Evaluating hydrodynamical simulations with green valley galaxies

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Abstract
We test cosmological hydrodynamical simulations of galaxy formation regarding the properties of the Blue Cloud (BC), Green Valley (GV) and Red Sequence (RS), as measured on the 4000Å break strength vs stellar mass plane at $z = 0.1$. We analyse the RefL0100N1504 run of EAGLE and the TNG100 run of IllustrisTNG project, by comparing them with the Sloan Digital Sky Survey, while taking into account selection bias. Our analysis focuses on the GV, within stellar mass log $M_\star / M_\odot \approx 10 - 11$, selected from the bimodal distribution of galaxies on the $D_n(4000)$ vs stellar mass plane, following Angthopo et al. methodology. Both simulations match the fraction of AGN in the green-valley. However, they over-produce quiescent GV galaxies with respect to observations, with IllustrisTNG yielding a higher fraction of quiescent GV galaxies than EAGLE. In both, GV galaxies have older luminosity-weighted ages with respect to the SDSS, while a better match is found for mass-weighted ages. We find EAGLE GV galaxies quench their star formation early, but undergo later episodes of star formation, matching observations. In contrast, IllustrisTNG GV galaxies have a more extended SFH, and quench more effectively at later cosmic times, producing the excess of quenched galaxies in GV compared with SDSS, based on the 4000Å break strength. These results suggest the AGN feedback subgrid physics, more specifically, the threshold halo mass for black hole input and the black hole seed mass, could be the primary cause of the over-production of quiescent galaxies found with respect to the observational constraints.

Key words: galaxies: evolution – galaxies: formation – galaxies: interactions – galaxies: stellar content.

1 Introduction
Galaxy formation and evolution represents one of the key important frontiers of astrophysics over the past decade. Owing to the complexity of physics concerning the transformation of gas into stars, a number of open questions remain. In order to advance the field, a combination of two main approaches are essential: (i) high quality surveys, most notably SDSS (York et al. 2000; Gunn et al. 2006), and (ii) cosmological hydrodynamical simulations, such as EAGLE (Schaye et al. 2015) or IllustrisTNG (Pillepich et al. 2018b; Marinacci et al. 2018; Springel et al. 2018; Nelson et al. 2018; Naiman et al. 2018). Both methods complement each other, as observations help to constrain various parameters in simulations to reproduce the fundamental properties of galaxies, while simulations enable the physical interpretation of the observations.

Large surveys, such as SDSS, that combine photometry and spectroscopy, enabled the discovery of fundamental properties of galaxies i.e. their bimodal distribution (Strateva et al. 2001), in colour-magnitude (Graves et al. 2007; Martin et al. 2007), star formation rate (SFR) - mass (Schiminovich et al. 2007), UVJ bi-colour (Williams et al. 2009) and colour-mass (Schawinski et al. 2014) diagrams. This bimodality is thought to be due to the existence of two distinct types of galaxies: Star Forming (SF) and Quiescent (Q). SF galaxies appear blue in optical colours, and have substantial amounts of gas and dust. In contrast, Q galaxies are redder in the same colours, and feature low amounts of dust or cold gas, resulting in little or no star formation activity. Due to these differences, SF and Q galaxies occupy different regions on the colour-mass plane. The region dominated by SF and Q galaxies were coined Blue Cloud (BC) and Red Sequence (RS), respectively.

The region situated between this bimodal distribution is thought to represent a transition phase, termed the Green...
Valley (hereafter GV, Salim 2014), where SF galaxies – typically found in the BC – slowly shift towards quiescence, gradually approaching the RS. Faber et al. (2007) proposed several evolutionary paths to explain this transition, mostly involving quenching of their star formation activity. Moreover, galaxies are also able to obtain a fresh supply of gas, via accretion or mergers, initiating subsequent episodes of star formation (rejuvenation), that cause galaxies in the RS to move “back” into the GV/BC (Thomas et al. 2005; Thomas et al. 2010), thus complicating the study of galaxy evolution.

Owing to the sparsity of the GV, it is thought that galaxies traverse rapidly this region (Salim 2014; Bremer et al. 2018), therefore having short quenching timescales. Observational constraints suggest a transition timescale of $\tau_{\text{GV}} \sim 100$ Myr and $\tau_{\text{GV}} \sim 7$ Gyr for elliptical and spiral galaxies, respectively, showing at least two modes of quenching with a strong dependence on morphology (Schawinski et al. 2014). A lower resolution study of GV galaxies, irrespective of morphology, and adopting exponentially decaying star formation histories (SFH), yields transition times in the range $\tau_{\text{GV}} \sim 2-4$ Gyr (Phillipps et al. 2019). Similar results are obtained when the GV is defined using the spectroscopic index $D_n(4000)$ (Angthopo et al. 2019, 2020, hereafter A19 and A20), finding transition times $\tau_{\text{GV}} \sim 1.0-3.5$ Gyr, for Q galaxies, and $\tau_{\text{GV}} \sim 0.5-5.0$ Gyr, for all types of galaxies. Furthermore the use of specific star formation rate (sSFR) or 4000Å break strength to define the GV have hinted at shorter timescales when evolving from BC to GV with respect to the GV to RS transition (Salim 2014, A20). Alternatively, the use of sub-millimeter fluxes to explore galaxy evolution, rather than optical light, suggests the presence of an overdensity in lieu of a valley, termed the “green mountain”, which questions the concept of rapid quenching (Eales et al. 2018). Note that by using longer wavelengths, the analysis shifts towards dust emission, and therefore focuses on the “active” sample. In optical light we probe more directly the contrast between the “active” and the quenched phases of evolution.

From a theoretical standpoint, state-of-the-art hydrodynamical simulations such as EAGLE (Schaye et al. 2015) and IllustrisTNG (Pillepich et al. 2018a) are able to reproduce the general fundamental properties of galaxies i.e. the evolution of the galaxy mass function (Furlong et al. 2015; Kaviraj et al. 2017; Pillepich et al. 2018a), AGN luminosity (Rosas-Guevara et al. 2016; Volonteri et al. 2016; McAlpine et al. 2017) as well as the bimodality of galaxy colour (Trayford et al. 2015, 2016; Nelson et al. 2018), and the SFR and UVJ-based quenched fraction at $z \lesssim 2-3$ (Donnari et al. 2019, 2020a,b). Studies based on simulations estimate a transition timescale ($\tau_{\text{GV}}$) that depends on stellar mass, similar to those derived from observational constraints, with $\tau_{\text{GV}} \sim 3$ Gyr at low stellar mass (log $M/M_\odot < 9.6$). Intermediate stellar mass galaxies (9.7 $\lesssim$ log $M/M_\odot \lesssim 10.3$) have longer transition timescales, whereas the most massive galaxies (log $M/M_\odot \gtrsim 10.3$) yield the lowest transition times $\tau_{\text{GV}} \lesssim 2$ Gyr (Wright et al. 2019). More detailed studies, reaching a higher mass resolution and segregating with respect to morphology (Tacchella et al. 2019; Correa et al. 2019), suggest elliptical galaxies have slightly lower quenching timescales $\tau_{\text{GV}} \sim 1.0$ Gyr, in comparison to disc-type galaxies $\tau_{\text{GV}} \sim 1.5$ Gyr.

Both observations and simulations show at least two evolutionary channels, as elliptical galaxies seem to quench rapidly, while spiral galaxies have a gradual decrease of the SFH, where they slowly exhaust their gas supply (Smethurst et al. 2015). Furthermore, velocity dispersion (or stellar mass) and galaxy structure, i.e. concentration, central density and effective density, seem to be the fundamental properties associated with galaxy evolution (Gallazzi et al. 2005a; Graves et al. 2009; Starkenburg et al. 2019; Barro et al. 2017; Chen et al. 2020), thus the quenching timescales and the physical mechanism behind quenching of star formation are heavily dependent on velocity dispersion and galaxy structure. However the primary mechanism for quenching star formation remains a debated topic. From the theoretical perspective, at low to intermediate stellar mass ($\log M/M_\odot \lesssim 10.5$) supernova-driven feedback (Dekel & Silk 1986; Dalla Vecchia & Schaye 2012a), radio-mode AGN (Croton et al. 2006) and environmental effects such as ram pressure stripping strangulation and harassment (see, e.g. Pasquali 2015) seem to be the dominant form of quenching. In contrast, massive galaxies (log $M/M_\odot \gtrsim 10.5$) appear to quench star formation with a combination of quasar-mode AGN (Schawinski et al. 2007; Dashyan et al. 2019; Man et al. 2019) and major mergers (Hopkins et al. 2006). Furthermore, galaxies with halo mass above a critical value $M_{\text{crit}} \sim 10^{12} M_\odot$, halo quenching is also thought to play an important role (Faber et al. 2007; McIntosh et al. 2014). Galaxy morphology plays an important role in the primary physical mechanism for quenching: for elliptical galaxies, AGN feedback is essential, while disc galaxies are sensitive to other quenching mechanism (Dashyan et al. 2019; Correa et al. 2019).

Simulations published over the last 5-6 years have succeeded in reproducing the general properties of galaxies. However even more detailed analyses reveal a number of mismatches between simulations and observations, and provide a way to advance our knowledge in such a complicated subject. Due to the complexity of simulations, we focus our analysis specifically on stellar population properties and try to infer how the subgrid physics affects galaxy formation and evolution. GV galaxies constitute a very informative sub-sample, where the effects of subgrid physics can be tested, regarding the varying stellar population content as galaxies evolve. Furthermore, since the GV is a transition region where the most fundamental quenching mechanisms operate, this comparison allows us to explore the prescriptions adopted by the modellers to trigger quenching. Hence we compare the observational constraints with state-of-the-art simulations (EAGLE and IllustrisTNG) following our robust definition of GV, as presented in A19 and A20, based on the 4000Å break strength. The paper is laid out as follows: Section 2 outlines the two simulations and the survey used for the analysis. Section 3 looks into pre-processing of the data to avoid selection biases. Section 4 presents the comparison of the simulated galaxies with the observational constraints. Finally in sections 5 and 6 we discuss the main results and summarise them.

2 SAMPLE
We present here some details of the simulation and observational data explored in this paper. We refer the reader to the
relevant papers quoted below for more details regarding the sample. We will focus our description here on some of the aspects more relevant to the analysis of green valley galaxies, especially on the way AGN feedback has been implemented in the simulations.

2.1 The EAGLE (RefL0100N1504) simulation

EAGLE (Schaye et al. 2015; Crain et al. 2015) represents a set of cosmological hydrodynamical simulations comprised of multiple runs with different box sizes and resolution. We use here the fiducial EAGLE simulation RefL0100N1504 (hereafter Ref100), that adopts a comoving box size of L=68h\(^{-1}\) Mpc=100 Mpc, containing 1054\(^3\) dark matter (DM) particles, with a baryonic particle mass of \(m_\text{p}=1.81\times10^8\,\text{M}_\odot\) and dark matter particle mass of \(m_\text{dm}=9.70\times10^9\,\text{M}_\odot\). EAGLE is based on a modified version of GADGET 3 (Springel 2005), in terms of the implementation of subgrid physics, the smoothed particle hydrodynamics (SPH) formulation and the choice of time steps. EAGLE adopts a flat ΛCDM cosmology, taking the parameters derived from Planck Collaboration et al. (2014), just for reference, \(\Omega_m=0.307\), \(\Omega_\Lambda=0.693\), \(\Omega_b=0.048\), \(h=0.6777\), \(\sigma_8=0.8288\).

Over galaxy scales, EAGLE, as all other galaxy simulations, depend on a number of prescriptions collectively termed “subgrid physics” that aim at describing: radiative cooling and photoheating; reionization of hydrogen; star formation; stellar mass loss and Type Ia Supernovae; feedback due to star formation and AGN; and growth of supermassive black holes (SMBH). The EAGLE simulation follows Schaye & Dalla Vecchia (2008), where the star formation rate depends on the gas pressure rather than its density, better reproducing the observed Kennicutt-Schmidt law. Due to the lack of resolution, simulations suffer from an ‘overcooling’ problem when considering stellar feedback, ineffective at forming the observed high mass galaxies. To compensate for this, a method following Dalla Vecchia & Schaye (2012b) is implemented, that makes stellar feedback a stochastic process, thus enabling the control of energy accessible per feedback event. A black hole seed with mass \(m_\text{BH}=10^8\,h^{-1}\,\text{M}_\odot\) is included in the simulated galaxies by converting a gas particle with the highest density to a collisionless particle. This is applied to any galaxy with a dark matter halo mass above \(\sim 3\times10^{12}\,\text{M}_\odot\) and dark matter mass \(m_\text{dm}=7.5\times10^6\,\text{M}_\odot\) (Pillepich et al. 2018b; Marinacci et al. 2018; Springel et al. 2018; Nelson et al. 2018; Naiman et al. 2018). The initial conditions of the TNG100 simulation are set at redshift \(z=127\), with cosmological parameters \(\Omega_m=\Omega_\Lambda=0.3089\), \(\Omega_b=0.0486\), \(\Omega_\Lambda=0.6911\), \(h=0.6774\), \(\sigma_8=0.8159\), in accordance with constraints proposed by the Planck collaboration (Planck Collaboration et al. 2016). Similarly to EAGLE, and the original Illustris simulation, the subgrid physics consists of radiative cooling, star formation and SN feedback, black hole formation and growth along with AGN feedback. However in contrast to Illustris, IllustrisTNG made key improvements on three areas - stellar evolution and gas chemical enrichment, growth and feedback of supermassive BHs and galactic winds (Weinberger et al. 2018; Pillepich et al. 2018a).

Star formation in TNG100 proceeds through gas stochastically converting to star particles if their gas density grows above a critical threshold \(n_\text{p}=0.13\,\text{cm}^{-3}\). The number is tuned so that it reproduces the observed Kennicutt-Schmidt law. Each star particle is treated as a single-age stellar population with a Chabrier (2003) initial mass function. These populations evolve with time, eventually return-

\[ \dot{m}_\text{accr} = \dot{m}_\text{Bondi} \times \min(C_{\text{vis}}^{-1}(c_s/V_\phi)^3, 1), \]

where \(C_{\text{vis}}\) is a free parameter that relates to the viscosity and is set at 2\(\pi\) for this simulation; \(V_\phi\) represents the rotation of the gas around the black hole. Therefore, unlike IllustrisTNG (see below), EAGLE takes into account the angular momentum of the particles (Rosas-Guevara et al. 2015). The accretion rate is contrasted with the Eddington mass accretion rate, where the minimum of the two values is chosen to describe black hole growth. The Eddington mass accretion rate is defined by:

\[ \dot{m}_\text{Edd} = \frac{4\pi G m_\text{BH} m_\text{p}}{c_s \sigma_T c}, \]

where \(c_s = 0.1\) is the radiative accretion efficiency, and \(\sigma_T\) is the standard Thomson cross-section. This can be converted to an AGN luminosity via \(L_\text{AGN} = \dot{m}_\text{BH} c_s^2\), and the Eddington Luminosity is \(L_\text{Edd} = 1.25 \times 10^{38} (m_\text{BH}/\text{M}_\odot)\). More detail on how the various subgrid physical mechanisms are implemented in EAGLE can be found in Schaye et al. (2015) and Crain et al. (2015). Note the simulated data used to create the photometric/spectroscopic equivalents of the SDSS measurements are computed within the central 3kpc of a galaxy, that corresponds to the mapping on the galaxies of the aperture size of the SDSS fibres. However, the stellar mass of the galaxy, which is used as the major parameter to characterize the overall properties of a galaxy, is determined for the whole system.
ing a fraction of their mass and elements to the surrounding interstellar medium. TNG100 incorporates both types of supernovae: core collapse SNIa, between the mass range $m_\star=8-100M_\odot$, as well as type Ia SN. For stellar mass between 1–8 $M_\odot$, stars are assumed to evolve through an AGB phase. More detailed information can be found in Pillepich et al. (2018a).

Regarding AGN feedback, when the galaxy is in the low-accretion state TNG100 uses kinetic AGN feedback rather than the bubble model (Sijacki et al. 2007). At high accretion rates TNG100 uses, analogously to EAGLE, a thermal black hole seed mass is $8 \times 10^5 h^{-1} M_\odot$, and the halo mass threshold is $M_{\text{th,seed}}=7.38 \times 10^9 M_\odot$. This difference with respect to EAGLE may be an important one that we present in the discussion, as a potential cause of the discrepancies found between these two simulations on the green valley.

The accretion rate implemented in TNG100 follows a similar prescription to EAGLE. However, TNG100 distinguishes between two modes of AGN feedback, kinetic and thermal, by use of the Eddington ratio given by:\n
$$\chi_{\text{Edd}} = \frac{\dot{m}_{\text{Bondi}}}{\dot{E}_{\text{Bondi}}}$$

The Bondi accretion rate, which is the same as the mass accretion rate ($\dot{m}_{\text{accr}}$), is formulated as:\n
$$\dot{m}_{\text{Bondi}} = \frac{4\pi G^2 m_{\text{BH}} \rho c^2}{\epsilon c^2}$$

where for this simulation, $\epsilon_c$ encapsulates both thermal and magnetic signal propagation, therefore $\epsilon_c = (\epsilon_{\text{therm}} + (B^2/4\pi \rho))^{1/2}$. The Eddington mass accretion rate is slightly different to the one defined in EAGLE (equation 2), as the radiative efficiency of a black hole is set at $\epsilon_c=0.2$ (Pillepich et al. 2018a), whereas EAGLE adopt $\epsilon_c=0.1$ (Crain et al. 2015). The AGN feedback mode is set by choosing a threshold $\chi$, so that $\chi_{\text{Edd}} < \chi$ will result in kinetic feedback, whereas in the high accretion state, $\chi_{\text{Edd}} \geq \chi$, thermal feedback will be enforced (Weinberger et al. 2017). The value of the threshold, $\chi$, is given by:

$$\chi = \min \left[ \chi_0 \left( \frac{m_{\text{BH}}}{10^8 M_\odot} \right)^\beta, 0.1 \right]$$

thus introducing a mass dependency. Both $\chi_0$ and $\beta$ are free parameters. The limit of 0.1, shown in the equation above, allows any black hole, regardless of mass to have a high accretion rate (Weinberger et al. 2018). Similarly to EAGLE, all parameters, including the spectroscopic index $D_n(4000)$, are measured within an aperture corresponding to the central 3 kpc of a galaxy, except for (total) stellar mass, which is measured over the whole galaxy.

2.3 Observational data (Sloan Digital Sky Survey)

Following from A19 and A20, our observational constraints on the green valley rely on the classic spectroscopic database of the Sloan Digital Sky Survey DR14 (Gunn et al. 2006; Abolfathi et al. 2018, hereafter SDSS). This catalogue consists of a subsample of galaxies with r-band magnitude between 14.5 and 17.7 AB, selected for spectroscopic follow-up from the SDSS photometric data. The spectra cover the 3,800–9,200 Å window, at resolution $R \equiv \lambda/\Delta \lambda$ (FWHM) of 1,500 at 3,800 Å, and 2,500 at 9,200 Å (Smee et al. 2013). To minimise any bias associated with redshift, we restrict the sample to $0.05 < z < 0.1$. We refer the reader to A20 for details regarding aperture effects and other potential biases of the selected sample. Finally to get reliable measurements of the spectral features, we impose a threshold in signal-to-noise ratio, $\text{snMedian}\_r >10$. Those constraints result in a total set comprising ~228,000 spectra.

In A19 and A20, we chose the velocity dispersion as the fundamental parameter that correlates with the population properties, following the well-known observational trend (see, e.g., Bernardi et al. 2003; Ferreras et al. 2019). Velocity dispersion is a “clean” observable in spectra with high S/N, with significantly fewer uncertainties than stellar mass – another important parameter that correlates strongly with population properties. However, in simulated data, the velocity dispersion of a galaxy is a complicated quantity that depends on many details of the formation process, especially the dynamics associated to the mass accretion history. Stellar mass provides a comparatively more robust indicator of the global properties of a galaxy in a simulation. Therefore, in contrast with A19 and A20, we adopt stellar mass as the main parameter in the analysis of the trends. We convert the six velocity dispersion bins of our previous study, $70<\sigma<250$ km s$^{-1}$, to stellar mass bins, by use of the observed trend $\log M_\star/M_\odot = (1.84 \pm 0.03) \log \sigma + (10.3 \pm 0.3)$, derived from stellar masses as quoted in the SDSS galSpecExtra catalogue (Brinchmann et al. 2004), where $\sigma_{100}$ is the velocity dispersion, measured in units of 100 km s$^{-1}$. Tab. 1 shows the mass bins derived using this conversion, along with the newly defined blue cloud (BC), green valley (GV) and red sequence (RS). Note this conversion between velocity dispersion and stellar mass is solely done for the stellar mass bins. For individual galaxies we use the stellar masses given by the galSpecExtra catalogue (Brinchmann et al. 2004).

To define BC, GV and RS, we follow a data-driven approach, whereby at fixed stellar mass, we use the observed distribution of SF and Q galaxies, identified using the BPT diagram (Baldwin et al. 1981), to define a probability distribution function (PDF) for the BC ($P_{\text{BC}}$) and RS ($P_{\text{RS}}$), respectively. The PDFs are assumed to follow a Gaussian distribution. From these, we define the PDF of GV galaxies ($P_{\text{GV}}$) as another Gaussian peaking at the value of $D_n(4000)$ for which $P_{\text{BC}} = P_{\text{RS}}$, i.e. both subsets are indistinguishable at this value of the 4000Å break strength. The GV is further split into upper (uGV), middle (mGV), and lower (lGV) green valley subsets, where we define the different regions by the terciles of the distribution within each stellar mass bin (see A19 and A20 for full details). We find good agreement between the BC, GV and RS defined with respect to stellar mass or velocity dispersion, within statistical uncertainties. The only significant deviation was found at the highest mass bin: $10.93<\log M_\star/M_\odot<11.03$, where a difference is found in the definition of the GV at the level $\Delta D_n(4000)\sim 0.1$ dex. At the highest mass bins, $\log M_\star/M_\odot \geq 10.5$, the BC is sparsely populated, therefore the probability-based methodology is less accurate.
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3 DATA PRE-PROCESSING

Before carrying out the analysis, we need to pre-process both the observational and simulation data to homogenise their distributions in order to minimise selection biases, and to produce synthetic spectra from the simulated galaxies with the same instrumental signature as the SDSS data. Note the spectra and the simulation parameters are extracted within a $R=3$ kpc aperture, to make a fair comparison with SDSS, while the stellar masses, for both simulation and SDSS, are derived for the whole galaxy. This section focuses on the methodology adopted to prepare the samples so that a direct comparison could be made.

3.1 Synthetic spectra

Our comparison uses the $z = 0.1$ snapshot of the simulations, comparable to the redshift range of the SDSS database (differences between $z = 0$ and $z = 0.1$ are minimal for this analysis). In both EAGLE and TNG, we produce a simple stellar population (i.e. single age and chemical composition) for each stellar particle, mixing those populations into composites for all particles in the same galaxy. The stellar particles have mass above $10^6 M_\odot$, therefore this approach is well justified and does not suffer from any issues related to the sampling of the IMF. Due to the mass resolution of the stellar component in state-of-the-art simulations at present, the low SFR regime is typically sampled by the creation of a few or eventually just one $10^6 M_\odot$ star particles. Note these will in turn produce a bias in the spectra, towards younger luminosity-weighted ages.

To produce spectra comparable to those from the 3 arcsec fibre-fed spectrograph of the classic SDSS data, we combine the spectra from all stellar particles within a 3 kpc galacto-centric radius. For reference, the SDSS fibre radius maps a physical distance of 2.8 kpc at redshift $z = 0.05$ for a vanilla flavoured ΛCDM cosmology with $\Omega_m = 0.3$, $h = 0.7$. The synthetic spectra are taken from the population synthesis models E-MILES (Vazdekis et al. 2016), based on a fully empirical stellar library (Sánchez-Blázquez et al. 2006) and Padova isochrones (Girardi et al. 2000). The E-MILES spectra extend from the far UV to the mid-IR (1680 Å to 5 μm), spanning stellar ages from 6.3 Myr to 17.8 Gyr (we restrict the oldest ages to the cosmological age of the Universe at the fiducial redshift, $\sim 12.4$ Gyr), and metallicity ranging from $[\text{M/H}] = -1.71$ to +0.22. The models adopt a Chabrier (2003) IMF, and we perform a bilinear interpolation in age and metallicity of the E-MILES SEDs. To avoid systematics caused by the modelling of dust attenuation, and taking advantage of the insensitivity of the 4000 Å break strength to typical amounts of dust in galaxies (see A20), we do not include dust in the modelling of the synthetic spectra. Finally, the data are convolved to the $R=2$ kpc resolution of the SDSS classic spectrograph, in quadrature with a Gaussian function mimicking the kinematic kernel that corresponds to each stellar mass bin, following the trend presented above, between stellar mass and velocity dispersion.
Previous work in the literature regarding the dust modelling in EAGLE and TNG100 (Trayford et al. 2015, 2017; Nelson et al. 2018) find a level of agreement with the observational constraints. We emphasize in this paper that the effect of dust on the spectra of galaxies represents an additional layer of complexity in galaxy formation models that go beyond the scope of this paper. Our main aim is to explore the evolution of the stellar population properties across the green valley to probe the more fundamental aspect of how feedback is implemented in models to shape the star formation history of galaxies. The use of the $D_n(4000)$ index to define the location of the GV allows us to bypass the complexity of dust, avoiding potential biases produced by the effect of dust attenuation on other observables, most notably colours based on broadband filters. Fig. B1 of A20 shows a dust correction on the SDSS data causes a change in the position of the $D_n(4000)$-defined BC, GV and RS by less than 0.06 dex. Just as a test of the actual effect of dust attenuation on our data, we applied the dust model described in Negri et al. (in prep.), which is a modification of the dust model of Trayford et al. (2015) for the EAGLE simulation. We found negligible changes in the definition of the BC, GV, RS when using the $D_n(4000)$ index, as expected.

### 3.2 Homogenisation of simulation and observation data

A fundamental step in the comparison between observations and simulations involves ensuring that similar galaxy samples are considered. Different selection effects in observations and simulations will yield samples with incompatible distributions of stellar mass, hence the need for a homogenisation process. More specifically, the Malmquist bias imposed by the r$<$17.77 AB limit for spectroscopic follow-up (see, e.g., Abolfathi et al. 2018) implies that low mass galaxies ($M_* \lesssim 10^9 M_\odot$) are missed in SDSS, with a clear trend with redshift. In contrast, simulations are biased against high mass galaxies ($M_* \gtrsim 10^{12} M_\odot$) due to their volume limitation (see, e.g., Schaye et al. 2015). Therefore for a fair comparison between these data sets, we must ensure the distributions are statistically compatible.

From the original samples, we select sets that are “homogeneous” regarding stellar mass – which is the parameter we assume to act as the major driver of the stellar population content. Note we have to proceed with two different sets of comparisons: one between SDSS and EAGLE and another one between SDSS and TNG100. Moreover, we homogenise a pair of samples by finding a pivot stellar mass, so that below (above) this mass we randomly exclude simulated (observational) galaxies, as we have a lower fraction of observational (simulated) galaxies. Here the pivot mass bin is chosen as the one for which there is a greater fraction of observed galaxies in a mass bin compared to the fraction of simulated galaxies. Fig. 1 shows the histogram of homogenised mass distribution of EAGLE (left) and TNG100 (right) galaxies, with respect to SDSS. The blue and red hatched areas represent SDSS and simulation histograms, respectively.

To numerically assess the level of homogeneity between the respective stellar mass distributions of observations and simulations, we carried out a Kolmogorov-Smirnov test (hereafter KS-test, see, e.g., Dodge 2008). When comparing the stellar mass distribution of the original samples, we get high values of the $D$-statistic ($\sim$0.56) between simulated and SDSS data (in both the EAGLE and TNG100 simulations), leading to a low probability that the samples are produced by the same parent distribution. However, after homogenisation, the $D$-statistic becomes, by construction, low ($\sim$6$\times$10$^{-3}$) with high values of the probability ($\gtrsim$90%) that the samples originate from the same distribution. However, note that we compare SDSS individually with either EAGLE or TNG100. We do not aim at creating a joint SDSS-EAGLE-TNG100 homogenised sample as this will reduce further the size of the working sample, restricting the stellar mass range. Therefore we have two sets of SDSS galaxies: one for EAGLE and a different set for TNG100. We note this will lead to some differences between the two sets of galaxy spectra from SDSS, quantified in Appendix A. Additionally, variations between the two simulation data sets are also expected due to the different cosmological volumes probed, as well as the prescriptions to model the subgrid physics that controls the stellar mass growth in galaxies. We emphasize that this procedure is needed for a fully consistent comparison of the simulations with observational data. Note that in all samples, we make no distinction between satellite and central galaxies, as an environment-related analysis will be published in a separate paper (Angthopo et al., in prep).

### 3.3 Galaxy Classification

Observationally, galaxies are traditionally classified regarding nebular emission into quiescent (Q), star-forming (SF), Seyfert AGN, LINER AGN, or composites (i.e. a mixture of those). Ratios of targeted emission line luminosities allow us to separate the ionization environments expected in the ISM of galaxies (Baldwin et al. 1981; Cid Fernandes et al. 2011). This is an important classification scheme, as both star formation activity and AGN are essential mechanisms in galaxy evolution, and the path to quiescence still remains an open question (Martin et al. 2007; Dashyan et al. 2019; Man et al. 2019, A19). Our simple methodology does not take into account nebular emission when creating the synthetic spectra from simulations. Therefore, we need to get back to physical parameters in order to classify the simulated galaxies as Q, SF or AGN. Regarding SMBH activity, we compare the black hole accretion rate with respect to the Eddington ratio:

$$\lambda_{\text{Edd}} = \frac{\dot{m}_{\text{accr}}}{m_{\text{Edd}}}$$

However, a non-trivial issue is to define the actual values of the threshold ratio to segregate galaxies according to AGN activity.

Observational studies conclude Seyfert AGN have Eddington ratios between $-2 < \log(\lambda_{\text{Edd}}) < -1$ (Heckman et al. 2004; Schulze et al. 2015; Georgakakis et al. 2017; Ciotti et al. 2017), whereas lower accretion rates correspond to radiatively ineffective AGN, i.e. LINER or even no AGN. Some studies suggest a lower limit for LINER AGN around $\log(\lambda_{\text{Edd}}) \sim -6$ (Heckman et al. 2004; Li & Xie 2017), while others choose values as low as $\log(\lambda_{\text{Edd}}) \sim -9$ (Ho 2008, 2009). Studies using SDSS galaxies have calculated the Eddington ratio from [OIII] emission, finding $\log(\lambda_{\text{Edd}}) \sim -4$ (Kewley et al. 2006). For the simulated galaxies, we adopt our own Eddington ratio limits, along with specific star formation rate (sSFR) to classify galaxies as Seyfert AGN,
LINER AGN, SF (including composite) or Q. Note the sSFR used here has been calculated using the instantaneous SFR. An alternative selection would use the average SFR over some timescale, but previous work from the literature have shown that measuring SFR in different ways makes little difference at low redshift (Donnari et al. 2019, 2020a). Furthermore, the criterion to select the corresponding values of $\lambda_{\text{Edd}}$ and sSFR is to impose equivalent global ratios of Seyfert, LINER, SF and Q to those found in the full homogenised SDSS samples. Note we are interested in the relative mass-dependent variation of these fractions, and that the homogenisation in mass makes the comparison between SDSS and the respective simulation meaningful.

EAGLE only imposes one form of AGN feedback, therefore it is not possible to differentiate between Seyfert or LINER AGN activity. From the simulations, we retrieve the black hole mass and their accretion rate – at the fiducial redshift $z = 0.1$ – and we use Eq. 6 to find $\lambda_{\text{Edd}}$ in each galaxy. Comparing the total fraction of Seyfert AGN with respect to SDSS, we obtain a threshold $\log(\lambda_{\text{Edd}}) \gtrsim -2.0$. We proceed similarly with the LINER galaxies, obtaining a range $-4.2 \lesssim \log(\lambda_{\text{Edd}}) \lesssim -2.0$. Moreover, for LINERs we also impose a constraint on $\log(\text{sSFR} \text{ yr}^{-1}) \lesssim -11$ to make sure SF activity is minimal. Note that most of the SDSS galaxies hosting LINERs have a sSFR similar to Q. Galaxies with $-4.2 < \log(\lambda_{\text{Edd}}) < -2.0$ but with $\log(\text{sSFR}) > -11$ are classified SF. Finally, galaxies with $\log(\lambda_{\text{Edd}}) \lesssim -4.2$ and $\log(\text{sSFR}) < -11$ are considered to be Q (SF). These criteria are summarised in Tab. 2, where the constraints are shown for both EAGLE and TNG100 simulations. In each case, the table shows the limits on $\lambda_{\text{Edd}}$ and sSFR as well as the fraction of galaxies of a given type in the homogenised simulations sample. The values in brackets show the percentage of different types of galaxies observed in the SDSS homogenised sample, identified via the BPT diagram (Baldwin et al. 1981; Kewley et al. 2001; Kauffmann et al. 2003b).

Both observation and simulation data contain SF and composite galaxies (classified with a BPT parameter either 1 or 3 in the SDSS galSpecExtra catalogue of Brinchmann et al. 2004), while we exclude low S/N star forming galaxies (BPT parameter 2).

The TNG100 simulation adopts two modes of AGN feedback – thermal and kinetic feedback – determined by Eq. 3 and 5, as defined in Weinberger et al. (2018). The fiducial approach fixes $\beta = 2$ and $\chi_0 = 2 \times 10^{-3}$, following Habouzit et al. (2019). However with this choice of parameters we get too many Seyfert AGN galaxies. To solve this, we carry out a similar procedure to EAGLE, adopting our own thresholds. Doing so may introduce a bias, as we exclude Seyfert AGN galaxies, and either consider them to be LINER AGN or SF galaxies in the fraction estimates. However, note the exclusion of Seyfert AGNs in the simulation data is justified, as we find a low fraction of Seyfert AGN in the observations. Furthermore, similarly to EAGLE, this is a necessary step as we have to ensure the ratios of Seyfert, LINER, SF, and Q galaxies are consistent, when comparing the properties of observational and simulation data. The comparison between the homogenised SDSS and TNG100 sets gives $\log(\lambda_{\text{Edd}}) \gtrsim -1.4$, slightly different to that of EAGLE. This is due to different subgrid physics regarding black hole growth and AGN feedback, as well as TNG100 having a larger black hole seed. For LINER AGN we find $-4.0 \lesssim \log(\lambda_{\text{Edd}}) < -1.4$ gives consistent fractions with respect to the observations. In TNG100, the threshold $\log(\text{sSFR})=-11.2$ gives a similar fraction of Q/SF galaxies with respect to the observations. Despite the slight variation in the selection criteria and in the homogenisation procedure, note the similarity of the parameter thresholds obtained to produce results matching the SDSS observations.

### Table 2. Criteria adopted to define galaxy activity: Seyfert/LINER AGN, quiescence (Q) or star-formation (SF). We constrain two parameters: the Eddington ratio ($\lambda_{\text{Edd}}$) and the specific star formation rate (sSFR, defined as the ratio between the instantaneous star formation rate and the stellar mass). Here $x$ represents the parameter at the top of each column. Also shown are the percentage of each type of galaxies produced in the simulation that matches the selection criteria. In columns 4 and 7 we show, in the same column, both the simulated and SDSS fractions, the latter in brackets.

| Type     | $\log(\lambda_{\text{Edd}})$ | $\log(\text{sSFR} \text{ yr}^{-1})$ | %    | $\log(\lambda_{\text{Edd}})$ | $\log(\text{sSFR} \text{ yr}^{-1})$ | %    |
|----------|-------------------------------|-----------------------------------|------|-------------------------------|-----------------------------------|------|
| Seyfert  | $x \geq -2.0$                 | -                                 | 3.86 (2.77) | $x \geq -1.4$                 | -                                 | 3.03 (3.04) |
| LINER    | $-4.2 \leq x < -2.0$         | $x \leq -11$                      | 9.46 (9.68) | $-4.0 \leq x \leq -1.4$       | $x \leq -11.2$                    | 10.07 (10.31) |
| SF       | $x < -2.0$                    | $x > -11$                         | 56.06 (62.91) | $x < -1.4$                    | $x > -11.2$                       | 53.43 (60.69) |
| Q        | $x < -4.2$                    | $x \leq -11$                      | 30.61 (24.64) | $x < -4.0$                    | $x < -11.2$                       | 33.47 (25.97) |

4 CONFRONTING OBSERVATIONS AND SIMULATIONS IN THE GREEN VALLEY

The state-of-the-art simulations explored in this paper are capable of matching the general fundamental properties of galaxies (Pillepich et al. 2018a; Nelson et al. 2018), as well as the bimodality of galaxies in colour (Trayford et al. 2015; Nelson et al. 2018). We focus here on how well simulations reproduce the bimodality of galaxies on the $D_n(4000)$ vs $\log M_*/M_\odot$ plane. More specifically, we look at the mass dependence of the fractions of AGN, SF and Q galaxies in the GV. Given that the GV is a transitional region where quenching processes efficiently drive galaxies to quiescence, this comparison allows us to analyse the ability of the subgrid physics imposed in the simulations to reproduce the observational data.

4.1 Blue Cloud, Green Valley and Red Sequence

Our first analysis of the data – before focusing on the GV – involves a comparison of the BC, GV and RS between SDSS and simulations. Note similar studies have been already performed on the colour-mass plane, finding general...
agreement of the simulations with observations (see, e.g., Trayford et al. 2016, 2017; Kaviraj et al. 2017; Nelson et al. 2018) and on the SFR-mass plane (Furlong et al. 2015; Donnari et al. 2019). We revisit this comparison with our new definition of the BC, GV, RS regions (A19, A20), looking for hints that could help improve the simulations.

4.1.1 Comparison with EAGLE (RefL0100N1504)

Fig. 2 shows the distribution of EAGLE galaxies (left) on the \( D_n(4000) \) vs \( \log M_\star/\text{M}_\odot \) plane, after sample homogenisation. The blue, green and red data points with error bars represent the observational (i.e. SDSS) BC, GV and RS. The red and blue histograms on the side panels show the distribution of EAGLE and SDSS galaxies, respectively – likewise for TNG100 on the rightmost panel. We find a mismatch in the distribution, of about 0.1–0.2 dex at low \( D_n(4000) \), and agreement at high \( D_n(4000) \). Combining this with the stellar mass distribution, we see that while there is an overall qualitative agreement, EAGLE seems to produce BC, GV and RS regions with higher \( D_n(4000) \), and the mismatch increases from BC to RS. This difference is greatest in the lowest mass bins, \( 9.5 \lesssim \log M_\star/\text{M}_\odot \lesssim 10.5 \). The higher value of \( D_n(4000) \) at low-intermediate mass could be due to the mass-metallicity relation, being shallower in EAGLE with respect to the observations (Schaye et al. 2015; Trayford et al. 2017).

One reason for the shallowness of the mass-metallicity relation could be due to galaxies having a stronger chemical enrichment history at low mass compared with the observations. \( D_n(4000) \) is sensitive to the metallicity (Balogh et al. 1999), one of the manifestations of the age-metallicity degeneracy. Moreover, the inclusion of only one mode of AGN feedback – resembling quasar-mode AGN, which happens to be dominant in high mass galaxies (Shankar et al. 2006; Faber et al. 2007; Smethurst et al. 2015) – could offer another potential explanation for this trend. AGN feedback plays an important role in quenching of star formation (Martin et al. 2007; Gonçalves et al. 2012; Wright et al. 2019; Dashyan et al. 2019), therefore specially for lower mass galaxies, quasar mode AGN could lead to quenching of star formation that operates too quickly. A combination of these two effects could also cause the effects we see here, where the red sequence features a shallower gradient with respect to the observations.

4.1.2 Comparison with IllustrisTNG (TNG100)

In the TNG100 simulated galaxies (see Fig. 2, right), a better agreement is found in the BC with respect to EAGLE; also evident from the histograms shown on the right. However, there is significant disagreement in the GV and RS, of \( \sim 0.1–0.3 \) dex. Note the gradient of the RS on the \( D_n(4000) \) vs stellar mass plane is shallower in TNG100 with respect to SDSS. It is also shallower that the EAGLE data, with an excess of RS galaxies at low mass (< \( 10^{10} \text{M}_\odot \)). Additionally, at the massive end (above \( 10^{10.5} \text{M}_\odot \)), a more drastic decrease in the number of BC galaxies is apparent. Note, the fraction of galaxies in the GV is lower in TNG100 with respect to the observations, specifically for \( 1.5 \lesssim D_n(4000) \lesssim 1.8 \), as shown by the histogram. Note that previous work in the literature (Nelson et al. 2018) find better agreement when looking at bimodality with respect to (g–r) colour. However, at lower stellar mass, \( 9 \lesssim \log M_\star/\text{M}_\odot \lesssim 10 \), they also find a surplus of galaxies in the simulated red sequence, suggesting over-quenching. More specifically, at low stellar masses, recent comparisons find a shallower mass-metallicity trend with respect to the observations (Nelson et al. 2018), which might offer a possible explanation to the excess of RS galaxies in TNG100.
4.2 Fractional Variation in the Green Valley

Although we already find limited differences between the EAGLE and TNG100 simulations in the BC, we find significant difference in the RS, so we focus on the analysis of the GV region, as it is a transition region where quenching processes are expected to leave stronger imprints, and where different feedback prescriptions are expected to be more prominent. Note that we start with \( \sim \) 226 872, 13 475 and 22 232 SDSS, EAGLE and TNG100 galaxies, respectively with \( \log M_*/M_\odot \gtrsim 9.0 \). After homogenisation we are left with 88 588 (39.05% of total) EAGLE-SDSS and 5 822 (43.21% of total) EAGLE galaxies and 90 709 (39.98% of total) TNG100-SDSS and 9 906 (44.56% of total) TNG100 galaxies. The number of galaxies is further reduced to 630 (10.82% of homogenised sample) for EAGLE and 486 (4.91% of homogenised sample) for TNG100 when considering only the GV. For the SDSS-EAGLE and SDSS-Illustris-TNG samples, we find 6 491 (7.32%) and 6 448 (7.11%) galaxies, respectively in the GV. Even though there are similar fractions of EAGLE and TNG100 galaxies after homogenisation, there is a greater drop in TNG100 compared to EAGLE. Using these GV galaxies we then compare the fraction of different types of galaxies regarding nebular emission (as defined in Sec. 3.3), in the IV, mgV and uGV. The classification separates galaxies into either SF, Q, LINER or Seyfert AGN. Fig. 3 compares the fraction of galaxies segregated by type as a function of stellar mass in EAGLE (left) and TNG100 (right), with respect to the observational constraints from SDSS. The horizontal dashed line at zero represents the ideal case where simulations and observations match perfectly. The top, middle and bottom panels correspond to the uGV, mgV and IV, respectively. The lines are colour coded, as labelled. At masses above \( 10^{10.5}M_\odot \), EAGLE consistently overproduces GV quenched galaxies, while underproducing SF GV galaxies, regardless of the GV region. Note the discrepancy lessens as we traverse the GV, from IV to uGV. There is an increase in the mismatch of the Q and SF galaxies as stellar mass increases, being largest in the IV. In addition, there is a consistent underproduction of Seyfert AGN galaxies, however the samples include very little Seyfert AGN galaxies, so the statistics is not so significant. The trend for LINER galaxies is noisier, so we cannot deduce any mass trend of the mismatch with respect to the observations. We note that the increasing mismatch of the fraction of Q and SF GV galaxies appears in a mass interval where both mergers and black hole activity, henceforth AGN feedback, is expected to steeply increase (Wright et al. 2019), as well as in the mass regime where halo quenching is suspected to occur, \( \log M_{\text{halo}}^\text{crit}/M_\odot \sim 12.0 \) (Faber et al. 2007; McIntosh et al. 2014).

TNG100 also shows a substantial mismatch with respect to the observational data, with an overproduction (underproduction) of Q (SF) GV galaxies. As stellar mass increases, the simulation overproduces Q galaxies until \( 10^{10.5}M_\odot \), above which the final mass bin shows a decrease in the mismatch. A similar trend can be seen in SF galaxies in the IV and mgV. Note this behaviour is similar to EAGLE, but the discrepancy in TNG100 is larger. The fraction of Seyfert AGN shows little difference. However this is once more owing to low number statistics.

There could be many reasons for the discrepancies found between the GV galaxies in observations and simulations. We explore them in Sec. 5. Note the overabundance of Q galaxies, along with the lack of SF galaxies in the simulation GV may indicate too rapid quenching with respect to the observations. This is consistent with the fact that both

---

**Figure 3.** Fractional difference between observations and simulations of GV galaxies, split between Seyfert AGN (black dotted), LINER AGN (green dash-dot), star forming (including composite, blue solid) and quiescent (red dashed). The fractional difference between observations and simulations is shown as a function of stellar mass. The comparisons with EAGLE (TNG100) are shown on the left (right) panels. From bottom to top, we show the lower (IV), mid (mgV) and upper (uGV) green valley (see text for details). The error bars show the propagated Poisson uncertainty.
EAGLE and TNG100 feature a RS with a greater 4000 Å break strength than the SDSS observations.

### 4.3 Specific Star Formation Rate

In addition to the comparison based on the BPT classification of the nebular emission lines, presented above, it is possible to further test the models by comparing the behaviour of the specific star formation (sSFR) rate, defined as the instantaneous star formation rate per unit stellar mass. sSFR is a powerful indicator of the ongoing stellar mass growth. Fig. 4 (left) shows sSFR against stellar mass. The blue, green and red dashed lines with error bars show the mean observational sSFR in the lGV, mGV and uGV, respectively, whereas the shaded regions delimit the results from the simulations. For note for galaxies with SFR= 0, we calculate the mean observational sSFR for each stellar mass bin. The black and gray data points correspond to the simulations. Galaxies with log sSFR < -14.5, and these galaxies are excluded when calculating the mean sSFR for each stellar mass bin. The blue and gray data points correspond to individual galaxies in the GV for simulations and SDSS, respectively. Galaxies with log sSFR < -14 (hereafter defined in yr^{-1}) represent fully quiescent systems, i.e. with negligible star formation. EAGLE produces a trend of sSFR with stellar mass that is closer to the observations. The SDSS data feature a wider separation between IGV and uGV, whereas the simulations show significant overlap. Moreover, the simulations show overall lower values of the sSFR with respect to the observations. This mismatch may be due to a systematic offset, as the sSFR of the simulations is retrieved from the output of the star formation activity, whereas the observational constraints are determined indirectly from standard relations involving emission lines (see, e.g., Kennicutt 1998).

However, this trend is consistent with our analysis based on the fraction of Q and SF galaxies, shown in the previous subsection.

The right hand panel of Fig. 4 corresponds to the combination of the GV galaxies. At the massive end, log M < 10.6, most TNG100 GV galaxies lack star formation whereas the observations feature a significant number of SF galaxies, once more supporting the argument towards an excess of Q galaxies in the simulations at the massive end.

### 4.4 Average Ages

The next step in the comparison of GV galaxies involves the comparison of the average age, between observations and simulations. For the observational (SDSS) data, we adopt the same procedure as in A19, and A20, stacking the spectra, following Ferreras et al. (2013). The stacks are presented to STARLIGHT (Cid Fernandes et al. 2005), to extract star formation histories. This code performs full spectral fitting with an MCMC-based algorithm that finds the best-fit weights of a set of simple stellar populations (SSP). From these weights the average age is calculated as follows:

\[
\langle \log t \rangle \equiv \sum_{j=1}^{N_j} x_j \log t_j, \tag{7}
\]

where \(x_j\) is the normalised luminosity weight and \(t_j\) is the stellar age corresponding to the \(j\)-th SSP. For spectral fitting we use 138 SSPs from the Bruzual & Charlot (2003) models, where the age varies from 0.001 to 13 Gyr and total metallicity varies from \(10^{-4}\) to 0.05. The ages in the simulated galaxies are determined directly from the stellar growth of the galaxies, i.e. by taking into account the distribution of stellar particles within a R=3 kpc aperture size; to better match the SDSS classic spectra, taken through optical fibres that map a 3 arcsec diameter. Analogously to the spectral stacking performed in the SDSS data, the star formation histories for each galaxy within the same bin (in stellar mass and location on the GV) are stacked to create a joint distribution of stellar ages from which the average is determined. The uncertainties in both cases are obtained from a bootstrap, where each realization randomly stacks 60% of the galaxies in each stellar mass bin. The uncertainties of average stellar ages vary between ~ 0.1 – 0.7 Gyr for observational constraints, from STARLIGHT, and ~ 0.3 – 0.5 Gyr for simulated galaxies. Note that the stellar ages can be weighed either by luminosity or by mass. The former are better constrained by the spectra, whereas the latter are more physically motivated. Similarly to the dilemma between velocity dispersion and stellar mass – where the former is better constrained by the observations, and the latter is the preferred choice for simulations, in this case luminosity-weighted ages are more accurately constrained by the observational spectra, whereas mass-weighted ages suffer less systematic in the simulations.

Taking into account that relative age variations are even more robustly constrained than absolute estimates, we decide to quote our results as a relative age difference, given by:

\[
\Delta \psi_k(t) = t_k^1 - t_k^0, \tag{8}
\]

where \(\psi\) represents either the average age or quenching timescale (see below). The index \(k=\{L, M\}\) denotes whether the parameter is luminosity- or mass-weighted, while \(t\) denotes the chosen stellar mass bin. Note for each of the four parameters explored – namely luminosity-weighted age and quenching timescale, and mass-weighted average age and quenching timescale – we select a single fiducial value throughout, defined as the estimate from simulations in the mGV, at mass bin \(10^{10.68} < M_\star / M_\odot < 10^{10.81}\). We then subtract this fiducial value, both in simulation and observational parameters, across all stellar mass bins and GV regions. Therefore, by construction, \(\Delta \psi_k\) for the fiducial bin will be zero for simulations, whereas the value of \(\Delta \psi_k\) in this fiducial bin for the observed data will account for systematic offsets between observations and simulations.

Fig. 5 shows the relative average stellar ages in the observations (solid lines) and the simulations (filled dashed lines), with EAGLE (TNG100) shown in the top (bottom) panels. We also show separately the luminosity- (left) and mass-weighted (right) values. In each case, the top, mid and bottom panels show the result of uGV, mGV and IGV, respectively. The values quoted in the mid panel show the actual estimate of the stellar age corresponding to the fiducial mass bin. The luminosity-weighted ages show an increasing trend with stellar mass in all cases, consistent with the well-established mass-age relation (Kauffmann et al. 2003a; Gallazzi et al. 2005a). In all three regions of the GV, EAGLE produces galaxies that are both older, in luminosity
weights, than the observed constraints (by about 2.8 Gyr at the fiducial bin), and with a steeper mass-age slope (see Tab. 3). The luminosity-weighted estimates show a substantial systematic between the spectral fitting results (i.e. the data points) and the constraints from the star formation histories of the cosmological simulations (i.e. the shaded regions), in all GV regions and in both EAGLE and TNG100. There is a slightly better agreement with observations in the slope of the luminosity-weighted estimates of TNG100, (see Tab. 3), and the fiducial age is also slightly closer to the observational constraints (~2.0 Gyr).

In both cases, the mass-weighted average ages show better agreement with observations, both regarding the systematic offset and the slope, although with larger error bars. However, note the discrepancy at the massive end of the TNG100 uGV, where simulated galaxies have substantially older ages. Note previous work hinted the upper part of the GV could be the least homogeneous, as one could have a more complex mixture of galaxies evolving from the BC to the RS via quenching, as well as galaxies moving “backwards” due to mild, but frequent episodes of rejuvenation (Thomas et al. 2010; Nelson et al. 2018, A20).

### 4.5 Quenching timescales

In A20, we presented a parameter that – under a number of simplifying assumptions – can serve as a proxy of the quenching timescale. It is defined as the time interval between two percentile levels of the stellar age distribution, namely:

$$\tau_Q \equiv t_{70} - t_{30},$$

where \(t_x\) represents the cosmic time when the cumulative stellar mass function reaches a percentile level of \(x\). Therefore \(\tau_Q\) is the time that the system takes to go from a stellar mass content of 30% to 70% of the final amount. Similarly to average age estimates we bootstrap 60% of the galaxies to average age estimates we bootstrap 60% of the galaxies to obtain uncertainties in the range \(\sim 0.07-2.3\) Gyr for the observational data, derived from \textsc{starlight}, and \(\sim 0.1-0.8\) Gyr for simulated data, directly from the star formation histories. In a simple scenario where the galaxy builds up the stellar content in a monotonic way, this parameter scales with the rate at which stellar mass grows. Ideally, one would consider higher levels of the percentile (i.e. \(x\)), in order to represent more accurately the final stages before quenching ensues. However, our choice is motivated by the unavoidable uncertainties of the analysis, notwithstanding the systematics related to the derivation of the star formation history from full spectral fitting, following the \textsc{starlight} code (Cid Fernandes et al. 2005).

Fig. 6 shows the relative trends in both luminosity-(left) and mass-weighted (right) quenching timescale. The symbols and panels are analogous to those presented in Fig. 5, comparing the results for EAGLE and TNG100 in the top and bottom panels, respectively. The slopes of these relations, assuming a simple linear trend, are quantified in Table 4. We emphasize that \(\tau_Q\) is less robust than the derivation of an average case, as presented above. However, we note that the constraints are imposed on stacked spectra of galaxies with very similar properties (same stellar mass and in the same GV region), and feature a high signal to noise ratio. Therefore, the relative variations in \(\tau_Q\) among the stacked data are more reliable than individual measurements of the same parameter. We also note that, similarly to the average age shown above, we present the data as relative to a
Figure 5. Relative luminosity- (left, $\Delta \tau_L$) and mass- (right, $\Delta \tau_M$) weighted average stellar ages, shown with respect to stellar mass. Comparison with EAGLE (TNG100) are shown in the top (bottom) figures, each one separated into panels that correspond (from bottom to top) to the lGV, mGV, uGV. The relative ages are measured with respect to a fiducial one ($t_{\text{fid}}$) corresponding to mGV galaxies in the $10.68 < \log M_*/M_\odot < 10.81$ mass bin of the simulation data, quoted in each figure (see text for details).

Note the sign reversal of $\Delta \tau_Q$ between the luminosity-weighted (left) and the mass-weighted cases (right), that appears in both EAGLE and TNG100. This sign change implies the observations produce shorter $\tau_Q$ than the simulations when luminosity-weighted, but longer values of $\tau_Q$ when weighed by mass. This result could be caused by the fact that the $D_n(4000)$ index is sensitive to the presence of younger stellar populations from a recent episode of star formation (Poggianti & Barbaro 1997). However, this could also be explained by the way STARLIGHT constrains the weights of individual SSPs when performing spectral fitting. Luminosity weighting puts high weights in a short and recent period of time. Hence the resulting $\tau_Q$ is short. In contrast, the mass-weighted SFH distributes evenly the weights of the different stellar populations, producing a more extended dis-
distribution that results in a longer $\tau_Q$. Simulations distribute the weight of the individual star particles evenly for all ages, hence is not so sensitive to the difference between luminosity and mass weighing.

### Table 3. Slopes of the relation between average age and stellar mass. The slope ($\alpha$) is obtained from a linear fit to the function $\Delta t_{L,M} = \alpha \log M_*/M_\odot + \beta$ (see Fig. 5). The uncertainty is quoted at the 1\,$\sigma$ level.

|            | Lum-weighted | Mass-weighted |
|------------|--------------|---------------|
|            | EAGLE        | SDSS          | EAGLE        | SDSS          |
| IGV        | $+3.31 \pm 0.49$ | $+0.92 \pm 0.20$ | $+3.62 \pm 0.72$ | $+2.31 \pm 0.95$ |
| mGV        | $+2.82 \pm 0.22$ | $+0.99 \pm 0.18$ | $+2.40 \pm 0.74$ | $+0.52 \pm 1.23$ |
| uGV        | $+3.09 \pm 0.27$ | $+0.91 \pm 0.22$ | $+2.23 \pm 0.52$ | $+3.11 \pm 1.81$ |

|            | Lum-weighted | Mass-weighted |
|------------|--------------|---------------|
|            | TNG100       | SDSS          | TNG100       | SDSS          |
| IGV        | $+2.40 \pm 0.16$ | $+0.92 \pm 0.18$ | $+0.85 \pm 0.28$ | $+1.08 \pm 0.69$ |
| mGV        | $+1.90 \pm 0.47$ | $+0.98 \pm 0.22$ | $+0.09 \pm 0.40$ | $+3.28 \pm 0.59$ |
| uGV        | $+1.16 \pm 0.31$ | $+1.10 \pm 0.11$ | $-0.56 \pm 0.58$ | $+4.14 \pm 1.80$ |

### Table 4. Equivalent of Table 3 for the quenching timescale, $\tau_Q$. The slope ($\alpha$) is obtained from a linear fit to the function $\Delta \tau_{Q,L,M} = \alpha \log M_*/M_\odot + \beta$ (see Fig. 6). The uncertainty is quoted at the 1\,$\sigma$ level.

|            | Lum-weighted | Mass-weighted |
|------------|--------------|---------------|
|            | EAGLE        | SDSS          | EAGLE        | SDSS          |
| IGV        | $+1.32 \pm 0.96$ | $-0.74 \pm 1.16$ | $-1.25 \pm 0.70$ | $-1.92 \pm 1.17$ |
| mGV        | $+0.71 \pm 0.98$ | $-0.03 \pm 0.64$ | $+0.30 \pm 0.48$ | $-1.83 \pm 1.31$ |
| uGV        | $-1.08 \pm 1.36$ | $-0.85 \pm 1.33$ | $-1.38 \pm 0.68$ | $-8.04 \pm 2.12$ |

|            | Lum-weighted | Mass-weighted |
|------------|--------------|---------------|
|            | TNG100       | SDSS          | TNG100       | SDSS          |
| IGV        | $+1.61 \pm 0.72$ | $-0.68 \pm 1.12$ | $-0.40 \pm 0.89$ | $-1.31 \pm 1.66$ |
| mGV        | $-0.13 \pm 0.78$ | $-0.20 \pm 1.35$ | $+0.07 \pm 0.72$ | $-0.20 \pm 3.17$ |
| uGV        | $-1.33 \pm 0.92$ | $-0.27 \pm 2.06$ | $-0.69 \pm 0.77$ | $+1.85 \pm 2.09$ |

### Section 5. DISCUSSION

This paper focuses on a recent classification of GV galaxies, following a probability-based methodology applied to the distribution of 4000Å break strength in a large sample of SDSS (classic) spectra with relatively high signal-to-noise ratio. The definition of the GV along with three sub-regions (lower-, mid-, and upper-GV, denoted IGV, mGV, uGV, respectively) was presented and analysed in A19 and A20. We contrast here the observational properties presented in those papers, with two state-of-the-art cosmological simulations, EAGLE and Illustris TNG. Since the GV can be interpreted as a transition region where galaxies evolve from actively star-forming to quiescent systems, it should be considered a fundamental sample where the physical mechanisms of feedback, described in cosmological simulations by an overly simplified set of equations, loosely termed subgrid physics, can be put to the test. In a way, constraints based on GV galaxies provide “the next order” in our perturbative approach towards galaxy formation, the lowest order being the standard constraints on the galaxy luminosity/mass function, the Tully-Fisher relation and the mass-metallicity relation (Schaye et al. 2015; Pillepich et al. 2018a).

#### 5.1 Potential Caveats

##### 5.1.1 Population synthesis models

In order to follow the same definition of the GV in the simulations as in A19 and A20, we had to create synthetic spectra by combining the star formation and chemical enrichment history of the simulations with the E-MILES population synthesis models of Vazdekis et al. (2016). Once the mock spectra were created, we measured the 4000Å break strength following the same $D_n$(4000) index (Balogh et al. 1999). A possible systematic lies in the choice of models, including stellar evolution/isochrone prescriptions and stellar libraries. One would consider contrasting the results with respect to independent population synthesis models, such as BC03 (Bruzual & Charlot 2003) or FSPS (Conroy & Gunn 2010), beyond the scope of this paper. We note, though, that our analysis is mostly focused on accounting for the differences in the simulations with the E-MILES population synthesis models. Here, the $\Delta t_{L,M}$ is obtained from a linear fit to the function $\Delta \tau_{Q,L,M} = \alpha \log M_*/M_\odot + \beta$ (see Fig. 6). The uncertainty is quoted at the 1\,$\sigma$ level.

#### 5.1.2 Green Valley definition

An additional caveat regarding the mismatch between simulations and observations may be due to the actual definition of the GV distribution function. Previous studies of the EAGLE and TNG100 samples selected GV galaxies based on...
Figure 6. Equivalent of Fig. 5 for the relative quenching timescale, $\Delta \tau_Q$, quoted with respect to a fiducial value ($\tau_{Q,\text{fid}}$), also taken from mGV galaxies in the $10.68 \lesssim \log M_*/M_\odot \lesssim 10.81$ mass bin of the simulation data, and quoted in each figure.

colour, or chose the GV on the SFR vs stellar mass plane (Trayford et al. 2015, 2017; Wright et al. 2019; Nelson et al. 2018; Correa et al. 2019). Our selection, based on 4000Å break strength is motivated by a fully empirical approach, and requires the “projection” of the output from the simulations on the observational plane by creating synthetic spectra (Sec. 3.1) whose $D_n(4000)$ is measured. This step may introduce a systematic that can affect the comparison. An alternative approach would require defining the GV in the simulations independently, similarly to Trayford et al. (2015), Wright et al. (2019) for EAGLE and Nelson et al. (2018) for TNG100, thus having independent definitions of the GV for EAGLE, TNG100 and SDSS. Using this methodology, we would have different GV locations for EAGLE, TNG100 and SDSS on the $D_n(4000)$ vs stellar mass plane. This would produce independent lGV, mGV and uGV samples in each data set. However this method is counterproductive to the aim of this paper, as we are aiming at comparing the empirical definition of the GV, based on SDSS data, with model predictions. Thus by projecting simulations onto the observational plane and comparing the results enables the improvement of the subgrid physics such that the models can reproduce the BC, GV and RS morphology as found in the observations. Moreover, by focusing on the GV in this manner, we isolate the cause of the discrepancy i.e. the over-abundance of Q GV population and lack of SF GV galaxies hinting towards over quenching or too rapid quenching in the simulations.
5.2 Contrasting observations with simulations

5.2.1 Overall distribution

Hydrodynamical simulations have been shown to successfully reproduce the fundamental scaling relations of galaxies. Furthermore, there have been multiple studies on the bimodality that find a qualitative agreement between observation and simulations: in EAGLE, multiple studies have tested using the colour (g–r) at $z = 0.1$, to find an overall agreement with the distribution with observation (Trayford et al. 2015). Implementing a more sophisticated treatment of dust attenuation – where younger stellar populations are dustier than older systems – a better agreement with data from the GAMA survey was obtained (Trayford et al. 2017). Note these authors report a red sequence that appears slightly flatter than observed, in agreement with our Fig. 2. The flatter red sequence gradient was attributed to a flatter mass-metallicity relation (Schaye et al. 2015). This discrepancy is also evident in the definition based on the $D_n(4000)$ index, as it is substantially more sensitive to metallicity than colour.

Concerning TNG100-based comparisons, Nelson et al. (2018) correct for dust attenuation, finding a good quantitative agreement on the bimodality with the observations on the colour vs stellar mass plane. We also find good qualitative agreement on the colour vs stellar mass plane, by applying a simple dust correction with the Calzetti et al. (1994) law. However, our analysis based on the $D_n(4000)$ index, which is significantly less sensitive to dust attenuation, shows a greater discrepancy (Fig. 2), and this behaviour is similar in the EAGLE simulations. This result would suggest that the prescriptions chosen by the simulations, especially manifesting on the mass-metallicity relation, are able to reproduce and explain the observed colours, whereas the 4000Å break selection of GV suggests these prescriptions are not good enough to explain in detail the properties of the underlying stellar populations. Note that both broadband colours and $D_n(4000)$ suffer from the age-metallicity degeneracy (see, e.g. Worthey 1994), whereas the latter has a negligible dependence on dust. Therefore, the subgrid physics needed to constrain either may introduce independent biases. We argue here that the 4000Å break strength is a more fundamental observable, as it removes the highly complex layer of dust production, destruction, geometry, radiative transfer, etc, needed to produce reliable estimates of broadband photometry.

5.2.2 Overquenching

We discuss here the potential explanation of the mismatch of the bimodality shown with 4000Å break strength as a result of overquenching. Note most of our analysis is carried out to stellar mass. The mass-weighted quenching timescale supports overquenching/rapid quenching as the primary reason for the discrepancy between observations and simulations: we obtain more extended SFHs for SDSS than both EAGLE and TNG100, $\tau_{Q,\text{obs}} > \tau_{Q,\text{sim}}$. Note both EAGLE and TNG100 reproduce the expected decreasing quenching timescale with stellar mass, as found in the literature (Kauffmann et al. 2003a; Gallazzi et al. 2005b). However for the luminosity-weighted overquenching timescale, we find a reversal of this trend, where the observational constraints show a shorter $\tau_Q$. This effect could be due to rejuvenation (Faber et al. 2007; McIntosh et al. 2014), where a recent episode of star formation will bias the luminosity-weighted estimates towards the younger (i.e. lower M/L) component. Since our estimate of $\tau_Q$ is based on the difference in the stellar age distribution at the 30% and 70%, in luminosity weighting, a recent episode of rejuvenation can drastically increase the $\tau_Q$ parameter, however if the episode is of a significant fraction, it will have an inverse effect, where $\tau_Q$ decreases drastically as seen in Fig. 6.

5.2.3 Simulation Star Formation Histories

We have shown that various indicators suggest overquenching or a more rapid quenching of GV galaxies in both EAGLE and TNG100 simulations with respect to the observational evidence provided by SDSS spectra. It is also interesting to explore the fact that we find a higher fraction of Q galaxies and lower sSFR in TNG100 with respect to EAGLE,
however EAGLE produces slightly older average ages and shorter quenching timescales, suggesting earlier and more rapid quenching. This scenario is illustrated in Fig. 7, that shows the mass-weighted SFHs, as cumulative functions with stellar age, where blue, green and red data correspond to the IGv, mGV and uGV, respectively. The solid and dashed lines show the mass-weighted star formation history in TNG100 and EAGLE simulations, respectively.

The blue, green and red data points show results for lGV, mGV and uGV, respectively. The solid and dashed lines show the cumulative distribution.

The fact that EAGLE galaxies undergo quicker quenching but still feature higher SFRs shows the nuance and complication we face when trying to understand galaxy formation and evolution. Normally, a low sSFR, specially in the sense noted a strong dependence of quenching within the quiescent population. The slower quenching leads to younger stellar components in TNG100 than EAGLE, thus we find younger luminosity-weighted average ages for TNG100, \( t_{\text{fid}} = 2.98 \pm 0.08 \text{ Gyr} \), than EAGLE, \( t_{\text{fid}} = 3.77 \pm 0.33 \text{ Gyr} \), (Fig. 5). The rapid change in the quenched fraction of GV galaxies and the higher number of galaxies with zero SFR (Fig. 4) provides an explanation for the observed excess of Q GV galaxies in TNG100 (Fig. 3); with respect to SDSS and EAGLE. Furthermore, the number of galaxies with zero SFR increases as we go from IGV to the uGV. This occurs at stellar masses above \( \gtrsim 10^{10.5} M_\odot \), where the kinetic feedback is switched on, thus suggesting the excess of kinetic feedback at late times might be the reason for this behaviour. Note Nelson et al. (2018) also explore rejuvenation in TNG100, however this is prominent at high stellar mass, \( \gtrsim 10^{11} M_\odot \), beyond the stellar mass interval explored in our study.

5.3 Subgrid interpretation

We explore in this section the details of the subgrid physics implemented in the simulations that could give rise to the differences presented above. Given the mass range we are studying, a valid assumption is to consider AGN feedback as responsible for the mismatch. Previous work in the literature noted a strong dependence of quenching within the stellar mass range studied (Kewley et al. 2006; Croton et al. 2006; Hopkins et al. 2006). For galaxies with stellar mass lower than \( 10^{9} M_\odot \), EAGLE finds very low AGN activity of Q GV galaxies with respect to the observational constraints, but with subtle differences. We argue that this difference may be, partly, caused by the difference in the definition of the black hole seed mass and halo mass threshold. In EAGLE, the choice is \( 10^{5} h^{-1} M_\odot \) for the BH seed and \( 10^{10} h^{-1} M_\odot \) for the halo mass threshold, whereas TNG100 adopts values about 8 times higher in both cases. This increase in the TNG100 simulation is justified to mitigate slow early growth (Pillepich et al. 2018a), but it might also delay the onset of AGN feedback into a stage that removes all chances of a later stage of star formation at the observed redshift (\( z = 0.1 \)), thus overproducing Q galaxies in the GV.

Fig. 8 shows the fraction of galaxies considered to be star forming (blue) or quiescent (red). Tab. 2 shows the value used to distinguish between star forming, log sSFR \( \gtrsim -11.0 \) and \( \gtrsim -11.2 \), and quiescent, log sSFR \( \leq -11.0 \) and \( \leq -11.2 \) for EAGLE and TNG100 galaxies, respectively. Note we apply the same selection criteria for SDSS data as their simulation counterpart. The solid, dashed and dotted lines show results for SDSS, TNG100 and EAGLE, respectively. From top to bottom, the panels represent the IGV, mGV and uGV, evolving from the part of the GV closest to the BC towards the RS. This figure, along with Fig. 7 allows us to provide an explanation for our results. Both EAGLE and TNG100 show an overall agreement with respect to their SDSS counterpart, where there is an increase (decrease) in GV quiescent (SF) galaxies with stellar mass. While at low stellar mass, \( \lesssim 10^{10.5} M_\odot \), we find good agreement between simulations and SDSS, at higher stellar mass, \( \gtrsim 10^{10.5} M_\odot \), we find a higher fraction of quiescent galaxies. The mismatch of the quenched population yields a fractional difference of 0.44 and 0.62, for EAGLE and TNG100, respectively. Note the TNG100 simulations also produce a greater rate of increase in the quiescent population than EAGLE.

The slower quenching leads to younger stellar components in TNG100 than EAGLE, thus we find younger luminosity-weighted average ages for TNG100, \( t_{\text{fid}} = 2.98 \pm 0.08 \text{ Gyr} \), than EAGLE, \( t_{\text{fid}} = 3.77 \pm 0.33 \text{ Gyr} \), (Fig. 5). The rapid change in the quenched fraction of GV galaxies and the higher number of galaxies with zero SFR (Fig. 4) provides an explanation for the observed excess of Q GV galaxies in TNG100 (Fig. 3); with respect to SDSS and EAGLE. Furthermore, the number of galaxies with zero SFR increases as we go from IGV to the uGV. This occurs at stellar masses above \( \gtrsim 10^{10.5} M_\odot \), where the kinetic feedback is switched on, thus suggesting the excess of kinetic feedback at late times might be the reason for this behaviour. Note Nelson et al. (2018) also explore rejuvenation in TNG100, however this is prominent at high stellar mass, \( \gtrsim 10^{11} M_\odot \), beyond the stellar mass interval explored in our study.
...and most quenching is due to stellar feedback or environment (see, e.g., Crain et al. 2015). Above $10^{9.7} M_\odot$ – corresponding to the mass range probed in this study – EAGLE galaxies quench star formation via AGN feedback (Bower et al. 2017). Note even within this regime, EAGLE has two distinct intervals where AGN feedback quenches in different ways. If the stellar mass is $10^{9.7} < M_*/M_\odot < 10^{10.3}$, EAGLE mimics radio-mode feedback, while more massive galaxies undergo a rapid increase in the super-massive black hole accretion rate (Wright et al. 2019). This coincides with the same mass regime where we see a drastic increase in the fraction of Q galaxies, with an excess over the observed constraint. Therefore we can assume the increase in SMBH accretion rate, while self-regulated, could be too rapid.

In TNG100, the black hole mass and the Eddington ratio has a strong dependence on how much energy is injected back onto the environment and in which form. In TNG100, primarily the AGN feedback, particularly the kinetic BH-driven winds, have been demonstrated to suppress star formation above $10^{10.9} M_\odot$ (Weinberger et al. 2017; Nelson et al. 2018; Terrazas et al. 2020; Davies et al. 2020; Donnari et al. 2020b), hence the choices in subgrid physics of SMBH seed, growth or feedback are probably the cause of the discrepancies we have seen in this analysis. Specifically at the massive end, $> 10^{10.8} M_\odot$, we find a substantial difference between SDSS and TNG100, where the simulation switches from predominantly thermal feedback:

$$\Delta E_{\text{therm}} = \epsilon_{\text{therm}} M_{\text{BH}} c^2,$$

(10)

to kinetic feedback:

$$\Delta E_{\text{kin}} = \epsilon_{\text{kin}} M_{\text{BH}} c^2,$$

(11)

thus injecting a higher amount of energy onto the interstellar medium (ISM) (Weinberger et al. 2017). Therefore we suspect that the kinetic feedback, along with the delay in SMBH growth imposed by the higher thresholds in the choice of seed mass, may be responsible for the over-quenching found in GV galaxies (see also Li et al. 2019, who found a similar discrepancy). At fixed stellar mass, the black hole mass in TNG100 is greater than the estimates derived from observations (Li et al. 2019), hence we should expect the energy output, as shown in Eq. 11, to be overestimated in this simulation. The overmassive black holes could also lead to the overquenching in the quasar mode as well, as more energy is injected to the surrounding ISM, thus yielding a higher fraction of Q galaxies in the IGV, mGV and uGV. Moreover, Terrazas et al. (2020) found a sharp decline in the SFR at $M_* \sim 10^{10.5} M_\odot$, further supporting this assumption. Note this sharp decline in star formation could mean TNG100 has a more rapid quenching timescale, compared to both EAGLE and SDSS. However the bulk of the quenched galaxies might reside already in the RS, rather than the GV. At the same time, the dependence of the quenched fraction with stellar mass in TNG100 matches the SDSS data, when we use a different definition to classify star-forming and quiescent galaxies in the general population (Donnari et al. 2020a).

6 CONCLUSIONS

We make use of a recent definition of GV galaxies based on 4000Å break strength, which uses SDSS classic spectra, and a probabilistic approach to separate BC, GV and RS (see A19, A20 for more details), to explore two of the latest, state-of-the-art cosmological hydrodynamical simulations: EAGLE, (RefL0100N1504), and IllustrisTNG (TNG100-1). We model the simulated galaxies to obtain a set of mock spectra without accounting for the effects of dust and by including the contribution from all the stellar particles in a cylinder within 3 kpc galacto-centric radius to mimic the 3 arcsec (diameter) SDSS fibre aperture. We make use of the E-MILES population synthesis models (Vazdekis et al. 2016) to create the spectra. The study projects the simulated data on the observationally motivated plane, comparing these simulations with high quality spectroscopic data from the classic SDSS survey (e.g. Abolfathi et al. 2018). The galaxy samples need to be homogenised to avoid selection biases. Although we homogenise in the stellar mass range $9 < \log M_*/M_\odot < 12$, our analysis focuses on a narrower region, 10.03 $< \log M_*/M_\odot < 11.03$, which is the stellar mass range obtained by converting velocity dispersion to stellar mass, see A19 and A20. The velocity dispersion ranges from 70 – 250 km/s. At higher velocity dispersion the analysis would be strongly limited by Poisson noise. Regarding nebular activity, that allows us to classify the observed spectra, we define a number of criteria based on the sSFR and the Eddington ratio of SMBH growth to separate the simulated galaxies into Seyfert AGN, LINER, Q or SF. We use the global fractions of the homogenised observational sample to define the constraints, and focus on differences in
the trends with respect to stellar mass. Despite the different subgrid physics implemented in these two simulations, we find similar constraints in EAGLE and TNG100 (Tab. 2).

A reasonable agreement is found in general between observations and simulations, where the simulations are able to produce the bimodal distribution on the $D_n(4000)$ vs stellar mass plane. Both EAGLE and TNG100 correctly produce the location of the BC. However EAGLE features a RS that appears too high regarding the 4000Å break strength (by $\Delta D_n(4000) \sim +0.1$ dex), while TNG100 produces a RS with an even higher discrepancy ($\Delta D_n(4000) \sim +0.2$ dex). Furthermore, as previously noted, both simulations produce a RS with a shallower gradient compared to SDSS constraints, with TNG100 producing the flattest RS (Fig. 2). Such a disagreement in the RS is expected to produce a similar mismatch in the GV, the main focus of our analysis. Due to the sparsity of the GV in optical bands, we only focus on 10.82% EAGLE and 4.91% IllustrisTNG galaxies of the homogenised samples. Even so, the analysis yields large constraining capabilities to improve the simulations. We emphasize that the analysis of GV galaxies provides a fundamental constraint beyond the zeroth order constraints such as the galaxy stellar mass function, the Tully-Fisher relation, or the mass-metallicity relation, and focuses narrowly on the subgrid physics that regulates the SFH of galaxies via feedback.

Finally, at the massive end, $10^{10.5-11.0} M_{\odot}$, EAGLE GV galaxies undergo more rapid quenching compared to TNG100 (Fig. 7). Both simulations show signs of overquenching, where, at higher stellar mass $10^{10.5-11.0} M_{\odot}$, there is a higher quenched fraction with respect to SDSS. While both over-produce quenched galaxies, we find a larger discrepancy between TNG100 and SDSS, up to 0.62 (fractional excess), compared to EAGLE and SDSS, with a difference up to 0.44 (Fig. 8). This shows that while TNG100 galaxies tend to quench at later times than EAGLE, they also quench more efficiently on the GV. This suggests that EAGLE allows for later episodes of star formation, when measured using the instantaneous SFR, which gives results that appear to be more in agreement with constraints from the SDSS sample (Fig. 4). Multiple studies have noted the strong quenching nature of the kinetic black hole-driven winds (Terrazas et al. 2020; Davies et al. 2020), therefore we ascribe this difference to AGN feedback, which sterilise the ISM of TNG100 galaxies, resulting in an excess of quiescent galaxies on the GV. This paper illustrates the power of the green valley as a key laboratory where feedback prescriptions can be put to the test on state-of-the-art simulations of galaxy formation.

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DATA AVAILABILITY

This project is fully based on publicly available data from SDSS, EAGLE, and IllustrisTNG project. The data used for this project are available on request.

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APPENDIX A: COMPARING HOMOGENISED SAMPLES

Since the homogenisation procedure results in different SDSS subsamples when comparing EAGLE and TNG100 simulations, we want to assess the level of overlap between these two pairs of samples. In each pair (i.e. either SDSS-EAGLE or SDSS-TNG100) we follow the methodology laid out in A19 and A20 to define the uGV, mGV and IGV subsamples within each stellar mass bin - defined as the lower-, mid-, and upper-GV, respectively, which are meant to map three regions, defined by splitting GV into three terciles of the 4000 Å break strength for individual stellar mass bins, that follow the transition from BC into RS. In each subset, for instance the mid green valley, mGV within the 10.30-10.51 (log) stellar mass bin, we cross-correlate the SDSS-EAGLE and SDSS-TNG100, and identify the number of galaxies in both sets, expressing this number as a fraction with respect to the total in each bin. Fig. A1 shows a comparison of these fractions as a function of stellar mass, where the blue, green and red data points refer to IGV, mGV and uGV, respectively. The top and bottom panels show the fractional match for EAGLE and TNG100, respectively.

The error bars have been obtained assuming Poisson noise in the count of overlapping galaxies. The fractional match decreases with increasing stellar mass in all subsets. This is due to (i) the independent homogenisation of EAGLE and TNG100, and (ii) the selection of GV galaxies is probability-based, therefore we do not find a unique solution, and is subject to Poisson noise. The difference in fractional match shown in Fig. A1 will lead to differences in the retrieved SDSS parameters for EAGLE and TNG100 sample, as seen below, specially in Section 4.4 and 4.5.