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Structural evolution of the most massive galaxies of the Universe

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Abstract

The most massive (10^{11} $M_\odot$) of the Universe are strikingly different than their local Universe counterparts. While in the present day Universe they consist of huge “red & dead” spheroids, they are better described as compact star forming disks at $z > 2$. I will explain how the photometric and spectroscopic evidence I gathered during my PhD shed light into this metamorphosis, and I will also highlight the more important works that have been produced since for the reader to have an accesible introduction to the present topic as of the end of 2014.

1 Introduction

My thesis, entitled “Structural evolution of massive galaxies in the last 11 Gyr”, was conducted in the University of Nottingham under the supervision of Ignacio Trujillo, Christopher J. Conselice and Alfonso Aragón-Salamanca. Its funding came from the Science and Technology Facilities Council (UK) and Institute of Astrophysics of Canary Islands (Spain) International Grant. Instead of following my thesis to the letter, which could be downloaded from

http://eprints.nottingham.ac.uk/12639/

I decided both in the SEA talk and in this conference proceedings, to put this work in context of what was already known at the time I started and what is already known at the time being. I would also suggest to the reader the perusal of the wonderful review by Ignacio Trujillo in [47] and consulting all the references therein. N. B. The definition for massive galaxies throughout this document is those galaxies with stellar masses greater than 10^{11} $M_\odot$.

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The galaxies are the bricks that compose our Universe. If one looks in detail, they have several subcomponents (stars, planets, dust, gas, stellar remnants, dark matter), but considering them as a whole entity, they constitute the tiny bright dots that bestow the Universe with all its magnificence. Our current paradigm of galaxy formation and evolution, ΛCDM, predicts that galaxies are assembled in a hierarchical scenario, whereby small primeval disks embedded within collapsing dark matter haloes are progressively merging and thus assembling more massive galaxies. When efficient Near InfraRed (NIR) detectors enabled us to investigate the high-z Universe a decade ago, it became obvious we still had many gaps in our knowledge. In particular, the most massive galaxies ($M_* \geq 10^{11}$ $M_\odot$) were already in place at $z > 2$ [36], being some of them "red & dead" even at these large cosmic distances [20, 43]. Strikingly, a large number of them had sizes $\leq$1 kpc, and this was utterly surprising as the local Universe seemed to be devoid of such objects.

2 The GOODS NICMOS survey (GNS)

Most of my thesis work was focused on studying this survey. The GNS was a large (180 orbits) HST programme (PI C. Conselice, for a full description consult [19]) for a total 60 images in the H-band using the NICMOS-3 camera in the H-band. It was the first large area (∼45 arcmin) NIR counterpart of the famous GOODS fields, which have become standard benchmarks on extragalactic studies. In order to optimize the scientific return, the survey strategy was envisaged in such a way to center the exposures on massive galaxies and other interesting high-z populations. As a result, the images contained 80 massive galaxies at $1.7 < z < 3$ (for which we were sampling the optical restframe at those redshifts) with a limiting magnitude of $H_{AB} = 26.8$ (5σ), and thus similar to present day HST WFC3 CANDELS observations but with a slightly larger (0.3 arcsec) PSF FWHM. Summarizing, we were dealing with the first statistically significant sample in the NIR of massive galaxies at $z > 2$ at that time, and many publications benefited from this unique dataset (please visit

http://www.nottingham.ac.uk/∼ppzgns/index.html

for the compendium of images, catalogs and scientific publications).

3 Extremely compact massive galaxies at high-z

The kick-off of this thesis was the size determination for the GNS massive galaxies. We chose to apply parametric fits to the surface brightness profiles of massive galaxies by using Sérsic functions [42]

$$I(r) = I_e \exp\left\{-b_n\left[\left(\frac{r}{a_e}\right)^{1/n} - 1\right]\right\}$$

where I_e is the intensity at the effective radius, and a_e is the effective radius along the semimajor axis enclosing half of the flux from the model light profile. The quantity b_n is a function of the radial shape parameter n (called the Sérsic index), which defines

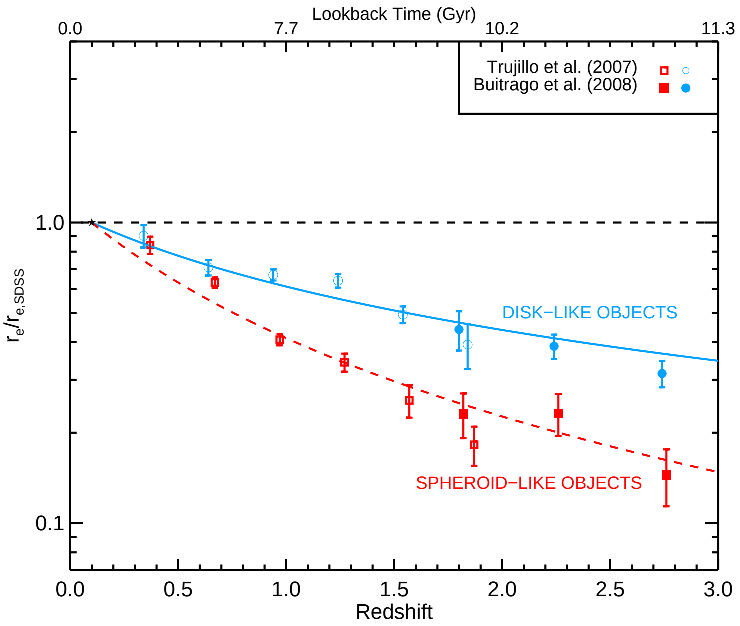

Figure 1: Size evolution of massive galaxies (10^{11} $M_\odot$) with redshift. Plotted is the ratio of the median sizes of galaxies in our sample with respect to the sizes of nearby galaxies in the SDSS local comparison (solid symbols). The results of [44] for systems at $0.2 < z < 2$ are overplotted (open symbols). The error bars indicate the uncertainty (1σ) at the median position. Image taken from [9].

the global curvature of the luminosity profile, and is obtained by solving the expression $\Gamma(2n) = 2\gamma(2n, b_n)$, where $\Gamma(a)$ and $\gamma(a, x)$ are, respectively, the gamma function and the incomplete gamma function. The sizes we provided were circularized, $r_e = a_e\sqrt{1-\epsilon}$, with ϵ the projected ellipticity of the galaxy. Traditionally, effective radii have been circularized to account for the uncertainty on the projection of ellipticals/spheroids due to their triaxiality, although for disks this is of course not necessary. The power of the Sérsic fits resides in the fact that, as a first approximation [39], one can identify disk- or late-type galaxies as those galaxies having lower values of the Sérsic index (n∼1) and early-type galaxies as those having a profile resembling a "de Vaucouleurs" shape (n∼4).

Our results could be summarized by Fig 1. To quantify the observed size evolution there, we calculated the ratio between the sizes we measured with respect to their same mass counterparts in SDSS and we obtained the median for each redshift bin. The $z < 2$ symbols come from [44] where the authors utilized ACS images and thus also sampling optical restframe. Massive galaxies are split according to their Sérsic index between disk- ($n < 2$) and spheroid-like ($n > 2$) objects. Regardless to which subset they belong, massive galaxies decrease their sizes continuously up to $z = 3$, where they exhibit (on average) ×3-5 smaller sizes than their local Universe counterparts, being this size evolution stronger for the spheroids. As a consequence, their 3D stellar densities are comparable with those of globular clusters, which are the densest objects in the present day Universe.

4 Morphological evolution at $0 < z < 3$

The present-day massive galaxy population is dominated by objects with early-type morphologies [1, 17]. However, it was unknown whether this was also the case at earlier cosmic epochs. Some preliminar investigations based on the ellipticity of massive galaxies were performed [51] suggesting an increase of disky objects at high-z but a thorough demonstration was lacking. We joined the massive galaxies in [44, 9] with a complete SDSS sample at $z = 0.03$ for a total 1082 massive galaxies, 639 of them having spectroscopic redshifts. We explored their morphologies using a combination of qualitative (visual morphologies) and quantitative (Sersic index) measurements. The reader interested on the details should go to [10], while I will summarize in the next paragraphs the main results.

We divided our visual classification into three main classes, namely early-type, late-type and peculiar (irregular and merging) objects. Splitting our sample according to their Sérsic index value (using $n = 2.5$ as the threshold between disk- and spheroid-like galaxies) we showed that, irrespective of the by-eye classification there was a steady decrease on the mean/median Sersic index value for massive galaxies over redshift (Figure 3 in the aforementioned paper). However, if one is to compare the frequency of Sersic index values with redshift (Figure 4 in that paper), we demonstrated (based on observations and simulations) that the high-z redshift Universe was almost devoid of high Sersic index galaxies. At decreasing redshift, we progressively see more and more massive galaxies with larger values of this Sérsic index parameter. Our interpretation for this shift towards larger values is that massive galaxies grow in an inside-out fashion, whereby their stellar outskirts (the wings of the surface brightness profiles) and galactic bulges become more prominent at lower z. It is important to note here that this is the explanation why (and why not in other occasions) there is not a one-to-one correspondence between Sersic index and visual morphology. High Sérsic index objects possess extended outer parts and peaky light profiles in their centers (as early-types galaxies do, specially the massive ones) while for spirals the profiles are exponential and there is much less light at large galactocentric distances. Sérsic index has then a well defined meaning, and should be regarded as a metric for the light concentration of galaxies, in both the very inner and external parts. Therefore it is a crude way (admittedly sometimes the only one) for devising the morphology of galaxies at high-z.

The key diagram of the paper is displayed in Figure 2. Here we plotted the percentages (top row) and number densities (bottom row) of massive galaxies according to their Sérsic index (left column) and visual morphology (right column) with redshift. There is a clear dichotomy between the high- and low-z Universe, whereby massive galaxies are better described by low Sersic indices at $z > 2$, whereas the situation is reversed at $z < 1$. Looking instead to the visual morphologies, both late-type and peculiars account for the 70-80% of objects at $z > 2$, and only since $z = 1$ massive galaxies are predominantly described by early-type galaxies. This is confirmed by using number densities. They also show that high-z disks are not the only progenitors of present day early-type galaxies. Whichever physical mechanisms are creating massive galaxies throughout the history of the Universe they are more efficient on building early-type/spheroid-like galaxies than otherwise.

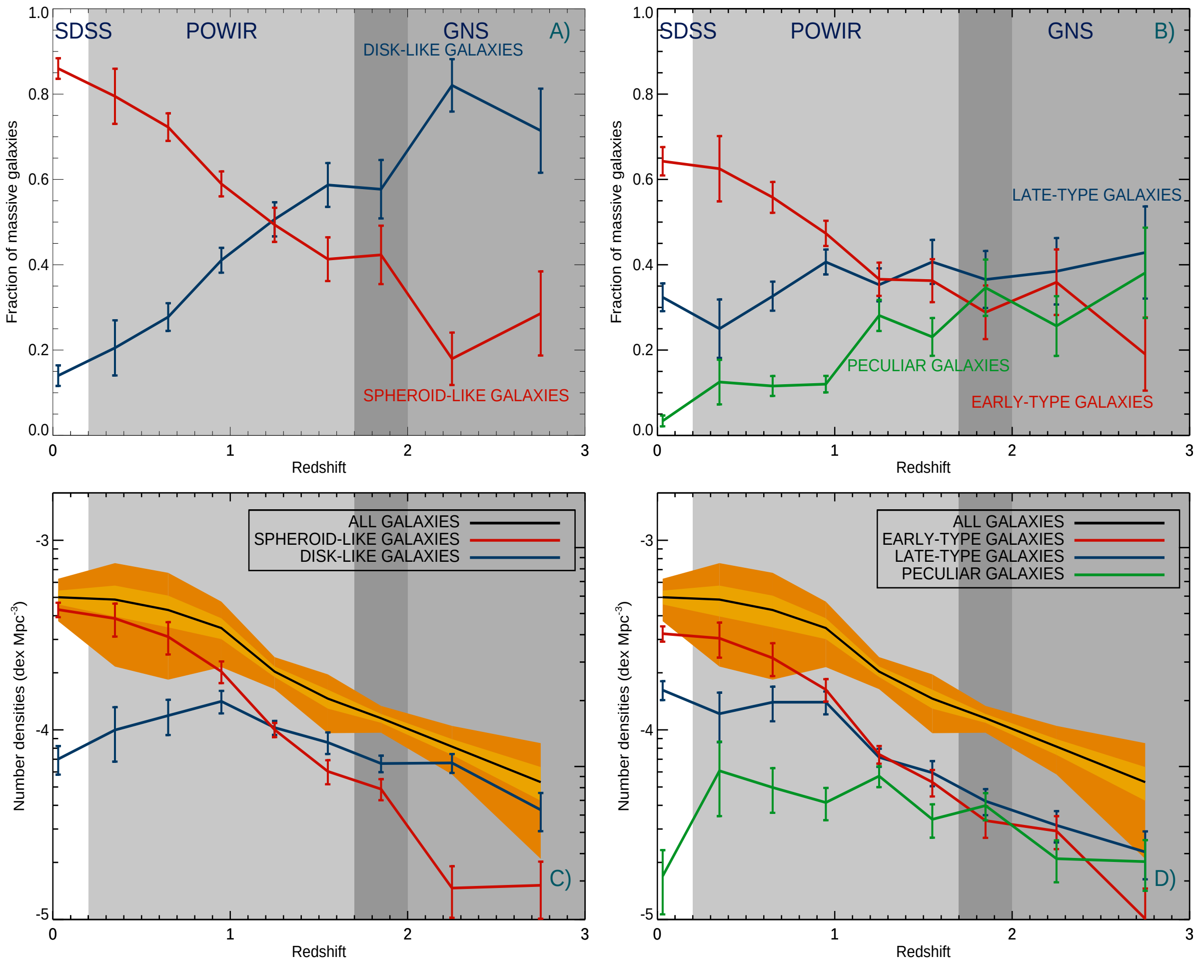

Figure 2: Panel A): Fraction of massive ($M_* \geq 10^{11} M_\odot$) galaxies showing disk-like surface brightness profiles ($n < 2.5$) and spheroid-like ones ($n > 2.5$) as a function of redshift. Different color backgrounds indicate the redshift range expanded for each survey: SDSS, POWIR/DEEP2 and GNS. Error bars are estimated following a binomial distribution. Sérsic indices are corrected based on our simulations [44, 9]. Panel B): Same as Panel A) but segregating the massive galaxies according to their visual morphological classification. Blue color represents late-type (S) objects and red early-type (E+S0) galaxies, while peculiar (ongoing mergers and irregulars) galaxies are tagged in green. Panel C): Comoving number density evolution of massive galaxies split depending on the Sérsic index value. The solid black line corresponds to the total number densities (the sum of the different components), with yellow and orange contours indicating 1σ and 3σ uncertainties in their calculation. Panel D): Same as panel C) but segregating the massive galaxies according to their visual morphological type. Image taken from [10].

5 3D spectroscopy evidence for the rotational support of massive galaxies at $z = 1.4$

However appealing and simple the development of the massive galaxy population appears to be (compact disks at high-z, large spheroids at low-z), we were relying only on the surface brightness profiles of our samples of massive galaxies to justify this assertion. To explore the consistency of this scenario, it was necessary to measure the dynamical status of these galaxies. Our group was granted 20h observations using the VLT/SINFONI 3D spectrograph. We targeted the 10 most massive galaxies in the POWIR/DEEP2 survey [12, 18, 34] with EW[OII]$>$ 15 Å, to secure their kinematic measurements, having thus a sample close to be solely selected by stellar mass. We refer the reader to our paper [11] for all the details concerning the analysis of our sample and the caveats in its interpretation. The seeing-limited observations were carried out in the H-band in order to track the Hα emission line due to the median redshift ($z \sim 1.4$) of our galaxy sample. On doing that, we were measuring the kinematics of the ionized gas, which may or may not follow the underlying stellar component of these galaxies. Having to observe one object at a time, emission line kinematics is the only feasible option if one wants to sample large numbers of objects, as corroborated by many other surveys (see [22]). Nevertheless, there is no reason to expect a disagreement, at least for relaxed systems.

After a careful data reduction and modelling, following the recipes in [21], we analysed the data cubes creating maps for the rotational velocity, velocity dispersion, [Hα] flux, [NII] flux, signal-to-noise and other ancillary information. We constructed the anisotropy plot for our sample (V_{max}/σ within the effective radius versus the galaxy's ellipticity) and we showed that all the members in our galaxy sample lie above the rotational support curve. However, as our kinematical information comes from gas kinematics, it is more interesting to focus our attention into Figure 3, which we supplemented with two typical rotational velocity and velocity dispersion maps from our sample. In the left side, we plot the rotational velocity versus the velocity dispersion for our sample of massive galaxies. We added up here other published objects with similar masses and redshifts as those in our sample, and studied with the same instrument. Again, all the objects have rotational velocities which exceed (usually several times) their velocity dispersions. Joining each object's kinematics with their visual morphologies in the K-band and Hα, we concluded that half of our sample were rotating disks, in agreement with our photometric expectations (Fig. 2). This is a factor of approximately 2 higher than what is observed in the present Universe for objects of the same stellar mass.

Considering as a whole both our sample and the rest of massive galaxies in other surveys, the fact that we always find large rotational gradients is an indication of an early rotational support and hence gravitational equilibrium. It is also noteworthy than these objects do not usually show a clumpy nature like less massive galaxies at the same cosmic distances. Consequently, it seems than massive galaxies acquire their rotational support and a defined morphology earlier than less massive galaxies, and thus accounting for a “morphological downsizing”.

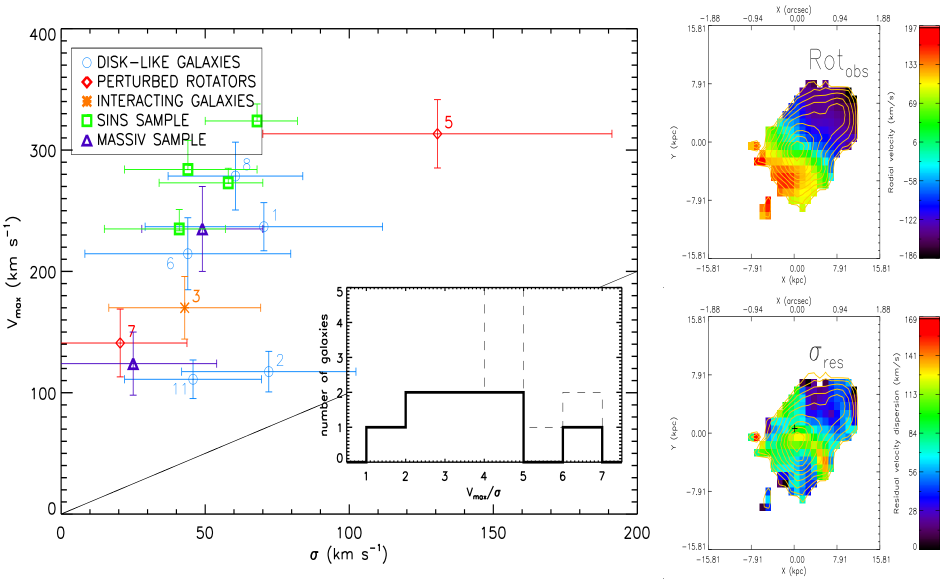

Figure 3: Maximum rotational velocity versus velocity dispersions for the massive sample in [11]. We also show the radial and velocity dispersion maps for one of the massive disks.

6 Other parallel projects and brief outline of the state-of-the-art as of 2014

At this point we should step out for a second and look at the overall panorama. In the local Universe massive galaxies are, broadly speaking, huge early-type objects that barely rotate. The more massive a galaxy is, the closer it follows this description. On the contrary, at high-z, they are (on average) compact disks with a strong evidence for a rapid rotational nature. My thesis measured those changes in a reliable and quantitative way, both using deep NIR photometry and spectroscopy, trying to remove any possible bias from cosmic variance or using only UV restframe images, as it has been done in the past. Moreover, I have collaborated during my thesis in many projects on the nature of massive galaxies. I will proceed to summarize them along with other crucial contributions that have improved our understanding (to date) of this fascinating galaxy population.

As stated before, massive galaxies are regarded as “red & dead” objects in the nearby Universe. How were they in the past? I actively participated in several works highlighting their star forming nature at high-z based on our GNS data and its ancillary multiwavelength information [15, 2, 53]. There is a growing consensus about massive galaxies undergo a very strong starburst phase at high-z [3] (linking them with the sub-mm galaxy population [40]). This would have triggered AGN activity which potentially quenched any further star formation, and after this moment, these galaxies would evolve passively [35, 24].

In the nearby Universe, the ATLAS^{3D} survey [13] has undoubtely make an impact on our current view of early-type galaxies. As we mentioned in Section 4, two thirds (not all) of massive galaxies are early-types at $z = 0$, and this survey observed the 260 closest ones using the SAURON integral field spectrograph, along with a dedicated campaign in other telescopes for fully characterizing these objects. It has set a clear distinction between slow- and fast-rotators, being the first the most massive and velocity dispersion dominated objects, while the second are more isotropic and lower Sérsic objects. This might tell us important lessons about different pathways in order to form a massive galaxy.

Other interesting aspect about massive galaxies is that are used to be found in high density environments in the local Universe. To ascertain whether this is also the case at high-z, one must characterise not only the massive (and thus luminous galaxies) but their less massive and fainter counterparts. Our GNS works [27, 28] were inconclusive on this regard because of the small area covered, and these studies remain challenging even for WFC3 observations.

Adaptive optics deep K-band images of the very compact galaxies have been achieved, confirming their very small sizes [14]. Larger samples of NIR images have set the mass size relation at high redshift not only for the high mass population but up to fairly low mass objects [8, 52]. There has been a significant increase on the number of spectra obtained for high-z massive galaxies [16, 50, 4, 5]. The study of their absorption lines has helped on discerning massive galaxies are truly massive (because of their large dynamical masses) and that there is a mild evolution on the decrease of velocity dispersion over redshift.

The galaxies which are already massive at high redshift should become the cores of brightest cluster galaxies in our galactic neighbourhood [29, 6]. Minor mergers must be the main drivers of this evolution [7] because of the scarcity of massive galaxies which translates into few major mergers [30]. It is still a mystery whether the size evolution and the quenching of star formation are produced by the same mechanism, and to what extent merging has to do with it. As stated previously, AGN feedback is the likely culprit for switching off star formation but thus far its importance, from an observational point of view, remains unclear [46].

Finally, the quest for finding compact massive galaxies at low-z has puzzled the extragalactic community. Searching in SDSS, [45] found ∼30 galaxies with $r_e < 1.5$ kpc and $M_{\rm stellar} > 8\times10^{10}\ M_\odot$. The surprise came when it was discovered these objects host young (∼2 Gyr) stellar populations. A number of observational and theoretical studies [37, 38] pointed out that some massive galaxies should remain intact from the high redshift Universe. Further exploration have yield only a handful of “high-z relics” [48, 41] (massive, compact and old galaxies). To add more mystery to previous conundrum, the careful study of their spectrum show a clear hint for a bottom-heavy IMF, which has been confirmed in the center of other massive galaxies both at $z = 0$ and $z = 1$ [25, 33]. The kinematics seem also to be most interesting: very large (∼300 km s^{-1}) rotational velocities and velocity dispersions [49, 23], making them a completely new phase on the galaxy formation.

7 Future projects and some final remarks

As the reader can see, there are still many questions unanswered for a global understanding of this massive galaxy population. These galaxies are, by definition, the most luminous "normal" galaxies at their redshift and, as such, they constitute perfect benchmarks to test ΛCDM predictions. Moreover, the dramatic transformations they undergo over redshift help us isolating which physical agent is playing a role at a given moment in their evolution.

The present thesis was a small (albeit necessary) step in their research. At the time being, my goal is understanding the contribution of "the hidden Universe" into their growth and evolution. What do I mean by "hidden Universe"? We know that surface brightness dimming plays a role not only for our understanding of massive galaxies but to comprehend any given object at high-z. Its contribution increases by $(1 + z)^4$, or in other words, by dimming the magnitude of extragalactic objects by a factor $-10 \times \log_{10}(1 + \mathrm{z})$. As a consequence, minor merging is poorly constraint at low-z (because of intrinsic faintness), while at $z > 3$ even the outer parts of massive objects become buried under the noise of standard observations (cf. CANDELS $\mathrm{H_{AB}} \sim 27$ $\mathrm{mag_{AB}}$ limiting magnitude). Another hurdle is that the 4000 Å break surpasses the H-band limit at these redshifts, and hence we sample the UV restframe coming from galaxies, unless we analyse large PSF (2") Spitzer IRAC images. We must also bear in mind that the large amount of gas available at these cosmic distances likely increase their star formation and as a result, their morphologies in the UV at this redshift range might be very different from the total underlying stellar component.

I am conducting several projects in order to tackle all these problems. Firstly, I created a software package within the European ASTRODEEP[3] FP7 programme to deconfuse IRAC data using standard tools such as SExtractor or GALFIT, apart from helping in the development of TPHOT (new generation TFIT code; Merlin et al. 2015 in preparation). Secondly, I am analysing the deepest image ever taken (the Hubble Ultra Deep Field) in order to dissect the few massive galaxies which happen to be in this very reduced area but extraordinary deep survey. Figure 4 show the contour plot for two galaxies within our sample, where we are able to track the surface brightness of these galaxies up to 31 mag arcsec^{-2}, i.e., >25 r_e effective radii for every object. We also want to highlight the large number of satellites which will potentially merge with these massive galaxies increasing both their masses and sizes (see also [31, 32, 26]). In addition to that, very deep K-band surveys enable us to push optical restframe studies up to $z = 4.5$, also confronting the information coming from shorter wavelengths. I hope that the reader will agree with me about no individual piece of work will solve the mystery about massive galaxies in the near future. A panchromatic, specially using spectroscopy, effort is mandatory in order to understand exactly the Physics of what it is actually occurring when these objects go through their metamorphoses. The effects of an AGN phase for massive galaxies should be addressed, the ratio of minor and major mergers for the size and morphology change must be constrained, the old stellar populations inspected with better models, the initial very dissipative star forming period (and its IMF) physically understood and the angular momentum loss between the high- and low-z populations properly explained.

I would like to finish stating again that this thesis prize is, more than a personal award, an acknowledgment by the Spanish Astronomical Society for the contributions of Spanish astronomers to this field of research. The quality level and the number of works that we have produced as a community have been superb. I am sorry I could not mention in this short

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[3] http://www.astrodeep.eu/

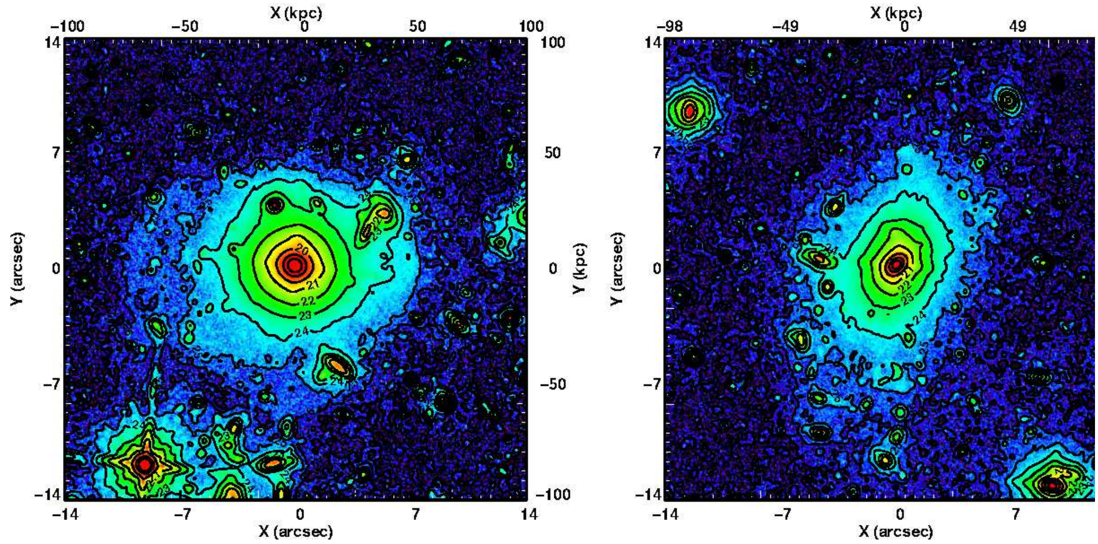

Figure 4: Surface brightness 2D maps (and contours) for two massive ETGs at $<z>$=0.65 in the HUDF12 H-band data. It is noteworthy the large number of asymmetries and galaxy satellites.

essay all the contributions which would deserve credit for this endeavour to comprehend more about the Cosmos we live in.

One of the most celebrated “Greguerías” by our own Ramón (Ramón Gómez de la Serna) says that, if at some point the astronomers stop watching the stars, they would change their place every single night (“Si no las vigilasen los astrónomos, las estrellas variarían de sitio todos los días”). Massive galaxies sometimes appear to be capricious objects, in the sense that after being studied meticulously for the last few years, the explanation for their properties remain elusive. Another beautiful example showing us that the Astronomy still fills our mind with awe and new questions.

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