Acta Polytechnica **65**(1):65–72, 2025
https://doi.org/10.14311/AP.2025.65.0065

MASS GROWTH OF MASSIVE QUIESCENT GALAXIES IN THE ILLUSTRIS TNG SIMULATION

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Abstract. Interactions between galaxies could potentially lead to increased rates of star formation within these galaxies, potentially leading to the occurrence of multiple core-collapse supernovae and the ejection of hot gas. Numerical simulations are crucial for understanding the formation and evolution of galaxies. Using the IllustrisTNG cosmological simulation, we show how the massive quiescent galaxies evolve in cosmic times. We use the merger tree from the TNG300-1 simulation to demonstrate the impact of dwarf galaxies on the mass augmentation of these galaxies during the early Universe. We made a galaxy sample with restrictions on the specific star formation rate log(sSFR) and mass (M). Most of the mergers have a <1:1 000 ratio to the host galaxy and 5–25 % of the falling material is connected to the merger events. These results show that dwarf galaxies could play a significant role in the growth of these massive galaxies.

Keywords: Galaxies: evolution, galaxies: star formation, galaxies: interactions, methods: numerical.

1. Introduction

Star formation in the Universe has been studied several surveys (see e.g. [1–3]), and it has already been shown using ISO (Infrared Space Observatory [4]) observations that the star formation rate density (SFRD) has decreased in the last 5 billion years. This was preceded by the so-called "cosmic noon" (see e.g. [5, 6]) when most of the still visible stars were formed. Frequent galaxy interactions are a characteristic feature of this period and can be studied using cosmological simulations.

It is worth noting, however, that gamma-ray bursts (GRBs) may also provide a clue to star formation in the early universe. As is well known, these phenomena are not only the largest energy emitters in the Universe after the Big Bang, but a significant fraction of them, the hypernovas, are associated with high star formation regions, despite the ultra-low metallicity of these stars [7]. As is well known, these bursts can vary significantly, both in length and intensity, which also carry the physical characteristics of the environment around the GRB [8, 9]. However, another interesting fact is that GRBs fill space in an absolutely non-isotropic way, with significant clustering and anisotropy [10–13].

Previous studies examined, how galaxy mergers can quench the star formation in galaxies. Using simulations, Pontzen et al. [14] showed, how mergers can start the quenching mechanism due to mechanical disruption, where the timescale of these events is about 250 Myr. Based on a sample of ∼500 post-merger galaxies, Ellison et al. [15] found, that mergers can indeed lead to a rapid halt in star formation. In addition, there is also observational evidence that this process occurs in a short period of time [16, 17].

IllustrisTNG [18–22] is a suite of large volume, cosmological, gravo-magneto-hydrodynamic simulations including a comprehensive model for galaxy formation. Each TNG simulation self-consistently solves for the coupled evolution of dark matter, cosmic gas, luminous stars, and supermassive black holes from redshift $z = 127$ to 0 and generates 100 resulting snapshots from $z = 20$ to 0. We used the TNG300-1 run for analysis, the second largest simulation box which has the size of 302.6 Mpc^3 and contains more than 30 billion resolution elements, therefore, enabling the study of galaxy clustering. There have been many publications on this topic using the IllustrisTNG simulation: Genel et al. [23] focused on the size evolution of quenched galaxies, and found that $M_* > 10^{9.5} M_\odot$ experience a steep size growth after their quenching time, while the mass of more massive galaxies increases less due to collisions. Davies et al. [24] examined the quenching and morphological evolution of central galaxies. Luo et al. [25] investigated the massive spiral galaxies, and their results suggest that the cooling from the hot gaseous halo in quenched spiral galaxies is suppressed by massive black holes. Quai et al. [26] presented an analysis of post-merger galaxies. They found that only 5 % of post-merger galaxies quench within 500 Myr after they merge. Xu et al. [27] investigated massive quenched central disk galaxies, and showed that mini-mergers have mainly contributed to the growth of their SMBHs. Previous articles have not dealt with the mass distribution of galaxies that have merged into larger galaxies, which is one of the major topics of this study.

2. Methods

We used the IllustrisTNG 300-1 merger tree, which links sub-haloes to their progenitors and descendants. It is created by the Sublink algorithm [28] that follows these steps: First, it identifies the candidates for each subhalo, looking for galaxies in the following snapshot that share particles with the selected galaxy. The second step involves scoring the candidates using a merit function, which determines the binding energy rank of each particle within the galaxies. The final step is identifying the unique descendant, which is determined to be the subhalo with the highest score. To construct the merger tree, Springel et al. [29] developed a linked-list structure that allows each subhalo to be assigned pointers to "key" subhalos. The "descendant" refers to the unique subsequent subhalo related to the subhalo in question. The "next progenitor" is the subhalo that shares the same descendant as the subhalo in question and has the next largest "mass history" following the progenitor. In our case, the progenitor galaxies are those subhalos for which the descendants and next progenitors have been determined. To analyse the merger trees, we used the Sublink tree files. These are divided into 125 separate files, each containing approximately 25 million galaxies. We made a galaxy sample with star formation rates $\log(\text{sSFR}) < -10.5$ and with masses $\log(\frac{M_*}{M_\odot}) > 10.6$ to reduce our sample only to those galaxies, which are massive and are in a quiescent state. After making this sample, we searched for the next progenitor galaxies which are connected to the massive galaxy. We used our method in a single merger tree since the merger trees are independent and have similar average characteristics [30] as we found in our previous paper. Using these criteria, we have found approximately 3 500 massive quiescent galaxies in the chosen merger tree. In our analysis, we have focused on the number of galaxy mergers, the mass distribution of the NextProgenitor galaxies, and the star formation rate history of the subhalo in question. We calculated mass ratios for the NextProgenitor galaxies, dividing their masses by the masses of the FirstProgenitor galaxies, the massive galaxies they merge into. We didn't include galaxies at higher redshifts $z > 8$, because there are only a few galaxies in general and the number of mergers is also low at higher redshifts. As a further investigation, we selected three galaxies with the following SubhaloIDs at $z = 0$: ID 0, ID 736368 and ID 1094694, where we have selected the first two for their large number of progenitors and the third one for an example with fewer galaxy mergers. The listed SubhaloIDs are connected to the galaxy at $z = 0$, for which we selected the FirstProgenitor galaxies at higher redshifts.

3. Results

First, we collected all merger companions for the 38 galaxies and compared their NextProgenitors (Appendix Tables 1 and 2). From the data, we can see that more massive galaxies have more mergers. Most of these galaxies have $1–5 \times 10^{12} M_\odot$ mass, which is similar to the Milky Way [31]. There are some exceptions, with lower masses and some subhalos are supermassive, such the ID 0, which has greater mass than $1.2 \times 10^{14} M_\odot$. Others have discussed these massive galaxies in the IllusrisTNG simulation in previous articles, see e.g. [32–34]. These galaxies encountered 100–200 mergers during their history. The median mass of the mergers is similar for all galaxies, at 0.088–0.104 ($10^{10} M_\odot$), which means, that most of these mergers are dwarf galaxies. If we compare the sum of the progenitors' mass to the SubhaloMass of the massive galaxy, we can see that in most of the cases, 5–25 % of the falling material is connected to these merger events. The merger companions' mass for each galaxy under discussion can be found in Appendix Table 2, where the mass of the progenitors is divided into 5 groups based on their relative mass to the subhalo in question. In each column on the left side is the number of the galaxies, and on the right is the percentage of all companions of that galaxy. Except for the smallest galaxies, most of the mergers have $a < \frac{1}{1\,000}$ ratio to the host galaxy. We consider mergers with a ratio of $< \frac{1}{10}$ to be minor. Because of the large number of minor mergers, we divided them into subgroups: $< \frac{1}{100}$ and $< \frac{1}{1\,000}$. This means that dwarf galaxies play an important role in the evolution of these galaxies.

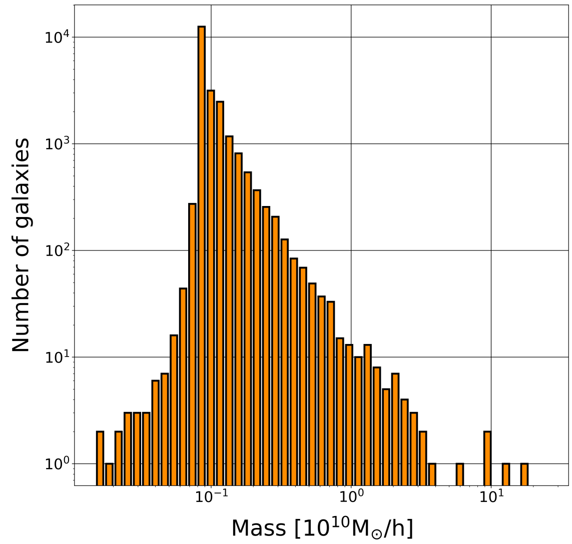


Figure 1. Mass distribution of the NextProgenitor galaxies of the subhalo ID 0. Most of the galaxies have approximately $10^9 M_\odot$, more than half of the sample. The number of galaxies decreases with increasing mass, and there are only a few galaxies with a mass of $\sim 10^{11} M_\odot$.

From these galaxies, we have selected the ID 0 subhalo, which is the most massive one in our sample. It has 22 392 merger companions and the additional material collected through mergers is more than $2.6 \times 10^{13} M_\odot$. We investigated the companions of this subhalo. In Figure 1, the mass distribution

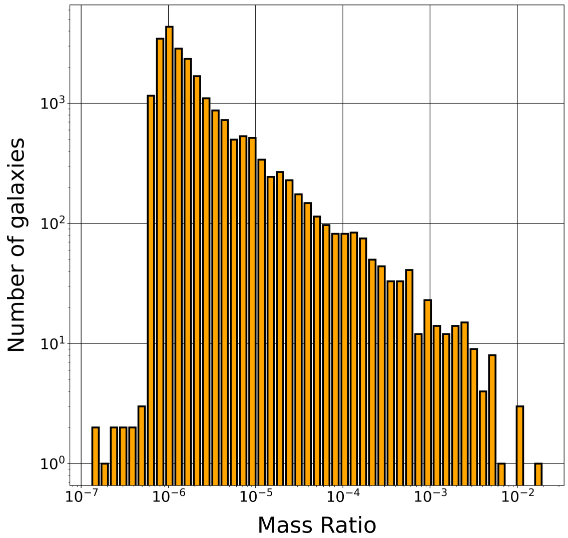
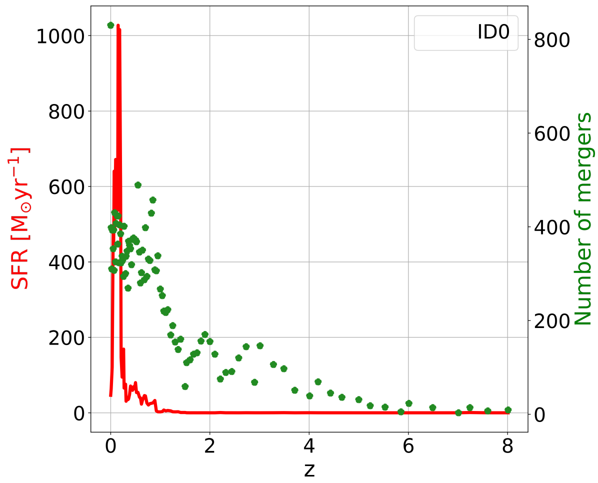


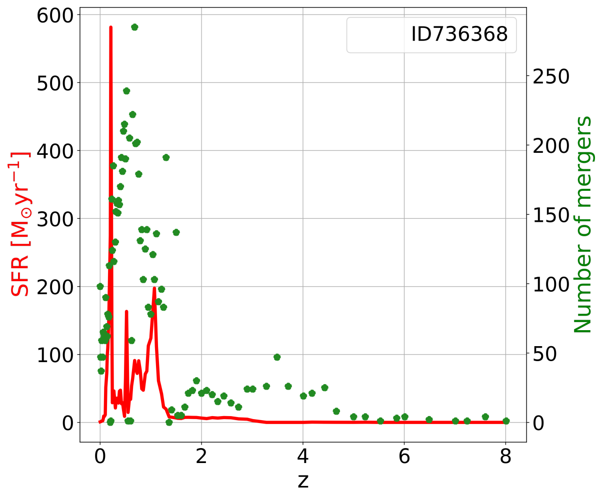
Figure 2. Mass ratio distribution of the NextProgenitor galaxies of subhalo ID 0, where their mass is compared to the FirstProgenitor galaxy at the redshift of the NextProgenitor. Most of the galaxies have a 10^{-6} mass ratio relative to the galaxy they have been merged into.

of the NextProgenitors is shown. We can see, that most of the galaxies (more than half of the companions) have about $10^9 M_\odot$, which means that these are dwarf galaxies. For higher masses, the number of mergers is decreasing, there are only 5 galaxies with around $10^{11} M_\odot$. In Figure 2, the same galaxies are selected, but in this figure, their mass is compared to the FirstProgenitor galaxy, at the same redshift at which the merger event took place.

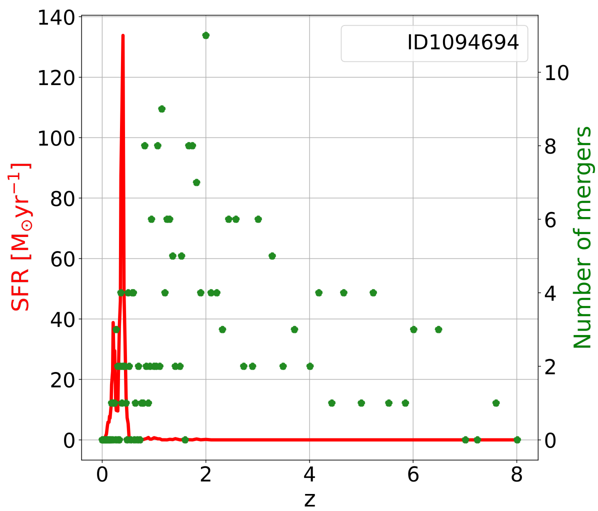
In the following step, we focused on the star formation history and the number of merger events. We investigated 3 different subhalos with the following IDs: ID 0, ID 736368, and ID 1094694. First, we compared their star formation rate and the number of events at different redshifts, shown in Figure 3. Before the subhalo was quenched, there was a star formation peak at $z < 0.5$ at all three galaxies. At $z > 1.5$, there was no significant increase in the star formation. The number of galaxy mergers was relatively low as well before $z > 2$. The galaxies with more merger events (ID 0 and ID 736368) have encountered their merger events mostly at $z < 2$. We can assume that the appearance of these merger events and the increase in star formation are in connection. Due to the galaxy interaction, active star formation started a few million years later. Next to the number of progenitors, we compared their total mass to the star formation, see Figure 4. Since most of these galaxies have similar masses, there is no significant difference between the number of mergers and the total mass of these companions. There are cases when a larger galaxy merges into the galaxy in question, where one galaxy can influence the total mass, but according to Figure 1, only a few galaxies have significantly larger mass than the average. In the case of the ID 1094694 galaxy, there



(a). ID 0.

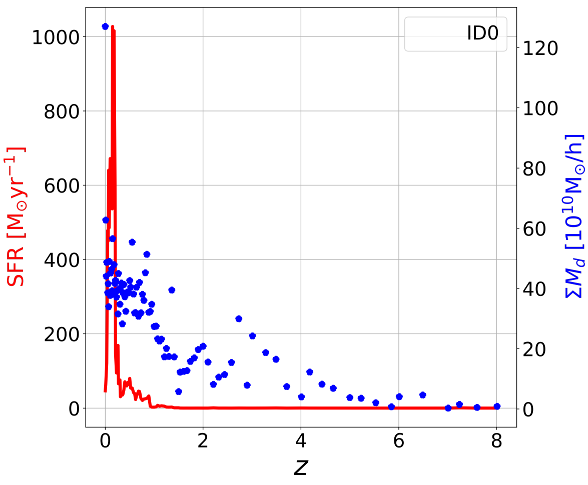


(b). ID 736368.

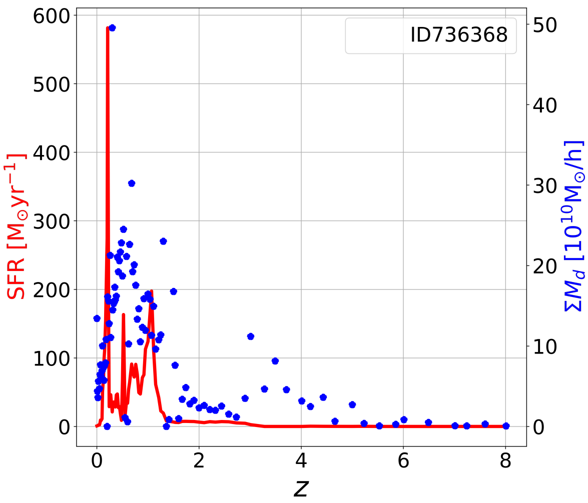


(c). ID 1094694.

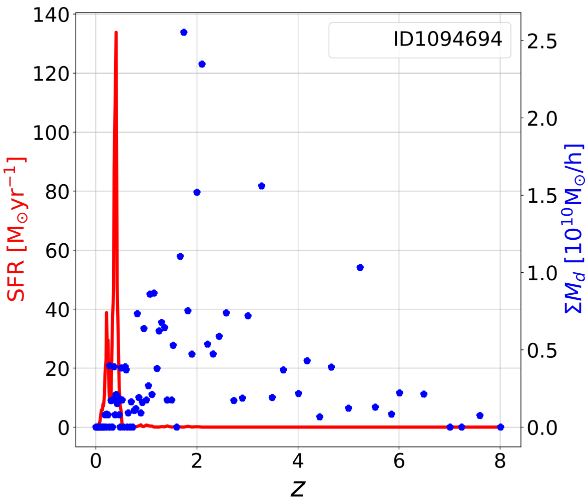
Figure 3. Star formation rate history (red line) and the number of infalling galaxies (green dots) versus the redshift at $0 < z < 8$. On the three panels, different subhalos are shown: ID 0, ID 736368, and ID 1094694. The star formation rate of the top two galaxies increases as the number of collisions increases, while at the bottom the smaller number of mergers has no significant effect.



(a). ID 0.



(b). ID 736368.



(c). ID 1094694.

Figure 4. Star formation rate history (red line) and the mass of the infalling galaxies (ΣM_d, blue dots) versus the redshift at $0 < z < 8$. On the three panels, different subhalos are shown: ID 0, ID 736368, and ID 1094694. Star formation in the top two galaxies increases with the amount of falling material, while in the bottom one we see no correlation, although the masses are orders of magnitude smaller.

are only 220 merger events, and the falling material is an order of magnitude smaller than the other two galaxies. Therefore, the impact of the mergers is not significant, in this case, the star formation increase may have a different cause.

4. Conclusion

In our work, we examined the growth of massive quiescent galaxies through galaxy mergers using the IllustrisTNG simulation. We made a highly restricted galaxy sample (which contains 38 galaxies) with star formation rates $\log(\mathrm{sSFR}) < -10.5$ and with masses $\log(\frac{M_*}{M_\odot}) > 10.6$, and focused on those galaxies, which merge into these galaxies. We found that the median mass of the mergers is similar for all galaxies, 0.088–0.104 ($10^{10} M_\odot$), which means, that the majority of these merging galaxies are dwarfs. Most of the mergers have a ratio $<\frac{1}{1000}$ to the host galaxy and 5–25 % of the falling material is connected to the merger events. We note that our sample of merging galaxies may include some false positives identified by the SUBFIND algorithm, such as disk fragments, as the merger trees lack the necessary flag to filter out these "non-cosmological" structures. This could introduce a bias towards the number of minor mergers; however, we anticipate only a subtle impact on the assembled mass. A more robust analysis could be attempted by linking the merger tree subhalos to the group catalogues of the corresponding simulation volume. Nonetheless, our results suggest that dwarf galaxies could play a significant role in the growth of these massive galaxies.

We investigated three individual subhalos and found that in two cases, where the number of galaxies mergers was significant, these merger events can lead to a rapid star formation, after which the quenched state occurs.

It would be worth making a larger galaxy sample with less strict limits so that we can study galaxy mergers in general. Comparing the results with future observations is essential, as recent telescope measurements, such as the JWST or SDSS, can determine the merger history of these galaxies.

Acknowledgements

We are grateful to L. Viktor Tóth for his supervision of this work and to the High Energy Astronomy Research Team (HEART [35]) for their support and thoughtful feedback.

The IBWS conference participation of B. Koncz was subsidized by the Dean's Council of ELTE Eötvös Loránd University Faculty of Science, Budapest.

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Appendix A. Data sets of galaxies

SubhaloID	Number of mergers	SubhaloMass (F.P.)	ΣM_{Next}	Median mass	Mass ratio [%]
0	22 392	127 397.82	2 635.83	0.091	2.068
736368	7 497	36 020.56	898.84	0.087	2.495
1018388	585	776.10	105.77	0.087	13.629
1048329	293	519.71	57.140	0.095	10.994
1058913	462	664.53	65.209	0.091	9.812
1069625	168	376.50	24.11	0.096	6.403
1075230	270	245.08	41.71	0.092	17.018
1085744	229	235.72	35.70	0.096	15.145
1089872	219	276.92	32.31	0.092	11.667
1094694	220	266.73	28.639	0.092	10.737
1099774	163	228.91	30.09	0.092	13.143
1104150	403	115.74	65.10	0.095	56.244
1116698	267	196.44	130.59	0.096	66.480
1121509	189	234.78	53.27	0.092	22.691
1125518	229	161.15	33.57	0.092	20.832
1130071	130	150.86	37.05	0.093	24.555
1132394	207	106.83	30.03	0.100	28.105
1136811	140	134.39	28.10	0.096	20.906
1140268	44	143.12	7.85	0.104	5.483
1142320	107	131.81	15.02	0.096	11.398
1144944	111	117.70	24.31	0.104	20.655
1147617	436	84.51	65.28	0.096	77.251
1155194	134	126.78	22.31	0.103	17.599
1157655	106	115.05	19.16	0.094	16.652
2780287	2 896	22 357.31	482.27	0.088	2.157
2875663	655	2 145.17	93.53	0.088	4.360
3358682	2 263	8 755.08	299.17	0.092	3.417
4021974	37	53.52	4.16	0.090	7.764
4023572	22	34.01	2.40	0.100	7.065
4026317	9	10.23	1.08	0.084	10.549
4027444	20	10.41	5.08	0.103	48.769
4028529	9	6.18	0.91	0.092	14.662
4501970	7	4.74	0.67	0.087	14.177
4503693	5	7.21	0.41	0.088	5.752
4505129	6	6.27	1.65	0.098	26.318
4575694	3 569	18 502.54	427.16	0.088	2.309
7115908	1 125	4 922.47	145.89	0.088	2.964
11088783	902	6 064.25	280.99	0.088	4.633

Table 1. Details of the progenitors connected to the massive quiescent galaxies. The columns are as follows: (1) SubhaloID of the massive quiescent galaxy, (2) number of galaxies that have merged into this at all redshift, (3) SubhaloMass of the FirstProgenitor of the Subhalo in question, (4) sum of the masses of the NextProgenitor galaxies, (5) median mass of the NextProgenitor galaxies, (6) NextProgenitors mass ratio to the SubhaloMass.

SubhaloID	$>\frac{1}{10}$ ratio [pc/%]	$>\frac{1}{100}$ ratio [pc/%]	$>\frac{1}{1000}$ ratio [pc/%]	$\frac{1}{1000}>$ ratio [pc/%]	Tiny ($\frac{1}{100}>$) mass ratio [%]
0	0 / 0.00	3 / 0.01	83 / 0.38	22 280 / 99.61	91.07
736368	0 / 0.00	128 / 1.71	74 / 0.99	7 292 / 97.30	19.21
1018388	1 / 0.17	8 / 1.39	131 / 22.74	436 / 75.69	61.22
1048329	2 / 0.68	10 / 3.45	62 / 21.38	216 / 74.48	13.95
1058913	0 / 0.00	12 / 2.60	71 / 15.37	379 / 81.03	50.50
1069625	0 / 0.00	21 / 12.50	22 / 13.10	125 / 74.40	22.89
1075230	3 / 1.11	13 / 4.81	100 / 37.04	154 / 57.04	4.54
1085744	4 / 1.75	9 / 3.93	50 / 21.83	166 / 72.49	19.95
1089872	2 / 0.91	9 / 4.11	47 / 21.46	161 / 73.52	28.43
1094694	0 / 0.00	15 / 6.82	46 / 20.91	159 / 72.27	37.77
1099774	2 / 1.23	12 / 7.36	52 / 31.90	97 / 59.51	1.45
1104150	2 / 0.49	11 / 2.73	78 / 19.35	312 / 77.42	29.29
1116698	1 / 0.37	17 / 6.37	44 / 16.48	205 / 76.78	10.48
1121509	2 / 1.06	12 / 6.35	35 / 18.52	140 / 74.07	0.86
1125518	2 / 0.87	8 / 3.49	47 / 20.52	172 / 75.11	2.49
1130071	10 / 7.69	10 / 7.69	45 / 34.62	65 / 50.00	0.18
1132394	0 / 0.00	6 / 2.90	75 / 36.23	126 / 60.87	77.10
1136811	0 / 0.00	23 / 16.43	48 / 34.29	69 / 49.29	28.02
1140268	2 / 4.54	10 / 22.73	18 / 40.91	14 / 31.82	11.10
1142320	0 / 0.00	13 / 12.15	41 / 38.32	53 / 49.53	24.40
1144944	0 / 0.00	16 / 14.41	54 / 48.65	41 / 36.94	29.53
1147617	0 / 0.00	12 / 2.75	84 / 19.27	340 / 77.98	52.14
1155194	2 / 1.49	14 / 10.45	58 / 43.28	60 / 44.78	14.74
1157655	1 / 0.94	13 / 12.26	44 / 41.51	48 / 45.28	29.38
2780287	1 / 0.03	13 / 0.45	137 / 4.73	2 745 / 94.79	47.59
2875663	7 / 1.07	5 / 0.76	22 / 3.36	621 / 94.81	1.77
3358682	0 / 0.00	8 / 0.35	62 / 2.74	2 193 / 96.91	66.34
4021974	1 / 2.70	11 / 29.73	25 / 67.57	0 / 0.00	18.08
4023572	1 / 4.54	9 / 40.91	11 / 50.00	1 / 4.55	7.76
4026317	3 / 33.33	6 / 66.67	0 / 0.00	0 / 0.00	0.00
4027444	9 / 45.00	9 / 45.00	2 / 10.00	0 / 0.00	0.07
4028529	1 / 11.11	7 / 77.78	1 / 11.11	0 / 0.00	2.45
4501970	2 / 28.57	5 / 71.43	0 / 0.00	0 / 0.00	0.00
4503693	1 / 20.00	3 / 60.00	1 / 20.00	0 / 0.00	1.59
4505129	2 / 33.33	4 / 66.67	0 / 0.00	0 / 0.00	0.00
4575694	0 / 0.00	17 / 0.48	65 / 1.82	3 487 / 97.70	45.40
7115908	0 / 0.00	8 / 0.71	71 / 6.31	1 046 / 92.98	71.96
11088783	4 / 0.44	20 / 2.22	30 / 3.33	848 / 94.01	0.27

Table 2. Details of the progenitors connected to the massive quiescent galaxies. The columns are as follows: (1) SubhaloID of the massive quiescent galaxy, (2) mumber of galaxies and their rate to all progenitors that have the mass ratio $>\frac{1}{10}$ with the Subhalo in question, (3),(4),(5) same as (2) but with other ratios, (6) progenitors with $\frac{1}{100}$ mass ratio total mass relative to the galaxy in question.