

# Evolution of the galaxy merger rate in model universes

Abílio Mateus<sup>\*</sup>

*Laboratoire d'Astrophysique de Marseille, CNRS UMR6110, Traverse du Siphon, 13012 Marseille, France.*

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## ABSTRACT

We investigate the evolution of the galaxy merger rate predicted by two semi-analytical galaxy formation models implemented on the Millennium Simulation of dark matter structure growth. The fraction of merging galaxy pairs at each time-step of the simulation is derived from the galaxy catalogues obtained by the models and the results are compared with various observational estimates of merger fractions taken from the literature. We find a good match between the pair fractions derived from the simulation and the observed counting of galaxy pairs obtained by different sources in the redshift range  $0 < z < 1.2$ . The predicted evolution of the number of galaxy mergers per Gyr grows with redshift as an exponential rate given by  $\Gamma_{\text{mrg}} \propto (1+z)^m$ , with  $m$  ranging from 0.6 to 0.8 for  $0 < z < 2$ , depending on the luminosity and mass ratios of the merging galaxies. Our results are in agreement with recent observational results that argue for a flat evolution in the fraction of galaxy mergers since  $z \sim 1.2$ . The weak evolution predicted for the galaxy merger rate in an hierarchical model universe shows that the mass assembly evolution of galaxies through mergers does not follow the rapid evolution of the halo merger rate obtained in previous studies.

**Key words:** galaxies: evolution — galaxies: formation — galaxies: interactions — method: data analysis

## 1 INTRODUCTION

The role played by galaxy mergers is of paramount importance for galaxy formation and evolution. Since the seminal numerical work by Toomre & Toomre (1972), galaxy mergers are thought to be relevant mechanisms in the build up of the spheroidal component of galaxies. Recent numerical works also argue that gas-rich mergers are able to form disk galaxies (Robertson et al. 2004; Governato et al. 2007). In the local Universe, observations of remnants of galaxy mergers strengthen their effects on galaxy morphologies and on triggering star formation in merging galaxies, unveiling their power on driving galaxy evolution (e.g. Jog & Maybhat 2006; Schweizer & Seitzer 2007). Actually, in a recent work Mateus, Jimenez, & Gaztañaga (2008) show that galaxy mergers are very correlated to the star formation history of galaxies, driving the environmental dependence in galaxy formation by regulating the star formation process.

The importance of galaxy mergers is highlighted when we consider the hierarchical build up of cold dark matter (CDM) structures according to the standard  $\Lambda$ CDM cosmology, which forms the basis of the subsequent processes related to galaxy formation and evolution. In this picture, the structure growth is driven by the hierarchical accretion and merging of dark matter haloes, with galaxies forming inside these structures following the radiative cooling of baryons and the condensation of the gas through dissipative cooling (White & Rees 1978). It follows that the rate at which galaxy

mergers evolve is a direct consequence of the hierarchical growth of structures in any galaxy formation model based on this framework. Predicting this evolution from the models and comparing it to observations of galaxy mergers at different lookback times represent, therefore, a key test to determine whether and how galaxies form by mergers or whether the models give us the correct predictions.

On the observational side, the galaxy merger counting is a challenging effort. Two main approaches are used to measure the evolution of galaxy mergers at low and high-redshift. The first one is based on the counting of close galaxy pairs, which provides reliable estimates of major mergers out to  $z \sim 1$  (e.g. Patton et al. 1997; Le Fèvre et al. 2000; Bundy et al. 2004; Lin et al. 2004; Kartaltepe et al. 2007), despite of the selection effects and biases inherent to this method (e.g. Patton et al. 2000). Other way to counting galaxy mergers is through detecting direct signatures of galaxy interactions, as visual disturbed morphologies or asymmetries detected by automated procedures (e.g. Conselice et al. 2003; De Propriis et al. 2007; Lotz et al. 2008).

In this Letter, we examine the galaxy merger rate evolution predicted by galaxy formation models and its comparison with observational measurements of merger rates taken from the literature. We use the public data available by the Millennium Simulation (Springel et al. 2005) to derive galaxy merger properties predicted by two semi-analytical galaxy formation models implemented on the simulation and described by Bower et al. (2006) and De Lucia & Blaizot (2007).

We present a brief description of the Millennium Simulation and the semi-analytical models used in this work in Section 2. In

<sup>\*</sup> E-mail: abilio.mateus@oamp.fr

Section 3 we describe the methodology used to estimate galaxy mergers from the simulation outputs. The main results of this work are presented in Section 4 and our conclusions are summarized on Section 5.

## 2 THE MODEL UNIVERSES

In this section we briefly describe the model universes used in this work based on one of the largest cosmological simulation of structure growth carried out so far, the Millennium Simulation, and on two state-of-the-art semi-analytical models of galaxy formation developed by independent groups.

The Millennium Simulation of dark matter structure growth, recently carried out by the Virgo Consortium, follows the evolution of  $N = 2160^3$  particles of mass  $8.6 \times 10^8 h^{-1} M_\odot$ , within a co-moving box of size  $500h^{-1}$  Mpc on a side, from redshift  $z = 127$  to the present (Springel et al. 2005). The adopted cosmological model is the concordance  $\Lambda$ CDM model with parameters  $\Omega_m = 0.25$ ,  $\Omega_b = 0.045$ ,  $h = 0.73$ ,  $\Omega_\Lambda = 0.75$ ,  $n = 1$  and  $\sigma_8 = 0.9$ , where the Hubble constant is parametrized as  $H_0 = 100h$  km s $^{-1}$  Mpc $^{-1}$ . Haloes and subhaloes in 64 output snapshots were identified using the SUBFIND algorithm described in Springel et al. (2001), and merger trees were then constructed that describe how haloes grow as the model universe evolves. These merger trees form the basic input needed by the semi-analytic models described in the following.

We explore the galaxy catalogues obtained by two semi-analytical galaxy formation models implemented on the Millennium Simulation. We use the results obtained by the model presented and discussed by De Lucia & Blaizot (2007), which is a modified version of the models used in Croton et al. (2006) and De Lucia et al. (2006). The galaxy catalogues generated by this model have been made public on the Millennium download site at the German Virtual Observatory<sup>1</sup>. We also use the model described in detail by Bower et al. (2006). It is an extension of the GALFORM model implemented by Cole et al. (2000) and Benson et al. (2003). The catalogues generated by this model are publicly available on the Millennium download site at the University of Durham.<sup>2</sup>

These semi-analytical galaxy formation models have significant differences in the general procedure to form galaxies from the dark matter haloes. First of all, many aspects of the baryonic physics involved in the galaxy formation process are treated in a completely different manner, mainly those related to the energy feedback from active galaxy nuclei to regulate the star formation in galaxies. In addition, the construction of the merger trees from the dark matter halo distribution, which form the basis of the semi-analytical approach integrated on the numerical simulations, has been done in independent ways.

## 3 GALAXY MERGER RATES

We derive the predicted evolution of the galaxy merger rate from the semi-analytical galaxy formation models implemented on the Millennium Simulation. We start selecting all  $z = 0$  galaxies with rest-frame absolute magnitudes  $M_B \leq -18$ , resulting in two base catalogues containing about  $3.33 \times 10^6$  galaxies from

the Bower et al. (2006) model and about  $4.35 \times 10^6$  galaxies from the De Lucia & Blaizot (2007) model. For all galaxies in these catalogues, we recovered their complete merger trees by using the post-processing facilities carried out on the Millennium databases.

The first step to derive the model predictions for the fraction of galaxies undergoing mergers is to identify the progenitors of each galaxy selected from the merger trees at each time-step  $t$  of the simulation. We then define that a galaxy has experienced a merger if it has at least one pair of progenitors at the previous time-step. In other words, we are able to select galaxy pairs at a given  $t$  that will merge to form a single galaxy in the immediately posterior time-step. This description is particularly interesting if one wants to compare the results from the simulation with observational estimates of merger fractions based on pair count statistics (e.g. Patton et al. 2002; Lin et al. 2004; Kartaltepe et al. 2007). In our analysis, the progenitor pair of a merge-product galaxy is composed by its main progenitor (defined as the progenitor with the largest stellar mass), selected to be brighter than a  $B$ -band absolute magnitude limit,  $M_B^{lim}$ , and an ordinary progenitor with  $M_B \leq -18$ . In our analysis, we considered two magnitude limits for the main progenitors,  $M_B^{lim} = -19.5$  and  $M_B^{lim} = -20$ , in order to inspect how this choice affects the derived pair fractions. We have also adopted an additional approach to select galaxy pairs by considering only the ordinary progenitors with stellar masses larger than  $1/4$ ,  $1/6$ , and  $1/10$  of the main progenitor stellar mass, independently of their luminosity. In such analysis, we selected only the main progenitors with  $M_B < -20$ . This procedure allows us to investigate how the estimated pair fractions depend on the mass ratio of the pair components.

We define the pair fraction as the number of galaxies in the progenitor pairs (main progenitors plus companions),  $N_p(z)$ , divided by the total number of main progenitors brighter than  $M_B^{lim}$ ,  $N_t(z)$ , at each time-step of the simulation:  $f_p(z) = N_p(z)/N_t(z)$ . The merge fraction is directly derived from the pair fraction by considering only the total number of progenitors pairs that will merge, that is,  $f_{mrg}(z) \simeq 0.5f_p(z)$ . We can directly relate this predicted merger fraction to observations of close galaxy pairs which are frequently used to derive observed merger fractions. From observations of physically close galaxy pairs one can determine the number of close companions per galaxy,  $N_c$ , which is identical to the pair fraction in a volume-limited sample with no triples or higher order N-tuples. Following the expression adopted by Lin et al. (2004), the galaxy merger rate per Gyr estimated through pair count statistics is given by

$$R_{mrg} = (0.5 + G)N_c(z)P_{mrg}T_{mrg}^{-1} \quad (1)$$

where  $N_c(z)$  is the average number of companions for galaxies within the observed magnitude range,  $P_{mrg}$  denotes the probability that galaxies in close pairs will merge (typically assumed to be 0.5), and  $T_{mrg}$  is the time-scale for physically associated pairs to merge. The factor 0.5 is to convert the number of galaxies into the number of merger events (assuming only pairs, ignoring triples and higher order N-tuples). The physical galaxy pairs are expected to merge on the time-scale  $T_{mrg}$  which depends on the intrinsic characteristics of the pairs, such as the relative mass ratio, orbit parameters, and on the structure of the merging galaxies, thus varying for each pair (e.g. Conselice 2006). In general, one assumes that  $T_{mrg} \sim 0.5$  Gyr, a value suggested by simplified models based on the dynamical friction time-scale and also predicted by N-body simulations (e.g. Mihos 1995; Patton et al. 2000; Conselice 2006). In equation (1) we also include an additional parameter,  $G$ , introduced by Lin et al. (2004) to account for differences in sample

<sup>1</sup> <http://www.g-vo.org/Millennium>

<sup>2</sup> <http://galaxy-catalogue.dur.ac.uk:8080/Millennium>

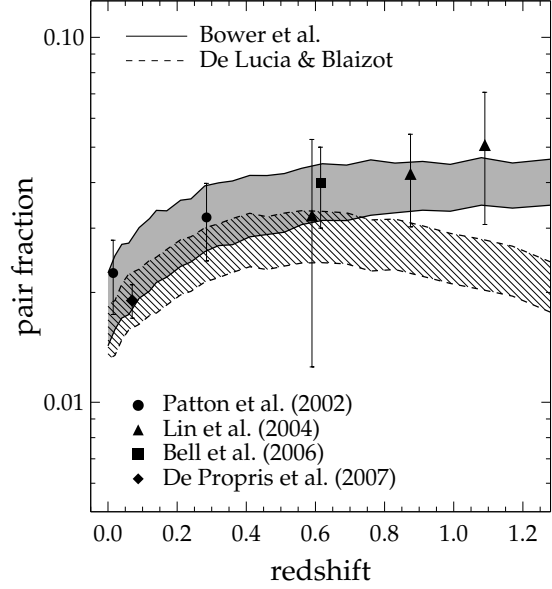
selections when comparing merger rates estimated by pair counts and by morphological approaches. Here we will adopt the value of  $G = 1.24$  determined by Lin et al. (2004).

In the case of the simulation, a merger between one or more ordinary progenitors and the main progenitor results in the formation of a single galaxy at a posterior time-step. Thus, we can evaluate a galaxy merger rate (number of galaxy mergers per Gyr),  $\Gamma_{\text{mrg}}(z)$ , by dividing the merger fraction at each  $z$  by the time interval between the two time-steps associated to the progenitors and to the new formed galaxy:  $\Gamma_{\text{mrg}}(z) = f_{\text{mrg}}(z)\delta t^{-1}$ . In the redshift range  $0 < z < 1$ , the mean value of  $\delta t$  is 0.34 Gyr, implying that the progenitor pairs of a given galaxy can be considered as physical pairs. Thus, the predicted galaxy merger rate can be easily compared with that derived from observational data,  $R_{\text{mrg}}$ , based on pair count statistics.

## 4 RESULTS

In Fig. 1, we show the predicted evolution of pair fractions derived from galaxy formation models,  $f_p(z)$ , and a compilation of observational results in the redshift range  $0 < z < 1.2$ . For the simulation, we show results of pair fractions obtained assuming magnitude limits to select the main progenitors of  $M_B^{\text{lim}} = -19.5$  (bottom lines) and  $M_B^{\text{lim}} = -20$  (top lines). The observational data points shown in this figure were obtained from estimates using galaxy pair counts by Patton et al. (2002), Lin et al. (2004), Bell et al. (2006), and De Propriis et al. (2007). For  $z < 0.3$ , we show the close pair fractions obtained by Patton et al. from counting close dynamical pairs of the CNOC2 survey, with luminosities in the range  $-22 \lesssim M_B \lesssim -19$ , and the result obtained by De Propriis et al. for a galaxy sample with  $-21 < M_B - 5 \log h < -18$  and  $0.010 < z < 0.123$  drawn from the Millennium Galaxy Catalogue. At higher redshifts, we show the mean value of the close pair fraction obtained by Bell et al. after analysing  $0.4 < z < 0.8$  galaxies with  $M_B < -20$  from the COMBO-17 survey and the pair fractions obtained by Lin et al. from analysis of galaxies with luminosities  $-22 \lesssim M_B \lesssim -20$  and redshift range  $0.5 < z < 1.2$  from the DEEP2 redshift survey. It is worth noting that we have adjusted the values of Lin et al. downward by 65 per cent to account for projection within galaxy groups, as suggested by Bell et al. (2006).

There is a good match between the evolution of the pair fractions predicted by the Bower et al. (2006) model and that inferred by the observational data, considering the magnitude limits adopted to select the main progenitors. The model by De Lucia & Blaizot (2007) underpredicts the pair fractions at  $z > 0.5$ , showing a decreasing evolution which is clearly inconsistent with the behaviour expected from the observations. The evolution of the pair fractions derived from the Bower et al. model is strong at  $z \lesssim 0.3$ , and becomes weak at higher redshifts, independent of the value of  $M_B^{\text{lim}}$  adopted to select galaxy pairs. The amplitude of the pair fractions is highly dependent on the value of  $M_B^{\text{lim}}$ , being higher for pairs containing brighter galaxies. This trend is associated with the strong dependence of the galaxy growth through mergers on stellar mass (Maller et al. 2006; Guo & White 2008). We have also compared our results with the recent measurements of close pair fractions obtained by Kartaltepe et al. (2007), who claims for a strong evolution of the pair fractions since  $z \sim 1.2$  after analysing the galaxy population in the COSMOS field. They adopted photometric redshifts to select galaxy pairs in the redshift range  $0.1 < z < 1.2$ , with a magnitude limit  $M_V < -19.8$ . We found a good agreement in the pair

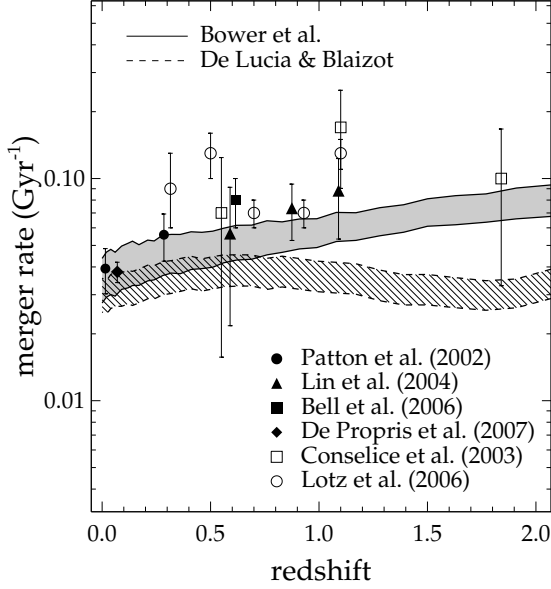


**Figure 1.** Evolution of the pair fractions predicted by the semi-analytical galaxy formation models of Bower et al. (2006, solid lines) and De Lucia & Blaizot (2007, dashed lines) and the observational data taken from different sources for galaxies in the redshift range  $0 < z < 1.2$ . The lines correspond to model predictions considering  $M_B^{\text{lim}} = -19.5$  (bottom lines) and  $M_B^{\text{lim}} = -20$  (top lines) to select the main progenitors, as described in Section 3.

fractions for  $z \lesssim 1$ . For higher redshifts, there is an excess in the pair fractions derived by Kartaltepe et al. (2007), inconsistent with the weak evolution of  $f_p(z)$  predicted by the Bower et al. model. This discrepancy can be due to the large errors in the photometric redshifts used to select the pairs and the consequent projection effects, which become more important at higher redshifts. We hope that a future spectroscopic follow-up of their data and other pair fraction estimates from high- $z$  surveys will help to clarify this issue.

In Fig. 2, we show the evolution of the merger rates predicted by the models,  $\Gamma_{\text{mrg}}(z)$ , and the merger rates derived from the observations. Galaxy merger rates are estimated from the observational data considering the time-scale  $T_{\text{mrg}} = 0.5$  Gyr for the measurements from pair counts, assuming by simplicity that this value is characteristic of the merging time-scale for close pairs (e.g. Patton et al. 2000), as discussed in Section 3. For this comparison, we also added the merger rates estimated from merger analysis based on galaxies showing morphological distortions. This approach is significantly distinct to the pair counts analysis, since the mergers are observed after their occurrence (see De Propriis et al. 2007 for a discussion between these two methods). We show the results obtained by Conselice et al. (2003) from a morphological analysis of galaxies in the Hubble Deep Field. They have detected ongoing major mergers by measuring an asymmetry parameter from galaxy images. We also show the recent measurements of morphologically identified galaxy mergers obtained by Lotz et al. (2008) from the analysis of galaxies brighter than  $M_B = -20.5$  in the HST survey of the Extended Groth Strip. Here we adopted a time-scale of 1 Gyr to derive the merger rates from these morphological studies.

As in Fig. 1, there is a good agreement between the observa-



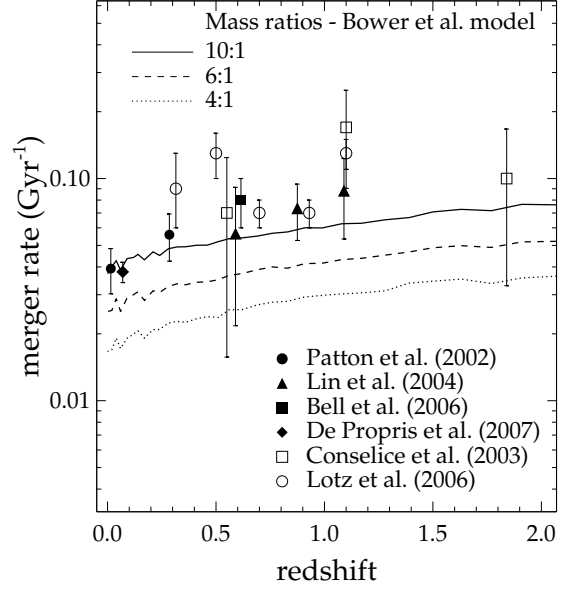
**Figure 2.** Evolution of the galaxy merger rate predicted by the semi-analytical galaxy formation models of Bower et al. (2006, solid line) and De Lucia & Blaizot (2007, dashed line) and the observational data taken from different sources for galaxies in the redshift range  $0 < z < 2$  (see Section 4 for detailed description). The lines are as in Fig. 1.

tional data points and the Bower et al. model predictions, considering the error bars of the measurements and all the uncertainties involved in deriving the observed merger rates (e.g. time-scales). The evolution of merger fractions derived from observational data sets is usually fitted with a function  $f \propto (1+z)^m$ , where the value of  $m$  varies from about 0 to 4 (e.g. Le Fèvre et al. 2000; Carlberg et al. 2000; Conselice et al. 2003; Lin et al. 2004; Lotz et al. 2008). In our analysis, the fitting of the Bower et al. model predictions with the same function, considering only the points in the redshift range  $0 < z < 2$ , gives:

$$\begin{aligned} \Gamma_{mrg}(z) &= 0.029(1+z)^{0.767} \quad \text{for } M_B^{lim} = -19.5, \quad \text{and} \\ \Gamma_{mrg}(z) &= 0.046(1+z)^{0.596} \quad \text{for } M_B^{lim} = -20.0. \end{aligned} \quad (2)$$

The  $m \sim 0.6 - 0.8$  value obtained for this model is consistent with recent results obtained by different approaches, which gives support for roughly a flat evolution of the merger rate (Bundy et al. 2004; Lin et al. 2004; Lotz et al. 2008). The model by De Lucia & Blaizot (2007) predicts a constant merger rate evolution, visibly at odds with the observations and the Bower et al. model results.

In Fig. 3 we investigate the dependence of the merger rate on the mass ratio of the pair components. We show results for the Bower et al. model from which we selected galaxy pairs with mass ratios smaller than 4:1, 6:1, and 10:1, as described in Section 3. The amplitude of the merger rate derived from the model depends strongly on the mass ratio adopted to select the pairs, and it is compatible with the observed one only when we consider a mass ratio threshold of 10:1. The fit of the results with the same function as in equation (2) gives  $m = 0.59$  for merger rates derived from pairs with mass ratios smaller than 10:1, 0.63 for mass ratios of 6:1, and 0.68 for mass ratios of 4:1. These results are consistent with a roughly flat evolution of the merger rate independently of the mass ratio threshold adopted.



**Figure 3.** Evolution of the galaxy merger rate predicted by the semi-analytical galaxy formation model of Bower et al. (2006) considering mass ratios of 4:1, 6:1, and 10:1 to select galaxy pairs, as described in Section 3.

## 5 SUMMARY AND CONCLUSIONS

In this Letter, we have explored galaxy mergers in model universes drawn from semi-analytical galaxy formation models implemented on the Millennium Simulation of structure growth. From the public galaxy catalogues and merger trees generated by the Bower et al. (2006) and De Lucia & Blaizot (2007) models we retrieved the pair fractions and the galaxy merger rate (number of galaxy mergers per Gyr), and compared their redshift evolution with observational results in the redshift range  $0 < z < 2$ .

The results from our study indicate that the evolution of the galaxy merger rate has been discrete since  $z \sim 2$ , following an exponential function given by  $\Gamma_{mrg} \propto (1+z)^m$ , with  $m$  ranging from 0.6 to 0.8 depending on the luminosity and mass ratios of the merging galaxies. We find that this behaviour is true only for the Bower et al. model, since the model by De Lucia & Blaizot (2007) predicts a null merger rate evolution ( $m \sim 0$ ), at odds with the observations and the Bower et al. trends. The results for the De Lucia & Blaizot (2007) model can be related to the study carried out by Guo & White (2008) on the galaxy growth through mergers and star formation based on it, where they have found a nearly constant growth by mergers in the range  $0 < z < 2$ , independent of the galaxy stellar mass.

The weak evolution of the galaxy merger rate found in our analysis is consistent with recent observational results obtained by different approaches which give support for a flat evolution of the galaxy merger rate, with  $m \sim 0.5 - 1$  (Bundy et al. 2004; Lin et al. 2004; Lotz et al. 2008). Previous studies have shown that in the hierarchical framework the merger rate of cold dark matter haloes increases rapidly with redshift also as  $(1+z)^m$ , but with the exponent  $m \sim 2 - 3$  (e.g. Gottlöber, Klypin & Kravtsov. 2001; Fakhouri & Ma 2007). However, as discussed by Berrier et al. (2006), multiple galaxies may occupy the same parent dark matter halo, resulting that the predicted galaxy merger rate should evolve slower than the halo merger rate. Actually, in the present work we



have confirmed this tendency. The weak evolution of the galaxy merger rate predicted by the galaxy formation models shows that the mass assembly evolution of galaxies through mergers does not follow the rapid evolution of the halo merger rate obtained in previous studies.

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