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Wet compaction to a blue nugget: a critical phase in galaxy evolution

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ABSTRACT

We utilize high-resolution cosmological simulations to reveal that high-redshift galaxies tend to undergo a robust ‘wet compaction’ event when near a ‘golden’ stellar mass of $\sim 10^{10} M_{\odot}$. This is a gaseous shrinkage to a compact star-forming phase, a ‘blue nugget’ (BN), followed by central quenching of star formation to a compact passive stellar bulge, a ‘red nugget’ (RN), and a buildup of an extended gaseous disc and ring. Such nuggets are observed at cosmic noon and seed today’s early-type galaxies. The compaction is triggered by a drastic loss of angular momentum due to, e.g. wet mergers, counter-rotating cold streams, or violent disc instability. The BN phase marks drastic transitions in the galaxy structural, compositional, and kinematic properties. The transitions are from star forming to quenched inside-out, from diffuse to compact with an extended disc or ring and a stellar envelope, from dark matter to baryon central dominance, from prolate to oblate stellar shape, from pressure to rotation support, from low to high metallicity, and from supernova to AGN feedback. The central black hole growth, first suppressed by supernova feedback when below the golden mass, is boosted by the compaction, and the black hole keeps growing once the halo is massive enough to lock in the supernova ejecta.

Key words: galaxies: evolution – galaxies: formation – galaxies: haloes – galaxies: high-redshift – galaxies: interactions – galaxies: starburst.

1 INTRODUCTION

About half the massive galaxies at $z \sim 2$ are observed to be compact and already quiescent, thus dubbed ‘red nuggets’ (hereafter RNs; Trujillo et al. 2007; Buitrago et al. 2008; Van Dokkum et al. 2008; Damjanov et al. 2009; Newman et al. 2010; Van Dokkum et al. 2010; Damjanov et al. 2011; Bruce et al. 2012; Whitaker et al. 2012; Van Dokkum et al. 2014, 2015). While star-forming discs of $\sim 10^{10-11} M_{\odot}$ can extend to several kpc (Genzel et al. 2006, 2008), the typical quenched systems of a similar mass have smaller effective radii of order 1 kpc. Most of these RNs are likely to be the progenitors of the central regions of today’s early-type galaxies, and some may remain as fossil naked RNs (Saulder, van den Bosch & Mieske 2015; Yıldırım et al. 2017).

What is the origin of the compactness of the RNs? It may partly reflect the high density of the Universe at early times when the RN

had formed (e.g. Lilly & Carollo 2016). This is provided that the RNs formed, quenched, and established their compactness much earlier than the time when they were observed. If angular momentum is conserved during the gas contraction from the dark matter (DM) halo virial radius R_v to the central galaxy of an effective, half-mass radius R_e , then one expects $R_e \sim \lambda R_v$, where $\lambda \sim 0.04$ is the halo spin parameter that is expected to be drawn from the same distribution at all times and masses (e.g. White 1984; Bullock et al. 2001). The virial radius of the halo of a given galaxy evolves on average as $R_v \propto M_v^{1/3} (1+z)^{-1}$, where the virial mass grows in time as $M_v \propto \exp(-\alpha z)$ with $\alpha \lesssim 1$ slowly varying with mass (Wechsler et al. 2002; Dekel et al. 2013, where it is derived analytically in the EdS regime at $z > 1$). Thus, if angular momentum is conserved for the gas inflowing to the galaxy, the average effective radius of an evolving galaxy is expected to grow as $R_e \sim 0.04 R_v$, namely $R_e \propto \exp(-\alpha z/3) (1+z)^{-1}$.

We refer to any further dissipative contraction, which must be associated with drastic angular-momentum (AM) loss, as ‘wet compaction’ (Dekel & Burkert 2014; Zolotov et al. 2015). It leads to typical sizes for the forming RNs that are smaller than $0.04 R_v$, and

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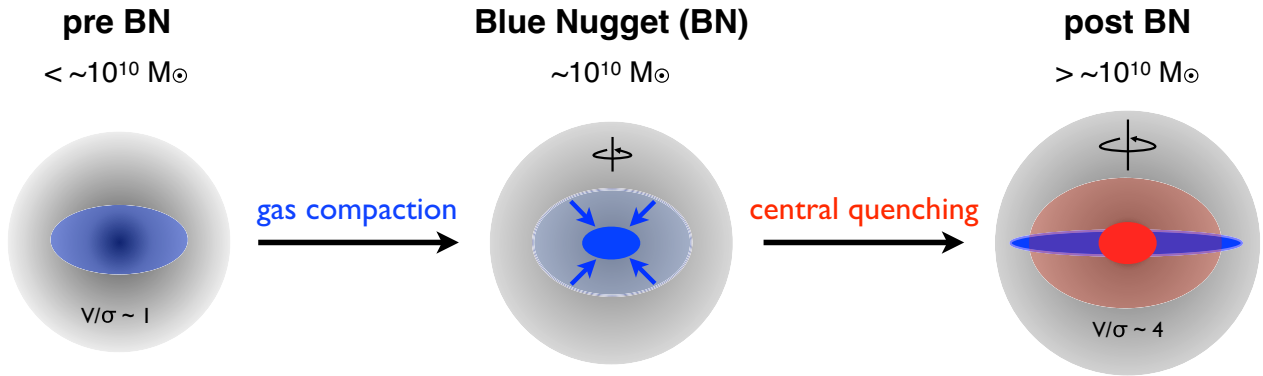


Figure 1. A cartoon illustrating the phases with respect to the BN at $M_s \sim 10^{10} M_\odot$. The pre-BN system is elongated, diffuse, and perturbed, only marginally supported by rotation and with a DM-dominated core. Gas compaction leads to a compact star-forming BN, which is baryon dominated. Post-BN, the gas is depleted from the centre leaving behind a compact passive nugget, while a new extended rotation-supported gas disc/ring and/or a stellar envelope develop.

predicts the existence of ‘blue nuggets’ (hereafter, BNs¹), namely compact, gas-rich, star-forming systems that are the immediate progenitors of the young RNs. Wet compaction is naturally expected at high z , where the accretion-merger rate is high (Neistein & Dekel 2008; Dekel et al. 2013) and where the gas fraction is high (Daddi et al. 2010; Tacconi et al. 2010, 2013, 2018; Freundlich et al. 2019; Tacconi, Genzel & Sternberg 2020). These permit frequent events of angular-momentum loss (Danovich et al. 2015) and allow the gas to fall in prior to its conversion into stars (Dekel & Burkert 2014).

Indeed, BNs are convincingly observed at $z \sim 2-3$, with consistent masses, structure, kinematics, and abundance for being the immediate progenitors of the RNs (Barro et al. 2013; Williams et al. 2014; Barro et al. 2014a, b; Van Dokkum et al. 2015; Williams et al. 2015; Barro et al. 2016a, b, 2017a). The observed sizes of the compact galaxies at $z \sim 2$ are on the order of 1 kpc (Tadaki 2016; Barro et al. 2016b), which is typically $\sim 0.01 R_v$, a factor of four smaller than that predicted without wet compaction associated with AM loss. This is a factor of ~ 64 in density. We conclude that the BNs must have formed by wet compaction events, thus explaining the compactness of both the BNs and the subsequent RNs.

Our cosmological simulations reveal a generic sequence of events in the evolution of galaxies at moderately high redshift, with dramatic consequences for the galaxy properties, as follows.

a. A typical high-redshift and low-mass galaxy is a gas-rich, star-forming, highly perturbed, and possibly rotating system, fed by intense streams from the cosmic web, including multiple wet mergers, which cause frequent spin flips (Dekel et al. 2020a).

b. When the stellar mass is in the ballpark of $\sim 10^{10} M_\odot$, the galaxy undergoes a major, last, wet compaction into a BN, starting with a compact gaseous star-forming system that rapidly turns into a compact stellar system.

c. A central gas-depletion process starts immediately after compaction, which leads to inside-out quenching into an RN.

d. Post compaction, there is sometimes a (partial) rejuvenation of a fresh extended gas-rich clumpy disc or ring about the compact stellar system and/or growth of an elliptical envelope by dry mergers.

Fig. 1 illustrates some of the properties of the three stages of evolution, pre-BN, the BN itself, and post-BN.

The BN phase thus marks major transitions in galaxy properties, which are key to understanding massive galaxies. These can be

translated to observable property dependencies on mass, redshift, position relative to the main sequence of star-forming galaxies, and galactocentric distance within each galaxy. In this paper, we explore these transitions using cosmological simulations. Table 1 lists many of the transitions of galaxy properties at the BN phase, to be elaborated on below, and listed with some more detail in Section 14.

As pointed out in Zolotov et al. (2015) and demonstrated in Tacchella et al. (2016a), the evolution of a galaxy through episodes of compaction and quenching is associated with a characteristic evolution with respect to the universal main sequence (MS) of star-forming galaxies (SFGs), as defined in the plane of specific star-formation rate (sSFR) versus stellar mass (M_s). Early oscillations about the MS ridge eventually bring the galaxy to a BN phase in the upper region of the MS (high sSFR), which triggers quenching of star-formation rate (SFR) towards the lower parts of the MS and down to the quenched regime, typically once more massive than $M_s \sim 10^{10} M_\odot$. This translates the transitions of galaxy properties through the phases of evolution to observable gradients along and across the MS as a function of M_s and sSFR, respectively.

The simulations reproduce the observed characteristic mass scale for galaxies at a stellar mass of $M_s \sim 10^{10-10.5} M_\odot$, or a dark matter halo mass of $\sim 10^{11.5-12} M_\odot$, roughly the same mass at all times. This mass scale is known to mark a peak in the efficiency of galaxy formation, as seen from the stellar-to-halo mass ratio (Moster et al. 2010; Moster, Naab & White 2013; Behroozi, Wechsler & Conroy 2013a; Rodríguez-Puebla et al. 2017; Moster, Naab & White 2018; Behroozi et al. 2019). It is imprinted as a peak time in the cosmic star-formation efficiency at $z \sim 1-2$ (Madau & Dickinson 2014) when the typical halo has a comparable mass (Press & Schechter 1974), and it marks a bimodality in many galaxy properties (e.g. Dekel & Birnboim 2006). We learn that the BN phase typically occurs in the ballpark of this mass scale, and the transitions associated with the BN phase are associated with the observed bimodality. Indications of a similar characteristic mass were also seen in observed galaxies from the *HST* CANDELS survey using machine learning models (Huertas-Company et al. 2018), revealing a preference for BNs near a stellar mass of $\sim 10^{10} M_\odot$. The rough constancy of this critical BN mass in time allows the useful advantage of translating the time evolution of galaxies through the BN phase to an observable mass dependence of galaxy properties. Several physical processes may give rise to this magic scale (Dekel, Lapiner & Dubois 2019), in particular, the upper limit for effective supernova-driven outflows at a virial velocity (or potential depth) of $V_v \sim 100 \text{ km s}^{-1}$ (Dekel & Silk 1986), and the threshold halo mass for virial shock heating (due to slow-enough

¹Most of the BNs may actually be red, by dust. They typically have lower U–V colours but higher V–J colours with respect to the RNs.

Table 1. Transitions in properties at the BN phase. The critical BN mass is marked as M_{BN} . Galaxy-scale properties are measured within $0.1R_v$. **Rows:** (1) M_s is the galaxy’s stellar mass. (2) M_v is the virial mass. (3) R_e is the 3D stellar half mass radius. (4) $\Sigma_{s,1\text{ kpc}}$ is the surface density of stars within 1 kpc. (5) $\Sigma_{g,1\text{ kpc}}$ is the surface density of gas within 1 kpc. (6) sSFR is the specific SFR. (7) t_{dep} is the depletion time (M_g/sSFR assuming that the SFR remains constant after the time of measurement). (8) f_{gs} is the gas fraction (M_g/M_s). (9) Z_g is the gas-phase metallicity. (10) ‘centre mass’ represents the dominant component (dark matter or baryons), see $f_{\text{DM}}(r < R_e)$. (11) ‘shape’ is the shape of the stellar component within R_e . (12) V/σ_g is the gas rotational velocity over velocity dispersion. (13) V/σ_s is the stellar rotational velocity over velocity dispersion. (14) ‘Jeans equil.’ represents whether or not Jeans equilibrium is valid in each phase. (15) ‘spin’ is the gas spin $\lambda_g = (J_g/M_g)/(\sqrt{2}V_v R_v)$. (16) $\Sigma_g(r)$ is the surface density of the gas as a function of radius. (17) $\Sigma_s(r)$ is the surface density of the stars as a function of radius. (18) $\text{sSFR}(r)$ is the specific SFR as a function of radius. (19) $Z_g(r)$ is the gas-phase metallicity as a function of radius. (20) ‘BH growth’ represents the mode of BH mass growth (suppressed or active accretion). (21) ‘feedback’ represents the most effective feedback in each phase.

Property	Pre BN	BN	Post BN
M_s	$<M_{\text{BN}}$	$M_{\text{BN}} \sim 10^{10} M_{\odot}$	$>M_{\text{BN}}$
M_v	$<M_{\text{BN}}$	$M_{\text{BN}} \sim 10^{12} M_{\odot}$	$>M_{\text{BN}}$
R_e	slow rise	contracted $\lesssim 1$ kpc	rapid rise
$\Sigma_{s,1\text{ kpc}}$	low	$> 10^{9.2} M_{\odot} \text{ kpc}^{-3}$	same high
$\Sigma_{g,1\text{ kpc}}$	low	$> 10^{8.7} M_{\odot} \text{ kpc}^{-3}$	very low
sSFR	MS	top of MS	quenching
t_{dep}	short	short	long
f_{gs}	high	higher	low
Z_g	rising	shoulder	plateau
centre mass	dark matter	mixed	baryon
shape	prolate	compact disc	oblate
V/σ_g	~ 1	rising	~ 4
V/σ_s	~ 1	V, σ_s rising	~ 1
Jeans equil.	crude		valid
spin	normal	low	high
$\Sigma_g(r)$	diffuse	compact	disc/ring
$\Sigma_s(r)$	diffuse	compact	compact
sSFR(r)	flat	declining	rising
$Z(r)$	shallow decline		steep decline
BH growth	slow by SN	activated, rapid	rapid \rightarrow self regul.
feedback	supernova		AGN

cooling) of the circum-galactic medium (CGM) (Birnboim & Dekel 2003; Dekel & Birnboim 2006). We will discuss how the processes responsible for this magic mass scale can combine to define the BN scale and a threshold for rapid black hole (BH) growth in the galaxy centre (Lapiner, Dekel & Dubois 2021) and, thus, an onset for AGN feedback, which in turn, helps quench the galaxy above this mass scale. We will discuss the mechanisms for the quenching process following the BN event, those triggered by the BN and maintained by the hot CGM and possibly AGN feedback. However, they deserve a detailed study using simulations incorporating black holes.

Several mechanisms could trigger the AM loss, which leads to a wet compaction event. These include major mergers, multiple minor mergers, counter-rotating streams, galactic fountains, violent disc instability, and more. Compaction is thus a generic process whose origin could be in a major merger but not necessarily so. We describe below preliminary results concerning the possible origins of compaction.

Our purpose in this paper is to present the characteristic details of the transitions in galaxy properties due to the wet compaction

events based on the VELA cosmological simulations. We will seek their origin and summarize observable predictions.

The paper is organized as follows. In Section 2, we present the simulations and discuss their limitations. In Section 3, we describe the phases of evolution as seen in the simulations, the way we identify the BN phase, and the associated characteristic mass. In Section 4, we connect the phases of evolution through the BN phase with the evolution of galaxies along and across the main sequence of SFGs and relate to observable gradients across the MS. In Section 5, we refer to the evolution of effective radii of galaxies. In Section 6, we address the transition in the overall shape of the galaxy as a result of the transition from dark matter to baryon central domination. In Section 7, we describe the transition in the kinematic properties of the galaxy and the validity of Jeans equilibrium for estimating dynamical masses. In Section 8, we study the evolution of metallicity through the BN phase. In Section 9, we summarize the evolution of profiles within the galaxy, including the DM fraction. In Section 10, we address the interplay between supernova feedback, black hole growth and the trigger of rapid black hole growth, and AGN activity by compaction at the critical mass. In Section 11, we address the origins of compaction. In Section 12, we estimate the abundance of BNs. In Section 13, we refer to results from other simulations. In Section 14, we summarize our results and conclusions.

In several sections, following the presentation of theory results, we refer to certain relevant observational results, but with little elaboration and no attempt to be complete. Detailed comparisons with observations are beyond the scope of this paper and are deferred to other papers by us and others. The same is true for comparisons with other simulations, which are discussed only briefly below.

2 SIMULATIONS

2.1 Method of simulation and analysis

We use zoom-in hydro-cosmological simulations of 32 moderately massive galaxies that comprise the VELA simulation suite (Ceverino et al. 2014; Zolotov et al. 2015). This is the generation-3 suite, in which radiation-pressure feedback has been added to earlier versions which were analysed in previous work. We have used this suite to study a variety of issues related to high-redshift galaxy evolution, including violent disc instability and clumpiness (Inoue et al. 2016; Mandelker et al. 2017), and the issues of compaction and quenching most relevant to the current paper (Zolotov et al. 2015; Ceverino, Primack & Dekel 2015b; Tomassetti et al. 2016; Tacchella et al. 2016a, b). We provide here a brief overview of the key aspects of the simulations, while more details are provided in Section A² and in Ceverino et al. (2014).

The VELA simulations utilize the ADAPTIVE REFINEMENT TREE (ART) code (Kravtsov, Klypin & Khokhlov 1997; Ceverino & Klypin 2009), which accurately follows the evolution of a gravitating N -body system and the Eulerian gas dynamics, with an AMR maximum resolution of ~ 25 pc in physical units at all times. The dark matter particle mass is $8.3 \times 10^4 M_{\odot}$, and the stellar particles have a minimum mass of $10^3 M_{\odot}$. This resolution is higher than in most current cosmological simulations, allowing a proper resolution of the central, compact ~ 1 kpc central regions of galaxies at $z \sim 1-5$, which are the subject of the current investigation.

Beyond gravity and hydrodynamics, the code incorporates the physics of gas and metal cooling, UV-background photoionization, stochastic star formation, gas recycling, stellar winds, and metal enrichment. The main feedback processes are thermal supernova feedback (Ceverino, Dekel & Bournaud 2010; Ceverino et al. 2012)

and radiative pressure from massive stars (Ceverino et al. 2014). AGN feedback is not included in the current simulations. The overall strength of the feedback in these simulations is on the moderate-low side compared to several other cosmological simulations that adopt stronger supernova feedback (e.g. Dubois et al. 2015; Wang et al. 2015) or stronger radiative feedback (e.g. Hopkins et al. 2014).

The initial conditions for the simulations are based on dark matter haloes drawn from dissipationless N -body simulations at lower resolution in larger cosmological boxes. We assume the standard Λ CDM cosmology with the WMAP5 cosmological parameters, namely $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$, $\Omega_b = 0.045$, $h = 0.7$, and $\sigma_8 = 0.82$ (Dunkley et al. 2009). The haloes were randomly selected from the haloes of a desired virial mass at $z = 1$ in the range $M_v = 10^{11.3-12.3} M_\odot$ uniformly distributed in $\log M_v$ with a median of $5.6 \times 10^{11} M_\odot$. The median halo mass at $z = 0$ would be $\sim 10^{12} M_\odot$, including massive galaxies and groups.

More than half the sample evolved to $z = 1$ (or later), and all but five evolved to $z \leq 2$. The simulation outputs were stored and analysed at times separated by fixed intervals of $\Delta a = 0.01$, where $a = (1 + z)^{-1}$ is the cosmological expansion factor, which at $z = 2$ corresponds to time-steps of about 100 Myr. Galaxies are found inside the haloes using the ADAPTAHOP group finder (Tweed et al. 2009; Colombi 2013) on the stellar particles. The central galaxy is identified in the final available output, and its main progenitor is traced back in time until it contains less than 100 stellar particles, typically at $a \sim 0.11$ ($z \sim 8$).

The virial mass M_v is defined as the total mass within a sphere of radius R_v that encompasses a given overdensity $\Delta(z)$ relative to the cosmological mean mass density, $\Delta(z) = (18\pi^2 - 82\Omega_\Lambda(z) - 39\Omega_\Lambda(z)^2)/\Omega_m(z)$, where $\Omega_m(z)$ and $\Omega_\Lambda(z)$ are the cosmological density parameters of mass and cosmological constant at z (Bryan & Norman 1998).

Table A1² lists halo and galaxy properties at $z = 2$, except for the five galaxies (marked by *) that were stopped at a higher redshift z_{fin} (specified in the table), for which, the properties are quoted at z_{fin} . For certain purposes, we divide the sample of galaxies into two sub-samples, a *high-mass* sub-sample and a *low-mass* sub-sample, according to the galaxy stellar mass at $z = 2$ being above and below the median value, $10^{10.06} M_\odot$, of the whole sample at that time.

The stellar mass M_s is the instantaneous mass in stars, typically within $0.1R_v$, accounting for past stellar mass loss. The SFR is obtained from the initial mass in stars younger than ~ 60 Myr, thus serving as a proxy for H_α -based SFR measurements (while UV-based measurements are sensitive to stars younger than ~ 100 Myr). The specific SFR is $\text{sSFR} = \text{SFR}/M_s$, the gas mass M_g is measured within the same volume, and the gas fraction is $f_g = M_g/(M_g + M_s)$.

2.2 Limitations of the current simulations

The cosmological simulations used in this paper are state-of-the-art in terms of high-resolution AMR hydrodynamics and the treatment of key physical processes at the subgrid level, highlighted above. These simulations successfully trace the cosmological streams that feed galaxies at high redshift, including mergers and smooth flows (e.g. Danovich et al. 2012, 2015; Goerdt et al. 2015; Ceverino et al. 2016a). They properly resolve the violent disc instability that governs high- z disc evolution and bulge formation (Mandelker et al. 2014, 2017), they reproduce galactic outflows (Ceverino et al. 2016b), and they capture the phenomenon of wet compaction on 1 kpc scales and its implications (Zolotov et al. 2015; Tacchella et al. 2016a, b).

However, like other simulations, they are not perfect in their treatment of star formation and feedback processes. While the SFR

recipe was calibrated to reproduce the Kennicutt–Schmidt relation and a realistic SFR efficiency per free-fall time (Ceverino et al. 2014), the code does not yet follow in detail the formation of molecules and the effect of metallicity on SFR (Krumholz & Dekel 2012). The resolution does not capture the Sedov–Taylor adiabatic phase of supernova feedback, where most of the energy and momentum is deposited in the ISM, which introduces significant uncertainty in the feedback strength (Gentry et al. 2017). The adopted radiative stellar feedback assumes low infrared trapping, in the spirit of the low trapping advocated by Dekel & Krumholz (2013) based on Krumholz & Thompson (2013). However, there is an ongoing controversy concerning the level of trapping (Murray, Quataert & Thompson 2010) and the counter effect of photon leakage through a porous medium (Hopkins, Quataert & Murray 2011), which led others to adopt stronger radiative feedback (Genel et al. 2012; Hopkins, Quataert & Murray 2012a; Hopkins et al. 2012b, 2014; Oklopčić et al. 2017). Finally, AGN feedback and feedback associated with cosmic rays and magnetic fields are not incorporated in the current VELA simulations.

The resultant star formation rates, gas fractions, and stellar-to-halo mass ratios are in the ballpark of the estimates deduced from observations based on abundance matching (Moster et al. 2010, 2013, 2018; Behroozi et al. 2013a, 2019; Rodríguez-Puebla et al. 2017), though with apparent mismatches by factors of order two. These offsets are comparable to the observational uncertainties, which can be estimated from the fact that other measurements, based on the kinematics of $z \sim 0.6$ –2.8 galaxies (Burkert et al. 2016, fig. 7)², reveal larger stellar-to-halo mass ratios for galaxies in the relevant mass range $M_v < 10^{12} M_\odot$ (see Mandelker et al. 2017, fig. 3). These uncertainties in accurately matching certain observations may lead to quantitative inaccuracies in the estimated characteristic masses and redshifts associated with certain events. Still, one can assume that these simulations properly capture the qualitative features of these events.

The details of the phenomena addressed in the current paper may depend on the strength of feedback effects and the resultant gas fraction. While one may assume that the VELA simulations qualitatively capture the effects of compaction and the associated transitions in galaxy properties, it will be important to study the effects of feedback on these phenomena in simulations that incorporate the feedback effects in different ways. For this purpose, we briefly refer in Section 13 to results from the NEWHORIZON simulations (Dubois et al. 2021), which incorporate strong supernova feedback as well as AGN feedback, showing similar compaction events (Lapiner et al. 2021) as seen in this work. In addition, we discuss preliminary results showing signatures of compaction events in the NIHAO simulations (Wang et al. 2015) and in the VELA6 simulations (Ceverino et al. 2022), both of which incorporate stronger supernova feedback.

3 PHASES OF EVOLUTION THROUGH THE BN: CENTRAL MASSES AND SFR

The generic pattern of evolution revealed by our simulations, from a diffuse galaxy through compaction to a BN and the following quenching, has been first pointed out in Zolotov et al. (2015). Here, we use the whole sample of simulations to explore the systematic evolution through a BN phase and demonstrate the associated characteristic mass.

²We note that these galaxies do not constitute a statistical sample (~ 360), and were selected to be SF discs.

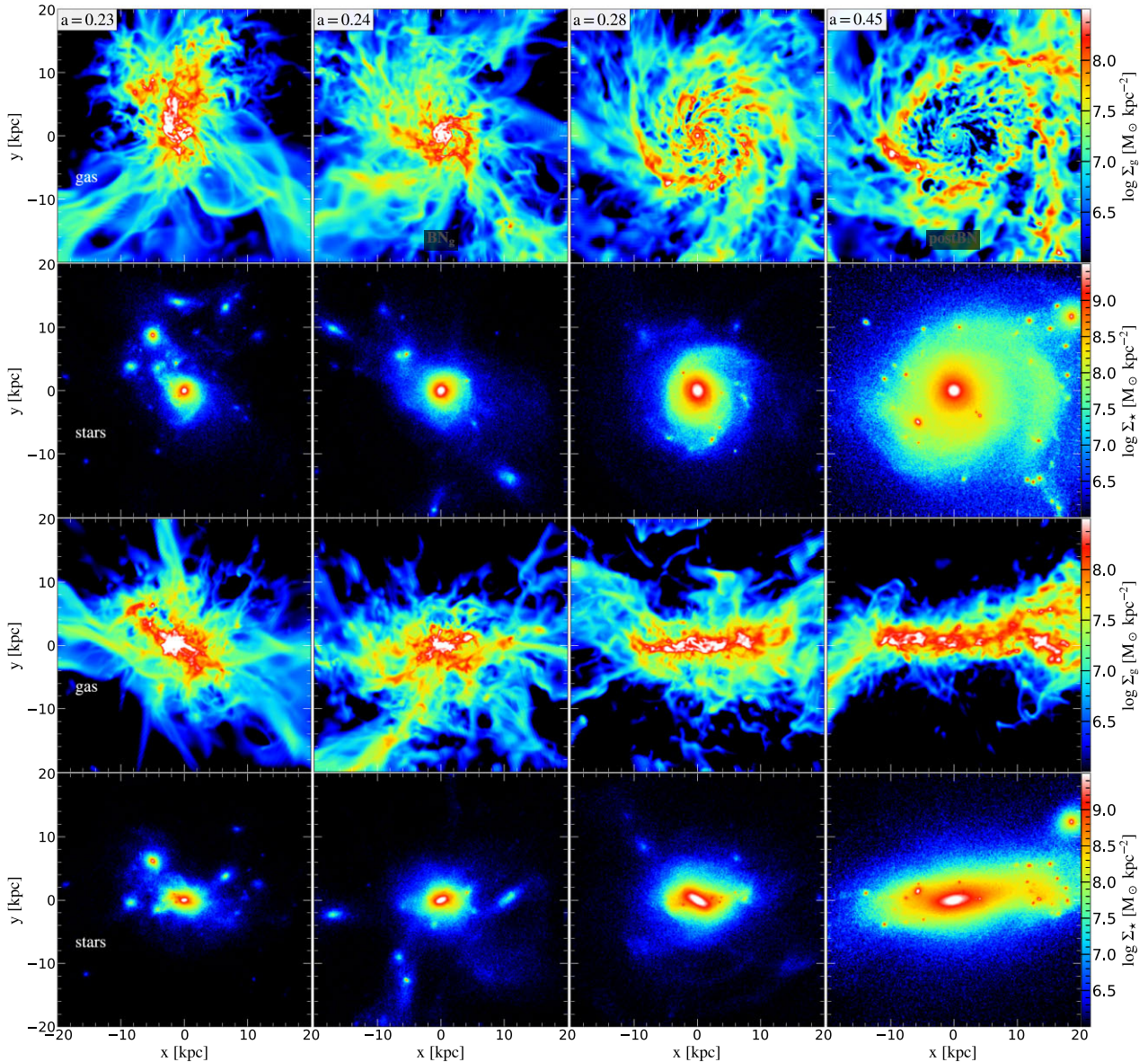


Figure 2. The evolution of V07 through the BN phase in pictures. Shown are the projected densities in gas (first and third row) and stars (second and fourth row), face-on (top two rows) and edge-on (bottom two rows). Gas compaction forms a compact, star-forming BN that leads to a compact stellar core. The latter remains compact while the gas depletes from the core that passively turns into a RN. The newly accreted gas forms an extended star-forming clumpy ring about the RN, and a stellar envelope grows by dry minor mergers. An additional example is shown in Fig. D1².

3.1 Example galaxies

Fig. 2 shows images of one galaxy, V07, at several stages of evolution. Shown are gas and stellar mass density, face-on (top) and edge-on (bottom). The first snapshot, at $a = 0.23$, is during the gas compaction phase, associated with intense multiple streams and minor mergers. The second snapshot, $a = 0.24$, is at the peak of gas density within the inner 1 kpc, which marks the gas BN phase, BN $_{\text{g}}$. The third and fourth snapshots, at $a = 0.28$ and much later at $a = 0.45$, demonstrate central gas depletion and the growth of an extended clumpy gaseous disc, eventually a ring, fed by in-spiralling fresh streams. The spatial distribution of SFR and young stars is similar to that of gas above a certain threshold density (see Fig. D2²). In terms of the stellar distribution, a compact stellar core emerges soon after the formation

of a gas core, to be identified as the stellar BN phase, BN $_{\text{s}}$. The stellar core remains compact at a rather constant density as it passively evolves into a compact RN. A stellar envelope develops around it in a disc/ring following the gas and in a spheroidal envelope due to dry minor mergers. Images of another galaxy, V12, are shown in Fig. D1².

Fig. 3 shows the time evolution of masses and SFR for two example galaxies, V07, and V12. Shown are the DM, gas, stellar mass and the SFR as a function of z . These quantities refer to either the inner 1 kpc (solid) or the whole galaxy out to $0.1R_v$ (dashed). The four events associated with the BN, as defined within 1 kpc, are marked: the peak of gas density (BN $_{\text{g}}$, at $z \sim 3.2, 4$, respectively), the shoulder of stellar density (BN $_{\text{s}}$, $z \sim 3, 3.8$), the onset of compaction (OC, $z \sim 3.5, 4.6$) and the transition from DM to baryon dominance (DM-

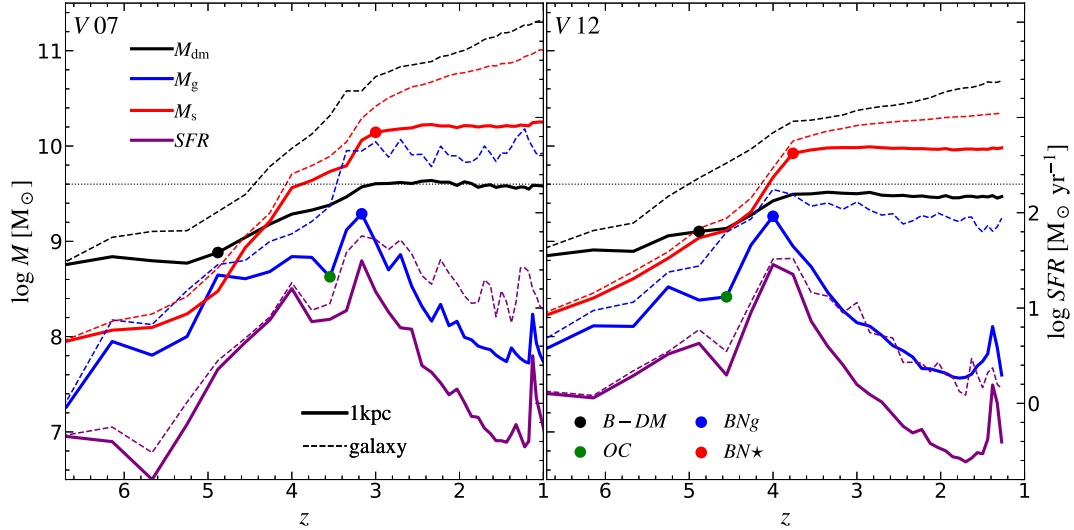


Figure 3. Examples (V07, V12) of the evolution of mass and its rate of change within 1 kpc (solid) and for the whole galaxy within $0.1R_v$ (dashed), as a function of expansion factor a . Shown are the masses of gas (blue), stars (red), dark matter (black), and SFR (purple). The BN is identified by the sharp peak in gas mass (or SFR) within 1 kpc and the subsequent saturation of the compact stellar mass to its high value. The transition from central dominance of dark matter to baryon dominance occurs in association with the BN.

B, $z \sim 5$). The compaction phase is seen as a drastic increase in central gas density and SFR, by order of magnitude, from OC to BNg. Immediately following is a gradual central gas depletion associated with the quenching of SFR. The central stellar mass is growing rapidly during the increase in central gas. It continues to grow after the peak of central gas and SFR until it flattens off at BN*, after which, it keeps a rather constant stellar density within the inner 1 kpc.

The evolution of the same quantities for the whole galaxy shows a more gradual quenching post-BN, associated with the formation of an extended disc or ring from fresh gas.

Fig. 4 shows the evolution tracks of V07 and V12 in the plane of overall sSFR and an inner measure of compactness, $\Sigma_{1\text{kpc}}$, the stellar surface density within 1 kpc (solid) or Σ_e within R_e (dashed). It shows an L-shape evolution pattern, where a phase of compaction at a roughly constant sSFR abruptly turns into a phase of quenching at a roughly constant $\Sigma_{1\text{kpc}}$. The turning point marks the BN* event, at which the galaxy spends a rather short time.

The evolution track with respect to R_e is similar pre-BN when R_e is comparable to 1 kpc. Post-BN, the quenching is associated with a gradual decrease in Σ_e due to the increase in R_e with time (Section 5).

Certain other galaxies in the simulations show a similar L-shape track which is preceded by several oscillatory episodes of minor compaction and quenching attempts. These oscillations eventually end with a more drastic compaction to a major BN phase, followed by fuller quenching, typically once the halo mass exceeds a threshold of $\sim 10^{11.5} M_\odot$ (Zolotov et al. 2015, Fig. 21). The characteristic mass is demonstrated below in Fig. 10.

3.2 Identifying the BN

We try to identify one major BN phase for each galaxy, the one that leads to significant central gas depletion and SFR quenching (second column in Table A2², $a_{\text{comp}^1:\text{BNg}}$). The most physical way to define it is at the highest peak of central gas density, as identified in Fig. 3

using the inner 1 kpc³, as long as a significant, long-term decline follows it in central gas mass and SFR. We term this event BNg. This event coincides with the peak in SFR, and it would be the observable BN if it is based on peak central SFR. The curve of central gas density also allows us to identify the onset of compaction, termed OC, as the start of the steep rise prior to the BNg.

An alternative for identifying the BN is by the shoulder where the inner stellar density in Fig. 3, or $\Sigma_{1\text{kpc}}$ in Fig. 4, reaches its plateau of maximum long-term compactness, slightly after the BNg. We term this event BN* and note that it may be closer to the BN phase as identified observationally based on the compactness of the stellar component.

Fig. 3 also reveals another characteristic feature associated with the onset of the BN phase, namely a transition of the core from being dominated by dark matter to being dominated by baryons, mostly stars. We refer to this event as the DM-B transition, to be discussed in Section 3.4. Finally, a fifth way to identify the BN phase is by its kinematic characteristics, to be described in Section 7.

3.3 Systematic evolution through the BN

In Fig. 5 (and Fig. D9²) we consider all the time-steps of the high-mass subsample of galaxies (with stellar mass above the median at $z = 2$). The same but for the low-mass subsample is shown in Fig. D10² (and Fig. D11²). In each figure, the top row refers to the inner sphere of radius 1 kpc and the bottom row to the whole galaxy out to $0.1R_v$. The four panels in each row refer to the quantities stellar mass (M_s), gas mass (M_g), dark matter mass (M_{DM}), and star-formation rate (SFR). The colour denotes Δ_{MS} , the sSFR with respect to the universal main sequence ridge (see Section 4 below). In Fig. 5, these quantities are shown versus the cosmological expansion factor $a = (1+z)^{-1}$ and stacked (normalized) with respect to the peak of the major compaction event as measured by the central gas density, namely, the BNg event at a_{BNg} . The curves mark the median in bins

³See Section A3² for the choice of 1 kpc in the identification of compaction.

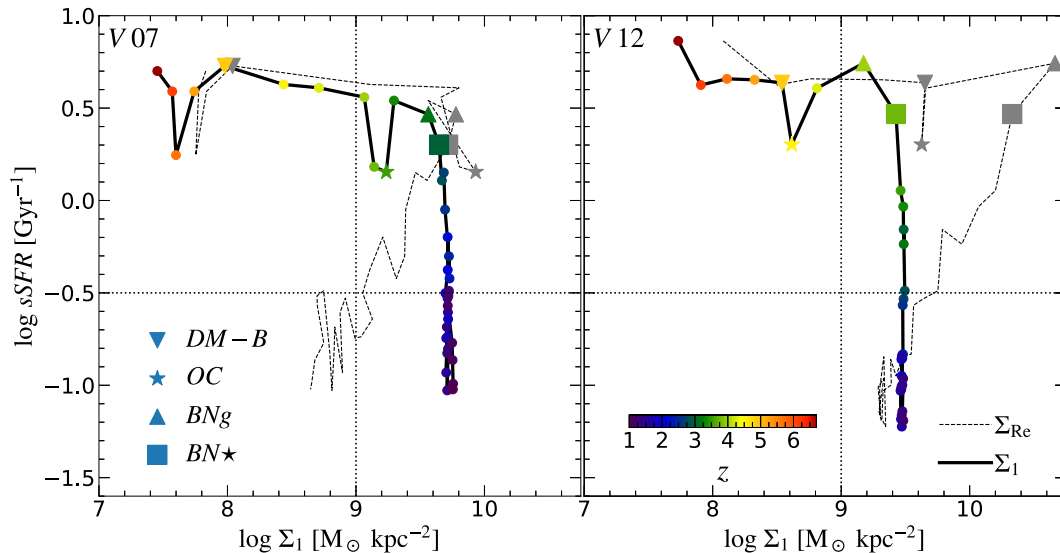


Figure 4. Examples (V07, V12) of evolution tracks in the plane of sSFR and stellar compactness, as measured by $\Sigma_{1\text{kpc}}$ (solid) or Σ_e (dashed). The colour marks redshift. The typical track has an L shape, starting with a compaction phase at a constant sSFR and turning at the BN* (at $z \sim 3, 3.8$) into quenching at a constant $\Sigma_{1\text{kpc}}$.

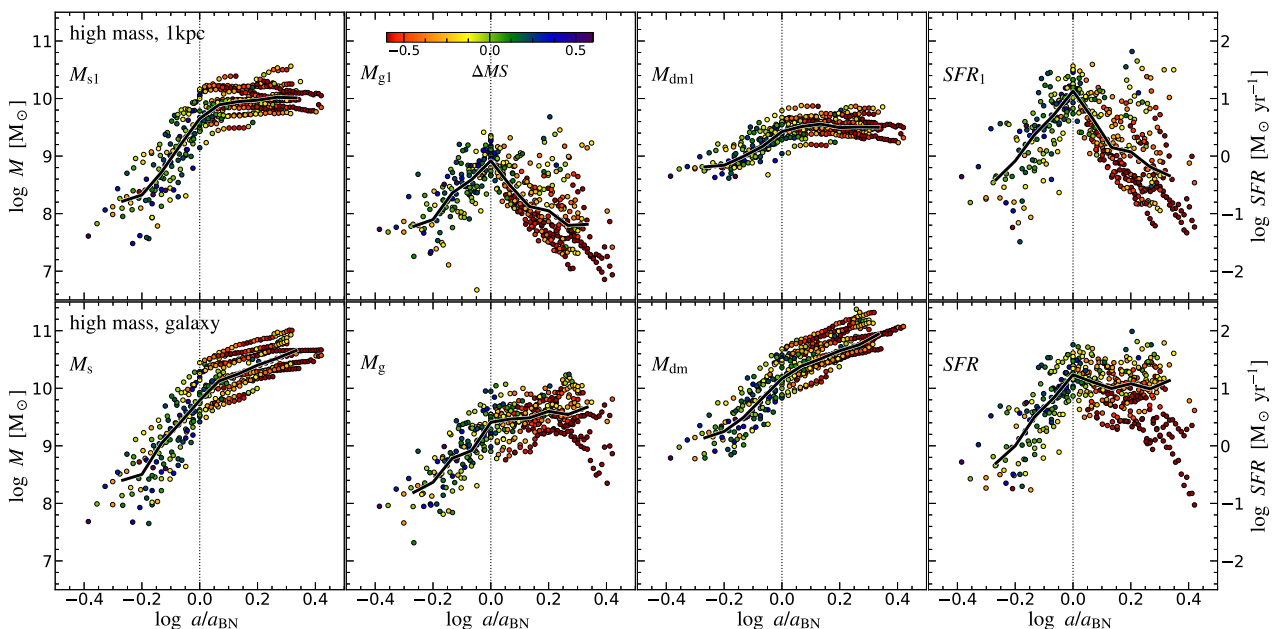


Figure 5. Evolution of global properties. All snapshots for the high-mass subsample are stacked such that the time is with respect to the BN (BNg). The properties refer to the inner 1 kpc (top, marked with a subscript ‘1’) or the whole galaxy within $0.1R_v$ (bottom). Shown are stellar mass, gas mass, dark matter mass, and SFR. Colour marks the deviations of sSFR from the universal main sequence, ΔM_S (see equation 1). The median in equal log bins is marked (black line). The BN is best identified by a peak in M_{g1} or SFR_1 , followed by a shoulder in M_{s1} . Fig. D10² shows the same for the low-mass subsample.

of a/a_{BNg} . Here and in similar calculations throughout the paper, before measuring the median in bins, we first calculate the median of each galaxy within each bin, thus preventing the possibility that one galaxy with many time-steps in one bin will dominate the median value. These median curves are displayed together in Fig. 6.

We see a universal evolution pattern shared by almost all the higher mass galaxies with a relatively small scatter about the median. We focus first on the inner 1 kpc shown in the top row. The mass within a sphere of 1 kpc serves as a proxy for the surface density within

a circle of 1 kpc (where, we approximate the stellar surface density by $\Sigma(<r) \sim M_s(<r)/(\pi r^2)$, e.g. M_{s1} approximates the observable central stellar surface density $\Sigma_{1\text{kpc}}$ (Zolotov et al. 2015), which is commonly used to identify compact BNs and RNs in observations.

A wet compaction phase is easily identified in the gas evolution (second column), where the central gas density rises steeply by an order of magnitude from the onset of compaction at $\sim 0.63 a_{\text{BNg}}$ up to a_{BNg} . Following a sharp peak at a_{BNg} , the central gas density steeply declines immediately thereafter. The central SFR follows the central

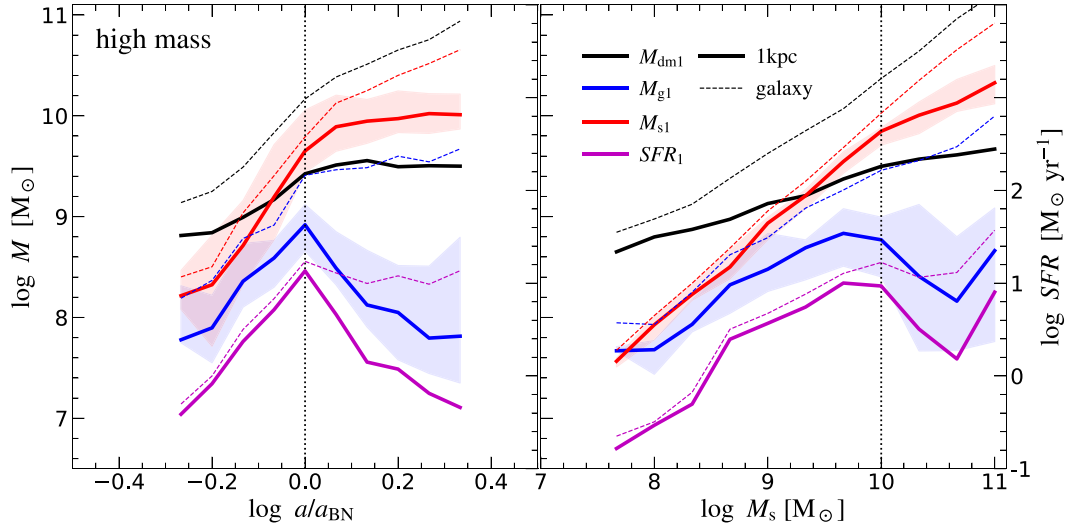


Figure 6. The medians for the properties shown in Fig. 5 and Fig. D9² are put together here for the inner 1 kpc (solid) and the whole galaxy (dashed). The shaded regions indicate the 1σ scatter about the median for the gas and stellar mass within 1 kpc (see Fig. D12² for the low-mass subsample). The BN is characterized by a peak in M_{g1} and SFR_1 and by a transition from central dark matter dominance to baryon (mostly stellar) dominance.

gas density, reflecting the Kennicutt–Schmidt law, $SFR \propto \Sigma_{\text{gas}}^{1.5}$. There is a sharp peak of SFR at the BN event, immediately followed by a central quenching process. A steep rise in central stellar density follows the rising gas and SFR density during the gas compaction phase, as gas efficiently turns into stars. This rise continues till $a_{\text{BN}\star} \sim 1.35a_{\text{BNg}}$, where the stellar density sharply flattens to a plateau. The central stellar density remains constant afterwards as the core quenches to a passive RN.

Before $\text{BN}\star$, $\Sigma_{1\text{kpc}}$ rises at a roughly constant sSFR, as indicated by comparing the SFR to M_s for the whole galaxy or by the colours of the symbols referring to Δ_{MS} . Post- $\text{BN}\star$, the sSFR (or Δ_{MS}) is declining at a rather constant $\Sigma_{1\text{kpc}}$. This is responsible for the universal L-shape in the sSFR- $\Sigma_{1\text{kpc}}$ diagram, as seen in Fig. 4 and in Section 3.5 below.

Turning to the galaxy as a whole, for the massive subsample, in the bottom row of Fig. 5, the BN event is still well defined. The pre-BN evolution is similar to the evolution in the inner 1 kpc because the effective radius is comparable to 1 kpc and because most of the star formation occurs there during the compaction phase. Post-BN, the total gas mass remains roughly constant; and even rises slowly, reflecting the formation of a new extended disc or ring while obeying the predictions of the bathtub model in a quasi-steady state for a constant gas mass (Dekel & Mandelker 2014). The overall SFR remains roughly constant for a while until $\sim 2a_{\text{BNg}}$, after which it drops. Therefore, the overall stellar mass keeps rising gradually in the post-BN phase. As a result, the sSFR is declining, eventually driving the galaxy below the MS, which reflects an overall quenching of star formation.

The low-mass sample shown in Fig. D10² tends to have the BN event at a similar critical mass (see below), hence at later times, when the gas fraction is lower. As a result, the central gas compaction is slower, it grows only by a factor of ~ 4 in density, the peak central gas density is lower, and so are the central SFR and the central stellar mass density $\Sigma_{1\text{kpc}}$ at the BN event. Nevertheless, the total stellar mass at a_{BNg} is comparable for the low-mass and massive galaxies.

Fig. D9² and Fig. D11² show the same quantities as in Fig. 5 and Fig. D10² but against the total stellar mass M_s instead of a/a_{BNg} , now without any x -axis scaling of the individual galaxies. The right-

hand panels of Fig. 6 show the corresponding medians in comparison to each other. The stacked evolution tracks are qualitatively similar to the tracks when plotted against a/a_{BNg} . The peak of central gas density and SFR always occurs near a critical total stellar mass of $M_s \sim 10^{9.5-10} M_{\odot}$, with the sharpness of the peak somewhat smeared. Pre-BN, the rise of the core gas density as a function of M_s , is similar to the rise as a function of a/a_{BNg} , but the post-BN drop as a function of M_s is steeper because the growth rate of M_s is suppressed in this quenching phase. The low-mass galaxies in our sample tend to reach the BN phase toward $z \sim 1$ when they reach the critical mass. This is when many of our simulations stop, which makes it harder to analyse the BN phenomenon in some of these low-mass galaxies.

3.4 Central dark matter to baryon dominance

One of the important transitions due to the compaction process is a transition from central dark matter dominance to baryon dominance. This transition and its association with the BN phase is clearly identified in Fig. 6 close to the crossing of the dark matter and stellar mass growth curves (black and red curves). The DM-B transition in the inner 1 kpc occurs near the same critical mass that characterizes the BN. For the whole galaxy, within $0.1R_e$, the dark matter always dominates over the baryons, but only by a factor of $\sim 2-3$.

Fig. 7 shows the dark matter fraction within R_e as a function of a/a_{BN} and as a function of M_s . It demonstrates the sharp transition due to the gas compaction from DM dominance pre-BN, at a level of $f_{\text{DM}} \sim 0.8$, to baryon dominance post-BN, with $f_{\text{DM}}(r < R_e) \sim 0.2$ for the high-mass subsample, and some cases as low as ~ 0.1 . During the post-BN phase, the central dark matter fraction is somewhat increasing. This is partly caused by the post-BN increase in the effective radius R_e (see Fig. 13). The transition in the central DM fraction is associated with a transition in shape, as discussed in Ceverino et al. (2015b), Tomassetti et al. (2016), and Section 6. Within $2R_e$ (Fig. D3²) we find a slightly higher f_{DM} , ~ 0.3 for the high-mass subsample.

The profiles of dark matter fraction, $f_{\text{DM}}(r)$, are shown in Fig. 23 at four evolutionary phases: pre-BN, BN, post-BN, and a late post-BN quenching phase (see Section 9). We see a significant decrease in the

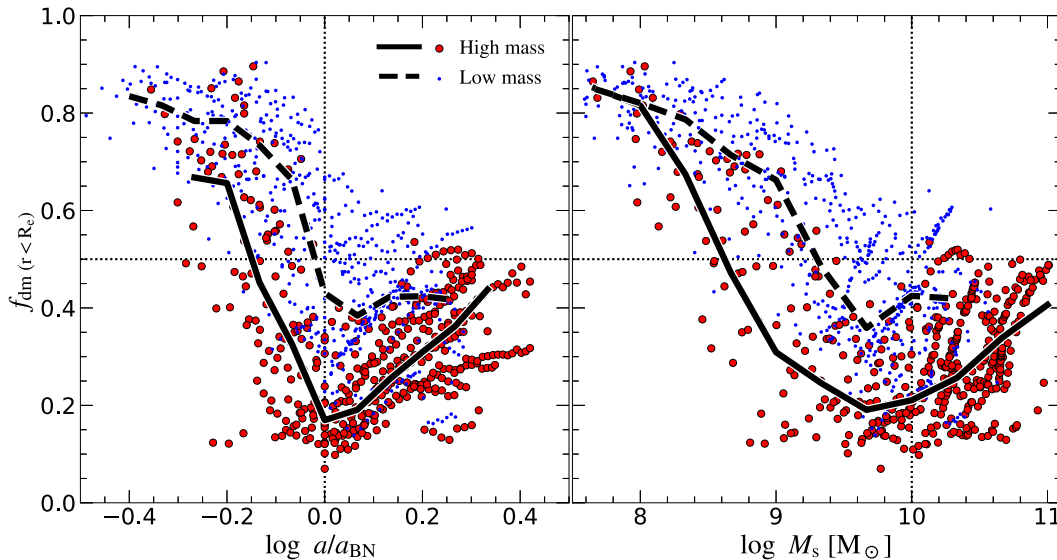


Figure 7. Dark matter fraction within R_e as a function of a/a_{BN} and M_s . Shown are all snapshots divided at $z \sim 2$ to a high-mass (red symbols, median in solid black line), and a low-mass (blue, dashed line) subsamples. The dark matter fraction is high pre-BN and drops to low values during compaction. Post-BN, f_{DM} is mildly rising, partly due to an increase in R_e . The qualitative similarity between the two panels demonstrates that the evolution with respect to the BN phase (left) can be translated to evolution with respect to the critical mass (right).

central dark matter fraction during the transition from the pre-BN phase to the peak of compaction at the BN and only mild central evolution in the post-compaction phases.

3.5 L Shape

Fig. 8 puts together typical evolution tracks of galaxies in the plane of sSFR versus $\Sigma_{1 \text{ kpc}}$. Stellar mass is indicated by colour, starting from $M_s > 10^{7.5} M_\odot$. Shown on the left are eight galaxies from our high-mass subsample, where the BN tends to occur at high redshift, $z \sim 4-2$. These galaxies demonstrate the characteristic L-shaped track, where pre-compaction, the galaxies are initially diffuse with low $\Sigma_{1 \text{ kpc}}$. They then evolve with a rather constant and slowly declining sSFR as they shrink into a BN once $M_s \sim 10^{9-9.5} M_\odot$. This is the trigger for an abrupt change in the evolution track, where the galaxies start their quenching process in which the sSFR is dropping while $\Sigma_{1 \text{ kpc}}$ remains roughly constant at $\Sigma_{1 \text{ kpc}} \sim 10^{9.5} M_\odot \text{ kpc}^{-2}$.

As discussed in Section 2, in most of the simulated galaxies, the quenching is not complete by the end of the simulations at $z \sim 2-1$ (partly due to the moderate-strength stellar/supernova feedback incorporated and the lack of AGN feedback). Still, the early stages of the quenching process are clearly identified.

The right panel of Fig. 8 shows eight galaxies from our low-mass subsample, where the BN tends to occur at lower redshifts, $z \sim 2-1$. Before the major compaction event, which occurs above the critical BN mass, these galaxies may show bigger oscillations in sSFR, indicating episodes of compaction and quenching attempts followed by rejuvenation Section 4. Nevertheless, the transition at the BN into quenching along an L-shape track is still clear. It occurs above the same critical BN mass as for the high-mass subsample, but with the quenching at a somewhat lower value of $\Sigma_{1 \text{ kpc}} \sim 10^9 M_\odot \text{ kpc}^{-2}$. The slow decline of the critical $\Sigma_{1 \text{ kpc}}$ with time is related to both the cosmological decrease in density and the decline of gas fraction with time, making the galaxy less susceptible to instabilities (as discussed in, e.g. Dekel & Burkert 2014), and resulting in a less dissipative contraction and smaller collapse factor.

3.6 A characteristic BN mass

The characteristic mass (or velocity) of the BN phase in the simulations is demonstrated in Figs 9 and 10, which refer to the global galaxy properties of stellar mass, virial mass and virial velocity. In Fig. 9, these quantities are plotted as a function of a/a_{BNg} for all snapshots of all galaxies in the sample. One can see that the halo mass is growing continuously, following on average $M_v \propto \exp(-\alpha z)$ with $\alpha \sim 0.8$, as predicted in the EdS regime at $z \geq 1$ (Dekel et al. 2013). At a_{BNg} , it has a characteristic value of $M_v = 10^{11.24 \pm 0.3} M_\odot$, the same for the massive and low-mass subsamples. The stellar mass grows at a similar pace before the BN event, and its growth is flattened off soon after this event. The critical value of the stellar mass at a_{BNg} for the whole sample is $M_s = 10^{9.6 \pm 0.3} M_\odot$, the same for the massive and low-mass subsamples. Huertas-Company et al. (2018) identified a consistent preferred characteristic stellar mass of $\sim 10^{10} M_\odot$ for BNs, by applying deep learning models on observed galaxies from the *HST* CANDELS survey.

The corresponding characteristic virial velocity at a_{BNg} is $\sim 125 \pm 25 \text{ km s}^{-1}$. The virial velocity post-BN is lower for the low-mass subsample. This is consistent with the virial relation $V_v \propto M_v^{1/3} a^{-1/2}$ and the fact that the BN occurs at later times for low-mass galaxies. At the time of the BN, the scatter in V_v is similar to the scatter in $M_v^{1/3}$, with the median V_v of the low-mass subsample lower by 0.1 dex than that of the massive subsample.

In figure Fig. B1², we show the circular velocity, V_e , measured within R_e . Although we see similar qualitative behaviour in V_e , as seen in V_v , the central circular velocity shows a significant scatter, with a factor of ~ 2 difference between the low-mass and high-mass subsample around the time of compaction. This is an indication of the weaker compactions experienced by the low-mass galaxies, which results in lower concentration (see Section B²).

Fig. 10 shows the same global properties for each galaxy at the slightly different events associated with the BN phase as a function of the time a when the event occurs. The events, referring to the inner 1 kpc, are the DM-B transition, the onset of compaction OC, the peak

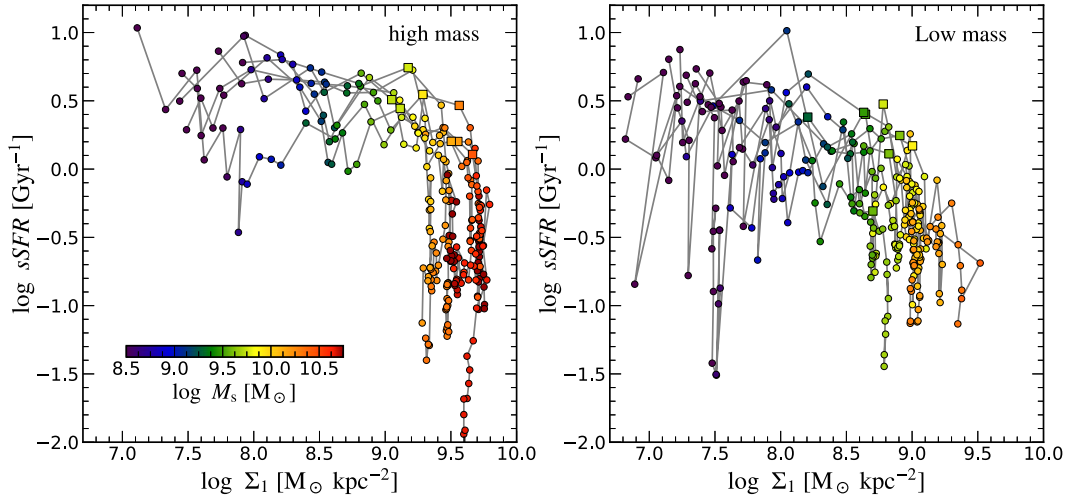


Figure 8. Typical L-shape evolution tracks in sSFR versus $\Sigma_{1 \text{ kpc}}$. Stellar mass is indicated by colour, starting from $M_s > 10^{7.5} M_\odot$. **Left:** Eight galaxies from our high-mass subsample, where the BN occurs at high redshift. The characteristic track is L-shaped: an early evolution as an SFG at a constant or slowly declining sSFR that changes abruptly at the BN phase (marked by squares) to quenching at a constant $\Sigma_{1 \text{ kpc}}$. This resembles the observed universal L-shape pattern in Fig. 9 of Barro et al. (2017a). **Right:** Eight galaxies from our low-mass subsample, where the BN occurs at a lower redshift. In the pre-BN phase, the oscillations in sSFR are larger, but the transition at the BN into quenching along an L-shape track is still apparent, with a somewhat lower $\Sigma_{1 \text{ kpc}}$ during the quenching. We find an indication for stronger major compaction events in the high-mass subsample compared to the low-mass subsample (see Section A3²).

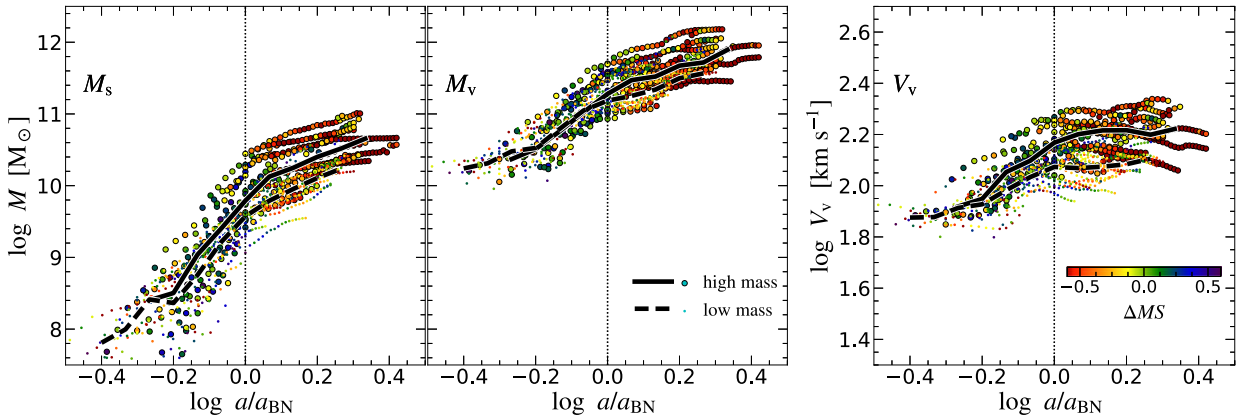


Figure 9. Characteristic BN mass. Shown are the stellar mass, virial mass and the virial velocity, as a function of time (expansion factor), stacked with respect to the BN time (a_{BN}). The medians are shown for the high-mass (solid) and low-mass (dashed) subsamples. The colour marks the deviation from the MS. The BN occurs at characteristic values of M_s and M_v , with a small scatter. The value of V_v is somewhat lower for the low-mass subsample (a later BN).

of gas density and onset of central quenching BNg, and the shoulder of peak stellar density BN \star where it turns into a plateau. The log y range of the velocities is one-third of that of the masses to reflect the virial relation $V \propto M^{1/3}$ with a characteristic density for all haloes at a given time.

All the quantities show a weak or no systematic variation with time. The trends with the time of the virial mass and velocity are related through $V_v \propto M_v^{1/3} a^{-1/2}$, which explains why the velocities are constant or slowly declining with time while the masses are constant or slowly growing.

The virial quantities M_v and V_v tend to show a smaller scatter than the galaxy quantity M_s , possibly indicating that the driving of compaction is more strongly associated with the halo properties.

While there are promising indications of a similar critical BN stellar mass in observed galaxies (Huertas-Company et al. 2018), it should be noted that the value found in simulations could be subject to the implemented feedback. One may assume that the simulations

capture a qualitative representation of the compaction process and its effect on the galaxy, keeping in mind their limitations (e.g. the deviation from the stellar-to-halo mass relation, see Section 2.2). When the compaction process is examined in simulations with a given feedback recipe, we expect the BN mass scale will maintain a critical value with little to no time dependence. We will assume throughout the paper that the critical BN stellar mass is in the ballpark of $\sim 10^{10} M_\odot$ and a halo mass of $\sim 10^{12} M_\odot$. To further study the effect of feedback, we briefly discuss in Section 13, the occurrence of compaction events (Lapiner et al. 2021) in the NEWHORIZON simulations (Dubois et al. 2021), and preliminary results from the NIHAO simulations (Wang et al. 2015) and the VELA6 simulations (Ceverino et al. 2022).

The DM-B transition tends to occur soon after the onset of compaction OC, followed by the BNg, which the BN \star immediately follow. The duration from OC to BN \star is typically $\Delta \log a \sim 0.2$, corresponding to $\Delta t/t \sim 0.3$ (Zolotov et al. 2015, fig. 16). During

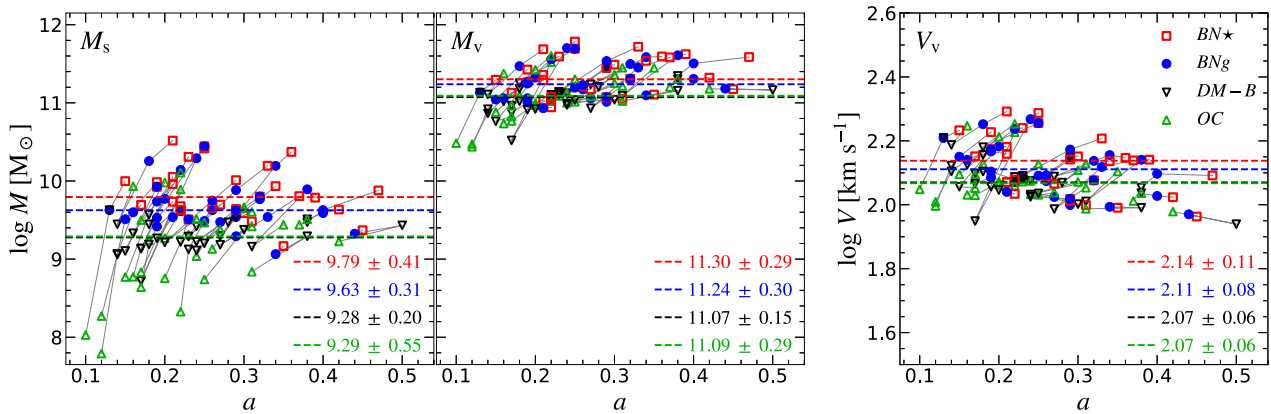


Figure 10. Characteristic BN mass at four events associated with the compaction phase. Shown from left to right are the stellar mass, virial mass, and virial velocity as a function of the expansion factor. We show the entire sample where each galaxy is marked four times, once for each compaction-associated event. The four events are as follows: (1) OC, the onset of compaction (green), (2) DM-B, transition from central DM to baryon dominance (black), (3) BNg, the peak of compaction measured in central gas density (blue), (4) BN*, the shoulder of a plateau in central stellar density (red). The median masses (and velocities) are shown in dashed horizontal lines, with values of the medians and the 1σ scatter quoted for each event. The BN occurs at a characteristic mass or velocity with negligible time dependence. The halo quantities, M_v and V_v show a smaller scatter, displaying a similar scatter given the virial relation $V_v \sim M_v^{1/3}$.

the compaction, while the halo mass typically grows by 0.2 dex, the stellar mass within 1 kpc typically grows by 0.5 dex.

In summary, the events associated with the BN phase occur at a critical mass to within a factor of two, rather independent of redshift. The medians of the OC, DM-B, BNg, and BN* events are respectively at $\log M_s/M_\odot \sim 9.3, 9.3, 9.6, 9.8$, $\log M_v/M_\odot \sim 11.1, 11.1, 11.2, 11.3$, and $\log V_v/\text{km s}^{-1} \sim 2.07, 2.07, 2.10, 2.14$. Therefore, the mass or velocity are proxies for al_{BNg} .

3.7 Comparison to observations

The L-shape evolution tracks in Fig. 8 are remarkably similar to the observed population of galaxies in the plane of sSFR versus $\Sigma_{1\text{kpc}}$. Fig. 6 of Barro et al. (2017a) shows this for CANDELS galaxies in redshift bins in the range $z = 0.5-3.0$. Fig. 7 of that paper shows the galaxies of all redshifts stacked, where the weak redshift dependence of the threshold $\Sigma_{1\text{kpc}}$ for nuggets (determined by the RNs) is scaled out, demonstrating that the L-shape is universal. This is a version of earlier presentations, e.g. fig. 2 of Barro et al. (2013) also spanning $z = 0.5-3.0$, Cheung et al. (2012) based on the DEEP/AGEIS survey at $z = 0.5-0.8$, and low-redshift SDSS galaxies in Fang et al. (2013) and Woo et al. (2017). Similar results are shown in figs 13–15 of Mosleh et al. (2017) for $z = 1-2$.

The top-right-hand panel of Fig. D9² shows a tight correlation between $\Sigma_{1\text{kpc}}$ and M_s , with a close to linear slope for SFGs, and a flatter slope for quiescent galaxies at high $\Sigma_{1\text{kpc}}$ and M_s . This is observed at high redshifts (Saracco, Gargiulo & Longhetti 2012; Tacchella et al. 2015a; Barro et al. 2017a; Suess et al. 2021) and at low redshifts (Cheung et al. 2012; Fang et al. 2013; Tacchella et al. 2017), as well as in different environment (Saracco et al. 2017). Tacchella et al. (2016b) demonstrated that the simulations agree both qualitatively and quantitatively with these observations of the $\Sigma_{1\text{kpc}} - M_s$ relation.

Fig. 7 predicts that compaction leads to a low fraction of DM within R_c in BN and post-BN galaxies, where $M_s \geq 10^{10} M_\odot$, reaching values as low as $f_{\text{DM}} \sim 0.1$. This is indeed consistent with the DM fractions deduced from observations for massive galaxies at $z \sim 2$ (Price et al. 2016; Wuyts et al. 2016; Genzel et al. 2017, 2020; Liu et al. 2023), typically $f_{\text{DM}} \sim 0.1$. However, one should bear in

mind the large uncertainties associated with estimating dynamical masses from observations, as discussed in Section 7.2. Observation by Genzel et al. (2020) of rotation curves in massive galaxies show a significant percentage of galaxies with low central DM fraction, $f_{\text{DM}}(< R_c) < 0.3$, which is associated with surprisingly extended DM cores (~ 10 kpc). Higher prevalence of both low f_{DM} and the existence of extended DM cores are shown in the high- z subsample. While we find low f_{DM} for post-compaction massive galaxies, as seen in Fig. 7, such extended DM cores in massive galaxies are not reproduced by cosmological simulations to date. Dekel et al. (2021) suggested a *two-step* scenario for core formation in massive haloes $M_v \geq 10^{12} M_\odot$. In the first step, the inner DM halo is heated by dynamical friction due to a merger with a post-compaction satellite. Once the DM is sufficiently pre-heated, namely closer to the escape velocity from the cusp, outflows by AGN activity may have a greater effect causing further expansion and creating extended cores. Using a combination of an analytical toy model, a semi-analytical model SatGen (Jiang et al. 2021) and results from the VELA simulations shown in this work, it was estimated that the pre-heating would be efficient for a satellite which went through a wet compaction event, with preference to high redshifts. Using the CuspCore model (Freundlich et al. 2020), it was shown that pre-heated cusps develop a DM core in response to the removal of half the gas mass by AGN feedback.

Fig. 5 and Fig. D9² show that at the BN phase the SFR within 1 kpc is at a peak. ALMA observations of CO and dust reveal that the SFR in blue nuggets is indeed enhanced in a sub-kpc core (Tadaki 2016; Barro et al. 2016b, 2017b; Tadaki et al. 2017, 2020; Elbaz et al. 2018).

Fig. 9 and 10 indicate a characteristic mass for the BN phase. Huertas-Company et al. (2018) used deep learning to search for BNs as defined in the simulations in the HST CANDELS survey. The machine was trained using mock images of simulated galaxies and successfully identified BNs among the observed galaxies. This clearly revealed a preferred stellar mass for BNs in the range of $10^{9.2-10.3} M_\odot$, as predicted. While an attempt has been made to eliminate the direct information concerning the total luminosity (and hence mass) from the training set, it is yet to be convincingly demonstrated that the classification as a BN was dominated by the compact young-SFR nature of the galaxy rather than by its mass.

4 PHASES OF EVOLUTION WITH RESPECT TO THE MAIN SEQUENCE

4.1 Galaxy properties along the main sequence

The evolution through compaction and quenching phases is naturally translated to evolution along and across the universal Main Sequence (MS) of SFGs in the diagram of Δ_{MS} versus stellar mass. The quantity Δ_{MS} is the log deviation from the universal MS ridge,

$$\Delta_{\text{MS}} = \log \text{sSFR} - \log \text{sSFR}_{\text{MS}} \quad (1)$$

with sSFR_{MS} defining the MS ridge and scaled by $1/(1+z)^{5/2}$ to reflect the systematic redshift dependence of the sSFR (following the systematic redshift dependence of the specific accretion rate, Dekel et al. 2013). This has been discussed based on the same simulations in Zolotov et al. (2015) and Tacchella et al. (2016a). Pre-BN galaxies evolve along the universal MS while oscillating across the MS ridge, and they climb to the top of the MS as they shrink to a compact BN. Then, once they reach the critical BN mass, they gradually transition into a quenched phase (Pandya et al. 2017), moving down across the MS through the ‘Green Valley’ at the bottom of the MS, aiming at the quenched region well below the MS.

In Tacchella et al. (2016a), we explain how this evolution pattern confines the SFGs into a flat, narrow sequence of width ± 0.3 dex in Δ_{MS} (as observed, Noeske et al. 2007; Whitaker et al. 2014), how it makes the MS bend down above the critical mass of $M_s \sim 10^{10} M_\odot$ (Schreiber et al. 2016), and how it is responsible for gradients of gas-related properties of galaxies across the MS ridge in the post-BN, massive end. In particular, it was shown in Tacchella et al. (2016a) and discussed here below (see Section 4.2, Fig. 12), that both the depletion time and the gas fraction in the VELA simulations reproduce a consistent dependence on Δ_{MS} as seen in observations by Genzel et al. (2015) and Tacconi et al. (2018).

The confinement is explained by the bound oscillations about the MS ridge of galaxies below the critical mass. These oscillations are illustrated in Fig. 8 as well as Fig. D13², which shows the evolution track of low-mass galaxies in the plane of sSFR and $\Sigma_{1 \text{ kpc}}$. These galaxies show several oscillations in sSFR, representing repeating episodes of compaction and quenching attempts before the final BN, which is followed by long-term quenching. The downturn and upturn at the top and the bottom of the MS, respectively, are understood in terms of the balance between the gas inflow rate into the core (*in*) and the gas consumption rate by star formation and outflows from the core (*out*) (Tacchella et al. 2016a, fig. 9). Wet compaction is expected when *in* > *out* (Dekel & Burkert 2014) while quenching by gas depletion is expected when *in* < *out*. At the BN★ after compaction, the central SFR and outflows are enhanced, and the lack of further gas supply from the shrunken disc tips the balance toward a quenching process, causing a downturn. The downturn is assisted by ‘morphological’ quenching, where the growing bulge suppresses the violent disc instability and the associated inflow (Martig et al. 2009; Cacciato, Dekel & Genel 2012).

An upturn by a new compaction event can occur once the replenishment of the disc by fresh gas is faster than the gas depletion, $t_{\text{rep}} < t_{\text{dep}}$. The depletion time is observed to be growing rather slowly with time, $t_{\text{dep}} \sim (1+z)^{-0.5} M_{12}^{-0.19}$ Gyr (Genzel et al. 2015; Tacconi et al. 2018), while from theory and simulations, the accretion time grows much faster, $t_{\text{rep}} \sim 25(1+z)^{-5/2} M_{12}^{0.14}$ Gyr (Dekel et al. 2013), implying that upturn is expected to be more common at $z \geq 3$.

The final long-term downturn at the major BN phase, which carries the galaxy off the MS (possibly even forever), occurs when $t_{\text{rep}} > t_{\text{dep}}$. This is caused by the overall suppression of gas supply into the galaxy

once the CGM becomes hot, which typically occurs once the halo exceeds $\sim 10^{11.5} M_\odot$ and at $z < 3$ (Dekel & Birnboim 2006). This threshold mass is associated with the bending down of the MS above a critical stellar mass, which is likely to be triggered by compaction-driven central gas depletion and maintained by the suppression of gas supply due to a hot CGM.

Fig. 11 addresses the evolution of certain galaxy properties with respect to the universal MS ridge. All the snapshots of all the galaxies in our sample are shown in the plane of Δ_{MS} versus M_s . The population reproduces the overall MS, which resembles the observed MS. Below the BN critical mass, the MS is roughly flat, constant as a function of mass. This is because, at a given redshift, the sSFR is roughly mass independent, following the negligible mass dependence of the specific cosmological accretion rate into the halo (Dekel et al. 2013), and the fact that $(1+z)^{5/2}$ captures the overall decline in time of the sSFR in SFGs. Most of the galaxies are confined to a narrow MS, while a few of the lowest-mass galaxies in our sample (that evolve through the BN phase late) quench below the MS for a short period and rejuvenate back into it. Above the BN mass, the MS naturally bends down in the post-BN phase, reflecting the progressing quenching process at the massive end.

The colour in Fig. 11 denotes the desired property in each panel. The top panels show quantities within the central 1 kpc, while the bottom panels refer to the whole galaxy. The gas mass within 1 kpc (top-middle) is the prominent tracer of compaction, the BN stage, and the following central depletion and quenching. A peak of central gas mass (blue) is reached at $M_s \sim 10^{10} M_\odot$ in the upper part of the MS, demonstrating that this is where the BNs are expected to reside. A similar peak in the same location is seen in the SFR within the inner 1 kpc (top-right), which naturally traces the central gas mass. On the other hand, the stellar mass within 1 kpc (top-left), which is a proxy for the observable $\Sigma_{1 \text{ kpc}}$ commonly used to identify the BN, shows only a horizontal gradient as a function of M_s (see also Ceverino et al. 2015a), with the stellar density growing rapidly during the compaction phase and settling to a constant (blue) after BN★, where $M_s \geq 10^{10} M_\odot$.

Observable global properties that are related to the gas mass M_g are the depletion time and the gas-to-star fraction defined by

$$t_{\text{dep}} = M_g / \text{SFR}, \quad f_{\text{gs}} = M_g / M_s. \quad (2)$$

The colours in the bottom panels of Fig. 11 indicate vertical gradients across the MS for both t_{dep} and f_{gs} . There is no horizontal gradient along the MS in t_{dep} , but f_{gs} also varies systematically with M_s , reflecting the overall decline of gas fraction with cosmological time because our sample follows the evolution of a given set of galaxies.

4.2 Gradients across the main sequence

Fig. 12 shows the vertical gradients of different galaxy properties (Q) across the MS for the galaxies above the critical BN mass. In these gradients, the systematic redshift and mass dependencies at the MS ridge were scaled out in the following way, similar to what we did in Tacchella et al. (2016a), which is close to the method applied by Genzel et al. (2015) to their observed sample. We assume the model,

$$\log Q = A + Bf(z) + C\Delta_{\text{MS}} + Dg(M_s), \quad (3)$$

where $f(z) = B_0/B + \log(1+z)$, $g(M_s) = D_0/D + \log(M_s/10^{10.5})$. We then determine the best-fitting values for the parameters A , B_0 , B , C , D_0 , and D . The specific procedure adopted here is as follows. First, we select the subsample of galaxy snapshots that lie near the MS ridge $|\Delta_{\text{MS}}| < 0.15$, temporarily assume $D = 0$ and obtain the

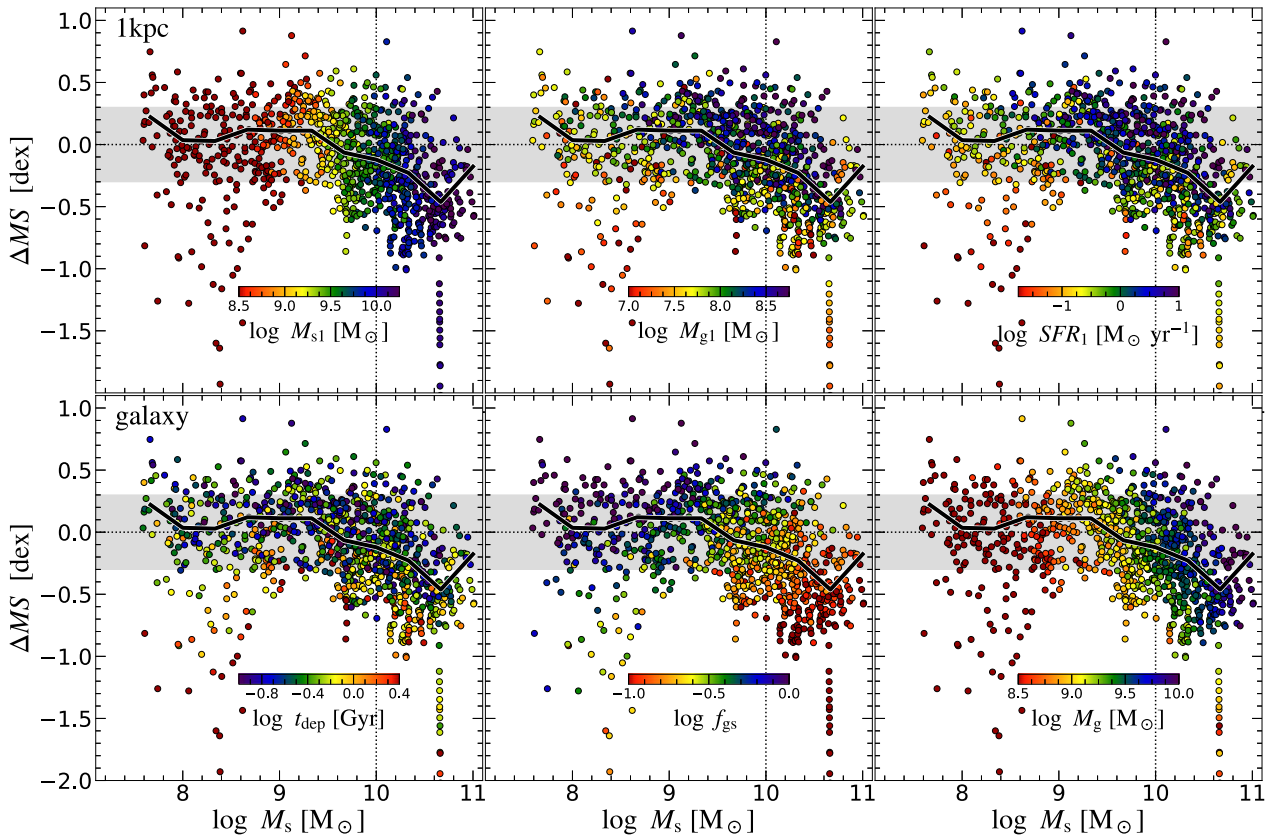


Figure 11. Galaxy properties with respect to the MS, in the plane of Δ_{MS} versus M_s . The value of the desired property is indicated by colour. **Top:** Stellar mass, gas mass and SFR within 1 kpc (left to right). **Bottom:** depletion time, gas-to-star fraction and gas mass for the whole galaxy.

best-fitting B and B_0 . Second, using the same subsample near the MS ridge, we eliminate the systematic z dependence by referring to the scaled quantity $\log Q - Bf(z)$ and obtain the best-fitting D . Finally, we return to the full sample where Δ_{MS} spans its full range of values, scale out the z and M_s dependencies by referring to the scaled quantity

$$\tilde{Q} = \log Q - Bf(z) - Dg(M_s) = A + C\Delta_{\text{MS}}, \quad (4)$$

and obtain the desired best-fitting C .

One could determine the best-fitting parameters in several alternative ways, e.g. by first eliminating the mass dependence and then the redshift dependence, by a more sophisticated procedure of successive fits (Tacconi et al. 2018), or by a straightforward simultaneous fit of all the parameters. Given the biases that the sample selection may introduce and the possible deviations from the model assumed in equation (3), in principle, the results may differ from method to method and sample to sample. Testing with mock catalogues reveals that the derived value of C is very robust to the sampling and the best-fitting method, while B , and to some extent also D , can be sensitive to both. Therefore, we show in Fig. 12 only the gradients across the MS.

The gradients of some properties may be different pre-BN and post-BN. Here, we limit the discussion to the galaxy snapshots above the BN critical mass. In this regime, a decline of Δ_{MS} reflects evolution across the MS, from the BN stage at the top of the MS, through the MS ridge, and finally descending below the MS toward the quenched regime.

In Fig. 12, the gas-dependent quantities show significant gradients with rather tight correlations (Pearson correlation coefficient $|r_p| \sim 0.7$), which are associated with the central gas depletion process. The slope of the gradients for the global t_{dep} , global f_{gs} , and the SFR within 1 kpc are -0.51 ± 0.07 , $+0.48 \pm 0.04$, and 1.22 ± 0.06 , respectively. The first two, similar to Tacchella et al. (2016a), are in excellent agreement with the observational results (Genzel et al. 2015; Tacconi et al. 2018). The strong super-linear gradient for the SFR within 1 kpc across the MS is an observable prediction.

On the other hand, the observable quantities that refer to the stellar component (second row) do not show tight correlations nor significant gradients across the MS ($|r_p| \sim 0.1$), as the stellar core is established during the BN phase and it remains roughly the same in the post-BN phase during the gas depletion process. In particular, the simulations predict no significant gradients for the stellar $\Sigma_{1\text{kpc}}$, the half-mass radius R_e , or the Sérsic index n . However, the young stars (not explicitly shown here) show correlations similar to the quantities that involve gas mass and density.

During the pre-BN phase (not shown in here), below the critical mass $M_s < 10^{9.5} M_\odot$, the gradients are not necessarily similar to the post-BN phase. We find similar gradients for the global t_{dep} , global f_{gs} and the SFR within 1 kpc, with slopes of: -0.47 ± 0.03 , $+0.47 \pm 0.03$, 1.10 ± 0.08 , respectively, and Pearson correlation coefficient of $|r_p| > 0.64$. Other properties shown in Fig. 12 show either mild or no significant gradient in the pre-BN phase. The best-fitting slopes of these gradients are listed in Table D1² for both the pre-BN and the post-BN phase.

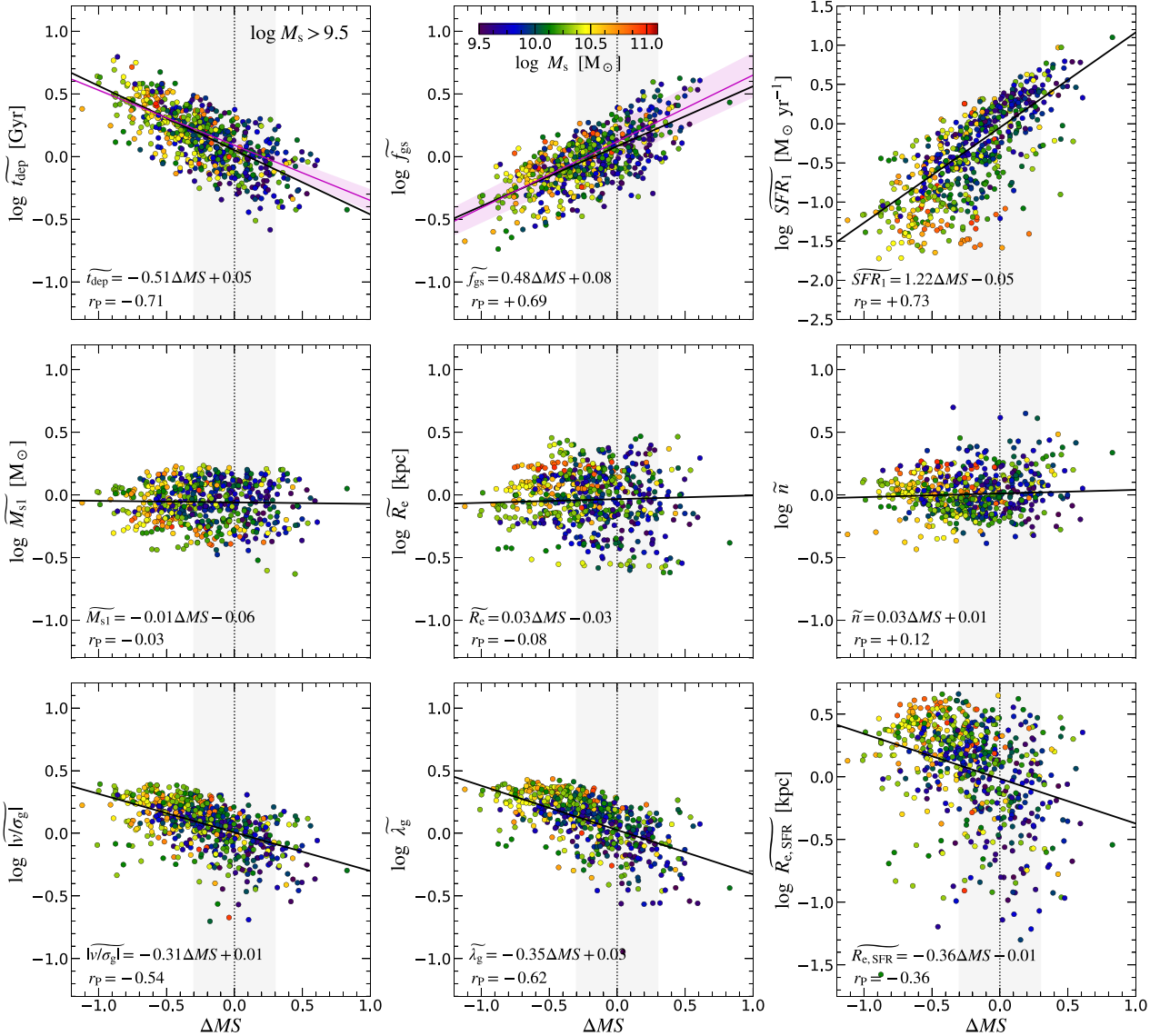


Figure 12. Gradients across the MS for galaxies above the critical BN mass. The systematic redshift and mass dependencies at the MS ridge are eliminated. The stellar mass, M_s , is indicated by colour. **Top:** properties involving gas, the depletion time (t_{dep}), and gas fraction (f_{gs}) for the whole galaxy, and SFR within 1 kpc (SFR_1). The magenta lines and shaded regions in t_{dep} (top-left) and f_{gs} (top-middle) indicate the best fitting and the uncertainties of observations by Tacconi et al. (2018). **Middle:** properties involving stars. The stellar mass within 1 kpc (M_{s1}), the 3D half mass radius of stars (R_c), and the Sérsic index (n). **Bottom:** gas rotational velocity over the velocity dispersion (v/σ_g), the spin parameter of the gas (λ_g), and the 3D effective radius of the SFR. We find that significant gradients across the MS in quantities which involve gas and SFR. Conversely, the stellar properties show neither significant gradients nor tight correlations.

4.3 Comparison to observations

As predicted in Fig. 11 and reported in (Tacchella et al. 2016a), the blue nuggets are observed preferentially in the upper parts of the Main Sequence of SFGs (Van Dokkum et al. 2015; Elbaz et al. 2018).

As already highlighted in Tacchella et al. (2016a), the gradients of quantities involving gas across the MS, as seen in Fig. 12, are observed. Tacconi et al. (2018) and Genzel et al. (2015) presented the scaling relations between galaxy-integrated molecular gas masses, stellar masses, and star formation rates as a function of redshift between $z = 0$ and $z = 4$. They determine molecular gas masses in different ways from CO line fluxes (from PHIBSS, xCOLD GASS and other surveys), far-infrared dust spectral energy distributions (from Herschel), and ~ 1 mm dust photometry (from ALMA), in 758

individual detections and 670 stacks of SFGs, covering the stellar mass range $\log(M_s/M_\odot) = 9.0\text{--}11.8$, and star formation rates relative to that on the MS, Δ_{MS} , from -1.3 to $+2.2$ dex. Tacconi et al. (2018) find that the molecular gas depletion time-scales as $t_{\text{dep}} \propto \Delta_{\text{MS}}^{-0.44}$, and the ratio of molecular-to-stellar mass scales as $f_{\text{gs}} \propto \Delta_{\text{MS}}^{+0.53}$. These scaling relations agree well with our simulation predictions $t_{\text{dep}} \propto \Delta_{\text{MS}}^{-0.51 \pm 0.07}$ and $f_{\text{gs}} \propto \Delta_{\text{MS}}^{+0.48 \pm 0.04}$.

Similar results have been quoted by other observations. Based on ALMA observations of the long wavelength dust continuum in the COSMOS field, Scoville et al. (2017) find that the ISM mass is $\propto \Delta_{\text{MS}}^{0.32}$ and $t_{\text{dep}} \propto \Delta_{\text{MS}}^{-0.7}$, which is in qualitative agreement with our simulations. Likewise, Sargent et al. (2014) and Puglisi et al. (2021) find that t_{dep} for molecular gas declines with SFR in starburst galaxies, though the gas fraction is lower in starbursts, presumably

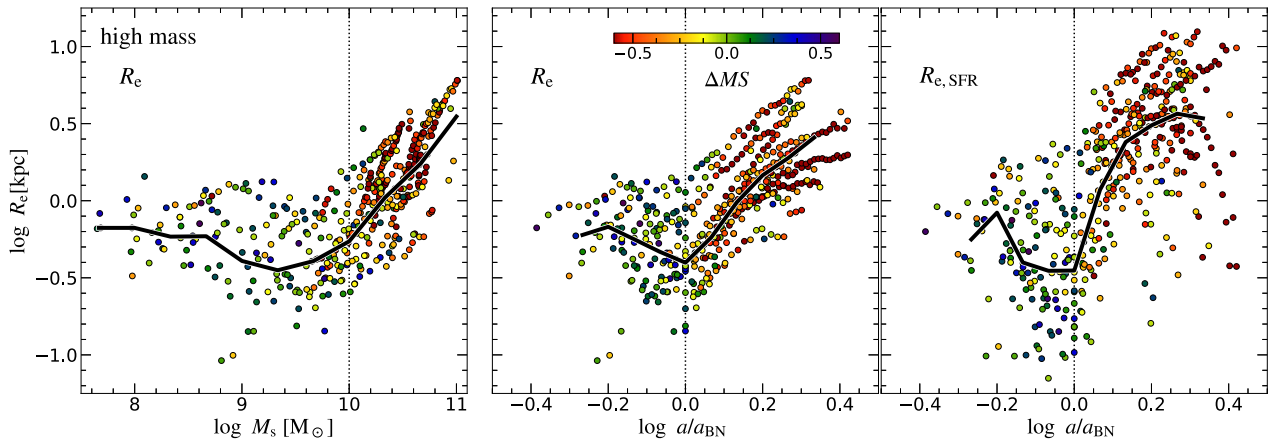


Figure 13. Size evolution of the high-mass subsample (defined at $z = 2$, see similar Fig. C1² for the low-mass subsample). The distance from the MS ridge, Δ_{MS} , is indicated by colour. **Two left-hand panels:** Evolution of effective radius, as a function of a/a_{BN} (left) and of M_s (middle). Pre-BN, the size evolution with mass tends to be roughly horizontal (with individual tracks slowly rising/decreasing). After a brief reduction in R_e during compaction, the post-BN effective radius of the high-mass subsample rises rather steeply as they fall below the MS and start to quench. In the low-mass subsample Fig. C1², their inclination for repeated episodes of small compactions tends to smooth out some of the above-mentioned features. **Third-panel:** Evolution of the effective radius of the SFR, $R_{e, \text{SFR}}$ as a function of a/a_{BN} . $R_{e, \text{SFR}}$ shows similar behaviour as R_e , albeit with a larger scatter.

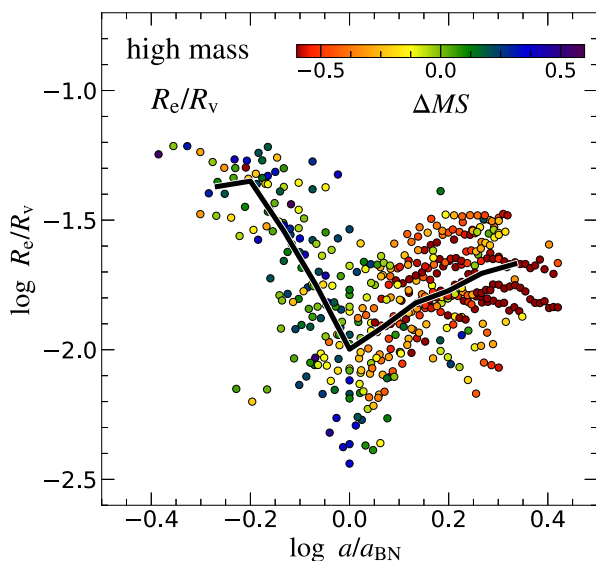


Figure 14. Evolution of the effective radius scaled by the virial radius, R_e/R_v , as a function of a/a_{BN} (see Fig. C2² for the low-mass subsample). The distance from the MS ridge is indicated by colour. The tendency for R_e to grow with time, as deduced from the growth of R_v and the universal spin parameter with angular-momentum conservation, is partly compensated by repeated episodes of compaction, in which R_e is pushed down.

because it has already been consumed. Silverman et al. (2015) find short t_{dep} well above the MS at $z \sim 1.6$. Huang & Kauffmann (2014) find that the primary correlation of t_{dep} is with sSFR, and quote $t_{\text{dep}} \propto \text{sSFR}^{-0.37}$ to $\text{sSFR}^{-0.50}$ based on the COLD-GAS survey at low redshifts.

5 RADIUS-MASS

The evolution in the effective radius of the stars and the SFR (or young stars) clearly reveals the BN phase and two different characteristic behaviours in the pre-BN and post-BN zones or below

and above the BN characteristic mass. This is also reflected in transitions in the surface density profiles $\Sigma(r)$ of gas and stars shown in Fig. 23 (Tacchella et al. 2016b).

Fig. 13 show the effective radius for the high-mass subsample, R_e for stars, versus a/a_{BN} and M_s , as well as for SFR $R_{e, \text{SFR}}$ versus a/a_{BN} . Pre-compaction, for galaxies below the critical BN mass, the overall evolution of the SFGs tends to be roughly horizontal, namely about a roughly constant R_e as the mass grows, with the individual tracks either slowly rising or slowly decreasing. The scatter is naturally larger for the instantaneous SFR than for the integrated stellar mass.

Post-BN, the R_e of the quenching galaxies is rising rather steeply with stellar mass, as the latter is growing slowly during this quenching phase. Similar behaviour of transition to a steep size growth during the quenching phase is also shown in Rodríguez-Puebla et al. (2017, fig. 20) using semi-empirical modelling. The compaction itself is marked by a shrinkage in radius over a short period, reaching a minimum at the BN, after which the steep rise commences. The shrinkage is somewhat smeared out when plotted against M_s , showing at the critical BN mass a transition from a flat and spread-out distribution to a steeply rising branch, with only a trace of shrinkage at the BN mass itself.

The right-hand panel in Fig. 13 shows the time evolution of the half radii for SFR, $R_{e, \text{SFR}}$. Pre-BN, $R_{e, \text{SFR}}$ is similar to R_e ; their ratio ($R_{e, \text{SFR}}/R_e$) is about unity, describing a diffuse star-forming galaxy. A short-term shrinkage can be seen at the BN phase, typically by 0.3 dex, as the SFR becomes largely confined to the compact BN. Post-BN, $R_{e, \text{SFR}}$ grows rapidly, and the ratio of $R_{e, \text{SFR}}/R_e$ becomes higher, typically 0.4 dex above unity, reflecting the appearance of a gas-rich star-forming extended ring.

In Fig. 14, we show the ratio of the effective radius and the virial radius, R_e/R_v . The tendency for R_e to grow with time, deduced from the growth of R_v and a universal spin parameter (λ) with angular-momentum conservation, is partly compensated by repeated compaction episodes, associated with the oscillations about the MS, in which R_e is pushed down. Using an earlier version of the VELA simulations, Ceverino et al. (2015a) showed that the assumption of a fixed spin parameter with AM conservation does not reproduce the evolution of the effective radius as derived from simulated galaxies.

A good match was achieved only under the assumption of $\lambda(z)$ decreasing with time. In Jiang et al. (2019), it was demonstrated that the halo spin is not a good predictor for the galaxy size on a one-to-one basis due to episodes of compaction or mergers; however, a model with the halo concentration parameter proved to reproduce a tighter relationship between the halo and galaxy size.

In Fig. 12, we show the post-BN gradients across the MS of both R_e (second row, middle panel) and for $R_{e, \text{SFR}}$ (third row, right-hand panel). After removing the systematic dependencies on z and M_s at the MS, one can see practically no gradient for R_e , while $R_{e, \text{SFR}}$ does show a gradient with a slope of -0.36 ± 0.09 ($|r_p| \sim 0.36$). The effective radius of SFR shows smaller values above the MS when the galaxy is compact and intensely star-forming at the BN phase. Below the MS, at a later post-BN stage, $R_{e, \text{SFR}}$ becomes larger due to the formation of an extended star-forming disc/ring around the gas-poor stellar nugget. The lack of MS gradient in R_e is expected since the central stellar component remains roughly the same in the post-BN phase. However, $R_{e, \text{SFR}}$ is related to the young stars, which show trends more closely related to quantities involving gas mass.

5.1 Comparison to observations

The behaviour in the $R_e - M_s$ diagram in Fig. 13 (left-hand panel) resembles the observed population of this diagram (e.g. Shen et al. 2003; Franx et al. 2008; Mosleh et al. 2011, 2020; Barro et al. 2013; Cibinel et al. 2013; Van der Wel et al. 2014a; Van Dokkum et al. 2015; Tacchella et al. 2015b; Suess et al. 2021). We note that it is difficult to constrain the evolutionary paths of individual galaxies in the $R_e - M_s$ diagram from the way galaxies populate this plane because of progenitor effects (e.g. Van Dokkum & Franx 1996; Lilly & Carollo 2016). Van der Wel et al. (2014a) combine redshifts, stellar mass estimates, and rest-frame colours from the 3D-*HST* survey with structural parameter measurements from CANDELS imaging to determine the galaxy size-mass distribution over the redshift range $0 < z < 3$. They find at all redshifts a shallow slope of $R_e \propto M_s^{0.22}$ for SFGs, and a steep slope $R_e \propto M_s^{0.75}$ for quiescent galaxies.

Fig. 13 (left) roughly matches the cartoon in Fig. 28 of Van Dokkum et al. (2015). Using observational samples with matching number densities, Van Dokkum et al. (2015) (also Patel et al. 2013; Van Dokkum et al. 2013) suggest that even though individual galaxies may have had complex histories with periods of compaction and mergers, the ensemble-averaged evolution of star-forming galaxies in the size-mass plane is well described by a simple inside-out growth track of $R_e \propto M_s^{0.3}$. This rather shallow track is confirmed by the sSFR profile within galaxies, which are roughly flat or slightly increasing at $M_s < 10^{11} M_\odot$ (Tacchella et al. 2015a; Nelson et al. 2016; Liu et al. 2017). The flat size growth in the simulations before compaction is rather consistent (see also Tacchella et al. 2016b). After quenching at high masses, the size grows steeply with mass, both in the simulations and observations. It is still debated how much size (and stellar mass) growth takes place in individual systems due to minor mergers (see e.g. Suess et al. 2019), and it probably depends on the stellar mass and environment of a galaxy (Carollo et al. 2013; Fagioli et al. 2016; Tacchella et al. 2017). In our simulations, we find that high-mass galaxies are going through a significant size growth on a steep track in the $R_e - M_s$ diagram mainly due to star formation in the outskirts (rising sSFR profiles toward the outskirts).

Somerville et al. (2018) used a combination of observed CANDELS galaxies at $z < 3$ with the stellar-to-halo mass ratio from abundance matching, to find the statistical relationship between the

effective stellar radius and the virial radius, R_e/R_v . It was shown that at high redshifts of $z \sim 2$, the ratio has a median value of $R_e/R_v \sim 0.02$, roughly constant with mass except for the most massive bins around $\sim 10^{11} M_\odot$. To compare these results, we select simulated galaxies at similar mass and redshift ranges, choosing post-BN galaxies ($M_s > 10^{9.5} M_\odot$) at $z = 1-3$. As seen in Fig. 14, the high-mass subsample shows a trend of rising R_e/R_v with ala_{BN} (or M_s) and a somewhat lower ratio. However, when the entire sample is considered, now including Fig. C2², we find a rather constant R_e/R_v as a function of mass with a median value of ~ 0.02 , mostly consistent with Somerville et al. (2018). We do not recover a decline in the ratio in the most massive bins, possibly due to the small number of simulated galaxies with such masses.

6 GLOBAL SHAPE

6.1 Transition in shape

The BN phase is associated with a transition in the global shape of the stellar system, from elongated-prolate before the BN event to oblate and disc-like structure post-BN. This has been analysed in the same simulations in Ceverino et al. (2015b) and Tomassetti et al. (2016), explaining the observational trends with redshift and mass (Van der Wel et al. 2014b), based on the transition from DM to baryon dominance in the core caused by the compaction, discussed in Section 3.4.

The DM halo is expected to be elongated and prolate as a result of its assembly along a dominant large-scale filament. This is demonstrated by a correlation between the velocity-dispersion anisotropy and the large-scale geometry of structure associated with the merger history (Tomassetti et al. 2016, figs 12–15). The stellar system follows the elongation and prolateness as long as the DM halo dominates the potential in the central galaxy. The torques exerted by the elongated halo indeed indicate that the halo is capable of inducing the elongated stellar shape (Tomassetti et al. 2016, fig. 16).

Once a compact baryonic core forms and dominates the inner potential, it is expected to make the inner system of old stars and DM rounder by deflecting small-pericenter box orbits. Then, the system of new stars follows the new high-AM gas into an oblate rotating system (Tomassetti et al. 2016, fig. 11).

As in Tomassetti et al. (2016), the shape within R_e is quantified by fitting an ellipsoid to the spatial mass distribution with semi-axes $a \geq b \geq c$. The shape is characterized by the parameters of ‘elongation’ and ‘flattening’,

$$e = [1 - (b/a)^2]^{1/2}, \quad f = [1 - (c/b)^2]^{1/2}. \quad (5)$$

Fig. 2 of Tomassetti et al. (2016) illustrates the interpretation of shape based on location in the plane of e and f . In particular, a large e with a small f corresponds to a prolate system, while a small e with a large f corresponds to an oblate system. Thus, the difference $e - f$ is a measure of prolateness versus oblateness. Triaxial systems span the diagonal line $e - f = 0$, with the sum $e + f$ measuring the degree of elongation from a sphere to very elongated triaxial systems. Fig. 7 of Tomassetti et al. (2016) shows the main features of the evolution of the shape of stars, gas and DM as a function of the ratio of baryonic to DM mass within R_e , which we denote here B/DM.

Fig. 15 addresses the evolution of stellar shape within R_e through the BN phase by showing $e - f$ and $e + f$ as a function of three different quantities, B/DM, ala_{BN} and M_s . Pre-BN, $e - f \sim 0.25$ and $e + f \sim 1.4$ with a scatter ± 0.2 , namely the systems are elongated, triaxial and prolate. Post-BN, we see $e - f \sim -0.6$ and $e + f \sim 1.2$, namely, the systems are rounder and oblate, tending toward a disc-

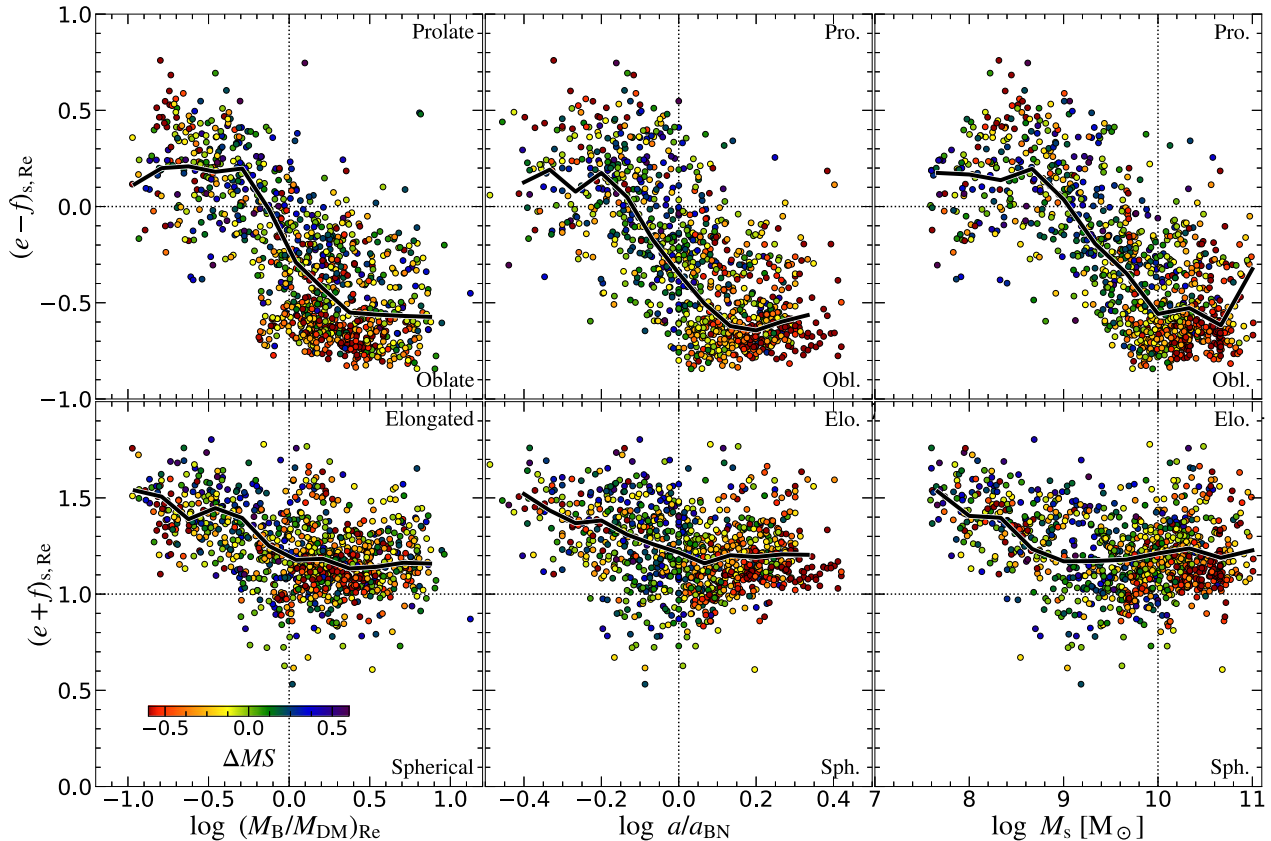


Figure 15. Transition in shape. We characterize the shape of the stellar distribution within R_e by the following two parameters: (a) $e - f$ refers to deviations from triaxiality, positive and negative for prolate and oblate configurations, respectively. (b) $e + f$, referring to variation along the triaxial line $e - f = 0$, from elongated at large $e + f$ to spherical at low $e + f$. The shape is plotted against the baryon-to-DM ratio within R_e , a/a_{BN} , and M_s . The colour marks the deviation from the universal MS ridge. Pre-BN, the stellar systems are elongated, triaxial, and prolate. Post-BN, the systems become less elongated and oblate, tending towards a disc-like structure.

like structure. The very clear transition in shape occurs near the BN event, associated with the compaction-driven transition from DM to baryon dominance in the inner galaxy (see Fig. 7).

The colour in Fig. 15, which marks Δ_{MS} , predicts a mild gradient of shape across the MS for galaxies above the BN mass, where the stellar systems become more oblate at the lower parts of the MS. In the post-BN phase, the most oblate and least elongated regimes in Fig. 15 tend to have a high density of red symbols, namely oblate and less elongated systems tends to be below the MS. However, except for this tendency, the colours do not show a clear correlation with the shape. Indeed, in Fig. D14² (see also Table D1²), we show that after the elimination of redshift and mass dependence, there are no gradients across the MS in the f parameter for the post-BN galaxies, the e parameter shows a very mild gradient with a best-fitting slope of $+0.15 \pm 0.03$ ($|r_p| \sim 0.3$).

At the BN phase itself, focusing on the inner 1 kpc, the typical stellar shape parameters are $e - f \sim -0.3$ and $e + f \sim 1.2$, namely an oblate spheroid. Fig. 16 shows the projected mass density in one galaxy at its BN stage, referring to gas and young stars in addition to the stellar system, edge-on and face-on, with respect to the angular momentum. While the inner stellar system is a flattened spheroid, the gas, and young stars populate a compact, thick disc. This appearance is typical for our simulated galaxies at the BN phase. This is a prediction for high-resolution sub-kpc observations of gas or young stars, such as expected from ALMA.

6.2 Comparison to observations

Constraining the intrinsic, three-dimensional shape from the observed two-dimensional shape is complicated by projection effects. However, it is possible to determine the distribution of shapes under certain simplifying assumptions.

In the present-day Universe, star-forming galaxies of all masses 10^9 – $10^{11} M_\odot$ are predominantly thin, nearly oblate discs (e.g. Sandage, Freeman & Stokes 1970; Lambas, Maddox & Loveday 1992; Padilla & Strauss 2008). At higher redshifts, Ravindranath et al. (2006) demonstrated that the ellipticity distribution of a large sample of $z = 2$ – 4 Lyman break galaxies is inconsistent with randomly oriented disc galaxies, lending credence to the interpretation that a class of intrinsically elongated (prolate) objects exists at high redshift. By modelling ellipticity distributions, Law et al. (2012) and Yuma, Ohta & Yabe (2012) concluded that the intrinsic shapes of $z > 1.5$ star-forming galaxies are strongly triaxial.

Van der Wel et al. (2014b) determined the intrinsic, three-dimensional shape distribution of star-forming galaxies at $0 < z < 2.5$, as inferred from their observed projected axis ratios from SDSS and CANDELS data. They find that among massive galaxies ($M_s > 10^{10} M_\odot$), discs are the most common geometric shape at all $z < 2$. However, lower-mass galaxies at $z > 1$ possess a broad range of geometric shapes: the fraction of elongated (prolate) galaxies increases toward higher redshifts and lower masses. Galaxies with

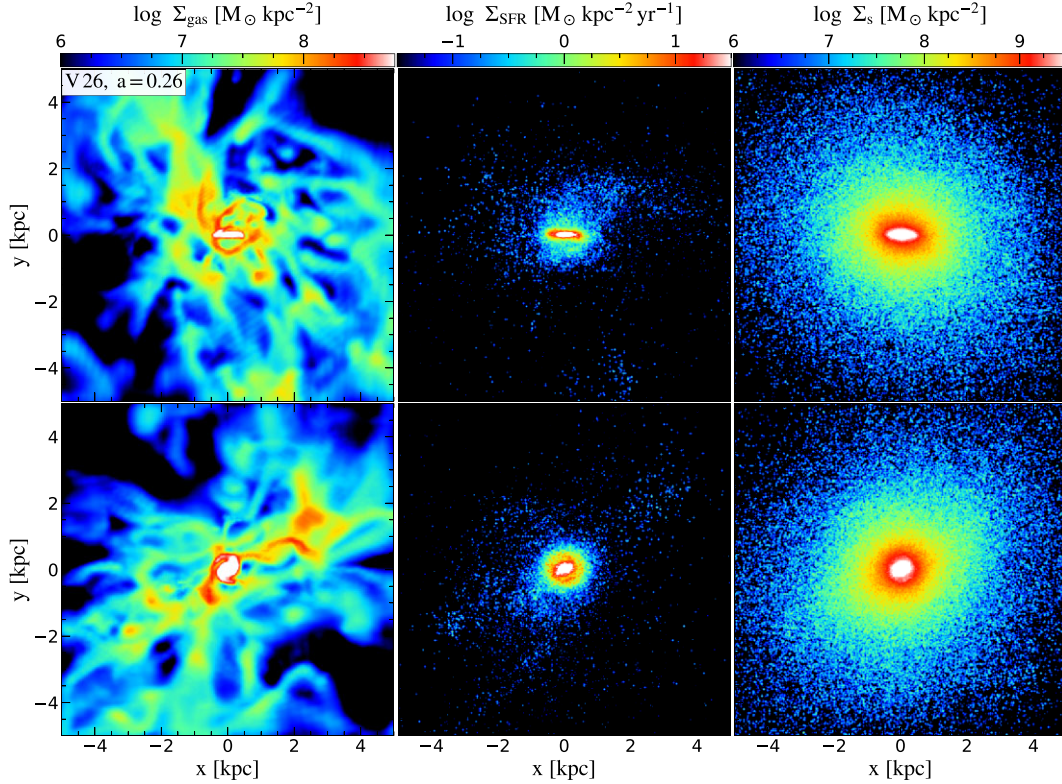


Figure 16. The shape of a typical BN is shown in the projected density (from left to right) of the gas, SFR and stars, edge-on (top) and face-on (bottom). The sub-kpc BN is a disc in gas and SFR (or young stars) and a flattened spheroid in stars.

stellar mass $M_s \approx 10^{10} M_\odot$ are a mix of roughly equal numbers of prolate and oblate galaxies at $z \sim 2$. Similarly, Takeuchi et al. (2015) find that the shape of the star-forming galaxies in the main sequence changes gradually and that the round discs are established at around $z \sim 0.9$. Zhang et al. (2019) improved the analysis using CANDELS galaxies. By approximating the intrinsic shapes as triaxial ellipsoids and assuming a multivariate normal distribution of galaxy size and two shape parameters, they construct the intrinsic shape and size distributions to obtain the fractions of prolate, oblate, and spheroidal galaxies in each redshift and mass bin. They confirmed the finding that galaxies tend to be prolate at low M_s and high redshifts, and oblate at high M_s and low redshifts. Overall, these analyses of observed shapes qualitatively agree with the simulation predictions, where the lower-mass, pre-compactation objects tend to be prolate systems before they become oblate after compactation.

The images of Fig. 16 illustrate that the blue nuggets within the inner 1 kpc are puffy discs. This is a prediction to be tested with high-resolution, sub-kpc observations, e.g. by ALMA or JWST.

7 KINEMATICS

7.1 Transition in kinematic properties

Fig. 17 shows basic kinematic properties within $0.1R_v$ as a function of a/a_{BN} for the high-mass subsample (see the complementary Fig. D4² as a function of M_s). Shown for gas and for stars are the rotation velocity V_{rot} , and the radial velocity dispersion σ_r . Also shown is the line-of-sight velocity dispersion σ_{los} , observable as a linewidth, averaged over 64 random directions for the line of sight.

The velocities are normalized by the virial velocity V_v and stacked together. The same kinematic properties for four example galaxies were shown in Zolotov et al. (2015, figs 10-11).

The pre-compactation galaxies are dispersion dominated, both for the gas and the stars, reflecting the intense feeding by streams, including mergers and the highly perturbed structure of the galaxy. The velocities are $\sim(0.4-0.6)V_v$ for the gas and $\sim(0.2-0.4)V_v$ for the stars. During the compactation, the rotation velocity increases significantly. Post-BN, the gas is mostly in an extended, perturbed ring/disc with $V_{rot}/\sigma \sim 3$. The stars are spheroid dominated with an overall $V_{rot}/\sigma \sim 1$, while the kinematically selected stellar disc component (not shown here) has $V_{rot}/\sigma \sim 3$, similar to the gas. This results in a jump in the line-of-sight velocity dispersion σ_{los} , which has important contributions from both V_{rot} and σ . High line-of-sight velocities are indeed observed in BNs and RNs (Barro et al. 2014b, 2015, 2016a).

For galaxies above the critical BN mass, the simulations show for the gas disc a median rotation velocity $\sim 1.3V_v$, and a velocity dispersion of $\sim 0.6V_v$. For the stars, both are $\sim(0.7-0.8)V_v$. This results in $\sigma_{los} \sim (0.8-1)V_v$ both for the gas and the stars. Galaxies with masses below the critical mass are expected to have $\sigma_{los} \sim 0.6V_v$ for the gas and $\sim 0.4V_v$ for the stars.

Fig. 18 shows the kinematic properties of galaxies with respect to their position on the MS in the plane of Δ_{MS} versus M_s . Shown by colour are V_{rot}/σ_r and σ_{los} for gas and stars within $0.1R_v$. In both quantities, we see a steep rise along the MS (namely as a function of M_s) near the critical BN mass, reflecting the time evolution involving a steep rise during the compactation phase (Fig. 17). For the gas, above the critical BN mass, we see a strong gradient of V_{rot}/σ_r across the

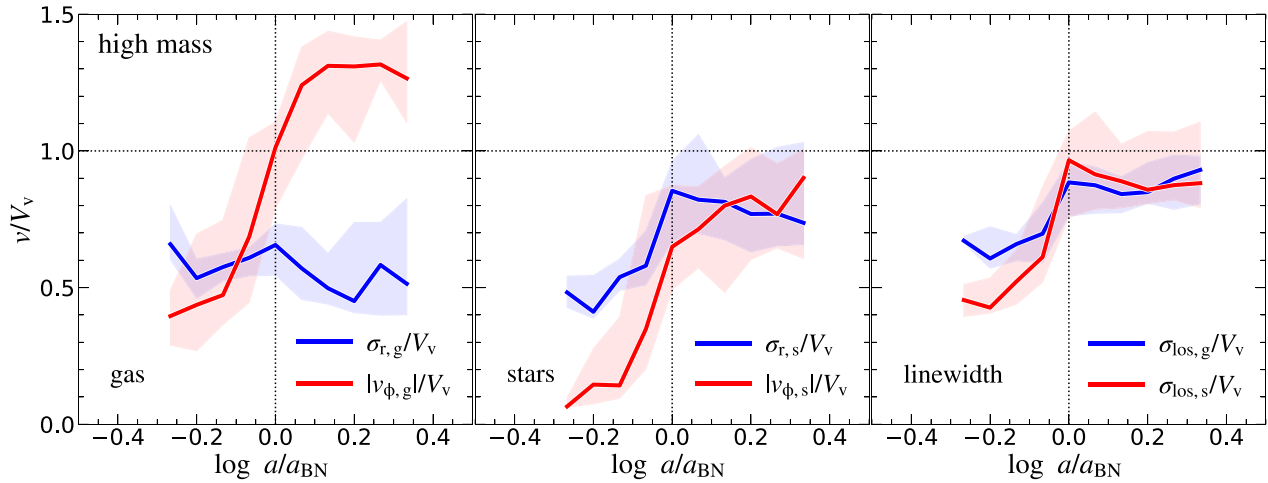


Figure 17. Kinematic properties versus a/a_{BN} for the high-mass subsample (see same properties as a function of M_s in Fig. D4²). All velocities are measured in units of V_v at the BN event (which is about 125 km s^{-1} , see Fig. 10). Shown are the rotation velocity and the radial velocity dispersion for the gas (left) and stars (middle), as well as the dispersion along the line of sight (linewidth) for gas and stars. Pre-BN, the galaxies are dispersion dominated, reflecting the highly perturbed structure of the galaxy at this phase. During compaction, the rotation velocity increases significantly, transitioning into rotationally supported gas systems. Post-BN, the gas is typically in an extended, perturbed ring/disc with $V_{\text{rot}}/\sigma \sim 3$.

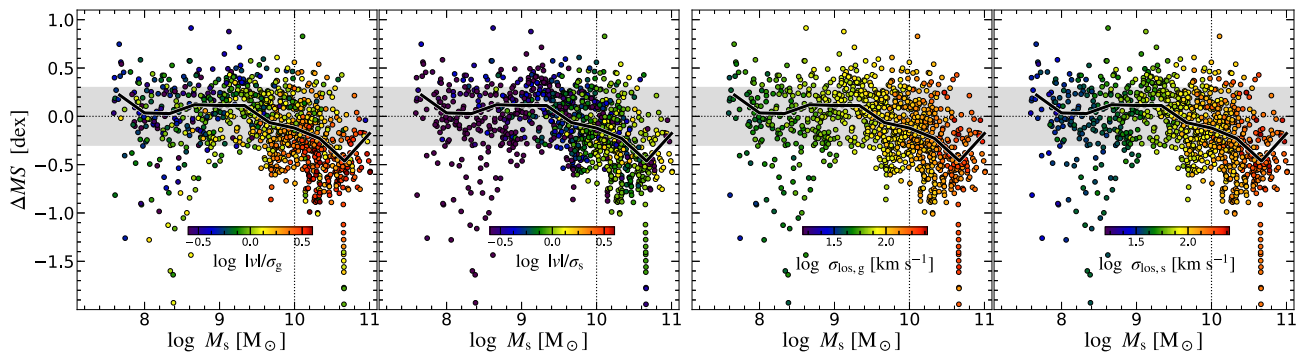


Figure 18. Kinematics with respect to the MS. All snapshots are shown in the plane of Δ_{MS} versus M_s . The colour refers to V_{rot}/σ and σ_{los} for gas and for stars in the galaxy.

MS (as a function of Δ_{MS}), from about unity at the top of the MS to 3 – 5 in the lower part of the MS. This gradient is due to the gradual appearance of an extended gas ring or disc after the BN phase. The gradient is largely smeared out in σ_{los} when averaged over all inclinations, showing mostly a gradual correlation with M_s . In Fig. 12 we show the gradient across the MS for v/σ_g (third row, left panel). After eliminating systematic redshift and mass dependencies, we find a slope of -0.31 ± 0.03 with a rather tight correlation, $|r_p| \sim 0.54$. Thus, an observational detection of the gradient across the MS would require an estimate of V_{rot}/σ_r , namely a decomposition of V_{rot} and σ_r from a two-dimensional line-of-sight velocity map. The kinematics of stars do not show a gradient across the MS, as both V_{rot} and σ_r grow together during the compaction phase (Fig. 17).

The evolution through the BN phase is also associated with changes in the spin parameter of the galaxy, reflecting the angular-momentum loss associated with the compaction and the buildup of a new extended gaseous disc/ring. We define the spin parameter of component i (gas, stars, or baryons within a given volume) by $\lambda_i = (J_i/M_i)/(\sqrt{2}V_v R_v)$, where J_i and M_i are the angular momentum and mass of that component. The volume considered here is for the entire galaxy, a sphere of radius $0.1R_v$.

Fig. 19 shows the evolution of the gas spin parameters in the entire sample as a function of a/a_{BN} (see the spin parameter as a function of M_s in Fig. D7²). Shown are all snapshots of all galaxies, with the colour referring to Δ_{MS} , and the two thick lines are medians in bins of a/a_{BN} for the subsamples of high-mass and low-mass (ranked at $z = 2$). The spins are roughly constant pre-BN. The angular-momentum loss associated with the central compaction is marginally indicated on the scale of the whole galaxy. Following the BN phase, the spin steeply rises, saturating to a plateau at $a \simeq 1.5a_{\text{BN}}$. This high spin is associated with the formation of a new extended gaseous ring from a freshly accreted inflow. The violent disc instability in this ring is partly suppressed by ‘morphological’ quenching due to the massive bulge (Martig et al. 2009), preventing a torque-driven shrinkage of the ring and keeping it extended (see Section 9.4). A post-BN plateau in the spin parameter is typical for the high-mass subsample, where the BN identified is indeed the last major BN event which is followed by a prolonged quenching process (yellow and red colours in the figure) with no further significant compaction events. In the low-mass subsample, some galaxies may go through one or more compaction events after the identified BN, which triggers central SFR rejuvenation and lower the galaxy spin.

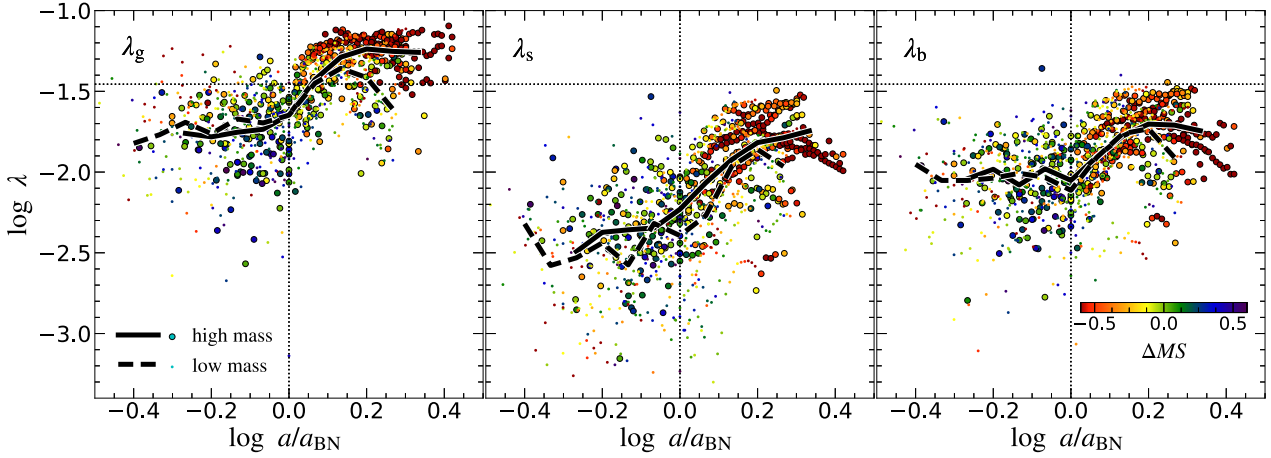


Figure 19. Galaxy spin parameter for gas, stars and baryons, as a function of a/a_{BN} . Colour refers to ΔM_{S} . The medians in bins of a/a_{BN} refer to the high-mass (solid) and low-mass (dashed) subsamples (defined at $z = 2$). The horizontal line refers to $\lambda = 0.035$, the typical halo spin parameter. The spins are roughly constant pre-BN. Following the BN phase, the spin steeply rises, saturating to a plateau at $a \simeq 1.5a_{\text{BN}}$. The high spin is associated with the formation of a new extended gaseous ring originating from fresh inflow through the streams.

The gradient across the MS of λ_{g} is shown in Fig. 12 (third row, middle panel). Low values of $\lambda_{\text{g}} \sim 1$ are seen above the MS ridge. When the central region is depleted from gas, and the galaxy is driven below the MS toward the green valley, we see higher values of ~ 2 reflecting the buildup of an extended gas ring. We find a best-fitting slope of -0.35 ± 0.04 and a fairly tight correlation, $|r_{\text{p}}| \sim 0.62$.

7.2 Jeans equilibrium and dynamical mass

Observational estimates of the total (dynamical) mass within a given radius (say R_{e}) are based on observed kinematic properties and the assumed validity of Jeans (or hydrostatic) equilibrium for stars (or gas) along the radial direction in the major plane. This serves, for example, for evaluating the fractions of DM and baryons within this radius, which we already know is expected to change drastically during the compaction phase. Unfortunately, the kinematic observational estimates commonly yield a dynamical mass which is larger than the baryonic mass, indicating that either the system is out of equilibrium or the way the Jeans (hydrostatic) equilibrium is applied is erroneous. In particular, the ability to measure the dynamical mass, namely the validity of Jeans (or hydrostatic) equilibrium, may vary with a/a_{BN} and with r/R_{e} .

The Jean equation in the plane is

$$V_{\text{circ}}^2 = V_{\text{rot}}^2 + \alpha \sigma_{\text{r}}^2, \quad (6)$$

where V_{circ} is the circular velocity derived from the potential ($V_{\text{circ}}^2 = GM(r)/r$ for a spherical mass distribution), V_{rot} is the rotation velocity in the given plane, and σ_{r} is the radial velocity dispersion, both approximated as constants in the relevant range of radii. The value of α depends on the density profile,

$$\alpha = -\frac{d \ln \rho}{d \ln r}. \quad (7)$$

For an isothermal sphere $\alpha = 2$. For a sphere with a projected Sérsic profile of index n , α at R_{e} ranges from $\simeq 2$ for $n = 1$ to $\alpha \simeq 2.8$ for $n = 4$, and it is increasing with the radius within the galaxy. For a thin self-gravitating exponential disc with an exponential radius r_{d} ($R_{\text{e}} = 1.67r_{\text{d}}$) one predicts a steep rise with radius, $\alpha = 2(r/r_{\text{d}})$ (Burkert et al. 2010).

Using both analytic considerations and simulations, Kretschmer et al. (2021) provided a prescription to evaluate the dynamical mass from kinematic measurements of stars or gas. The validity of the simplified Jeans equation for stars is evaluated in Fig. 20, which shows the values of α_{v} and α_{ρ} as derived from equation (6) and equation (7), respectively. When plotted at R_{e} against stellar mass (left), one can see that the Jeans equation is approximately valid for masses above the critical BN mass; namely post-BN, where the median values of α deviate by less than 10 per cent, and the scatter in α_{v} is ± 20 per cent. However, for masses below the BN mass, the medians of the two α s deviate by ~ 25 per cent, and the scatter in α_{v} is ± 25 per cent, indicating somewhat larger deviations from Jeans equilibrium in the highly perturbed pre-BN galaxies. When the α values are plotted for the high-mass galaxies against radius (right), one sees that the medians agree to within 5 per cent out to $\sim 5R_{\text{e}}$.

The value of α varies with mass and especially with radius. At R_{e} , for galaxies $\geq 10^{10} M_{\odot}$ where Jeans equilibrium is valid, we measure $\alpha_{\text{v}} = 2.6 \pm 0.5$. This is consistent with the values obtained for a spheroidal system with Sérsic indices in a wide range of about $n \sim 2$ and is smaller than what is expected from a thin disc. For the galaxies below the BN mass, at $M_{\text{s}} \sim 10^9 M_{\odot}$, where Jeans equilibrium is a cruder approximation, $\alpha_{\text{v}} = 2.0 \pm 0.5$. For the massive galaxies post-BN, α is increasing with radius, from $\alpha_{\text{v}} = 2.5 \pm 0.5$ at $r = R_{\text{e}}$, through $\alpha_{\text{v}} = 3.0 \pm 0.7$ at $r = 2R_{\text{e}}$ to $\alpha_{\text{v}} = 3.5 \pm 1.0$ at $r = 4R_{\text{e}}$. This is significantly shallower than the linear rise with radius predicted for a thin self-gravitating disc.

For the gas, when plotted at the gas half mass radius ($R_{\text{e, gas}}$), Fig. 5 in Kretschmer et al. (2021) showed that hydrostatic equilibrium is achieved in massive galaxies with $M_{\text{s}} > 10^{9.5} M_{\odot}$ only if corrections for non-constant velocity dispersion and deviation from spherical potential are included. The large errors in the gas (see Fig. 2 and 5 Kretschmer et al. 2021) may indicate deviations from equilibrium. When α_{v} and α_{ρ} are plotted against radius in Fig. 2(d) in Kretschmer et al. (2021), we see that the agreement between the medians indicates a hydrostatic equilibrium in post-compaction galaxies out to $3.5R_{\text{e, gas}}$.

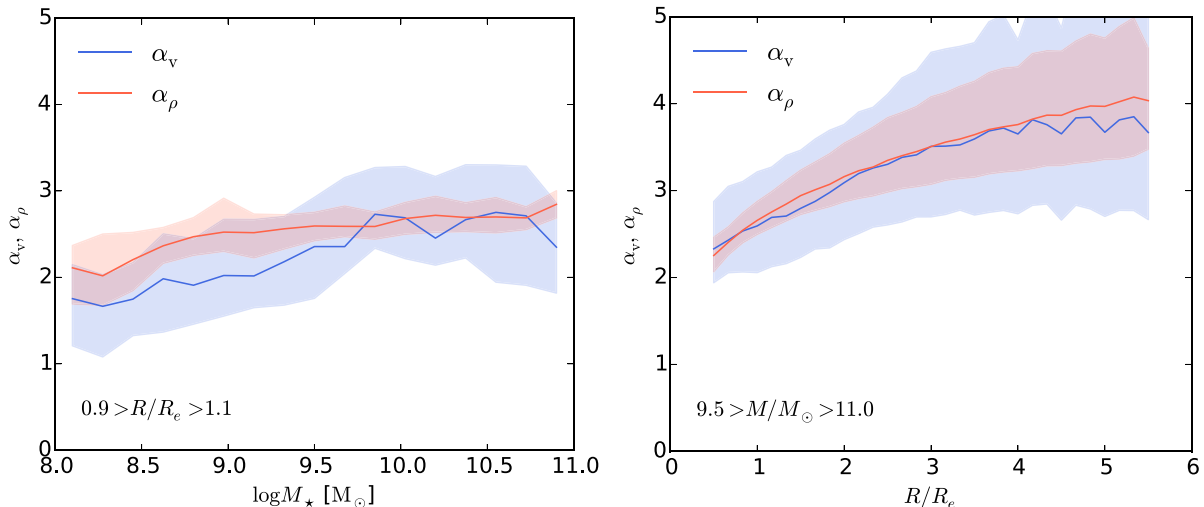


Figure 20. Validity of the simplified Jeans equation for stars. Shown are the value of α_v and α_ρ , derived from equation (6) and equation (7), respectively. For Jeans equilibrium with isotropy and $\sigma_r = \text{const.}$, one expects $\alpha_v = \alpha_\rho$. **Left:** at R_e as a function of stellar mass. The simplified Jeans equation is valid in the massive galaxies post-BN, with $\alpha_v = 2.6 \pm 0.5$. **Right:** for post-BN massive galaxies as a function of radius. The simplified Jeans equation is valid out to $5R_e$, with α increasing with radius.

7.3 Comparison to observations

Information on galaxy kinematics at $z \sim 2$ has become available through integral-field spectroscopy of optical emission lines such as $H\alpha$, tracing the ionized gas (see Glazebrook 2013, for a detailed review). A key point that has emerged from these studies is that substantial fractions of high-redshift galaxies have regular kinematics despite irregular photometric morphologies; this is likely due to the presence of a large number of highly gas-rich discs. Particularly, it appears that at least 50 per cent of 10^{10} – $10^{11} M_\odot$ SFGs on the $z \sim 2$ MS are rotationally supported structures with typical rotation velocities of 100 – 300 km s^{-1} , and with high values of velocity dispersion $\sigma \sim 50$ – 100 km s^{-1} (Förster Schreiber et al. 2006; Genzel et al. 2006). Using the ratio of circular rotation velocity to dispersion v_{rot}/σ as a tracer of the kinematics, larger galaxies ($M_s > 5 \times 10^{10} M_\odot$) have typically $v_{\text{rot}}/\sigma = 1$ – 10 at $z \sim 2$ (Förster Schreiber et al. 2009, 2018; Law et al. 2009; Jones et al. 2010; Genzel et al. 2011; Gnerucci et al. 2011; Swinbank et al. 2012, 2017; Wisnioski et al. 2015). These observations are in agreement with our simulated galaxies above the critical mass, which have $v_{\text{rot}}/\sigma \sim 3$ due to the post-BN extended gas ring or disc.

At lower masses, at 10^9 – $10^{10} M_\odot$, the abundance of dispersion-dominated SFGs increases significantly. This is again consistent with our simulated, pre-compact galaxies being dispersion dominated for both the gas and the stars. However, caution is advised because a significant contribution to the velocity dispersion deduced from observations may be due to instrumental broadening and beam smearing (Newman et al. 2013), so observations at higher resolution (e.g. with adaptive optics) are needed to shed more light on the true nature of these dispersion-dominated systems.

Recent observation of massive $10^{10} M_\odot$ galaxies at very high redshifts, $z > 4$, reveal the existence of dynamically cold discs (Smit et al. 2018; Neeleman et al. 2020; Rizzo et al. 2020; Lelli et al. 2021; Rizzo et al. 2021; Herrera-Camus et al. 2022). We find that the gas in post-BN galaxies, namely galaxies above the critical mass, tend to be rotationally dominated with typical values similar to observed massive galaxies at $z \sim 2$ of $v_{\text{rot}}/\sigma \sim 3$, consistent with some observations (Smit et al. 2018; Neeleman et al. 2020; Herrera-Camus et al. 2022). Several studies find indications for surprisingly

large values of $v_{\text{rot}}/\sigma \sim 7$ – 30 (Rizzo et al. 2020; Fraternali et al. 2021; Lelli et al. 2021; Rizzo et al. 2021), well above the expected values from the evolution of observed SFGs between $z \sim 0$ and 4. While the differences between observational studies could be partly caused by a difference in the nature of these sources, the different implemented modelling approaches may also affect the results. In Kretschmer, Dekel & Teyssier (2022), it was shown using MIGA simulation (Kretschmer, Agertz & Teyssier 2020) that v_{rot}/σ is highly dependent on the tracer used in the analysis. Namely, while moderate values of $v_{\text{rot}}/\sigma \sim 3$ were found when using HI gas, very high values of ~ 8 were obtained for molecular CO or H_2 , which tend to reside closer to the mid-plane.

8 METALLICITY

8.1 Transition in the metallicity–mass relation

In Fig. 21, we show the distribution of our simulated galaxies in metallicity–mass relation Z – M_s , in bins of redshift (distinguished by colour). To crudely mimic observations, the gas metallicity is measured within 3 kpc of the galaxy centre. As suggested in Maiolino et al. (2008), the volume selection is motivated by the typical aperture size of ~ 6 kpc in several surveys (Savaglio et al. 2005; Erb et al. 2006; Maiolino et al. 2008; Zahid et al. 2014a) observed within a wide range of redshifts ($z \sim 0.7$ – 3.5). One can see at a given redshift a continuous rise of Z with M_s for masses below the critical BN mass, with a linear or slightly sub-linear slope, and a shallower rise towards a plateau for masses above the BN mass. We do not find evolution in the zero point for a given mass, and the shoulder remains near the same mass at all redshifts, defined by the critical BN mass. The steep rise pre-BN reflects a continuous enrichment by star formation, while the post-BN flattening reflects saturation as the SFR is gradually suppressed.

Fig. 22 shows the evolution of gas metallicity as a function of ala_{BN} . The colour indicates Δ_{MS} . The two thick lines show the medians in bins of ala_{BN} for the subsample of high-mass and low-mass galaxies (defined at $z = 2$). The metallicity is rising in the pre-BN phase. Post-BN, we see a transition to a shallower slope

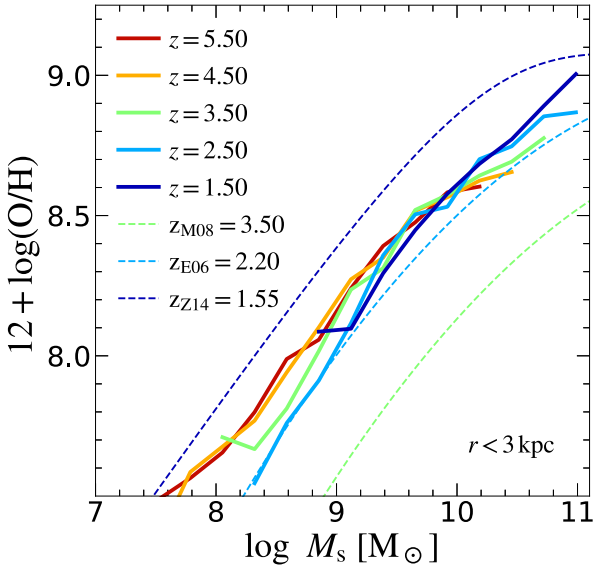


Figure 21. Gas metallicity versus stellar mass in different redshift bins. The metallicity is measured within the inner 3 kpc. Dashed lines show fits of observational data at redshifts: $z = 1.55$ from Zahid et al. (2014a), $z = 2.2$ from Erb et al. (2006, fits are taken from Maiolino et al. 2008), $z = 3.5$ from Maiolino et al. (2008). At a given redshift, we find a continuous rise of Z with M_s for masses below the critical BN mass and a shallower rise for masses above the BN mass. The simulations do not show evolution with redshift in the zero point for a given mass, and the shoulder remains near the same mass at all redshifts, defined by the critical BN mass.

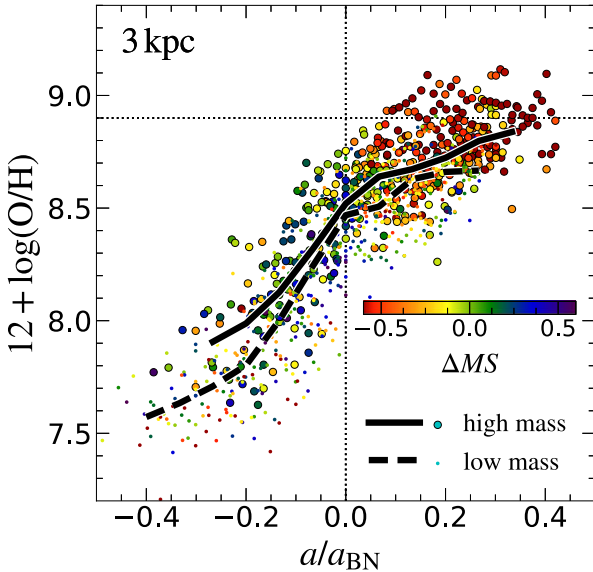


Figure 22. Gas metallicity as a function of a/a_{BN} . The metallicity is measured within the inner 3 kpc. The colour indicates the distance from the MS, Δ_{MS} , the medians refer to the high-mass and low-mass subsamples (defined at $z = 2$), and the horizontal dotted line marks solar metallicity ($0.02 Z_{\odot}$ or $12 + \log(\text{O}/\text{H}) \sim 8.9$). The metallicity sharply rises during the compaction phase and transitions into a shallower slope post-BN. In Fig. D8² we show the metallicity measured within 1 kpc and $0.1R_v$.

(measured within 3 kpc). The gas metallicity within 1 kpc or $0.1R_v$ (see Fig. D8²) shows a plateau after compaction. The metallicity in the inner 1 kpc tends to plateau due to the characteristic central gas depletion and low central SFR in the post-BN phase. At the galaxy scale of $0.1R_v$, an extended disc/ring forms around the quenching nugget. During this phase, the expected increase in metallicity due to star formation in the disc may be compensated or overpowered by low-metallicity gas accreted from the cosmic web. Although, on the one hand, there is an increase in the formation of metals as a result of star formation in the disc, the gas in the disc is diluted by low-metallicity accreted gas from the streams.

The colour in Fig. 22 indicates Δ_{MS} . We do not find a significant gradient across the MS after we remove the dependence of z and M_s . This is true when measured within 3 kpc as well as within $0.1R_v$ (as seen in the two right panels of Fig. D15²). However, the metallicity within the inner 1 kpc of the post-BN galaxies shows a significant gradient (see the left-hand panel in Fig. D15²). Moreover, when we compare the post-BN and the pre-BN galaxies, we find a sharp transition in the gradient across the MS occurring at the BN. While the pre-BN galaxies show no gradient across the MS and no correlation (listed in Table D1²), the post-BN galaxies show a significant gradient with a slope of -0.48 ± 0.02 and a rather tight correlation with $|r_p| \sim 0.66$.

8.2 Comparison to observations

The characteristic shape of the distribution in the Z - M_s diagram at each redshift, as seen in Fig. 21, is consistent with observations (Savaglio et al. 2005; Erb et al. 2006; Maiolino et al. 2008; Mannucci et al. 2009, 2010; Troncoso et al. 2014; Wuyts et al. 2014; Zahid et al. 2014a, b; Sanders et al. 2015; Onodera et al. 2016). We do not find evolution in the zero point for a given mass as seen in certain observations (Wuyts et al. 2014; Zahid et al. 2014a, b), it is closer to evolution of galaxies along a universal track at all times. This may be due to the large uncertainties in the observations (e.g. metallicity calibration), which are performed differently at different redshifts. It may alternatively reflect an inaccuracy in the simulations, perhaps associated with the too-early star formation and the too-low gas fraction. The estimation of metallicity is especially uncertain because it is a ratio of two uncertain quantities, the mass in metals and the gas mass. Nevertheless, the universal shape in the Z - M_s diagram and the characteristic turnover at the critical BN mass is robust and confirmed in observations.

9 PROFILES

9.1 Transition in profiles

The evolution through the phases of compaction, BN and quenching is reflected in the evolution of the profiles of the relevant quantities as a function of radius in the galaxy. This has been studied using the same simulations in Tacchella et al. (2016b). We summarize these results here and add the profiles of gas metallicity and DM fraction.

Fig. 23 shows the medians of individual galaxy profiles stacked at times which refer to the four phases of evolution: pre-BN, BN, early post-BN, and the late post-BN quenching phase. The BN event is defined as described in Section 3.2, referring to the global peak of gas mass (and SFR) within the inner 1 kpc. The pre-BN phase is defined at the onset of compaction, OC (see Section 3.2), where the central gas density starts to rise towards the peak of compaction, which typically occurs ~ 300 Myr before the BN event. The early post-BN phase is taken to be the first snapshot where the galaxy is at the lower

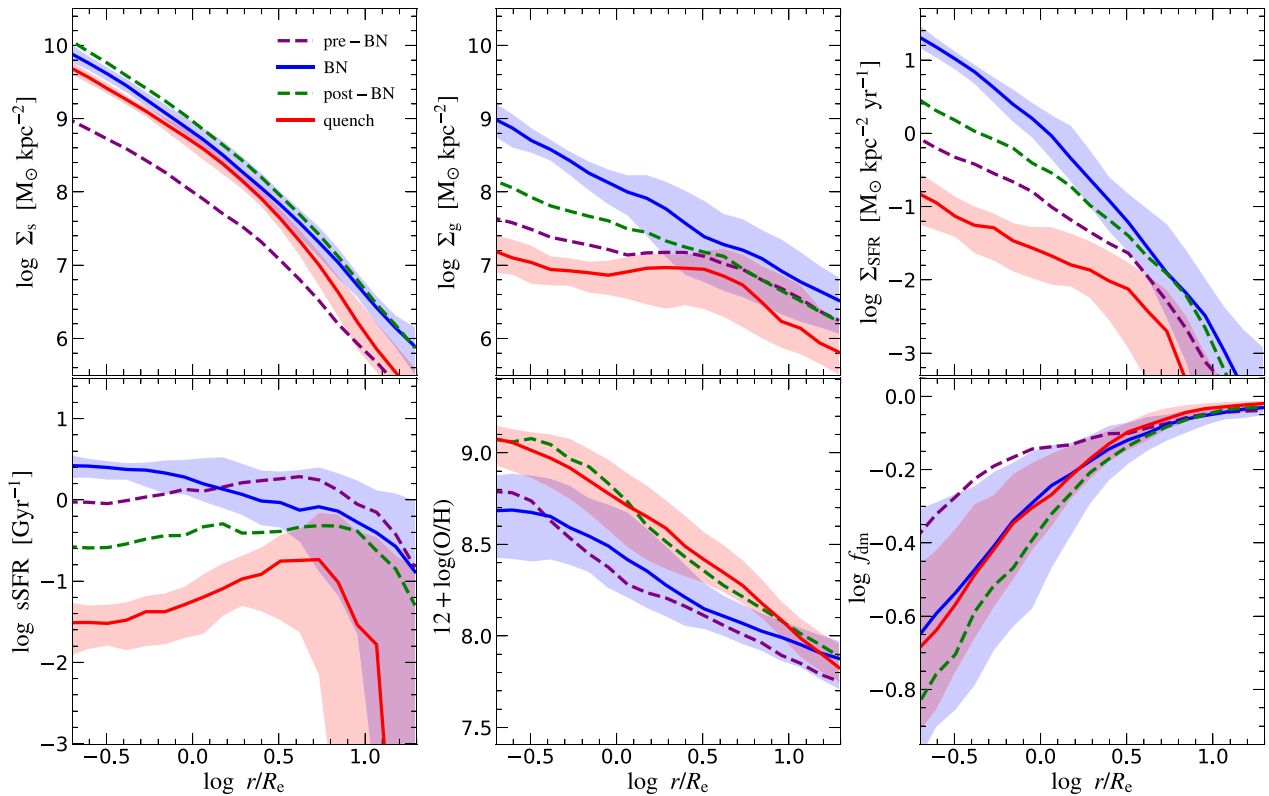


Figure 23. Profiles of different quantities stacked at four galaxy evolutionary phases as a function of the radius with respect to R_e . **Top, from left to right:** shown are the profiles of the stellar surface density (Σ_s), gas surface density (Σ_g), and SFR surface density (Σ_{SFR}). **Bottom:** The specific SFR ($s\text{SFR}$), gas metallicity (Z_g), and the dark matter fraction (f_{DM}). All quantities are measured within concentric spherical shells. The four phases are (1) pre-BN (dashed purple) measured at the onset of compaction. (2) BN (blue). (3) post-BN (dashed green). (4) quenching phase (red). The lines indicate the median of the profiles. The shaded areas show the 1σ scatter about the median of the BN and the quenching phase. Each individual profile of the quantities Σ_s , Σ_g , Σ_{SFR} , and $s\text{SFR}$ is scaled to have the same median $\Sigma(r < R_e)$ of all the galaxies in each phase. We do not scale the y-axis in the gas metallicity and dark matter fraction before stacking (see raw profile medians without scaling in Fig. D16²).

edge of the MS with $\Delta_{\text{MS}} < -0.2$, which generally corresponds to the time when the inner 1 kpc starts to quench, typically ~ 300 Myr after the BN event. Finally, the late post-BN quenching phase occurs when the galaxy drops below the lower edge of the MS, at its lowest Δ_{MS} , typically one of the latest snapshots of $z \sim 1-2$. For all quantities except for the two mass fractions (Z_g and f_{DM}), before stacking, we scale each individual galaxy profile to have the same median effective density ($\Sigma(r < R_e)$) of all the galaxies in each phase. In Fig. D16², we show raw profile medians, scaling neither the x nor the y -axis.

The key to the wet-compaction-driven BN phenomenon is the inner ~ 1 kpc cusp that has developed in the gas density profile at the BN phase, while the inner profile of both the pre-BN and post-BN shows a rather flat core. The central gas surface density (top, middle panel) at BN exceeds $10^8 M_\odot \text{ kpc}^{-2}$ within the effective radius, while all the other phases are significantly lower. The pre-BN and late post-BN are lower by an order of magnitude or more in the innermost regions. The SFR profile (top, right-hand panel) closely follows the gas profile in accordance with the local SFR recipe in the simulations. At the BN phase, the SFR profile is cuspy within the inner few kpc, and the central SFR density is higher by an order of magnitude than before the BN and late after the BN.

The $s\text{SFR}$ profile tells us the relative activity of star formation at different radii. Pre-BN, the $s\text{SFR}$ is weakly rising with radius, while at the BN, the central $s\text{SFR}$ is higher by a factor of a few such that

the profile is gradually declining. This reflects the vanishing of the outer gas disc into a compact gaseous and star-forming BN. It can be interpreted as an early ‘outside-in’ quenching process associated with the compaction. During the quenching phase, the central $s\text{SFR}$ becomes lower than at the BN phase by two orders of magnitude, while at $2 - 6R_e$ it is only a factor of $\sim 3-10$ below its value at the BN phase. The $s\text{SFR}$ profile rises with radius, more and more so with time. This reflects the gas depletion in the core and the formation of an extended gaseous star-forming ring. It can be interpreted as ‘inside-out’ quenching.

The self-similar growth of the stellar-mass density profile during the pre-BN, BN, and post-BN reflects the weak dependence of $s\text{SFR}$ on radius during these phases. We find little evolution in the central density during the three later phases (BN, post-BN and quenching phases), reflecting saturation of growth in the centre as the BN completes its main period of star formation and becomes a passive RN. In Fig. D16², we see that the median stellar density profile at the quenching phase is generally somewhat larger, as expected for a later stage in the evolution. However, when we scale the x -axis with respect to R_e , as seen in Fig. 23, the density at the quenching phase lies slightly below the BN and post-BN profiles. This reflects the central stellar growth saturation after compaction, combined with a typically larger R_e , by a factor of ~ 2.5 , compared to the BN or post-BN phase (see Fig. D16² for the median R_e in each phase).

9.2 Gas phase metallicity profiles

The gas metallicity profiles (Fig. 23 bottom, middle panel) do not show significant evolution between the pre-BN and BN phases. Both display a relatively low sub-solar metallicity at all radii. The BN phase is characterized by the contraction of gas from the outskirts of the galaxy and intense star formation closely followed by SN feedback from the recently formed massive stars. As a result, competing processes may affect the metallicity during this phase: On one hand, intense star formation during compaction will cause a rise in metal production from explosions of massive stars. On the other hand, feedback from these SN explosions may expel the recently enriched gas. In addition, the ongoing contraction of gas may also help sustain low metallicity by diluting the centre as gas from the outskirts of the galaxy is funnelled inside. Post-BN, we see enrichment by a factor of ~ 2 above the BN phase in the inner regions $< R_e$, exceeding solar metallicity, while the metallicity in the outskirts remains relatively low. As a result, the profiles show a steeper decline with radius at the post-BN phases. The two post-BN phases have very similar metallicity profiles when we scale the radius by R_e (Fig. 23), with a hint of a steeper slope around $1 - 3R_e$ in the post-BN compared to the quenching phase. For a given radius (Fig. D16²) at the quenching phase, we see metallicity of $\sim 0.3-0.4$ dex above the BN phase in the outskirts ($2-6$ kpc), while the metallicity in the post-BN phase is only < 0.1 dex above it. The post-BN phase is taken to be the time in which the galaxy goes down to the lower edge of the MS, namely about the time it is processing toward the ‘green valley’. After this stage, we typically find that the centre becomes increasingly passive and later often surrounded by a gaseous, low-metallicity, and star-forming ring. The metal production increase due to star-formation in the post-compaction ring competes with dilution by accretion of high angular-momentum fresh gas from cold streams (see Section 9.4). Although the metallicity for a given radius during the time between the post-BN and quenching phase increased in the galaxy outskirts, one can still see that in both post-compaction phases, the metallicity is declining with a steeper slope than that of the BN, similar to the behaviour seen in Fig. 23.

9.3 Dark matter fraction and declining rotation curves

The profiles of dark matter fraction, $f_{\text{DM}}(r)$, are shown in Fig. 23 (bottom right) and Fig. D16². $f_{\text{DM}}(r)$ is measured within thin concentric spherical shells around the galactic centre. The profiles generally show an increase with radius at the four phases, all reaching values close to 1 at large radii where the dark matter dominates over all other components. Pre-BN, the central dark matter fraction shows significantly higher values (~ 0.7 at R_e) than the three following stages (< 0.5 for $r \sim R_e$). The profiles at the BN, post-BN, and quenching phases show similar fractions when the radius is scaled by R_e . This reflects what we have already shown in Fig. 7, namely the reduction of the dark matter fraction when measured within $r < R_e$ from high values > 0.5 before compaction to a median of ~ 0.3 at the BN. Only mild evolution is seen after compaction, which can be partly attributed to the post-compaction increase in R_e .

Fig. 24 shows stacked rotation curves, $V_{\text{circ}}(r)$, $V_{\text{rot}}(r)$, and $\sigma_r(r)$, normalized by the maximum V_{rot} for each snapshot. The snapshots are divided into two subsamples, pre and post-BN, with stellar masses below and above $10^{9.5} M_{\odot}$, respectively. Also shown is a subsample of 20 per cent of the post-BN sample, selected to have $\sigma_r > V_{\text{rot}}$ at $4 < r/R_e < 6$. The post-BN rotation curves are declining beyond R_e , and σ_r is rising, summing up to an almost flat V_{circ} . The subsample selected to have $\sigma_r > V_{\text{rot}}$ at large radii shows steeply declining

rotation curves, compatible with the ones observed by (Genzel et al. 2017), shown in the figure for comparison as blue symbols.

9.4 Extended ring/disc

If fresh gas is supplied after compaction and onset of inside-out quenching, a new extended disc/ring may form around the depleting nugget and develop a new VDI phase with some star formation, as seen in Fig. 2. Zooming out from such pictures clearly shows that the ring is forming due to new high-angular-momentum gas that spirals in through streams of cold gas, penetrating the DM halo from the cosmic web into its centre. The fact that the post-compaction ring originates from fresh gas can be seen by the metallicity profiles in Fig. 23. Although some increase in metal enrichment is expected at the outskirts of the galaxy as a result of star-formation in the post-compaction ring, dilution by fresh gas sustains a relatively low metallicity at large radii ($> 3R_e$) as seen in Fig. 23, where both post-compaction phases show a steeper decrease with radius than the slope at the two earlier phases.

Using both an analytical model and simulations, Dekel et al. (2020b) studied the origin and formation mechanism of extended gas rings in massive galaxies at high redshifts $z < 4$. By analytically evaluating the torques which are exerted by tightly wound spiral structure, it was shown that ring shrinkage depends on the cold-to-total mass ratio (δ_d). A long-lived ring is expected to form when the ring transport time, $\propto \delta_d^{-3}$, becomes longer than the time-scales of ring replenishment by accretion and depletion by SFR interior to the ring. These conditions become valid when $\delta_d < 0.3$. When compared to simulations, it was shown that long-lived rings tend to form once a compaction-driven increase in the central mass results in a lower value of δ_d .

9.5 Comparison to observations

The predictions for the evolution of the surface-density profiles for stellar mass, gas mass, and SFR, as in Fig. 23, have been compared to observations in Tacchella et al. (2016b). The robustness of gaseous rings about the quenched red nuggets is a prediction to be tested. Galaxies with star-forming $H\alpha$ rings about massive bulges have been observed at $z \sim 2$ (Genzel et al. 2014), but their abundance has not been verified yet as they may be of low surface brightness and, therefore, hard to detect. Nelson et al. (2016, 2021) created deep stacked $H\alpha$ images of 3D-HST data to map out the SFR distribution in $z \sim 1$ SFGs, finding that the $H\alpha$ emission is more extended than the stellar continuum emission (Matharu et al. 2022), consistent with the inside-out assembly of galactic discs. This effect grows stronger with mass, indicating that the more massive systems have an extended star-forming component in their outskirts. Abdurro’uf et al. (2023) studied galaxies at $0.3 < z < 6$ in two clusters and a blank field by combining data from HST and JWST to perform a spatially resolved spectral energy distribution modelling. The high spatial resolution, combined with lensing magnification in the cluster fields, allowed a sub-kpc scale resolution in some galaxies. They find flat sSFR radial profiles and similar R_e and $R_{e, \text{SFR}}$ radii at the highest redshift bin, a significant fraction of central starbursts in SF galaxies at $1.5 \leq 2.5$ and $R_{e, \text{SFR}} < R_e$. Finally, at the low redshift bin, they find a higher fraction of galaxies with suppressed central SF while they continue to form stars in the disc. This is consistent with the inside-out assembly (see also Abdurro’uf et al. 2022, for nearby galaxies). Tacchella et al. (2015a) measured the $H\alpha$ emission distribution in individual systems at $z \sim 2.2$, comparing the stellar mass and SFR surface density profiles of individual galaxies. The main finding is that

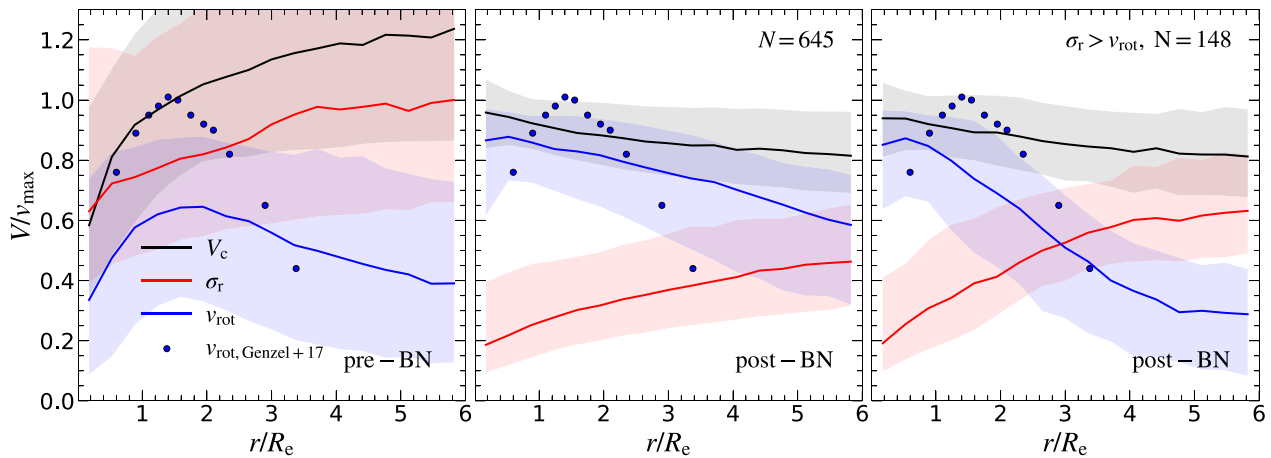


Figure 24. Rotation curves: $V_{\text{circ}}(r)$, $V_{\text{rot}}(r)$ and $\sigma_r(r)$, normalized by the maximum V_{rot} for each snapshot. **Left:** Pre-Compaction, stacked are all snapshots (454) with $M_s < 10^{9.5} M_\odot$. **Middle:** Post-compaction, based on the snapshots (645) with $M_s > 10^{9.5} M_\odot$. **Right:** Post-compaction subsample containing the ~ 20 per cent of the snapshots (148) selected by $\sigma_r > v_{\text{rot}}$ at $4 < r/R_e < 6$. The blue symbols mark V_{rot} from observed $z \sim 2$ massive discs (Genzel et al. 2017). The selected post-BN subsample resembles the observations, showing declining rotation curves and dispersion dominance at large radii.

lower mass systems have roughly flat sSFR profiles, while galaxies at $M_s > 10^{11} M_\odot$ have reduced sSFR profiles, which indicates those galaxies have their star-formation activity taking place in an extended ring, consistent with the simulated post-compaction galaxies. Similar results have been reported by Tacchella et al. (2018) after taking special care of the dust attenuation distribution within the galaxies. Mancini et al. (2019) studied the star formation history (SFH) in 10 observed ‘green-valley’ galaxies at $0.45 < z < 1$. By performing a multiwavelength bulge-to-disc decomposition, the SFH for the two components were derived separately. It was shown that these galaxies, at the bending of the MS, tend to have old bulges and significantly younger discs. It was argued that the bending of the MS is mostly due to galaxies which formed their bulge at very high redshifts, with ages approaching the age of the Universe (see also Tacchella et al. 2022), and later experienced a rejuvenation of SF in the outer regions of the disc (Dimauro et al. 2022). This is again consistent with the simulated post-compaction galaxies shown here.

While we find a good agreement between the reported shapes of the observed and simulated profiles, the SFR surface density profiles in the simulations have a too-small normalization in comparison to observations at a given mass and redshift. This might indicate that the galaxies in the simulations are consuming the gas too early, resulting in too small SFR at low redshifts ($z \sim 1$).

As highlighted above, during the BN phase, the star formation takes place primarily in the central ~ 1 kpc. We expect that this star formation is heavily obscured by dust. Recent observations with ALMA (Tadaki 2016; Barro et al. 2016b; Tadaki et al. 2017, 2020) detected massive, dusty SFGs that are experiencing a dusty nuclear starburst and are doubling their mass quicker in their centres than in their outskirts, consistent with the rising sSFR as seen in the simulated BN galaxies, Fig. 23.

The simulation prediction of central baryon dominance after the compaction phase, namely above the critical mass, as seen in Fig. 7, is confirmed observationally Price et al. (2016); Genzel et al. (2017, 2020). We find in Fig. 24 that a fraction of the simulated galaxies at $z \sim 2$ have declining rotation curves beyond R_e , while observationally this seems to be the typical behaviour Lang et al. (2017). The modelling involved in the dynamical analysis of observed rotation curves includes an assumption of radially constant velocity dispersion, in the absence of any clear contradicting evidence, it is utilized as the

simplest assumption. In Fig. 24, we see that the simulations indicate a radially rising velocity dispersion in massive post-compaction galaxies; such behaviour may leave room for somewhat higher dark matter fractions within R_e .

10 SN FEEDBACK AND BH GROWTH

10.1 Transition in BH growth at a critical mass

We propose that the compaction event has a crucial role in the growth of the black hole in the galaxy centre, and in triggering AGN feedback that helps the quenching of massive galaxies. The characteristic mass of BNs, at $M_s \sim 10^{10} M_\odot$ or $M_v \sim 10^{12} M_\odot$, indeed appears in many other observed properties of galaxies, such as the peak mass of galaxy formation efficiency M_s/M_v , defining the scale of bimodality in galaxy properties (e.g. Dekel & Birnboim 2006). In particular, strong AGN activity tends to show up in observed galaxies above this critical mass, indicating rapid BH growth in this regime.

At least two relevant physical processes give rise to a characteristic mass in the same ballpark. First, the lower limit is set by the critical scale for supernova feedback, corresponding to a potential well with a virial velocity of $V \sim 100 \text{ km s}^{-1}$ at all redshifts, below which the SN energy deposited in the ISM and CGM is capable of significantly heating a large fraction of the gas and ejecting massive outflows, while above which SN-feedback becomes ineffective (Dekel & Silk 1986). Second, the upper limit is set by the critical mass for virial shock heating, $M_{\text{crit}} \sim 10^{12} M_\odot$ at all redshifts, below which most of the gas entering the halo streams cold into the galaxy, while above which a virial shock is stable and can support a hot CGM (Birnboim & Dekel 2003; Kereš et al. 2005; Dekel & Birnboim 2006), which in turn may lower the efficiency or even suppress cold gas supply to the galaxy. Cold streams can penetrate the hot haloes even slightly above the critical mass at high redshifts, but cold gas supply to the galaxy is significantly suppressed in such haloes at $z \leq 2$ (Dekel & Birnboim 2006; Ocvirk, Pichon & Teyssier 2008; Dekel et al. 2009; Kereš et al. 2009). To some extent, these two scales are related as they both arise from a balance between cooling and dynamical times, but they arise in two different contexts. A third scale, of unrelated origin, is the scale for non-linear clustering, the Press–Schechter mass, which is rapidly growing with time but is in the ballpark of $\sim 10^{11-12} M_\odot$ at

$z \sim 1$, thus possibly relevant to the characteristic scale of galaxy formation at moderate redshifts $z \sim 1-2$ (e. g. see fig. 2 of Dekel & Birnboim 2006, for a summary of the three processes as a function of M_v and redshift).

Several cosmological simulations which incorporate both SN feedback and an accreting BH yield similar robust results concerning the cross-talk between these two processes. These include simulations in various codes (such as AMR, SPH, and quasi-Lagrangian) with different sub-grid models, and more to the point, using different implementations of BH growth and SN feedback (Dubois et al. 2015; Anglés-Alcázar et al. 2017; Bower et al. 2017; Habouzit, Volonteri & Dubois 2017; Habouzit et al. 2019; Dubois et al. 2021). All are showing consistent results that the BH growth is suppressed below the critical halo mass of $\sim 10^{11.5} M_\odot$ ($M_s < 10^{10} M_\odot$), and rapid BH growth starts quite abruptly and prevails at larger masses. This can be seen, for example, in Dubois et al. (2015, fig. 2) and Bower et al. (2017, figs 6-7).

This asymptotic behaviour below and above the critical mass can be naturally understood in terms of the characteristic masses associated with SN feedback and virial shock heating. Well below the critical mass, SN feedback is efficient in removing gas from the galaxy potential well, helped by the buoyancy of SN-driven gas through the cooler CGM, thus suppressing accretion onto the BH and starving it. Well above the critical mass, the SN-driven winds are bound to the galaxy, both by the deep halo potential and by the hot (T_v) CGM that prevents buoyancy of the cooler SN-driven gas, so any outflows recycle and cannot prevent accretion onto the black hole (The role of buoyancy is nicely argued in Bower et al. 2017). Note that, the rapid BH growth naturally activates AGN feedback, which in turn (a) can suppress star formation and therefore SN feedback, and (b) can keep the CGM hot after the gas was heated by the virial shock.

The wet compaction event, which tends to occur at a similar critical mass, triggers the transition between these asymptotic regimes. The sudden condensation of gas into the inner 1 kpc drives a stimulated accretion onto the BH, which overcomes any pushback by SN feedback and starts the phase of rapid BH growth. In the simulation described in Dubois et al. (2015, fig. 8), the onset of rapid BH growth is indeed associated with a compaction event driven by a minor merger. This role of compaction is being studied in detail in the NEWHORIZON simulations (Lapiner et al. 2021).

10.2 Comparison to observations

There is observational evidence for a correlation between BNs and AGN activity. Kocevski et al. (2017) find in the CANDELS sample at $z \sim 2$ that in the BN regime of the SFR- $\Sigma_{1\text{kpc}}$ diagram, namely galaxies with high $\Sigma_{1\text{kpc}}$ and high SFR, the fraction of galaxies that host X-ray AGNs is about 40 per cent. While in the pre-compaction SFG regime and the post-compaction quenched regime, it is less than 25 per cent. Juneau et al. (2013), using a sample of X-ray obscured AGN at $z = 0.3-1$, find that they tend to be hosted in compact galaxies of high sSFR above the MS ridge, namely in the BN regime. Chang et al. (2017) analysed the morphology of obscured AGNs at $0.5 < z < 1.5$ in the COSMOS survey, finding that such galaxies have a typical stellar mass of $> 10^{10} M_\odot$, and tend to be more compact in terms of both R_e and their Sérsic index than normal SFGs of a given redshift and stellar mass. Again, consistent with BNs. Förster Schreiber et al. (2019) identify AGN-driven winds preferentially above a threshold stellar mass of $\sim 10^{10} M_\odot$, and an anticorrelation with R_e , consistent with the predicted compaction-driven black hole growth. In Lapiner et al. (2021, fig. 9), it was shown, using eight massive galaxies in

the NEWHORIZON simulations, that a similar trend is seen in the fraction of AGNs as a function of stellar mass. That is, the fraction of AGNs is very low below the turn-up mass and steeply rising above it. The results are overall consistent with Förster Schreiber et al. (2019, figs. 6,13), with a slight offset to lower masses or higher AGN fractions, which depends on the selected AGN luminosity threshold.

11 TRIGGER OF COMPACTION

11.1 Mergers

What are the mechanisms that trigger wet compaction? In principle, it could be any mechanism that causes significant dissipative AM loss. Wet major mergers are obvious candidates, as they are known to be capable of pushing gas in (Barnes & Hernquist 1991; Mihos & Hernquist 1996; Dekel & Cox 2006; Hopkins et al. 2006, 2010; Covington et al. 2008, 2011). However, their expected frequency has to be compared to the abundance of BNs. Indeed, we see in the simulations compaction events that are not associated with major mergers and some not even with mergers of any kind. Therefore, we attempt to estimate the statistics of the triggers of compaction.

The galaxy merger rate could be approximated by the halo merger rate, which could be estimated based on the EPS formalism from fig. 6 and equation 24 of Neistein & Dekel (2008). We obtain that the rate of major mergers (with a mass ratio larger than 1: 3) for a $\sim 10^{12} M_\odot$ halo in the EdS regime is

$$\frac{dN}{dt} \simeq 0.4 [(1+z)/3]^{2.5} \text{Gyr}^{-1} \quad (8)$$

We wish to compare this to the rate of onsets of compaction events. We note in Fig. 10 that most galaxies undergo a major compaction event when their halo mass is typically in a mass range of $\Delta \log M \sim 0.4$ about the critical BN mass. In order to relate this mass range to a redshift range, we appeal to the average growth of haloes in the EdS regime (Dekel et al. 2013, equation 9),

$$M(z) \propto M_0 e^{-\alpha(z-z_0)}, \quad (9)$$

where the mass at z_0 is M_0 and $\alpha \simeq 0.8$ in the relevant mass range. This gives $\Delta z \simeq 3 \Delta \log M \simeq 1.2$. In the EdS regime, where $(1+z) \simeq (t/t_1)^{-2/3}$ with $t_1 \simeq 17.5$ Gyr, this corresponds at $z = 2$ to $\Delta t \simeq 1.4$ Gyr. A comparison to equation (8) implies that about half the galaxies in the given mass range undergo major mergers, so the latter can be responsible for about half the onsets of compaction. Minor mergers (1: 10 to 1: 3) are expected to have a similar frequency.

We study the origin of compactions in our simulations in Ginzburg et al. (in preparation) and summarize the main result here. Fig. 25 summarizes the correlation between the BN events and merger events using the entire sample. The merger events are identified by rapid variations of stellar mass within the inner $(0.1-0.2)R_v$ over the output time-step of ~ 100 Myr. The events are divided into BNs associated with (a) major mergers (mass ratio $> 1: 3$), (b) minor mergers (1: 10 to 1: 3), and (c) BNs that are not associated with any merger event. We also identified a couple of BNs associated with mini-minor mergers (1: 20 to 1: 10) and counted them as ‘no mergers’. A small fraction of the mergers (medium darkness in the figure) is identified as flyby events, most of which are first-passages before the final coalescence. The association with a compaction event is evaluated by the co-occurrence (to within ± 100 Myr) of the merger event either with the onset of compaction (O) or with any time during the compaction process, between the onset and the BN (O-B).

We thus estimate that major mergers trigger about 48 per cent of the compaction events, about 26 per cent are associated with

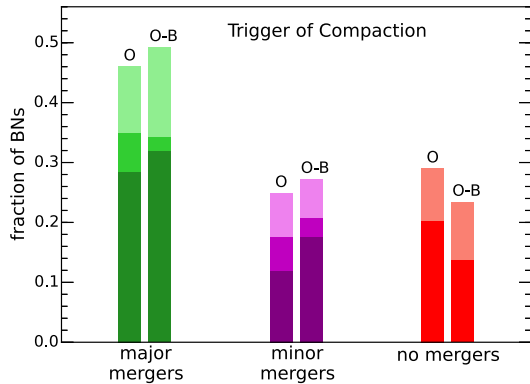


Figure 25. Fraction of compaction events that are triggered by major mergers ($> 1:3$), by minor mergers ($1:10$ to $1:3$), and by another mechanism. The identification of a co-occurring merger and compaction is made near the onset of compaction (O) or during the compaction from the onset to the BN (O—B). Dark colours refer to solid identifications of bound mergers, medium colours refer to fly-byes (that mostly end up as mergers), and light colours refer to uncertain mergers. The best-estimate fractions of these events are 0.48, 0.26, and 0.26, respectively.

minor mergers, and another 26 per cent are not associated with stellar mergers and thus must be triggered by a different mechanism. We find no significant difference between the triggers of all the compaction events and those of the major BNs that lead to significant quenching. We also find that about one-third of the major mergers do not lead to compaction events. These results are indeed in the ballpark of the toy estimates above. They indicate that, as expected, major mergers serve as a major trigger of compaction events and that, together with minor mergers, they are responsible for about 70 per cent of the compaction events. However, about 30 per cent of the compaction events are not triggered by mergers as identified by their stellar component.

11.2 Other potential triggers of compaction

The other mechanisms that may trigger AM loss and lead to compaction events are being studied elsewhere using these simulations. A partial list is as follows.

(b) Counter-rotating streams. The streams could drive compaction by generating low AM patches once they are counter-rotating with respect to the disc and other streams. Our simulations indicate that typically one stream out of three is counter-rotating (Danovich et al. 2015, fig. 14).

(c) Recycling. We see a new fountain pattern in our simulations, where feedback-driven winds from the disc outskirts carry out high AM and return to the galaxy with low AM, generating low AM patches and possibly triggering global compaction (DeGraf et al. in prep.). A similar mechanism has been proposed by Elmegreen, Struck & Hunter (2014).

(d) Triaxial cores. The torques induced by the pre-BN triaxial haloes discussed in Section 6 could induce AM loss that could lead to compaction, while the disappearance of such torques in the post-BN rounder halo would end the occurrence of compaction events.

(d) Satellite compression. In a study of SDSS satellite galaxies (Woo et al. 2017), we found that they are compact when quenched, indicating that satellite quenching may also involve compression. This could be induced in the outer host halo by ram-pressure compression when self-gravity overcomes the ram-pressure push. Alternatively, it could be induced by tidal compression in the inner

halo where the host halo density profile is core-like (Dekel, Devor & Hetzroni 2003).

(e) VDI-driven disc contraction. In Dekel & Burkert (2014), based on Toomre instability, we analysed the wet shrinkage due to torques in a galaxy undergoing violent disc instability (VDI), energetically powered by the inflow to the bottom of the potential well. We found that VDI in our cosmological simulations is externally stimulated (Inoue et al. 2016), e.g. by minor or major mergers, tidal interactions, or counter-rotating streams. The VDI is thus commonly associated with the same mechanisms that can trigger AM loss and wet compaction. The toy model based on VDI thus captures many of the properties of wet compaction even when not solely driven by VDI.

12 ABUNDANCE OF BNS

12.1 Evolution of abundance

The predicted abundance of BNS as a function of redshift is not straightforward to deduce from the simulations, as our sample consists of a given group of galaxies that grow in time and is not a fair sample at any redshift. Therefore, the abundances plotted in fig. 15 of Zolotov et al. (2015) are not directly comparable with observations. However, based on the characteristic halo mass M_{crit} for most BNS, and the typical lifetime of a galaxy in the BN phase Δt_{BN} , both derived from the simulations, one can make a toy-model estimate of the abundance of BNS at any time in the EdS regime ($z > 1$). Using the average growth of haloes in equation (9), at any given z , we translate Δt_{BN} to a mass interval ΔM . We then use the Sheth–Tormen version of the Press–Schechter approximation (Sheth & Tormen 2002; Dekel & Birnboim 2006, appendix) to compute the comoving number density of haloes with masses in the interval $(M_{\text{crit}}, M_{\text{crit}} + \Delta M)$. Finally, the abundance of post-BN galaxies is estimated as the integral of all past BNS after they are turned off as star-forming BNS.

Assuming that half the compactations are caused by major mergers (as estimated in our simulations, Section 11), one may adopt a delay in the onset of BN by half the mean time between major mergers. Based on equation (8), the latter is

$$\frac{\Delta t}{t} \simeq \frac{0.56}{(1+z)/4}. \quad (10)$$

As above, using equation (9), this can be translated to a mass increment to be added to M_{crit} .

Fig. 26 shows the result of this toy-model estimate, assuming a constant threshold halo mass, a delay of half the mean time between major mergers, and a constant duration for BNS. We show the model in five typical fixed duration of compaction, $\Delta t_{\text{BN}} = 0.1, 0.2, 0.3, 0.4, 0.5 t_{\text{hub}}$ (bottom to top, respectively), and two threshold halo masses $M_v = 10^{12} M_{\odot}$ (blue) and $M_v = 10^{11.5} M_{\odot}$ (green). Our fiducial model (dark blue line) assumes a threshold halo mass for BNS of $\sim 10^{12} M_{\odot}$, and a fixed duration for BNS of $\Delta t_{\text{BN}} = 0.3 t_{\text{hub}}$ (Zolotov et al. 2015, fig. 16). While the simulations indicate a somewhat lower critical halo mass, we assume a threshold of $10^{12} M_{\odot}$ given the possible dependence on feedback and the tendency of the simulations to overestimate the stellar-to-halo mass relation (see Section 2.2). From abundance matching, this threshold halo mass is expected to correspond to a median stellar mass of $\sim 10^{10.3} M_{\odot}$ at $z \sim 2$ with a scatter of ± 0.3 – 0.4 dex. Assuming the fiducial case, we see that the abundance of BNS is predicted to rise with time from high redshifts till $z \sim 3$, reaching a broad

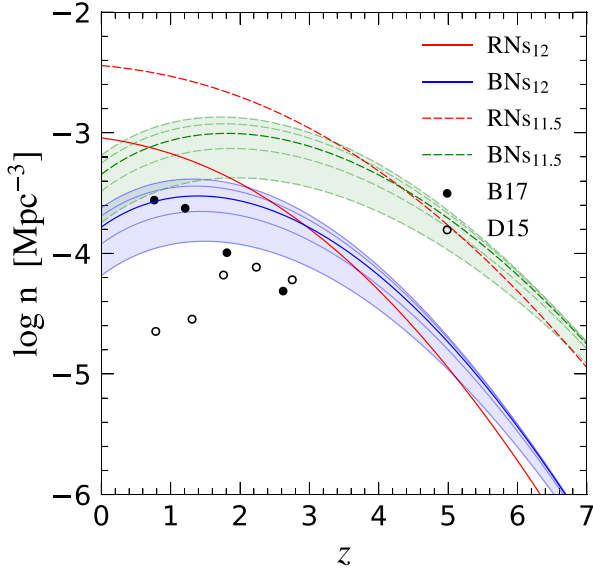


Figure 26. Evolution of the abundance of BNs according to a toy model assuming a constant threshold halo mass of $M_v = 10^{12} M_\odot$, plus a compaction trigger by major mergers, and assuming several constant duration of BNs with $\Delta t_{\text{BN}} = 0.1, 0.2, 0.3, 0.4, 0.5 t_{\text{hub}}$ (blue, bottom to top, respectively). Also shown is the evolution of BNs abundance assuming a lower threshold halo mass for BNs of $M_v = 10^{11.5} M_\odot$ (green). Our fiducial case (dark blue line) assumes a threshold halo mass of $M_v = 10^{12} M_\odot$ (median of $M_s \sim 10^{10.3} M_\odot$ at $z \sim 2$) and $\Delta t_{\text{BN}} = 0.3 t_{\text{hub}}$. Recent observational estimates of compact star-forming systems with $M_s > 10^{10.3} M_\odot$ are shown for comparison in solid and open black symbols, from Barro et al. (2017a, fig. 8) and Van Dokkum et al. (2015, fig. 19), respectively. The model (assuming the fiducial case) overestimates the observed abundance at $z \sim 2-3$. However, this should serve as an upper limit, partly because of a larger threshold mass for BNs in the observed abundances and a high threshold of $\Sigma_{1 \text{ kpc}}$. In addition, the fixed duration of compaction is expected to be lower for observed compact BNs due to a stellar-based high threshold for $\Sigma_{1 \text{ kpc}}$, while our measurements for the duration rely on the evolution of central gas. The abundance of post-BN passive central RN (fiducial case in solid red, dashed red indicates a mass threshold of $10^{11.5} M_\odot$) is expected to rise in time continuously.

peak somewhat above $n \sim 10^{-4} \text{ Mpc}^{-3}$ near $z \sim 1-2$. Moreover, we see that BNs are expected to be observable also at higher redshifts, e.g. with $n \sim 10^{-5} \text{ Mpc}^{-3}$ at $z \sim 5$, but only with $n < 10^{-6} \text{ Mpc}^{-3}$ at $z > 7$. The fiducial case overestimates the observed abundance at $z \sim 2-3$; however, we expect the model to serve as an upper limit to the observed abundance partly due to the following reasons. First, we expect a shorter duration for observed BNs when a high threshold for $\Sigma_{1 \text{ kpc}}$ is adopted for observed BNs. We measure the BN duration (Δt_{BN}) based on the evolution of the central gas through the whole compaction event (compact with high SFR), starting from the onset of compaction and up to the post-BN phase before the galaxy is leaving the Main Sequence. When a central stellar-based threshold of $\Sigma_{1 \text{ kpc}}$ is introduced, the duration is expected to start after a massive central stellar body is formed, roughly starting the duration from or even after the peak of compaction (BNg). Second, taking into account, the scatter in the stellar-to-halo mass relation for a $10^{12} M_\odot$ halo at $z \sim 2$, the observed sample is selected above a threshold stellar mass which is larger than the critical BN mass. Finally, the prediction would also serve as an upper limit if only a fraction of the galaxies in the mass range following the critical BN mass actually become BNs. We also

show a lower halo mass threshold of $10^{11.5} M_\odot$ (green). However, this threshold is significantly lower than the mass threshold of the observed abundances.

The abundance of post-BN passive galaxies is expected to rise in time continuously, crudely matching the BN abundance at $z \sim 2-3$, as observed.

12.2 Comparison to observations

The evolution of BN abundance has been estimated observationally earlier (e.g. Barro et al. 2013; Van Dokkum et al. 2015), using a constant and rather high threshold in central stellar surface density, and yielding comoving densities that peak at $\sim 10^{-4} \text{ Mpc}^{-3}$ near $z = 2-3$. The most reliable measurement so far is provided in fig. 9 of Barro et al. (2017a), based on a threshold in $\Sigma_{1 \text{ kpc}}$ that varies with redshift following the observed threshold for compact quiescent RNs. This observed number density of BNs peaks at $n \sim 3 \times 10^{-4} \text{ Mpc}^{-3}$ near $z \sim 1$, in general agreement with the prediction. The selection threshold is $M_s > 10^{10.3} M_\odot$, which may explain why the prediction overestimates the observed abundance at $z \sim 2$.

13 DISCUSSION

13.1 BNs in other simulations

The occurrence of wet compaction events, and therefore the abundance of BNs and their properties, may depend on the strength of feedback assumed in the simulations. The feedback may suppress the level of dissipative compaction or affect the central depletion and the overall quenching process. In particular, a different feedback strength may affect the critical mass of BNs, perhaps through the evolution of gas fraction. Since there is certain degeneracy between the SFR and feedback that allows a match of galaxy properties with observations, different cosmological simulations use different SFR and feedback recipes and may thus result in different BN properties. It is, therefore, important to verify the validity of our results concerning the BN properties using different simulations with different feedback recipes.

13.1.1 BNs in the NIHAO simulations

Preliminary tests using the NIHAO simulations indicate the occurrence of compaction events at a similar critical mass. The NIHAO cosmological simulations (Wang et al. 2015) use the N -body SPH code GASOLINE (Wadsley, Stadel & Quinn 2004; Keller et al. 2014). While the VELA and NIHAO simulations differ in many respects, one of the key distinctions we would like to explore is the effect of different stellar feedback on the phases of compaction. In NIHAO, the efficiency of stellar feedback in the pre-SN stage is boosted from 10 to 13 per cent of the total stellar flux, aiming for a better match with the stellar to halo mass ratio based on abundance matching by Behroozi, Wechsler & Conroy (2013b). In addition, during the SN stage, energy is fed into the gas through a blast-wave SN feedback (Stinson et al. 2006), with delayed cooling for ~ 30 Myr for particles within the blast region. As a result, the NIHAO simulations incorporate stronger stellar feedback than the VELA simulations (see Section A²). Due to the nature of compact objects, one must ensure an adequately resolved inner region for the study of compaction events. The choice of particle mass and force softening in NIHAO ensures a properly resolved mass profile in the inner ~ 1 per cent of the virial radius. Therefore, the NIHAO simulations properly resolve the central region of $\sim 1 \text{ kpc}$ at high redshifts and halo mass about the critical mass of

$\sim 10^{12} M_{\odot}$, making them suitable for the study of compaction events at high redshifts. Preliminary results show that the main difference from the current VELA simulations is in a more temperate post-BN central depletion, which leads to a slower central quenching and thus a longer lifetime for the BNs. The detailed analysis of BNs in the NIHAO simulations is deferred to a separate paper.

13.1.2 BNs in the NEWHORIZON simulations

Using the NEWHORIZON cosmological simulations, Lapiner et al. (2021) studied compaction events in eight massive galaxies, selected to have exceeded a stellar mass of $10^{10} M_{\odot}$ at some point in their evolution. The NEWHORIZON simulations exhibit compaction events with similar features and at a similar critical mass as seen in the current work. The NEWHORIZON is a zoom-in cosmological simulation (Dubois et al. 2021), run with the AMR RAMSES code (Teyssier 2002). Briefly, the NEWHORIZON simulation is a zoom-in on a spherical patch, with a radius of 10 cMpc, embedded in the large-scale box of HORIZON-AGN simulations (Dubois et al. 2014, 2016). The maximum spatial resolution in this patch is ~ 40 pc. The sub-grid model incorporates both SN and AGN feedback. The relatively strong SN feedback models the phases of momentum and energy conservation (Kimm & Cen 2014; Kimm et al. 2015), considers the effect of SN clustering (Gentry et al. 2017; Kimm et al. 2017), and takes into account the momentum due to preheating near OB stars. Black holes grow through Bondi–Hoyle accretion (Bondi & Hoyle 1944), with a spin-dependent radiative efficiency computed on-the-fly and restricted to the Eddington limit. The AGN feedback consists of two modes, a thermal ‘quasar’ and a kinetic ‘radio’ mode, determined by the accretion rate efficiency. (see further details in Dubois et al. 2021).

Lapiner et al. (2021) identified major compaction events in six galaxies. The two galaxies which showed only mild compaction events were below the critical mass until relatively low redshifts, hardly exceeding it until the final analysed redshift. The two main differences from the current VELA simulations are as follows: (1) In some cases, the post-BN central gas depletion in NEWHORIZON is more pronounced than the VELA simulations. Lapiner et al. (2021) showed that the compaction phase marks a transition from suppressed BH growth pre-BN to rapid growth during and after compaction (followed by a self-regulated growth phase at late times), demonstrating a tight correlation between the time of compaction and the onset of BH growth, and therefore, the associated onset of frequent AGN activity episodes. The cause for this tight correlation was ascribed to a compaction-driven deepening of the potential well, shown to affect both the position of the BH and the stable availability of a gas reservoir for its accretion. Consistent correlations between compact central density and onset of high BH accretion rate were also seen in Byrne et al. (2022) using post-processed BH accretion in the FIRE simulations. While we find that one of the hallmarks of the BN phase is the subsequent central gas depletion and inside-out quenching, as seen in the current work using simulations without AGN, this attribute may be further accentuated by the inclusion of AGN feedback, which is expected to be active once the galaxy is above the critical BN mass scale. (2) Another difference is the time of transition from dark matter to a baryon-dominated central region. Although the transition usually occurs before the peak of compaction in both simulations, in VELA, it is typically close to the BN time (see Fig. 10), and in NEWHORIZON, the transition tends to happen somewhat earlier. Further analysis is required to quantify and understand the cause of this difference.

13.1.3 BNs in the VELA6 simulations

Preliminary results using the VELA generation 6 simulations (Ceverino et al. 2022) show that the compaction events are still robust in the presence of stronger feedback and display very similar results in terms of the strength of compaction. However, in VELA6, we find a delay in the time of compaction when compared to the current VELA (VELA3) simulations. The VELA6 simulations include the same galaxies with the same initial conditions as VELA3. One of the main differences is the inclusion of stronger SN feedback, introducing the injection of momentum from the unresolved expansion of SN and stellar wind gas bubbles (Ostriker & Shetty 2011). In particular, the injected momentum is boosted by a factor of 3 to account for the effect of clustered SN explosions (Gentry et al. 2017), which may lower the gas density in the vicinity of a star cluster and increase momentum per supernova in the subsequent explosions. A detailed analysis of BNs in the VELA6 simulations and comparison with VELA3 is deferred to a separate paper (Lapiner et al. in prep.).

13.2 Compaction of high- versus low-mass subsamples

The simulations reveal several differences between the high-mass (HM) and the low-mass (LM) subsamples; these are divided by the median of the total stellar mass in the galaxy at $z = 2$. When these two subsamples are compared, one should keep in mind that the LM typically experiences the major compaction at later times, closer to the final redshift of the simulations; therefore, the late post-BN phase is often unexplored in these galaxies (e.g. as seen at the high mass end for LM in Fig. C1² compared to the HM in Fig. 13).

The LM generally display the following differences when compared to the HM: App

- a. Less prominent major compactations with a lower central gas density and SFR (LM: Fig. D12², HM: Fig. 6).
- b. More frequent episodes of central gas rejuvenation, namely small compaction events in the post-BN phase (Fig. D12²).
- c. More oscillations about the MS and reaching lower post-BN central surface density (Fig. 8).
- d. Overall higher central dark matter fraction (Fig. 7).
- e. Overall larger effective radius with a larger scatter (Fig. C1², 13).
- f. Lower v/σ_g (Fig. D5², 17) during the post-BN phase.
- g. Post-BN drop in the gas spin λ_g (Fig. 19) and in v/σ_g (Fig. D5², 17), reflecting the late rejuvenation episodes again.
- h. Lower metallicity (Fig. 22, Fig. D8²).

However, some of the key features of compaction are still seen in most of the simulated galaxies, including the LM subsample. Overall, the evolution of the LM with respect to the BN shows similar trends as the HM subsample, although the typical values are frequently different, and the scatter is larger. We emphasize that the major compaction to a BN occurs about the same critical mass with negligible redshift dependence, as seen in Fig. 9, where we use the entire sample. The critical BN mass forces a delay in the compaction time of the LM subsample compared to the HM.

It should be noted that the difference in the compaction time and strength of the HM versus the LM subsample may have other implications. For example, given the tendency of the HM subsample to experience a more prominent major compaction event at earlier times than the LM, the central BH may be affected. Namely, early major compactations are expected to form a stable massive stellar body in the centre and deepen the potential well at early times; this may lead to more efficient growth of the massive central BH (Lapiner et al. 2021) and, in turn, to a rapid quenching by the associated AGN feedback. The simulations presented here do not include BHs

and AGN feedback. However, the current simulations reveal that the compaction process triggers the onset of central quenching, with the HM subsample typically displaying clearer long-term central gas depletion. Therefore, the addition of early BH growth and the onset of AGN activity may further assist an earlier and faster quenching (e.g. Park et al. 2022) of the HM subsample compared to the LM.

In summary, the LM subsample reaches the critical mass for compaction at later times when the Universe is less dense and relatively gas poor. Therefore, the compaction process, which is governed by gas-rich conditions and drastic AM loss, tends to be less pronounced in these galaxies. A deeper understanding of these differences and their origin deserves a more detailed study beyond the scope of this paper.

14 CONCLUSION

Cosmological simulations reveal a robust event of dramatic consequences during the evolution of galaxies at high redshifts – wet compaction to a blue nugget. The blue nugget phase marks drastic transitions in the galaxy structural, compositional, and kinematic properties as follows (see a summary in Table 1).

1. Structure and star formation:

a. The major BN event, the one preceding a significant quenching process, tends to occur near a critical ‘golden’ mass, M_{BN} , independent of redshift, which in the current simulation is a stellar mass $M_s \sim 10^{10} M_\odot$ corresponding to a halo virial mass $M_v \sim 10^{12} M_\odot$ (Fig. 10). Therefore, evolution in time with respect to the BN event can in practice be translated to dependence on mass with respect to M_{BN} .

b. The compaction to a BN makes the surface density within the inner 1 kpc (or R_e) grow above a critical value (that is slowly decreasing with time) at the BN and post-BN phases, typically $\Sigma_{1 \text{ kpc}} > 10^{9.5} M_\odot \text{ kpc}^{-2}$ for the stellar surface density.

c. The typical galaxy evolution track in the sSFR – $\Sigma_{1 \text{ kpc}}$ diagram has a characteristic L shape: a pre-BN contraction at a roughly constant sSFR that abruptly changes to post-BN quenching at a roughly constant $\Sigma_{1 \text{ kpc}}$ (Fig. 8).

d. The typical evolution of the effective radius R_e as a function of M_s is a shallow increase pre-BN that turns into a steep rise post-BN after a short-term shrinkage near the BN mass (Fig. 13).

e. The metallicity is rising roughly linearly with M_s below M_{BN} , and it saturates to a plateau above M_{BN} (Fig. 22, Fig. D8²).

2. Evolution with respect to the Main Sequence:

f. One can translate the evolution of galaxy properties with respect to the BN phase to the evolution with respect to the universal Main Sequence of SFGs in the universal sSFR – M_s diagram (where the overall decline of sSFR with redshift is scaled out). Pre-BN, the sSFR oscillates about the MS ridge, climbs to the upper MS at the BN and then descends through the ridge and the bottom of the MS to the quiescent regime (the ‘green valley’) during the post-BN quenching process (Tacchella et al. 2016a).

g. This is reflected in gradients across the MS of galaxy properties that are associated with gas and SFR, especially at the BN and post-BN masses. For example, the depletion time, gas-to-stellar mass ratio, SFR and gas kinematics, after the systematic redshift and mass dependence have been eliminated, relate to the deviation from the MS as $t_{\text{dep}} \propto \Delta_{\text{MS}}^{-0.5}$, $f_{\text{gs}} \propto \Delta_{\text{MS}}^{0.5}$, $\text{SFR}_1 \propto \Delta_{\text{MS}}^{1.2}$, $v/\sigma_g \propto \Delta_{\text{MS}}^{-0.3}$, and $\lambda_g \propto \Delta_{\text{MS}}^{-0.35}$ (Fig. 12).

3. Dark matter fraction and shape:

h. Pre-compaction, the central region (1 kpc or R_e) is dominated by dark matter, and it becomes baryon-dominated at the BN and after, with a DM fraction ~ 0.2 within R_e (Fig. 7).

i. As a result, the pre-BN stellar system tends to be elongated, triaxial, or prolate, and it becomes oblate post-BN (Fig. 15). The BN itself is a sub-kpc compact thick disc in gas and SFR and is less flattened in stars (Fig. 16), with a median global Sérsic index of $n \sim 3.5$ at the peak of compaction.

4. Kinematics:

j. Pre-BN, the system is kinematically highly perturbed, with $V/\sigma \sim 1$. Both V and σ rise during the compaction, such that post-BN, the gas becomes a rotation-dominated extended disc with $V/\sigma \sim 4$, while the high-dispersion bulge with $V/\sigma \sim 1$ dominates the stars (Fig. 17).

k. Pre-BN, the systems are on average in a rather crude Jeans (and hydrostatic) equilibrium for stars (and gas) and closer to equilibrium post-BN. This is crudely valid out to several R_e ; still, the contribution of dispersion velocity to the estimated dynamical mass does not necessarily follow the familiar predictions for a self-gravitating thin disc or an isothermal sphere (Fig. 20).

l. The galaxy spin, which is low at the BN due to the angular-momentum loss associated with the compaction, is steeply rising immediately after the BN, saturating to a high plateau that reflects a post-BN extended ring (Fig. 19).

5. Profiles:

m. The gas surface density profile is rather flat pre-BN; it develops a steep cusp at the BN and rises with r from a central hole to an extended ring post-BN.

n. The stellar density profile grows self-similarly at all radii pre-BN, and its growth gradually saturates post-BN.

o. The sSFR profile is roughly flat pre-BN. It is declining with r at the BN and rising with r post-BN, reflecting inside-out quenching (Fig. 23).

p. The metallicity profile, which was weakly declining pre-BN, shows a steep decline with r post-BN, reflecting the fresh origin of the extended ring (Fig. 23).

q. The dark matter fraction profile, which was high pre-BN, becomes low at small radii during and after compaction – reflecting the formation of a dominant massive stellar body in the centre during compaction (Fig. 23).

6. Supernova feedback, black hole growth, and quenching:

r. Pre-BN, the growth of the central black hole is suppressed by supernova feedback. The compaction allows favourable conditions for gas accretion onto the BH, triggering rapid BH growth post-BN in masses above M_{BN} (Lapiner et al. 2021).

s. This allows a transition from SN-dominated feedback pre-BN to active AGN feedback post-BN.

t. Central quenching starts at the BN, and quenching is maintained post-BN by the shutdown of the gas supply through a hot CGM in haloes above the critical mass for virial-shock heating, which may be kept hot by AGN feedback.

u. The major compaction events which are followed by the onset of quenching tend to occur when the galaxy is in the vicinity of the golden mass of galaxy formation, a stellar mass of about $10^{10} M_\odot$ within dark matter haloes of $\sim 10^{12} M_\odot$. This mass scale is confined by the supernova and stellar feedback from below and by a hot CGM, as well as AGN feedback from above. These processes limit the dissipative contraction of gas and allow a significant contraction to occur once near the golden mass. The actual trigger of a compaction event is a mechanism that causes a drastic loss of angular momentum. About half the compaction events in our simulations are triggered by wet mergers. Otherwise, they can be caused by collisions of counter-rotating cold streams, violent disc instability, outflows, and recycling, as well as other mechanisms (Dekel et al. 2019).

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DATA AVAILABILITY

Data and results underlying this article will be shared on reasonable request to the corresponding author.

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Supplementary data are available at *MNRAS* online.

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