MOSEL and IllustrisTNG: Massive Extended Galaxies at $z = 2$ Quench Later Than Normal-size Galaxies

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Abstract

Using the TNG100 (100 Mpc)$^3$ simulation of the IllustrisTNG project, we demonstrate a strong connection between the onset of star formation quenching and the stellar size of galaxies. We do so by tracking the evolutionary history of extended and normal-size galaxies selected at $z = 2$ with $\log(M_*/M_\odot) = 10.2$–$11$ and stellar-half-mass-radii above and within $1\sigma$ of the stellar size–stellar mass relation, respectively. We match the stellar mass and star formation rate distributions of the two populations. By $z = 1$, only 36% of the extended massive galaxies have quenched, in contrast to a quenched fraction of 69% for the normal-size massive galaxies. We find that normal-size massive galaxies build up their central stellar mass without a significant increase in their stellar size between $z = 2$–4, whereas the stellar size of the extended massive galaxies almost doubles in the same time. In IllustrisTNG, lower black hole masses and weaker kinetic-mode feedback appears to be responsible for the delayed quenching of star formation in the extended massive galaxies. We show that relatively gas-poor mergers may be responsible for the lower central stellar density and weaker supermassive black hole feedback in the extended massive galaxies.

Unified Astronomy Thesaurus concepts: Galaxies (573); Galaxy evolution (594); Hydrodynamical simulations (767); Galaxy formation (595)

1. Introduction

How and when massive galaxies stop forming stars (a.k.a. quenching) remains a mystery after decades of study. A significant fraction of massive galaxies have either stopped forming stars or show suppressed star formation in the first 15%–20% of the age of the universe ($z = 2$–3) (van Dokkum et al. 2008; Damjanov et al. 2009; Straatman et al. 2014; Glazebrook et al. 2017). The emerging picture is that star formation is quenched in field galaxies either via feedback processes such as those related to supernovae and active galactic nuclei (AGN), or a truncation of gas supply to fuel the star formation (Springel et al. 2005; Zhang et al. 2019). In massive dark matter halos, the infalling gas can be shock-heated, further preventing the inflow of gas at virial radii (Dekel & Birnboim 2006). At higher redshifts, mergers and violent disk instabilities can also trigger a burst of star formation and AGN activity in the core, subsequently quenching star formation (Dekel & Burkert 2014; Zolotov et al. 2014). AGNs are thought to be primarily responsible for the quenching of star formation in massive galaxies (Fabian 2012; Harrison 2017).

The physical processes responsible for quenching leave imprints on the spatial distribution of stars and stellar ages (McDermid et al. 2015; Wu et al. 2018). A central starburst will rapidly quench star formation in the center, either by rapid consumption of gas or by triggering strong outflows, and produce galaxies with a dense stellar core (Springel et al. 2005; Snyder et al. 2011; Zolotov et al. 2014). Less centrally focused feedback processes such as shock heating of gas in massive dark matter halos, energy injected by the supernovae and/or AGN would quench star formation gradually without significantly altering the stellar distribution of galaxies (Dekel & Birnboim 2006; Fabian 2012; Terrazas et al. 2017). Therefore, we expect to see a correlation between the star formation histories and the spatial distribution of stars.

Large extragalactic surveys in the local and high redshift universe find that star formation in compact galaxies quench on a shorter timescale compared with larger, more extended, galaxies. In the local universe, at a fixed stellar mass, compact galaxies have relatively older stellar populations indicative of either rapid star formation quenching and/or an earlier formation epoch (McDermid et al. 2015; Barone et al. 2020). Massive diffuse galaxies in the local universe such as Malin I build up their stellar disk slowly over an extended timescale (Boissier et al. 2016; Zhu et al. 2018). Using data from the Sloan Digital Sky Survey, Fang et al. (2013) find that most galaxies quench after they cross a certain threshold in the central stellar mass density.

Studies at high redshift ($z \sim 1$) also find that massive compact galaxies have older stellar populations compared with their larger counterparts, suggesting that star formation quenched in compact galaxies earlier (Williams et al. 2017; Faglioli et al. 2016). In contrast, Keating et al. (2015) find that compact massive galaxies at $z \sim 1.5$ have younger stellar ages compared with a control population, suggesting that compactness is the result of a recent burst of star formation. Observations by Barro et al. (2017) show that the connection between the central stellar mass surface density and the status of the star formation exists as early as at $z \sim 2.5$ – 3. Using spectroscopic data from the Lega-C survey (van der Wel et al. 2016; Straatman et al. 2018), Wu et al. (2018) show...
that massive galaxies at $z \sim 1$ seem to follow two distinct star formation quenching pathways: (i) slow (>1 Gyr) quenching producing quiescent galaxies with large galactic disks and younger stellar populations, and (ii) fast (<1 Gyr) star formation quenching producing post-starburst galaxies with various sizes depending on their formation history.

In cosmological simulations, massive compact galaxies at $z = 2$ exhibit two main formation pathways: (i) a recent burst of star formation between $z = 2$–4 triggered by a gas-rich major merger or (ii) they formed at $z > 4$ when the universe was denser than today (Wellons et al. 2015). In agreement with observations, compact galaxies that formed via mergers have relatively younger stellar populations, whereas compact galaxies that formed at earlier epochs have older stellar populations. However, Wellons et al. (2015) focus on only a small fraction of extremely compact galaxies from the Illustris simulation with a stellar size almost 2$\sigma$ below the galaxy size–mass relation and log$(M_*/M_\odot)$>11.0.

Genel et al. (2018) analyzed the size evolution of galaxies in the Illustris TNG simulations (https://www.illustris-project.org). They find that most quenched galaxies at $z = 0$ started off at the lower end of the stellar mass–size relations, i.e., quenched galaxies have relatively compact stellar distribution at higher redshift. In Gupta et al. (2020), we use the MOSEL survey (Tran et al. 2020) to track how galaxies at $z \sim 3$ grow. Combining our observations with predictions from IllustrisTNG, we show that massive galaxies after $z \sim 3$ tend to form new stars from ex situ processes. An intriguing result from Gupta et al. (2020) is a dramatic increase in the stellar size of massive galaxies at $z = 2$.

In this follow-up study, we investigate the size evolution of the massive galaxies and its link with the star formation quenching by analyzing the outcome of the publicly available IllustrisTNG simulations (Nelson et al. 2019b). We select normal-size and extended massive simulated galaxies at $z = 2$ according to their location on the stellar mass–stellar size plane of IllustrisTNG and track their evolutionary histories backwards and forwards in time. To minimize the bias due to the different mass–size relations of quiescent and star-forming galaxies, also in place in the simulations (Genel et al. 2018), we select two samples of galaxies with consistent stellar mass and star formation rate distributions at the time of selection, here $z = 2$.

The paper is organized as follows. In Section 2, we provide a brief description of the simulations and our selection method of the extended and normal-size massive galaxies. In Section 3 we compare the star formation histories of the two samples and how the two populations evolve on the size–mass plane. In Sections 4 and 5, we discuss and summarize our main findings.

2. Methods

2.1. The TNG100 Simulation of IllustrisTNG

We use a cosmological hydrodynamical simulation from the IllustrisTNG project (Piellepich et al. 2018a; Nelson et al. 2018a; Springel et al. 2018; Marinacci et al. 2018; Naiman et al. 2018) to understand the relation between stellar disk size and star formation history of massive galaxies. In particular, we use the publicly available outcome (Nelson et al. 2019b) of the TNG100 simulation (∼100 Mpc$^3$, $\Omega_b = 9.4 \times 10^3$/h) to ensure a statistically significant sample of galaxies with log$(M_*/M_\odot)$>9 at $z \gg 3$, i.e., galaxies with ∼1000 baryonic resolution elements. We start from a selection of galaxies with log$(M_*/M_\odot)$>9 at $z = 0$ and track them back in time using the merger tree catalogs (Rodriguez-Gomez et al. 2015).

2.2. Selection of Extended versus Normal-size Massive Galaxies

To select extended massive galaxies in TNG100, we bin the stellar mass–size relation at $z = 2$ into bins of 0.15 dex in stellar mass. Throughout this paper, we use the three-dimensional stellar half-mass–radius ($R_{\text{halfmass}}$ = radius containing 50% of the stellar particles) to represent the stellar size, or stellar extent, of a galaxy. All properties of galaxies are measured within twice the stellar half-mass–radius, unless otherwise specified. We select massive galaxies with stellar mass $10.2 < \log(M_*/M_\odot) < 11$ at $z = 2$ with stellar sizes 1$\sigma$ above the stellar mass–size relation (Figure 1); this leads to the selection of 123 extended massive galaxies. We limit our extended massive galaxies sample to log$(M_*/M_\odot)$<11.0 due to the low number of galaxies at higher stellar masses.

From TNG100, we build a control sample of normal-size simulated galaxies (normal galaxies hereafter). For each extended massive galaxy, we select a normal-size massive galaxy whose $R_{\text{halfmass}}$ is within 1$\sigma$ of the median stellar mass–stellar size relation, and whose stellar mass and star formation rate (SFR) match the corresponding values of the extended massive galaxy within 0.1 dex at $z = 2$. This ensures statistically identical stellar mass ($p = 1.0$) and SFR ($p = 0.7$) distributions for the normal-size and extended massive galaxies at $z = 2$ (Figure 1, right-hand panels). This results in a minimal stellar mass and SFR bias between the two samples upon selection. Under this selection at $z = 2$, the TNG100 extended massive galaxies have on average twice the stellar $R_{\text{halfmass}}$ compared with the normal-size massive galaxies.

Figure 2 shows the distribution of gas and stars in five randomly selected extended and normal-size massive galaxies at redshift $z = 2$ and their descendants at $z = 0$. It
demonstrates the diversity of galaxy types in both populations. In the following sections, we track the evolutionary histories of extended and normal-size massive galaxies to understand the build up of the extended stellar disk and its connection with the star formation quenching or suppression. We use the merger tree catalogs by Rodriguez-Gomez et al. (2015) to identify progenitors and descendents of our extended and normal-size massive galaxies.

3. Results

3.1. Star Formation Histories

Figure 3 shows the stellar mass build up and star formation histories of the extended and normal massive galaxies. By selection, both extended and normal massive galaxies have similar sSFR at $z = 2$. Even at $z > 2.0$, the sSFR distributions of the extended and normal massive galaxies remains the same (KS-test $p > 0.2$), suggesting both populations build up their stellar mass at a similar rate until $z = 2.0$. The stellar mass distribution of the two populations remains statistically similar until $z = 2$, although by $z = 0$ the extended massive galaxies have on average 0.15 dex higher stellar mass than the normal massive galaxies.

The star formation in the extended massive galaxies quenches later than in the normal-size massive galaxies (Figures 3 and 4). By $z = 1.5$ more than 41% of the normal massive galaxies are quenched, whereas only 17% of the extended massive galaxies are quenched. To calculate the quenched fraction, we use the redshift dependent sSFR cut by Tacchella et al. (2019). Even until $z = 1$, only 36% of the extended massive galaxies are quenched in contrast to the 69% quenched fraction in the normal massive galaxies. However, by $z \sim 0.3$ both normal and extended massive galaxies have a similar quenched fraction. Our measurements suggest that by using only stellar size, we can predict when star formation will quench in massive galaxies.
3.2. Quenching of Star Formation

3.2.1. Environment and Gas Density

Both observations and simulations show that galaxies living in more massive halos quench earlier (Peng et al. 2010; Gabor & Davé 2015; Wang et al. 2018). However, the average halo mass of the extended massive galaxies remains within 1σ scatter to the average halo mass of the normal massive galaxies throughout the cosmic time (Figure 5 left panel). We find that the median halo mass of the extended massive galaxies is ∼0.08 dex higher than the normal massive galaxies, directly opposite to our expectations based on their delayed star formation quenching timescale.

Martizzi et al. (2020) shows that at a fixed halo mass, galaxies residing in voids and sheets tend to have lower stellar mass compared with the median of all galaxies, suggesting a clear role of the large-scale environment on the mass assembly history of galaxies. However, our preliminary analysis does not yield any significant evidence that the extended massive galaxies occupy a special place in the cosmic web compared with the normal massive galaxies.

Focusing on internal galaxy properties, the middle and right panels in Figure 5 show how the fraction and the density of total gas (neutral and warm) within twice the \( R_{\text{halfmass}} \) evolves with redshift. To get the average gas density, we divide the total gas mass within twice the stellar \( R_{\text{halfmass}} \) with the total enclosed volume. The extended massive galaxies have systematically higher gas fraction and gas density compared with the normal massive galaxies at \( z < 2 \). It could be hypothesized that the higher gas fraction and gas density were responsible for the delayed onset of SF quenching in the extended massive galaxies compared with the normal massive galaxies.

Interestingly, we find that the extended massive galaxies have lower gas density between \( z = 2–4 \), i.e., just before the selection. The lower gas density in the extended massive galaxies could be responsible for their relatively diffuse stellar core at \( z = 2 \) and lower black hole feedback (see Section 3.2.2).

3.2.2. Central Star Formation and Feedback from Supermassive Black Holes

To understand the spatial variation of the SFR, we estimate the radial star formation, gas mass and stellar mass surface density profiles in the extended and normal-size massive galaxies at the time of the selection (Figure 6). The extended massive galaxies have lower star formation and gas mass surface densities in their galactic center (<4 pkpc) in comparing with the normal massive galaxies.

The star formation and gas mass density profiles remains almost flat between 2–10 pkpc for the extended massive...
galaxies. In contrast, the density profiles of the normal massive galaxies falls off rapidly beyond 2 pkpc ($ \sim R_{\text{halfmass}}$). The extended galaxies have about 1 dex higher star formation surface density at $r > 4$ pkpc. We hypothesize that the higher gas mass and star formation surface density in the galactic outskirts is responsible for the build up of an extended stellar disk in the extended massive galaxies.

Observations in both the local and high redshift universe show that central stellar mass surface density correlates strongly with the onset of star formation quenching (Fang et al. 2013; Barro et al. 2017; Mosleh et al. 2017). The stellar mass surface density of the extended massive galaxies has a shallower slope compared to the normal massive galaxies. The extended galaxies have nearly 0.3 dex lower stellar mass surface density in the central 1 kpc than the normal massive galaxies. We suspect that the slow build up of the central stellar core in the extended massive galaxies might be linked to their delayed star formation quenching timescale.

In massive galaxies, feedback from supermassive black holes (SMBHs) is typically invoked for the quenching of star formation (see the review by Fabian 2012). This is certainly the case in the IllustrisTNG model for galaxy formation (Pillepich et al. 2018b; Weinberger et al. 2017). In the IllustrisTNG model SMBH feedback operates in two different modes: the quasar-mode and the kinetic-mode. The quasar-mode occurs when the mass accretion rate is high, releasing an enormous amount of thermal energy into the surrounding medium. The kinetic-mode occurs when the mass accretion rate is low and kinetic energy is deposited into the gas, producing jets and outflows or winds. SF quenching in particular is triggered by black hole driven winds at low-accretion rates (see, e.g., Weinberger et al. 2017; Nelson et al. 2018b; Terrazas et al. 2020) because it determines the physical and thermodynamical properties of the gas within and around galaxies (see Truong et al. 2020; Davies et al. 2019; Zinger et al. 2020).

Figure 7 shows that at $z = 2$, the SMBHs in the extended massive galaxies are half as massive and accrete two times slower than the SMBHs in the normal-size massive galaxies. Already, at $z = 3$, the normal-size massive galaxies host slightly more massive black holes than the more extended analogs. On the other hand, by $z = 1.5$, the black hole accretion rate reverses and becomes almost 10 times higher in the extended massive galaxies probably due to the reduced supply of gas in the normal-size massive galaxies (Figure 5).

Nelson et al. (2019a), Davies et al. (2020), and Zinger et al. (2020) show that in IllustrisTNG SMBHs quench star formation primarily by pushing the gas out from the central regions of galaxies via the kinetic-mode feedback. The last column in Figure 7 shows the ratio of the cumulative amount of energy injected by the SMBHs in the kinetic-mode versus the quasar-mode. In the extended massive galaxies, the ratio of energy injected in the kinetic-mode versus the quasar-mode is 10 times lower than the normal-size massive galaxies at $z = 2$. In IllustrisTNG, kinetic-mode feedback becomes comparable to quasar-mode feedback once the SMBHs cross the transitional BH mass of about $10^8 M_\odot$ (Zinger et al. 2020). Most extended massive galaxies have SMBH masses well below the transitional SMBH mass at $z = 2$, and hence have relatively smaller fractions of energy injected in kinetic-mode.

Our analysis suggests that, at least in the case of IllustrisTNG galaxies, weaker AGN-driven kinetic feedback is responsible for the overall delayed quenching of star formation in the extended massive galaxies compared with the normal-size massive galaxies. We suspect that the lower gas density in the galactic center (Figure 6) might be responsible for the slower black hole growth in the extended massive galaxies until $z = 2$.

### 3.3. Build Up of the Extended Stellar Disk

The extended and normal-size galaxies follow a range of evolutionary pathways on stellar mass–size plane (Figure 8). The median stellar size of the extended massive galaxies increases steadily as they build up their stellar mass between $z = 2$–4. In contrast, the median stellar size–mass track of the normal-size massive galaxies is almost flat at least until $z = 2.5$, i.e., on average normal-size massive galaxies build up their stellar mass without a significant increase in their stellar size. Between $z = 2$–4, the median stellar mass of the normal-size massive galaxies increases by 1 dex, while the median $R_{\text{halfmass}}$ radius remains roughly the same. Interestingly, $R_{\text{halfmass}}$ almost doubles within the same time period for the extended massive galaxies again with roughly 1 dex increase in their stellar mass.
we hypothesize that relatively gas-poor mergers encountered by the extended massive galaxies at \( z \approx 2 \) are responsible for their lower central stellar mass density and slower SMBH growth.

### 4. Discussion

Observations of compact quiescent galaxies, “red-nuggets,” at \( z \approx 2 \) have triggered a fruitful debate over the onset of star formation quenching and the factors that may affect it in the early universe (Damjanov et al. 2009; Glazebrook et al. 2017; Damjanov et al. 2009; Glazebrook et al. 2017; Lu et al. 2019). In Gupta et al. (2020), we found evidence that massive galaxies after \( z \approx 3 \) build up their stellar mass from ex situ processes in both MOSEL observations and IllustrisTNG simulations. We also observed a significant increase in the stellar sizes of the massive galaxies at \( z \approx 2 \). In this paper, we have analyzed the TNG100 simulation to gain insights as to why the stellar sizes of some massive galaxies increase dramatically around \( z = 2 \) and how this affects their subsequent evolutionary history.

We find that, in the TNG100 simulation, the onset of star formation quenching in massive galaxies is connected to their stellar spatial distribution and extent. We find that \( z = 2 \) galaxies with extended stellar distribution quench later than their relatively compact counterparts (Figures 3 & 4). To minimize the bias at the time of selection, we have matched the stellar mass and SFR distributions of the extended and the normal-size massive galaxies at \( z = 2 \). Our findings are similar to those by Wu et al. (2018), who show that observed large quiescent galaxies at \( z > 1 \) have younger stellar ages indicative of the relatively recent star formation quenching history.

We hypothesize that relatively gas-poor mergers encountered by the extended massive galaxies at \( z > 2 \) are responsible for their lower central stellar mass assembly by accretion and slower black hole growth (Figure 9). Gas-rich mergers are excellent at funneling the gas toward the galactic center triggering central star formation and the growth of the central SMBH (Hopkins & Quataert 2010; Medling et al. 2015; Wellons et al. 2015; Sparre & Springel 2016; Hani et al. 2020). Other physical mechanisms

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**Figure 6.** Median radial star formation (top), gas mass (middle), and stellar mass (bottom) surface density profiles for the normal (red dotted) and extended (purple dashed) massive galaxies at \( z = 2 \). The \( R_{200\text{mass}} \) radius for the respective population is given by the short vertical lines along the bottom edge of each panel. The gray shaded region corresponds to the nominal resolution limit of TNG100 at \( z = 2 \). The extended massive galaxies have lower SFR and gas mass surface density compared to the normal-size massive galaxies in their galactic centers.

Using data from the MOSEL survey in Gupta et al. (2020), we find that massive galaxies at \( z \sim 2 \) have higher integrated velocity dispersion compared to the counterpart galaxies at \( z = 3–4 \). We conclude that build up of stellar mass via ex situ processes in massive galaxies after \( z = 2–3 \) (Rodriguez-Gomez et al. 2016; Gupta et al. 2020) increases the integrated velocity dispersion of gas. In our current analysis, we find that the median stellar size of normal-size massive galaxies only increases after \( z < 2 \), again due to the stellar mass build up via ex situ processes (mostly dry merger, Figure 9).

As in Gupta et al. (2020), we use catalogs by Rodriguez-Gomez et al. (2016) to estimate the ex situ stellar mass fraction, which is the fraction of stellar mass built via external processes such as mergers and stripping from orbiting satellites. The mean gas fraction of mergers in Figure 9 is taken from catalogs by Rodriguez-Gomez et al. (2017) representing the average fraction of cold gas in already merged galaxies weighted by their stellar mass. The median ex situ fraction of the extended massive galaxies is 0.06–0.09 higher than the normal-size massive galaxies, i.e., extended galaxies accrete a larger fraction of their stars. The accreted stars tend to reside at a larger galactocentric distance (Rodriguez-Gomez et al. 2016) and might be responsible for the higher stellar surface density of the extended massive galaxies at large galactocentric distance (Figure 6).

Moreover, we find that the mean gas fraction of mergers encountered by the extended massive galaxies by \( z = 2 \) is lower by 10% compared with the normal-size massive galaxies. The (mildly) lower gas fraction of mergers at \( z = 2 \) coupled with the higher ex situ fraction suggests that the extended massive galaxies have encountered relatively gas-poor mergers compared to the normal-size massive galaxies between \( z = 2–4 \). Gas-rich mergers are excellent at funnelling the gas toward the galactic centers, driving central star formation and the growth of central supermassive black holes (Hopkins & Quataert 2010; Medling et al. 2015; Wellons et al. 2015; Sparre & Springel 2016; Hani et al. 2020). Our analysis suggests that relatively drier mergers in the extended massive galaxies might be responsible for their lower central stellar mass density and slower SMBH growth.
such as disk instabilities introduced by the gas inflows and/or gravitation can also funnel the gas toward the galactic center triggering growth of central SMBH (Dekel & Burkert 2014; Zolotov et al. 2014). Relatively gas-poorer mergers between $z = 2$–4 could explain the smaller black hole masses and lower gas density in the extended massive galaxies between $z = 2$–4 (Figures 6 and 7).

SMBHs in the extended massive galaxies are almost half as massive and have injected a lower fraction of their energy in the kinetic-mode rather than in the quasar-mode compared with the normal-size massive galaxies at $z = 2$. In both the EAGLE and IllustrisTNG simulations, expulsion of dense gas has been shown to trigger the star formation quenching (e.g., Davies et al. 2020). Zinger et al. (2020) show that the AGN-driven kinetic-mode feedback in IllustrisTNG suppresses star formation by increasing the gas cooling timescales from 10–100 Myr to 1–10 Gyr. The lower fraction of kinetic energy injected by SMBHs in the extended massive galaxies due to their lower black hole masses would lead to weaker or less effective AGN-driven outflows, within the IllustrisTNG model, compared with the normal-size massive galaxies. This might be insufficient to trigger quenching of SF activity in the extended massive galaxies at $z = 2$.

Habouzit et al. (2019) also find that compact massive galaxies in illustrisTNG simulations have higher star formation rates and stronger AGN feedback than their extended counterparts. Observationally, compact star-forming galaxies at $1 < z < 3$ have a higher fraction of AGNs than the counterpart normal-size star-forming galaxies in line with our prediction from the IllustrisTNG simulations (Barro et al. 2014; Rangel et al. 2014; Gu et al. 2020; Lu et al. 2020). Our analysis suggests that weaker SMBH feedback is responsible for the delayed onset of star formation quenching in the extended massive galaxies. Future IFU surveys such as the MUSE MAGPI survey (MAGPI Collaboration 2020) would be excellent to test our prediction that the onset of star formation quenching depends on the size of the stellar disk.

![Figure 7.](image-url) Distribution of the mass (left), accretion rate (middle), and ratio of cumulative energy injected in the kinetic-mode vs. the thermal-mode (right) by the central supermassive black hole in the normal (red) and extended (purple) massive galaxies at $z = 1.5$ (top row), $2.0$ (middle row), and $3.0$ (bottom row). The dashed lines in each panel represent the median for the respective population. The normal massive galaxies have stronger black hole feedback than the extended massive galaxies at $z = 2$.  

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**Figure 7.** Distribution of the mass (left), accretion rate (middle), and ratio of cumulative energy injected in the kinetic-mode vs. the thermal-mode (right) by the central supermassive black hole in the normal (red) and extended (purple) massive galaxies at $z = 1.5$, $2.0$, and $3.0$. The dashed lines in each panel represent the median for the respective population. The normal massive galaxies have stronger black hole feedback than the extended massive galaxies at $z = 2$.  

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5. Conclusions

Growth via dry mergers has been shown to be responsible for the dramatic increase in the scatter on stellar mass–stellar size plane at the massive end in Gupta et al. (2020) at $z = 2$. In this paper, we have used the TNG100 simulation of the IllustrisTNG project to gain insights on the connection between star formation activity and galaxy stellar sizes. In particular, we find that in the IllustrisTNG simulation $z = 2$ massive galaxies with extended stellar distributions quench later than the normal-size galaxies with similar stellar masses and star formation rates at selection.

In particular, we have tracked the evolutionary histories of extended and normal-size massive galaxies ($\log(M_*/M_\odot) > 10.2$) selected at $z = 2$ with identical stellar mass and SFR distributions. By $z = 1$, only 36% of the extended massive galaxies have quenched, in contrast to more than 69% quenched fraction in the normal-size massive galaxies (Figure 4).

The stellar size of the extended massive galaxies almost doubles between $z = 2$–4, with about 1 dex increase in average stellar mass (Figure 8). In contrast, the median stellar size of the normal-size massive galaxies does not change significantly between $z = 2$–4, even if they experience similar increase in their stellar mass. At $z = 2$, the extended massive galaxies have almost 0.3 dex lower stellar mass surface density in the central 1 kpc compared with the normal-size massive galaxies (Figure 6). Stellar mass build up via ex situ processes leads to an increase in the sizes of both normal-size and extended...
massive galaxies after $z < 2$, as also shown in Gupta et al. (2020) using the MOSAIC survey (Tran et al. 2020).

We hypothesize that relatively gas-poor mergers experienced by the extended massive galaxies at $z > 2$ are responsible for their lower central stellar mass density and SMBH mass. Our analysis shows that relatively lower SMBH mass and weaker kinetic-mode feedback from SMBHs are responsible for the delayed quenching of the star formation activity in the extended massive galaxies (Figure 7). However, details of large-scale environment and merger histories need to be further investigated to understand why some massive galaxies experience gas-poor mergers and do not develop a central stellar core.

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