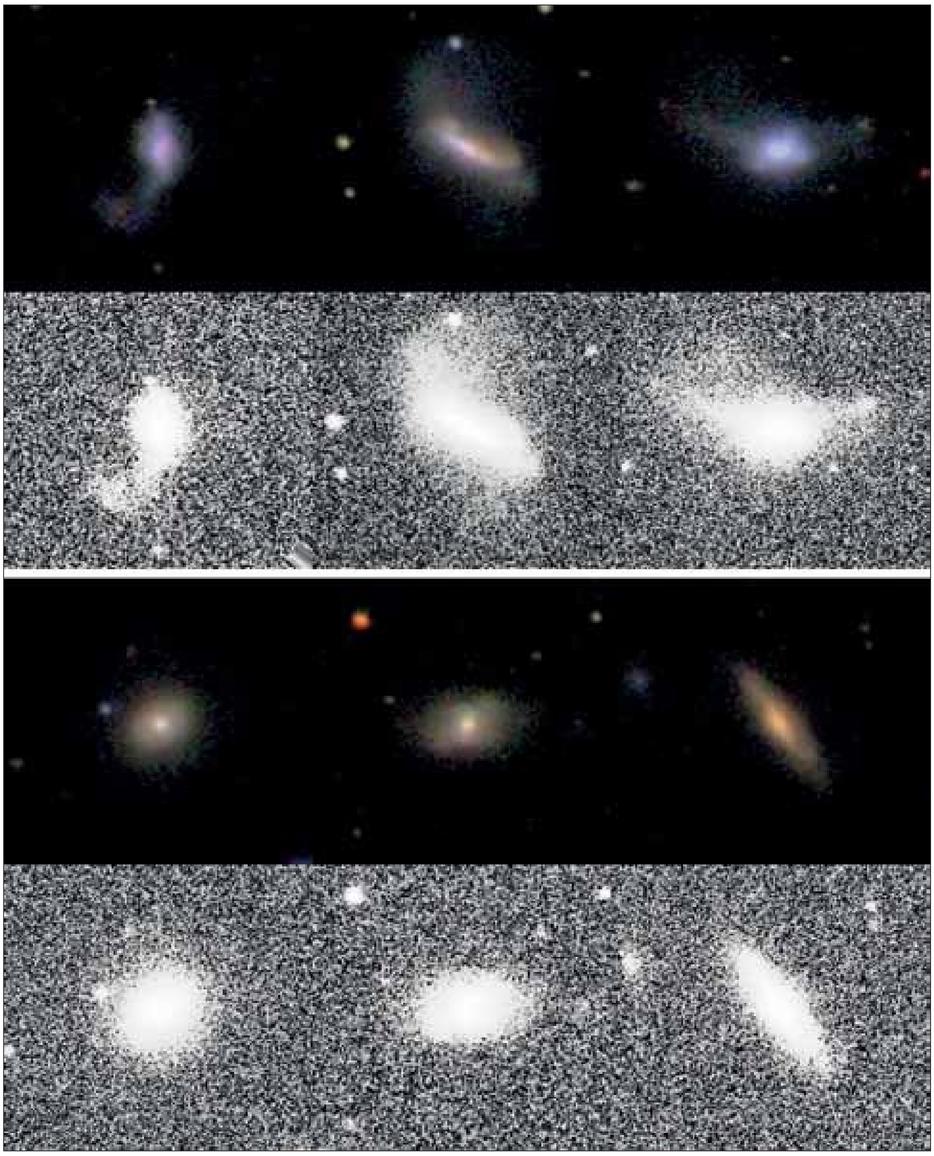
Quantifying galaxy morphology



1: Local galaxies with post-starburst stellar populations. Young (post-)starbursts (top pairs) show significantly more disturbance in their morphology than the older systems (bottom pairs). (The three-colour and r-band images were taken from the seventh data release of the Sloan Digital Sky Survey)

How do the different shapes of galaxies arise? Milena Pawlik describes work to identify the role of galaxy mergers and starbursts in galactic evolution.

One of the main goals of modern astronomy and astrophysics is to understand the nature, origin and fate of the universe we live in. Within the currently favoured model of ΛCDM cosmology, ordinary (baryonic) matter makes up only 5% of the total content of the universe (with 25% cold dark matter and 70% dark energy; Ade *et al.* 2013); however, baryonic matter remains the only component we are able to study through direct observations – for example, by tracing the distribution of galaxies in the universe, and studying their formation and evolution.

Data from large surveys reveal bimodality in the galaxy population at low redshifts (Strateva *et al.* 2001, Baldry *et al.* 2004, 2006). This means that, broadly speaking, local galaxies form two distinct types: star-forming late-type galaxies, composed of a disc with spiral arms surrounding the central bulge; and massive, passively evolving early-type galaxies with no sign of a disc in their structure. Because of the separation in colour of the two galaxy types, they are sometimes referred to as blue-sequence and red-sequence galaxies, respectively. What is the origin of this separation? Have different galaxy types come to being via distinct formation mechanisms, or are they stages of galaxy evolution?

It is believed that one of the channels of galaxy evolution is via transformations from star-forming discs to massive dead spheroids. Such transformations can be caused by galaxy interactions, the most violent of which are mergers, where galaxies collide and, over time, coalesce to form a single object. This hypothesis naturally emerges from ΛCDM cosmology favouring a hierarchical mechanism of structure formation via mergers of dark matter halos. Moreover, it is also supported both by observational evidence of the presence of galaxy mergers in the universe (e.g. Arp 1966, De Propris *et al.* 2007) and theoretical models confirming that such a transformation between the two galaxy types is, indeed, possible (e.g. Toomre and Toomre 1972, Naab and Burkert 2003). But because there are many physical processes at work to form the observed galaxy bimodality, direct observations of the different stages of galaxy mergers are required to understand the importance of particular processes in the evolution of galaxies. This is one of the main goals of my work.

The transition phase

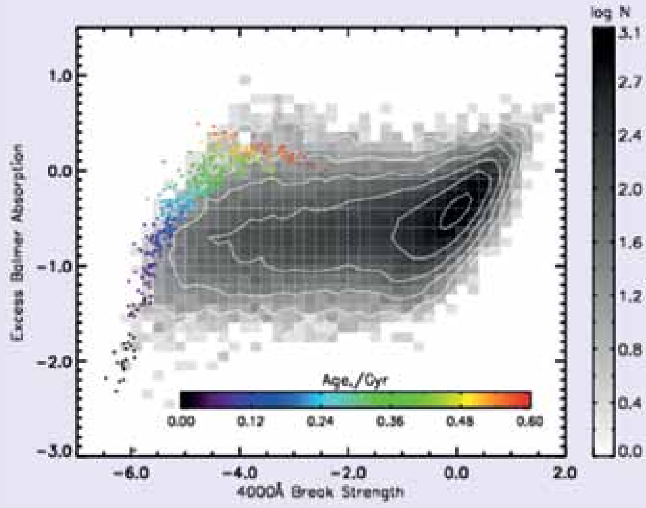
Theoretical models show that when galaxies of comparable masses interact, they are subjected to tidal forces which can alter their morphology (Toomre and Toomre 1972). In the case of interactions as violent as galaxy mergers, the forces at play are so strong that they can disrupt the kinematics of the material within the galaxies, break galactic structures and, eventually, lead to formation of tidal tails and bridges composed of both stellar and interstellar material. The disruptive phase of a merger finishes with the coalescence of the interacting galaxies; the subsequent stages of the process are dynamically more quiescent, meaning that the merger remnant will gradually lose the tidal signatures. In the study of galaxy interactions, we distinguish between "dry" and "wet" mergers. The former involve galaxies that have exhausted their gas reservoir and already reside on the red sequence; these dry mergers can lead to formation of the most massive observed elliptical galaxies. But in my work I focus on the latter, wet mergers of gas-rich galaxies with ongoing star-formation. This type of interaction is often linked to the transformation between blue and red galaxies, and therefore it has the potential to explain the bimodality observed in the galaxy population at low redshifts.

In the case of a wet merger, the interaction can not only cause morphological disturbances and mass build-up; it can also trigger starbursts – brief episodes of enhanced star-formation – at the time of the coalescence of the two progenitors (Springel *et al.* 2005, Wild *et al.* 2009). In starburst galaxies, the rates of star-formation can be as high as 10 times those of normal galaxies, such as the Milky Way, with the size of the star-forming regions up to 100 times smaller. This means that the specific star formation rate in galaxies with an ongoing starburst can be 10^3 times higher than in ordinary galaxies forming stars continuously.

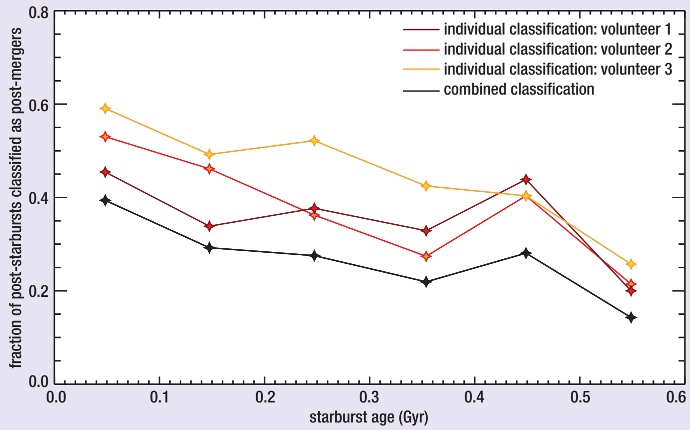
I focus on galaxies that are no longer undergoing a starburst but show evidence of historical rapid increase followed by quenching in their star formation (post-starbursts); I study them in relation to galaxy mergers, for two reasons. First, observational studies of post-starburst galaxies (for example, Zabludoff *et al.* 1996) showed that at low redshifts, they could be remnants of gas-rich major merger events. Secondly, unlike mergers, post-starburst galaxies can be identified using well-defined selection criteria, given the wealth of good quality spectroscopic data now available. Because of the variability and chaotic nature of mergers, there are no such strict criteria for selecting those objects; selection methods vary from looking for galaxies in close pairs, through measuring their structural asymmetry, to identifying galaxies with sudden enhancement in their star formation. Consequently, we are able to obtain samples of post-starburst galaxies that are more robust and complete than those of galaxy mergers. Examples of post-starburst galaxies are shown in figure 1. To investigate the true role of gas-rich major mergers in galaxy evolution I study how the morphology of galaxies changes as they pass through their post-starburst phase, and I look for parallels between their evolution and the evolution of galaxies from clear mergers to early-type merger remnants (post-mergers).

Identifying post-starbursts

Distinguishing between star-forming and passively evolving galaxies involves studying their underlying stellar populations and gas and dust content, which can be done by inspecting their spectral energy distributions. Galaxies with ongoing star formation will show presence of young and massive (O- and B-type) stars, with lifetimes of about 10–100 million years. These stars emit mainly ultraviolet light, which is energetic enough to ionize the gas in their vicinity, giving rise to recombination emission lines in the galaxy spectrum. There will be no signatures of the presence of these stars in spectra of passively evolving galaxies, because they will have already gone through their short lifetimes leaving the long-lived, evolved stars of lower mass as the dominant populations. Spectra of galaxies with old stellar populations will show absorption features arising from the abundance of metals in the atmospheres of the stars. In a similar manner, we can identify galaxies that have undergone a recent burst and subsequent quenching of star formation, and are now passively evolving. Moreover, by tracing their underlying stellar populations we can infer how long ago the starburst occurred and, by so doing, construct a time-sequence for galaxies at different stages of the post-starburst phase.



2: Identifying post-starburst galaxies involves tracing their stellar populations, which can be done by considering their spectral indices (principal component analysis, Wild *et al.* 2007). This can also give us an indication of the starburst age – the time elapsed since the starburst event. The plot (Wild *et al.* 2010) shows post-starburst galaxies, selected from a mother sample of local galaxies using the above method, colour-coded by their starburst ages.



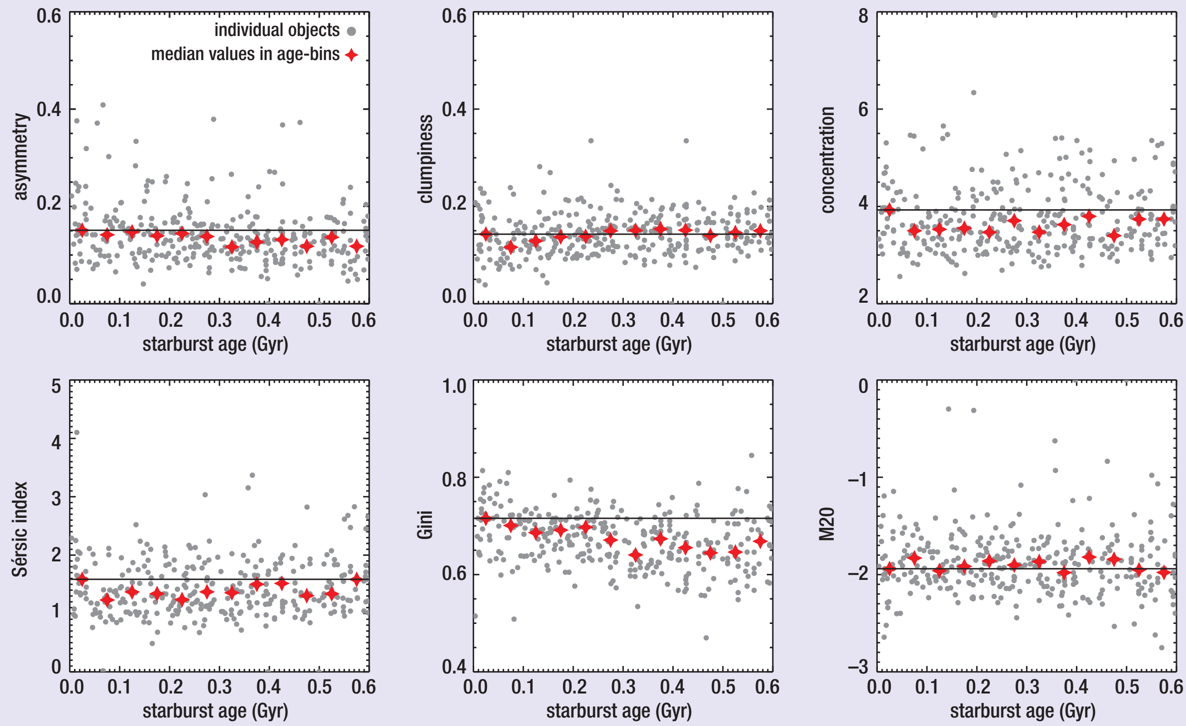
3: Results of visual inspection of post-starburst galaxies suggest that as they age, they tend to show fewer features characteristic to post-mergers in their morphology.

The plot in figure 2 illustrates the essence of a selection method of galaxies with post-starburst stellar populations using two spectral indices (principal component analysis, Wild *et al.* 2007). The first principal component (PC1), the 4000 Å break, is a prominent feature in spectra of passively evolving galaxies and indicates presence of old stellar populations; the second one (PC2) is a measure of the strength of higher order Balmer absorption lines, which varies between different spectral types of stars. Galaxies experiencing a starburst will move to the bottom left corner of the plot, while their gas supply is rapidly turned into newborn stars. As they use up their fuel and begin to evolve passively through the post-starburst phase, their massive, short-lived stellar populations will gradually die out, leaving the A and F-type stars dominating the total luminosity. As a result, those galaxies will move across the PC1–PC2 space, towards higher values of both 4000 Å break and Balmer absorption lines. The coloured points in the plot represent (post-)starburst galaxies selected using that method (Wild *et al.* 2010). For each galaxy, the colour corresponds to the time that has passed since the starburst event, which is also referred to as the "starburst age" (t_{SB}).

What can we see?

With an indication of the starburst age, we can move along the post-starburst time-sequence and study the morphology of galaxies in successive stages. Do they change significantly? How do those changes resemble the morphological evolution of post-mergers?

The first step to answering those questions is simply to look at the images of both young and old post-starburst galaxies and search for differences. It can be seen in figure 1 that galaxies that experienced a relatively recent burst in star formation (<100 Myr ago) tend to show more disturbance in their morphology than the older objects (t_{SB} > 500 Myr). In particular, the morphology of young post-starbursts is rich



4: Application of the standard morphology measures to post-starburst galaxies yields no obvious trends with the starburst age.

in faint irregular structures in the outskirts of those galaxies that show a significant resemblance to tidal features induced by galaxy mergers. Such structures make the galaxies appear more asymmetric and clumpy, when compared to their older counterparts.

The next question we should ask is whether this trend is consistent throughout all starburst ages. Figure 3 shows the result of an experiment conducted to answer that question – a visual inspection of 700 shuffled images of both post-starbursts and normal star-forming galaxies. Every image was inspected separately by three volunteers whose aim was to decide whether or not that galaxy is likely to be a post-merger. The classification process was based on one criterion: the presence or absence of tidal features. Each of the coloured lines in the plot corresponds to the fraction of post-starbursts in the sample identified as post-mergers by an individual volunteer, and the black line shows the combined result (i.e. only those galaxies for which all three volunteers agreed on the classification). The plot shows that, in fact, there is a clear and consistent trend throughout all ages, which suggests that post-starburst galaxies show fewer post-merger features as they get older. This result fits very well in the galaxy merger picture, where the merger remnant loses the tidal signatures as it evolves through the dynamically cold stages. Although the result of visual inspection of post-starbursts links their morphology with that of post-mergers, this does not mean that we are free to insert an equality sign between the two phenomena. Before drawing any conclusions, we need to find a way of quantifying the similarities and differences between them.

“The plot shows a clear trend, suggesting post-starbursts have fewer post-merger features as they get older”

Automated measures of morphology

Galaxy classification by morphology dates back to the work of Edwin Hubble in the early 20th century, when he introduced a sequence, commonly referred to as the Hubble tuning fork, which (along with some altered versions by others) has become the most widely used visual classification scheme for galaxies. Classifying galaxies visually is probably the most reliable method; however, it can be efficient only for relatively small samples of objects. In the era of large telescopes and extensive surveys, the amount of data being acquired every day makes this difficult. For this reason, the literature on methods for quantifying the morphology of galaxies has been growing for the past few decades.

In 1963, JL Sérsic introduced a mathematical law that accurately described the relation between the galaxy's surface brightness and its radius, which became a powerful tool in distinguishing between different galaxy types. It is now common knowledge among extragalactic astronomers that galactic discs usually have a Sérsic index, n, (one of the parameters of the model) of about 1, while spheroids tend to show a range of slightly higher values ($2<n<5$). Sérsic's law serves as a good description of the surface brightness for normal galaxies but, because it is a parametric method, it relies on an underlying model of the distribution of light, which makes it less suitable for studying irregular galaxies, where the luminous material does not form a well-ordered pattern.

An alternative approach is to consider non-parametric measures of morphology. Perhaps the most widely used methods in literature are the CAS volume (Conselice 2003) and the Gini-M20 space (Lotz 2004). CAS stands for concentration, asymmetry and clumpiness – three independently computed galaxy structural parameters. The first one, concentration of light (C), is an indication of whether most of the galaxy's light is contained within its central region or spread out across its surface. This parameter relies on the computation of the galaxy's growth curve radii, which are the radii that contain a given fraction of the total galaxy light, in particular those for 20% and 80%. The value of C is related to the ratio of those radii, and it tends to be higher in elliptical galaxies than in spirals. Asymmetry – A – is measured by rotating the image of a galaxy by 180° with respect to the original image and considering their difference: precisely, the flux from the residual image compared to the original one. The values of A range from 0 to 1 and tend to be low for objects showing symmetry under 180° rotation, such as most discs and spheroids, and higher for irregular galaxies with deviations from symmetric shapes.

The final CAS-parameter, clumpiness (S), measures whether or not the distribution of light in the galaxy is smooth across its surface. Its computation is similar to that of asymmetry, but this time the image being subtracted from the original is one with an appropriately reduced resolution. In this case the residual image contains information about the high-frequency structures in the galaxy's light distribution. Since spheroids are generally "smoother" than discs, where the regions of star formation can lead to a more "clumpy" appearance, they tend to have lower values of *S* than the latter.

The Gini-M20 method was introduced specifically to separate mergers from noninteracting galaxies. The Gini index had originally been used by economists to quantify the distribution of wealth across various countries in the world. In galaxy morphology, Gini is a measure of the inequality of the distribution of light within the galaxy. Gini = 0 means an equal distribution across all galaxy pixels in an image, and Gini = 1 points to extreme inequality (all light contained within 1 pixel). M20 statistics measure the spatial extent of the brightest galaxy regions, computed by measuring the second-order moment of the brightest 20% of the galaxy pixels. All of the above parameters are standard morphology measures of normal galaxies, with some being also suitable for tracing structural asymmetry and galaxy mergers. Therefore, it seemed like a natural root to be taken in the study of the morphology of galaxies with post-starburst stellar populations.

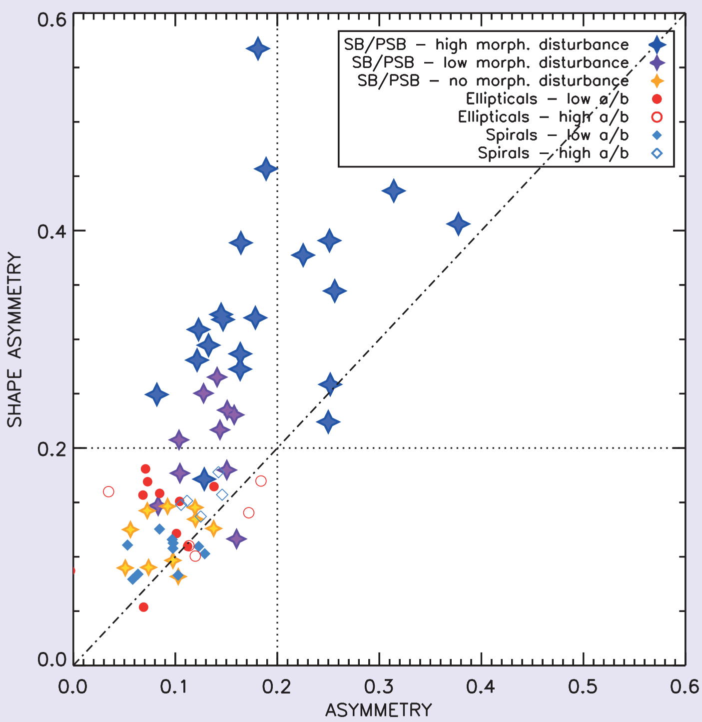
The plot in figure 4 shows all six parameters computed for a sample of post-starburst galaxies at $z < 0.07$ selected from SDSS DR7 (coloured data points in figure 2). The grey data points correspond to all galaxies in the sample, and the blue circles show the median values calculated in 100 Myr age bins. Surprisingly, apart from a slight decrease in the Gini index, all parameters fail to show obvious trends with the starburst age. But the results of the visual classification showed changes in morphology as the galaxies evolve through the post-starburst phase, and one would expect them to be reflected at least in some of the measures considered – in particular, in the measure of asymmetry. Why is that not the case?

"I have developed a method of object detection sensitive to the faint outskirts of galaxies"

Hidden in the dark

The problem seems to lie in the nature of the parameters and, in particular, their sensitivity to light. The parameters considered in this study are computed in a way that favours the information coming from the most luminous galaxy parts. This approach is well suited to distinguishing between discs and spheroids, where the key difference lies in the main, most luminous galaxy components, or to separate mergers from the noninteracting systems, in which case the former will show the presence of multiple (bright) nuclei. However, a similar approach does not prove useful in the study of morphology of post-mergers. The differences in the structure of galaxies in different post-merger stages are much more subtle and lie mostly in the faint outskirts of those objects. Their inner, brightest regions tend to show less disturbance and asymmetry than the outer parts, and yet it is those regions that make the most significant contribution to the values of the morphology measures.

A solution is to introduce a new way of quantifying galaxy morphology, a way that is designed to pick out signal from the faint outskirts of those peculiar galaxies in various stages of post-starburst. Such regions are not trivial to detect because of their low surface brightness, which means that they can be easily mistaken for noise. However, during the development of the image analysis tools for the purpose of this work, I arrived at a method of object detection that is sensitive to the faint outskirts of galaxies. I used this detection method to study the "shape" asymmetry (*A-shape*) of the two-dimensional projections of galaxies by means of a modified version of the standard asymmetry parameter. This new measure provides a robust method of distinguishing between normal galaxies and post-starburst galaxies showing signatures of post-mergers. Figure 5 compares the new approach with the standard asymmetry measure. It is evident that the new asymmetry parameter is more suitable for detecting the post-merger signatures in post-starburst galaxies: while only 35% of the investigated galaxies with strong post-merger features are picked up by $A > 0.2$, $A\text{-}shape > 0.2$ recovers 95% of the sample (it fails for a single galaxy with the tidal features forming an azimuthally symmetric pattern). The new parameter is also useful for detecting post-starbursts with minor asymmetric features: it recovers 60% of the studied sample, while the standard measure fails to detect any.



5: Comparison of the new "shape" asymmetry measure with the standard asymmetry parameter for samples of normal galaxies (elliptical, red; spiral, blue) and post-starburst galaxies classified visually into three subsets: those showing no morphological disturbance (yellow), and those with minor (purple) and major (blue) features characteristic to post-mergers. The dotted lines show a threshold value of 0.2 for both measures. (Pawlik *et al.* in prep.)

The new method of measuring galaxy morphology (Pawlik *et al.* in prep) is fully automated and will be used on samples of hundreds of galaxies to study how the morphology of post-starburst galaxies resembles that of post-mergers modelled via hydrodynamic simulations. ●

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