies as a function of their stellar mass from redshift $z = 9$ to $z = 0$, for our four model variants. Thick lines mark the 50th percentiles, whereas the narrow dotted lines mark the 16th and 84th percentiles. The $z = 0$ prediction by our fiducial model is shown as a dashed double dotted grey line in the higher-redshift bins for comparison. Model predictions are compared to observations from Ciesla et al. (2014) Remy-Ruyer et al. (2014a) at $z = 0$, Santini et al. (2014) at $z = 1$ and $z = 2$, da Cunha et al. (2015) at $z = 3$, 4, and 5, and a compilation of data in Mancini et al. (2015) at $z = 6$ and 7, taken from Kanekar et al. (2013), Ouchi et al. (2013), Ota et al. (2014), Maiolino et al. (2015), Schaerer et al. (2015), and Watson et al. (2015).

We immediately notice differences at low stellar masses ($M_\star < 10^9 M_\odot$) between our fiducial model and the other model variants at $z = 0$. All model variants predict dust masses approximately 0.5 dex more massive than our fiducial model for galaxies in this stellar mass range. This is driven by higher efficiencies for the condensation of dust in stellar ejecta in the ‘no-acc’ and ‘high-cond’ model variant and shorter dust-growth timescales in low mass galaxies with low metallicities for the ‘fix-tau’ model variant. All model variants are in good agreement with the observed dust masses for galaxies with $M_\star > 10^{8.5} M_\odot$.

We find that the normalisation of the relation between galaxy dust mass and stellar mass as predicted by our fiducial model gradually decreases from $z = 3$ to $z = 0$. The decrease is weak for galaxies with $M_\star < 10^9 M_\odot$ (≈ 0.1 dex).
The dust content of galaxies from $z = 0$ to $z = 9$

Figure 3. The dust-to-gas ratio of galaxies as a function of their metallicity from redshift $z = 9$ to $z = 0$, for our four model variants. Thick lines mark the 50th percentiles, whereas the narrow dotted lines mark the 16th and 84th percentiles (note that the scatter predicted by the different model variants for this plot is very small). The $z = 0$ prediction by our fiducial model is shown as a dashed double dotted grey line in the higher-redshift bins for comparison. Model predictions at $z = 0$ are compared to the observations by Remy-Ruyer et al. (2014). The $12 + \log(O/H)$ values corresponding to metallicities of 0.1, 0.5, and 1.0 $Z_{\odot}$ are represented by small black vertical lines. The solar dust-to-gas ratio (0.006; Zubko, Dwek & Arendt 2004) is represented for comparison as small horizontal black lines in every panel.

and much stronger for more massive galaxies ($\sim 0.5$ dex; we will later see that this is the regime where the growth of dust in the ISM dominates). At higher redshifts, the relation between galaxy dust mass and stellar mass remains constant with time. The slope of the relation remains fairly constant. Our fiducial model successfully reproduces the dust masses observed in galaxies from redshift $z = 0$ to $z = 7$.

The ‘no-acc’ and ‘high-cond’ model variants predict a similar evolution in galaxy dust masses as our fiducial model. The ‘no-acc’ model predicts dust masses slightly lower than found by Santini et al. (2014), but is in good agreement with the observations by da Cunha et al. (2015) and Mancini et al. (2015). The ‘fix-tau’ model on the other hand predicts a reverse trend in the evolution between galaxy dust mass and stellar mass. The dust mass of galaxies is constant from $z = 9$ to $z = 4$, and increases by $\sim 0.5$ dex from $z = 4$ to $z = 0$. This model variant fails to reproduce the observational constraints in the highest redshift bin.
5.2 Dust-to-gas and dust-to-metal ratios

5.2.1 Dust-to-gas ratio

We present the dust-to-gas ratio \( \frac{M_{\text{dust}}}{(M_{\text{HI}} + M_{\text{H2}})} \) of galaxies in Figure 3. We find that the dust-to-gas ratio predicted by our fiducial model rapidly increases with metallicity up to a gas-phase metallicity of \( \sim 0.7 \, Z_{\odot} \). Above this metallicity the dust-to-gas ratio still increases, but the slope of this trend is very shallow. Although the shape of relation between gas-phase metallicity and dust-to-gas ratio agrees with the observational constraints, the predicted dust-to-gas ratios are 0.2–0.3 dex below the mean trend in the observations. Only at the lowest metallicities (\(< 0.1 \, Z_{\odot}\)) do we predict dust-to-gas ratios slightly higher than suggested by observations.

We find less good agreement between model predictions and observations for the other model variants. Especially at metallicities lower than 0.1 \( Z_{\odot} \), the other model variants predict dust-to-gas ratios that are too high. In the case of the ‘no-acc’ and ‘high-cond’ models this is easily explained by the high condensation efficiencies in SNe. In the case of the ‘fix-tau’ model variant, the time-scale for dust growth
Figure 5. The dust-to-metal ratio of galaxies as a function of their metallicity from redshift $z = 9$ to $z = 0$, for our four model variants. Thick lines mark the 50th percentiles, whereas the narrow dotted lines mark the 16th and 84th percentiles (note that the scatter predicted by the different model variants for this plot is very small). The $z = 0$ prediction by our fiducial model is shown as a dashed double dotted grey line in the higher-redshift bins for comparison. Model predictions at $z = 0$ are compared to the dust-to-metal ratios derived from Rémy-Ruyer et al. (2014a). The $12 + \log(O/H)$ values corresponding to metallicities of 0.1, 0.5, and 1.0 $Z_\odot$ are represented by small black vertical lines.

is shorter than in our fiducial model at low metallicities (for H$_2$ surface densities less than 300 $M_\odot$ yr$^{-1}$, see Figure 1). Therefore, the accretion of dust plays a more important role and increases the dust-to-gas ratios at low metallicities rapidly. At the highest metallicities on the other hand the 'fixed-tau' model variant predicts dust-to-gas ratios lower than our fiducial model. This is because the accretion times at these high metallicities is never high enough to deplete enough metals on dust grains (see Figure 1). Similarly, the 'no-acc' model also predicts dust-to-gas ratios that are too low, due to the lack of growth of dust in the ISM in general.

Our fiducial model predicts weak evolution in the relation between dust-to-gas ratio and gas-phase metallicity. At metallicities less than 0.5 $Z_\odot$ the dust to gas ratio increases with $\sim$0.3 dex from $z = 9$ to $z = 0$. At higher metallicities the relation between dust-to-gas ratio and metallicity at $z > 5$ is similar to the $z = 0$ relation. The relation then decreases with approximately 0.2 dex to $z = 4$ and slowly
Figure 6. The dust-to-metal ratio of galaxies as a function of their stellar mass from redshift \( z = 9 \) to \( z = 0 \), for our four model variants. Thick lines mark the 50th percentiles, whereas the narrow dotted lines mark the 16th and 84th percentiles. The \( z = 0 \) prediction by our fiducial model is shown as a dashed double dotted grey line in the higher-redshift bins for comparison. Model predictions at \( z = 0 \) are compared to the dust-to-metal ratios derived from Remy-Ruyer et al. (2014).

We show the dust-to-gas ratio of galaxies as a function of their stellar mass in Figure 4. The dust-to-gas ratio increases with stellar mass. Our fiducial model reproduces the dust-to-gas ratios observed in local galaxies. We find a rapid increase in the dust-to-gas ratio with stellar mass in the mass range \( 10^8 < M_* < 10^{9.5} M_\odot \) and a shallower increase at lower and higher stellar masses. The other model variants all also predict an increase in dust-to-gas ratio, although not as strong. All the other model variants predict dust-to-gas ratios almost an order of magnitude higher than our fiducial model in the mass range \( M_* < 10^{9.5} M_\odot \). The

increases again with cosmic time to its \( z = 0 \) value. We will discuss the origin of this strange behaviour in Section 6.3.

We find basically no evolution in the relation between dust-to-gas ratio and gas-phase metallicity for the ‘no-acc’ model variant. The predictions by the ‘high-cond’ model variant are very similar to our fiducial model. The ‘fix-tau’ model variant on the other hand predicts a strong evolution in the dust-to-gas galaxies. This variant predicts an increase in the dust-to-gas ratio of galaxies from \( z = 9 \) to \( z = 0 \) of almost an order of magnitude, independent of gas-phase metallicity. This increase especially happens at redshifts \( z < 3 \).
dust-to-metal ratio increases gradually towards the \( z = 0 \) relation. At higher redshift and metallicities larger than \( \sim 0.5 \, Z_\odot \), the dust-to-metal ratio is slightly higher than at \( z = 0 \). As for the dust-to-gas ratio, we will further discuss this in Section 5.3.

The predictions by our fiducial model for the dust-to-metal ratios of galaxies at \( z = 1-4 \) are in poor agreement with the observational constraints from Damped Lyman-alpha and GRB absorbers by De Cia et al. (2013), De Cia et al. (2016), and Wiseman et al. (2016). Our fiducial model predicts dust-to-metal ratios systematically lower than found in the absorbers, especially at low metallicities. Although the disagreement is discouraging, it is important to remember that we did not try to select for absorbers in any way and that the exact nature of Damped Lyman-alpha absorbers and their host galaxy properties remain unclear. We will perform a more fair comparison between absorbers and our model results in a future work, employing selection techniques to mimic the observational selection of DLAS as in Berry et al. (2014). Moreover, the method for determining both dust mass and metallicity in absorbers is quite different from that used for galaxies that are selected via their stellar or dust emission. It is unknown whether these measurements can be compared on a consistent scale. Certainly, the strong change from a very flat dust-to-metal ratio with metallicity seen in DLAS at high redshift and the strong dependence on metallicity seen in nearby galaxies is intriguing, if true. DLAS are thought to arise from the outskirts of gas disks in galaxies and perhaps even from the circumgalactic medium [Berry et al. (2014)]. This discrepancy may reflect a difference in dust growth or destruction timescales in different environments rather than an evolutionary effect.

The ‘no-acc’ and ‘high-cond’ model variants also only show very weak evolution in their dust-to-metal ratio. The dust-to-metal ratios predicted by the ‘fixed-tau’ model variant increase by an order of magnitude from \( z = 9 \) to \( z = 2 \) for galaxies with gas-phase metallicities of \( 12 + \log(O/H) \sim 8 \). An interesting difference compared to our fiducial model is that the other model variants seem to agree much better with the dust-to-metal ratios found in absorbers, especially at low metallicities. This is driven by the high-condensation efficiencies for the ‘no-acc’ and ‘high-cond’ model, and the lower accretion timescale at low metallicities for the ‘fixed-tau’ model than in our fiducial model (Figure 1). The trend with metallicity on the other hand is the opposite from what the observations suggest. The absorbers show a shallow increase in dust-to-metal ratio with increasing metallicity, whereas the model variants all show a decreasing trend with metallicity.

We plot the dust-to-metal ratio of galaxies as a function of their stellar mass in Figure 1. We find that the dust-to-metal ratio at \( z = 0 \) predicted by our fiducial model is constant up to stellar masses of \( 10^{8.5} \, M_\odot \) at 0.07, then increases till 0.3 at \( M_\ast = 10^{10} \, M_\odot \), and slowly decreases again at higher stellar masses. Just as in the previous plot, these phases represent the regimes where only condensation in stellar ejecta is relevant (at low masses), dust growth in the ISM starts to become important (at intermediate masses), and the destruction becomes more efficient (at the highest masses). Our model predictions are in the same regime as the observations, though the shape of the trend appears to
be very different and on average our model predicts dust-to-metal ratios that are a bit too low for galaxies with stellar masses larger than $10^{8.5} \, M_\odot$.

The other model variants show very different trends, where the highest dust-to-metal ratios are found at the lowest stellar masses, and the dust-to-metal ratio gradually decreases towards lower values at higher stellar masses. The latter is due to more efficient destruction. Although the agreement with the data seems better at stellar masses larger than $10^{8.5} \, M_\odot$, at lower stellar masses the predicted dust-to-metal ratios are an order of magnitude (or more for the `fix-tau' model variant) too high. The high dust-to-metal ratios at lower stellar masses are driven by the high condensation efficiencies for the `no-acc' and `high-cond' model and the shorter accretion times for dust growth in low-metallicity environments for the `fix-tau' model variant.

There is only very weak evolution in the relation between stellar mass and dust-to-metal ratio predicted by our fiducial model up to $z = 6$. We find that at redshifts $z > 3$ the dust-to-metal ratio tends to be approximately 0.1 dex higher in the mass range $10^8 < M_*/M_\odot < 10^{10}$ than at $z = 0$, the regime where the growth of dust in the ISM becomes important. At higher redshifts we predict dust-to-gas ratios in the most massive galaxies that are up to 0.2 dex higher than at $z = 0$. Although the mean trend is very similar, the scatter in the relation increases significantly when going to further lookback times. The `high-cond' and `no-acc' model variants behave in the same way. The `fix-tau' model variant on the other hand predicts a strong increase in the dust-to-metal ratio of galaxies with cosmic time of an order of magnitude (or even more at the lowest stellar masses) from $z = 9$ to $z = 0$. We will discuss this further in Section 5.4.

### 5.3 Dust mass functions

Figure 1 shows our predictions for the dust mass function of galaxies. No selection criteria was applied for this Figure, so all galaxies are taken into account. We compare our predictions to the observed dust mass function in the local Universe and up to $z \sim 3$. We warn the reader that different groups have used different approaches to infer the dust mass of a galaxy based on its IR and sub-mm fluxes. This can lead to systematic uncertainties in the observed dust masses up to a factor of three.

We find that our predicted dust mass functions closely follow a Schechter (1976) function with a characteristic dust mass of $\sim 10^{8.5} \, M_\odot$ at $z = 0$. This characteristic dust mass is similar for the `high-cond' and `fix-tau' model variants. The dust mass function predicted by our fiducial model is in good agreement with the observed dust mass functions at dust masses less than $10^{8.5} \, M_\odot$. Our fiducial model predicts number densities for galaxies with larger dust masses that are too high.

The `no-acc' model variant predicts a dust mass function with slightly higher number densities than our fiducial model at dust masses lower than $10^8 \, M_\odot$. At higher dust masses the number densities predicted by the `no-acc' model variants are lower than by our fiducial model and right between the Vlahakis, Dunne & Eales (2005) and Dunne et al. (2011) model predictions. We predict hardly any difference between the fiducial and the `high-cond' model variants. Only at dust masses smaller than $10^7 \, M_\odot$ does the `high-cond' variant predict a number density $\sim 0.3$ dex higher than our fiducial model. The `fix-tau' model variant predicts number densities approximately 0.5 dex larger for galaxies with dust masses than $10^{7.5}$ and larger than $10^8 \, M_\odot$. The elevated number densities at low dust masses with respect to our fiducial model are driven by the high condensation efficiencies in the `high-cond' and `no-acc' model variants, and the short timescales for dust growth in the ISM in low-metallicity environments for the `fix-tau' model variant.

Our fiducial model predicts a rapid increase in the number density of the dust mass function from $z = 9$ to $z = 3$, independent of galaxy dust mass. The dust mass function is remarkably constant from $z = 2$ to $z = 0$ for galaxies with dust masses less than $10^{8.5} \, M_\odot$, whereas the number densities keep increasing from $z = 2$ to $z = 0$ for galaxies with larger dust masses. Our fiducial model predicts too few galaxies more massive than $\sim 10^9 \, M_\odot$ at redshifts $z > 2$. We note that the observational constraints by Eales et al. (2000) and Dunne, Eales & Edmunds (2003) are based on surveys of sub-mm sources with large beam sizes (larger than 14 arcsec). High spatial resolution observations with ALMA have suggested that the brightest sub-mm sources in such surveys consist of multiple lower luminosity objects, blended within one large beam (Karim et al. 2013; Hayward et al. 2013a).

The evolution of the dust mass function predicted by the `high-cond' model variant is very similar to our fiducial model. The same is true for the `no-acc' variant, although with lower number densities at the highest dust masses. The `fix-tau' model variant also predicts an increase in the number density with time, but the rate of increase is much slower than for our fiducial model and continues up to $z = 1$. The slow growth of dust masses is in accordance with the evolution in the relation between dust mass and stellar mass (Figure 2).

### 5.4 Dust formation and destruction rates

We present the dust formation and destruction rate (only in the cold ISM, not in the hot halo) of galaxies as a function of their stellar mass in Figure 5. We only focus on our fiducial model, as this model most successfully reproduce the trends in local observations. We present the formation rate through the individual channels for the other model variants in Appendix A. We find that the formation rate through the different dust formation channels (SNe, AGB stars, and dust growth in the ISM) all increase as a function of stellar mass. The formation rate by stellar ejecta can be described by one linear relation as a function of stellar mass. The relation between formation rate through accretion and stellar mass is made up of multiple components. It is steepest in the stellar mass range $10^{8.5} - 10^{9} \, M_\odot$ and flattens at higher stellar masses. The dust destruction rate is systematically $\sim 0.2$ dex lower than the formation rate through dust accretion for galaxies with stellar masses larger than $10^9 \, M_\odot$. In galaxies with lower stellar masses the destruction rate of dust roughly equals the formation rate through accretion.

The normalisation in the relation between dust formation rate by stellar ejecta and stellar masses slowly decreases from $z = 9$ to $z = 0$ by approximately 2 dex and 1 dex for SNe and AGB stars, respectively. We also find an 2 dex decrease in this redshift range for the formation rate by ac-
Figure 7. The redshift evolution of the dust mass function for four model variants. Predictions are compared to mass functions obtained from the literature (Dunne, Eales & Edmunds 2003; Vlahakis, Dunne & Eales 2005; Eales et al. 2009; Dunne et al. 2011; Clemens et al. 2013). The $z = 0$ prediction by our fiducial model is shown as a dashed double dotted grey line in the higher-redshift bins for comparison.

cretion and the destruction rate of dust. The characteristic stellar mass at which the formation rate through accretion and stellar mass flattens also evolves with time, from $\sim 10^9 M_\odot$ at $z = 9$ to $\sim 10^{10} M_\odot$ at $z = 0$.

An interesting prediction is that the formation rate of dust through accretion is almost always higher than the formation rate by SNe and by AGB stellar ejecta. Only at stellar masses of $\sim 10^7 M_\odot$ is the formation rate through SNe as high as the formation rate through growth in the ISM, although not at all redshift.

5.5 Dust in the hot halo and ejected reservoir

Besides dust in the ISM of galaxies, our model also tracks the dust in the hot halo and the ejected reservoir. If we make the simple assumption that dust in the hot halo corresponds to the dust in the CGM, we can compare our model predictions to recent observations (Ménard et al. 2010; Peek, Ménard & Corrales 2015).

We present the relation predicted by our fiducial model between host galaxy stellar mass and dust in the hot halo in Figure 8 (the predictions of the other model variants are very similar). For this Figure we required galaxies to
Figure 8. The formation and destruction rate of dust as a function of stellar mass from redshift $z = 9$ to $z = 0$, for our fiducial model. Dust formation rates are separated into formation due to AGB stars, SNe, and growth of dust in the ISM. Thick lines mark the 50th percentiles, whereas the narrow dotted lines mark the 16th and 84th percentiles.

We first of all find that at $z \leq 5$ there seem to be two distinct ‘branches’ on the plot of stellar mass and hot halo dust mass, one with high dust masses and the other with low dust masses. These two branches reflect two different regimes for cooling and accretion in our model. When the predicted “cooling radius” is larger than the virial radius, we assume that gas (and dust) accrete directly onto the central galaxy on a dynamical timescale, so little gas and dust collect in the “hot” reservoir. When the predicted cooling radius is smaller than the halo virial radius, gas and dust cool onto the central galaxy on a cooling timescale, so more material builds up in the hot halo reservoir (see Somerville et al. 2008b for more details). These two regimes correspond to the “cold mode” and “hot mode” accretion also seen in numerical hydrodynamic simulations (Birnboim & Dekel 2003; Dekel & Birnboim 2006; Keres et al. 2005). One should keep in mind that the plotted means in Figure 8 represent the mean of these two relations.

We find that the mass of dust in the hot halo at
The dust content of galaxies from $z = 0$ to $z = 9$

Figure 9. The mass of dust in the ISM (solid line), hot halo (dashed line), and the ejected reservoir (dotted line) as a function of host galaxy stellar mass from redshift $z = 9$ to $z = 0$, as predicted by our fiducial model. Thick lines mark the 50th percentiles, whereas the narrow dotted lines mark the 16th and 84th percentiles. The color scale shows the logarithm of the conditional probability distribution $P(M_* | M_{\text{dust hot halo}})$, which represents the likelihood to find a dust mass $M_{\text{dust hot halo}}$ in the hot halo as a function of central galaxy stellar mass. The $z = 0$ prediction by our fiducial model for the dust mass in the hot halo is shown as a dashed double dotted grey line in the higher-redshift bins for comparison. We compare our predictions to the CGM constraints at $z = 0$ by Peek, Ménard & Corrales (2015).

The mass of dust in the ejected reservoir increases gradually with central galaxy stellar mass. At $z = 0$ predicted by our fiducial model increases with host galaxy stellar masses and flattens above stellar masses of $\sim 10^{10.5} M_\odot$. The amount of dust in the hot halo is comparable to or even larger than the amount of dust in the ISM for galaxies with stellar masses of $\sim 10^{10} M_\odot$ and larger. Our predictions are in the same mass range as the observational constraints derived by Peek, Ménard & Corrales (2015). However, we find a distinct difference between our model predictions and the Peek et al. results for the slope between central galaxy stellar mass and CGM dust mass. The Peek et al. slope is significantly shallower than our model predicts. We will further discuss this in Section 6.5.

We find that the mass of dust in the ejected reservoir increases gradually with central galaxy stellar mass. At $z = 0$ the mass of dust in the ejected reservoir is significantly larger than the mass of dust in the hot halo and the cold gas components. It is unclear what physical conditions or even spatial distribution the material in our ejected reservoir should
Figure 10. Left: The cosmic density of dust in the ISM of galaxies as a function of redshift for the four model variants. Model predictions are compared to constraints from the literature (De Bernardis & Cooray 2012; Clemens et al. 2013; Thacker et al. 2013; Clark et al. 2015). Right: The cosmic formation rate (by AGB stars, SNe, and metal accretion) and destruction rate of dust in the ISM as a function of redshift.

possess, or what observational quantities it should correspond to. Moreover, in our current model we do not include any processes that destroy dust in the ejected reservoir (see Section 6.7.2). These results should thus be treated with caution, but demonstrate that very large amounts of dust may be removed from galaxies by winds in these models.

Our model predicts that the mass of dust in the hot halo gradually increases with cosmic time. Especially in the most massive central galaxies ($M_\ast > 10^{10} M_\odot$), we see an increase in hot halo dust mass from $z = 9$ to $z = 0$ of two orders of magnitude. In this mass range, the mass of dust in the hot halo starts to dominate over the mass of dust in the cold gas at redshifts $z < 2$. We find a very similar evolution for the dust in the ejected reservoir.

5.6 The cosmic density and formation history of dust

5.6.1 Evolution of the dust density of our Universe

We show the cosmic density of dust in the ISM of galaxies in the left panel of Figure 10. All modeled galaxies are taken into account, so no selection criteria were applied for this Figure. The cosmic density of dust in the ISM in our fiducial model gradually increases with time up to $z = 0$. At $z = 0$ our model predictions are in decent agreement with the findings by [Clark et al. 2015], but overpredict the constraints by [Dunne et al. 2011] by a factor of four. We again note that these different studies adopted different methods to estimate the dust mass of galaxies, which accounts for some of the discrepancy between them (see Section 4). Our model predicts too much dust at $z > 0$ compared to the constraints by [Dunne et al. 2011]. It is in good agreement with the constraints by [Thacker et al. 2013] at $z < 0.5$, but predicts too little dust compared to the observations by De Bernardis & Cooray (2012) and Thacker et al. (2013) at higher redshifts.

The cosmic dust density predicted by the ‘no-acc’ model variant starts to deviate from our fiducial model from $z = 1$, where it predicts lower dust mass densities. These predictions are still to high compared to the Dunne et al. (2011) results at $z < 0.5$, but in better agreement at redshifts $0.5 < z < 1$. The predictions are too low compared to the densities found by De Bernardis & Cooray (2012) and Thacker et al. (2013). The predictions of the ‘high-cond’ and fiducial model variants are almost identical. The ‘high-
The dust content of galaxies from $z = 0$ to $z = 9$

Figure 12. The gas-phase metallicity of galaxies as a function of their stellar mass from redshift $z = 9$ to $z = 0$. Plotted is our fiducial model where metals are depleted on to dust grains and a model variant where dust-chemistry is turned off. Thick lines mark the 50th percentiles, whereas the narrow dotted lines mark the 16th and 84th percentiles. Model predictions are compared to observations from Maiolino et al. (2008), Mannucci et al. (2009), Andrews & Martini (2013), and Zahid et al. (2014).

cond’ model predicts slightly higher cosmic densities for dust, driven by the high condensation efficiencies of dust in the stellar ejecta. The ‘fix-tau’ model variant predicts lower densities for dust at $z > 1.5$, up to approximately 0.8 dex less dust at $z = 6$ than our fiducial model. As the other model variants, the ‘fix-tau’ model predicts too low dust densities compared to the De Bernardis & Cooray (2012) and Thacker et al. (2013) results at $z > 1.5$.

We present the integrated density of dust in hot halos and ejected reservoirs as predicted by our fiducial model in Figure 11. We find that the cosmic density of dust in hot halos is larger than the mass of dust in cold gas, independent of redshift. This ratio is especially large below redshifts of $z \sim 1.5$ (up to $\sim 0.7$ dex at $z = 0$), when the cosmic density of dust in cold gas decreases, whereas the density of dust in hot halos keeps increasing. We find that the density of dust in ejected reservoirs is almost two dex higher than in cold gas, independent of redshift. We will further discuss this large reservoir in Section 6.5 and Section 6.7.2. We compare our predictions to the observations of dust in the IGM by Menard & Fukugita (2012). Interestingly, the density of dust in the ISM predicted by our model is in close agreement with the density...
observed for the IGM. The predicted densities of dust in the hot halo and ejected reservoirs are significantly larger than the constraints for the density of dust in the IGM.

5.6.2 Formation history of dust

We present our predictions for the global dust formation and destruction rate in the Universe in the right hand panel of Figure [11]. We note that we only show the predictions of our fiducial model.

The total dust formation rate increases from redshift $z = 6$ to $z = 2$ and decreases again at later times. At its maximum, the formation rate is almost four times higher than at $z = 0$. The evolution of this trend is similar to the cosmic SFR density (Madau & Dickinson 2014), though the difference between its maximum and the $z = 0$ value is not as large. The accretion of metals onto dust grains in the ISM is the dominant mode of dust formation/growth, independent of redshift. The contribution by SNe and AGB stars to the dust formation rate density of our Universe is more than two orders of magnitude less. We emphasise that the dust formation rate density will be dominated by galaxies with dust masses close to the knee of the dust mass function at the respective redshifts. As seen in the previous section, the relative importance of the different dust formation channels may be different in individual galaxies.

The cosmic rate of dust destruction follows a trend very similar to the formation rate; it increases up to $z = 2$ and decreases again at later times.

5.7 Depletion of gas-phase metals

The inclusion of dust in our galaxy formation model immediately impacts the gas-phase metallicity of galaxies. A fraction of the metals in the ISM will be depleted onto dust grains, effectively lowering the gas-phase metallicity of galaxies.

We show the effects of the depletion of metals on to dust in Figure [12]. We present the gas-metallicity of galaxies using our fiducial model and the gas-phase metallicity of galaxies when not including dust chemistry. We find that the depletion of metals typically only becomes relevant in galaxies with stellar masses more massive than $10^9$ $M_\odot$. The depletion of metals lowers the gas-phase metallicity of galaxies by approximately 0.1 dex.

Now that metal depletion is properly accounted for, we can assess how well our model reproduces the observed relation between stellar mass and gas-phase metallicity (Maiolino et al. 2008; Mannucci et al. 2009; Andrews & Martini 2013; Zahid et al. 2014). It is important to note that gas-phase abundance measures are sensitive to calibration (Kewley & Ellison 2008), but usually relative abundances are consistent among various indices. Hence the slope of the observed gas-phase metallicity relation is more robustly known than the amplitude, though the amplitude should still be accurate to within a factor of 2–3. We find that at $z \leq 2$ our model predicts metallicities systematically below the observed relation in our local Universe, up to as much as 0.4 dex in low-mass galaxies at $z = 1$. Our predictions are in good agreement with the observations by Zahid et al. (2014) at $z = 2$, and the observations by Mannucci et al. (2009) at $z = 3–4$.

The slope of the mass-metallicity relation is in decent agreement with the observations at $z > 0$. We correctly predict the flattening of the mass-metallicity relation in galaxies with stellar masses larger than $10^{10.5}$ $M_\odot$. At $z = 0$ on the other hand the slope is correct in low mass galaxies, but we don’t predict the flattening observed in galaxies with stellar masses larger than $10^{10}$ $M_\odot$. Although the depletion of metals decreases the gas-phase metallicity of galaxies, it is not responsible for the flattening of the mass-metallicity relation in our models.

6 DISCUSSION

In this paper we have included tracking of the formation and destruction of dust in the Santa Cruz semi-analytic model of galaxy formation. We discuss the conclusions that can be drawn from our model predictions for dust evolution in galaxies in this section.

6.1 Insights from comparing model variants

In our fiducial model, dust is produced in the ejecta of AGB stars and supernova, and also through accretion onto grains in the dense ISM. The timescale for dust growth by accretion is a function of the density, temperature, and metallicity of the molecular clouds in which this process is efficient. In addition to our fiducial model we have also explored three other model variants: one in which no growth of dust through accretion onto grains in the ISM occurs, and condensation efficiencies in stellar ejecta are large; one in which the only change is that the dust condensation efficiencies in stellar ejecta are high; and finally one in which a fixed time scale for the accretion of metals onto dust grains is assumed.

Recent work by Ferrara, Viti & Ceccarelli (2016) has suggested that the contribution of dust growth by accretion onto grains in dense environments to the dust mass of galaxies is negligible. Ferrara et al. argue that in dense environments accreted materials form icy water mantles. These mantels quickly photo-desorb once the grains return to the diffuse ISM at the end of the cloud lifetime. This would have significant implications for our main conclusion, that dust-growth in the ISM is a key ingredient to reproduce both the observed dust masses in galaxies and the shape of various scaling relations. Our ‘no-aac’ model variant is an attempt to explore the global consequences of the Ferrara, Viti & Ceccarelli (2016) picture. Assuming a condensation efficiency of 100% in the stellar ejecta, this model is able to reproduce the dust masses observed in very high redshift galaxies ($z \approx 4–7$). The model also reproduces dust masses in massive galaxies at $z = 0$. However, the model predicts $z = 0$ dust masses in low-metallicity objects that are too high and dust-to-gas ratios in metal-rich galaxies that are too low.

There are significant uncertainties in other aspects of our modelling that could plausibly bring this model into better agreement with observations. For example, it is possible that the efficiency of dust destruction depends on environment in a more complex manner than we have represented in
our models (indeed, Temim et al. 2015) found the dust destruction rate in the Large Magellanic cloud to be lower than in the Small Magellanic Cloud). It is also possible that galactic winds could preferentially eject dust relative to gas, or that dust could be destroyed in these winds. However, these processes must lead to an effective metallicity dependence in the net production of dust in order to steepen the dust-to-gas and dust-to-metal ratio relation and bring this model into agreement with observations. Moreover, clearly our assumption of 100% efficiency of dust production in stellar ejecta is extreme. In tests in which we adopt condensation efficiencies of 50%, we find that our model is unsuccessful in reproducing the dust masses of local galaxies. Lower condensation efficiencies would result in even larger discrepancies. As an example of this we can take the ‘fix-tau’ model variant that fails to reproduce the dust-masses of high-redshift galaxies. If a fixed timescale for dust growth of 100 Myr is not sufficient, than a model variant with shorter accretion times or no accretion at all can certainly not reproduce high-z observations (without increasing the condensation efficiency in SNae and AGB stars).

It is interesting that the ‘no-acc’ model predicts hardly any evolution in the dust-to-gas ratios of galaxies as a function of their stellar mass, independent of redshift. We do predict an evolution in these trends for all the other model variants (that include metal accretion). This suggests that the evolution seen in our fiducial model is driven by the effective dependence of the dust growth timescale on galaxy properties which evolve with cosmic time. A more complete census of the dust-to-gas of galaxies as a function of cosmic time and galaxy properties would therefore be an important test of the importance of dust growth in the ISM.

We find that differences between our fiducial model and the ‘high-cond’ model variants are only prevalent in galaxies with low stellar masses and low metallicity. In massive and metal-rich galaxies the dust properties are dominated by the accretion of metals onto dust grains (Figure 5). The ‘high-cond’ model variant overpredicts the dust abundance for galaxies with low metallicities (< 0.2 Z⊙) and low stellar masses (< 10^8 M⊙). Besides theoretical work on the condensation efficiency of AGB stars and SNe (Ferrarotti & Gail 2006, Bianchi & Schneider 2007), our predicted dust abundances also suggest that constant high condensation efficiencies (as in e.g., Bekki 2013, McKinnon et al. 2016) are an unrealistic way of building up large dust masses in galaxies. The buildup of dust is too efficient in low-mass galaxies. This same conclusion applies to the ‘no-acc’ model variant.

Differences between our fiducial model variant and the ‘fix-tau’ model are prevalent across the metallicity and stellar mass range probed by our models. The ‘fix-tau’ model predicts dust abundances in low metallicity galaxies at z = 0 that are much higher than predicted fiducial model. Dust abundances are much lower for galaxies with metallicities higher than 1 Z⊙. The build up of dust in galaxies when adopting the ‘fix-tau’ model variant is much slower (i.e., much lower dust masses as a function of stellar mass and redshift) than for our fiducial model (see for example Figures 2, 7 and 10). As briefly mentioned before, the slow buildup is driven by the long accretion time scales of 0.1 Gyr compared to accretion time scales of 10 Myr or even less in dense environments for our fiducial model (see Figure 1). A variable accretion time scale allows for much more efficient accretion of metals onto dust grains in the early Universe, speeding up the formation in dust.

In low metallicity objects on the other hand the accretion time scale is easily shorter than we would calculate with our density and metallicity variable recipe (see Figure 11). This allows for a higher rate of dust growth in the low-metallicity ISM in small objects, and an increase in dust mass with respect to our fiducial model. This can also be seen when looking at the formation rate of dust through growth in the ISM in Figure A2.

The poor agreement between the predictions by the ‘fix-tau’ model and observed dust masses in galaxies at z = 6 and z = 7 seems to rule out fixed accretion times of 100 Myr. This is further supported by the poor agreement between model predictions and observations for the dust-to-gas ratio and dust-to-metal ratio of galaxies. McKinnon et al. (2016) adopted a fixed accretion timescale and predicts dust reservoirs in galaxies at z = 2.5 that are much too small compared to observations. What this tells us is that accretion times-scales should be much shorter than 100 Myr in the early Universe. We tested shorter fixed accretion times of for example 10 Myr to reproduce the z = 6 and z = 7 dust masses, but this led to an even stronger disagreement between model predictions and observations at z = 0 at both low and high stellar masses.

We thus conclude that a variable accretion time scale as adopted in our fiducial model is necessary to reproduce the buildup of dust in galaxies (Mancini et al. 2015, Schneider, Hunt & Valiante 2016). There is a need for short depletions times in the early Universe, but these short depletion times can not be sustained, otherwise too much dust grows in the low-redshift Universe. An accretion time-scale that is solely a function of metallicity could not provide this behavior. Gas-phase metallicity increases with cosmic time, therefore accretion time-scales would only become shorter with cosmic time, the opposite from what we needed. With density as an additional parameter, we can reverse this trend and reproduce the dust mass of low- and high-redshift galaxies simultaneously (Mancini et al. 2015).

6.2 Importance of the different dust formation channels

We have implemented three different modes of dust formation in our dust-tracking model: condensation of dust in AGB ejecta, condensation of dust in SNe ejecta, and the accretion of gas-phase metals onto existing dust grains. Figure 5 clearly shows that in our fiducial model, the growth of dust in the ISM is the dominant channel through which dust builds up in galaxies. Although AGB stars and SNe are necessary to form the first grains of dust, the accretion of metals onto dust grains rapidly takes over. This is also clear when focusing on the cosmic formation rate of dust (Figure 10), where the formation rate through accretion is approximately four orders of magnitude larger than the formation rate by stellar ejecta. These results support the hypothesis that metal accretion is the dominant mode of dust formation for high-redshift galaxies with large observed dust reservoirs (e.g., Dwek, Galliano & Jones 2007, Michalowski 2015). Only in galaxies with stellar masses less than 10^7 M⊙ does the condensation of dust in SN ejecta take over as most important channel through which dust forms.
Besides formation, it is also important to consider the destruction of dust in the ISM. We find that the destruction rate of dust by SNe is much higher than the formation rate of dust by stellar ejecta. Furthermore, Figures 8 and 10 both show that the destruction rate of dust closely follows the formation rate of dust through accretion onto grains. Galaxies quickly achieve a balance between these two processes. At $z < 2$, the destruction rate of dust is approximately two thirds of the formation rate through accretion onto grains. At higher redshifts this number drops to approximately half of the formation rate through metal accretion at $z \sim 4$, up to almost a tenth at $z = 9$.

We can understand why the dust growth rate and destruction rate track each other so closely by examining the recipes for each of these processes. The rate of accretion of metals onto dust grains is set by the abundance of the species of interest, as well as by the volume density, which we derived from the SFR and molecular hydrogen surface density. The destruction rate is set by the number of SNe, which closely follows the SFR. The SFR surface density is set by the molecular hydrogen surface density and metallicity of the gas. Since the accretion timescale and destruction rate are to first order set by the same physical parameters (metallicity and molecular hydrogen/SFR surface density) it is not surprising that the two closely follow each other. The variation in the ratio between destruction and growth is then set by the exact conditions under which the processes occur, depending on for instance the available gas-phase metals for dust growth, the available diffuse gas to be cleared from dust, and the effective exchange times of the molecular clouds.

It should be noted that the ‘no-acc’ model variant is also able to reproduce the dust masses in galaxies without invoking any growth of dust through accretion onto grains at all. In this model variant the production of dust in SNe ejecta is the dominant mode of dust formation. However, this model requires a perhaps unrealistically high value for the condensation of dust in stellar and SN ejecta, and does not reproduce scaling relations for dust-to-gas ratios and dust-to-metal ratios in the local Universe as well as our fiducial model.

### 6.3 Gas-to-dust and metal-to-dust ratios

In recent years it has become clear that the dust-to-gas ratio of galaxies in the local Universe can be described by a double power-law (and not a single one) as a function of gas-phase metallicity (Remy-Ruyer et al. 2014a). Our model successfully reproduces the observed trend. This is, however, only achieved in our fiducial model, which suggests that it is the combination of low condensation efficiencies and the growth of dust in the ISM which shapes the relation between dust-to-gas ratio and gas-phase metallicity.

We found that the relation between dust-to-gas ratio and gas-phase metallicity is constant to within $\sim 50\%$ for galaxies with gas-phase metallicities larger than 0.5 $Z_\odot$. The dust-to-gas ratio decreases a bit with lookback time from $z = 0$ to $z = 4$, but increases again at higher redshifts. In these galaxies the reservoir of dust is fully determined by the balance between dust growth in the ISM and the destruction of dust by SNe. We have seen in the previous sub-section that these two processes closely follow each other, as they depend on the same set of physical quantities. The variations with redshift are thus the result of small variations in the ratio between dust growth in the ISM and destruction. These were driven by properties such as the available metals for dust growth, the amount of diffuse gas, and the exchange time of molecular clouds. We see the same actions at play when looking at the evolution of the dust-to-metal ratio of galaxies as a function of their gas-phase metallicity. Only at $z = 9$ is the relation between dust-to-metal ratio and gas-phase metallicity very different from the $z = 0$ relation.

The small evolution between metallicity and dust-to-gas and dust-to-metal ratio is important for observations of galaxy gas masses based on the dust continuum. Our predictions suggest that the locally derived dust-to-gas ratio as a function of gas-phase metallicity can be adopted within a certainty of approximately 50 $\%$ when estimating gas masses based on inferred dust masses.

The dust-to-metal ratio of galaxies predicted by our fiducial model cannot be described by a single power law as a function of gas-phase metallicity. There are three distinct regimes: one in which condensation in ejecta dominates, one in which dust growth in the ISM becomes increasingly important, and one in which the destruction of dust is almost in balance. This has important implications for modelling dust in cosmological simulations of galaxy formation. Typically it is assumed that metals and dust scale linearly (e.g., Silva et al. 1998; Granato et al. 2000; Baugh et al. 2005; Lacey et al. 2008, 2010; Fontanot & Somerville 2011; Niemi et al. 2012; Somerville et al. 2012; Hayward et al. 2013a, 2013b; Cowley et al. 2016). Future models need to properly account for the possible dependence of dust-to-metal ratio on galaxy properties and redshift.

Our model predicts a clear evolutionary trend in the relation between dust-to-gas ratio and stellar mass of galaxies. At fixed stellar mass, high-redshift galaxies have lower dust-to-gas ratios, especially for galaxies with stellar masses larger than $10^{10} M_\odot$ and at redshift $z > 2$. We previously saw that the relation between dust-to-gas ratio and gas-phase metallicity shows only weak evolution with time, and at the highest redshifts is similar to the $z = 0$ relation. This means that the evolution in the relation between dust-to-gas ratio and stellar mass must come from build-up of metals in galaxies in general. Indeed, we see an evolution in the gas-phase metallicity of galaxies at fixed stellar mass from $z = 9$ to $z = 3$ in Figure 12. This implies that one cannot use a fixed number for the dust-to-gas ratio when inferring a gas mass from massive galaxies at high-redshift (especially $z > 2$). Knowledge of the gas-phase metallicity is necessary to reliably estimate a galaxy gas mass. Interestingly, the relation between stellar mass and dust-to-metal ratio is relatively constant up to $z = 6$. A close look reveals that the scatter in this relation increases significantly with look-back time, again emphasising that one cannot estimate the dust-to-metal ratio of a galaxy by its stellar mass and $z = 0$ relations alone.

We compared the dust-to-metal ratios predicted by our fiducial model to the dust-to-metal ratios inferred from absorption studies up to $z = 4$. The observations suggest that the dust-to-metal ratios are similar to the values observed in our Local Group over a large redshift and metallicity range (Zafar & Watson 2013; Sparre et al. 2014; De Cia et al. 2013; 2016; Wiseman et al. 2016). Our predictions strongly dis-
agree with these observational constraints and predict much lower dust-to-metal ratios in low metallicity environments. In our fiducial model, the growth of dust in the ISM has not contributed significantly yet to the dust budget of the low-metallicity galaxies, causing this disagreement. It must be noted that the nature of high-redshift absorbers is not very clear and we have not tried to apply similar selection criteria to make a fair comparison. The physical conditions along an average DLA line of sight may differ significantly from a galaxy-wide average (Berry et al. 2014). Future models need to be able to reconcile these different constraints in conjunction with measurements of dust in emission in the local- and high-redshift Universe.

6.4 The evolution of dust masses in galaxies

In this subsection we focus on the buildup of dust in galaxies. From a galaxy-wide average (Berry et al. 2014) Future models need to be able to reconcile these different constraints in conjunction with measurements of dust in emission in the local- and high-redshift Universe. We find that the number density of these dusty low-metallicity galaxies, causing this disagreement. It must be noted that the nature of high-redshift absorbers is not very clear and we have not tried to apply similar selection criteria to make a fair comparison. The physical conditions along an average DLA line of sight may differ significantly from a galaxy-wide average (Berry et al. 2014). Future models need to be able to reconcile these different constraints in conjunction with measurements of dust in emission in the local- and high-redshift Universe.

The normalisation of the relation between stellar mass and dust mass decreases from $z = 3$ to $z = 0$. At higher redshifts the relation between stellar mass and dust mass is roughly constant with time. The amount of dust in the ISM of a galaxy is given by the balance between the amount of gas available and the dust-to-gas ratio. A redshift $z < 2$ (where the relation between dust-to-gas ratio and stellar mass of galaxies is largely constant as a function of time) the decrease in dust mass can be explained by the observed and inferred decrease in the gas fraction of galaxies (e.g., Tacconi et al. 2010, Narayanan et al. 2012, Tacconi et al. 2013, Santonja et al. 2013, Santini et al. 2013, Bethermin et al. 2015, Popping et al. 2015, Scoville et al. 2016). For a constant dust-to-gas ratio, the dust mass of galaxies as a function of stellar mass will therefore decrease as well. At higher redshift the dust-to-gas ratio still increases with cosmic time. The gas mass of massive galaxies on the other hand decreases at these redshifts (e.g., SPT14; Popping, Behroozi & Peeples 2015, Popping et al. 2015). Interestingly, there is a balance between the decrease in gas mass and the increase in dust-to-gas ratio, such that the relation between stellar mass and dust mass remains constant.

The number of dusty galaxies with masses larger than $10^9 M_\odot$ at the highest redshifts probed is relatively low (see Figure 7). We find that the number density of these dusty galaxies rapidly increases till $z = 3$, and then keeps growing till $z = 0$. This behaviour is in sharp contrast with the observed decline in the H$_2$ number density of galaxies at $z < 2$ (PST14; Walter et al. 2014, Decarli et al. 2016). The evolution of the dust mass function is reflected in our predicted cosmic density of dust, which grows up to a redshift of $z = 0$ and remains fairly constant at lower redshifts.

Our results have significant consequences for studies of the redshift distribution of sub-mm continuum selected galaxies (Aravena et al. 2016, Bouwens et al. 2016, Dunlop et al. 2016). The buildup of the dust mass function suggests that (depending on the sensitivity) blind surveys are most likely to pick up galaxies with redshifts lower than three. We do emphasise that our conclusion is based only on the dust mass of galaxies. We have not discussed how the temperature of the dust shapes the sub-mm SED and the detectability of the galaxy.

6.5 Dust in the hot halo and ejected reservoir

We have presented predictions for the mass of dust in the hot halo component in Figure 10. We found that the reservoir of dust in the hot halo increases with host galaxy stellar mass. At stellar masses larger than $10^{10} M_\odot$ the mass of dust in the hot halo is comparable to or larger than the mass of dust in the cold gas. The mass of dust in the reservoir of ejected baryons is larger than the mass of dust in the cold gas and hot halo at any stellar mass at $z = 0$. In Figure 10 we also show that the density of dust in the hot halo and ejected reservoir is always higher than the density of dust in the cold gas, especially at redshifts $z < 1.5$. These predictions suggest that a large fraction of the dust (and metals) ever formed may be stored outside galaxies (Peeples et al. 2014, Peek, Ménard & Corrales 2015). If we can quantify these reservoirs observationally, they will provide unique additional constraints for the ejective feedback recipes in galaxy formation models. It may well be that most of the ejected dust is destroyed in the winds or in the CGM/IGM. Future observations of absorption systems and reddening in the halos of galaxies will constrain these processes.

Peek, Ménard & Corrales (2015) found that galaxies at $z = 0$ with a luminosity of $0.1 L_\odot$ have as much dust in their CGM as in the ISM. We find similar results, where MW type galaxies have as much or even more of their dust in the hot halo gas as in the cold gas in the galactic disk. Our predicted slope between host galaxy stellar mass and hot halo dust mass is much steeper than that derived by Peek, Ménard & Corrales (2015) for the CGM. However, it is currently difficult to compare observations of the CGM in detail with our model predictions, so we prefer to avoid drawing strong conclusions. It is clear, nonetheless, that this is an important avenue to pursue in the future in order to constrain the importance of galactic winds in removing dust from galaxies and polluting diffuse gas in the CGM and IGM.

6.6 Depletion of metals

As discussed before, a fraction of the metals in the ISM is depleted onto dust grains, which lowers the gas-phase metallicity of galaxies. We have shown in Figure 12 that the depletion of metals becomes relevant in galaxies with stellar masses larger than $10^8 M_\odot$, where almost 40% of the gas-phase metallicity is in dust at $z = 1$. This correction should always be taken into account when comparing model predictions of the gas-phase metallicity of galaxies to observations. At the same time these results also suggest that the agreement between model predictions and observations for the gas-phase metallicity of galaxies is perhaps worse than previously thought. Low gas-phase metallicities are a common problem for many galaxy formation models (Somerville & Davé 2015), but the depletion of metals makes the dis-
agreement even stronger. To make matters worse, the dust-to-metal ratios predicted by our fiducial model appear to be too low (Figure 5). More accurately reproduced dust-to-metal ratios may therefore result in an even lower gas-phase metallicity. This emphasises the need for new or modified recipes that model the cycle of gas and metals in and out of galaxies. These issues are likely also linked to other problems galaxy formation models face, such as producing too many low-mass galaxies at $z > 0$ and too-low specific star-formation rates and gas masses at $z = 2$ (Somerville & Davé 2015; Popping, Behroozi & Peeples 2015).

6.7 Caveats

Here we discuss a number of caveats that should be taken into account when interpreting our results.

6.7.1 Dust as an ingredient of gas physics

Dust plays an important role in the cooling and shielding of gas. We have not included these processes in this work, but treat dust as ‘normal metals’. Future work should self-consistently include dust as a coolant, as well as the role of dust in molecular clouds. The latter is of particular interest. Star-formation rates in our model are calculated based on the surface density of molecular hydrogen. The molecular hydrogen fraction of gas in our model is a function of gas-phase metallicity, whereas this should actually be a function of dust abundance (Gnedin & Kravtsov 2011). We have so far made the assumption of a linear scaling between dust abundance and gas-phase metallicity, but observations (Edmunds 2001; Rémy-Ruyer et al. 2014a) and our modelling efforts show that this assumption is incorrect. This should especially manifest itself in low-mass and low-metallicity galaxies, where the linear scaling between dust-abundance and metallicity clearly breaks down. The low dust abundances (with respect to the gas-phase metallicity) in low mass galaxies will result in lowered molecular hydrogen fractions and consequently lower star-formation rates. It is possible that the build up of stellar mass in low-metallicity galaxies can thus be slowed down by adopting a dust-based molecular hydrogen recipe (though see SPT15 for a discussion on how the self-regulating nature of star formation means that lowering the efficiency of star formation does not always result in the production of fewer stars). Preliminary tests show that (without changing any of the free parameters) this mostly affects galaxies in haloes with masses less than $\sim 10^{11} M_\odot$. We will explore the effects of self-consistently modelling the formation of molecular hydrogen based on our estimated dust masses in a future work.

6.7.2 Dust in the ejected reservoir and hot halo

When dust is ejected by SNe out of the hot halo it ends up in the ejected reservoir. From there it may reaccrete back into the hot halo and ultimately the galaxy. We have not included any physical processes acting on the dust in the ejected reservoir and in the ejected winds. It may very well be that dust is destroyed while it is driven out the galaxy in winds, or that the dust is destroyed once it leaves the hot halo of a galaxy. These processes could completely alter our predictions for the mass of dust in the ejected reservoir (and hot halo) and could also lower the dust masses of galaxies. We have run tests where all the dust in the ejected reservoir is destroyed immediately and found that this has minimal effect on the dust content in the ISM of galaxies.

Similarly, we have not explored the effects of dust-enriched winds (i.e., the dust-to-gas ratio in winds leaving the galaxy is higher than the galaxy mean). Such processes have been proposed for metals (i.e., metal enriched winds, Krumholz & Dekel 2012). If dust-enriched winds exist, this would lower the dust-to-gas ratio in galaxies and would be of particular importance in low-mass objects. Dust-enriched winds would increase the abundance of dust in the ejected reservoir and the hot halo.

6.7.3 A homogeneous distribution of dust in galaxies?

In this work we make the assumption that dust distribution is smooth and follows the gas distribution within galaxies. In reality there may be differences in the dust-to-gas ratio from one region of a galaxy to another (Watson 2011; Smith et al. 2012; Sandstrom et al. 2013; Draine et al. 2014; Roman-Duval et al. 2014; Galametz et al. 2016). If for instance thermal sputtering occurs in a region with an elevated dust-to-gas ratio compared to the galaxy mean, a larger mass of dust is destroyed than predicted by our models. The same could occur the other way around. We expect the net effect of this to be minimal for our model predictions. Nevertheless, we acknowledge that numerical hydrodynamical simulations that resolve galaxy structures are necessary to fully explore this.

6.7.4 The density of the ISM

In our model we assume that the timescale for accretion of metals onto dust grains is a function of the gas-phase density and metallicity. As pointed out before, SAMs do not explicitly track volume densities. In Section 5.2 we presented an approach to calculate the volume density of molecular hydrogen, based on the molecular hydrogen and SFR surface density. This approach implicitly assumes that star formation has one fixed efficiency in molecular clouds of varying density. Theoretical work has already shown that depending on the Mach number of the gas in a molecular cloud, a smaller or larger fraction of the gas in a cloud may reach some critical density above which it can collapse within a free-fall time (e.g., Krumholz & McKee 2005). Although the exact value for this critical density may vary, this also shows that the star-formation efficiency does not need to be a fixed number in reality. A higher (lower) efficiency would result in a lower (higher) derived density of the molecular hydrogen, and therefore in a longer (shorter) timescale for metal accretion onto dust grains. Numerical simulations of resolved structures are necessary to properly address this issue and derive appropriate scaling relations for one-zone models (Zukovska et al. 2016).

6.7.5 The destruction of dust in the ISM

In this work we have assumed fixed parameters for the destruction of dust by SNe, based on theoretical work from
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7 SUMMARY & CONCLUSIONS

We have included the tracking of dust production and destruction in a semi-analytic model of galaxy formation and made predictions for the dust properties of galaxies from $z = 9$ to $z = 0$. We present results for different model variants for the dust production processes. The first is our fiducial model with dust condensation efficiencies in stellar ejecta of around 15% and a density and metallicity dependent timescale for the accretion of metals onto dust grains. The second includes no accretion of metals onto dust grains, the third assumes much higher dust condensation efficiencies than in our fiducial model, whereas the fourth assumes a fixed accretion time scale of 100 Myr. We summarise our main findings below.

- Our fiducial model successfully reproduces the trends between stellar mass and total mass in the local and high-redshift Universe, as well as the dust-to-gas ratio of local galaxies as a function of their stellar mass. It furthermore reproduces the double power law relation between dust-to-gas ratio and gas-phase metallicity, the number density of galaxies with dust masses less than $10^{7.3} M_\odot$ and the cosmic density of dust at $z = 0$.
  - The relation between galaxy dust mass and stellar mass slowly decreases with cosmic time from $z = 3$ to $z = 0$. This is mainly driven by a decrease in galaxy gas fractions. At higher redshift the relation between stellar mass and dust mass remains constant with time. The dust mass function of galaxies on the other hand increases rapidly from $z = 9$ to $z = 3$, after which only the number density of the galaxies with largest dust masses ($10^{5.5} M_\odot$) keeps increasing.
  - The relation between the dust-to-gas ratio of galaxies and their gas-phase metallicity remains constant to within 50% up to $z = 9$. There is no clear evolutionary trend in this relation. The dust-to-gas ratio of galaxies increases with cosmic time at fixed stellar mass, following the buildup of metals in a galaxy’s ISM.
  - Our model predicts a significant reservoir of dust in the CGM (hot halo) of galaxies. These reservoirs can be as large or even larger than the reservoir of dust in the ISM of the host galaxy. Our models predict that even more dust is ejected from galaxies, but it is unclear whether this dust can survive.
  - Up to 25% of the gas-phase metals at redshift $z = 0$ can be depleted onto dust. This lowers the gas-phase metallicity relation by $\sim 0.1$ dex. This depletion should be taken into account when comparing model predictions to observations. Similarly, a significant fraction of the CGM metals may be locked up in dust.
  - Within our fiducial model the accretion of metals onto dust grains is the dominant mode of dust formation in galaxies. The contribution of metal accretion becomes increasingly important with stellar mass. Only at the lowest stellar masses (less than $10^7 M_\odot$) does the condensation of dust in SN ejecta become the dominant mode of dust formation.
  - The ‘high-cond’ and ‘fix-tau’ model variants can not reproduce the dust-to-gas ratio of galaxies with metallicities less than 0.2 $Z_\odot$. Furthermore the ‘fix-tau’ model can not reproduce the high dust masses observed in galaxies at $z \sim 6$. A model without accretion of metals onto dust grains can reproduce observations relatively well if an unrealistically high efficiency of 100% is assumed for the condensation of dust in stellar ejecta, but predicts too high dust masses in low-metallicity galaxies. We conclude that a model where the rate of accretion of metals onto dust grains is set by the metallicity and the density of the cold gas is necessary to reproduce the shape of the observed scaling relations and dust mass budgets.

The results presented in this paper can serve as predictions for future surveys of the dust content of galaxies. We look forward to observations from new and upcoming facilities that will be able to confront our predictions. In this work we have ignored the effects dust has on the ISM physics and chemistry in galaxies, affecting the growth rate of molecular hydrogen, and the absorption of stellar light. In future work we will explore these effects, and their consequences for the stellar buildup and appearance of galaxies.

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APPENDIX A: DUST FORMATION CHANNELS FOR OTHER MODEL VARIANTS

We presented the formation rate of dust in our fiducial model via the different formation channels in Figure 8. Here we present the same plot for the remaining model variants (Figures A1 through A3).
Figure A1. The formation and destruction rate of dust as a function of stellar mass from redshift $z = 9$ to $z = 0$, for the ‘no-acc’ model variant. Dust formation rates are separated into formation due to AGB stars, SNe, and growth of dust in the ISM. Thick lines mark the 50th percentiles, whereas the narrow dotted lines mark the 16th and 84th percentiles.
Figure A2. The formation and destruction rate of dust as a function of stellar mass from redshift \( z = 9 \) to \( z = 0 \), for the ‘fix-tau’ model variant. Dust formation rates are separated into formation due to AGB stars, SNe, and growth of dust in the ISM. Thick lines mark the 50th percentiles, whereas the narrow dotted lines mark the 16th and 84th percentiles.
Figure A3. The formation and destruction rate of dust as a function of stellar mass from redshift $z = 9$ to $z = 0$, for the ‘high-cond’ model variant. Dust formation rates are separated into formation due to AGB stars, SNe, and growth of dust in the ISM. Thick lines mark the 50th percentiles, whereas the narrow dotted lines mark the 16th and 84th percentiles.