**iMaNGA: mock MaNGA galaxies based on IllustrisTNG and MaStar SSPs – II. The catalogue.**

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**ABSTRACT**

Strengthening the synergy between simulations and observations is essential to test galaxy formation and evolution theories. To achieve this goal, in the first paper of this series, we presented a method to generate mock SDSS-IV/MaNGA integral-field spectroscopic galaxy observations from cosmological simulations. In this second paper, we build the iMaNGA catalogue consisting of ~1,000 unique galaxies from the TNG50 cosmological simulations, selected to mimic the SDSS-IV/MaNGA-Primary sample selection. Here we present and discuss the iMaNGA sample and its comparison to the MaNGA Primary catalogue. The iMaNGA sample well recovers the MaNGA-Primary sample in terms of stellar mass vs angular size relation and spatial resolution. The Sérsic index vs angular size relation, instead, is not reproduced well by the simulations, mostly because of a paucity of high-mass elliptical galaxies in TNG50. We also investigate our ability to recover the galaxy kinematics and stellar population properties with full-spectral fitting. We demonstrate that ‘intrinsic’ and ‘recovered’ stellar kinematics, stellar ages and metallicities are consistent, with residuals compatible with zero within 1σ. Also ‘intrinsic’ and ‘recovered’ star formation histories display a great resemblance. We conclude that our mock generation and spectral fitting processes do not distort the ‘intrinsic’ galaxy properties. Therefore, in the third paper of this series, we can meaningfully test the cosmological simulations, comparing the stellar population properties and kinematics of the iMaNGA mock galaxies and the MaNGA observational results.

**Key words:** Galaxy: evolution – Galaxy: formation – Galaxy: general – Galaxy: stellar content – Galaxy: structure – catalogues

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**1 INTRODUCTION**

During cosmic history, galaxies are shaped by complex physics acting on multiple scales (Somerville & Davé 2015). Hence, hydrodynamical simulations in a cosmological context have been utilised to theoretically predict what we observe (Vogelsberger et al. 2020). Nowadays, large-scale hydrodynamical simulations of galaxy formation are available, such as Illustris (Nelson et al. 2015), IllustrisTNG (Nelson et al. 2019a), and EAGLE (Schaye et al. 2014): in large cosmological volumes, baryonic matter and dark matter evolve together from the primordial density fluctuations to the local universe. Thanks to these large simulated samples, we can now test theoretical predictions against the tremendous amount of observational data provided by modern surveys, e.g. the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDLES, Grogin et al. 2011), the Sloan Digital Sky Surveys (SDSS, York et al. 2000; Abazajian et al. 2003), the Calar Alto Legacy Integral Field Area survey (CALIFA, Sánchez & et al. 2012), the Sydney-AAO Multi-object Integral field spectrograph (SAMI, Allen 2014), and Mapping Nearby Galaxies at Apache Point Observatory (MaNGA, Bundy et al. 2015).

‘Forward modelling’ is a technique to compare theory to observations, which places model galaxies on the observational plane taking into account a variety of observational effects. This has been employed in e.g. Tonini et al. (2010); Snyder et al. (2015); Torrey et al. (2015); Trayford et al. (2015); Bottrell et al. (2017); Trayford et al. (2017); Rodriguez-Gomez et al. (2019); Huertas-Company et al. (2019a); Schulz et al. (2020). Below we provide a brief synopsis of each of these works. Tonini et al. (2010) and Henriques et al. (2012) show that semi-analytic models of galaxy formation (for an overview of these models see Vogelsberger et al. 2020) better reproduce the observed colours and near-infrared luminosities of high-redshift (z ~ 2 – 3) massive galaxies when calculated with stellar population models accounting for the thermally pulsing asymptotic giant branch (TP-AGB) phase of stellar evolution. Snyder et al. (2015) includes the effect of a Gaussian Point Spread Function and noise into synthetic images from Illustris galaxies in order to study how optical galaxy morphology depends on mass and star formation rate in the simulations. Trayford et al. (2015) develop a method to build a
catalogue of 7,000 synthetic images and 40,000 integrated spectra from the Illustris simulations at redshift 0, proving how, from the synthetic data products, it is possible to produce monochromatic or colour-composite images, perform SED fitting, classify morphology, and determine galaxy structural properties, as for the analysis of real galaxies. Trayford et al. (2015) include the effects of obscuration by dust in birth clouds and the interstellar medium in EAGLE simulated galaxies, using a two-component screen model. In Trayford et al. (2017), the dust effect is included with radiative transfer simulations, demonstrating an improvement between the predicted optical colours as a function of the stellar mass with the observed ones. Bottrell et al. (2017) generate synthetic images from the Illustris simulations, including noise and the effect of the point spread function, in order to carry out bulge+disc decompositions for SDSS-type galaxy images. Their work reveals that galaxies in Illustris are approximately twice as large and 0.7 mag brighter on average than galaxies in the SDSS, because of a significant deficit of bulge-dominated galaxies in Illustris for log $M_*/M_\odot < 11$. Rodriguez-Gomez et al. (2019) generate synthetic images of ~27,000 galaxies from the IllustrisTNG and Illustris, to match Pan-STARRS (Chambers et al. 2016) galaxy observations. The synthetic and real Pan-STARRS images are analysed with the same code (STAMP/MORPH). The comparison reveals that the optical morphologies of IllustrisTNG galaxies are in good agreement with observations, improving the predictions of the original Illustris simulation. However, the IllustrisTNG model still does not reproduce the observed strong morphology–colour relation because of an excess of both red discs and blue spheroids. Moreover, at a fixed stellar mass, observations find discs to be larger than spheroids, while IllustrisTNG does not predict this trend. Huertas-Company et al. (2019a) select around 12,000 galaxies in TNG100 to generate mock SDSS images, using the radiative transfer code SKIRT (Camps & Baes 2014; Baes & Camps 2015) and including PSF and noise to mock SDSS r-band images. Observed and model morphologies are studied with a Convolutional Neural Network. The mass-size relations of the galaxies, divided by morphological type, match satisfactorily. However, there are discrepancies at the high mass end of the Stellar Mass Functions (SMF), which is dominated by disk galaxies in TNG100 and by early-type galaxies in SDSS. Schulz et al. (2020) investigate the relationship between the UV slope, $\beta$, and the ratio between the infrared and UV luminosities (IRX) of galaxies from TNG50 on 7280 star-forming main-sequence (SFMS) galaxies. A general good agreement is found at $z \geq 1$. However, they find a redshift-dependent systematic offset concerning empirically derived local relations, with the TNG50 IRX-$\beta$ relation shifting towards lower $\beta$ and steepening at higher redshifts. This selection of papers highlights how complex the comparison between observations and simulations is and the need for including observational effects in the simulations in order to allow for a close comparison.

This is the approach we take in the papers of this series, which focus on simulating the MaNGA (Mapping Nearby Galaxies at Apache Point Observatory) sample, which is an integral-field spectroscopic survey of 10,010 nearby galaxies (see §2.3). In Nanni et al. (2022), hereafter Paper I, we introduced our forward modelling procedure to generate realistic mock MaNGA-like galaxies. The main novelties of our method are: the adoption of the MaStar stellar population models (Maraston et al. 2020), that are based on stellar spectra obtained with the same MaNGA spectrograph (see §2.2 for details); a radiative transfer-based treatment of the dust; the reconstruction of a wavelength-dependent spectral noise based on MaNGA data; the use of the MaNGA effective Point Spread Function to include observational effects such as dithering. Furthermore, we follow the steps of the MaNGA Data Analysis Pipeline (DAP; Westfall et al. 2019) to analyse the mock data. Specifically, we use two spectral fitting algorithms, namely pPXF (see Cappellari 2017) in order to obtain stellar and gas kinematics and FIREFLY (Wilkinson et al. 2017) to obtain the stellar populations’ properties - age, chemical composition, star formation history (SFH), reddening and stellar and remnant masses - as in several analysis of the MaNGA data (e.g. Goddard et al. 2016; Goddard et al. 2017; Neumann et al. 2021, 2022). As for cosmological simulations of galaxy formation and evolution here we adopt IllustrisTNG (Nelson et al. 2019a; Pillepich et al. 2018b), but we stress that our procedure can be easily applied to any other simulation suite.

In this paper, we describe how we construct a mock MaNGA-like catalogue - which we call the ‘iMaNGA sample’ - by applying the MaNGA-Primary target selection boundaries in redshift and i-band absolute magnitude (see §2.3) to the TNG50 and employing the post-processing and analysis pipeline presented in Paper I over this selection. This results in ~1,000 unique TNG50 galaxies obeying the selection. Here we present and discuss the general properties of the mock galaxy catalogue, i.e. morphology, kinematics, and stellar populations. We then discuss how iMaNGA compares to the MaNGA-Primary sample, in particular focusing on the mass vs angular size relation, the spatial resolution and the Sérsic index vs angular size and mass relations, see §6. We finally demonstrate our ability to recover the truth values, i.e. the ‘intrinsic’ galaxy properties in the simulations. In the third paper of this series, we shall conduct a systematic comparison between our mock galaxies and observational results, including our own recent analysis published in Neumann et al. (2021).

The paper is organised as follows. Data and models in use are described in §2, while our forward modelling procedure is recalled in §3. The construction of the mock galaxy catalogue is presented in §4 and results are discussed in §5. In particular, we show the general properties of the iMaNGA sample in §5.1; we illustrate the morphological characteristics of the iMaNGA sample in §5.2; we compare the MaNGA-Primary sample to the iMaNGA one in §5.3; we present the results of the analysis of the kinematics in §5.4; we study the stellar population properties in §5.5. Also, in §6 we discuss other works on the construction of MaNGA-like galaxies from simulations. We draw our conclusions in §7.

2 INPUT MODELS AND DATA

Here we recap the description of models and data used in this work.

2.1 The IllustrisTNG simulation suite

IllustrisTNG (Pillepich et al. 2018b; Pillepich et al. 2019; Nelson et al. 2018, 2019a; Nelson et al. 2019b; Springel et al. 2018; Marinacci et al. 2018; Naiman et al. 2018a) is a suite of large-scale hydrodynamical simulations of galaxy formation and evolution, based on its predecessor Illustris (Vogelsberger et al. 2014; Genel et al. 2014; Sijacki et al. 2015). IllustrisTNG, while maintaining the fundamental approach and physical models of Illustris, expands its scientific goal with larger volumes (up to 300 Mpc) and higher resolution (up to a mass resolution for the baryonic matter of $8.5 \times 10^8 M_\odot$ instead of $1.6 \times 10^9 M_\odot$). Moreover, new physics is incorporated (including magnetic fields, and dual-mode black hole feedback, as described in Weinberger et al. 2017; Pillepich et al. 2020).
The fundamental physical processes comprised in these projects are the formation of cold dense gas clouds and stars; the stellar populations’ evolution and stellar wind and feedback; the supernovae physics and evolution; the formation of supermassive BHs and their accretion, radiation and feedback; the interstellar medium and its chemical enrichment. Indeed, the formation and evolution of galaxies are shaped by these processes which act across a broad range of spatial and time scales, governing galaxies’ fundamental characteristics, such as their stellar and gas content, star formation activity, chemical composition, morphology, and also their interactions with the external environment, e.g. in a cluster. Star formation in particular occurs stochastically when the gas number density is $\geq 0.13$ particle/cm$^3$ according to a Chabrier (2003) Initial Mass Function (IMF) and assuming the Kennicutt-Schmidt law (Schmidt 1959; Kennicutt 1989).

IllustrisTNG simulates three physical box sizes, with cubic volumes of roughly 50, 100, and 300 Mpc side lengths (named TNG50, TNG100, and TNG300, respectively). Each run has a different resolution. Particularly, in TNG50 (Pillepich et al. 2019; Nelson et al. 2019b), the gravitational softening for baryonic and dark matter is $\epsilon_{\text{gas, min}} = 74$ pc and $\epsilon_{\text{DM, min}} = 288$ pc; the mass resolution for baryonic and dark matter is: $m_{\text{bar}} = 8.5 \times 10^4 M_\odot$ and $m_{\text{PM}} = 4.5 \times 10^5 M_\odot$. Each run outputs 100 snapshots from redshift 20.05 to redshift 0.0. Haloes and subhaloes are identified with the Friends-of-Friends and the SUBFIND algorithms, respectively (see Springel et al. 2001b; Nelson et al. 2015).

In this paper, we focus on subhaloes simulated by TNG50 and identified in snapshots from redshift 0.15 to redshift 0.01, which approximately corresponds to the redshift range observed with MaNGA (see §2.3). TNG50 is chosen because it allows the high spatial resolution typical of the MaNGA datacubes (pixel size of 0.5”, i.e. a spatial sampling ranging from $\approx 100$ pc at $z \approx 0.01$ to $\approx 1.5$ kpc at $z \approx 0.15$, §2.3). A further discussion about the subhalo selection is presented in §4.

### 2.2 MaStar: SDSS-based Stellar Population Models

We use stellar population models from Maraston et al. (2020) which adopt the MaNGA stellar library MaStar (Yan et al. 2019) for the definition of stellar spectra as a function of effective temperature, gravity and chemical composition in the population synthesis. MaStar (Abdurrou’uf et al. 2021) consisting of $\approx 60,000$ is the largest stellar library ever assembled. MaStar stellar spectra were obtained with MaNGA fiber bundles and the BOSS optical spectrographs, i.e. the same observational set-up as for MaNGA galaxy observations (see §2.3). Therefore, the stellar spectra and the correspondent population models share the same wavelength range, spectral resolution and flux calibration as the MaNGA datacubes.

Here we use an updated version of the Maraston et al. (2020) models, spanning a wider age range, with ages down to $\approx 3$ Myr, with a grid of 42 age values in total. The chemical composition of the models goes between $-2.25$ to 0.35 dex in [Z/H], allowing a [Z/H] grid of 9 values (see Hill et al. 2021). Population models are calculated for 8 different values for the IMF slope below 0.6 $M_\odot$.

In all simulations the Planck cosmology from Ade et al. (2016) is adopted, with matter density parameter $\Omega_m = 0.31$; dark energy density parameter $\Omega_k = 0.69$; Hubble constant $H_0 = 100h$ km/s/Mpc, with $h = 0.68$; matter power spectrum amplitude of $\sigma_8 = 0.82$ and spectral index $n_s = 0.97$.

Energetics and synthesis method are the same as in Maraston (2005); Maraston & Strömbäck (2011) ranging between 0.3 and 3.8 in the notation in which the Salpeter (1955)’s slope is 2.35, for each age and metallicity combination.

With the MaStar-based population models we generate a synthetic spectrum for each stellar particle in the TNG50 galaxies (assuming the Kroupa (2002) IMF).

Stellar population models are a key input of galaxy formation simulations and “forward-modelling” (Baugh 2006; Tornyi et al. 2010; Gonzalez-Perez et al. 2014); they provide the link to the observables, and they are instrumental to obtain the physical properties of data, through spectral fitting. Consequently, the choice of the model is an essential part of the comparison between galaxy simulations and observed data. Our adoption of MaNGA-based population models ensures we use the same spectral properties in the simulations as well as in the interpretation of galaxy data. We are therefore able to exclude any bias that would be caused by the adoption of different spectral models. Moreover, as all spectra involved in our work have been obtained with exactly the same instrument and observational set-ups, we achieve the highest degree of consistency to start a meaningful comparison between data and simulations (Paper III).

### 2.3 The MaNGA galaxy survey

MaNGA (Mapping Nearby Galaxies at Apache Point Observatory, Bundy et al. 2015) is the largest Integral Field Spectroscopy (IFS) survey of galaxies to date. It observed 10,010 unique galaxies at a median redshift of $z \approx 0.03$ (Abdurrou’uf et al. 2022) providing spatially resolved spectra for each of them. MaNGA is part of the SDSS-IV survey (Blanton et al. 2017) and concluded its observations in August 2020.

The MaNGA IFS (Drory et al. 2015) was based around the SDSS 2.5-meter telescope at Apache Point Observatory (Gunn et al. 2006) and utilises the SDSS-BOSS spectrograph (Smeee et al. 2013; Dawson et al. 2013), with a wavelength range from 3,600 to 10,300 $\AA$ and an average spectral resolution $R \approx 1800$. In particular, the SDSS-BOSS spectrograph has a red and a blue camera, with a dichroic splitting the light around 6000 $\AA$. In the blue channel, the resolution goes from $R = 1560$ at $3,700 \AA$ to $R = 2,270$ at 6,000 $\AA$; in the red channel, the resolution goes from $R = 1,850$ at 6,000 $\AA$ to $R = 2,650$ at 9,000 $\AA$. In Paper I, we explain how we mimic the resolution of the SDSS-BOSS spectrograph at different wavelengths when we generate both the synthetic spectra and the noise.

MaNGA has hexagonal-formatted fiber bundles, made from 2”-core-diameter fibers, conducting dithered observations with Integral Field Units (IFUs), which vary in diameter from 12”-5 (19 fibers) to 32”-5 (127 fibers) (see Table 2 in Bundy et al. 2015). The hexagonal-formatted fiber bundles are mimicked in our forward modelling of the simulated galaxies, as explained in Paper I.

MaNGA is characterised by a spatial resolution of 1.8 kpc at the median redshift of 0.037 (Law et al. 2016). The MaNGA’s characteristic fiber-convolved Point-Spread Function (PSF) has a full width at half maximum (FWHM) of 2.5” (Law et al. 2015). For each MaNGA datacube, the ‘reconstructed’ PSF, or effective PSF (ePSF), is supplied in different bands (Law et al. 2016). We use the ePSFs in the different bands when generating the mock MaNGA-like galaxy datacubes (see Paper I).

The MaNGA galaxy sample is divided into a ‘Primary’ and a ‘Secondary’ sample, with a 2:1 split, for which the galaxy light sampling extends out to 1.5 effective radius ($R_{\text{eff}}$) and 2.5 $R_{\text{eff}}$, respectively, (Wake et al. 2017). In this paper, we focus on building a Primary MaNGA-like sample from TNG50 simulated galaxies, see §4.
3 MOCK GALAXY INPUT AND CALCULATION

Here we recapitulate our procedure to generate and analyse mock MaNGA galaxies, as introduced in Paper I.

3.1 Modelling the spectrum

Once a simulated galaxy is selected for post-processing, the first step is to model its stellar spectra. Our spectral modelling depends on the particle’s age. If a stellar particle is younger than 4 Myr, we assume it to be a star-forming region and model its emission with the MappingsIII star-forming region models (MIII models, see Groves et al. 2008). For older ages, we use MaStar stellar population models (see Maraston et al. 2020, and §2.2). It is important to emphasise that the synthetic spectra are associated directly with the stellar particles in TNG50 by interpolating within the SSP model grid. This is different from the studies presented by Ibarra-Medel et al. (2018) and Sarmiento et al. (2022) in which the stellar particles in the simulations are assigned model spectra from the closest properties in the stellar population model template grid without interpolation, introducing a difference between ‘intrinsic’ and ‘assigned’ properties. This point will be reprised in §6.

We mimic an IFU observation to collect the light, generating a datacube with the MaNGA pixel size (0.5") and a square FoV of 150" per side. Thanks to the use of the MaStar stellar population models the synthetic datacube’s spectral resolution and flux calibration are equal to MaNGA observations by construction. The virtual instrument is positioned along the z-axis of the cosmological volume in which the galaxy is identified. Note that observing the simulated galaxies with a line-of-sight (LOS) fixed to the cosmological z-axis effectively implies random viewing angles. An in-depth discussion of galaxy inclinations in iMaNGA sample will be done in Paper III.

3.2 Dust

Dust effects are included in the synthetic datacubes by reconstructing the attenuation curves spaxel by spaxel employing low-resolution radiative transfer simulations with SKIRT (Baes et al. 2011; Baes & Camps 2015). We define and discuss this original and fast way to exploit radiative transfer simulations in Sec. 3.2.2 of Paper I. With SKIRT, we mimic an IFU observation with the same FoV and pixel size as for the synthetic datacubes, but with lower spectral resolution. It is important to underline that we do not assume any model for the attenuation curves; the attenuation curves are defined simply as the ratio between the signal in the spaxel with and without dust included in the radiative transfer simulations. The attenuation curves defined at lower spectral resolution are then interpolated on the wavelength array of the synthetic datacubes. The attenuation curves are then applied to the synthetic datacubes, spaxel by spaxel.

3.3 Kinematics

The kinematics are incorporated as follows. Spectra are Doppler-shifted and broadened according to stellar kinematics, from the TNG50 simulations (see Sec. 3.2 in Paper I).

The iMaStar code, which performs these steps, can be found here: https://github.com/lonanni/iMaNGA.

3.4 Morphology

For the morphological analysis, we first obtain r-band SDSS-like images by applying the SDSS r-band filter and PSF to the synthetic datacubes. Images are then analysed with STATMORPH, a Sérsic 2D fitting code (Rodriguez-Gomez et al. 2019, see Paper I, sec. 3.3). The analysis with STATMORPH provides us with the effective radius $R_{\text{eff}}$ which is needed to construct a mock MaNGA Primary sample.

3.5 Inclusion of observational effects

Once the $R_{\text{eff}}$ values of the galaxies are known, we select the appropriate hexagonal fiber-bundle configuration that would be employed by MaNGA to collect the light from the galaxy within 1.5 $R_{\text{eff}}$. The available hexagonal diameters in the MaNGA set-up go from 12.5" to 32.5", see §2.3. As discussed in Paper I, we do not simulate the detailed spatial sampling mechanics of MaNGA observations, as done in Bottrell & Hani (2022), for instance. Instead, we select all the spaxels within the MaNGA hexagonal-formatted fiber-bundle FoV (see also Nevin et al. (2021)) and mimic observational effects such as dithering and resulting covariances between spaxels by exploiting the reconstructed PSF (or effective PSF) provided for each of the observed MaNGA galaxies in different bands.

The effective PSF depends on the exposure time and the observing condition in the considered band, and includes also dithering effects (Law et al. 2016). The convolution of the datacubes with the effective PSF happens after the implementation of noise. The noise is modelled based on an analysis of the real wavelength-dependent SNR in MaNGA (see Paper I). Since the convolution happens after the inclusion of the noise in each spaxel, this results in the signal of adjacent spaxels being correlated, including also the noise. This indirect approach of mimicking the effects of the MaNGA IFS observations leads to significant savings in computing time. It is a simplification compared to reconstructing the detailed mechanics of the observations, as for instance done by Bottrell & Hani (2022). Both the reconstruction of the effective PSF (hereafter ePSF) and the noise are based on MaNGA LOGCUBE output (Law et al. 2016). We refer the reader to Sec. 3.4 of Paper I for more detail.

Following this approach, and thanks to the combination of TNG50 and MaStar Stellar Population models, we produce datacubes having the same spatial sampling, spatial resolution, spectral resolution, SNR as a function of the wavelength, flux calibration, and wavelength range of MaNGA observations.

3.6 Data analysis

We follow the procedure developed for the MaNGA Data Analysis Pipeline (Westfall et al. 2019) to analyse the iMaNGA galaxies. Firstly, we employ the Voronoi algorithm of Cappellari & Copin (2003), with target S/N $> 10$. We then run the Penalized PiXel-Fitting algorithm (pPXF, Cappellari 2017), to reconstruct gas and stellar kinematics and model the emission lines.

We finally fit the mock spectra with FIREFLY (Wilkinson et al. 2017) to infer the stellar populations’ properties, i.e. age, metallicity, mass and age, and also reddening and the SFH. As we show in Paper I on two test galaxies with vastly different properties, our ‘mocking’ and fitting procedures do not alter the intrinsic properties of the TNG50 galaxies.

4 MOCK CATALOGUE CONSTRUCTION

Here we illustrate our method to construct the mock MaNGA catalogue from TNG50, i.e. our iMaNGA sample.
4.1 The initial sample of TNG50 galaxies

As explained in §2.1, the SUBFIND algorithm is run over all the saved snapshot of the Illustris and IllustrisTNG output cosmological volume. This algorithm identifies structures in the cosmological volumes as galaxies. To construct the iMaNGA sample from the TNG50 simulations, at first, we select all the TNG50 galaxies in the MaNGA redshift range (i.e. the 48,248 TNG50 galaxies selected to lie in the MaNGA redshift range (i.e. 0.01 – 0.15) and to having more than 10,000 stellar particles.

Figure 1. Distribution of (from top to bottom): i-band absolute magnitude (AB) (where $h = H_0/100\text{km}\text{s}^{-1}\text{Mpc}^{-1}$ and $h = 1$), stellar mass and half-mass-stellar radius (as a proxy of a galaxy size), of the ‘initial sample’, i.e. the 48,248 TNG50 galaxies selected to lie in the MaNGA redshift range (i.e. 0.01 – 0.15) and to having more than 10,000 stellar particles.

4.2 Obtaining a smooth spatial sampling

Since we want to recover a smooth distribution in spatial sampling, as in the MaNGA-Primary sample, we need to alter the discreteness of the TNG50 redshift sampling, due to the fact that - at low-z - the TNG50 snapshots are output every 150 Myr, and make it a continuum sample. To this end, we associate to each galaxy in the initial sample (see §4.1) a new redshift, which we call $z_{\text{random}}$. This redshift is randomly extracted from a uniform distribution with lower limit equal to the galaxy’s snapshot redshift (we refer to it as $z_{\text{TNG50}}$), and upper limit equal to the redshift of the previous, higher-redshift snapshot. In other words, we allow a galaxy in a given snapshot to have a redshift between the redshift characterising its snapshot and the redshift of the preceding snapshot. We do not change the redshift of galaxies at the upper redshift boundary, i.e. $z \approx 0.15$. In this way, we obtain a smooth distribution in spatial sampling, as for MaNGA datacubes. The results of the whole procedure are visualised in Fig. 2.

From now on, we consider the galaxies in the initial sample as characterised by $z_{\text{random}}$, instead of their original redshift $z_{\text{TNG50}}$. It should be noted that the new redshift $z_{\text{random}}$ is solely used to construct a MaNGA-like catalogue, and to observe the galaxies in it when producing mock MaNGA-like observations (see §3). The ages of stellar particles as provided by TNG50 are not modified.

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4 https://www.tng-project.org/data/docs/specifications/
5 http://nsatlas.org/data
Figure 3. Upper panel: The distribution of the 3,152 TNG50 galaxies in the parent sample in the magnitude-redshift space, colour-coded by the galaxy number density, and the MaNGA-Primary sample selection boundaries (black solid line). The grey points represent the galaxies excluded from the sample because not in the MaNGA-Primary target. Bottom panel: The distribution in i-band magnitude of the parent sample.

Figure 4. Comparison between the initial (hatch-filled histograms) and the parent (yellow histograms) samples of TNG50 galaxies, in i-band magnitude, stellar mass and half-mass stellar radius (from top to bottom panel).

4.3 Magnitude selection: The parent sample

The MaNGA sample selection is solely based on the galaxies’ absolute i-band magnitude and redshift, with the final sample achieving an approximately flat distribution in the i-band magnitude (for more information see Yan et al. 2019).

The top panel of Fig. 3 presents the MaNGA-Primary sample selection boundaries (in black) (see Wake et al. 2017), and the TNG50 galaxies in the initial sample falling into it, identified by the new redshift $z_{\text{random}}$. The bottom panel shows their distribution in the i-band magnitude. After imposing the Primary sample selection boundaries, we are left with 3,152 TNG50 galaxies. We refer to this sample as the "parent sample".

Fig. 4 displays the magnitude, the stellar mass $M_*$, and the half-mass-stellar radius $R_{\text{hmsr}}$ distributions (from top to bottom) for the initial (hatched-filled histograms) and the parent sample (yellow histograms). Excluding galaxies outside the MaNGA selection boundaries (grey points in Fig. 3) changes the galaxy distributions substantially. There is a significantly higher density of high-luminosity objects and high-mass objects once these selection criteria are applied. The size distribution, instead, remains largely unchanged.
4.4 The final iMaNGA sample

In order to achieve the final, flat distribution in i-band magnitude over the TNG50 parent sample (§4.3), we perform the following steps:

(i) We build the galaxy distributions in i-band magnitude and redshift of the parent sample (bottom panel of Fig. 3).

(ii) To each TNG50 galaxy in the parent sample, we associate a probability \( p \) inversely proportional to their containing bin count, \( N \) (bottom panel of Fig. 3);

(iii) We randomly extract unique galaxies from this sample, assuming a selection probability for each of them equal to \( 1/N \). In other words, the probability of being selected is larger in underpopulated bins.

The requirement to achieve a flat distribution constrains the number of galaxies, which ends up being about 1,000 in our case. We will refer to this sample as the ‘iMaNGA sample’. This is our final sample, which we then post-process and analyse following the method presented in Paper I and recapitulated in §3.

The top panel of Fig. 5 displays the MaNGA-Primary sample selection boundaries (in black), and the TNG50 galaxies in the iMaNGA sample, colour-coded by number. The bottom panel shows the distribution in i-band magnitude in the initial (black hatch-filled histogram), parent (yellow histogram), and final iMaNGA (teal empty histogram) samples of TNG50 galaxies. Our method allows us to successfully generate a flat distribution in i-band magnitude. In Fig. 6 we compare these three samples in terms of stellar mass (top panel) and size (bottom panel, where the half-mass-stellar radius is considered a proxy of the galaxy size as usual), with the same meaning of symbols as in the bottom panel of Fig. 5. The iMaNGA sample of \( \sim 1,000 \) unique TNG50 galaxies is characterised by an approximately flat distribution in mass, as well as in i-band magnitude.

5 RESULTS

In this Section, we present the main characteristics of the iMaNGA sample, in particular the galaxy sizes, masses and environmental densities (§5.1). Then, we report the outcome of the morphological analysis, based on mock r-band SDSS-like images (§5.2). Next, we present a direct comparison between some key characteristics of the iMaNGA and the Primary MaNGA samples (§5.3). Afterwards, we describe the results of the kinematic analysis over the entire sample, discussing our ability to recover the ‘intrinsic’ kinematics, as given by TNG50 (§5.4). At the end, we present the analysis of the stellar populations’ properties and our ability to recover the ‘intrinsic’ stellar population properties from TNG50 (§5.5).

5.1 Characteristics of the iMaNGA sample

Fig. 7 shows the size (half-mass stellar radius \( R_{hsmr} \), top panel), the i-band magnitude (\( M_i \), central panel), and the environmental density (\( \log(1 + \delta) \), bottom panel) of the galaxies in the iMaNGA sample as a function of stellar mass (\( M_\ast [10^{10} M_\odot] \)) and colour-coded by redshift.

The environment is defined with the N-th nearest neighbour method: the distance to the N-th nearest neighbour, \( d_N \), with \( N \) typically varying from 3 to 10, is used as a measure of the local galaxy (projected) overdensity (Muldrew et al. 2011; Etherington & Thomas 2015). The dimensionless overdensity, \( 1 + \delta \), is described by the following equation:

\[
1 + \delta = 1 + \frac{\Sigma_N - < \Sigma >}{< \Sigma >}
\]  

(1)

where \( \Sigma_N \) is the surface number density described using the N-th neighbour method (\( \Sigma_N = N/\pi d_N^2 \)), while \( < \Sigma > \) is the mean surface density of galaxies. We assume \( N = 5 \) and compute \( < \Sigma > \) within the TNG50 snapshot the galaxies are in, projecting the subhaloes in each of the simulated volumes along the z-axis of the cube. As a proxy of the galaxy environment, we use \( \log(1 + \delta) \) (for more details see Paper I). In each panel of Fig. 7, we report the linear regression (black line) and the Pearson correlation coefficient (in the upper left corners) are reported in each panel.

As expected, galaxy mass and i-band magnitude are closely correlated. However, there are also significant correlations between stellar mass and the half-mass radius as well as the environmental density. These correlations are consistent with observations of real galaxies (see Li et al. 2018; Bernardi et al. 2010; Kauffmann et al. 2004). As expected, due to the design of the MaNGA target selection (see Yan et al. 2019), there is a strong redshift bias, with more massive galaxies lying at higher redshift in order to fit into the IFU apertures. Our iMaNGA sample reproduces this effect.

5.2 Morphological analysis

As said earlier (and explained in Paper I), morphologies are obtained from the r-band images. Fig. 8 displays the RGB images of 8 galaxies in our iMaNGA sample, to showcase the variety of morphologies reproduced by the TNG50 simulations, and therefore also present in
the iMaNGA sample. The RGB images are obtained from the synthetic datacubes, with a square FoV of 150" as side length, including the effects of dust. Note that we do not include any observational effects, such as noise or PSF, as these images do not have a scientific purpose, being solely meant to visualise the variety of morphology and inclination in iMaNGA.

Table 1 reports the key properties of these galaxies: snapshot id, redshift \( z_{\text{random}} \), i-band magnitude, stellar mass, HMSR, environment (see §5.1), effective radius and Sérsic index. Comparing the Sérsic indices with Fig. 8, we notice how galaxies showing spiral structures (ID 3, ID 452563, ID 532259, and ID 598178) have \( n \sim 1 \), while elliptical-looking galaxies (ID 439126, ID 561122) have \( n > 2 \).

Fig. 9 shows the distribution of Sérsic index \( (n) \) in iMaNGA. The top panel presents the entire catalogue (teal histogram). In the central panel, the catalogue is split into galaxies with and without dust particles (grey and black dashed histogram). In the bottom panel, the catalogue is divided into galaxies with and without star-forming particles (grey and black dashed histogram). The distribution in Sérsic index of the galaxies with star-forming and dust particles peaks at low \( n \) values \((n \sim 1)\). Indeed, it is expected to have star formation and dust in disc-like and irregular galaxies (Lianou et al. 2019).

We note that the overall distribution of the Sérsic index in iMaNGA has a peak around \( n \sim 1 \). A similar peak is also present in the distributions of the Sérsic index in the MaNGA catalogue. However, the Sérsic index distribution in MaNGA is bimodal, with another, slightly smaller peak around 4 (see Fig. 12 in Fischer et al. 2018). This second peak is also present in the iMaNGA sample, but significantly smaller. This is the direct consequence of a paucity of elliptical galaxies in the underlying TNG50 catalogue. We will discuss this point further in the following section.

### 5.3 Comparison with the MaNGA-Primary sample

In this section, we present a comparison between the main characteristics of the MaNGA-Primary sample and the iMaNGA catalogue. All the properties of the MaNGA-Primary sample, i.e. total stellar mass, effective radius, Sérsic index, and redshift, are retrieved from DRPALL MaNGA data (Law et al. 2016). The total stellar mass of a galaxy in the iMaNGA sample is intrinsic, hence is directly computed as the sum of the stellar particles used to construct the synthetic datacube. Other quantities like Sérsic index and effective radius, instead, are derived from the synthetic iMaNGA images.

#### 5.3.1 Angular size and spatial resolution

In Fig. 10, we present the distributions of angular size (left-hand panels), spatial resolution expressed in kpc (central) and in terms of the effective radius (right-hand panels) for MaNGA (top panels) and iMaNGA (bottom panels). The figure mimics Fig. 5 of Wake et al. (2017), including the fine binning in the stellar mass range \( 8.9 \leq \log_{10} M_*/M_\odot \leq 11.3 \). The vertical lines illustrate the radius of the hexagonal FoV of the smallest and biggest fibre-bundle configurations used in MaNGA observations.

A slight shift towards smaller angular sizes in iMaNGA with respect to MaNGA is noticeable in the left panels, which is most pronounced for low-mass galaxies. The tails to large angular sizes are very similar between simulated and real sample, though. This plot demonstrates the necessity of the redshift cut in both the MaNGA and the iMaNGA samples to ensure coverage of 1.5\( R_{\text{eff}} \) by the 5 hexagonal FoVs in MaNGA.

The central panels show spatial resolution, calculated from the nominal angular resolution element (2.5", both in MaNGA and iMaNGA) and galaxy redshift. The distributions for MaNGA and iMaNGA are very similar. Both peak at around 1 kpc, and exhibit a
5.3.2 Stellar mass and effective radius

Fig. 11 shows a density plot of total stellar mass as a function of the effective radius for both the MaNGA-Primary sample (top panel) and the iMaNGA sample (central panel). As in Fig. 10, we select galaxies with a stellar mass in the range $8.9 \leq \log_{10} M_*/M_\odot \leq 11.3$. Coloured hexagons represent galaxy densities, and the small black points show individual galaxies. The red diamonds represent the median of the total stellar mass along 5 equally-sized bins in effective radius, the red error-bars represent the standard deviation in each bin, and the red dashed line shows the linear regression with the Pearson correlation coefficient in the top-left corner. The bottom panel shows the residual calculated as

$$
\Theta = \frac{O_{\text{MaNGA}} - O_{\text{iMaNGA}}}{\sqrt{\sigma_{\text{MaNGA}}^2 + \sigma_{\text{iMaNGA}}^2}}
$$

(2)

where $O_{\text{MaNGA}}$ and $O_{\text{iMaNGA}}$ represent the median of total stellar mass along the 5 equally-sized bins considered for the two samples, and $\sigma_{\text{MaNGA}}$ and $\sigma_{\text{iMaNGA}}$ represent the standard deviation in each of the bins for the two samples. The correlation between effective radius and stellar mass is well recovered in the iMaNGA sample, in particular at smaller angular size.

5.3.3 Sérsic index

Fig. 12 presents a density plot of the Sérsic index as a function of effective radius (left-hand panels) and stellar mass (right-hand panels), both for the MaNGA-Primary sample (top panels) and the iMaNGA sample (central panels). We show all galaxies in the mass range $8.9 \leq \log_{10} M_*/M_\odot \leq 11.3$. The red diamonds represent the median along 5 equally-sized bins with the red error-bars showing the median standard deviation within each bin. We also display the linear regression for the median values (red dashed lines), the Pearson correlation coefficient (in the upper left corners). With black points, we represent all the galaxies in the catalogues. In the bottom panels, we report the normalised residual between the two samples, computed as from Eq. 2 where $O_{\text{MaNGA}}$ and $O_{\text{iMaNGA}}$ represent the median of the Sérsic index, and $\sigma_{\text{MaNGA}}$ and $\sigma_{\text{iMaNGA}}$ represent the standard deviation in each of the bins.

The MaNGA-Primary sample shows a trend of Sérsic index slightly increasing with effective radius, while the paucity of galaxies with high Sérsic indices leads to the opposite trend in the iMaNGA sample. The right-hand panels show that a correlation exists also between Sérsic index and total stellar mass for both the MaNGA and the iMaNGA sample. The correlation is weaker in iMaNGA, though.

Our results are in agreement with the study by Huertas-Company et al. (2019b) who compare mock SDSS r-band images from TNG100 to SDSS. In particular they find that, although the observed mass-size relation is well recovered by TNG100, both in normalization and in slope, SDSS is dominated by elliptical galaxies at the high-mass end while TNG100 is dominated by late-type systems, with a lack of lenticular galaxies at intermediate masses and ellipticals at the high-mass end. This discrepancy is not due to volume, as shown by re-sampling the SDSS results over smaller volumes.

Similar results are also presented in Rodriguez-Gomez et al. (2019).

5.4 Kinematic analysis

The kinematic analysis of iMaNGA follows the procedure of the MaNGA DAP. In brief (see Paper I for details):

(i) We apply the Voronoi binning scheme to meet a given SNR threshold (i.e. a minimum SNR of about 10 in the g-band images), averaging over neighbouring spaxels. In this way, we define the Voronoi tessellation (Cappellari & Copin 2003) in each iMaNGA datacube. This step is necessary, both for real and mock MaNGA-like datacubes, since accurate measurements of stellar kinematics and stellar population characteristics need a good SNR to be extracted without bias. Where a good SNR cannot be reached, a mask is applied to not analyse those spaxels any further.

### Table 1. Selected properties of the 8 galaxies in the iMaNGA sample. From left, the redshift, the magnitude in the i-band, the stellar mass, and the $R_{\text{HMSR}}$ as given by the TNG50 data, while the environment $(1 + \delta)$, the effective radius $R_{\text{eff}}$ and the Sérsic index $n$ are computed as described in Paper I, from r-band SDSS mock images.

| snap-id | $z_{\text{random}}$ | $M_i$ | $\log_{10} M_*$ [$M_{\odot}$] | $R_{\text{HMSR}}$ [kpc] | $(1 + \delta)$ | $R_{\text{eff}}$ [kpc] | $\sigma_{\text{MaNGA}}$ [kpc] | $\sigma_{\text{iMaNGA}}$ [kpc] | $n$ |
|---------|-----------------|------|-----------------|-----------------|---------------|-----------------|-----------------|-----------------|-------|
| 96-3    | 0.034           | -22.13 | 10.55           | 3.3             | 1.94          | 4.86            | 0.94            | 0.37             |       |
| 94-439126 | 0.072       | -22.35 | 11.11           | 3.22            | 1.81          | 4.0             | 2.39            | 0.37             |       |
| 92-452563 | 0.093       | -22.85 | 10.95           | 6.11            | 2.7           | 8.15            | 1.48            | 0.37             |       |
| 98-735412 | 0.023       | -18.53 | 9.11            | 2.67            | 0.39          | 2.39            | 0.49            | 0.37             |       |
| 95-532259 | 0.05        | -21.88 | 10.53           | 7.62            | 3.41          | 13.66           | 0.62            | 0.37             |       |
| 97-597886 | 0.033       | -20.76 | 9.95            | 8.87            | 2.84          | 8.64            | 0.32            | 0.37             |       |
| 97-598178 | 0.034       | -21.35 | 10.31           | 4.39            | 2.65          | 4.75            | 0.58            | 0.37             |       |
| 96-561122 | 0.046       | -21.98 | 10.97           | 1.78            | 1.89          | 1.26            | 2.16            | 0.37             | 1.56  |
(ii) We run pPXF (Cappellari 2017) to obtain the stellar kinematics, as well as the gas kinematics and the emission lines best-fit (see Westfall et al. 2019; Belfiore et al. 2019). The MILES-HC libraries are used as templates by pPXF for the stellar continuum, while the templates for the emission lines are constructed as explained in Westfall et al. (2019), Section 9.

In total we analyse ~ 8 million Voronoi tassels in the iMaNGA sample.

Fig. 13 reports examples of a fit with pPXF to the stellar continuum (upper panel) and to the gas component (bottom panel); the best-fit values for the stellar and gas kinematics are labelled in the figure. Fig. 14 displays the stellar peculiar velocity maps for the 8 galaxies in the iMaNGA sample, presented in Fig. 8 and Table 1, as recovered by running pPXF over the stellar continuum in each Voronoi tassel. In Fig. 15 we show the stellar velocity dispersion maps for the same galaxies, as recovered from the pPXF analysis. A variety of kinematical states, FoVs, Voronoi binning tessellation and masking can be appreciated. Comparing these with Fig. 8 and the Sérsic indices listed in Table 1, we notice how elliptical galaxies (ID 439126 at z ~ 0.06, ID 561122 at z ~ 0.03) have n > 2 and the highest values of stellar velocity dispersion, while still presenting some pattern of rotation. Disc-like galaxies (ID 3 at z ~ 0.03, ID 452563 at z ~ 0.08, ID 532259 at z ~ 0.05, ID 598178 at z ~ 0.02), instead, have n ~ 1, exhibit a clear rotational velocity pattern, and a lower velocity dispersion compared to the ETGs.

In Paper I, we presented an initial comparison between the ‘intrinsic’ kinematics (peculiar stellar velocity and stellar velocity dispersion), i.e. determined directly from the simulations calculated from Eq. 5 in Paper I, and the ‘recovered’ kinematics obtained from running pPXF over the Voronoi-binned mock datacubes, for two example galaxies. We found that residuals are compatible with zero at the 68% confidence level, with no systematic bias for the two iMaNGA datacubes.

We now repeat this comparison, this time for all the tassels in the iMaNGA sample (~8 million) to test our ability to recover the input values statistically. Fig. 16 displays the distributions of the residuals (red histograms), both for the stellar velocity (i.e. Δvz = vz,pPXF − vz,TNG50) and the stellar velocity dispersion (i.e. Δσvz = σvz,pPXF − σvz,TNG50) over all the tassels in the iMaNGA sample. We also report the 0.16, 0.5, and 0.84 quartiles (vertical black lines). The quartiles for the Δvz distribution are equal to q16 = −11.24, q50 = −2.61 and q84 = 6.35; for the Δσvz are q16 = −4.04, q50 = 6.16, and q84 = 16.94.

At the 1-σ level, the residuals are compatible with zero, hence we recover unbiased measurements of the stellar velocity and the stellar velocity dispersion along the line-of-sight (LOS).

Fig. 17 presents recovered stellar velocity dispersion as a function of intrinsic stellar mass (green circles). The median in 5 equally-sized bins in stellar mass (black diamonds) and the standard deviation in each bin (black error bars) are also shown. The black line is the linear regression line for the median values, and the Pearson correlation coefficient is given in the top-left corner. A robust linear correlation between the stellar mass and log(10)metallicity is found, in good agreement with both real observations (e.g. Zahid et al. 2016) and other simulations (e.g. Pillepich et al. 2019).

In closing this section, we would like to emphasise that our analysis naturally considers random orientation, since we observe the galaxies with a fixed line-of-sight along the z-axis of the cosmological volume, and the simulated galaxies are randomly orientated in it. Different orientations can be appreciated in Fig. 8.

5.5 Stellar population analysis

As discussed in Paper I, after following the steps in the DAP, we can proceed to perform full spectral fitting of population models to the iMaNGA galaxies’ datacubes in order to derive stellar population properties. The Voronoi tassels, stellar kinematics and emission-line best-fits are used as input to the full spectral fitting code FIREFLY (Wilkinson et al. 2017), using the same strategy detailed in Neumann et al. (2021) and Neumann et al. (2022) for the analysis of real MaNGA galaxies adopting MaaStar stellar population models as fitting templates. The fitting results for the MaNGA galaxies are publicly available as value-added catalogue (Neumann et al. 2021)⁶.

Based on the full-spectral fitting with FIREFLY, fundamental galaxy properties are recovered including mass-weighted and light-weighted metallicities and ages. These properties are essential to investigate the formation and evolution of galaxies. Fig. 18 exemplifies a fit with FIREFLY to the stellar continuum for a relatively young stellar population (top panel) and an old stellar population (bottom panels). The best-fit values for the stellar age and metallicity ([Z/H]) are reported in the top-left corners of the figure.

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⁶ https://www.sdss4.org/dr16/manga/manga-data/manga-firefly-value-added-catalog/
at $z \sim 0.03$ are metal-rich and old overall as expected. The iMaNGA disc galaxies (ID 3 at $z \sim 0.03$, ID 452563 at $z \sim 0.08$, ID 532259 at $z \sim 0.05$, ID 598178 at $z \sim 0.02$), instead, have generally young stellar populations and show a metal-rich stellar component in the centre, with a steep drop in metallicity towards larger radii.

In Paper I we compared intrinsic age and chemical composition, calculated directly from the stellar particle data in TNG50, with the values recovered from FIREFLY for two iMaNGA galaxies, finding that residuals were consistent with zero at the 68\% confidence level with no systematic bias. Here we repeat this comparison for the entire iMaNGA catalogue, thereby testing if, after the post-processing of the TNG50 galaxies, the ‘intrinsic’ information is correctly retrieved with our analysis.

To this end, weighted ‘intrinsic’ properties for the same Voronoi grid are constructed directly from the simulated stellar particles. The weighted properties in each tassel are:

$$\theta_{W,tassel} = \frac{\sum_{i=1}^{N_i} W_{s,i} \times \theta_i}{\sum_{i=1}^{N_i} W_{s,i}},$$

where $\theta_{W,tassel}$ is either the mass-weighted metallicity ($\langle Z/H \rangle_{MW}$), the light-weighted metallicity ($\langle Z/H \rangle_{LW}$), the mass-weighted age ($\langle \text{Age} \rangle_{MW}$), or the light-weighted age ($\langle \text{Age} \rangle_{LW}$) in the selected tassel; $\theta_i$ is the age or metallicity of the $i$-particle of the considered tassel with weight, either mass or light, $W_{s,i}$; $N_i$ is the number of stellar particles in the selected tassel. For the mass-weight, i.e. $M_{*,i}$, we simply consider the stellar particle mass as provided by TNG50; for the light-weight, i.e. $L_{*,i}$, we consider the total luminosity of the stellar spectrum, either from MaStar or MIII, depending on the stellar particle’s age.

Fig. 21 reports the residual distributions for the metallicity (i.e. $\Delta [Z/H] = [Z/H]_{\text{FIREFLY}} - [Z/H]_{\text{TNG50}}$, top panel), and the residual distributions for the age (i.e. $\Delta \log(\text{Age}) = \log(\text{Age})_{\text{FIREFLY}} - \log(\text{Age})_{\text{TNG50}}$, bottom panel). The empty red histograms are the residual distributions for mass-weighted quantities, while the grey histograms illustrate the residual distributions for light-weighted quantities. We also plot the 0.16, 0.5 and 0.84 quartiles of the residual distributions: in red dashed lines, the quartiles for the mass-weighted residuals, in black, the quartiles for the light-weighted. The quartiles

5.5.1 Mass-weighted metallicity and age maps

Running FIREFLY over the mock IFU datacubes, we are able to spatially resolve the stellar population properties. Therefore, as in e.g. Neumann et al. (2022), we are in the position to produce maps of stellar properties for the iMaNGA datacubes.

Figs. 19-20 show maps of recovered stellar metallicity and age for the eight galaxies presented in Fig. 8. Here we report the mass-weighted metallicity and age, i.e. $[Z/H]_{MW}$ and $\log(\text{Age})_{MW}$ [Gyr]. We notice that elliptical galaxies (ID 439126 at $z \sim 0.06$, ID 561122

![](image1.png)

**Figure 10.** Comparison of angular size (left panels), resolution in terms of kpc (central panels) and in terms of the effective radius (right panels), of the iMaNGA sample, generated from TNG50 as described in this paper, to the MaNGA-Primary sample. This plot reproduces the plots in Wake et al. (2017). The information for the MaNGA-Primary sample galaxies is retrieved from DRPALL MaNGA data (Law et al. 2016), as for all the other plots in this Section. The vertical lines report the smallest and biggest FoV of the 5 hexagonal fiber-bundles configurations used in MaNGA observations (see §2.3).

![](image2.png)

**Figure 11.** Stellar mass as a function of effective radius in the MaNGA-Primary (upper panel) and iMaNGA (central panel) samples. For both samples we show the median in 5 different equally-sized bins in effective radius (red diamonds), the linear regression (red dotted line), the standard deviation (red error-bars), the Pearson coefficient $\rho$. Colours represent the galaxy density in the tassels and the small black points show all galaxies in the samples. **Bottom Panel:** normalised residuals (red line), and the 1-, 2-, and 3- sigma level intervals (dashed grey lines).
Figure 12. As in Fig. 11, for the distribution of the galaxies' Sérsic index $n$ as a function of the r-band $R_{\text{eff}}$ and the total stellar mass, both for the MaNGA-Primary sample (upper panels) and the iMaNGA sample (central panels). Bottom panels: normalised residuals (red line), and the 1-, 2-, and 3- sigma level intervals (dashed grey lines).

Symbols, curves and colours as in Fig. 11.

Figure 13. Examples of fit with rPXF for two spectra in the iMaNGA sample. Upper panel: the original spectrum (black line) and the best-fit spectrum (teal line) determined by rPXF for the stellar continuum. In the upper left corner, the best-fit values for the stellar velocity ($v_z$) and velocity dispersion ($\sigma_{v_z}$) are stated. Bottom panel: the original spectrum (black line) and the best-fit spectrum (golden line) determined by rPXF for the emission lines.

are reported at the top of the panels, in red for the MW residuals, and in grey for the LW ones. The figure shows the following:

- The residual distribution for the mass-weighted metallicity is characterised by $q_{16} = -0.31$, $q_{50} = -0.07$ and $q_{84} = 0.13$, and $q_{16} = -0.34$, $q_{50} = -0.12$ and $q_{84} = 0.07$ for light-weighted metallicity.
- The residual distribution for the mass-weighted age is characterised by $q_{16} = -0.18$, $q_{50} = 0.04$ and $q_{84} = 0.26$, and $q_{16} = -0.17$, $q_{50} = 0.06$ and $q_{84} = 0.32$ for light-weighted age.

These results show that our analysis does not introduce any biases: the residuals are well consistent with zero within the 68% confidence intervals. As to be expected, the realistic observational effects implemented in iMaNGA lead to a scatter in the residuals that is well consistent with the measurement errors.

In Appendix A we further show the residual as a function of the intrinsic properties (see Fig. A1) and the relation between the residuals on metallicity and age (see Fig. A2). We conclude that we are able to recover the intrinsic properties of the TNG50 galaxy sample.
Figure 14. Stellar velocity maps, obtained with pPXF, for the 8 galaxies in the iMaNGA sample from Fig. 8 and Table 1. Maps are colour-coded by the stellar peculiar velocity along the LOS. Galaxy redshifts and IDs are stated in the plots, as well as the diameter of the hexagonal MaNGA FoV the galaxy falls in, which is used to ‘observe’ the galaxy, see §3.

Figure 15. As in Fig. 14 for the stellar velocity dispersion.
The number of tassels $(\sigma_{z})$ and $v_{z}$ are shown in Figure 16. The distributions of residuals (red histograms), both for the stellar velocity ($\Delta v_{z} = v_{z,pPXF} - v_{z,TNG50}$) and stellar velocity dispersion ($\Delta \sigma_{vz} = \sigma_{vz,pPXF} - \sigma_{vz,TNG50}$) over all the tassels in iManGA. We report the 0.16, 0.5, and 0.84 quartiles of the residual distributions (vertical black lines). Residuals are compatible with zero over all tassels at the 68% confidence intervals.

Figure 16. The distributions of residuals (red histograms), both for the stellar velocity ($\Delta v_{z} = v_{z,pPXF} - v_{z,TNG50}$) and stellar velocity dispersion ($\Delta \sigma_{vz} = \sigma_{vz,pPXF} - \sigma_{vz,TNG50}$) over all the tassels in iManGA. We report the 0.16, 0.5, and 0.84 quartiles of the residual distributions (vertical black lines). Residuals are compatible with zero over all tassels at the 68% confidence intervals.

6 DISCUSSION

Other works have presented methods to obtain mock MaNGA data from simulations (Ibarra-Medel et al. 2018; Duckworth et al. 2019; Nevin et al. 2021; Bottrell & Hani 2022; Sarmiento et al. 2022). In the following, we briefly compare these works to our project.

6.1 Ibarra-Medel et al 2018

Ibarra-Medel et al. (2018) post-process two simulated Milky-Way-size galaxies (from Colín et al. 2016). The synthetic spectra are constructed using a combination of MILES and GRANADA models (more details in Cid Fernandes, R. et al. 2013), with 156 spectral templates that cover 39 stellar ages (from 1 Myr to 14.2 Gyr), 4 metallicity ($Z/Z_{\odot} = 0.2, 0.4, 1$ and $1.5$), and a wavelength range between 3,600 and 7,000 Å. When generating the synthetic spectra, the SSP models are not interpolated to the exact intrinsic quantities as we do, rather the `closest’ models in terms of age and metallicity are adopted. Because of this choice, Ibarra-Medel et al. (2018) have to distinguish between intrinsic and assigned stellar particles’ properties. Also different from us, these authors do not run a radiative transfer code to model dust effects, but apply a simple dust extinction model.

The MaNGA fiber-bundle configuration is mimicked: each stellar particle is associated with one of the MaNGA fibers, each with an FoV of 2.5”, and the final spectrum in each fiber is given by the stack of all the spectra in it. To each stellar particle, one of the spectra from the templates is assigned, therefore, the final spectrum in each fiber is formed by a combination of discrete ages and metallicities. This operation is repeated three times to mimic the dithering in MaNGA observations. The noise is implemented with a combination of sigmoid functions to mimic the eBoss spectrograph behaviours at short and long wavelengths. This sample of mock galaxies is then used to test the ability of Pipe3D (Sánchez et al. 2016) to recover the stellar populations’ properties. Ibarra-Medel et al. (2018) find some biases in the recovered properties, in particular, they recover younger stellar populations in the inner, older regions, and slightly older stellar populations in the outer, younger regions, as well as lower global stellar masses.
Figure 18. Examples of spectral fits for iMaNGA galaxies obtained with FIREFLY adopting the MaStar stellar population models as fitting templates. Original and best-fit spectra determined by FIREFLY (black and teal lines, respectively) are shown for a relatively young stellar population (upper panel) and an older one (bottom panel). In the upper left corners, the best-fit values for the stellar age and stellar metallicity ([Z/H]) are stated.

Figure 19. Stellar metallicity maps, measured by FIREFLY, for 8 galaxies in the iMaNGA sample, presented in Fig. 8. The redshift and the ID of the galaxies in TNG50 are listed in the upper-left corner for each galaxy, as well as the MaNGA FoV the galaxy falls in.

6.2 Duckworth et al 2019

Duckworth et al. (2019) construct the spectra for around 4,500 galaxies in TNG100 (Naiman et al. 2018b; Marinacci et al. 2018; Springel et al. 2018; Nelson et al. 2018; Pillepich et al. 2018b) adopting the FSPS stellar population models (Conroy & Gunn 2010). FSPS contains 22 metallicity steps (from $\log_{10} Z = -3.7$ to $\log_{10} Z = -1.5$), and 94 age steps (from $\log_{10} t = -3.5$ [Gyr] to $\log_{10} t = 1.15$ [Gyr]), and a wavelength range between 3,600 and 7,000 Å. They bin particles within spaxels of a length-side of 0.5", over a hexagonal fibre bundle footprint, mimicking the MaNGA data cubes. In each bin, the mean velocity, velocity dispersion and total flux for all particles are computed. No extinction is assumed. The SNR as a function of the effective radius in the g-band is computed and used to assign noise to the synthetic spectra. A Gaussian kernel with 2" FWHM is assumed to mimic the MaNGA PSF. The data cubes are then re-binned with the Voronoi algorithm as in the official MaNGA DAP. Then, the intrinsic properties of the stellar and gas particles in each Voronoi tassel are used to investigate the relationship between the rotation of stars and gas with morphology and halo spin. The analysis is conducted over both TNG100 galaxies and MaNGA galaxies within the paper. They find a good agreement between TNG100 and MaNGA.

6.3 Nevin et al 2021

Nevin et al. (2021) test an algorithm to identify galaxy mergers with
stellar kinematics. Five merging galaxies and matched isolated ones in GADGET (Springel et al. 2001a) are considered. The stellar populations are modelled with the code SUNRISE (Jonsson 2006) based on STARBURST99 stellar population synthesis models (Leitherer et al. 1999), and synthetic datacubes are created. STARBURST99 has 5 metallicities (between log_{10} Z = −1.40 and log_{10} Z = −3.), and the age coverage is between 1 Myr to 1 Gyr, with a wavelength range between 0.009 and 160 μm. Also in this work, as in ours, and differently from Ibarra-Medel et al. (2018), the stellar spectra are interpolated and therefore, the intrinsic stellar population properties are used to define each spectra. The effects of dust attenuation as well as AGN are included. A Gaussian kernel with FWHM equal to 2.5" is used to mimic the PSF in MaNGA. Then, the datacubes are re-binned to have a spatial sampling of 0.5". Also in this work, the morphology is studied with STATMORPH on SDSS-like r-band images. The hexagonal FoV of the smallest fiber bundles in MaNGA capable of observing the galaxies within 1.5 Reff is adopted. They produce a typical noise spectrum, which is then normalised and used to include random noise to each spaxel in the datacube. The MaNGA DAP is followed, except that pPXF is run only for the stellar component.

The methodology of this work is most similar to ours, albeit with some important differences. The convolution with the PSF in our pipeline is the last step, after the inclusion of the noise, such that the noise between adjacent spaxels correlates. Also, different from Nevin et al. (2021), we do not assume a Gaussian kernel for the PSF, but we reconstruct a MaNGA effective PSF, which includes dithering effects and seeing. The PSF in our approach is wavelength dependent like the ePSF in MaNGA. Instead of reconstructing a typical MaNGA noise, we reconstruct SNR as a function of the wavelength at 1.5R_{off} and then this information is used as in Eq. 4 in Paper I. Finally, we adopt population model spectra based on stellar spectra observed with the same SDSS spectrograph used for the MaNGA galaxies.

6.4 Bottrell & Hani 2022

Bottrell & Hani (2022) present the code REALSIM-IFS, which is capable of modelling the instrumental sampling mechanics for any IFS instrument, MaNGA included. REALSIM-IFS includes the effects of atmospheric seeing, IFU fibre characteristics and set-up (designs), dithered exposure strategy, line-spread function, and spatial reconstruction of fibre measurements. Instead, Bottrell & Hani (2022) test the application of REALSIM-IFS with TNG50 to create synthetic MaNGA stellar kinematic maps. To our knowledge, this method is the only one capable of reconstructing all the details of the MaNGA observational setup. On the other hand, spectra are not included in their work.

6.5 Sarmiento et al 2022

Sarmiento et al. (2022) apply the method by Ibarra-Medel et al. (2018) to TNG50 galaxies, using template spectra from Bruzual (private communication) based on the MaStar stellar library (Yan et al. 2019). These include a total of 273 synthetic spectra, with 39 ages between 0.0023 and 13.5 Gyr and 7 metallicities between 0.0001 and 0.43, and a linearly sampled wavelength range between 2,000 and 10,000 Å. Stellar particles are associated to the closest on among these 273 synthetic spectra as in Ibarra-Medel et al. (2018). This implies that also in their case, and differently from us, "assigned" properties do not necessarily coincide with the "intrinsic" properties predicted by the simulations (see their Fig. 6 and 7). The difference between assigned and intrinsic properties jeopardises the comparison with the recovered values, leading to larger scatters and potentially larger residuals.

Figure 20. As in Fig. 14 for the stellar age, as measured by FIREFLY.
Figure 21. Residuals in metallicity and age of the stellar populations as measured by FIREFLY and intrinsic in the iMaNGA sample. The red empty histograms show the residual distribution for the mass-weighted metallicity ($\Delta [Z/H]_{MW} = [Z/H]_{MW,Firefly} - [Z/H]_{MW,TNG50}$ upper panel) and mass-weighted age ($\log_{10} (Age)_{MW} = \log_{10} (Age)_{MW,Firefly} - \log_{10} (Age)_{MW,TNG50}$, bottom panel); the vertical red lines are the 0.16, 0.5 and 0.84 quartiles of these residual distributions. Grey histograms show the residual distribution for the light-weighted metallicity ($\Delta [Z/H]_{LW} = [Z/H]_{LW,Firefly} - [Z/H]_{LW,TNG50}$, upper panel) and light-weighted age ($\log_{10} (Age)_{LW} = \log_{10} (Age)_{LW,Firefly} - \log_{10} (Age)_{LW,TNG50}$, bottom panel); the vertical black dashed lines are the 0.16, 0.5 and 0.84 quartiles for these residual distributions; quartiles values are reported on top of the panels, in red for the MW residuals distributions, in black for the LW ones.

6.6 Mock MaNGA catalogues

Among these works, Duckworth et al. (2019) and Sarmiento et al. (2022) produced mock MaNGA catalogues. In both, the approach was to associate a galaxy in TNG with an observed MaNGA galaxy directly. Duckworth et al. (2019) look for unique matches for a total of 4,500 galaxies in TNG100. Galaxies are matched by stellar mass, size and SDSS $g-r$ colour. Sarmiento et al. (2022) follow a similar approach, matching galaxies in mass, redshift and effective radius, but they do not match galaxies uniquely rather allow galaxies drawn from TNG50 to be selected multiple times. When a TNG50 galaxy is selected multiple times, it is observed with different line-of-sights. In this way, Sarmiento et al. (2022) match the full MaNGA catalogue to galaxies in TNG50, that are however not physically distinct.

Their approach is different from ours. In our work, we adopt the TNG50 catalogue and apply the MaNGA selection criteria to it, in order to construct our mock MaNGA sample. As a consequence, there are no direct matches between MaNGA and TNG50 galaxies. Because we wanted to match the MaNGA observed sample selection criteria, our simulated iMaNGA catalogue is significantly smaller than the MaNGA sample because of the relatively small simulated volume in TNG50.

Both approaches have benefits and pitfalls, but they appear to serve different scopes. In our approach, we aim to observe the universe as generated by the Illustris simulation as if it was observed, rather than matching the simulation to the observation. As a consequence, our iMaNGA catalogue allows us to test the characteristics of the simulation, such as fraction of certain galaxy types, galaxy scaling relations, etc. For example, we find a paucity of massive elliptical galaxies. Interestingly, residual biases are still observed by Sarmiento et al. (2022), including an excess of disc galaxies at high mass in agreement with our findings.

7 CONCLUSIONS

We present a mock MaNGA catalogue, called iMaNGA, generated from the state-of-the-art magneto-hydrodynamical galaxy simulations TNG50. We illustrate the general characteristics of the iMaNGA sample in terms of morphology, kinematics, and stellar populations. We further run detailed tests comparing intrinsic galaxy properties from TNG50 with the recovered properties in iMaNGA derived through full-spectral fitting.

We identify galaxies in TNG50 through friends-of-friends algorithms, and initially select by redshift ($0.01 \leq z \leq 0.15$) and number...
of stellar particles \(N > 10,000\), and exclude all galaxies that are flagged as of non-cosmological origin (for more details see Genel et al. 2017; Pillepich et al. 2018b, and the Data Specification page for IllustrisTNG\(^7\)). These criteria lead to the selection of 48,248 galaxies. Since we want to recover a smooth distribution in spatial sampling, as for the MaNGA-Primary sample, we then randomise galaxy redshifts in the initial sample, and select galaxies by i-band magnitude and redshift. In this way, we directly mimic the MaNGA selection criteria, which yields our “parent sample” containing 3,152 galaxies. We finally impose a flat distribution in absolute i-band magnitude following the MaNGA survey design, by randomly selecting unique galaxies from the parent sample. The resulting sample comprises 1,000 galaxies from TNG50 and represents the final iMaNGA catalogue. We then post-process our iMaNGA galaxies following the method presented in Paper I (Nanni et al. 2022). We investigate whether the iMaNGA sample reproduces general trends of the MaNGA-Primary Sample. We find that angular sizes and spatial resolution (both in kpc and in terms of \(R_{\text{eff}}\)) are well consistent between iMaNGA and MaNGA. Likewise, the relationship between angular size and total stellar mass is matched well. The correlations of morphology with angular size and stellar mass are instead not recovered by the iMaNGA sample. These differences are driven by the fact that TNG50 is dominated by late-type systems with a paucity of intermediate-mass lenticular galaxies and massive elliptical galaxies as also found in Huertas-Company et al. (e.g., 2019b).

We demonstrated a generally good agreement between ‘recovered’ and ‘intrinsic’ properties, including stellar kinematics, stellar population ages, metallicities, and star formation histories. In particular, the stellar kinematics is recovered running the full-spectral fitting code PXPX, as in the MaNGA DAP. The ‘intrinsic’ stellar peculiar velocity and the stellar velocity dispersion along the LOS are both recovered within 1-\(\sigma\). The stellar populations’ properties are recovered by running another full-spectral fitting code, i.e. FIREFLY. Both the ‘intrinsic’ stellar age and stellar metallicity are well recovered, i.e. the residuals over all tassels in the iMaNGA sample are consistent with zero within the 68 % confidence interval. We also show the ‘recovered’ and ‘intrinsic’ SFHs for 22 galaxies in the iMaNGA catalogue, which show a generally good agreement.

Finally, we present a comparison with other works which have produced mock MaNGA datacubes and/or mock MaNGA catalogues. While there are a number of differences in methodology for the construction of the mock MaNGA data cube, the most important difference to highlight for the present paper is the method of constructing the mock MaNGA sample. Other works in the literature assign simulated galaxies from TNG50 or TNG100 directly to MaNGA galaxies by matching their basic properties such as mass and effective radius, whereas we take the simulations at face value and apply the target selection criteria from MaNGA to the simulated catalogue. Both approaches have merits. While the former aims at producing a theoretical catalogue that resembles MaNGA as closely as possible, our approach is designed to test galaxy formation models. In our next paper in this series, we will present the scientific analysis of the iMaNGA catalogue in direct comparison with MaNGA.

ACKNOWLEDGEMENTS

The authors would like to thank Chris Lovell and Harry Desmond for their feedback during the revision process. LN is supported by an STFC studentship. STFC is acknowledged for support through the Consolidated Grant Cosmology and Astrophysics at Portsmouth, ST/S000550/1. Numerical computations were done on the Sciama High Performance Compute (HPC) cluster which is supported by the ICG, SEPlnet and the University of Portsmouth. Funding for the Sloan Digital Sky Survey IV has been provided by the Alfred P. Sloan Foundation, the U.S. Department of Energy Office of Science, and the Participating Institutions. SDSS-IV acknowledges support and resources from the Center for High Performance Computing at the University of Utah. The SDSS website is www.sdss.org. SDSS-IV is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS Collaboration including the Brazilian Participation Group, the Carnegie Institution for Science, Carnegie Mellon University, Center for Astrophysics | Harvard & Smithsonian, the Chilean Participation Group, the French Participation Group, Instituto de Astrofísica de Canarias, The Johns Hopkins University, Kavli Institute for the Physics and Mathematics of the Universe (IPMU) / University of Tokyo, the Korean Participation Group, Lawrence Berkeley National Laboratory, Leibniz Institut für Astrophysik Potsdam (AIP), Max-Planck-Institut für Astronomie (MPIA Heidelberg), Max-Planck-Institut für Astrophysik (MPA Garching), Max-Planck-Institut für Extraterrestrische Physik (MPE), National Astronomical Observatories of China, New Mexico State University, New York University, University of Notre Dame, Observatório Nacional / MCTI, The Ohio State University, Pennsylvania State University, Shanghai Astronomical Observatory, United Kingdom Participation Group, Universidad Nacional Autónoma de México, University of Arizona, University of Colorado Boulder, University of Oxford, University of Portsmouth, University of Utah, University of Virginia, University of Washington, University of Wisconsin, Vanderbilt University, and Yale University. The primary TNG simulations were realised with compute time granted by the Gauss Centre for Supercomputing (GCS): TNG50 under GCS Large-Scale Project GCS-DWAR (2016; PIs Nelson/Pillepich), and TNG100 and TNG300 under GCS-ILLU (2014; PI Springel) on the GCS share of the supercomputer Hazel Hen at the High Performance Computing Center Stuttgart (HLRS).

DATA AVAILABILITY

The iMaNGA catalogue is made available through the following website: http://www.icg.port.ac.uk/imanga/. A list of all the galaxies post-processed and analysed in this paper, i.e. the iMaNGA sample, is available here: https://github.com/lonanni/iMaNGA/. Finally, the iMaStar code can be found here: https://github.com/lonanni/iMaNGA.

MaNGA data are part of SDSS-IV, publicly available at (Abdurro‘uf et al. 2022). The FIREFLY code is available at: https://www.icg.port.ac.uk/FIREFLY and the MaStar population models at https://www.icg.port.ac.uk/mastar. Illustris and IllustrisTNG data are publicly available at https://www.illustris-project.org/data (Nelson et al. 2019a).

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positive residuals (hence overestimation of age) at low ages and slightly negative residuals (hence underestimation of age) at old ages. No such bias is seen for metallicity.

Fig. A2 shows the relation between the residuals in metallicity and age, for both mass-weighted (left-hand panel) and light-weighted (right-hand panel) quantities, colour-coded by the number of tassels. We can see again that the residuals are consistent with zero within the 1-σ confidence level (the green solid lines report the 0-value). The degeneracy between age and metallicity is visible for the light-weighted quantities, i.e. when metallicity is overpredicted, age is underpredicted and vice versa.

Finally, we discuss the SFH recovered by FIREFLY considering all the Voronoi bins for each galaxy, following the same method as in §5.5.2. In Fig.A3 we plot 20 ‘intrinsic’ SFHs in comparison with the ‘recovered’ SFHs for galaxies in a redshift range between 0.03 and 0.1, and a total stellar mass between 9.5 and 11. \( \log_{10} M_*/M_\odot \). We separate between ellipticals (for a Sérsic index above 2.5, left-hand columns) and spirals (for a Sérsic index between 0.5 and 1, right-hand columns). Some systematic differences between intrinsic and recovered SFHs become apparent. The recovered SFHs tend to be flatter (more uniform in time) than the intrinsic SFHs, which is more pronounced for the MW SFHs. Our fitting procedure seems to add a fraction of old populations, which is then balanced by a younger component.

For the spirals, instead, a preferred population at around 2 Gyr seen in the recovered SFHs. A more detailed analysis of these discrepancies in light of our methodology for spectral fitting will be subject of further work, which goes beyond the scope of the present paper. It is important to underline here that for the ‘intrinsic’ SFH history, all the stellar population particles present in the simulated galaxies are considered, while the ‘recovered’ SFH is instead obtained running FIREFLY over the Voronoi-tessellated galaxy.

The galaxies in this mass and redshift range categorised as ellipticals are (listed here as snapshot-id in TNG50): 96-216478, 97-279747, 97-22, 96-480963, 95-496556, 96-8, 96-98927, 97-568905, 96-395465, 95-477720, 95-481051, 95-493913.

The spiral galaxies are: 95-181049, 92-489917, 96-528258, 95-514781.
Figure A3. The SFH recovered by FIREFLY and computed from the stellar particle information provided by TNG50, for 20 galaxies in the iMaNGA sample. These galaxies are selected in the iMaNGA sample with a redshift range between 0.03 and 0.1, and a total stellar mass between 9.5 and 11. $\log_{10} M_\odot$, and dividing them into ellipticals (when the Sérsic index is above 2.5) and spirals (when the Sérsic index is between 0.5 and 1). *First two columns*: the SFH of elliptical galaxies in the defined redshift and mass range. In the first column, the teal histograms show the SFHs resolved by FIREFLY compared to the black hatch-filled histograms which illustrate the ‘intrinsic’ SFH reconstructed from TNG50 stellar particle data. Here, the SFHs are represented as SSP mass-weights as a function of lookback time. The second column, as the first one, this time considering the SFHs as SSP light-weights as a function of lookback time. In particular, the SFHs as recovered by FIREFLY (yellow histograms), and ‘intrinsic’ to TNG50 galaxies (black empty histograms). *Last two columns*: as the first two columns, this time for spiral galaxies in the discussed range in mass and redshift.