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Connecting traces of galaxy evolution: the missing core mass–morphological fine structure relation

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ABSTRACT

Deep exposure imaging of early-type galaxies (ETGs) are revealing the second-order complexity of these objects, which have been long considered uniform, dispersion-supported spheroidals. ‘Fine structure’ features (e.g. ripples, plumes, tidal tails, rings) as well as depleted stellar cores (i.e. central light deficits) characterize a number of massive ETG galaxies, and can be interpreted as the result of galaxy–galaxy interactions. We discuss how the time-scale for the evolution of cores and fine structures are comparable, and hence it is expected that they develop in parallel after the major interaction event which shaped the ETG. Using archival data, we compare the ‘depleted stellar mass’ (i.e. the mass missing from the depleted stellar core) against the prominence of the fine structure features, and observe that they correlate inversely. This result confirms our expectation that, while the supermassive black hole (SMBH) binary (constituted by the SMBHs of the merger progenitors) excavates the core via three-body interactions, the gravitational potential of the newborn galaxy relaxes, and the fine structures fade below detection levels. We expect the inverse correlation to hold at least within the first Gyr from the merger which created the SMBH binary; after then, the fine structure evolves independently.

Key words: galaxies: bulges – galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: photometry – galaxies: structure.

1 INTRODUCTION

Owing to the development of advanced instrumentation during the last decades, we are realizing that early-type galaxies (ETGs) deviate from the iconic picture of a perfectly spheroidal and dynamically relaxed system. For example, integral field unit surveys such as SAURON (e.g. Cappellari et al. 2007; Emsellem et al. 2007) and ATLAS^{3D} (Cappellari et al. 2011) recently showed that ETGs are not purely ‘dispersion-supported’ systems (i.e. their stars only follow disordered orbits), but also present a rotational component.

Higher-order characteristics of ETGs represent precious information which potentially allow to address the different patterns which lead to their formation, within the widely supported scenario of

hierarchical galaxy evolution (e.g. White & Rees 1978; Springel et al. 2005; Hopkins et al. 2006, 2010, and references therein), in which elliptical galaxies are the end-products of violent galaxy interactions. In this work, we concentrate in particular on two attributes of ETGs: fine structures and depleted stellar cores.

Fine structures. Fine structures are extremely faint (24–27 mag arcsec^{−2}; e.g. Duc et al. 2011) features which manifest in ETGs as a mixed collection of morphological structures, including ripples, plumes, tidal tails, ‘boxy’ isophotes or rings. Such features, originally identified by Schweizer & Seitzer (1988) as a peculiarity of a few objects, are now recognized to be ubiquitous once an appropriate image depth is reached (e.g. Duc et al. 2011; Spavone et al. 2017). Fine structures depict the remnants of the last interaction which shaped the observed morphology of the galaxy, and are expected to fade out progressively as the gravitational potential relaxes (Barnes 1988; Hernquist & Quinn 1988, 1989). They therefore represent a unique tool for studying galactic archaeology, and

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are ideal to investigate the history of dry (i.e. relatively gas-free) mergers, where the lack of star formation limits the possibility to estimate the time elapsed from the event.

The seminal papers on the subject could be considered the works by Schweizer et al. (1990) and Schweizer & Seitzer (1992), in which the authors provide a semi-empirical definition of a ‘fine structure parameter’ Σ , which they visually estimated on (unsharp-masked) images by identifying the number and/or strength of structures. Currently, several projects are creating extended, deep mosaics of nearby galaxies with the ultimate intent of studying the traces of interactions and low-brightness galaxy satellites, such as the Next Generation Virgo Cluster Survey (NGVS; Ferrarese et al. 2012), the Fornax Cluster Deep Survey (FCDS; e.g. Iodice et al. 2016), the Mass Assembly of early-Type GaLaxies with their fine Structures (MATLAS; P.I.: P.A. Duc) or the VST survey of Early-type Galaxies in the Southern hemisphere (VEGAS; P.I.: E. Iodice).

Depleted stellar cores. Luminous ($M_B < -20.5$ mag) ETGs present one additional idiosyncrasy which distinguishes them from the smaller mass ones: they are characterized by the presence of a ‘core’, i.e. a central luminosity deficit (not due to dust obscuration) with respect to the inward extrapolation of the outer light profile (e.g. Lauer 1985).

According to the generally accepted scenario, depleted stellar cores are thought to be related to the dry merger of galaxies. In this context, the supermassive black holes (SMBHs) at the centre of each of the merging progenitor are dragged by dynamical friction towards the centre of the gravitational potential and eventually form an SMBH binary at the centre of the merger remnant. The basic idea is that three-body interactions between the stars and the SMBH binary transfer energy to the stars, hence ejecting them from the centre of the newly formed galaxy, creating the central stellar mass deficit (Begelman, Blandford & Rees 1980). This hypothesis is supported by the observed scaling relations between the SMBH mass and the core size or the ‘missing stellar mass’ (e.g. Lauer et al. 2007; Dullo & Graham 2014). The energy is transferred to the interacting stars at the expense of the SMBH binary, whose orbital separation shrinks along the process, leading the binary to coalescence while the core is excavated.

An important caveat is that the SMBH binary scouring is not expected to happen in a gas-rich environment. In fact, in this case the gas would disperse a significant fraction of the energy of the SMBH binary in lieu of the stars. Moreover, any excavated core could be replenished by central star formation (e.g. Mihos & Hernquist 1994; Barnes & Hernquist 1996; Hopkins et al. 2008, 2009). This caveat is consistent with the observation that core galaxies are almost exclusively radio-loud objects (e.g. Capetti & Balmaverde 2005, 2006, 2007; Richings, Uttley & Körding 2011), given that radio-loud active galactic nuclei (AGNs) are long thought to be cold-gas starved systems in a low activity state (e.g. Best et al. 2006).

In this context, the amount of missing stars – or ‘mass deficit’ – can be quantified from the difference between the extrapolation of the outer radial profile (indicative of the pristine galaxy) and the observed profile (with an excavated core; see panel C-2 in Fig. 1). The surface brightness profile of the spheroidal component of galaxies hosting a core can in fact be described by a smooth connection between an inner power law and an outer Sérsic function (the ‘core-Sérsic model’; Graham et al. 2003).

We have therefore a coherent theoretical framework – the hierarchical merging scenario – able to simultaneously explain: (1) the emergence of fine structure features in post-merger massive galax-

ies, (2) the excavation of stellar cores and (3) the merging of SMBH binaries at their centres. What was still lacking, is a coherent *observational* investigation which would ultimately connect the merger history of massive ETGs with the fine structure, prominence of core and central SMBH.

With this work, we demonstrate that these aspects are indeed intimately connected. In Section 2, we discuss how the time-scale for the creation of the core and the disappearance of fine structures are consistent, in Section 3, we present observational results supporting the core–fine structure connection, in Section 4, we discuss our interpretations, while in Section 5, we summarize our results.

2 TIME-SCALE CONSIDERATIONS

According to the hierarchical galaxy formation scenario, massive ETGs are mostly assembled through mergers, whose traces – the residual fine structure features – progressively fade out with time. At the same time, in the case a dry merger event, a core is excavated by a coalescing SMBH binary at the centre of the newly formed galaxy. How do the time-scale of these two processes compare?

In a recent numerical simulation, Khan et al. (2012a) showed that (at least in the case of minor mergers of disc galaxies) SMBHs with masses 10^6 – $10^7 M_\odot$ will completely coalesce within 1–2 Gyr after the merger. This figure encompasses the whole time span from the merger to the actual SMBH merger. In a related simulation, the same authors (Khan et al. 2012b) showed that, while the total coalescence time is ~ 2.9 Gyr, the SMBH scouring phase lasts ~ 1 Gyr (after which the SMBH pair rapidly merges via gravitational wave emission). In general, there seems to be consensus on that, in dry mergers, the scouring phase alone can last a few Gyr (for a review, see Colpi 2014).

On the other hand, the average survival time of fine structures is a parameter much more difficult to estimate, simulation-wise because it requires to reproduce a great variety of features, and observational-wise because of the low surface brightness of the structures compared to the main body of the galaxy. Despite the obstacles, the literature regarding simulations aimed at interpreting the interaction and merger debris is rich. The variety of these idealized simulations yielded diverse results, but estimations of survival times in both the spatial- and the phase-space agree in that fine structures should remain coherent for at least 1 Gyr (e.g. Hibbard & Mihos 1995; Johnston, Sackett & Bullock 2001; Feldmann, Mayer & Carollo 2008; Johnston et al. 2008; Michel-Dansac et al. 2010; Peirani et al. 2010; Torrey et al. 2015; Duc 2017). Studying colour differences between the fine structures and the host galaxy, Schweizer & Seitzer (1992) estimated the average survival time to 1–2 Gyr. Using a wider sample and deeper exposures, Duc et al. (2011) argue that, although an upper limit could be set at 5 Gyr, the vast majority of the collisional debris would fall back on to the main body of the galaxy within a couple of Gyr (e.g. Hibbard & Mihos 1995). The aforementioned studies additionally show that the specific time-scale clearly depend upon the type of merger which generated a given fine structure. Structures predominantly associated with ‘wet’ (i.e. gas-rich) events, such as tidal tails and plumes, are relatively short-lived (1–2 Gyr), while structures potentially associated with dry mergers such as shells (e.g. Paudel et al. 2017) could survive up to 4 Gyr.

Thus, the theoretically estimated time-scale for the merger remnants fine structures to significantly (if not completely) fade out is at least sufficiently large to complete the formation of cores through SMBH scouring. In other words, it is expected that fine structure coexists with SMBH binaries at different stages in their process

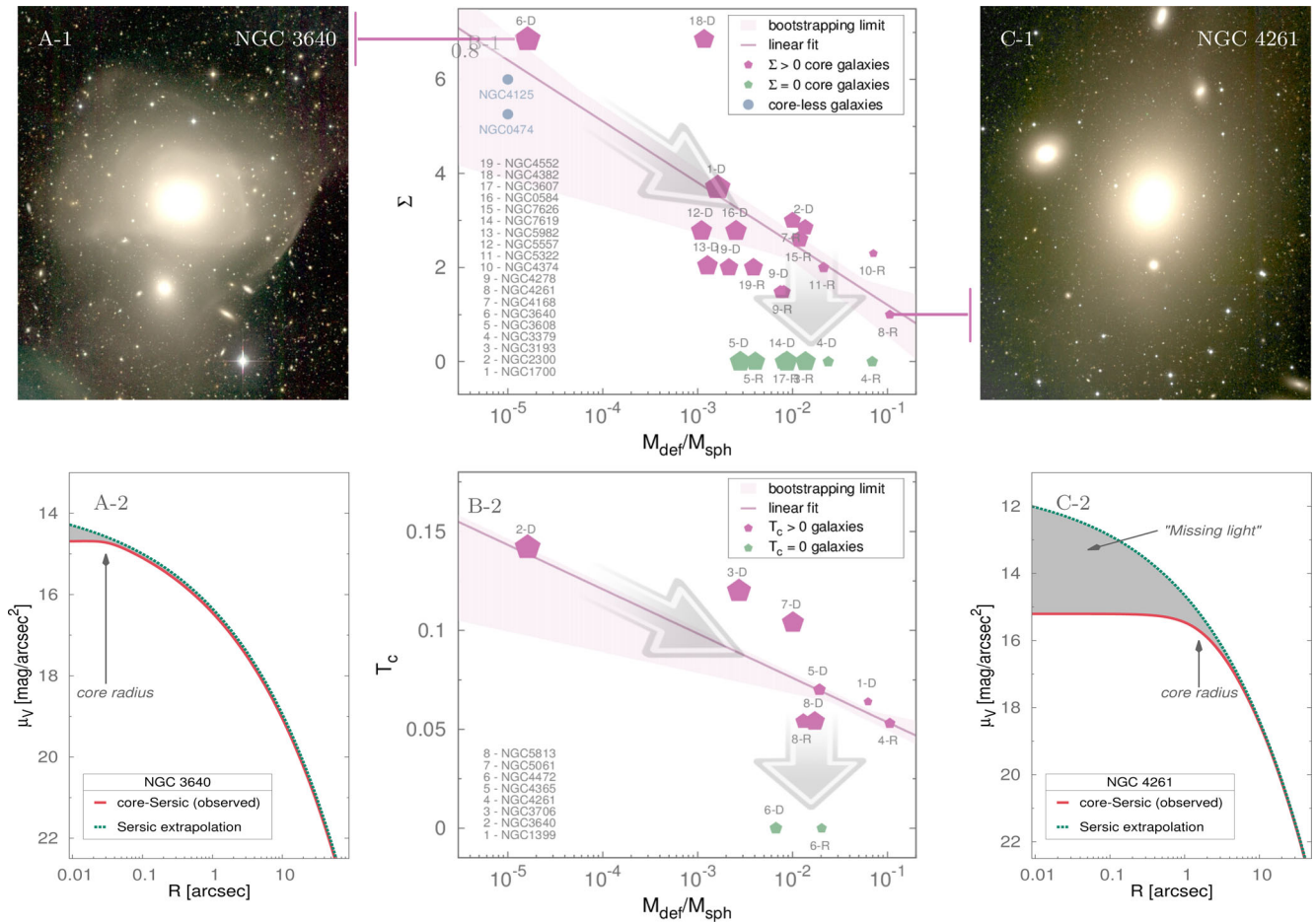


Figure 1. Relation between fine structure and depleted stellar mass, and suggested evolutionary tracks. Central panels (B) – fine structure parameter (Σ ; Schweizer et al. 1990, *B-1*), and tidal parameter (T_c ; Tal et al. 2009, *B-2*) as a function of relative mass deficit ($M_{\text{def}}/M_{\text{sph}}$). The pink pentagons represent the data points for the core galaxies with detected fine structures ($\Sigma > 0$ or $T_c > 0$), while the green pentagons represent data values for the comparison sample of core galaxies without fine structure ($\Sigma = 0$ or $T_c = 0$). The relative mass deficits were calculated from the core-Sérsic profiles reported by Richings et al. (2011) and Dullo & Graham (2014), as schematically shown in the side panels. The size of the data points is inversely proportional to the reliability of the core, for which we adopted the ratio between the core size and the seeing FWHM of the relevant observation as a proxy. The reference for each data point has been indicated with a label ‘R’ for Richings et al. (2011), or ‘D’ for Dullo & Graham (2014). Notice that the two studies have two (one) galaxies in common in the $\Sigma > 0$ ($T_c > 0$) sample, and two (one) in the $\Sigma = 0$ ($T_c = 0$) sample. The solid pink line represents the one-to-one fit to the $\Sigma > 0$ ($T_c > 0$) sample, while the light pink shaded area shows the limits of all the possible curves determined through a two-points (one-point) bootstrapped linear fit. The dark blue circles in panel *B-1* represent the galaxies classified as core-less by Richings et al. (2011), but which could potentially host an unresolved core or develop one in the future, as suggested by their *B*-band luminosity (see Section 3). The grey arrows show the proposed evolutionary track, according to which the core and the fine structure initially co-evolve (moving diagonally along the plot), while – once the core has been completely excavated – a galaxy should move vertically down as the fine structure gradually disappears. Side panels (A and C) – MATLAS false-colour images (*A-1* and *C-1*) and surface brightness radial profiles (*A-2* and *C-2*) of two galaxies at the opposite extremes in terms of both fine structure and core depletion. The red solid curves represent the best-fitting core-Sérsic parameters from Dullo & Graham (2014, NGC 3640, left) and Richings et al. (2011, NGC 4261, right). The green dashed curves represent the inward extrapolation of the Sérsic part of the core-Sérsic profile. We indicate with a vertical arrow the location of the best-fitting core radius (i.e. the transition point between the inner power law and the outer Sérsic), while the grey shaded areas show how the ‘missing light’ is calculated as the area between the core-Sérsic curve and its Sérsic extrapolation.

of excavating the core. In fact, the two processes should initially advance in parallel: while the SMBH binary (created soon after the merger event) proceeds with its scouring action, the fine structure features gradually disappear due to the relaxation of the gravitational potential. Since however the fine structure life span is on average larger than the time-scale of core excavation, at some point this co-evolution could cease. After about ~ 1 Gyr, while the core will not expand significantly, the galaxy will still keep reducing its fine structure.

3 MEASUREMENTS OF CORES AND FINE STRUCTURES

We defined a sample of nearby ETGs, for which we could retrieve literature values for both the fine structure and the stellar mass deficit. The ‘bottleneck’ for this selection was dictated by the scarcity of studies reporting numerical evaluations of diverse fine structures. For our purpose, we used the semi-quantitative ‘fine structure parameter’ (Σ) defined by Schweizer et al. (1990, see Section 1). We additionally considered the ‘tidal parameter’ (T_c) by Tal et al.

(2009), which however represents a simplified statistics based on the presence of distortions on the residual images after subtracting a (symmetric) galaxy model, similar to the only other studies we are aware of, nominally van Dokkum (2005) and McIntosh et al. (2008). We stress that, despite its name, the tidal parameter does *not* exclusively describe ‘tidal tails’, but dishomogeneities in general (see equations 1 and 2 of Tal et al. 2009).

For the 69 objects in Schweizer et al. (1990), we searched in the literature for core-Sérsic fits to their surface brightnesses, and found 19 among the samples of Richings et al. (2011) and Dullo & Graham (2014). Of those galaxies, 14 display fine structure ($\Sigma > 0$): these objects represented the primary sample for the current study (nine have core parameters from Dullo & Graham 2014, seven from Richings et al. 2011, two are in common). The remaining five galaxies did not present any evident structure ($\Sigma = 0$): we used this as a comparison sample, keeping in mind that the lack of structure might be due to the limited sensitivity of the data used in Schweizer & Seitzer (1992, 40–60 min exposure images from the 0.9 m KPNO telescope), rather than an intrinsic feature. Our small sample is representative of the range of Σ in Schweizer et al. (1990), and of the depleted mass in typical core galaxies. Similarly, the sub-sample of 52 galaxies by Tal et al. (2009) with disturbed morphology ($T_c > 0$) was cross-correlated against Dullo & Graham 2014 and Richings et al. 2011, obtaining six and two matches, respectively (one in common). In this case, the comparison sample of featureless objects ($T_c = 0$) consisted only in one, common galaxy.

We calculated the spheroid mass (M_{sph} ; mass associated with the ‘bulge’ of the galaxy, excluding any disc structure) by integrating the core-Sérsic profiles by Dullo & Graham (2014) and Richings et al. (2011) to obtain the total luminosity, and then converting to stellar mass by assuming a mass-to-light ratio for a uniformly old (12 Gyr), solar metallicity stellar population (as appropriate for massive ETGs, e.g. Gallazzi et al. 2006). To derive our mass-to-light ratios, we used the ‘Worthey model interpolation engine’ applet¹ based on the evolutionary models by Worthey (1994), where we adopted the default Salpeter initial mass function prescriptions. Similarly, the mass deficit (M_{def}) was inferred from the difference between the full core-Sérsic profile, and the extrapolation of its Sérsic part (the latter being indicative of the pre-depletion profile; Graham et al. 2003) – see side panels in Fig. 1.

In the central panels of Fig. 1, we show the fine structure parameter (panel B-1) and tidal parameter (panel B-2) as a function of the mass deficit normalized by the spheroid mass ($M_{\text{def}}/M_{\text{sph}}$). The scatter in the plots is due to the uncertainty on both quantities.

(1) The parametrization of fine structure is the main source of uncertainty, due to both the lack of a robust definition, and the dependence of Σ (or T_c) on the image data quality and depth. A good example is NGC 5557, for which Schweizer et al. (1990) reported $\Sigma = 2.87$, while more recent and deeper observations revealed additional structure, increasing Σ to 6.00 (Duc et al. 2011). Such depth biases are expected to similarly affect all data points, hence maintaining the observed distribution. Moreover, one can reasonably assume that any present structure was detected with similar efficiency within the Schweizer et al. (1990) or Tal et al. (2009) samples, except possibly for the $\Sigma = 0$ ($T_c = 0$) galaxies (as discussed above).

(2) There is often a significant mismatch in the recovered depleted mass due to differences in fitting techniques. For the galaxies

they have in common (other than the ones shown in Fig. 1), the mass deficit derived from Richings et al. (2011) and Dullo & Graham (2014) differ on average by ~ 40 per cent.

In the same panels, we show with a solid pink line a linear fit to the $\Sigma > 0$ and $T_c > 0$ samples, respectively, of the form:

$$\Sigma = c_{\Sigma} + m_{\Sigma} \times \log(M_{\text{def}}/M_{\text{sph}}) \quad (1)$$

$$T_c = c_T + m_T \times \log(M_{\text{def}}/M_{\text{sph}}) \quad (2)$$

which yielded the best-fitting parameters $c_{\Sigma} = -0.10$ and $m_{\Sigma} = -1.30$, and $c_T = 0.03$ and $m_T = -0.02$. These fits have been weighted by the reliability of the core measurement, with the weights estimated as the ratio between the core size and the seeing FWHM of the relevant observation. In order to exclude the possibility that the two highest Σ galaxies (nominally NGC 3640 and NGC 4382) drive the relation, we applied a two-point bootstrapping. In practice, we devised an iterative procedure in which two random points were removed from the sample at each iteration and the fit was re-performed, until all possible combinations were covered. For T_c we performed a similar test, but adopting a one-point bootstrapping, given the smaller number of data. This analysis yielded a range of best-fitting relations which span within the shaded pink area in panels B-1 and B-2, representative of the error on our best fits. Additionally, we calculated the Pearson correlation coefficient for the fit of equation (1), obtaining $R = -0.71$ and -0.44 for the full sample and after excluding the two points with the largest Σ , respectively. For the fit of equation (2), we obtained $R = -0.85$ and -0.75 for the full sample and after excluding the point with the largest T_c , respectively. A test based on the Fisher z transformation showed that, for both fits, the Pearson coefficients obtained with the full or the reduced samples are consistent within the 95 per cent confidence level. This indicates that there is no significant difference by excluding the aforementioned two (one) data points, and further confirms the solidity of the linear relations.

As a further test of our analysis, we wanted to check if galaxies which have not yet developed a core consistently present high levels of fine structure. Richings et al. (2011), apart from the core-Sérsic galaxies we referred up to now, also reported 41 objects whose spheroidal component was successfully fit with a simpler Sérsic profile: this implicitly classifies them as *core-less*. However, not all *core-less* galaxies are suitable to our test: we need to select only those which are indeed ‘pre-destined’ to develop a core, but were by chance observed very early in their formation, and hence only momentarily appear as Sérsic because they did not develop yet an measurable core. *Core-less* galaxies, however, also include ‘pure’ Sérsic galaxies, which will never develop a core because their formation, e.g. involved significant gas fractions – these are contaminant objects we want to segregate. Lacking an age estimation, one indicative way to select ‘pre-destined’ core galaxies is to adopt the magnitude limit: it is in fact observed that ETG brighter than $M_B \sim -20.5$ mag are statistically prone to present cores (e.g. Kormendy et al. 2009; Graham 2013, and references therein). We therefore applied this magnitude cut to the *core-less* (Richings et al. 2011) galaxies with a measured Σ (or T_c), resulting in the selection of NGC 0474 and NGC 4125². Such a small number of matching objects (2 out of the parent 41) was indeed expected since observing a core-Sérsic

² We excluded NGC 5982 for coherency, being one of the few objects for which Richings et al. (2011) did not report a distance, although the distance retrieved from NED technically makes this object the part of the selection.

¹ http://astro.wsu.edu/worthey/dial/dial_a_model.html

galaxy soon after its formation is a statistically rare occurrence: the vast majority core-less objects are ‘pure’ Sérsic galaxies. These two objects appear in panel B-1, where their mass deficit has been set to an arbitrarily small value. Under the assumption that NGC 0474 and NGC 4152 are in-the-making core galaxies, their location in the plot is consistent with our evolutionary scenario.

Notice that the overall Σ value does not distinguish between features primarily associated with gas-rich interactions and star formation (e.g. tidal tails and streams) and those potentially associated with gas-poor mergers and/or no star formation (e.g. shells), despite its numerical value is more biased towards shell structures (see formulation in Schweizer et al. 1990). For our study, we are in principle interested in fine structures *not* associated with gas infall since this would hamper the formation of a depleted core (see Section 1). To exclude the possibility that the fine structures of the core galaxies in our sample were associated with significantly gas-rich mergers, we visually inspected SDSS-DR13 images of the sample galaxies using the ‘SDSS Navigator’ applet³. We found that the only fine structures presented by the galaxies were shells, with the exception of NGC 4552 and NGC 5557, which also presented plumes. This observation also suggests that the galaxies considered here underwent similar gas-abundant mergers, and in turn it supports the implicit assumption that the significance of fine structure monotonically declines in time.

A similar argument can be constructed for the T_c galaxies. Differently from Σ , the tidal parameter is not particularly sensitive towards a specific feature (although the name might suggest it is biased towards tidal tails). By inspecting the notes reported by Tal et al. (2009) in their table 1 (which describe the appearance of the features), we identified only one galaxy, namely NGC 5061, which could bear signs of a past wet merger. Tal et al. (2009) report that this object shows a pronounced tidal tail on top of shell structures. Notably, by virtually removing the contribution to T_c due to the tidal tail (i.e. solely considering the shells), the corresponding data point in panel B-2 of Fig. 1 would fall even closer to the best-fitting line.

4 DISCUSSION

In the recent years, alternative formation scenarios for the excavation of a core have been promoted. The need for alternative models arose partly to explain the observation of a growing number of objects with extremely large cores (>1 kpc; e.g. Hyde et al. 2008; Postman et al. 2012; López-Cruz et al. 2014; Dullo, Graham & Knapen 2017) which would imply extremely large depleted masses. In Bonfini & Graham (2016), we calculated that as much as $10^{11} M_\odot$ have been displaced from the centre of the brightest cluster galaxy (BCG) of Abell 2261, and created a 3.6 kpc core, much more than what simulations predict for SMBH binary scouring (Merritt 2006).

As a corollary to the binary SMBH scenario, it has been suggested that – after coalescing – the merged SMBH will receive a kick due to the anisotropic emission of gravitational waves: this might explain larger cores. In fact, the displacement of the merged SMBH transfers large amounts of energy to the surrounding stars, and this might not only directly generate a core (e.g. Boylan-Kolchin, Ma & Quataert 2004; Merritt et al. 2004), but also significantly enlarge an existing one, possibly by multiple oscillations (Gualandris & Merritt 2008; Lena et al. 2014). Among the emerging alternative scenarios, there is also the ‘AGN feedback’ mechanism proposed by

Martizzi, Teyssier & Moore (2012), and the core excavation by an infalling, captured perturber (e.g. Goerdt et al. 2010; Petts, Gualandris & Read 2015). The latter was actually proposed to explain the formation of constant density cores in dark matter haloes, but in Bonfini & Graham (2016) we proved it could also be applied to the study of extremely large baryonic cores.

However – although few exceptional cases might require alternative models – the SMBH scenario is still the most favoured due to the extended theoretical support, and the existence of scaling relations between the core properties and the SMBH mass (e.g. Lauer et al. 2007; Dullo & Graham 2014). There are also growing observational indications for SMBH pairs at the kpc scale, observed at the centre of merger remnants (e.g. NGC 6240, Komossa 2003; Arp 299, Ballo et al. 2004; 0402+379, Rodriguez et al. 2006; Mrk 463, Bianchi et al. 2008). The recent ‘visual’ detection of a binary whose SMBHs are separated by a projected distance of only ~ 7 pc poses the strongest observational confirmation so far (Bansal et al. 2017). At the same time, we are aware that galaxies with the largest cores (>1 kpc) also host the most massive SMBH in the Universe, plausibly produced by a coalesced binary (e.g. Laine et al. 2003; Lauer et al. 2007). The recent, direct detection of gravitational waves in stellar-sized merging black holes (Abbott et al. 2016a,b,c, LIGO collaboration) arguably constitutes the strongest evidence of black hole coalescence (even if at a smaller mass scale).

Our results provide additional support to the SMBH scouring scenario. The linear relation in the central panels of Fig. 1 shows clear indication that the significance of fine structures scales inversely to the relative depleted mass over four orders of magnitude in $M_{\text{def}}/M_{\text{sph}}$. Remarkably, galaxies which will eventually develop a core (see NGC 4125 and NGC 0474 in panel B-1) consistently present indication of prominent fine structure. This strongly suggests that galaxy relaxation and core excavation are indeed happening in parallel. Once the core is almost completely excavated and the SMBH binary coalesced (1 Gyr), a galaxy stops moving diagonally along the relation and it starts moving vertically down until the complete disappearance of fine structures (which could take up to 4 Gyr). This evolutionary track is represented in the central panel of Fig. 1 with grey arrows. The observation that no galaxy with large $M_{\text{def}}/M_{\text{sph}}$ presents significant fine structure, and that all featureless galaxies have large $M_{\text{def}}/M_{\text{sph}}$, is coherent with this picture.

The observed trend it is instead at odds with stochastic core depletion events, like the capture of an infalling satellite (e.g. Goerdt et al. 2010). On the contrary, a larger core would require a larger satellite infall, which in turn would produce larger fine structures. The considerations about the AGN-feedback scenario (e.g. Martizzi et al. 2012) are instead more complex. In the first place, AGN activity acts on a way smaller temporal scale ($\sim 10^7$; Kauffmann & Haehnelt 2000; Hopkins et al. 2005) than fine structure evolution. Outflows are impulsive and might produce a core of arbitrary size at any stage of the galaxy life. Secondly, focusing on the objects in our analysis, we exclude that they involved large gas fractions (Section 3), hence we do not expect a significant AGN feedback able to justify the creation of the largest cores in our sample. As a matter of fact, the Martizzi et al. (2012) mechanism has been proposed for BCGs, in which the large cool inflow of cluster gas can explain extreme accretion events. Finally, one could argue that large depleted mass would imply a strong AGN activity, which in turn requires significant gas infall on the SMBH which is more prone to happen when the gravitational potential is not relaxed yet, i.e. right after the merger, when Σ is still large (at odds with Fig. 1). Furthermore, it has also been questioned whether merger events

³ skyserver.sdss.org/dr13/en/tools/chart/navi.aspx

are associated with a higher AGN activity in the first place (Li et al. 2008).

5 CONCLUSIONS

We promote the idea that depleted stellar cores in ETGs are progressively excavated in parallel with the disappearance of the fine structure features (remnant of the last major interaction experienced by the galaxy). This prediction is in line with the expectations from the hierarchical formation scenario of galaxies, and with the SMBH mechanism for core depletion.

We observe that the time-scale for core excavation and relaxation of the galaxy potential are similar or in excess of 1 Gyr (from the merger event which assembled ETG), hence large enough for the two processes to initially co-evolve. We show observational evidence that the prominence of fine structure anticorrelates with the amount of mass removed from the core (normalized by the total mass of the host galaxy). We argue that this anticorrelation shall hold at least within the first Gyr from the assembly of the galaxy (i.e. until the core is fully developed), after which time the fine structure evolves independently. Our results support the SMBH scouring as the main channel (although not necessarily the only one) for the formation of depleted stellar cores.

Deep follow-up of ETGs known to host cores will allow us to better constrain the relation presented in Fig. 1, and to reduce the systematic uncertainties due to the parametrization of the fine structure. By properly quantifying fine structures, and by calibrating them against numerical simulations, we will be able to replace the fine structure measurement (the y-axis) with a time proxy. By interpreting Fig. 1 in this way, our approach will therefore represent a sophisticated method to exploit the structure of galaxies to estimate the age of a merged ETG, overcoming the known measurement limitations related to their uniformly old stellar populations.

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