Binaries drive high Type Ia supernova rates in dwarf galaxies

James W. Johnson,1,2* Christopher S. Kochanek1,2 and K. Z. Stanek1,2
1 Department of Astronomy, The Ohio State University, 140 W. 18th Ave., Columbus, OH, 43210, USA
2 Center for Cosmology and Astroparticle Physics (CCAPP), The Ohio State University, 191 W. Woodruff Ave., Columbus, OH, 43210, USA

ABSTRACT
The scaling of the specific Type Ia supernova (SN Ia) rate with host galaxy stellar mass \( \dot{N}_{\text{Ia}}/M_\star \sim M_\star^{0.3} \) as measured in ASASSN and DES strongly suggests that the number of SNe Ia produced by a stellar population depends inversely on its metallicity. We estimate the strength of the required metallicity dependence by combining the average star formation histories (SFHs) of galaxies as a function of their stellar mass with the mass-metallicity relation (MZR) for galaxies and common parametrizations for the SN Ia delay-time distribution. The differences in SFHs can account for only \( \sim 30\% \) of the increase in the specific SN Ia rate between stellar masses of \( M_\star = 10^{10} \) and \( 10^{12} M_\odot \). We find that an additional metallicity dependence of approximately \( \sim Z^{-0.5} \) is required to explain the observed scaling. This scaling matches the metallicity dependence of the close binary fraction observed in APOGEE, suggesting that the enhanced SN Ia rate in low-mass galaxies can be explained by a combination of their more extended SFHs and a higher binary fraction due to their lower metallicities. Due to the shape of the MZR, only galaxies below \( M_\star \approx 3 \times 10^9 M_\odot \) are significantly affected by the metallicity-dependent SN Ia rates. The \( \dot{N}_{\text{Ia}}/M_\star \sim M_\star^{0.3} \) scaling becomes shallower with increasing redshift, dropping by factor of \( \sim 2 \) at \( 10^{7.2} M_\odot \) between \( z = 0 \) and \( 1 \) with our \( \sim Z^{-0.5} \) scaling. With metallicity-independent rates, this decrease is a factor of \( \sim 3 \). We discuss the implications of metallicity-dependent SN Ia rates for one-zone models of galactic chemical evolution.

Key words: stars: supernovae – stars: white dwarfs – galaxies: abundances – galaxies: dwarf – galaxies: evolution – stars: mass function

1 INTRODUCTION
Type Ia supernovae (SNe Ia) arise from the thermonuclear detonation of a white dwarf (WD; Hoyle & Fowler 1960; Colgate & McKee 1969), the exposed carbon-oxygen core of a low-mass star. SN surveys have revealed that low-mass galaxies are more efficient producers of these events than their higher mass counterparts (e.g., Mannucci et al. 2005; Sullivan et al. 2006; Li et al. 2011; Smith et al. 2012). In particular, Brown et al. (2019) found that the specific SN Ia rate – the rate per unit stellar mass – scales approximately with the inverse square root of the stellar mass itself (\( \dot{N}_{\text{Ia}}/M_\star \sim M_\star^{-0.5} \)) using SNe Ia from the All-Sky Automated Survey for Supernovae (ASASSN; Shappee et al. 2014; Kochanek et al. 2017) and assuming the Bell et al. (2003) stellar mass function (SMF). The measurement depends on the SMF because the number of observed SNe must be normalized by the number of galaxies in order to compute a specific SN rate. Consequently, the scaling becomes shallower (\( \dot{N}_{\text{Ia}}/M_\star \sim M_\star^{-0.3} \)) when using the steeper Baldry et al. (2012) double-Schechter SMF parametrization (Gandhi et al. 2022). This change leads to agreement between the ASASSN measurements and Wiseman et al.’s (2021) estimates from the Dark Energy Survey (DES; Dark Energy Survey Collaboration et al. 2016) using the Baldry et al. (2012) SMF. Although the exact strength of the scaling depends on the SMF, it is clear that the specific SN Ia rate is higher in dwarf galaxies. There are a handful of potential pathways which could give rise to this empirical result.

First, the mean star formation histories (SFHs) of galaxies vary with the stellar mass of the system. In semi-analytic models of galaxy formation (see, e.g., the reviews of Baugh 2006 and Somerville & Davé 2015), dwarf galaxies in the field have more extended SFHs than their higher mass counterparts. This mass dependence is also seen in hydrodynamical simulations of galaxy formation (e.g., Garrison-Kimmel et al. 2019). Since SN Ia delay-time distributions (DTDs) decline with age, galaxies with more recent star formation should have higher specific SN Ia rates.

Second, Kistler et al. (2013) argued that the dependence of the specific SN Ia rate on stellar mass may be driven by metallicity. Lower mass galaxies host lower metallicity stellar populations (Gallazzi et al. 2005; Kirby et al. 2013) and lower metallicity gas reservoirs (Tremonti et al. 2004; Zahid, Kewley & Bresolin 2011; Andrews & Martini 2013; Zahid et al. 2014). Kistler et al. (2013) point out that lower metallicity stars leave behind higher mass WDs which could potentially grow to the Chandrasekhar mass and subsequently explode more easily than their less massive, high metallicity counterparts. Lower metallicity stars have weaker winds during the asymptotic giant branch phase (Willson 2000; Marigo & Girardi 2007), leading to lower mass loss rates and more massive cores (Kalirai et al. 2014), producing more massive WDs for fixed initial mass stars at lower metallicity (Umeda et al. 1999; Meng, Chen & Han 2008; Zhao et al. 2012). Furthermore, in both the single (e.g., Whelan & Iben 1973)
and double degenerate scenarios (e.g., Iben & Tutukov 1984; Webbink 1984), SNe Ia arise in binary systems. Based on multiplicity measurements of Solar-type stars from the Apache Point Observatory Galaxy Evolution Experiment (APOGEE; Majewski et al. 2017), Badenes et al. (2018) and Moe, Kratter & Badenes (2019) find that the stellar close binary fraction increases toward low metallicities. Consequently, dwarf galaxies should have more potential SN Ia progenitors per unit mass of star formation due to more massive WDs and a higher close binary fraction. Motivated by these results, Gandhi et al. (2022) explore a handful of parametrizations for the metallicity dependence of the SN Ia rate in re-simulated galaxies from FIRE-2 (Hopkins et al. 2018). They find that a $Z^{-0.3}$ scaling where $Z$ is the metallicity leads to better agreement with the empirical relationship between galactic stellar masses and stellar abundances than when using metallicity-independent SN Ia rates.

In this paper, we assume that the strong scaling of the specific SN Ia rate with stellar mass is due to metallicity and conduct simple numerical calculations to investigate its origin. We combine the mean star formation histories of galaxies at fixed stellar mass from the UniverseMachine semi-analytic model (Behroozi et al. 2019) and the popular $\tau^{-1}$ SN Ia DTD (e.g., Maoz & Mannucci 2012) with the mass-metallicity relation (MZR) for galaxies (Tremonti et al. 2004; Andrews & Martini 2013; Zahid et al. 2011, 2014). Given the mean SFH and DTD, we can compute the characteristic SN Ia rate for galaxies of a given stellar mass, and by assuming that they lie along the observed MZR, we can include various scalings of the rate with metallicity. We describe the model in § 2 and the effect on Type Ia rates in § 3. In § 4 we present simple models exploring the consequences of metallicity-dependent SN Ia rates for galactic chemical evolution models. We summarize our findings in § 5.

2 GALACTIC PROPERTIES

We begin by examining how the mean galactic SFH varies with present-day stellar mass as predicted by the UniverseMachine semi-analytic model (Behroozi et al. 2019). Using dark matter halo properties supplied by the Bolshoi-Planck and MultiDark-Planck 2 dark matter only simulations (Klypin et al. 2016; Rodríguez-Puebla et al. 2016), UniverseMachine follows a conventional semi-analytic model framework (see, e.g., the review in Somerville & Davé 2015) and successfully reproduces a broad range of well-constrained observables, including stellar mass functions, cosmic SFRs, specific SFRs, quenched fractions, and UV luminosity functions. While some semi-analytic models have used the extended Press-Schechter formalism (Press & Schechter 1974; Bond et al. 1991) to generate halo merger trees and push the lower stellar mass limit of their model down to $M_* \approx 10^7 \, M_\odot$ (e.g. Somerville et al. 2015), an advantage of UniverseMachine is that the high mass resolution of the Bolshoi-Planck and MultiDark-Planck 2 simulations allows merger trees down to $M_* \approx 10^{7.2} \, M_\odot$ to be obtained directly from the simulations. Conveniently, this limit is approximately the lowest mass for which there are empirical constraints on the specific SN Ia rate from ASAS-SN (Brown et al. 2019) and DES (Wiseman et al. 2021). To relate these predictions to data from the untargeted ASAS-SN survey (Shappee et al. 2014; Kochanek et al. 2017), we take the full galaxy sample from UniverseMachine, including both star forming and quenched galaxies as well as both centrals and satellites, though centrals are the dominant population across the full stellar mass range.

In the left panel of Fig. 1, we show the best-fit mean SFH as a function of lookback time in four narrow bins of present day stellar mass. In general, low stellar mass galaxies have more extended SFHs than their higher mass counterparts. This effect is sufficiently strong that for stellar masses of $10^{-5.5} \, M_\odot$, typical SFRs are still increasing at the present day, while $10^{10.5} \, M_\odot$ galaxies experienced their fastest star formation long ago.

We adopt a DTD that scales with the age of a stellar population as $\tau^{-1}$ starting at a delay time $\tau_D = 100$ Myr as suggested by comparisons of the cosmic SFH with the volumetric SN Ia rate as a function of redshift (Maoz & Mannucci 2012; Maoz, Mannucci & Brandt 2012; Graur & Maoz 2013; Graur et al. 2014). We conducted our analysis using alternative choices of the power-law index as well as an exponential DTD with an e-folding timescale of $\tau_D = 1.5$ Gyr and found similar conclusions in all cases. We do not consider metallicity-dependent variations in the shape of the DTD here, instead focusing on the overall normalization. In principle, the minimum delay of the DTD could be as short as $\sim 40$ Myr if WDs are produced by $\lesssim 8 M_\odot$ stars (e.g., Hurley, Pols & Tout 2000), and perhaps even shorter at low metallicity if the total metal content of a star significantly impacts its lifetime (e.g., Kodama & Arimoto 1997; Vincenzo et al. 2016). However, if SNe Ia require some additional time following WD formation, the minimum delay will be longer. Since we are interested in the first-order effects of variations in the SFH on specific SN Ia rates, we assume a value of $\tau_D = 100$ Myr. In calculations using both $\tau_D = 40$ Myr and $\tau_D = 150$ Myr, we found similar results.

For an SFH $M_\star$ and DTD $R_{\text{Ia}}$ as functions of lookback time $\tau$, the specific SN Ia rate at a stellar mass $M_\star$ is

$$\frac{N_{\text{Ia}}(M_\star | \tau)}{M_\star} \propto Z(M_\star)^3 \int_0^{\tau - \tau_D} M_\star(\tau | M_\star) R_{\text{Ia}}(\tau) d\tau$$

where $T = 13.2$ Gyr is the time elapsed between the onset of star formation and the present day. To investigate the effects of metallicity, we add a power-law metallicity scaling $Z(M_\star)^\gamma$ where $Z$ is given by the MZR. We are only interested in the scaling of the rates with $M_\star$, so we normalize all rates to unity at $M_\star = 10^{10} \, M_\odot$ following Brown et al. (2019). Although the denominator of equation (1) in detail should depend on mass loss from stars as they eject their envelopes, this is an approximately constant term which can safely be neglected in the interest of computing relative rates ($\approx 40\%$ for a Kroupa 2001 IMF; see discussion in §§ 2.2 and 3.7 of Weinberg, Andrews & Freudenburg 2017).

To qualitatively illustrate how the specific SN Ia rate scales with the timescale over which star formation occurs, we consider the simple example of a linear-exponential parametrization $\dot{M}_\star \propto \dot{t} e^{-t/t_{\text{sfh}}}$ where $t = T - \tau$. The middle panel of Fig. 1 shows equation (1) as a function of the e-folding timescale $t_{\text{sfh}}$ assuming $\gamma = 0$. The specific SN Ia rate is lowest in the limiting case of a single episode of star formation (i.e., $t_{\text{sfh}} \rightarrow 0$), rises steeply until $t_{\text{sfh}} \approx 10$ Gyr, and then flattens once $t_{\text{sfh}} \geq T$. A higher specific SN Ia rate as observed in dwarf galaxies is therefore a natural consequence of their more extended SFHs, though we demonstrate below that this effect accounts for only a factor of $\sim 2$ increase in the rate between $10^{7.2}$ and $10^{10} M_\odot$.

The right panel of Fig. 1 shows the MZR parametrized by Zahid et al. (2014, see their equation 5) at redshifts $z = 0, 0.5$ and 1 We have transformed from their $\log_{10}(\text{O/H})$ measurements to the logarithmic abundance relative to the Sun $\log_{10}(Z/Z_\odot)$ assuming the Solar oxygen abundance derived by Asplund et al. (2009).
In comparison to the Andrews & Martini (2013) parametrization at $z = 0$. Although UniverseMachine allows us to investigate these effects at stellar masses as low as $10^{7.2} \, M_{\odot}$, the Zahid et al. (2014) measurements are available only for $M_{\star} \approx 10^{9} - 10^{11} \, M_{\odot}$ galaxies. Andrews & Martini (2013) used stacked spectra from the Sloan Digital Sky Survey (SDSS; York et al. 2000) to obtain direct measurements of the oxygen abundance in bins of stellar mass extending as low as $\sim 10^{7.4} \, M_{\odot}$. Relative to Zahid et al. (2014), the Andrews & Martini (2013) parametrization has a lower plateau but otherwise a similar slope and turnover mass. Because we simply normalize the rates to unity at $M_{\star} = 10^{10} \, M_{\odot}$, only the shape of the MZR matters, and we find similar results using both parametrizations. In order to estimate SN Ia rates at redshifts of $z = 0.5$ and $z = 1$, we use the redshift-dependent Zahid et al. (2014) formalism in § 3.

Given a present-day stellar mass, we compute its SFH as a function of lookback time by interpolating between the stellar mass and snapshot times included in the UniverseMachine predictions. We then compute the specific SN Ia rate according to equation (1) given the implied SFH and a $\tau^{-1}$ DTD, amplifying the rate by a factor of $Z^\gamma$ where the metallicity $Z$ is computed from the Zahid et al. (2014) MZR. Because these calculations are simply using the UniverseMachine SFHs, the results are unaffected by the SMF dependence of the observational estimates (i.e., Eq. 1 can simply be divided by $M_{\star}$ as opposed to an integral over the SMF).

### 3 PREDICTED SN Ia RATES

The left panel of Fig. 2 shows the specific SN Ia rate as a function of $\gamma$ in comparison to the $N_{\text{gal}}/M_{\star} \sim M_{\star}^{0.5}$ and $N_{\text{gal}}/M_{\star} \sim M_{\star}^{0.3}$ scalings of the observed rate with the Bell et al. (2003) and Baldry et al. (2012) SMFs, respectively. The metallicity dependence has a significant impact only below $M_{\star} \approx 3 \times 10^{9} \, M_{\odot}$ due to the shape of the MZR; this is the mass above which the MZR flattens considerably (see Fig. 1). Assuming no metallicity dependence (i.e., $\gamma = 0$), these calculations suggest that the variations in SFHs between $\sim 10^{7.2}$ and $\sim 10^{10} \, M_{\odot}$ can account for only a factor of $\sim 2$ increase in the specific SN Ia rate. The $\gamma = -0.5$ case is generally consistent with a mass dependence of $M_{\star}^{-0.3}$, while the steeper dependence of $M_{\star}^{-0.5}$ would require a stronger scaling of roughly $\gamma \approx -1.5$.

In the right panel of Fig. 2, we compare the same scalings to the close binary fractions in APOGEE measured by Moe et al. (2019). The line at $Z \approx 10^{-0.6} \, Z_{\odot}$ is the characteristic abundance of an $M_{\star} = 10^{7.2} \, M_{\odot}$ galaxy in the Zahid et al. (2014) parametrization. For the range of metallicities spanned by the stellar masses we explore here, the close binary fraction is remarkably consistent with a $\gamma = -0.5$ scaling with metallicity. If one instead takes $Z \approx 0.1 \, Z_{\odot}$ for a $\sim 10^{7.2} \, M_{\odot}$ galaxy as suggested by Andrews & Martini (2013), then there is a slight tension between a $\gamma = -0.5$ scaling and the close binary fraction measured by Moe et al. (2019). There is some additional freedom to adjust the metallicity dependence beyond that of binaries, so the agreement need not be perfect. For example, any additional increase in the SN Ia rates not supplied by an increased binary fraction could arise due to more massive WDs forming at low $Z$ -- the scenario postulated by Kistler et al. (2013). Nonetheless, it appears that the scaling of the close binary fraction with metallicity can explain the majority of the effect if rate scales with mass as $N_{\text{gal}}/M_{\star} \sim M_{\star}^{-0.3}$. If, instead, the $\sim M_{\star}^{-0.5}$ scaling found using the Bell et al. (2003) SMF is accurate, then the required $\gamma \approx -1.5$ scaling cannot be explained by the close binary fraction alone as it would reach unphysical values (> 1) within the range of observed metallicities.

Due to the evolution of the MZR, the mass dependence of the specific SN Ia rate at different redshifts could empirically distinguish between $\gamma = 0$ and $\gamma = -0.5$. To investigate this possibility, we simply evaluate equation (1) over the appropriate range of lookback times assuming standard cosmological parameters (Planck Collaboration et al. 2014). For the $\gamma = 0$ case, we also show the effect of applying an additional $(M_{\star}/10^{10} \, M_{\odot})^{-0.15}$. This prefactor brings the $\gamma = 0$ predictions into better agreement with the empirical $N_{\text{gal}}/M_{\star} \sim M_{\star}^{-0.3}$ scaling at $z = 0$ and is intended to encapsulate the mass scaling needed for some other unknown process to sufficiently amplify the SN Ia rate at low stellar masses if it is instead not due to metallicity effects.

We show the resulting specific SN Ia rates as a function of stellar mass at $z = 0$, 0.5 and 1 in Fig. 3. In both the $\gamma = 0$ and $\gamma = -0.5$ cases, the scaling of the specific SN Ia rate with galaxy stellar mass becomes shallower with increasing redshift. If $\gamma = -0.5$, these calculations suggest that it should decrease by a factor of $\sim 2$ between $z = 0$ and $z = 1$ at $M_{\star} \approx 10^{7.2} \, M_{\odot}$, the lowest stellar mass for which we have made predictions at all three redshifts. If $\gamma = 0$, then the rate instead decreases by a factor of $\sim 3$ at $10^{7.2} \, M_{\odot}$. This difference
Figure 2. Left: Predicted scalings of the specific SN Ia rate with galaxy stellar mass (see equation 1) assuming the mean UniverseMachine SFHs and a single power-law $Z^\gamma$ metallicity-dependence with $\gamma = 0$ (i.e. no dependence; black), $\gamma = -0.2$ (red), $\gamma = -0.5$ (green), $\gamma = -1$ (blue), and $\gamma = -2$ (purple). Following Brown et al. (2019) and Gandhi et al. (2022), we normalize all rates to a value of 1 at $M_\star = 10^{10} M_\odot$. Black dashed lines denote the scalings of $\dot{N}_{\text{Ia}} / M_\star \propto M^{0.5}_\star$ and $\dot{N}_{\text{Ia}} / M_\star \propto M^{-0.3}_\star$ derived when normalizing the observed rates by the Bell et al. (2003) and Baldry et al. (2012) SMFs, respectively. Right: The same metallicity scalings as in the left panel in comparison to the close binary fractions observed in APOGEE (Moe et al. 2019, black dashed line with error bars) normalized to the observed binary fraction of 10% at $\log_{10}(Z/Z_\odot) = +0.5$. The characteristic metallicities of $M_\star = 10^{7.2} M_\odot$ ($\log_{10}(Z/Z_\odot) \approx -0.6$) and $10^{10} M_\odot$ galaxies ($\log_{10}(Z/Z_\odot) \approx +0.4$) are marked with black dotted lines.

Figure 3. The specific SN Ia rate normalized to 1 at $10^{10} M_\odot$ as a function of stellar mass with ($\gamma = -0.5$, left) and without a metallicity dependence ($\gamma = 0$, right) at redshifts $z = 0$ (black), $z = 0.5$ (blue), and $z = 1$ (red). In the right panel, we artificially scale the rates by a factor of $(M_\star / 10^{10} M_\odot)^{-0.15}$ to bring the $z = 0$ predictions into better agreement with an $-M_\star^{-0.3}$ scaling as predicted by the $\gamma = -0.5$ case. Stellar masses correspond to the appropriate redshift (i.e., the rates for $z = 1$ use the $z = 1$ stellar masses and not the present-day stellar masses). We show the unmodified rates as dotted lines (the black solid line in the left panel and the black dotted line in the right panel are the same as the green line and black solid line in the left panel of Fig. 2).
arises because the metallicities of dwarf galaxies decrease with increasing redshift and $\gamma = -0.5$ allows them to sustain higher SN Ia rates than if $\gamma = 0$. Empirically, the cosmic SN Ia rate increases with redshift (e.g. Graur et al. 2014), and we have verified that our framework reproduces this result by integrating over the SMF (similar to equation 2 below). Given this result and the lower stellar masses of the host galaxies at high redshift, one might expect the trend to steepen with increasing $z$. The slope instead decreases here because the lines in Fig. 3 (right panel) are moving to the right with time as galaxies grow in mass, and we normalize to unity at a stellar mass of $10^{10} M_\odot$ at all redshifts.

While empirical measurements of the specific SN Ia rate as a function of stellar mass depend on the assumed SMF (Gandhi et al. 2022), the host galaxy mass distribution of observed events does not, making it a potentially more observationally feasible diagnostic. As noted in Fig. 2, only dwarf galaxies are significantly affected by a metallicity-dependent scaling of SN Ia rates due to the shape of the MZR, so a $\gamma = -0.5$ scaling should appear as an enhanced SN Ia rate at the low-mass end of the distribution. Although this empirical measurement does not depend on the SMF, our theoretical prediction does because we must take into account the relative abundances of galaxies of different stellar masses. The observed rate in a bin of stellar mass can be expressed as the product of the characteristic rate $N_{\text{Ia}}$ at a given stellar mass and the integral of the SMF $\Phi(M_*)$ over the bin in stellar mass,

$$N_{\text{Ia, cosmic}}(M_* | \gamma) = N_{\text{Ia}}(M_* | \gamma) \int_{M_*}^{M_*+dM_*} \Phi(M_*) \, dM_*,$$

where $N_{\text{Ia}}$ is the numerator of equation (1). We show this distribution in Fig. 4 for each combination of $\gamma = 0$ and $-0.5$ and the Bell et al. (2003) and Baldry et al. (2012) SMFs, normalizing to a maximum value of unity. For untargeted surveys like ASAS-SN, equation (2) should describe the observed host galaxy stellar mass distribution exactly, whereas targeted surveys like the Lick Observatory SN Search (LOSS; Li et al. 2000; Filippenko et al. 2001) would need to correct for their target galaxy selection criteria.

Fig. 4 shows that galaxies with stellar masses of $M_* = 10^{10} - 10^{11} M_\odot$ should dominate the SN Ia rate for all choices of the SMF and $\gamma$. This peak rate simply represents the galaxies that dominate the stellar mass. For a given choice of the SMF, $\gamma = -0.5$ increases the number of SNe Ia at $M_* \approx 10^{7.2} M_\odot$ by a factor of $\sim 3$ relative to $\gamma = 0$. However, Fig. 4 also shows that the enhancement is small compared to the differences between the two SMFs. Between the peak and $10^{7.2} M_\odot$, the Bell et al. (2003) host mass distribution drops by $\sim 2.5$ orders of magnitude while that of Baldry et al. (2012) drops by $\sim 1.5$ orders of magnitude. Fig. 4 illustrates the need for precise knowledge of the SMF to accurately determine the metallicity-dependence of SN Ia rates.

### 4 GALACTIC CHEMICAL EVOLUTION

The realization that SN Ia rates likely depend on metallicity with a $\gamma = -0.5$ dependence has important implications for galactic chemical evolution models, which typically assume metallicity-independent rates. To demonstrate this, we briefly explore several one-zone models based on Johnson & Weinberg (2020) which predict the evolution of O (produced only in massive stars) and Fe (produced in both massive stars and SNe Ia). We use an exponential SFH with an e-folding timescale of $\tau_{\text{SFH}} = 6$ Gyr and a minimum delay of $\tau_D = 100$ Myr before the onset of SNe Ia from a given stellar population. For metallicity-dependent rates, we simply apply a $(Z/Z_\odot)^{-0.5}$ prefactor to their Fe yield of $Y_{\text{Fe}} = 0.0017$, which assumes that the shape of the DTD does not vary with metallicity only the normalization. Otherwise, these models are the same as Johnson & Weinberg (2020).

Fig. 5 illustrates the predictions of this SFH with $(\eta, \tau_*) = (2.5, 2$ Gyr), $(2.5, 10$ Gyr), and $(20, 10$ Gyr) where $\eta \equiv M_{\text{out}}/M_*$ is the mass-loading factor describing the efficiency of outflows and $\tau_* \equiv M_{\text{gas}}/M_*$ is the inverse of the star formation efficiency. These values are appropriate for the Solar neighbourhood with efficient (left panel) and inefficient (middle panel) star formation and for a dwarf galaxy (right panel). In all cases, $\gamma = -0.5$ predicts a much more abrupt descent from the high [O/Fe] plateau because of the higher Fe yield at low metallicity. If incorporated into GCE models, this could impact the inferred evolutionary timescales of the thick disc, known to host many of the high [O/Fe] stars in the Milky Way (Hayden et al. 2017). When the equilibrium abundance is near-Solar but star formation is slow (middle panel), the model predicts a “secondary plateau” in [O/Fe] because the Fe enrichment rate slows down due to the metallicity-dependence of the yield (see inset). This is a noteworthy theoretical prediction because generally [O/Fe] and [Fe/H] reach equilibrium at similar times and no secondary plateau arises (e.g., Weinberg et al. 2017).

These models are intended to be illustrative rather than quantitative. In general, the only regions of chemical space where $\gamma = 0$ and $\gamma = -0.5$ agree are at near-Solar abundances and along the high [O/Fe] plateau, which occurs before the onset of SN Ia enrichment. A $\gamma = -0.5$ scaling has the strongest impact at low Z, where the metallicity-dependence of the yield shifts the Fe abundances by $\sim 0.5$ dex in this example.

### 5 DISCUSSION AND CONCLUSIONS

Building on LOSS (Li et al. 2011), Brown et al. (2019) and Wiseman et al. (2021) found the SN Ia rates rise steeply toward low stellar mass. The exact slope depends on the adopted SMF, with $N/M_* \sim M_*^{-0.3}$ for Baldry et al. (2012) and $N/M_* \sim M_*^{-0.5}$ for Bell et al. (2003).
To explain this scaling with mass, we use the mean SFHs of galaxies predicted by the UniverseMACHINE (Behroozi et al. 2019) semi-analytic model of galaxy formation, a standard $\tau^{-1}$ DTD (e.g., Maoz & Mannucci 2012), and the empirical MZR as parametrized by Zahid et al. (2014) to relate stellar mass to metallicity and build-in a $Z^*$ SN Ia rate dependence. Our results depend only on the shape of the MZR and not its absolute calibration. While lower mass galaxies have younger stellar populations, we find that this accounts for only a factor of ~2 increase in the specific rate between $M_*$ = $10^{7.2}$ and $10^{10}$ $M_\odot$. We can match the $M_*$ dependence if $\gamma \approx -0.5$, but $\gamma \approx -1.5$ is required to explain the steeper $\dot{N}/M_* \sim M_*^{-0.5}$ scaling.

A scaling of $\gamma = -0.5$ is in excellent agreement with the dependence of the close binary fraction measured in APOGEE, which increases from ~10% at $-3Z_\odot$ to ~40% at $-0.12Z_\odot$ (Moe et al. 2019). This close match suggests that if a scaling of $\dot{N}/M_* \sim M_*^{-0.5}$ is accurate, then the elevated SN Ia rates in dwarf galaxies can be explained by a combination of their more extended SFHs and an increased binary fraction compared to their higher mass counterparts due to differences in metallicity. While Gandhi et al. (2022) motivate their investigation from this viewpoint, here we take this argument one step further and postulate that this accounts for the entire increase in the specific SN Ia rate because the binary fraction can naturally account for a factor of ~3 increase over the ~1 decade in metallicity spanned by $M_*$ = $10^{7.2}$ – $10^{10}$ $M_\odot$ galaxies. The suggestion by Kistler et al. (2013) that the increased WD mass at low metallicities drives the effect is likely a subdominant effect. Higher mass WDs for lower metallicity may be an important component if the steeper $\sim M_*^{-0.5}$ scaling inferred by the Bell et al. (2003) SMF is correct.

At first glance, an inverse dependence of SN Ia rates on metallicity may seem at odds with the results in Holoiien et al. (2022) finding that dwarf galaxy hosts of ASAS-SN SNe Ia tend to be oxygen-rich relative to similar mass galaxies. However, SN hosts are likely not a representative sample of the underlying galaxy population because the steeply declining DTD (e.g., Maoz & Mannucci 2012) means that the intrinsically highest SN Ia rates at any mass should be in systems which experienced a recent starburst ($\leq 1$ Gyr ago). Since oxygen is produced by massive stars with short lifetimes (e.g., Hurley, Pols & Tout 2000; Johnson 2019), these galaxies should also have a higher-than-average oxygen abundance (see, e.g., Johnson & Weinberg 2020). In other words, SN Ia hosts at fixed mass should be more metal-rich than the average galaxy.

The calculations we have presented here are simplified in several regards. We assumed the characteristic SFH predicted by a semi-analytic model of galaxy formation at all stellar masses. Our parametrization of the MZR includes no intrinsic scatter, and taking the Zahid et al. (2014) MZR at face value for use in a power-law scaling implicitly assumes that all SNe Ia arise from stellar populations near the gas-phase abundance. Although in principle galaxies populate distributions of finite width in each of these quantities, these approximations should be fine for the purposes of predicting average trends.

Although current surveys lack the depth required to pin down SN rates across multiple decades of stellar mass at $z = 1$, the sample sizes necessary to do so may be available from next-generation facilities. First and foremost, the Nancy Grace Roman Space Telescope (Spergel et al. 2013, 2015) will obtain large samples of SNe. Roman has excellent prospects for discovering all classes of SNe at redshifts as high as $z \geq 2$ and beyond (Petrushevksa et al. 2016). The difficulty in empirically constraining the specific SN Ia rate at $z \approx 1$ instead comes from uncertainties in the SMF. Even at $z = 0$, these measurements are difficult due to the flux-limited nature of most surveys and the broad range of luminosities and mass-to-light ratios spanned by galaxies (see the discussion in Weigel et al. 2016). Between $10^{7.2}$ and $10^{10}$ $M_\odot$, the factors of 2 and 3 predicted by our calculations with $\gamma = -0.5$ and $\gamma = 0$ are produced by power-law indices of $-0.108$ and $-0.170$, respectively. The difference between the two (0.062) is the minimum precision required for the scaling of the SMF at the low-mass end – only slightly larger than the precision achieved by Baldry et al. (2012, $\pm 0.05$, see their Fig. 13). This empirical test therefore requires at least their level of precision but at $z \approx 1$.

A metallicity dependence of $Z^{-0.5}$ strongly impacts the evolution of Fe in one-zone models of galactic chemical evolution. The considerable impact that a $\gamma = -0.5$ scaling has on the predictions indicates that evolutionary parameters inferred from one-zone model fits to multi-element abundance ratios may need revised. The strongest impact is for dwarf galaxies, where the abundances are low and the higher yields predict substantial shifts in the position of the evolutionary track in abundance space.

Figure 5. A comparison of one-zone galactic chemical evolution models based on Johnson & Weinberg (2020, for details, see their §2) with $\gamma = -0.5$, solid) and without (\(\gamma = 0\), dotted) metallicity-dependent SN Ia rates. Tracks denote the O and Fe abundances in the interstellar medium parametrized as a function of time with points marked at $T = 2$, 4, 6, 8, and 10 Gyr. Insets illustrate [O/H] and [Fe/H] as a function of time in Gyr for the corresponding model. We note on each panel the choice of the outflow mass-loading factor $\eta$ and the star formation efficiency timescale $\tau$. 

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Software: NumPy (Harris et al. 2020), SciPy (Virtanen et al. 2020), Matplotlib (Hunter 2007), Astropy (Astropy Collaboration et al. 2013, 2018, 2022).

7 DATA AVAILABILITY

The only data in this paper are the mean star formation histories of the UNIVERSE MACHINE galaxies, publicly available at https://www.peterbehroozi.com/data.html.

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