

The significant contribution of minor mergers to the cosmic star formation budget

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ABSTRACT

We estimate an empirical lower limit for the fraction of cosmic star formation that is triggered by minor mergers in the local Universe. Splitting the star-formation budget by galaxy morphology, we find that early-type galaxies (ETGs) host $\sim 14\%$ of the budget, while Sb/Sc galaxies host the bulk ($\sim 53\%$) of the local star formation activity. Recent work indicates that star formation in nearby ETGs is driven by minor mergers, implying that at least $\sim 14\%$ of local star formation is triggered by this process. A more accurate estimate can be derived by noting that an infalling satellite likely induces a larger starburst in a galaxy of ‘later’ morphological type, both due to higher availability of gas in the accreting galaxy and because a bigger bulge better stabilizes the disk against star formation. This enables us to use the star formation in ETGs to estimate a lower limit for the fraction of star formation in late-type galaxies (LTGs) that is minor-merger-driven. Using a subsample of ETGs that is mass and environment-matched to the LTGs (implying a similar infalling satellite population), we estimate this limit to be $\sim 24\%$. Thus, a *lower limit* for the fraction of *cosmic* star formation that is induced by minor mergers is $\sim 35\%$ (14% [ETGs] + $0.24 \times 86\%$ [LTGs]). The observed positive correlation between black hole and galaxy mass further implies that a similar fraction of black hole accretion may also be triggered by minor mergers. Detailed studies of minor-merger remnants are therefore essential, to quantify the role of this important process in driving stellar mass and black hole growth in the local Universe.

Key words: galaxies: formation – galaxies: evolution – galaxies: interactions – galaxies: elliptical and lenticular, cD – galaxies: starburst

1 INTRODUCTION

Understanding the processes that drive stellar mass growth is a central topic in observational cosmology. While the galaxy evolution literature has traditionally relied on relatively small samples of galaxies (e.g. de Zeeuw et al. 2002), the advent of large spectro-photometric surveys, like the Sloan Digital Sky Survey (SDSS), is revolutionizing our understanding of the statistical properties of galaxy populations, by delivering samples of objects numbering in the hundreds of thousands.

A topic that is rapidly gaining prominence is the significant role of minor mergers (mass ratios $\lesssim 1:4$) in influencing the evolution of massive galaxies (e.g. Weinmann et al. 2009; Nierenberg et al. 2011; Wang & White 2012). Recent work on nearby early-type (elliptical and lenticular) galaxies that reside in low-density environments (groups and the field) indicates that the star formation in these systems is driven by minor mergers. In the *HST-COSMOS* field – which, by virtue of being an ‘empty’ field, is dominated by low-density environments – a strong correlation is observed between morphological disturbances in ETGs and blue UV colours (due to young stars). This indicates that the star formation is driven by mergers and not by processes like stellar mass loss or accretion that would leave the stellar morphology unperturbed (Kaviraj et al. 2011). However, the major-merger rate at late epochs ($z < 1$) is far too low to satisfy the num-

ber of disturbed ETGs, indicating that *minor* mergers drive the star formation in these objects (Kaviraj et al. 2011).

Theoretical work supports this observational picture. At late epochs the gas supply from internal stellar mass loss is an order of magnitude too low to produce the levels of star formation implied by the blue UV colours of star-forming ETGs (Kaviraj et al. 2007). Furthermore, Kaviraj et al. (2009) have combined realistic numerical simulations of minor mergers with the expected frequency of these events in the Λ CDM paradigm, to show that the predicted UV-optical colour distributions are remarkably consistent with observations (see their Fig 3). The relative lack of native sources of gas makes ETGs excellent tracers of minor-merger-driven star formation. The star formation is observed against a ‘blank canvas’ of old stars, enabling us to quantify the impact of this process with good precision.

While our focus in this study is on star formation, it is worth noting that the work on minor-merger-driven stellar mass growth is mirrored by studies of the size evolution of massive ETGs. Both observational (e.g. Trujillo et al. 2006; Huertas-Company et al. 2012) and theoretical (e.g. Bournaud et al. 2007; Naab et al. 2009; Oser et al. 2012) work suggests that minor mergers are likely responsible for the bulk of the factor 3-5 evolution observed in ETG sizes over cosmic time (e.g. Daddi et al. 2005; Cimatti et al. 2012).

While it is increasingly clear that minor mergers may

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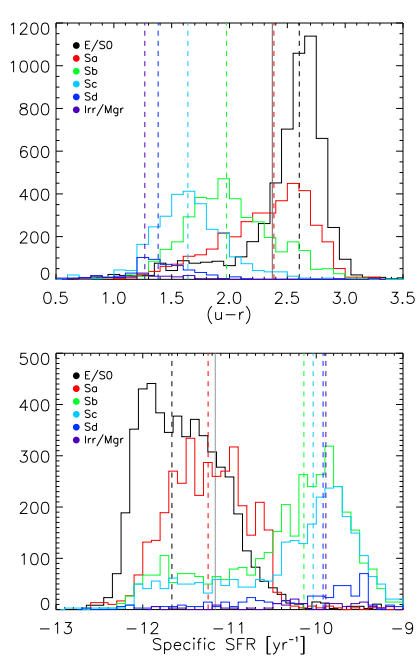


Figure 1. Rest-frame $(u - r)$ colours (top) and specific SFRs (bottom) of galaxies of various morphological types (see legends). Dashed vertical lines indicate median values. The solid grey line indicates a sample of ETGs that is matched in stellar mass and environment to the LTGs (see Section 4). The magnitudes are K-corrected using the publicly available *KCORRECT* code of Blanton & Roweis (2007).

strongly influence both the star-formation and structural properties of massive galaxies, their total contribution to the cosmic star formation budget remains poorly understood. Quantifying this contribution holds the key to understanding the *overall* significance of this process in influencing galaxy evolution, and is the principal aim of this paper.

This Letter is organized as follows. In Section 2, we describe the galaxy sample – drawn from the SDSS Stripe 82 – that underpins this study, the classification of galaxy morphologies via visual inspection and the measurement of galaxy properties such as stellar masses and star formation rates (SFRs). In Section 3 we explore the cosmic stellar mass and star formation budgets in the local Universe and in Section 4 we quantify the minor-merger contribution to local star formation. We summarize our findings in Section 5. Throughout, we use the *WMAP3* cosmological parameters (Komatsu et al. 2011): $\Omega_m = 0.241$, $\Omega_\Lambda = 0.759$, $h = 0.732$, $\sigma_8 = 0.761$.

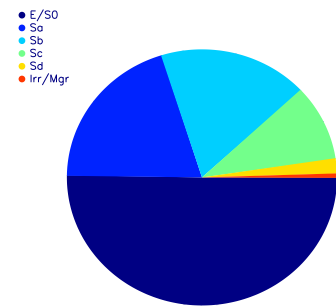
2 DATA

2.1 Galaxy sample and morphological classification

The galaxies in this study are drawn from the SDSS Stripe 82, a region along the celestial equator in the Southern Galactic Cap ($-50^\circ < \alpha < 59^\circ$, $-1.25^\circ < \delta < 1.25^\circ$) that has been multiply imaged as part of the SDSS Supernova Survey (Frieman et al. 2008). The $\sim 300 \text{ deg}^2$ area of the Stripe 82 offers a co-addition of 122 imaging runs (Abazajian et al. 2009), yielding images that are ~ 2 mags deeper than the standard-depth, 54 second SDSS scans (which have magnitude limits of 22.2, 22.2 and 21.3 mags in the g , r and i -bands respectively).

We classify galaxy morphologies via visual inspection

Mass budget (Vmax corrected)



Morphology	Fraction of stellar mass budget
E/S0	0.502 ± 0.068
Sa	0.199 ± 0.043
Sb	0.179 ± 0.039
Sc	0.096 ± 0.020
Sd	0.019 ± 0.003
Irr/Mgr	0.005 ± 0.001

Figure 2. The cosmic stellar mass budget at $z < 0.07$, split by galaxy morphology and corrected for Malmquist bias. The errors are calculated by combining the uncertainties on individual galaxies using standard error propagation formulas.

of both standard-depth, multi-colour images from the SDSS DR7 and their deeper r -band Stripe 82 counterparts. Recent work has widely used visual inspection for morphological classification of bright ($r < 16.8$), nearby ($z < 0.1$) SDSS galaxies (see e.g. Kaviraj et al. 2007; Lintott et al. 2008; Nair & Abraham 2010). Here we restrict our study to $r < 16.8$ and $z < 0.07$, which yields a sample $\sim 6,500$ galaxies. Note that all galaxies in this sample have stellar mass, SFR and environment measurements, on which our subsequent analysis is based.

While past studies have typically not exploited the deep Stripe 82 imaging for morphological classification, these images enhance our ability to identify faint disks and tidal features that are difficult to detect in the standard-depth SDSS exposures, maximising the accuracy of the morphological classification (Kaviraj 2010). We classify galaxies into standard morphological types (Hubble 1926; de Vaucouleurs 1959): E, S0, Sa, Sb, Sc, Sd, Irregular/Mergers. The percentage of galaxies in our morphological classes are E : S0 : Sa : Sb : Sc : Sd : Irr/Mgr = $19.5^{+0.84} : 21.5^{+0.88} : 18.1^{+0.81} : 21.4^{+0.88} : 15.1^{+0.74} : 3.39^{+0.35} : 1.01^{+0.22}$. This is similar to equivalent values from past studies, such as Fukugita et al. (2007, see their Fig 13): 20.6 : 24.5 : 16.6 : 19.8 : 15.0 : 2.10 : 1:30. The slightly higher fraction of late-type systems in our study, compared to previous work based purely on standard-depth images, is plausibly driven by better identification of faint disks in the deeper Stripe 82 scans.

2.2 Stellar masses, star formation rates and local environments

We employ published stellar masses (Kauffmann et al. 2003) and star formation rates (SFRs; Brinchmann et al. 2004, B04 hereafter) from the latest (DR7) version of the publicly-available MPA-JHU SDSS catalogue¹, which is the largest, most homogeneous value-added SDSS catalogue to date. Briefly, stellar masses are calculated by comparing galaxy $ugriz$ photometry to a large grid of synthetic star formation histories, based on the Bruzual & Charlot (2003) stellar

¹ <http://www.mpa-garching.mpg.de/SDSS/DR7/>

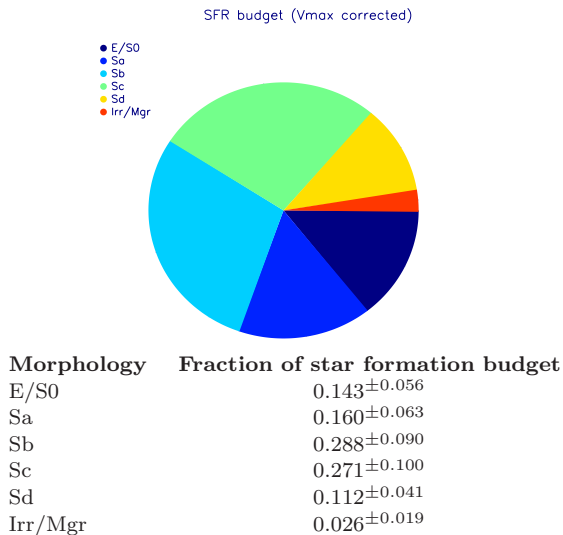


Figure 3. The cosmic star formation budget at $z < 0.07$, split by galaxy morphology and corrected for Malmquist bias. The errors are calculated by combining the uncertainties on individual galaxies using standard error propagation formulas.

models and assuming a Kroupa (2001) initial mass function. Model likelihoods are calculated from the values of χ^2 , and 1D probability distributions for free parameters like stellar mass are constructed via marginalisation. The median of the 1D distribution provides a best estimate for the parameter in question, with the 16th and 84th percentile values (which enclose 68% of the total probability) yielding an associated ‘ 1σ ’ uncertainty. The median stellar mass of our galaxies is $\sim 10^{10.3} M_{\odot}$ and the 5th and 95th percentile values of the mass distribution are $\sim 10^8 M_{\odot}$ and $\sim 10^{11.2} M_{\odot}$ respectively (i.e. 90% of the galaxies lie between these two values).

SFRs are estimated via two different methods (see Brinchmann et al. 2004), depending on the classification of the galaxy in a standard optical emission-line ratio analysis (Kauffmann et al. 2003, see also Baldwin et al. 1981; Kewley et al. 2006). For galaxies classified as ‘star-forming’ (i.e. where the nuclear emission is dominated by star formation), SFRs are estimated by comparing galaxy spectra to a library of models based on Charlot & Longhetti (2001), with a dust treatment that follows the empirical model of Charlot & Fall (2000). For galaxies that are unclassified (due to their emission lines being too weak) or that are classified as ‘AGN/Composite’ (in which a significant fraction of the nuclear emission is from a central AGN), SFRs are calculated using the D4000 break. The D4000 feature is produced via blanket absorption of short-wavelength photons from metals in stellar atmospheres, and is stronger in galaxies that are deficient in hot, blue stars (e.g. Poggianti & Barbaro 1997). This makes it a useful estimator of SFR in systems with weak emission lines, or those in which the diagnostic lines are contaminated by non-thermal sources (e.g. AGN). The relation between specific SFR and D4000 for the ‘star-forming’ subsample is used to estimate the specific SFR of the galaxy in question, which is then converted to a total SFR via the measured galaxy stellar mass. Note that the SFRs used here are both extinction and aperture-corrected. 55% of our galaxies are classified as ‘star-forming’, with 20% unclassified and 25% classified as AGN/Composite. The median SFR of our galaxies is $\sim 1 M_{\odot} \text{ yr}^{-1}$ and the 5th and 95th percentile values of the SFR distribution are $\sim 0.4 M_{\odot} \text{ yr}^{-1}$ and $\sim 6.8 M_{\odot} \text{ yr}^{-1}$ respectively (i.e. 90% of the galaxies

lie between these two values). It is worth noting that the emission-line results in B04 are consistent with the recent literature (e.g. Tresse & Maddox 1998; Pérez-González et al. 2008) and their D4000-measured SFRs for ETGs (which have a median value of $\sim 0.08 M_{\odot} \text{ yr}^{-1}$) are in agreement with those calculated via UV/optical/IR photometry (e.g. Kaviraj et al. 2013a).

When considering the cosmic star formation and stellar mass budgets below, we must correct for the fact that brighter galaxies in our magnitude-limited sample can be observed to larger distances (Malmquist bias). We perform this correction via the standard method of weighting galaxy properties by the maximum volume over which they can be detected (V_{MAX} ; Mo et al. (2010)), given the magnitude limit of the SDSS spectroscopic sample ($r = 17.77 \text{ mag}$).

Finally, to estimate galaxy environment we employ the environment catalogue of Yang et al. (2007), who use an iterative halo-based group finder to separate the SDSS into structures across a broad dynamical range, spanning clusters to isolated galaxies. The catalogue provides estimates of the mass of the dark-matter (DM) halo that hosts each SDSS galaxy, which can be used as a proxy for environment (e.g. van den Bosch 2002). For example ‘cluster-sized’ halos are typically more massive than $10^{14} M_{\odot}$, ‘group-sized’ halos have masses between $10^{13} M_{\odot}$ and $10^{14} M_{\odot}$, while smaller halos constitute what is commonly termed the ‘field’, e.g. Kaviraj et al. (2009).

3 THE COSMIC STAR FORMATION AND STELLAR MASS BUDGETS

Figure 1 presents rest-frame ($u - r$) colour distributions (top) and specific SFRs (bottom) for different morphological classes (see also Strateva et al. 2001). The dashed vertical lines indicate median values. Not unexpectedly, the colours become bluer as galaxies move towards ‘later’ morphological types. In Figures 2 and 3 we present the (V_{MAX} corrected) stellar mass and star formation rate budgets. In agreement with previous work (e.g. Bernardi 2009), ETGs account for almost half the stellar mass budget in the local Universe. Indeed, systems with prominent bulges (ETGs + Sa systems) account for $\sim 70\%$ of the stellar mass in today’s Universe, with disk-dominated galaxies (Sb and later morphological types) hosting the remaining $\sim 30\%$. In contrast, ETGs contribute only $\sim 14\%$ of the cosmic star formation budget, which is dominated by late-type systems, with Sb and Sc galaxies hosting the bulk ($\sim 53\%$) of the star formation activity in the local Universe.

4 THE MINOR-MERGER CONTRIBUTION TO THE STAR FORMATION BUDGET

We note first that, by virtue of being drawn from a blind, wide area survey, our galaxies predominantly inhabit low-density environments (groups and the field, e.g. Kaviraj 2010). Moreover, since environmental processes such as ram-pressure stripping and harassment make clusters hostile to star formation (e.g. Dressler 1984; Moore et al. 1999; Kimm et al. 2011), cluster galaxies are not expected to contribute significantly to the cosmic star formation budget, leaving our overall results unaffected.

If star formation in ETGs is driven by minor mergers, then the ETG portion of the star formation budget ($\sim 14\%$) places an absolute lower limit on the minor-merger contribution to local star formation. However, since all systems,

regardless of morphology, experience minor mergers, calculating the overall contribution of this process also requires an estimate of the minor-merger-driven fraction of star formation in late-type galaxies (LTGs).

It is reasonable to expect that, all other things being equal (galaxy mass, environment etc.), the same satellite falling into a system with a ‘later’ morphological type will trigger a larger starburst. This is both because of the availability of more gas, since later-type systems have higher native gas fractions (e.g. Kannappan 2004), but also because a larger bulge better stabilizes the gas disk against star formation (e.g. Hernquist & Mihos 1995; Martig et al. 2009). Simulations of minor mergers (e.g. Hernquist 1989; Mihos & Hernquist 1994; Hernquist & Mihos 1995) indicate that this is indeed the case. Minor mergers induce radial inflows of native disk gas (as well as gas brought in by the satellite itself), triggering starbursts in the central regions of the primary galaxy. However, in a simulated minor merger with a 1:10 mass ratio, the star formation produced by an identical satellite is almost an order of magnitude lower if the system hosts a modest bulge that has 1/3 of the mass of the disk (e.g. Mihos & Hernquist 1994). Not unexpectedly, disks with larger gas fractions and less prominent bulges experience larger gas inflows and central star formation, given the same initial merger configuration (Hernquist & Mihos 1995). Since ETGs, by definition, have the most prominent bulges and negligible native gas reservoirs compared to late-type galaxies, we can use the star formation activity in ETGs to calculate a lower limit for the minor-merger-driven activity in their late-type counterparts.

However, we note first that ETGs and LTGs typically have different distributions in stellar mass and local environment (e.g. Kauffmann et al. 2003), both of which will affect the characteristics of the infalling satellite population. For example, more massive galaxies will attract more satellites, while infalling satellites are expected to be more gas-poor in denser environments, due to processes like ram-pressure stripping (e.g. Kimm et al. 2011). Therefore, we first draw an ETG subsample that has the same stellar mass and environment distribution as the LTGs (indicated by the solid grey lines in Figure 1). This ETG subset contains ~ 1300 galaxies, with a median stellar mass, SFR and $(u-r)$ colour of $10^{10.3} M_{\odot}$, $\sim 0.2 M_{\odot} \text{yr}^{-1}$ and ~ 2.4 mag. Compared to the full ETG sample, this subset is a factor of ~ 2 less massive, with a median SFR that is a factor of ~ 2 higher. Finally, while this ETG subset is matched in mass and environment to the LTGs, its median SFR is around a factor of ~ 3 lower than that of the LTGs.

From a statistical point of view, this ETG subsample will experience a similar infalling satellite population to that experienced by the LTGs. We divide the total star formation rate in this ETG subsample ($\psi_{ETG'}^{tot}$) by its total stellar mass ($M_{ETG'}^{tot}$), which yields an estimate for the (globally-averaged) star formation activity per unit mass in these ETGs. We then multiply this value by the total stellar mass in the LTGs (M_{LTG}^{tot}), to produce an estimate for the star formation that is attributable to the minor-merger process (ψ_{LTG}^{MM}) in the late-type galaxy population. In other words,

$$\psi_{LTG}^{MM} = \frac{\psi_{ETG'}^{tot}}{M_{ETG'}^{tot}} \times M_{LTG}^{tot}. \quad (1)$$

If similar satellites typically produce more young stars in galaxies of later morphological type, then ψ_{MM}^{LTG} becomes a reasonably robust lower limit to the star formation in the LTG population that is plausibly triggered by minor merg-

ers. Our calculated value for ψ_{LTG}^{MM} is $\sim 24\%$ of the total star formation budget hosted by the LTGs. In other words at least a quarter of the star formation activity in today’s LTG population is likely triggered by minor mergers. Since late-type systems host $\sim 86\%$ of the overall star formation budget, this then implies that a *lower limit* for the fraction of cosmic star formation that is induced by minor mergers locally is then $\sim 35\%$ (14% [ETGs] + $0.24 \times 86\%$ [LTGs]).

It is worth noting that the observed correlation between stellar and black-hole mass in galaxies of all morphological types (see e.g. Gültekin et al. 2009; McConnell et al. 2011) indicates that, on average, stellar mass buildup and accretion on to the central black hole occur in lockstep. This, in turn, implies that a similar fraction of black hole accretion in today’s Universe is also likely to be induced by minor mergers. Our results therefore indicate that *minor mergers drive at least a significant minority ($\sim 35\%$) of local star formation and black hole accretion* that should not be ignored.

Persistent star formation in ETGs at $z < 1$ (Kaviraj et al. 2008), coupled with the paucity of major mergers at late epochs (e.g. Stewart et al. 2008; López-Sanjuan et al. 2009; Conselice et al. 2009), indicates that minor mergers remain influential in driving star formation over at least the latter half of cosmic time (Kaviraj et al. 2011). Indeed, minor-merger-driven star formation is likely to become more intense at progressively higher redshift (e.g. Kaviraj et al. 2008), due to the higher gas fractions in both the infalling satellites and the accreting galaxy. While the $z > 1$ Universe remains comparatively unexplored, both observational (e.g. Förster Schreiber et al. 2011) and theoretical (e.g. Kereš et al. 2009; Dekel et al. 2009) work indicates that major mergers are an insignificant driver of cosmic star formation at these epochs, hosting only $\sim 15\%$ of the cosmic star formation budget at $z \sim 2$ (Kaviraj et al. 2013b). This implies a significant role for other processes such as minor mergers and direct accretion (e.g. via cold streams) in building the old stars that dominate today’s Universe (e.g. Dekel et al. 2009; Kaviraj et al. 2013b). Indeed, the triggering of starbursts by accreted satellites is likely to have been more efficient in the early Universe if disks formed before bulges. Systematic empirical studies of minor-merger-driven stellar-mass and black-hole growth are therefore essential, both in the nearby Universe and at high redshift.

5 SUMMARY

We have estimated an empirical *lower limit* to the fraction of cosmic star formation that is likely to be triggered by minor mergers in the local Universe, using a sample of $\sim 6,500$ bright ($r < 16.8$), nearby ($z < 0.07$) galaxies in the SDSS Stripe 82. We have split our galaxy sample into standard morphological classes (E, S0, Sa, Sb, Sc, Sd, Irr/Merger), via visual inspection of both their standard-depth multi-colour images and their deeper r -band Stripe 82 counterparts. The availability of deep imaging enables us to better identify faint disks and tidal features, maximizing the accuracy of the visual inspection. The percentages of galaxies in our morphological classes are E : S0 : Sa : Sb : Sc : Sd : Irr/Mgr = $20.6^{+2.30} : 21.7^{+2.30} : 18.8^{+2.30} : 20.8^{+2.30} : 14.4^{+2.30} : 2.89^{+2.30} : 0.62^{+2.30}$.

In agreement with previous work (Bernardi 2009), we have found that ETGs account for around half the stellar mass budget in the local Universe, with disk-dominated galaxies (Sb and later morphological types) accounting for

$\sim 30\%$. In contrast, ETGs contribute only $\sim 14\%$ of the cosmic star formation budget, while Sb and Sc galaxies host the bulk ($\sim 53\%$) of the local star formation activity.

Previous work has demonstrated that star formation in nearby ETGs that inhabit low-density environments is driven by minor mergers (Kaviraj et al. 2011). The ETG portion of the star formation budget ($\sim 14\%$) is therefore an absolute lower limit to the minor-merger contribution to local star formation. However, since all galaxies, regardless of morphology, experience minor mergers, a more accurate calculation requires an estimate of the fraction of star formation in LTGs that is also attributable to this process.

It is likely that, all other things being equal (galaxy mass, environment, etc.), the same satellite will trigger a larger starburst in a system of ‘later’ morphological type, both due to greater availability of native gas and because a larger bulge better stabilizes the disk against star formation (a picture supported by numerical simulations of minor mergers). This allows us to use the star formation in ETGs to estimate a lower limit for the fraction of star formation in LTGs that is likely to be induced by minor mergers.

Using a subsample of ETGs that is mass and environment-matched to the LTGs (implying similar infalling satellite populations) we have estimated that this lower limit to the minor-merger-driven fraction of star formation in local LTGs is $\sim 24\%$. Our results then imply that a lower limit to the fraction of *cosmic* star formation that is induced by minor mergers is $\sim 35\%$ (14% [ETGs] + $0.24 \times 86\%$ [LTGs]). The observed correlation between black hole and galaxy mass further suggests that a similar fraction of the black hole accretion in the local Universe may also be triggered by minor mergers. Thus minor mergers are likely to drive a significant minority of star formation and black hole accretion in the local Universe.

Recent work indicates that minor mergers remain influential in fuelling star formation in ETGs at least until $z \sim 1$. Together with an emerging literature which suggests that the major-merger channel triggers a relatively insignificant fraction of cosmic star formation at $z > 1$, this suggests that minor mergers may have had an important role in stimulating the growth of a large fraction of the stellar mass in today’s Universe. Given our poor current understanding of the minor-merger process, detailed observational and theoretical studies of minor-merger remnants are essential, in order to fully quantify the significant role of this process in galaxy evolution.

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