Interacting galaxies in the IllustrisTNG simulations - III: (the rarity of) quenching in post-merger galaxies.

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1 INTRODUCTION

Galaxies show bimodal distributions in fundamental properties, such as colours and structure, both locally (e.g., Strateva et al. 2001; Blanton et al. 2003; Baldry et al. 2004; Kauffmann et al. 2003) and out to at least $z \sim 2$, (e.g., Bell et al. 2004; Willmer et al. 2006; Whitaker et al. 2011; Wuyts et al. 2011; Bell et al. 2012; Cheung et al. 2012; Muzzin et al. 2013). Moreover, there is strong evidence that there is continuous growth in the number density and stellar mass of the red and passively evolving early-type population from $z \sim 1$ to the present (e.g., Bell et al. 2004; Faber et al. 2007; Pozzetti et al. 2010; Ilbert et al. 2013). This implies that a large fraction of late-type galaxies convert into early-types, due to the suppression of star formation (hereafter quenching) that accompanies their change in morphologies (e.g., Drory et al. 2004; Faber et al. 2007; Peng et al. 2010; Pozzetti et al. 2010; Tacchella et al. 2015; Woo et al. 2015). It is also thought that these transitional scenarios depend on the environment in which the galaxies are located (e.g., Goto et al. 2003; Balogh et al. 2004; Peng et al. 2010; Woo et al. 2017).

Many mechanisms have been proposed for the physical origin of star formation quenching (see for example the review by Somerville & Davé 2015), including (i) the heating of the inner halo gas by cosmological accretion via ram pressure drag and local shocks (i.e. gravitational quenching, Dekel & Birnboim 2008), (ii) the stability of discs against fragmentation to bound clumps (i.e. morphological quenching, Martig et al. 2009; Gensior et al. 2020; Gensior & Kruijssen 2020), (iii) the removal of the gas supply due to active galactic nuclei (AGN) activity, and/or stellar feedback (e.g., Di Matteo et al. 2005; Bower et al. 2006; Sijacki et al. 2007; Cattaneo et al. 2009; Fabian 2012), (iv) the interaction between the galaxy gas with the intracluster medium in high density environments (i.e. environmental or satellite quenching, Gunn & Gott 1972; Larson et al. 1980; Moore et al. 1998; Bekki 2009; Peng et al. 2010, 2012), and (v) the interaction with other galaxies (i.e. major mergers, Di Matteo et al. 2005; Springel et al. 2005a,c; Croton et al. 2006; Hopkins et al. 2008; Somerville et al. 2008). Quenching processes tend to be classified as internal or environmental depending on whether they originated...
within a galaxy or if they are triggered by the influence of the external factors (e.g. the intra-cluster medium). These processes are not mutually exclusive, and they could in principle take place together on different timescales.

AGN quenching is one of the most popularly invoked mechanisms for quenching star formation, but it remains controversial. On the one hand, several observational studies have supported the thesis that AGN feedback should be able to remove gas from the galactic reservoir, eventually leading to quenching (e.g., Kaviraj et al. 2007; Fabian et al. 2013; Cimatti et al. 2013). The link between AGN and quenching is also supported by the theoretical results obtained combining N-body simulations of dark matter halo evolution (Springel et al. 2005b; Boylan-Kolchin et al. 2009) with semi-analytic models for galaxy formation (White & Frenk 1991; Springel et al. 2005b; Lu et al. 2011; Benson 2012). On the other hand, there is a growing body of literature that finds that AGN have normal gas reservoirs, both in the atomic (e.g., Ellison et al. 2019), and molecular gas-phase (e.g., Shangguan et al. 2018, 2020; Koss et al. 2020; Jarvis et al. 2020), with the possible exception of gas depletions in the dwarf regime (Bradford et al. 2018; Ellison et al. 2019). The persistence of large gas reservoirs is at odds with the scenario of AGN driven feedback leading to quenching.

Since many models of galaxy interactions lead to AGN triggering, it has long been suggested that galaxy mergers could provide a major pathway for galaxy quenching (Di Matteo et al. 2005; Springel et al. 2005a,c; Croton et al. 2006; Hopkins et al. 2008; Somerville et al. 2008). Strong mechanical AGN feedback triggered by the inflow of gas at low angular momentum, could potentially drive out the gas from the galaxy. This halts the star formation, and hampers the replenishment of the galactic gas reservoir. At the same time, theory predicts strong morphological disturbances (e.g., Di Matteo et al. 2007) that should accompany the migration from the blue cloud to the red sequence (Mihos & Hernquist 1996; Hopkins et al. 2008; Somerville et al. 2008) consistent with observations that quenched galaxies tend to have spheroidal morphologies (e.g., the review by Conselice 2014).

Given the advances in simulations over the last decade, it is worth reviewing the predicted link between mergers, AGN triggering and quenching. Previous simulations that linked mergers to AGN activity tended to have very aggressive feedback recipes (e.g., Springel et al. 2005c; Bower et al. 2006; Khalatyan et al. 2008; Hopkins et al. 2008). However, we currently know from observations that the majority of interacting galaxies (i.e., mergers and pairs) in the local universe show a relatively modest enhancement in both star formation and AGN luminosity (Patton et al. 2005; Li et al. 2008; Ellison et al. 2008; Jogee et al. 2009; Scudder et al. 2012; Patton et al. 2013; Ellison et al. 2013; Rodighiero et al. 2015; Knapen et al. 2015; Ellison et al. 2019; Thorp et al. 2019; Patton et al. 2020). Both theoretical and observational studies agree on an increase of the major merger rate with redshift out to at least z ~ 1.5 (e.g. Lin et al. 2008; de Ravel et al. 2009; Lotz et al. 2011; López-Sanjuan et al. 2013; Rodríguez-Gomez et al. 2015), whilst minor mergers show little evolution with redshift (e.g. Lotz et al. 2011). However, there is no consensus on whether the contribution of galaxy mergers to star formation decreases with increasing redshift (e.g. Rodighiero et al. 2011; Wilson et al. 2019), or continue to produce enhanced star formation (e.g. Lin et al. 2007; Wong et al. 2011). Moreover, there has been no previous work to study the quenching statistics of mergers in a full cosmological setting. The work presented here investigates merger driven quenching in an unbiased statistical galaxy sample, using a modern AGN implementation offered by the IllustrisTNG simulations (Springel et al. 2017; Nelson et al. 2017; Pillepich et al. 2017b; Naiman et al. 2018; Marinacci et al. 2018; Nelson et al. 2019). We follow the evolution of simulated star-forming post-mergers within a realistic cosmological context. We then compare their evolution to that of non-post-merger galaxies with similar physical parameters and environment.

The paper is organised as follows: in Section 2, we introduce our methodology. In Section 3, we present the results quantifying the impact of galaxy mergers on star formation quenching. In Section 4 and Section 5, we discuss the effects of our methodology on the results. Finally, we summarise our work in Section 6.

2 DATA AND METHODS

2.1 The IllustrisTNG simulation suite

The work we present here is primarily aimed at quantifying the impact of galaxy mergers on star formation quenching. We identify galaxy post-mergers in the IllustrisTNG simulation suite (Nelson et al. 2019) to study the relationship between mergers and the interruption of star formation within a cosmological framework. The IllustrisTNG project includes a suite of large-box magnetohydrodynamical cosmological simulations in a ΛCDM Universe which provides an exquisite sample of galaxies spanning a variety of galaxy properties (e.g., mass, environment, star formation rate - SFR). Here we briefly summarise the main characteristics of the simulations. The simulations and physical model are introduced in detail in Marinacci et al. (2018); Naiman et al. (2018); Nelson et al. (2017); Pillepich et al. (2017b); Springel et al. (2017). IllustrisTNG (or TNG) is the descendant of the Illustris cosmological simulation (Vogelsberger et al. 2013; Vogelsberger et al. 2014) with an improved physical models and numerical scheme. Moreover, TNG introduces a number of additional features to obtain a better agreement with observational results. In this paper, we focus on TNG300-1, the highest resolution run for the publicly released volume of 302^3 cMpc^3. TNG300-1 offers the largest statistics, whilst still guaranteeing adequate numerical resolution. TNG300-1 has 2500^3 initial resolution elements, with dark matter and stellar mass resolutions of 5.9 × 10^7 M⊙ and 1.1 × 10^3 M⊙, respectively. The simulation runs from redshift 127 to the present day using the AREPO moving-mesh code (Springel 2010; Pakmor et al. 2016). The cosmological parameters used in IllustrisTNG are in accordance with Planck Collaboration et al. (2016) which is given by a matter density Ω_M,0 = 0.3089, baryon density Ω_b,0 = 0.0486, dark energy density Ω_Λ,0 = 0.6911, and a Hubble parameter h = 0.6774. For our purposes, it is relevant to introduce some features of the IllustrisTNG physical model:

(i) Star formation: star formation occurs in a pressurised, multi-phase interstellar medium following the Springel & Hernquist (2003) formalism. Gas particles whose density exceeds a threshold of ~ 0.1 cm^{-3} are “star-forming” and their gas is converted to stars stochastically following the Schmidt-Kennicutt law (Kennicutt 1998) assuming a Chabrier (2003) initial mass function (see Nelson et al. 2015; Pillepich et al. 2017a, for further details).

(ii) Black holes and AGN feedback: black holes are seeded with an initial mass of 1.18 × 10^7 M⊙ at the centres of the potential wells of haloes exceeding a threshold mass of 7.38 × 10^10 M⊙. Black holes can grow their mass either through (1) accretion following the modify Bondi-Hoyle scheme, or (2) mergers with other black holes. AGN feedback is directly related to the accretion rate onto the central black holes (E ∝ M_{BH}^2). At high accretion rates (i.e., quasar mode feedback), thermal energy is returned to the black hole’s environment, whereas at low accretion rates (i.e., radio mode feedback, or kinetic feedback), energy accumulates until it reaches an energy threshold,
then mechanical energy is instantaneously released along a random direction into the gas around the black hole (see Weinberger et al. 2017, for further details).

In the work presented here, each galaxy is parametrised by:

- **Galactic radius** ($R_{\text{gal}}$): we define a galaxy’s radius to be twice the stellar half mass radius.
- **Stellar mass** ($M_*$): the sum of the masses of all stellar particles contained within $R_{\text{gal}}$ from a galaxy’s centre (which is defined as the position at the minimum of the gravitational potential).
- **Gas mass** ($M_{\text{gas}}$): the gas mass is measured by summing the mass of all gas particles within $R_{\text{gal}}$ from the galaxy’s centre.
- **Black hole mass** ($M_{\text{BH}}$): is the mass of the supermassive black hole at the minimum of a galaxy’s potential well.
- **SFR**: this is the instantaneous star formation rate within $R_{\text{gal}}$. We use a metric based on the SFR to select and analyse the TNG post-merger galaxies. Specifically, we fit a redshift dependent star-forming main sequence (SFMS) to the TNG sample, and define quenched galaxies as those lying at least below $-3\sigma$ from the SFMS.
- **Cumulative kinetic feedback** ($\int E_{\text{kinetic}}dt$): in our analysis we use the total amount of kinetic AGN feedback energy injected into the gas surrounding the central black hole in the low accretion rate mode, accumulated over the entire lifetime of the black hole in the centre of the galaxy. During black hole mergers the cumulative kinetic energy is summed for the two merging components.
- **Potential** ($V(r_{\text{gas}})$): the gravitational potential energy experienced at the position of a gas cell ($r_{\text{gas}}$), representing the energy required to unbind the gas. $V(r_{\text{gas}})$ is used to calculate the total gravitational binding energy of the gas particles as in Terrazas et al. (2020):

$$E_{\text{binding}}(\leq R_{\text{gal}}) = \frac{1}{2} \sum_{r_{\text{gas}}} m_{\text{gas}} V(r_{\text{gas}}),$$

where the sum is extended to all the gas particles ($m_{\text{gas}}$) within $R_{\text{gal}}$. The total binding energy defines the amount of energy that is needed to void a galaxy of the gas within $R_{\text{gal}}$.

### 2.2 Star-forming post-mergers

We use the post-merger galaxy sample identified in Hani et al. (2020), wherein galaxy mergers are defined as nodes in the Sublink merger trees (Rodriguez-Gomez et al. 2015). Namely, we define a post-merger (or PM) in the snapshot immediately after the coalescence phase as the remnant of two interacting galaxies. Given the time resolution of the TNG snapshots, this approach identifies mergers within ~ 160 Myr after coalescence (i.e. the average time between successive snapshots at $z < 1$). Following Hani et al. (2020), our post-merger sample is restricted to those satisfying the following criteria:

- **$z \leq 1$:** we only follow the redshift evolution of post-mergers in the last ~ 8 Gyr.
- **$M_* \geq 10^{10} M_\odot$:** in IllustrisTNG, galaxies are well resolved above $M_* \geq 10^9 M_\odot$ (i.e. 90 stellar particles per galaxy at the resolution of TNG 300-1). Therefore, our criterion ensures a complete sample of post-mergers with mass ratio (secondary/primary) larger than 1:10.
- **The mass ratio (secondary/primary, $\mu$) in the range $0.1 \leq \mu \leq 1$:** We prevent numerical stripping issues by adopting the maximum...
stellar mass over the past 0.5 Gyr for all mass ratio calculations following Patton et al. (2020).

- The relative separation from the nearest neighbour \( r_{\text{sep}} \geq 2 \).

The parameter \( r_{\text{sep}} \) is defined by Patton et al. (2020) as:

\[
r_{\text{sep}} = \frac{r}{R_{1/2}^{\text{host}} + R_{1/2}^{\text{comp}}},
\]

where \( r \) is the 3D separation between the centres of the host (i.e. post-merger in our case) and its closest neighbour, and \( R_{1/2}^{\text{host}} \) and \( R_{1/2}^{\text{comp}} \) are the stellar half mass radii of the post-merger and the closest neighbour, respectively. The criterion \( r_{\text{sep}} \geq 2 \) avoids post-mergers that are undergoing further close interactions which could interfere with the descendant’s evolution.

- The time elapsed since the previous merger must be larger than 2 Gyr, i.e. we exclude post-mergers that have experienced another merger within the last 2 Gyr. This criterion reinforces our purpose of isolating the effect of a single merger on galaxy evolution.

- Galaxies must be star-forming when first selected (in order that we can later observe them quenching). In practice this is implemented by requiring SFRs higher than \(-1\sigma\) from the star-forming main sequence best-fit. Unlike the original sample by Hani et al. (2020) which include passive post-mergers, in the work presented here, we are interested in star-forming post-mergers in order that we may track whether the merger causes them to quench. Given the arbitrary choice of our SFR threshold value, we investigate the impact of imposing different limits to separate quenched and star-forming galaxies in Section 3.

Our selection criteria yield a sample of 3472 star-forming post-mergers with stellar masses \( 10^{10} \leq M_*/M_\odot \leq 10^{10.8} \), at redshift \( z \leq 1 \). We note that \( \leq 10\% \) of post-mergers in our sample have a mass ratio \( \mu \geq 0.5 \), therefore the results we present in this paper are statistically dominated by minor mergers (\( \mu < 0.3 \)).

### 2.3 Statistical control sample

We are interested in investigating the link between galaxy mergers and the quenching of star formation. We quantify the impact of galaxy mergers on the quenching of star formation using an observational approach that consists of identifying control galaxies that are matched to each post-merger galaxy in redshift, stellar mass, local density, and isolation (e.g., Ellison et al. 2013; Patton et al. 2013). In this section, we describe the steps of creating the control sample.

We implement an adaptation of the matching procedure used in Patton et al. (2016) and Patton et al. (2020) to select statistical controls (CTRL) for galaxies in our sample (see also Hani et al. 2020). For each star-forming post-merger, we first define a star-forming control pool (i.e. non-post-merger galaxies with SFR higher than \(-1\sigma\) from the SFMS), in the same snapshot (i.e. same redshift), with \( M_* \geq 10^{10} M_\odot \), and a relative separation from the nearest neighbour \( r_{\text{sep}} \geq 2 \). We then reject galaxies that have experienced a merger (\( \mu \geq 0.1 \)) within 2 Gyr (i.e. \( t_{\text{PM}} \geq 2 \) Gyr). Then, for each post-merger in our sample, we identify the control galaxies that match the post-merger properties as follows:

- \( \log(M_*) \) within a tolerance of 0.05 dex.
- The environmental parameters \( N_2 \) and \( r_1 \), defined by Patton et al. (2016) as the number of neighbours within a radius of 2 Mpc (i.e. local density), and the distance to the nearest neighbour with \( M_* \geq 0.1 \times M_{*,\text{host}} \) (i.e. isolation), respectively, within a tolerance of 10%.
- \( \log(\text{SFR}) \) within a tolerance of 0.01 dex.
- \( \log(M_{\text{BH}}) \) within a tolerance of 0.05 dex. By matching in black hole mass we prevent possible bias related to the AGN feedback model (see Section 3.3). In Section 4, we discuss how this requirement affects our results.

If more than one control is found for a given post-merger, we follow the weighting scheme of Patton et al. (2016) to select up to 5 control galaxies. We then define the post-merger’s control galaxy as the single best control galaxy that shares the most number of subsequent snapshots with the post-merger’s descendants whilst maintaining environmental parameters within 40% of the descendants’. Figure 1 shows the distributions of redshift, \( M_* \), \( N_2 \), \( r_1 \), SFR, and \( M_{\text{BH}} \) for the star-forming post-mergers and their control galaxies. The matching process offers a control population that well matches our post-merger sample in all the aforementioned parameters.

Once the control galaxy sample has been identified, we follow the evolution of the SFR in descendants of post-mergers and controls forward in time through the simulation. For each galaxy, we evaluate the relative relevance of star formation by calculating, on a logarithmic scale in the SFR-M* plane, the vertical offset between its SFR and the SFMS (hereafter, ASFR). Then, we define galaxies to be quenched...
when their $\Delta \text{SFR}$ drops below $-0.9$ dex (i.e., a deviation of $<-3\sigma$ from the SFMS). Figure 2 shows the evolution of $\Delta \text{SFR}$ as a function of time since merger ($t_{\text{PM}}$) for three example post-mergers and their controls. The top panel shows a post-merger that remains star-forming after coalescence, while its matched control galaxy quenches around $2.4$ Gyr after $t_{\text{PM}}=0$. The central panel shows a post-merger that quenches within $500$ Myr after the merger. Finally, the bottom panel depicts a post-merger that remains star-forming up to $1$ Gyr after the merger, then quenches, though not permanently (i.e., it experiences some episodes of low SFR). The control galaxy, instead, keeps forming stars for the entire period over which we follow its evolution (i.e., at $z = 0$).

We quantify the effects of mergers on star formation quenching using two metrics: (i) the fraction of post-merger descendants with quenched star formation, and (ii) the number of quenched post-mergers (#Q$_{\text{PM}}$) normalized by the number of quenched controls (#Q$^{\text{CTRL}}$) in 160 Myr intervals ($Q_{\text{excess}}$):

$$Q_{\text{excess}} = \frac{#Q_{\text{PM}}}{#Q^{\text{CTRL}}}.$$  

$Q_{\text{excess}}$ measures the relative tendency of mergers to experience quenching compared to other evolutionary processes which are accounted for in the controls. Taken together, these two metrics allow us to quantify both the absolute rate of quenching in post-mergers, as well as assessing whether quenching happens more frequently in post-mergers that in controls.

3 RESULTS AND DISCUSSION

3.1 Quenching in descendants of star-forming post-mergers

In this section, we analyse the impact of mergers on the interruption of star formation during the early stages after the coalescence phase. We apply the methods defined in Section 2.3 to quantify differences between the evolution of star-forming post-mergers and matched control galaxies that have not experienced any merger in the past $2$ Gyr. The top panel in Figure 3 shows the evolution of the total number of post-mergers and their associated controls as a function of time elapsed since coalescence ($t_{\text{PM}}$), in bins of $160$ Myr. The black dotted curve represents the total number of post-mergers (and, by definition, an equal number of control galaxies) in each bin. The total number of galaxies decreases with time for three reasons: (1) the merger rate increases with increasing redshift (e.g., Lin et al. 2008; Lotz et al. 2011), (2) we analyse the post-mergers in the range $0 \leq z \leq 1$, therefore the maximum time after the merger that we can analyse decreases as the snapshots approach $z = 0$, and (3) we only follow the evolution of a given post-merger up to the moment when its descendant, or the descendant of its control galaxy, experiences a new close encounter or a merger. We also interrupt tracing the evolution when the match between the environmental parameters (i.e. N2 and r1) exceeds a tolerance of $40\%$. We divide the post-merger population, at any given time, into those that are star-forming and those that are quenched (recalling that we require the post-mergers to be star-forming at $t_{\text{PM}} = 0$). Figure 3 shows that, in the early phase after the merger, the vast majority of post-mergers remain star-forming, with only a small fraction of them becoming quenched (e.g., $\sim 50/3500$ at $t_{\text{PM}} = 125$ Myr). The control sample shows a qualitatively similar behaviour but with an even smaller number of quenched systems at $t_{\text{PM}} < 1$ Gyr. The bottom panel of Figure 3 provides a complementary perspective by showing these results as percentages of each population. We find that only $1.4\%$ of the star-forming post-mergers quench their star formation within $125$ Myr following coalescence, compared to $0.7\%$ for the controls. The fraction of quenched post-mergers rises to $\sim 5\%$ at $t_{\text{PM}} = 500$ Myr ($3.5\%$ for the controls) and $16\%$ within $1$ Gyr from the merger ($12.5\%$ for the controls). After $1.5$ Gyr the fraction of quenched post-mergers and control galaxies grow together with no appreciable distinction. We conclude from Figure 3 that the process of coalescence does not result in widespread quenching of the post-merger population. Nonetheless, the quenched fraction is slightly larger (an effect we quantify shortly) in the post-merger sample compared to the controls at $t_{\text{PM}} \leq 1.5$ Gyr, which may be indicative of the subtle effects of galaxy mergers on the quenching of merger descendants, which provide a low level facilitation of the quenching process.

In Figure 4, we quantify the enhancement in quenched post-mergers relative to their controls as the ratio of quenched post-mergers to quenched control galaxies. It is important to stress that $t_{\text{PM}} = 0$ is not displayed in Figure 4. By construction, we selected star-forming post-mergers and star-forming control galaxies, therefore there are $0$ quenched post-mergers and control galaxies at $t_{\text{PM}} = 0$. Around $150$ Myr after coalescence, we find that post-mergers are quenched with an excess of $1.83 \pm 0.47$ compared to their controls which have not experienced a recent merger (within the past $2$ Gyr). The error is quantified as the propagation of the Poissonian $1\sigma$ error of the ratio in Equation 3. The excess is confirmed at a

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1 When we express the time evolution of control galaxies in terms of $t_{\text{PM}}$, we measure the time relative to their matched post-mergers.
The ratio between the number of quenched post-mergers and quenched control galaxies as a function of the time elapsed since coalescence $t_{PM}$. The shaded contours represent the error, that is quantified as the propagation of the Poissonian 1σ error of the ratio. The figure demonstrates that post-mergers show an excess of quenched galaxies, relative to expectations from the control of up to a factor $\sim 2$. The excess of quenched galaxies persists for approximately 1.5 Gyr after the merger.

The significance level of $1.8\sigma$, with respect to $\#Q_{PM}/\#Q_{CTRL} = 1$. We find that the excess is larger in the early post-merger phase when the mergers’ effects are stronger (e.g., Hani et al. 2020), and then it decreases steadily towards $\#Q_{PM}/\#Q_{CTRL} = 1$. Beyond 1.5 Gyr after the merger, the number of quenched post-mergers becomes statistically indistinguishable from that of the control sample. We speculate that this short term enhancement of quenched post-mergers is the result of the merger expediting quenching in a system that was already close to achieving the conditions necessary for halting star formation (i.e. a critical AGN feedback). We return to this in Section 3.3.

In order to test whether our results presented in Figures 3 and 4 depend on our definition of quenched and star-forming galaxies, we investigate the impact of different SFR thresholds. Recall that since we find that the scatter around the SFMS is of $\sim 0.3$ dex at any given snapshot (in accordance with observational results), our fiducial threshold for labelling a galaxy as quenched is $\Delta SFR < -0.9$ to be quenched (i.e. below $-3\sigma$ from the SFMS). In TNG this threshold corresponds to a specific SFR (i.e. $\log_{10}$ SFR/$M_\odot$) of about $-11$ yr$^{-1}$, a limit often used in observational studies to separate passive galaxies from star-forming ones (e.g., Ilbert et al. 2010, 2013; Pozzetti et al. 2010). We re-run our analysis by applying both less conservative thresholds ($-2\sigma$ from the SFMS) and more conservative ones ($-4\sigma$ and $-5\sigma$ from the SFMS), and we do not find a significant difference in the main result presented in this section.

In the next two sub-sections, we will explore the properties of the post-mergers that do/do not quench. In order to distinguish a quenching event that can plausibly be linked directly to the merger, we re-define the quenched post-merger sample as those galaxies which quench within 0.5 Gyr after coalescence (171 galaxies). I.e. we remove from the $Q_{PM}$ sample the 589 post-mergers that quench on timescales longer than 0.5 Gyr. Since none of the control galaxies have experienced a significant merger within at least 2 Gyr (by definition), all of the quenched controls are retained in the $Q_{CTRL}$ sample (772 galaxies). Thus, the $Q_{PM}$ and $Q_{CTRL}$ samples represent galaxies that have/have not quenched as the result of a recent merger. The star-forming samples ($SF_{PM}$ and $SF_{CTRL}$) also remain unchanged and contain 2114 and 2102 galaxies, respectively. These are the samples used in the following sub-sections.

### 3.2 Gas evolution in TNG post-mergers and control galaxies

Altering the absolute gas content, or its spatial distribution, is a possible mechanism for driving quenching. In the literature, processes that remove gas from the reservoir of star-forming galaxies are described as ejective feedback, while those that slow down the cooling of gas or halt gas inflow from the halos surrounding galaxies are described as a preventive feedback (e.g., Somerville & Davé 2015). In practice, quenching could result from both types of feedback. In this section, we explore the evolution of the amount of gas in the reservoir of TNG post-mergers, to understand what kind of feedback leads to the quenching of star-formation. Moreover, we explore whether the process(es) that drive quenching are the same in the quenched post-mergers (i.e. $Q_{PM}$) and quenched control galaxies (i.e. $Q_{CTRL}$).

To analyse the nature of the feedback responsible for quenching in post-merger galaxies, we start by studying the evolution of gas in quenched post-merger galaxies and in the other three samples. In Figure 5 we show the distribution of the amount of gas at $t_{PM} = 0$ in quenched post-mergers ($Q_{PM}$), quenched control galaxies ($Q_{CTRL}$), star-forming post-mergers ($SF_{PM}$) and star-forming control galaxies ($SF_{CTRL}$). At $t_{PM} = 0$, the four sub-samples have similar gas masses between $10^{9.4} M_\odot$ and $10^{10.5} M_\odot$, with over 50% of galaxies possessing a gas mass larger than $10^{9.95} M_\odot$.

We quantify the fractional change in gas mass between $t_{PM} = 0$ (or $t_0$) and the time at which a galaxy quenches ($t_Q$) as follows:

$$\Delta[M_{\text{gas}}] = \frac{M_{\text{gas}}(t_Q) - M_{\text{gas}}(t_0)}{|M_{\text{gas}}(t_0)|} \times 100.$$  \hspace{1cm} (4)

Since we select the $Q_{CTRL}$ sub-sample without any constraints on

![Figure 4](https://example.com/figure4.png)

**Figure 4.** The ratio between the number of quenched post-mergers and quenched control galaxies as a function of the time elapsed since coalescence $t_{PM}$. The shaded contours represent the error, that is quantified as the propagation of the Poissonian 1σ error of the ratio. The figure demonstrates that post-mergers show an excess of quenched galaxies, relative to expectations from the control of up to a factor $\sim 2$. The excess of quenched galaxies persists for approximately 1.5 Gyr after the merger.

![Figure 5](https://example.com/figure5.png)

**Figure 5.** Distributions of the gas mass at $t_{PM} = 0$. The post-mergers are represented by filled histograms: red for post-mergers that will quench within 500 Myr after coalescence ($Q_{PM}$ galaxies), and blue for post-mergers that keep forming stars at least 500 Myr after coalescence ($SF_{PM}$ galaxies). Control galaxies are represented by the dashed open histograms: red for control galaxies that will quench ($Q_{CTRL}$ galaxies), and blue for control galaxies that keep forming stars ($SF_{CTRL}$). The vertical coloured ticks around the bottom/centre of the distributions indicate the median of the respective distributions. The figure shows that, at $t_{PM} = 0$, our four populations ($Q_{PM}$, $SF_{PM}$, $Q_{CTRL}$, and $SF_{CTRL}$) have very similar distributions of gas.
the time of the quenching (see Section 3.1), several QCTRL galaxies quench on very long (∼ Gyr) timescales. Therefore, we calculate Δ%[Mgas] for the QCTRL sample relative to their gas mass ∼ 500Myr before they quench which is consistent with the timescale used for comparison for the post-merger sample. For the SFPM (and SFCTRL), we instead evaluate Δ%[Mgas] at the third snapshot after coalescence (i.e. ∼ 500Myr). The red coloured histogram in Figure 6 shows the Δ%[Mgas] distributions for the quenched post-merger galaxies (QPM). We find that all QPM galaxies have at least 25% less gas than their initial amount. However, 68% of them between the 16th and 84th percentile) experienced a much larger gas removal in the range between 60 – 92% and a median loss of 82% of the initial gas mass. The distribution of quenched post-merger galaxies shows remarkable similarity with that of the quenched control galaxies sample (red dashed histogram), thus suggesting that quenching is not special in post-mergers, and that it is characterized by gas loss in both post-mergers and controls. Figure 6 also shows the gas percentage change of the star-forming post-merger population (SFPM, blue colour histogram) and star-forming control population (SFCTRL, blue dashed histogram). These two star-forming sub-samples show distributions of Δ%[Mgas] different from those of the quenched galaxies: the median values for SFPM and SFCTRL galaxies are Δ%[Mgas] = −25% and −10%, respectively, and almost 25% of SFPM and 35% of SFCTRL galaxies have even accreted gas mass (Δ%[Mgas] > 0) with respect to the initial amounts.

Possible reasons for the decline in the measured gas mass in galaxies include: (1) conversion of gas into stars, and (2) the gas has been moved beyond Rgal. Considering the case of gas conversion into stars, this would require converting ∼ 8 × 10^9 M_☉ of gas into stars in about 500 Myr, equivalent to a steady SFR ≥ 15 M_☉/yr. Although post-merger galaxies show particularly enhanced star formation activity, their star-burst phase lasts for only some tens Myr after coalescence and then their SFR drops exponentially to a more typical star-forming level (e.g., Hani et al. 2020). Figure 7 shows the stellar mass growth distributions in our four sub-samples, measured in the same interval of time as for Figure 6. In the interval of time between the merger and quenching, the stellar mass in quenched post-merger galaxies increases, on average, by ∼ 10^{8.7} M_☉, with a maximum of ∼ 10^{9.3} M_☉. This amount of new stellar mass is far lower than the measured loss in gas mass. For example, we find that quenched post-mergers that show an increment in stellar mass of ∼ 10^{8.7} M_☉, have experienced a gas loss in the range 10^{9.5} – 10^{10.1} M_☉ (i.e. 16th – 84th percentiles), with a median gas loss of 10^{9.8} M_☉.

We do not find a significant difference between quenched post-mergers and quenched control galaxies. Thus, we can rule out the conversion into stars as a cause of the observed reduction of gas in quenched galaxies, which instead can be only explained by gas ejected from the galaxy beyond Rgal. We also find that 70.8 ± 8.4% of quenched post-merger galaxies remain quenched for the rest of the simulation (i.e. up to z= 0), 22.8 ± 4% of them exhibit only sporadic episodes of low star formation rates and only around 6.4 ± 2% of the quenched post-merger galaxies rejuvenate. These numbers are in accordance with the evolution of the quenched control population, with 72.4 ± 4% permanently quenched, 15.8 ± 1.5% that show some episodes of low star formation, and 11.8 ± 1.3% which return to the star-forming main sequence. The aforementioned results suggest that the the mechanism responsible for the gas removal must also be responsible for preventive feedback, which would explain the lack of rejuvenation.

We showed earlier in this section that the star-forming post-merger and control populations experience less gas mass loss than quenched post-merger and control galaxies (see Figure 6), therefore, this would require converting ∼ 1 – 2 × 10^9 M_☉ of gas into stars in about 500 Myr. Figure 7 reveals that ∼ 49.5% of star-forming post-mergers and ∼ 60% of star-forming control galaxies have increased their stellar mass of at least 1 × 10^9 M_☉ over 500 Myr, an amount consistent with the measured gas loss.

In this section, we showed that both quenched post-merger and control galaxies show high rates of gas loss and a high fraction of...
permanent quenching. This common behaviour supports a scenario where the vast majority of both quenched post-mergers and quenched control galaxies are quenched because of a common feedback process that ejects the gas out of galaxies and prevents its further accretion by either supplying kinetic energy to the remaining medium or by increasing the entropy of the ejected gas and prolonging its cooling time (see Zinger et al. 2020). In the next section, we focus on the quenching mechanism in the quenched post-merger population and we compare the outcome with that of the quenched control galaxies, in order to understand the origin of the excess of quenched post-mergers in the early times after the coalescence phase.

3.3 The impact of AGN feedback

In the previous section, we showed that gas loss is the cause of quenching in post-merger galaxies, as well as controls, which suggests that ejective quenching mechanisms are responsible for the gas loss in both samples. In this section, we explore the possibility that different mechanisms are responsible for the quenching in the post-mergers and control quenched galaxies. In Section 2.1 we briefly described the AGN feedback implemented in TNG model. To recap, the TNG AGN model feedback employs either pure kinetic feedback at low accretion rates, or thermal feedback at high accretion rates. This scheme is in accordance with the two modes of activity in observed AGNs (e.g., Crenshaw et al. 2010; Villar-Martín et al. 2011; Woo et al. 2016; for the high accretion mode, and Fabian 2012; McNamara & Nulsen 2007, for the low accretion mode), with improved agreement with the observational results regarding co-evolution of galaxies and black-holes (Weinberger et al. 2017, 2018). At high accretion rates, the TNG model injects pure thermal energy into the gas surrounding the black hole. However, Weinberger et al. (2017) show that such energy does not efficiently couple with the gas, resulting in almost unaltered thermodynamics of the TNG gas cells, with no or insufficient impact on the cooling/heating functions and, therefore, on the star formation in TNG galaxies (Weinberger et al. 2017; Terrazas et al. 2020). To simulate the feedback at low accretion rates, instead, TNG uses a kinetic wind model. The energy accumulates proportionally to the accretion rate until a threshold amount is reached. Then, the kinetic energy is released impulsively into the gas surrounding the black hole in a random direction (Weinberger et al. 2017).

Studies of quenching in IllustrisTNG (Weinberger et al. 2017; Nelson et al. 2017; Terrazas et al. 2020) reveal that only the kinetic mode of AGN feedback offers the necessary conditions to suppress the star formation in TNG galaxies with $M_* \geq 10^{10} M_\odot$, by pushing gas away from the galaxy. Moreover, Terrazas et al. (2020) demonstrate that the ejective feedback in TNG becomes effective at quenching star formation once the cumulative kinetic energy overcomes the total gravitational binding energy of the gas in a galaxy. They also show that the kinetic feedback process dominates in galaxies whose $M_{\text{BH}}$ exceeds $10^{8.2} M_\odot$, the black hole mass threshold above which more than 90% of the TNG galaxies are quenched (see also Zinger et al. 2020). This $M_{\text{BH}}$ threshold for quiescence arises from the TNG model parameters chosen to reproduce observational properties of the galaxy population at the present time (Pillepich et al. 2017a).

In the top panel of Figure 8 we investigate the role of the AGN on quenching in our post-merger sample by showing the correlation between the cumulative kinetic energy released into the gas and the central black hole mass. Most of the quenched post-mergers sample galaxies occupy the high $M_{\text{BH}}$ regime $M_{\text{BH}} \geq 10^{8.2} M_\odot$ and also have the largest cumulative kinetic energies. The star-forming post-merger galaxies instead preferentially have $M_{\text{BH}} < 10^{8.2} M_\odot$ and exhibit a wide range of cumulative kinetic energies. The behaviour of the TNG controls is broadly consistent with that of the quenched and star-forming post-merger populations, although quenched post-merger galaxies have slightly larger $M_{\text{BH}}$ than quenched control galaxies, with ~80% of quenched post-mergers exceeding the threshold of $M_{\text{BH}} = 10^{8.2} M_\odot$, whereas only ~60% of the quenched control galaxies have larger $M_{\text{BH}}$ than the threshold value. Therefore neither the black hole mass threshold nor a large amount of cumulative kinetic feedback are sufficient conditions for quenching TNG galaxies.

Terrazas et al. (2020) show that the additional key ingredient necessary to understand star formation quenching in TNG galaxies is the proportion between the total amount of energy released into the gas via AGN kinetic feedback and the total gravitational energy felt by

![Figure 8](image-url)
the gas cells. Indeed, Terrazas et al. (2020) showed that TNG galaxies whose kinetic energy overcomes the binding energy are typically quenched because the feedback has enough energy to push the gas out from the galaxies.

In the bottom panel of Figure 8, we show the ratio between the total amount of energy released into the gas via AGN kinetic feedback and the total gravitational energy of the gas cells ($\frac{\int E_{\text{kinetic}} dt}{E_{\text{binding}}}$), as a function of black hole mass. We find that the TNG post-mergers and controls follow the same trend, with a sharp transition when the kinetic energy overtakes the binding energy of the gas. In ~ 99% of quenched post-mergers and in all quenched control galaxies the total kinetic energy is higher than the binding energy, in contrast to only ~ 12.7% of star-forming post-mergers and ~ 22.7% of star-forming control galaxies. Therefore, the distinction between quenched and still star-forming galaxies is clearer when binding energy is considered, as already reported by Terrazas et al. (2020). However, closer analysis of the bottom panel of Figure 8 shows that there are some differences between quenched-post-mergers and quenched control galaxies. At fixed $M_{\text{BH}}$, quenched post-merger galaxies have, on average, lower $\frac{\int E_{\text{kinetic}} dt}{E_{\text{binding}}}$ than quenched control galaxies, thus suggesting they have higher binding energy (because quenched post-mergers and quenched control galaxies have similar cumulative kinetic energy, see the top panel of Figure 8). Another difference between quenched-post-merger and control populations is that there is a tail of quenched control galaxies with $M_{\text{BH}} < 10^{8.2}$ $M_\odot$. We recall that the definition of quenched control galaxies includes all the quenched controls, hence the quenched control population represents the behaviour of the whole TNG quenched population. Therefore, though rare, there are quenched galaxies with black hole masses below the typical TNG mass threshold.

The results in Figure 8 represent the instantaneous situation at the moment of quenching in the quenched post-merger population. It is instructive to observe how the two energy types evolve with time. Figure 9 shows the relation between the cumulative kinetic energy and the binding energy at $t_{\text{PM}} = 0$ (top panel) and at the time of the quenching (bottom panel): red for quenched post-mergers ($Q_{\text{PM}}$ galaxies), and blue for star-forming post-mergers ($SF_{\text{PM}}$ galaxies). Control galaxies are represented by dashed contours: red for quenched control galaxies ($Q_{\text{CTRL}}$ galaxies), and blue for star-forming control galaxies ($SF_{\text{CTRL}}$).

At $t_{\text{PM}} = 0$ (Figure 9, top panel), we find the quenched post-mergers and quenched control galaxies show, on average, similar values of binding and kinetic energies. Conversely, for the star-forming post-mergers and star-forming control galaxies the binding energy is larger than the kinetic energy, hence the gas is retained for ongoing star formation. Instead, at the time of quenching (Figure 9, lower panel), we find that both quenched post-mergers and quenched control galaxies have reduced binding energy, by typically ~ 0.5 dex for quenched post-mergers and ~ 1.1 dex for quenched control galaxies, while increasing their kinetic energy by ~ 0.3 dex.

Following the evolution of the two energy types (as in Figure 9) between $t_{\text{PM}} = 0$ and the time of quenching, we find that the binding energy decreases steadily, while the total kinetic feedback only slightly increases. It is worth noting that there is a significant fraction of star-forming galaxies that exhibit an energetic ratio $\frac{\int E_{\text{kinetic}} dt}{E_{\text{binding}}} > 1$, as the quenched populations (see bottom panels of Figure 8 and Figure 9). This means that the energy balance between kinetic and binding energies is not by itself a sufficient condition for quenching in TNG galaxies. By definition (see equation 1), the binding energy is proportional to the amount of gas in the reservoir of the galaxies. Consequently, it is expected that the binding energy decreases subject to the high gas loss we find in the quenched galaxy population in TNG (see Section 3.2). Moreover, the binding energy of the gas depends also on the strength of the gravitational potential, hence on the global mass distribution. Therefore, the binding energy, by definition, reflects the gas fraction in galaxies.

Figure 10 shows the relation between the energetic ratio $\frac{\int E_{\text{kinetic}} dt}{E_{\text{binding}}}$ and the gas fraction (i.e., the fraction of the whole gas mass over the baryonic mass, $f_{\text{gas}}$) at the time $t_{\text{PM}} = 0$ of merging (top panel) and at the time of quenching (bottom panel). At the time of merging (Figure 10, top panel), when all our galaxies are still star-forming, the gas fractions of the populations that will eventually quench (i.e. $Q_{\text{PM}}$ and $Q_{\text{CTRL}}$) are lower than those that remain star-forming (i.e. $SF_{\text{PM}}$ and $SF_{\text{CTRL}}$). Quantitatively, ~ 50% of $Q_{\text{PM}}$ and $Q_{\text{CTRL}}$ galaxies have $f_{\text{gas}} \leq 0.2$, whilst $SF_{\text{PM}}$ and $SF_{\text{CTRL}}$ galaxies have instead gas fraction in the range 0.2 $\leq f_{\text{gas}} \leq 0.5$. This fact suggests that there is a pre-disposition towards quenching if the gas fraction is low to start with.

At the time of quenching (Figure 10, lower panel), the separation between the quenched and star-forming populations is seen as a very sharp distinction in gas fraction. We find a gas fraction threshold at roughly $f_{\text{gas}} < 0.1$, below which all the TNG galaxies are quenched, and above which more than 98% of galaxies are still star-forming. Therefore, the gas fraction is a better discriminator than the energy ratio between TNG quenched and star-forming galaxies.

In summary of this section, we find that quenching is rare amongst...
Figure 10. (Top) The ratio between the cumulative kinetic energy (released from the time when the black hole is seeded in the centre of the galaxy to the time of coalescence $t_{PM} = 0$) and the total gravitational binding energy of the gas at $t_{PM} = 0$, as a function of the gas fraction at $t_{PM} = 0$. (Bottom) The same relation but at the time of quenching (in the cases of the QPM and QCTRL populations), or $t_{PM}$ = 500Myr (in the cases of the SFPM and SFCTRL populations). The post-merger galaxies are represented by solid contours: red for quenched post-mergers (QPM galaxies), and blue for star-forming post-mergers (SFPM galaxies). Control galaxies are represented by dashed contours: red for quenched control galaxies (QCTRL galaxies), and blue for star-forming control galaxies (SFCTRL). The figure demonstrates that TNG post-merger galaxies (but also non-post-merger galaxies) quench when their gas fraction is below $f_{gas} \leq 0.1$.

4 IMPACT OF $M_{BH}$ MATCHING SCHEME

A key part of our experimental set up is the construction of the control sample. Our fiducial scheme includes matching in stellar mass, SFR, environment and black hole mass. In particular, in order to limit any bias related to AGN in post-mergers and their controls, our matching criteria includes a maximum tolerance of 0.05 dex (i.e. ~12%) on black hole mass of control galaxies (see Section 2). Nonetheless, we find an excess of quenched galaxies in post-mergers compared to control galaxies that have not experienced any merger in the last 2 Gyr. Therefore, it is worth investigating whether the excess is real or if it depends on the chosen $M_{BH}$ tolerance, or in other words, to what extent the $M_{BH}$ matching could bias our results.

In order to test the impact of our matching scheme, we re-measure the excess of post-mergers for different $M_{BH}$ matching tolerances. We first remove any restrictions on $M_{BH}$ in our search for control galaxies, then we selected three further control samples with more stringent tolerance in the $M_{BH}$ difference than in the fiducial case, with 0.02 dex (i.e. a maximum mismatch around 5%), 0.015 dex (i.e. a maximum mismatch of roughly 3.5%), and 0.01 dex (i.e. a maximum mismatch of about 2.3%). The top panel of Figure 11 shows the ratio between the number of quenched post-mergers and quenched control galaxies matched without any restrictions on $M_{BH}$, while the bottom panel of Figure 11 shows the same ratio for each of the three cases with more stringent tolerance on $M_{BH}$ match. As a reference, in both panels we also display the ratio obtained with our fiducial tolerance, as in Figure 4. We find that the different matchings show qualitatively consistent results, with an excess of quenched post-mergers immediately after coalescence followed by a steadily decreasing ratio with the time passed after the merger. Therefore, our qualitative conclusion, that mergers lead to an excess of quenched galaxies, is robust against the choice of the tolerance criterion on $M_{BH}$. However, changing the matching tolerance has a quantitative effect on the quenched fraction in the two populations. In the case where we do not match in black hole mass, we find a larger excess immediately after the coalescence phase (i.e. $\lesssim$ 160 Myr after the merger) compared to Section 3.1. The excess of quenched galaxies when no $M_{BH}$ matching is used is $3 \pm 0.6$ times, at a significance level of 3.3$\sigma$ (where $\sigma$ represents the Poissonian error of the ratio). In the three cases with lower tolerances, the excess is $1.4 \pm 0.6$ times the number of QCTRL galaxies in all the three cases, only slightly smaller than the excess referred to the fiducial case, and the excess is confirmed at a significance level of $\sim 1\sigma$. We point out that by requiring more stringent constraints on the black hole mass of the control galaxies we reduce the chance of finding a control galaxy for each post-merger, with the drawback of worsening the statistics of our result. Indeed, only 3% of TNG post-mergers have a control galaxy that can be matched in $M_{BH}$ with a tolerance of 0.01 dex. However, we find consistent trends for all tolerances considered, thus suggesting that the excess in the early phase after the merger would be present even with more extreme constraints on $M_{BH}$ of matched control galaxies.

We next investigate the origin of the larger excess of post-mergers in the case without matching on black hole mass. Since AGN feedback is the driver of quenching in TNG, we expect that the higher fraction of quenched post-mergers compared with control galaxies should be related to an excess of post-mergers with $M_{BH} \geq 10^{8.2}M_\odot$, that is the black hole mass threshold above which more than 90% of the TNG galaxies are quenched (see Section 3.3) and that can sustain efficient kinetic feedback. The inset panels in Figure 11 show the distributions of the difference between the $M_{BH}$ of TNG post-mergers that have $M_{BH} \geq 10^{8.2}M_\odot$ and their controls ($\Delta M_{BH} = M_{BH}$ of PMS...
To summarise, the results presented in this section suggest that TNG post-mergers have a higher chance to quench the star formation in the early stages after coalescence compared to non-post-merger galaxies with similar characteristics and environment. The excess of quenched post-mergers cannot be simply ascribed to a mismatch in the black hole mass of the two populations. Indeed, the excess persists when we remove any matching on the black hole mass. Therefore, even if the quenching in TNG post-mergers is strictly connected to AGN activity (see Section 3.3), the dynamics of galactic mergers could contribute to halting star formation in post-mergers.

5 RESOLUTION EFFECTS

In the work presented thus far, we exclusively analyse the evolution of post-mergers from TNG300-1. TNG300-1 offers the most robust statistics (a larger number of post-mergers) while maintaining a reasonable spatial and mass resolution. In this section, we perform a convergence test to investigate the robustness of our results against changes in the simulation’s resolution (see Pillepich et al. 2017a for details about the convergence of the IllustrisTNG physical model). IllustrisTNG offers two other flagship simulations that use the same physical model but have different spatial and mass resolutions. The simulation TNG100-1 has 2 \times 2500^3 resolution elements, and a dark matter particle mass resolution of \( m_{\text{halo}} = 7.5 \times 10^8 M_\odot \) and a baryonic target mass \( m_{\text{bar}} = 6 \times 10^7 M_\odot \), respectively, which corresponds to approximately an order of magnitude better spatial and mass resolution than TNG300-1. TNG100-1 simulates a smaller volume of \( 110.7^3 \) Mpc\(^3 \), that is around \( 1/20^{th} \) of the volume simulated in TNG300-1 (see Section 2.1). The second simulation, TNG100-2, has the same volume as TNG100-1, but roughly the same mass and spatial resolutions as TNG300-1. Analysing the three simulations allows us to perform a test on the robustness of our results against distinct spatial and mass resolutions.

We note that TNG100-1 includes a total of 1855 post-mergers in the redshift range between \( 0 \leq z \leq 1 \), whereas TNG300-1 provides a sample of 25836 post-mergers (see Hani et al. 2020). By applying to TNG100-1 the same matching prescription we use for TNG300-1 (that consists of finding a control sample to the star-forming post-mergers with a match in the six parameters of redshift, stellar mass, SFR, \( N_2 \), and \( r_1 \) and \( M_{\text{BH}} \)), we would find control galaxies for only 64 star-forming post-mergers (compared with 3472 in TNG300-1). We find that the requirement on \( M_{\text{BH}} \) is the one that most significantly reduces the yields of controls. However, in Section 4 we showed that including a match in black-hole mass only impacts the excess of quenched post-mergers slightly, therefore, to increase the number of star-forming post-mergers in TNG100-1 and TNG100-2 and improve the statistics of the result, we compare the behaviour of the three simulations without matching the control samples in black hole mass, but only in the other five aforementioned parameters. This way, we obtain a sample of 252 and 261 star-forming post-mergers in TNG100-1 and TNG100-2, respectively.

Figure 12 shows the ratio between the number of quenched post-mergers (\( Q_{\text{PM}} \)) and quenched control galaxies (\( Q_{\text{CTRL}} \)) as a function of \( t_{\text{PM}} \) for the three TNG simulations. TNG300-1 and TNG100-2, the two simulations at a similar numerical resolution, show a very similar result, thus the reduced volume in TNG100-2 has little im-
Figure 12. The ratio between the number of quenched post-mergers (QPM) and quenched controls (QCTRL) as a function of time elapsed since coalescence (tPM) for three TNG simulations at different mass and spatial resolutions, and different volumes. The black curve and grey shading represent the result from TNG300-1 without any match in black-hole mass. The green solid curve with light green shading, and the blue solid curve with light blue shading represent the ratios obtained from TNG100-1 and TNG100-2, respectively. To improve the statistics, the ratios from TNG100-1 and TNG100-2 are evaluated in bins of tPM 500 Myr, instead of tPM 160 Myr as is done for TNG300-1. The figure reveals that the resolution of the simulation significantly affects the result, whilst the volume of the distribution affects only the statistics of the result but not the trend.

The excess of quenched post-mergers: although quenching in post-mergers is rare, quenching occurs in post-mergers at twice the rate of the controls (see Figure 4), i.e. 2.4% of the control sample is quenched within 500 Myr. The excess of quenched galaxies within the post-merger sample dissipates with time post-merger. After ~ 1.5 Gyr, the post-merger quenched population is statistically indistinguishable from the control’s quenched population (see Section 3.1).

The effect of AGN feedback: the kinetic mode of AGN feedback is responsible for quenching post-mergers in the TNG model. The feedback acts in two ways: (1) the kinetic feedback injects momentum into the gas particles surrounding the central black hole, thus ejecting the gas from the galaxy (ejective feedback, see Figure 6), and (2) the kinetic feedback also prevents the gas from cooling to replenish the galactic reservoir for sustaining new episodes of star formation (preventive feedback, see Section 3.2). Quenching is most effective in galaxies with M_{BH} ≥ 10^{8.2} M_\odot. At black hole masses higher than M_{BH} ≥ 10^{8.5} M_\odot the total kinetic energy injected into the gas by the central black hole dominates over the gas’s gravitational binding energy; as a result a notable fraction of the gas reservoir is removed from the galaxy (see Figure 8, and Figure 9).

Quenching and gas fraction: We find that: (1) there is a predisposition towards quenching if the gas fraction in a galaxy is low, and (2) the separation between the quenched and star-forming populations at the time of quenching is demarcated by a very sharp distinction in gas fraction, as quenched galaxies dominate at gas fractions below f_{gas} ∼ 0.1 (see Figure 10).

The effect of different M_{BH} matching schemes: the excess of quenched post-mergers with respect to the number of quenched galaxies in the control population is stronger when we do not include a matching criterion for the black hole mass. Nonetheless, though slightly weaker, the excess persists also when we match control galaxies with a maximum tolerance of 0.015 dex in black hole mass (see Figure 11).

The picture that arises from our analysis is that mergers in TNG do not contribute significantly to the quenching of star-forming galaxies. The rarity of quenching in post-mergers is qualitatively in accordance with other cosmological simulations and observational results. For instance, Rodríguez Montero et al. (2019) find that major mergers in the SIMBA simulation (Davé et al. 2019) are not directly related to quenching, as the typical delay between the merger and subsequent quenching is larger than 1 Gyr. By analysing a sample of galaxies extracted from the SDSS DR7, Weigel et al. (2017) show that major mergers should not be the preferred path leading to permanent quenching. They found that major merger quenched galaxies account for a maximum of 5% of the quenched population at a given stellar mass, both at low- and intermediate-redshift.

Despite the small absolute fraction of promptly quenched galaxies, there is a notable excess of quenched post-mergers compared to the control population, thus suggesting that mergers could have a non-negligible contribution to the quenching of star formation. Mergers disturb the internal kinematics of the galaxy (i.e. dark matter, stars, gas). The induced turbulence in the ISM could dissipate angular momentum of the infalling gas, and we are investigating this process in TNG post-mergers in a follow-up project. Gas infalling with reduced angular momentum could reach the centres of the galaxies and feed the central black holes. The temporary excess of quenched post-mergers found in the early phase after coalescence completely vanishes after ~ 1.5 Gyr following the merger, suggesting that the mergers accelerate the quenching process in those post-merger descendants of star-forming post-merger galaxies. Only around 5% of TNG post-merger galaxies quench within 500 Myr after merging (see Figure 3).

6 SUMMARY AND CONCLUSIONS

In this work, we present an analysis of the incidence and the causes of quenching in a N-body cosmological simulation of the Universe (TNG) and a comparison of these results to those from a hydrodynamical simulation (IllustrisTNG). We follow the evolution of the star formation rate in the post-merger descendants, and we compare the evolution to that of a control sample of non-post-merger galaxies matched in redshift, stellar mass, SFR, black-hole mass, environment, and isolation. Our findings can be summarised as follows:

- Quenching in TNG post-mergers: quenching is rare among the descendants of star-forming post-merger galaxies. Only around 5% of TNG post-merger galaxies quench within 500 Myr after merging (see Figure 3).
mergers whose progenitors were close to sustaining effective AGN kinetic feedback.

Our results may be dependent on the AGN feedback model implemented in IllustrisTNG. However, the dynamics of galactic mergers could contribute to halting star formation in post-mergers for a variety of reasons. For example, Pontzen et al. (2017) applied a genetic modification approach (Roth et al. 2016) to generate sets of controlled numerical realisations in a fully cosmological context of a halo of $10^{12} M_\odot$, by altering its accretion history. They find that in major mergers (a mass ratio of 2:3) AGN feedback alone is not sufficient to permanently quench star formation, but it acts in synergy with the kinetic effects of the merger. The interaction disrupts the gaseous disk of the galaxy, resulting in a turbulent medium able to remove angular momentum from inflowing material; then, the inflowing material can easily reach the galactic centre to feed the black hole and the subsequent AGN activity contributes significantly to removing the remaining gas from the galaxy (see also Chadayammuri et al. 2020). More recently, Sanchez et al. (2020) used a similar approach to analyse the impact of minor mergers on the star formation of simulated Milky Way analogues. They find that two small satellites interacting with the host can quench a Milky Way-like galaxy. The mechanism is similar to the one in Pontzen et al. (2017), but in this case, it requires a tandem operation of a merger with the first satellite and subsequent close interaction with the second satellite to disrupt the gaseous disk and trigger intense AGN activity to halt the star formation. In a follow-up project, we will statistically analyse the repercussions of multiple interactions/mergers on quenching in large cosmological simulations. In a follow-up project, in order to gain new insights on the impact of mergers on quenching, we will analyse other cosmological simulations that implement different models to regulate black hole accretion, such as the Eagle simulation (Schaye et al. 2015) and the Illustris simulation (Vogelsberger et al. 2014).

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DATA AVAILABILITY

The data used in this work are publicly available at https://www.tng-project.org.

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