









The stellar fundamental metallicity relation: the correlation between stellar mass, star formation rate, and stellar metallicity

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ABSTRACT

We present observational evidence for a stellar fundamental metallicity relation (FMR), a smooth relation between stellar mass, star formation rate, and the light-weighted stellar metallicity of galaxies, analogous to the well-established gas-phase FMR. We use the non-parametric software PPXF to reconstruct simultaneously the star formation and chemical-enrichment history of a representative sample of galaxies from the local MaNGA (Mapping Nearby Galaxies at Apache Point Observatory) survey. We find that (i) the metallicity of individual galaxies increases with cosmic time and (ii) at all stellar masses, the metallicity of galaxies is progressively higher, moving from the starburst region above the main sequence (MS) towards the passive galaxies below the MS, manifesting the stellar FMR. The scatter is reduced when replacing the stellar mass M_* with M_*/R_e (with R_e being the effective radius), in agreement with previous results using the velocity dispersion σ_e , which correlates with M_*/R_e . Our results point to starvation as the main physical process through which galaxies quench, showing that metal-poor gas accretion from the intergalactic medium/circumgalactic medium – or the lack thereof – plays an important role in galaxy evolution by simultaneously shaping both their star formation and their metallicity evolutions, while outflows play a subordinate role. This interpretation is further supported by the additional finding of a young stellar FMR, tracing only the stellar populations formed in the last 300 Myr. This suggests a tight co-evolution of the chemical composition of both the gaseous interstellar medium and the stellar populations, where the gas-phase FMR is continuously imprinted on to the stars over cosmic times.

Key words: galaxies: evolution – galaxies: formation – galaxies: star formation – galaxies: statistics – galaxies: stellar content.

1 INTRODUCTION

The intertwined co-evolution of the chemical composition of both the gaseous interstellar medium (ISM) and the stellar populations within a galaxy is governed by numerous physical processes. These processes include star formation via gravitational collapse of baryonic clouds in the ISM (see e.g. Kennicutt & Evans 2012 for a review), nucleosynthesis of metals in stellar cores, supernovae explosions and stellar winds returning metals to the ISM (e.g. Maiolino & Mannucci 2019), (pristine) gas accretion from the intergalactic medium/circumgalactic medium (IGM/CGM), or gas outflows caused by stellar winds, shocks, feedback from active galactic nuclei (AGNs), and supernova feedback (e.g. Veilleux, Cecil & Bland-Hawthorn 2005).

The metal content of stellar populations and ISM is therefore highly informative for galaxy evolution studies, because metallicity (defined as the fractional mass of metals relative to the mass of all

baryons) carries the imprint of the physical processes driving the baryon cycle over cosmic times (see Maiolino & Mannucci 2019 for a review). This sensitive interplay of physical processes leads naturally to a set of observable scaling relations between galaxy metallicity and other global galaxy properties.

Previous studies have shown that both the stellar and gas metallicities scale with stellar mass M_* (e.g. Tremonti et al. 2004; Gallazzi et al. 2005), known as mass–metallicity relations (MZR), stating that more massive galaxies are on average more chemically enriched than lower mass galaxies. The gas MZR has been shown to hold to at least $z \sim 3.3$ (Sanders et al. 2021; Li et al. 2023), with growing evidence that it holds up to $z \sim 10$ (Nakajima et al. 2023; Curti et al. 2024). These findings together suggest that the stellar MZR reflects the imprint of the observed gas MZR on the stellar populations by the baryon cycle over cosmic times.

In addition to its primary dependence on M_* , the gas metallicity has been shown to depend on the recent star formation activity of a galaxy (on the time-scale of ~ 10 Myr), a relation known in the literature as the gas-phase fundamental metallicity relation (gFMR; e.g. Ellison et al. 2008; Mannucci et al. 2010; Curti et al. 2020;

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Kumari et al. 2021; Baker et al. 2023b). These studies use either star formation rate (SFR), the specific SFR ($sSFR = SFR/M_*$), or the distance to the star-forming (SF) main sequence (MS; Δ_{MS}) as a quantitative metric for the recent star formation activity in galaxies (see Salim et al. 2014 for a discussion).

While the gFMR has been studied in detail in the literature, it is to date unclear how and even *if* the gFMR leaves its imprint on the stellar metallicity [see e.g. Pipino, Lilly & Carollo (2014), based on the gas-regulator model by Lilly et al. (2013), for a discussion].

Peng, Maiolino & Cochrane (2015) present distinct stellar MZR for a binary classification into SF and quiescent galaxies in the Sloan Digital Sky Survey (SDSS), showing that SF galaxies exhibit, on average, lower metallicities than their quiescent counterparts at fixed stellar mass. This trend is present across the whole stellar mass range, with the difference becoming more significant at the low end of the galaxy mass function. Trussler et al. (2020) add ‘green-valley’ galaxies as a third classifier and show that this population follows an MZR with a normalization between SF and passive galaxies. Similar results are also found in large hydrodynamical cosmological simulations, e.g. in EAGLE (Schaye et al. 2015), where De Rossi et al. (2018) find equivalent trends in the MZR by splitting their sample into three bins of $sSFR$, or in semi-analytical models (Fontanot et al. 2021).

Scott et al. (2017), Li et al. (2018), and Neumann et al. (2021) further show that spiral galaxies with typically younger stellar populations have lower stellar metallicities compared to older early-type galaxies at all stellar masses.

Lu et al. (2023) used data from the Mapping Nearby Galaxies at Apache Point Observatory (MaNGA) survey (Bundy et al. 2015) to show that galaxy stellar metallicity exhibits a continuous correlation with stellar age at $z \lesssim 0.1$, a trend that Cappellari (2023) showed to be already in place at $z \approx 0.8$, using data from the LEGA-C (Large Early Galaxy Astrophysics Census) survey (van der Wel et al. 2022).

In this paper, we complement these previous studies by studying MZR as a function of *recent* star formation activity. Instead of focusing on stellar ages, which trace and average past star formation activity of galaxies over long time-scales, we study the stellar MZR as a *continuous* function of SFR, similar to studies of the gas MZR, which established the existence of a gFMR.

More concretely, in this work, we analyse stellar metallicities, recovered using an astro-archaeological approach, as a function of two parameters: (i) stellar mass (M_*) and (ii) distance of a galaxy from the SF MS (Δ_{MS}) – as our quantitative measure of the SF activity of a galaxy – in a statistically significant number of observed galaxies. We show a ‘stellar fundamental metallicity relation’ (sFMR) analogous to the successful gFMR, as also proposed by Fontanot et al. (2021). Further, we present observational evidence that the sFMR holds not only for the cumulative stellar metallicity of all stellar populations (i.e. averaged over all cosmic times), but also when considering only the youngest stellar populations, which were most recently formed in galaxies.

The layout of this work is as follows. In Section 2, we describe the data and the techniques this study is based on. In Section 3, we present the sFMR in MaNGA, the sFMR in IllustrisTNG, and the FMR of the young stellar populations. In Section 4, we discuss our results and present a literature comparison. In Section 5, we summarize the main findings and conclusions of this work.

Throughout this work, we assume a Salpeter (1955) initial mass function (IMF) and a Lambda cold dark matter (Λ CDM) cosmology with the following parameters: $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$.

2 DATA AND DATA PROCESSING

2.1 The MaNGA sample

This work is based on spatially resolved spectroscopic data from the MaNGA survey (Bundy et al. 2015). The MaNGA survey is one of the core programmes of the fourth-generation Sloan Digital Sky Survey (SDSS-IV), providing spatially resolved spectroscopic data for a sample of ca. 10 000 galaxies in the local Universe with redshifts $z \lesssim 0.15$. For this work, we use Data Release 17 (DR17), the final data release of SDSS-IV (Abdurro’uf et al. 2022).

MaNGA observed with 17 fibre-bundle integral field units that vary in fibre number from 19 fibres to 127. Two dual-channel spectrographs provide a wavelength coverage over 3600–10 300 Å at a resolution of $R \sim 2000$. MaNGA targets are selected using NSA (NASA-Sloan Atlas) redshifts and *i*-band luminosity to have a total stellar mass of $M_* \gtrsim 10^{9.5} M_\odot$, to achieve a uniform radial coverage in terms of the effective radius (R_e , where the sample covers galaxies to $1.5R_e$ and $2.5R_e$ for the primary and secondary samples, respectively), and to approximately achieve a flat distribution in stellar mass. For more details on the MaNGA survey, we would like to refer to the existing literature. Specifically to Drory et al. (2015) for a description of the instrument, to Law et al. (2015) and Wake et al. (2017) for the target selection and observing strategy, and to Law et al. (2016, 2021) and Yan et al. (2016) for the data reduction.

In this work, we leverage the high quality of MaNGA’s spatially resolved spectra, to study stellar populations in galaxies at an unprecedented combination of high signal-to-noise ratio (S/N) and large sample size. This unique data set allows us to investigate physical processes within nearby galaxies by combining astro-archaeological and statistical approaches across a wide range of stellar masses, morphologies, and other distinctive galaxy characteristics.

2.2 IllustrisTNG

In order to compare our MaNGA results with state-of-the-art cosmological simulations, we collect an analogous sample of simulated galaxies from the (100 cMpc)³ volume run of the IllustrisTNG simulation suite (Marinacci et al. 2018; Naiman et al. 2018; Nelson et al. 2018; Pillepich et al. 2018; Springel et al. 2018). More precisely, we use the publicly available redshift $z = 0$ TNG100-1 SUBFIND catalogue (Nelson et al. 2019) to extract stellar masses and mass-weighted mean metal mass fractions of star particles (mass-weighted stellar metallicities). To ensure a consistent comparison with the MaNGA field of view, all quantities are measured within twice the stellar half-mass radius for a given subhalo (i.e. galaxy). We further make use of catalogues provided by Donnari et al. (2019) and Pillepich et al. (2019), to extract SFR values averaged over 10 Myr of the simulation to match the time-scale associated with $H\alpha$ -based estimate of SFR in observations. We also convert M_* and SFR from Chabrier to Salpeter IMF by dividing the catalogue values by constant factors of 0.61 and 0.63, respectively (Madau & Dickinson 2014). When normalizing metallicity by solar values we use the solar metallicity, defined as the bulk mass fraction of metals, estimated by Asplund et al. (2009) of $Z_\odot = 0.0142$, to ensure consistency with spectral fitting performed in MaNGA.

2.3 Distance from the star-forming main sequence

For each galaxy in the entire MaNGA sample, we calculate its distance from the SF MS as

$$\Delta_{MS} = \log_{10}(\text{SFR} [M_\odot \text{ yr}^{-1}]) - \text{MS}(M_*), \quad (1)$$

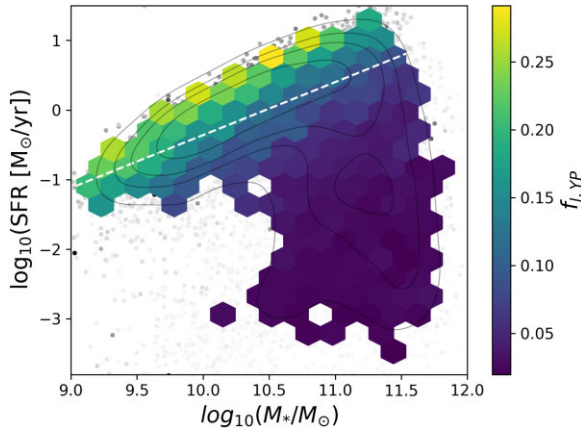


Figure 1. M_* -SFR diagram of our MaNGA galaxy sample, colour coded by the fraction of light originating from stellar population younger than $10^{8.5}$ yr, $f_{l,YP}$. Each hexagonal bin comprises at least 15 galaxies. The white line represents our best fit of the SF MS in MaNGA.

where

$$MS(M_*) = -7.96 + 0.76 \log_{10}(M_* [M_\odot]) \quad (2)$$

is our best fit of the SF MS, as presented in Fig. 1. To perform this fit, we consider only galaxies with $\log_{10}(sSFR[1/yr]) > -11.5$, and perform a simple linear fit to all SF galaxies. For stellar masses M_* and SFRs, we use the values provided by the PIPE3D MaNGA value-added catalogue from Sánchez et al. (2016), which are calculated from integration within the field of view of the data cubes, without further aperture correction. The integrated SFRs from PIPE3D are based on the well-established $H\alpha$ calibration (Kennicutt 1998), tracing star formation on short time-scales of ~ 10 Myr. The integrated $H\alpha$ flux is dust-corrected spaxel by spaxel based on the Balmer decrement and the Cardelli, Clayton & Mathis (1989) dust attenuation law.

In IllustrisTNG, we also calculate Δ_{MS} with equation (1) for all galaxies in the sample. To do that, we follow the method adopted by Donnari et al. (2019), performing a linear fit to converged median SFR values of all galaxies with non-zero SFR, in bins of 0.2 dex in stellar mass, in the range $9 < \log_{10}(M_*/M_\odot) < 10.6$. This yields an MS_{TNG} of the form

$$MS_{TNG}(M_*) = -6.28 + 0.63 \log_{10}(M_* [M_\odot]), \quad (3)$$

shown as a black dashed line in Fig. 2. We note that our definition of MS_{TNG} has a shallower slope and a higher intercept than other studies (e.g. Donnari et al. 2019; Piotrowska et al. 2022). This discrepancy results from our choice of a different SFR averaging time-scale and the applied conversion between Chabrier and Salpeter IMFs.

2.4 Spectral stacking and fitting

For each MaNGA galaxy, we discard all the spaxels with a median $S/N < 1$ per spectral pixel within the rest-frame wavelength range 4000–4500 Å. Then, we bin the spatially resolved MaNGA data in radial annuli (i.e. elliptical bins in the observed 2D projection of each galaxy, taking the viewing angle into account) using an adaptive scheme in order to ensure a high enough median $S/N (> 35)$ per spectral pixel for our purposes (the reason for this approach is to be consistent with our radial gradient analysis – we will discuss radial trends discovered with our methodology in a separate paper).

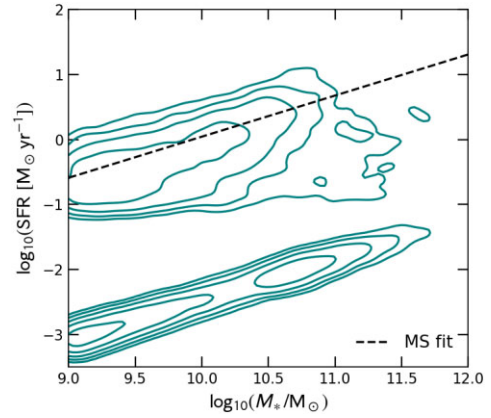


Figure 2. M_* -SFR diagram of the galaxy sample in IllustrisTNG. The black dashed line represents the MS fit (equation 3), while the logarithmically spaced contour lines indicate the object density in the plane. In order to show the whole galaxy population, all subhaloes with $SFR = 0$ are assigned a nominally low SFR value by taking a random draw for their Δ_{MS} from a normal distribution of $N(-2.5, 0.1)$.

The resulting binned spectra (summed without any weighting) are then fitted with our customized methodology, which is based on the χ^2 -minimization Penalized PiXel-Fitting (PPXF) code¹ (Cappellari 2017, 2023). To fit gas emission lines, we use Gaussians. To fit the stellar continuum, we use a library of simple stellar population (SSP) templates coupled with a 10th-order multiplicative Legendre polynomial. The SSP spectra are the synthetic spectra from the C3K library (Conroy et al. 2019) using the MIST (MESA Isochrones and Stellar Tracks) isochrones of Choi et al. (2016), solar abundances, a Salpeter IMF, and a resolution of $R = 10\,000$. We use a total of 484 synthetic SSP spectra uniformly spanning the full 2D logarithmic grid of 44 ages and 11 metallicities from $\text{age}_{SSP} = 10^{6.0}$ to $10^{10.3}$ yr and $[M/H] = -2.0$ to 0.5 , respectively. The large advantage of the C3K library is its expansion into young SSP ages in combination with its complete metallicity grid.²

By fitting the observed spectra simultaneously with a superposition of SSPs and gas templates, we can reconstruct the complex formation and evolution history of the stellar system under consideration with this ‘astro-archaeological’ approach, where we use the observed remaining stellar populations as the ‘fossil records’ of the system’s star formation history (SFH).

In more detail, our method, which we apply to each individual MaNGA galaxy in the selected sample (see Section 2.5), works as follows:

(i) First, the sky emission lines in each spectrum are masked; the templates are broadened to match the wavelength-dependant spectral resolution of the spectrum; and both the spectrum and the templates are renormalized by the median flux per spectral pixel in the spectrum to avoid numerical issues, and to enable the use of regularization in PPXF, allowing to penalize non-smooth weight distributions (we use a second-order regularization, see Cappellari 2017, 2023 for more details).

(ii) Then, an initial PPXF fit is performed with a small regularization parameter of $\text{regul} = 5$ in order to estimate the intrinsic noise of the spectrum and to exclude bad spectral pixels from the spectrum

¹<https://pypi.org/project/ppxf/>; version 8.0.2.

²These SSP templates are available from the author C. Conroy upon reasonable request.

that might bias the fit. We estimate the noise $\sigma(\lambda)$ in the spectrum as a function of wavelength λ via a running average of the 16th and 84th percentile residuals within ± 50 spectral pixels for each pixel in the spectrum.

(iii) Next, we perform a 3σ clipping on the spectrum. As the flux of gas emission lines often exceeds the underlying flux of the stellar continuum by multiple factors or even order of magnitudes, and with that also their residuals are often substantially larger, gas emission lines are excluded from σ clipping. Typically, 1–3 per cent of spectral pixels are excluded by σ clipping.

(iv) We fit the spectrum again with PPF, excluding the σ -clipped pixels and using our updated noise estimate, again with $\text{regul} = 5$. This initial PPF fit with best-fitting solution $y(\lambda)$ is the basis function of our running bootstrapping method described in the next items.

(v) We perform a residual-based bootstrapping by perturbing $y(\lambda)$ with the residuals $\epsilon(\lambda) = y(\lambda) - s(\lambda)$ of the initial fit: $y^*(\lambda) = y(\lambda) \pm \epsilon(\lambda')$, where $s(\lambda)$ is the observed galaxy spectrum and $\epsilon(\lambda')$ is randomly chosen from all residuals within ± 50 pixels for each spectral pixel.

(vi) We fit the perturbed spectrum $y^*(\lambda)$ again with PPF, this time without regularization ($\text{regul} = 0$).

(vii) We iteratively repeat steps (iv) and (v) 100 times.

(viii) We average each grid point of the age–metallicity weight grid over all iterations to recover an SFH consistent with the intrinsic noise of the spectrum. This method probes the sampling distribution of each individual SSP grid weight.

One of the key advantages of our approach is that the fitted weights of the 484 SSP templates are independent of one another (apart from the little regularization we use to slightly smooth the weight distribution, see Cappellari 2017 for more details). Hence, our recovered SFHs are non-parametric and do not depend on any assumption about the underlying physics of galaxy evolution. Crucially, any recovered scaling relation cannot have been introduced by parametric assumptions about the shape of our fitted 2D SFHs.

While this non-parametric astro-archaeological approach is extremely powerful, the analysis of its outputs has to be done with utmost care. Depending on the S/N of a considered spectrum, the 2D shape of the recovered SFHs (e.g. due to the well-known age–metallicity degeneracy), and known and unknown systematics, such as dust obscuration, or flux calibration issues, we can trust returned SSP weights to different degrees. To assess the stability of the SSP weights, the bootstrapping methodology described above is highly instructive, as it returns a scatter distribution for each individual SSP weight, as well as for any quantity derived from the weight grid; e.g. the light-weighted metallicity, given as the weighted average metallicity of all fitted SSPs. The thorough tests performed to assess the validity and stability of our results discussed in this paper will be discussed in detail in Looser et al. (in preparation). Our tests showed that numerous interesting, ‘collapsed’ (i.e. averaged over many galaxies and radial bins therein) quantities derived from a large subsample of SSPs are highly reliable.

To give an example of a collapsed quantity derived from the full spectral fitting, Fig. 1 shows the fraction of total fitted light stemming from all SSPs younger than $10^{8.5}$ yr, $f_{1,\text{YP}}$, averaged over all galaxies with similar stellar masses and SFRs. Contributing to this plot are all galaxies in the MaNGA subsample used in this work, see Section 2.5. The reader will note the small scatter in $f_{1,\text{YP}}$ between neighbouring hexagonal bins, as well as the general agreement with physical expectations between $f_{1,\text{YP}}$ and the location of galaxies on the SFR– M_* plane.

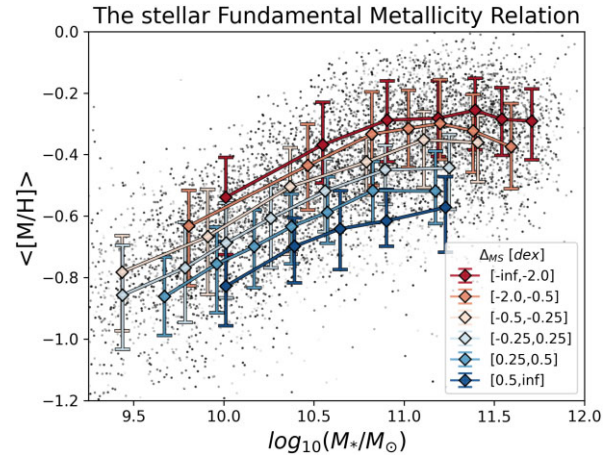


Figure 3. The global light-weighted sFMR in local galaxies from MaNGA. Each grey dot represents one galaxy. The diamonds represent the median integrated stellar metallicity in each $\Delta_{\text{MS}}-M_*$ bin, while the error bars indicate the 16th and 84th percentiles. Each $\Delta_{\text{MS}}-M_*$ bin comprises at least 80 galaxies.

2.5 Sample selection

For the purposes of this analysis, we only consider MaNGA galaxies that have an integrated median S/N > 35 per spectral pixel in the wavelength range 4000–4500 Å (in rest frame). This ensures the reliable inference of the quantities presented in this paper (see e.g. Barone et al. 2020). Further, we discard targets classified as AGN in the BPT diagram and discard 20 galaxies for which our fitting methodology failed due to flux calibration or contamination issues. This results in the subsample of 7323 MaNGA galaxies used in this work.

As can be seen in Fig. 1, the selected sample densely populates both the MS and the quiescent population (each hexagonal bin comprises at least 15 galaxies) over a wide range of stellar masses.

In IllustrisTNG, we select all subhaloes of cosmological origin (i.e. genuine structures with $\text{SubhaloFlag} = 1$, as opposed to spurious SUBFIND algorithm identifications) with $M_* > 10^9 M_\odot$, to match simulated and observed galaxy samples in mass. Additionally, we remove all satellite galaxies with dark matter mass fraction lower than 10 per cent, to confidently eliminate subhaloes potentially misidentified with the SUBFIND algorithm (Genel et al. 2018; Pillepich et al. 2018). These combined selection criteria yield a total sample size of 17 206 individual galaxies.

3 THE STELLAR FUNDAMENTAL METALLICITY RELATION

3.1 The light-weighted stellar fundamental metallicity relation in local galaxies from MaNGA

In Fig. 3, we present the global sFMR. For this purpose, we collapse our spatially resolved results into a global analysis, simply by summing the results over the annular bins in each galaxy. The stellar metallicity of each galaxy ($[M/H]$) is defined as the light-weighted average metallicity of all SSPs fitted with the methodology described in Section 2.4. Further, we split the selected sample of 7323 MaNGA galaxies into six Δ_{MS} bins, as indicated in the legend of Fig. 3. In addition to the Δ_{MS} binning, we apply an adaptive M_* binning in each Δ_{MS} bin to create a $\Delta_{\text{MS}}-M_*$ 2D binning of the sample with at least 80 galaxies in each 2D bin.

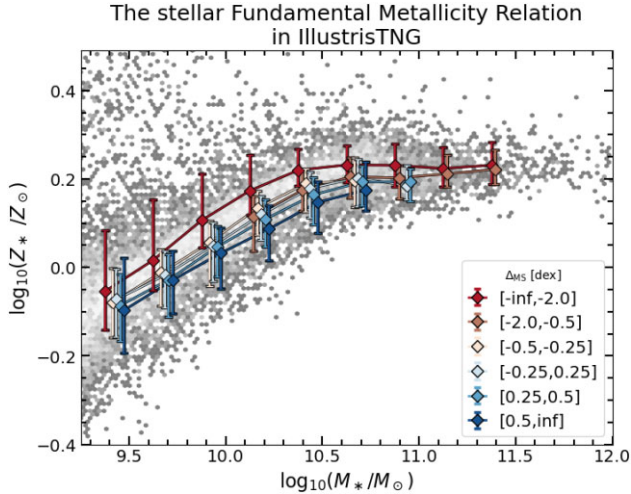


Figure 4. Global mass-weighted stellar FMR in IllustrisTNG. The diamonds show median mass-weighted stellar metallicity in each $\Delta_{\text{MS}}-M_*$ bin, while the error bars correspond to the 16th and 84th percentiles of the associated Z_* distribution. Each of these bins comprises at least 40 galaxies and Δ_{MS} bins are horizontally offset to improve figure clarity. Hexagonal bins indicate the density of objects in the plane.

It is evident that different local Δ_{MS} galaxy populations follow different MZR, where the higher Δ_{MS} populations are systematically metal poorer than the more quiescent populations; at all stellar masses and between all Δ_{MS} bins. While the MZR is steeply increasing for less massive systems in all Δ_{MS} bins, a flattening is evident at the high-mass end for galaxies on and below the MS. In summary, we clearly identify a sFMR in our non-parametric SSP analysis of the MaNGA data, analogous to the well-known gFMR.

3.2 The mass-weighted stellar fundamental metallicity relation in IllustrisTNG

In Fig. 4, we present the stellar FMR extracted from the IllustrisTNG cosmological simulation. Similarly to our MaNGA analysis, we split the simulated sample in ranges of Δ_{MS} identical to Section 3, and within each Δ_{MS} range, we further divide objects into bins of 0.25 dex in M_* . Each coloured diamond indicates a median value in a bin with at least 40 galaxies, while error bars indicate the 16th and 84th percentiles of the Z_* distribution in said bin. Grey-scale hexagonal bins indicate the density of objects in the plane.

Fig. 4 shows a well-defined relationship between total stellar mass of simulated galaxies and the average metallicity of their constituent stars. The simulated sFMR evolves modestly by ~ 0.3 dex over 2.5 dex in M_* , an evolution similar to that of the gFMR reported in Torrey et al. (2019), albeit with a smaller apparent scatter. Comparing trends among individual mass bins, we find that all Δ_{MS} bins follow similar trajectories in the M_*-Z_* plane, which are vertically offset in a direction of higher metallicity associated with the highest negative deviation from the SF MS. This trend agrees well with our analysis in Section 3, however, appears less pronounced owing to the tight nature of the simulated sFMR.

At this point, we stress that *one cannot compare the absolute values of light-weighted stellar metallicities* estimated in the observations with *mass-weighted metal fractions* calculated for stellar particles within cosmological hydrodynamical simulations. As demonstrated in Nelson et al. (2018), in the absence of full forward modelling and observation-like spectral fitting, stellar metallicities estimated in

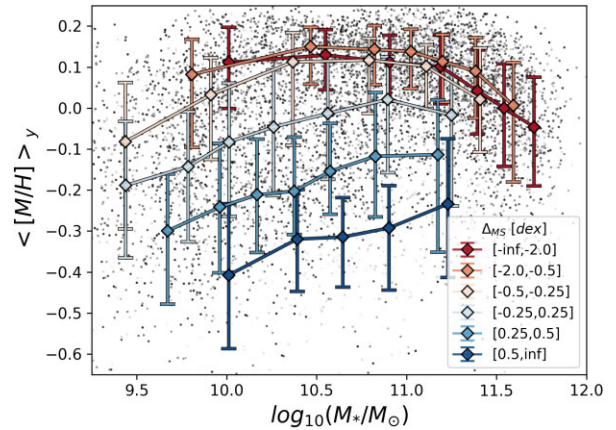


Figure 5. The sFMR for young stellar populations in MaNGA. Each dot represents one galaxy. The diamonds represent the median-integrated stellar metallicity in each $\Delta_{\text{MS}}-M_*$ bin, while the error bars indicate the 16th and 84th percentiles dispersion.

simulations are offset to higher values with differences reaching up to ~ 0.5 dex. Even if complex forward modelling is applied to simulate observations, the light-weighted metallicity values recovered from simulated galaxies are likely to show quantitative deviations from their observed counterparts (see Appendix B). On the other hand, mass-weighted metallicities for local galaxies are unreliable due to outshining and degeneracies between the oldest stellar populations (Appendix A). For this reason, our main focus lies in a qualitative comparison between relative trends in Z_* , rather than its absolute values.

To attempt a more direct comparison, the observed mass-weighted sFMR and the simulated light-weighted sFMR are presented in Figs A1 and B1. A direct, quantitative comparison between observations and simulations is beyond the scope of this paper.

3.3 The fundamental metallicity relation in young stellar populations

In Fig. 5, we present the FMR of the young stellar populations in local galaxies, as recovered by our non-parametric methodology described in Section 2.4. The ‘young metallicity’ of each galaxy is defined as the light-weighted average metallicity of all SSPs younger than $10^{8.5}$ yr. We use the same $\Delta_{\text{MS}}-M_*$ 2D binning as in Section 3, with at least 80 galaxies in each bin. Analogous to the sFMR, galaxies in different Δ_{MS} bins follow different young SSP MZR: at all stellar masses and between all Δ_{MS} bins, the more SF populations are systematically metal poorer than the more quiescent populations. The young metallicity values are systematically higher than the total metallicity values for galaxies at all masses and distances from the MS, showing that we recover the expected chemical enrichment of galaxies with cosmic time, at least qualitatively. This serves as an independent validation of the methodology, because our non-parametric approach allows *any* chemical evolution history. A detailed study of the chemical enrichment of individual galaxies is presently beyond the scope of this work.

Quiescent galaxies show a negative mass–metallicity slope at high stellar mass. Due to the very small amount of flux stemming from young SSPs in these massive, quiescent systems (as one arguably expects), see Fig. 1, this particular trend likely cannot be trusted. A detailed analysis of the reliability of the recovery of metallicity for young stellar populations will be presented in future work.

However, if confirmed, the young sFMR consistently links the time-scales between the well-established gFMR and the stellar FMR in local galaxies presented in this work.

4 DISCUSSION

It is now a well-established result that younger galaxies (as measured by their average stellar ages) have systematically lower metallicity compared to older galaxies (Scott et al. 2017; Li et al. 2018; Neumann et al. 2021). Recently, it has been shown that stellar metallicities of local galaxies show a *continuous* trend with age (Cappellari 2023), tracing the complex SFH of galaxies over cosmic times.

In this work, instead, we connected the chemical-enrichment histories of galaxies to their star formation activity in the recent past, by presenting evidence for the existence of a stellar FMR, analogous to the well-known gas-phase FMR. This is evidence of the chemical evolution of the ISM being imprinted on to the chemical evolution history of the stars over cosmic times. In addition to connecting the gas and stellar metallicities, we also ‘resolve’ the gap in stellar metallicity between SF and quiescent galaxies. More concretely, we show that there is a *continuous* distribution of metallicities, which correlates with the distance from the MS in both observed local galaxies in MaNGA and equivalent simulated galaxy populations in IllustrisTNG.

Additionally, we find strong evidence that a stellar FMR also exists in the young (<300 Myr) stellar populations of local galaxies, despite these populations being systematically more metal-rich than the older populations. Thus, we find that our non-parametric star formation and chemical-enrichment histories require (i) the metallicity of individual galaxies to increase with cosmic time and (ii) the total metallicity to be progressively larger, moving from above the MS towards the passive galaxies.

4.1 The starvation hypothesis

Peng et al. (2015) and Trussler et al. (2020) interpreted the ‘metallicity gap’ between local SF and quiescent galaxies as evidence for so-called ‘starvation’, i.e. the continuation of star formation after the supply of low-enrichment gas has been interrupted. Starvation causes efficient enrichment of the ISM because – by definition – it requires repeated recycling of the SF gas without diluting it with low-enrichment, newly accreted gas. The underlying assumption of the starvation hypothesis is that – eventually – low-metallicity/high- Δ_{MS} galaxies will evolve in high-metallicity/low- Δ_{MS} galaxies. Admittedly, we are comparing the metallicities of different Δ_{MS} bins in the local Universe, corresponding to different galaxies that are not linked by progenitor–descendant relations in Figs 3–5. However, if we were to compare the stellar metallicities of quiescent galaxies to the metallicities of their SF progenitors, the gap would be even wider (Peng et al. 2015; Trussler et al. 2020).

4.2 The metal retention hypothesis

In contrast to the starvation hypothesis, Vaughan et al. (2022) argue that the offset between the MZR of SF and passive galaxies is mostly due to their differing gravitational potential wells, for which they use M_*/R_e as a proxy: everything else being equal, galaxies with higher M_*/R_e might be able to retain more metals by reducing metal-loaded outflows. Indeed, analogously to Vaughan et al. (2022), we find that the scatter in the $\langle [M/H] \rangle - M_*/R_e$ relation is reduced relative to the $\langle [M/H] \rangle - M_*$ relation (Fig. 6, where R_e is taken from the PIPE3D MaNGA value-added catalogue; Sánchez et al. 2016).

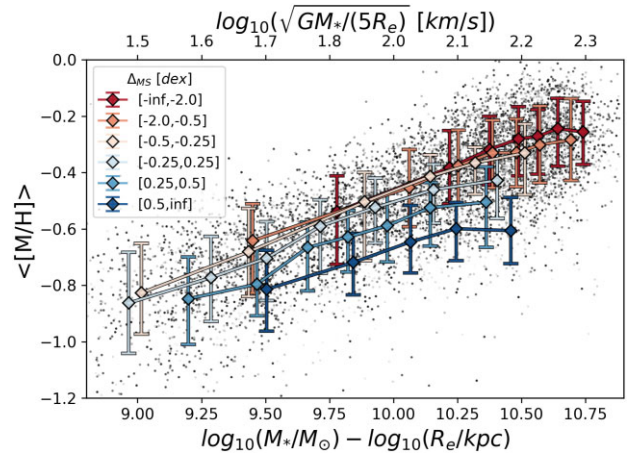


Figure 6. The difference in average stellar metallicities of different Δ_{MS} populations as a function of M_*/R_e , equivalent to the virial estimate of the velocity dispersion: $\sigma_{\text{vir}}^2 \equiv GM_*/5R_e$. Each dot represents one galaxy. The diamonds represent the median-integrated stellar metallicity in each $\Delta_{\text{MS}} - M_*/R_e$ bin. The error bars indicate the 16th and 84th percentiles dispersion.

We note that $M_*/R_e \equiv 5\sigma_{\text{vir}}^2/G \approx 5\sigma_e^2/G$ is equivalent to the virial estimate σ_{vir} of the stellar velocity dispersion σ_e ; this means that the reduced scatter going from M_* to M_*/R_e is also consistent with previous works, which showed that σ_e is better than M_* as a predictor of stellar population properties (Kauffmann et al. 2003; Franx et al. 2008; Cappellari 2011; Cappellari et al. 2013) like colour (e.g. Bell et al. 2012; Wake, van Dokkum & Franx 2012), metallicity (Barone et al. 2018, 2020, 2022), or both age and metallicity (McDermid et al. 2015; Cappellari 2016, 2023; Li et al. 2018; Lu et al. 2023).

In particular, the three lowest Δ_{MS} bins follow a nearly identical $\langle [M/H] \rangle - M_*/R_e$ relation. However, the scatter we find between individual Δ_{MS} bins on or above the MS is still significant and the offset between the most SF to the most quiescent bin only reduces from ca. 0.3–0.4 to 0.2–0.3 dex, when exchanging M_* with M_*/R_e on the x -axis. The difference between our results and Vaughan et al. (2022) is most likely due to the different samples used. Compared to SAMI (Sydney-AAO Multi-object IFS), MaNGA contains more high- M_* SF galaxies, enabling us to measure the metallicity of massive galaxies on and above the MS.

When considering M_*/R_e instead of M_* , the metallicity offset between SF and quiescent galaxies reduces by ≈ 0.1 dex. Assuming that M_*/R_e is a good proxy for the gravitational potential (as proposed by e.g. Vaughan et al. 2022), the observed reduction in scatter going from the mass–metallicity to the potential–metallicity relation could be explained by the fact that M_*/R_e encapsulates the capability of galaxies to retain metals (by resisting outflows). However, the decrease in scatter by 0.1 dex is only 25 per cent of the spread in metallicity between different Δ_{MS} bins. This fact indicates that – even though the capability of galaxies to retain metals by preventing outflows is having an effect – other physical processes are likely dominant in forming the stellar FMR.

4.3 The fundamental metallicity relations: correlating star formation over long time-scales

The gFMR connects star formation and gas metallicity on time-scales that are at least as long as the time-scale probed by the SFR indicators (e.g. ≈ 10 Myr for $H\alpha$). This is consistent with short-lived ‘episodic’ accretion of gas, capable of lowering the metallicity of the ISM

and increasing the SFR (e.g. Sánchez Almeida et al. 2014; Sánchez Almeida 2017). The sFMR enables us to extend this correlation to a time-scale of order $1/\text{sFMR}$, because galaxies have to form enough new stars to change the total light-weighted metallicity, including the extant stellar populations. This means that the FMRs are not due to short-lived ‘episodic’ accretion, but to long-lasting inflow of low-metallicity gas from the IGM/CGM, simultaneously fuelling star formation and keeping the ISM in a chemical-enrichment equilibrium between metal production and dilution. This finding is in agreement with theoretical models (see e.g. Forbes et al. 2014 for IGM accretion and Torrey et al. 2019 for CGM accretion). Our interpretation can also explain the gFMR, which is consistent with the existence of a ‘gas FMR’ (i.e. the relation between metallicity, stellar mass, and gas mass; Bothwell et al. 2013), and agrees with the observation that (central) galaxies lying below the MS have lower gas fractions (Saintonge et al. 2016; Tacconi, Genzel & Sternberg 2020; Baker et al. 2023a – with star formation efficiency playing at most an equal role; Piotrowska et al. 2020). We also note that the existence of a long time-scale correlation for SF galaxies does not contradict the presence of short-duration bursts (e.g. Wang et al. 2019), because the two can co-exist (Caplar & Tacchella 2019; Tacchella, Forbes & Caplar 2020).

4.4 Starvation drives galaxy quenching

The anticorrelation between stellar metallicity and distance from the MS at all masses shows that galaxies increase their stellar metallicity as they leave the MS. If this was not true, we should be observing low-metallicity galaxies on their way to quiescence and in the quiescent population, but this is not supported by observational evidence: the 1σ scatter of the quiescent stellar MZR is only ≈ 0.1 dex, inconsistent with a large population of local low-metallicity quiescent galaxies lying 0.2–0.3 dex below it. The absence of such galaxies and the independent observation of lower gas fractions below the MS (Saintonge et al. 2016; Baker et al. 2022, 2023a) suggest that galaxy quenching is accompanied by starvation.

The three Δ_{MS} bins below the MS show very similar $\langle[\text{M}/\text{H}]\rangle - M_*/R_e$ relations, with only a very small residual dependence on Δ_{MS} (red hues in Fig. 6). In contrast, the $\langle[\text{M}/\text{H}]\rangle - M_*/R_e$ relations of the three bins on or above the MS still exhibit a strong dependence on Δ_{MS} (blue hues in Fig. 6). This difference suggests that different physical mechanisms set the stellar metallicities in SF and quiescent galaxies.

The galaxies below the MS are either quiescent or on their way to quiescence; this means that they are not going to form a significant amount of stars relative to their extant stellar mass, which in turn means that it is unlikely they are going to significantly change their current stellar metallicity, which strongly correlates with M_*/R_e . On the other hand, at all M_*/R_e , the metallicity of SF galaxies anticorrelates with Δ_{MS} . Recalling that Δ_{MS} is primarily related to the gas fraction, this observation suggests that for SF galaxies stellar metallicity is set jointly by M_*/R_e (or by M_*) and by the specific inflow rate of metal-poor gas. These systems are expected to significantly increase their stellar mass; therefore, their stellar metallicity will evolve during the starvation process.

Coupled with independent strong evidence that quenching is *causally connected* to the integrated supermassive black hole feedback (Piotrowska et al. 2022; Bluck, Piotrowska & Maiolino 2023), the emerging scenario is one where AGN activity reduces and eventually interrupts the inflow of cold gas to the galaxy. During the extended phase of halted or significantly decreased accretion of pristine gas from the CGM/IGM, galaxies continue to consume gas, form stars, and recycle gas via supernova explosions and stellar

winds, which enriches their ISM – out of which stars with higher metallicities are born. During this long-lasting starvation process, the galaxies continuously decrease their gas reservoirs and transition through the different Δ_{MS} bins, while increasing their average metallicities – driven by the increase in metallicities of their youngest stellar populations – until they run out of gas, cease forming stars, and end up on the red sequence.

This process establishes the observed stellar FMR and the $\langle[\text{M}/\text{H}]\rangle - M_*/R_e - \Delta_{\text{MS}}$ relation in local galaxies. These relations therefore pose constraints to the duration of quenching itself.

5 SUMMARY

In this work, we use integral field spectroscopy from the local MaNGA survey coupled with a non-parametric SFH recovery methodology based on the full spectral fitting code PPXF, to connect the stellar mass, SFR, and stellar metallicity of a representative sample of local galaxies ($z < 0.15$).

(i) The main result of this work is the discovery of the stellar FMR, analogous to the well-established gas FMR.

(ii) When we compare the observed sample of MaNGA galaxies to an equivalent population in IllustrisTNG, we find matching relative trends in Z_* and M_* . The absolute values are offset, however, due to the intrinsic differences between methods employed in measuring metal content in simulations and observations.

(iii) Similarly to the overall stellar FMR, we find a young stellar FMR, when considering the average metallicity of only the SSPs younger than $10^{8.5}$ yr in local galaxies.

(iv) As stars continuously form from the gas in the ISM, we propose that the young stellar FMR and the total stellar FMR are both a natural consequence of the gFMR (which is valid to at least $z = 3$), which continuously gets imprinted on the stellar populations over cosmic epochs. Hence, the stellar, the young stellar, and the gFMR all trace the same physical processes, imprinted into the baryonic properties of galaxies over cosmic time-scales, intermediate time-scales, and time-scales of ca. 10 Myr, respectively.

(v) The observed presence of a stellar FMR suggests that starvation is the dominant mode through which galaxies quench.

(vi) The ability of galaxies to retain metals, by hindering outflows during their starvation phase, which might be correlated with M_*/R_e , can partially explain the differences in MZRs between different Δ_{MS} bins. However, even after incorporating this information, the metallicity differences are still significant.

(vii) The continuous accretion of metal-poor (or even pristine) gas on to SF galaxies, still ongoing in the local Universe, plays an important role in forming all three, the stellar FMR, the young FMR, and the gFMR. The continuous accretion of metal-poor gas on to SF galaxies – over cosmic epochs – simultaneously provides the fuel for ongoing star formation and continuously dilutes the ISM, out of which new stars are formed.

The existence of the stellar FMR leads to the conclusion that the total star formation of galaxies is correlated on long time-scales (at least in the low-redshift Universe), and that the stellar metallicity of local quiescent galaxies is largely set during quenching via starvation, i.e. a slow transition to quiescence due to the suppression of cold gas accretion.

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DATA AVAILABILITY

This paper uses data from the MaNGA survey (Bundy et al. 2015), which is part of the SDSS-IV. We use MaNGA DR17, which is publicly available at <https://www.sdss4.org/dr17/manga/>. All extracted quantities used in this work are publicly available on GitHub: <https://github.com/tobiaslooser/The-stellar-FMR>.

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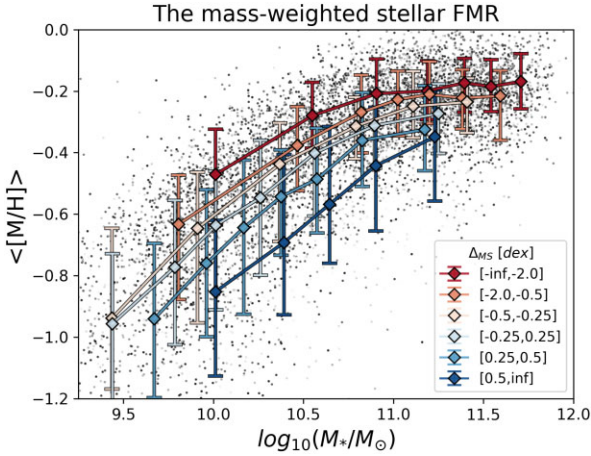


Figure A1. The global mass-weighted sFMR in local galaxies from MaNGA. Each grey dot represents one galaxy. The diamonds represent the median-integrated stellar metallicity in each $\Delta_{MS}-M_*$ bin, while the error bars indicate the 16th and 84th percentiles. Each $\Delta_{MS}-M_*$ bin comprises at least 80 galaxies.

APPENDIX A: THE MASS-WEIGHTED STELLAR FMR

In Fig. A1, we present the mass-weighted global sFMR. The mass-weighted stellar metallicity of each galaxy ($[M/H]$) is defined as the mass-weighted average metallicity of all SSPs fitted with the methodology described in Section 2.4. In other words, Fig. A1 is identical to Fig. 3, apart from mass weighting the SSP grid before calculating the stellar metallicity of each galaxy. The observed mass-weighted FMR is qualitatively similar to the mass-weighted sFMR predicted by IllustrisTNG, presented in Fig. 4. None the less, we caution against the overinterpretation of the observed mass-weighted stellar FMR, particularly against mass-weighted metallicities inferred for individual galaxies. The old (and metal-rich) SSPs are hard to constrain due to the faintness of these stellar populations. This makes them susceptible to outshining by the younger, brighter populations. Conversely, the fit may infer spurious old stellar populations, biasing the metallicity measurement. In light-weighted quantities this is not an issue, as the oldest templates only contribute little to the fit and only marginally to the inferred light-weighted SSP grid (typically less than 5 per cent). However, these untrustworthy populations may contribute considerably to the mass-weighted SSP grid, making mass-weighted quantities less reliable. The introduction of spurious old, metal-rich populations in the PPF fits explains the dominantly increased normalization of the mass-weighted sFMR in Fig. A1 compared to Fig. 3.

APPENDIX B: THE LIGHT-WEIGHTED STELLAR FMR IN TNG50

To further investigate discrepancies between the stellar FMR seen in observations and cosmological simulations, we use publicly available catalogues of MaNGA-like mock-galaxy observations generated from the highest resolution run of the IllustrisTNG suite, TNG50-1, performed for a volume of $(50 \text{ cMpc})^3$. In particular, we make use of MaNGIA (Mapping Nearby Galaxies with IllustrisTNG Astrophysics) 2D stellar property maps (Sarmiento et al. 2023) to extract global light-weighted mean metallicities for a sample of 10 000 galaxies selected from the simulation to match the MaNGA survey in

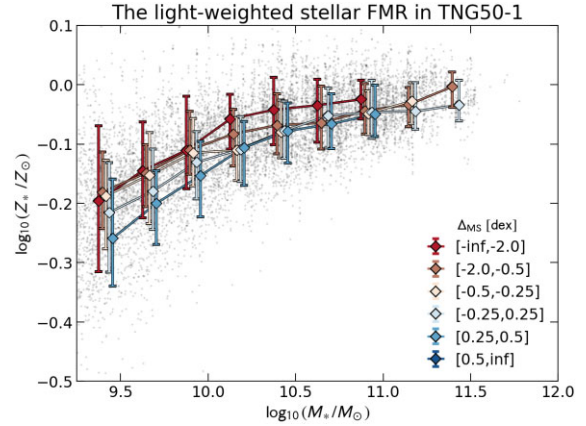


Figure B1. The global light-weighted sFMR in a sample of TNG50-1 galaxies selected to match the MaNGA sample selection criteria (Sarmiento et al. 2023). Each grey dot represents one galaxy. The diamonds represent the median-integrated stellar metallicity in each $\Delta_{MS}-M_*$ bin, while the error bars indicate the 16th and 84th percentiles. Each $\Delta_{MS}-M_*$ bin comprises at least 80 galaxies.

terms of mass, size, and redshift. Each mock galaxy observation was produced by assuming synthetic stellar templates based on the MaStar (MaNGA Stellar Library; Yan et al. 2019), a uniform metallicity-dependent dust screen model and CLOUDY templates for H II region emission associated with SF gas cells. Each mock was then analysed with PYPipe3D in a fashion identical to Sánchez et al. (2022) to generate 2D maps of stellar properties including age, metallicity, and kinematics.

In Fig. B1, we present the light-weighted global sFMR in the MaNGIA mock galaxy catalogue in TNG50-1. Fig. B1 is identical in spirit to Fig. 4, however, both the sample of galaxies and the metallicity estimates are replaced. In order to calculate Δ_{MS} values for the sample, we extract stellar masses and SFR values averaged over 10 Myr within twice the stellar half-mass radius for each MaNGIA galaxy. We then perform a linear fit to the MS, following methods described in Section 2.3, arriving at an MS fit of $MS(M_*) = -8.00 + 0.78 \log_{10}(M_*/[M_\odot])$, which is in close correspondence with the MS fit in the observed MaNGA sample in equation (2).

Fig. B1 shows a range in stellar metallicity offset to lower values with respect to Fig. 4. This way, the FMR is shifted closer towards the observations as seen in Fig. 3, however, simulations remain concentrated around values higher than those observed in MaNGA. Similar to Fig. 4, the simulated FMR is more compact than in the observations and different ranges in Δ_{MS} show significant overlap within their error bars.

Although a direct comparison between Figs B1 and 3 might suggest potential physical differences between the chemical composition of simulated and observed galaxy stellar contents, one still needs to remain cautious about the challenges associated with modelling the measurable electromagnetic signal emitted by stellar populations in cosmological simulations. With simulations currently lacking an explicit dust component and direct treatment of the cold ISM, mock observation studies like those conducted by Sarmiento et al. (2023) need to rely on a set of simplifying assumptions in order to estimate the impact of the ISM on the intrinsic stellar emission. These caveats, coupled with differences in stellar parameter recovery among different continuum fitting

approaches, are not unlikely to yield quantitative differences in the inferred stellar FMR between observed and simulated galaxies. Therefore, having explored the light-weighted approach in the mock TNG50-1 observation catalogue, we decide to focus on a qualitative

comparison of trends between MaNGA and IllustrisTNG in the main text.

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