# Characterization of a Jellyfish Galaxies Population in X-ray Clusters Surveys

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# Abstract

This thesis work involved the characterization of a population of confirmed Jellyfish galaxies within hosts with a wide range of mass, including groups and clusters of galaxies, with masses $M \geq 10^{13} M_{\odot}$. The hosts were observed by X-ray surveys MCXC and RXGCC, both were used used to collect data from galaxies observed with the Subaru visible telescope from Hyper Suprime Cam Survey Public Data Realese 3. High-quality RGB images were generated from these observations for the identification and confirmation of galaxies undergoing Ram Pressure Stripping (RPS) by a visual inspection employed for experts and with citizen science component using the Galaxy Zoo portal that allowed us to classify all the main sample, while a sub-set of galaxies were classified by experts. Our analysis in the confirmed Jellyfish samples revealed a slight correlation in the occurrence of Jellyfish galaxies with increasing host mass, with an approximate 5% change. Additionally, a correlation was found between the angular distance Jellyfish galaxy to Host centre and parameters of the intracluster medium's (ICM) gas density distribution, $\beta$ and $r_{core}$. Hosts with concentrated density had Jellyfish galaxies closer to the center, while those with more extended and flatter distributions don't present Jellyfish galaxies at nearby distances to the hosts centre. The distribution of galaxy tails was also studied, indicating that tail direction frequently points away from the cluster when hosts are more massive, while tail directions frequently align with the group when they are less massive hosts. This preliminary and general description is based on the analysis of 333 galaxies voted on by experts and an official sample of 5252 galaxies, which will be incorporated for further investigation.

# Acknowledgment

Firstly, I would like to extend my heartfelt gratitude to Professor Rory Smith, the guiding teacher of this Thesis. From the beggining he has provided a lot of support in helping me introduce in the scientific research as an undergraduate student. His guidance, advice, and crucial assistance have been crucial in my way to understand, improve and advance in the research objectives and my skills. His consistent emphasis on perseverance, and active involvement have been fundamental throughout the development of this work.

I also wish to express my sincere appreciation to Professor Yara Jaffé and her entire team, who generously offered invaluable feedback and facilitated the inclusion of my galaxy sample in the Galaxy Zoo for classification. Also to all the professors and researchers who helped me in the classification.

I extend my gratitude to all the professors who supported and encouraged my motivation to delve into scientific research. The advice, teachings and confidence in my research abilities have been a motivation to continue learning and improving.

Finally, I would like to convey my deep gratitude to my family and friends. The support has been a constant throughout the creation of this thesis and all my undergraduate journey in Astrophysics at the university.

In summary, this work would not have been the same without the guidance, support and collaboration of these exceptional people. I am deeply grateful for their contributions and their influence on my academic and personal growth.

Sincerely, Ignacio Quiroz Carmona

# Contents

# Chapter 1

# Introduction

Throughout the universe, galaxies are clustered and hosted in a variety of structures, ranging from groups with masses less than $10^{14}M_{\odot}$ to galaxy clusters whose masses are greater than $10^{14}M_{\odot}$. [1] These hosts exhibit a wide types of properties important to model the intracluster medium ICM based on X-ray brightness measurements and ICM density and their spatial distribution (Mohr et al. (1999)). The ICM composed mainly of hot gas inside the host interacts with the contained galaxies and drives the transformation and evolution of galaxy properties, indeed the environment affects directly with galaxy properties and its evolution, Peng et al. (2010). Understanding how these interactions vary in galaxy groups and clusters contribute for studying the transformation and evolution of galaxies in the environments of hosts where they are located, Hester (2006), Roberts et al. (2021). The so-called Jellyfish galaxies within their host are known by the gas stripping due to hot gas pressure from the surrounding ICM, Jaffé et al. (2018), giving the appearance of perturbed asymmetric disks and prominent tails due to the pressure felt by the galaxy's gas disk as it moves at through ICM, Smith et al. (2022), it is possible to study the phenomena with visible images of galaxies and see how the galaxy morphology is according to how the surrounding environment looks like. The described interaction, called ram pressure stripping RPS, is caused by the pressure of the ICM and scales with the density of the hot gas in the ICM and the square of the galaxy's infall velocity $P = \rho v^2$, Gunn and Gott III (1972). RPS affects the evolution of galaxies, it can quench main star formation in the blue gaseous disk by extracting gaseous material and conduce it in the star-forming gas of their tails, these effects can be studied from continuous radio surveys of the HI line Ignesti et al. (2023) but also it is possible to study the Ram pressure effects using study in visible wavelenghts, Roberts and Parker (2020).

There are lot of interactions different than Ram pressure that could be happen in a galaxy cluster and produce similar features that RPS, here is brief description of some. Harassment, refers to a rapid succession of collisions between galaxies, which can result in disruption and alterations to their structures. Tidal interactions, on the other hand, occur when two or more galaxies come into close proximity, and the gravitational forces between them cause significant distortions, often leading to the formation of prominent tidal tails. Moore et al. (1999). Ram Pressure Stripping, in comparison, involves the interaction between the intracluster medium (ICM) and an infalling galaxy. As the galaxy moves through the dense medium, the pressure exerted by the ICM can strip away the star-forming gas from the galaxy's blue

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[1] In this work we will refer to groups and clusters of galaxies as galaxy hosts.

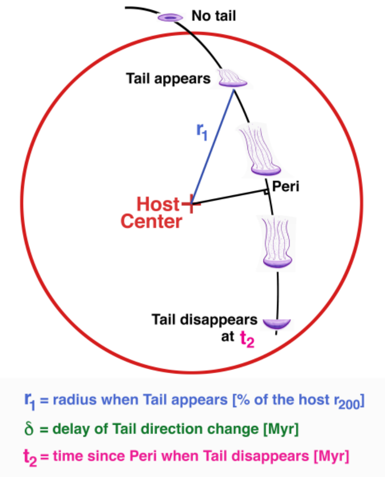


Figure 1.1: Schematic cartoon showing the tails formation in a infall galaxy inside a dense medium of host. Initially tail does not appear but in a insertion into a denser medium the RPS becomes more effective and tail appears while the galaxy moves through the host's ICM gas environment, tails remain for a period of time until their disappearance. Plot are found in Smith et al. (2022) (Thanks to Rory for let me use this schematic illustration).

disc, leaving behind isolated and quiescent galaxies with disrupted shapes, tails, or remnant gas that may continue to form stars for a period of time, see a scheme cartoon useful to understand the situation. It is important to distinguish Ram Pressure Stripping as a type of interaction between the galaxy and the surrounding medium, while harassment and tidal interactions are interactions between galaxies themselves.

It is of great interest to ask how RPS vary significantly in different environment contexts and property studied, affecting the Jellyfish galaxy fraction in low or high-mass hosts, the tail direction, or the spatial distribution. This allows us to study how correlated the host properties are with the frequency of Jellyfish found. Therefore, in this work, we collected information from groups and clusters observed in the RXGCC (Xu et al. (2022)) and MCXC X-ray surveys (Piffaretti et al. (2011)), as well as deep observations obtained from the Public Data Release 3 (PDR3) of the Hyper Suprime-Cam (HSC) telescope, Aihara et al. (2022). Our goal is to characterize the population of jellyfish galaxies in these clusters and groups based on host properties measured by both X-ray surveys and look for a correlation between properties and Jellyfish confirmation. Looking for answers about if in visual observation of Jellyfish galaxies are a relation between the occurrence and the host mass in a similar way than radio continuum, or if the model's parameter of density are related with spatial distribution of Jellyfish and Ram Pressure effects or if tail directions are related also with the surrounding environment.

Due to the growing search for objects such as Jellyfish galaxies and the development of new techniques that actually detect more and more candidates, it is really necessary to introduce new tools that help classify these objects, the best techniques are Machine learning algorithms. and also citizen science, which through sophisticated statistical analysis techniques it is possible to help the scientific community interested in the search for these objects. In this sense, in this work we test and compare Jellyfish results classified by experts and people in order to work with a huge number of galaxies that will be calibrated using expert criteria.

We will present in Chapter 2 the methodology, in terms of data analysis employed to collect a galaxy sample of images from the HSC catalog search data, discuss on technical measurement issues, as well as the process of creating RGB images for a posterior visual inspection driven by Galaxy Zoo classifiers for public and experts. We will also make a description of the hosts used for a galaxy target mapping within the main host.

In Chapter 3, we will present the results obtained by both experts and the general public classification comparing how much agreement and disagreement are in galaxies classified. We will analyze and tested the reliability of public classifications compared to expert classifications by those Jellyfish that are confirmed using criteria of selection based on the galaxies morphological features voted by giving a method of combination that can help us to choose those confirmed Jellyfish from the visual inspection results.

Subsequently, in Section 4, we will compare the results from confirmed Jellyfish Galaxies frequency versus their host mass, as well as how much affect the X-ray compactness properties of hosts such as $\beta$ profile and $r_{core}$ to how distant are those Jellyfish confirmed. Finally a general description of tails direction is discussed to understand how different is tail direction in their hosts.

In the final section, we present the conclusions of the work, summarising the main results, findings, issues and future projection for this work.

It is important to note that in this study, we assume the standard cosmological parameters according to the Lambda Cold Dark Matter ($\Lambda CDM$) model derived from the Planck 2018 mission Aghanim et al. (2020).

# Chapter 2

# Construction of galaxy samples

In this section, we will present the methodology employed to generate visible images of galaxies identified as candidates to be Jellyfish galaxies. We describe the steps on the collection of galaxies within the various host, such as clusters and groups, which are observed by X-ray surveys called MCXC and RXGCC, then overlapping with the Hyper Suprime Cam telescope observations. The election to use data from HSC-Public Data Realese 3 is based on its high-resolution capabilities for observations at deeper distances, includes over 600 square degrees of multi-band data at the nominal survey depth. Surpassing in terms of deep quality to other visible data sources such as SDSS or similar surveys. We display in figure 2.1 a simple comparative for a galaxy field visual image mounted by HSC visible filters i,g and r, with another image for same galaxy but in SDSS-DR7, where it is evident that visible features and environment surrounding is more detailed and less faint for HSC-PDR3 than SDSS, for that reason we selected HSC data because allows us to get better resolution for our galaxy images at the moment to make the visual inspection and recognize as many features about the galaxy structure and the environment around as well.

From these observations, we generated RGB images that provide close visual representations of the galaxies, highlighting their morphological features. Additionally, we obtain wider field-of-view images that allow for the exploration of the galactic environment, facilitating the identification of potential signs of ram-pressure interactions in the surrounding field.Typically Jellyfish galaxies are a type of galaxy that shows a blue disk structure with asymmetrical aspect, rich in gas stripped like a tail-shape and they are usually blue objects from blue cloud and could include also Green Valley. Thus all candidate galaxies were chosen using a color cutoff because this is a way to filter our objects of interest at any distance, since color is a distance-independent measure, is an excellent way to ensure the filtering of objects that in a color-magnitude diagram would be blue cloud and green valley, we will discuss later the technical complications of why we did not select galaxies using color-magnitude diagrams, but using this color filtered method we maximise as many photometrical blue objects as possible. Then they candidates were voted by Galaxy zoo making a general visual inspection that helps us to detect all features related with the shape of galaxy and take account the environment around it. Each galaxy is labeled with its respective images, and additional information such as coordinates, photometry, photometric redshift, Kron radius, all given by Public Data Realese 3 of HSC, and also, other properties related to the host, provided by

Figure 2.1: Simple comparison for a galaxy field observed using visual images built from visible filters in HSC-PDR3 on right panel and SDSS-DR7 on left panel.

the corresponding X-ray surveys.

This methodological approach allows us to obtain a extensive and detailed dataset that will be used for the analysis and inspection of the physical properties of Jellyfish galaxies in the context of their galactic environment and their X-ray description of the gas density within the cluster or group in which they are located.

## 2.1 Hosts description

RXGCC, Xu et al. (2022) and MCXC, Piffaretti et al. (2011), are selected as main X-ray surveys used in this study, both catalogs provide lots of valuable information on clusters and groups measurements, such as their mass M500, flux F500, luminosity L500, among others. In the case of RXGCC, they also provide information on the compactness of the gas density distribution in the host, based on the beta parameter and core radius, being this X-ray survey the most important in terms of the compactness data given by them, that is useful to make a model on the density gas distribution, eq 2.1, known as King's approximation which is an analytical approximation of an isothermal sphere measured by X-ray surface brightness profiles of galaxy clusters, (King (1962); Sarazin (1986) see eqs. 3.5 and 3.7) . Therefore, all of clusters observed by both surveys are redirected to the RXGCC observations, in order to get more details in compactness.

$$\rho_g(r) = \rho_{g,0}\left[1 + \frac{r}{r_{core}}\right]^{-3\beta/2} \tag{2.1}$$

Initially, we extracted all clusters according a mass-cut $M_\odot \geq 10^{13}$ and a Redshift cut $Z \geq 0.2$, figure 2.6, in order to obtain clusters and groups in different mass-range and to obtain as many galaxy targets within the host as possible, maximizing the possibility to find Ram Pressure signs in the environment of different masses as study of Roberts et al. (2021) suggested. Besides it's crucial the redshift cut because is a way to improve visible morphological features in the RGB images, otherwise, all images would be faint and poorly resolved. Then, we identified all clusters in X-ray surveys that are observed also by the HSC telescope, specifically in Public Data Release 3 (PDR3)-Wide 3 version Aihara et al. (2022). This was achieved by performing an overlap between the footprints of the HSC visual filters and the groups or clusters detected by MCXC or RXGCC within these regions, it is shown in figure 2.2.

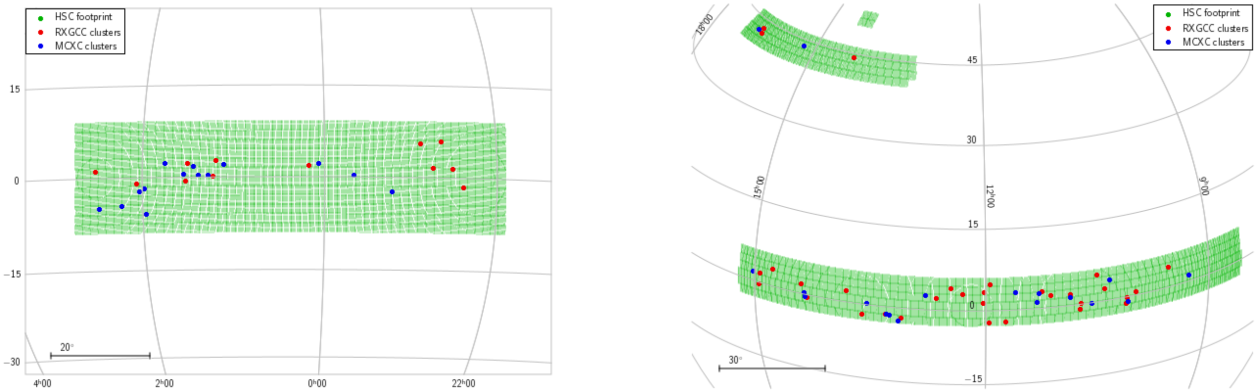
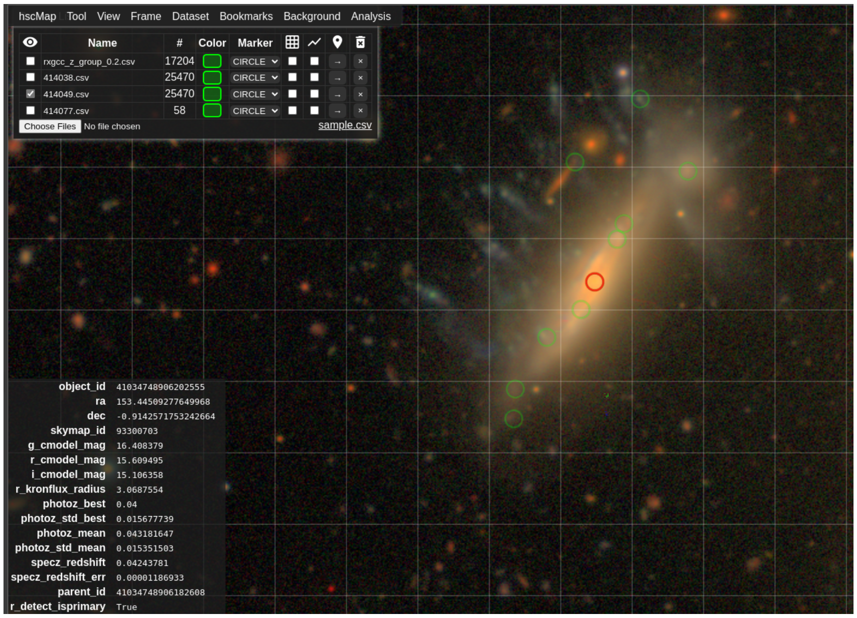


Figure 2.2: Sky plot showing the position on sky of hosts from X-ray surveys RXGCC and MCXC, also the green shaded region representing the triple footprint corresponding to the covered area by PDR3-HSC visible filters r, g and i

## 2.2 Counting galaxies inside clusters

Once the HSC-observed objects were identified, we determined the galaxies that were effectively located within 2 times the virial radius of the group. To achieve this, we converted the R500 radius (commonly used in X-ray studies) to R200 using a reference value $r_{500}/r_{200} = 0.61$–$0.65$ for $c = 2 - 4$ found in Laganá et al. (2013). The choice of twice the virial radius $r_{200}$ was based on the probability of finding Jellyfish galaxies at a certain radial distance from the center of the group, as Jaffé et al. (2018) suggested to find based on the phase-space diagram results in their figure 7. By computing using TOPCAT the diameter angle size $d_A = r/(1+z)$ for a flat universe in a standard cosmological frame, we projected the halo's radius onto the sky and then count the galaxies within the virial radius converted into arcsecond units. This was achieved using an SQL search algorithm present in the data tables of PDR3-WIDE. The algorithm, known as conseSearch, searched for galaxies located



| 👁 | Name | # | Color | Marker | ▦ | ∕ | 📍 | 🗑 |
|---|---|---|---|---|---|---|---|---|
| ☐ | rxgcc_z_group_0.2.csv | 17204 | 🟩 | CIRCLE | ☐ | ☐ | → | × |
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| ☑ | 414049.csv | 25470 | 🟩 | CIRCLE | ☐ | ☐ | → | × |
| ☐ | 414077.csv | 58 | 🟩 | CIRCLE | ☐ | ☐ | → | × |

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|---|---|
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| ra | 153.44509277649968 |
| dec | -0.9142571753242664 |
| skymap_id | 93300703 |
| g_cmodel_mag | 16.408379 |
| r_cmodel_mag | 15.609495 |
| i_cmodel_mag | 15.106358 |
| r_kronflux_radius | 3.0687554 |
| photoz_best | 0.04 |
| photoz_std_best | 0.015677739 |
| photoz_mean | 0.043181647 |
| photoz_std_mean | 0.015351503 |
| specz_redshift | 0.04243781 |
| specz_redshift_err | 0.00001186933 |
| parent_id | 41034748906182608 |
| r_detect_isprimary | True |

Figure 2.3: Galaxy image showing the problem of duplicated sources in a size object larger than 1 arcmin.

at a specific radial distance from the center of the group up to a radius of 2 times the virial radius within a circle on sky.

After the identification of the galaxies, we had problems related to duplicated and blended sources that arose due to the detection depth of the HSC telescope, which detects many parent sources in close and large galaxies whose diameter is larger than 1 arcmin, this was consulted directly with the people in charge of PDR3, arguing it is quite possible that the analysis software thought the whole galaxy as background and subtracted it from the image before detecting and measuring objects.

In some cases, multiple sources appeared within main target galaxy detection, therefore we had to perform an algorithm to remove as many of these duplicate images in large and nearby galaxies as possible. To do this, we created a simple algorithm considering for a main target galaxy the relative distance between the detected double sources, with the goal of identifying those duplicated sources in each parent galaxy target. We selected only that brightest detection source, which was normally centered on the galaxy nucleus. This algorithm allowed us to determine only one image for all those largest and closest galaxies with duplicated sources. This challenge imposed by the deep observing capability of the HSC telescope was that some duplicate sources had differential photometry (see figure 2.3) in sections or parts of the parent galaxy, as the photometry was adapted to the more distant object, making it impossible to calculate accurately the apparent magnitude of the whole parent galaxy. Thus, using the magnitudes that HSC provided for a significant part of our galaxy collection and correcting that photometry by evolution using Yang et al. (2007) equation and K-correction computed by TOPCAT for SDSS for filters r,g and i (except for the most massive galaxies with radii larger than 1 arcmin), then we made a $g - r \leq 0.8$ color cut to select as many blue, gas-rich, star-forming galaxies as possible, because it was a way to include those objects independently at a distance. However a better practice in the future will be performance well for ourselves the photometry and use of color-magnitude diagram cut to select objects in green valley + blue cloud regions to have greater security in the type of objects that we are selecting.

## 2.3 Creation of RGB galaxy images

Once the galaxies were identified, FITS files for the i, g, and r bands were obtained from the Image-Cutout service on the Hyper Suprime-Cam (HSC) website. By combining the data from these three visible filters, we created RGB images that effectively reveal the galaxies and their morphology.

For each galaxy, two versions of the images were generated, see image 2.4. The first version, referred to as the close image, allows for the clear identification of morphological features. The close images were produced by rescaling the original images using the photometric Kron radius [arcmin], which provides an estimate of the galaxy's size. Specifically, the close images were created by extending the image boundaries to 2.5 times the Kron radius.

The second version, known as the wide image, provides a far and wide view of the galaxy's surroundings. This wider perspective is valuable for identifying potential interactions beyond Ram Pressure Stripping, such as tidal interactions between pairs of galaxies or noticeable morphological asymmetries resulting from harassment. The wide images were generated by further extending the image boundaries to 17.5 times the Kron radius.

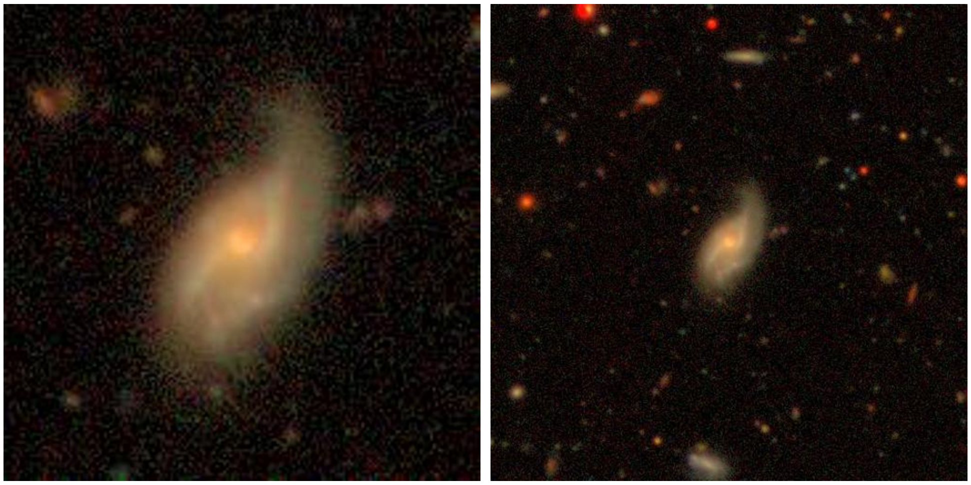


Figure 2.4: Both plots show a RGB galaxy image mounted in its two versions from candidates to be JF. *Left panel* shows a narrow and close perspective and *right panel* shows a far and wide view for the galaxy and environment around it.

The RGB images were constructed using the algorithm described in Lupton et al. (2004), which is an Astropy.visualization module implemented in Python called `make_lupton_rgb`.

This module simplifies the creation of RGB images by using the FITS files containing observations in the visible filters and parameters for fix the brightness and contrast of the image you want, so we try setting different parameters for adjusting the brightness and contrast of the desired image, choosing those that highlight the brightness of the disc to identify the shape well, but also that would allow distinguishing the environment around it. The resulting visible images included each candidate Jellyfish galaxy and we double checked by a visual inspection to remove remaining duplicate elements from blended sources discussed before. These images were then classified based on the morphological characteristics of the galaxies to determine if the observed features corresponded to manifestations of Ram Pressure Stripping.

The described methodology allowed us to obtain visually informative images of the candidate Jellyfish galaxies, facilitating further analysis of their morphological features and the potential influence of Ram Pressure Stripping.

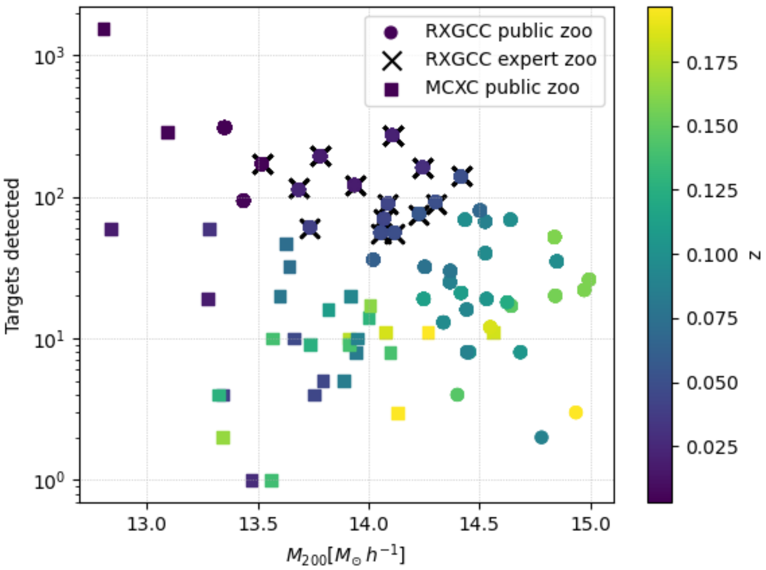


Figure 2.5: The plot illustrates the number of galaxy targets detected by `ConeSearch` algorithm in hosts from RXGCC and MCXC X-ray surveys, considering all host mass range and painted by a color scale indicating redshift. The cross markers correspond to the total number of targets in the expert zoo dataset, while the circle markers represent detections for the RXGCC and a square for MCXC clusters in the public zoo dataset. (Expert and public zoo data-sets are discussed completely on section 2.4 but please note that the selection of galaxies for the expert sample considers 20% of the total confirmed targets. Therefore, this plot displays the entire population, not just the 20% subset.)

## 2.4 Expert & Public galaxy Zoo sample

Throughout this work and subsequent analyses, we will be working with a publicly available galaxy sample, referred to as the Public Zoo. This sample consists of all the galaxies detected within the hosts obtained from the previously discussed mass and distance ranges. The Public Zoo comprises approximately 5254 candidate galaxies, with 2777 sourced from RXGCC and 2477 from MCXC. These galaxies were publicly classified through the Galaxy Zoo platform. Specifically in the Morphological Classification section we will emphasis in vote handling and criteria.

For this undergraduate thesis, a more manageable sample, referred to as the Expert Zoo was created as a subsample from the public zoo. The Expert Zoo was constructed by reducing the initial mass range to include only hosts with masses $M_\odot \geq 10^{13.5}$, and a redshift cut of $z \leq 0.05$ as it was discussed in Cluster's description section. This selection process resulted in a total of 5 groups and 9 clusters. In order to ensure unbiased and homogeneous comparisons, we have taken 20% of the randomly selected targets, which they are extracted from every group and cluster resulting by those criteria employed for expert zoo. The Expert Zoo consists of 333 galaxies, which were exclusively classified by experts in the field, including professors and postdoctoral researchers closely associated with the Galaxy Zoo project and the study of galaxy environments in general.

The fact of working with two data-sets experts and public are useful to compare future results and improve the accurate of selection by calibrating public votes from experts results. Besides the mission of vote completely whole sample of 5254 galaxies was impractical to do for a group of 11 experts, therefore the need to use a more workable sample was necessary for this thesis, however this is something that is also being implemented in scientific routines, since the number of galaxies with Ram pressure signs are too many and citizen science can be implemented in order to facilitate the detection task but being very cautious and thorough with the refinement of results, in order to improve the quality and accuracy of people's votes.

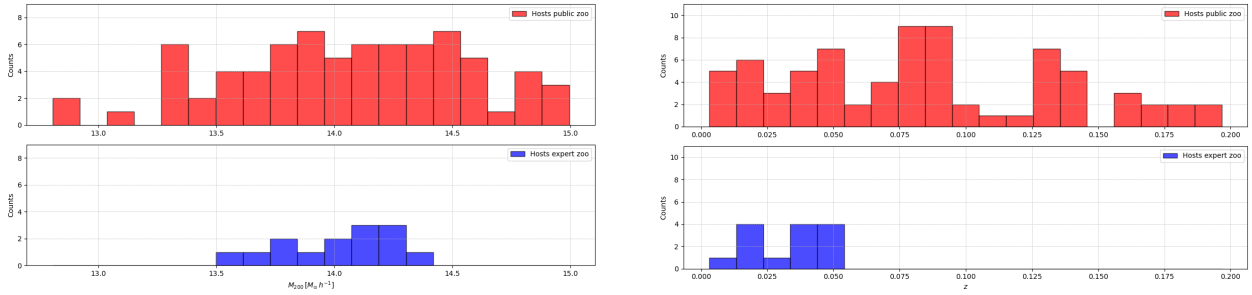


Figure 2.6: Histograms showing mass and redshift distribution for all host population in both expert and public Zoo, *Left panel:*$M_{200}$ distribution and *Right panel:* shows the redshift distribution.

# Chapter 3

# Morphological classification in galaxy zoo portal

This section is dedicated to the classification process of each Jellyfish candidate image based on distinctive morphological features resulting from Ram Pressure effects on galaxies as they interact with clusters or groups. We employed the Galaxy Zoo portal, an important citizen science platform known for classify various types of galaxies through an accessible and user-friendly tutorial. This approach enables contributions from individuals outside the research field when a manual classification in a large data sets would be impractical.

The Galaxy zoo webpage (Click to redirect to workflow) presents a set of specific questions regarding morphological features that classifiers must consider during their visual inspection of the galaxies, for a better understanding a schematic is shown in 3.1. Each question focuses on different evidences that could indicate the presence of Ram Pressure Stripping, as it is typically manifested through a combination of morphological perturbations, see a collage showcasing different examples of the manifestations we are searching for is presented in Figure 3.2. These perturbations include a disturbed or asymmetrical disc, gas stripped into a distinct tail or displaced material, extended or unwinding arms, and a compressed or sharp edge appearance are expected for RPS signs because the pressure by the ICM gas modifies the galaxy disc structure giving those morphological features when ram pressure surpasses the galaxy self-gravity in outer regions $\rho v^2 \geq 2\pi G \sigma_{stars}(r)\sigma_g(r)$, where disc gas bounds is less strong and can be stripped outside forming those distinctive tails and asymmetrical features of Jellyfish galaxies. However, it is important to note that we are specifically looking for signs of Ram Pressure Stripping, that is galaxy-medium interaction and not other types of interactions like galaxy-galaxy that can produce similar features, such as harassment or tidal interaction. Although there could be galaxies that suffer from RPS+Tidal interaction, but in the study we did not look for Tidal interaction or any other isolated effect different from RPS. The fundamental requirement is that the galaxy has at least one representative feature of RPS, if also has tidal interaction alone then this galaxy it is not considered like RPS even if it has prominent asymmetrical features.

Each question in the classification process corresponds to a specific manifestation resulting from these interactions and is applied to every galaxy candidate within their respective

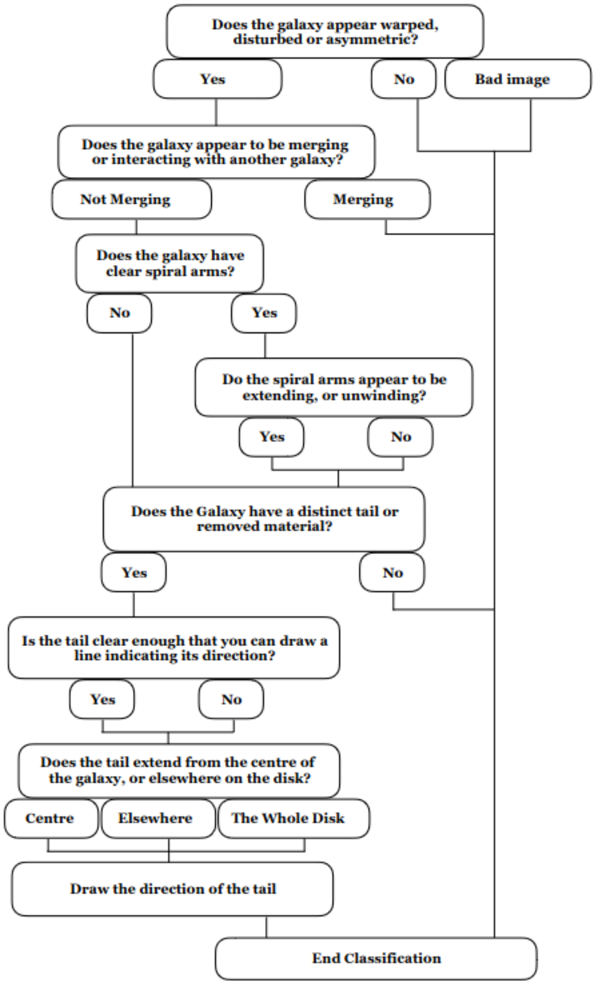
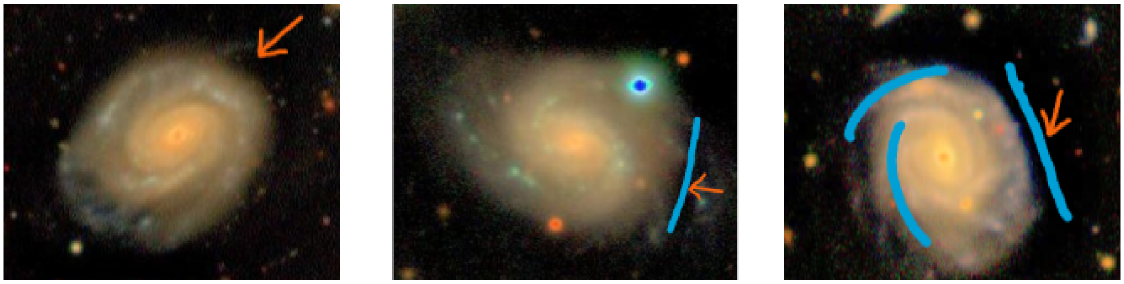


Figure 3.1: This is a representative diagram of the voting process during the visual inspection of the expert and public Zoo images. Mention and thanks to Callum for his work in producing this diagram of the questions.

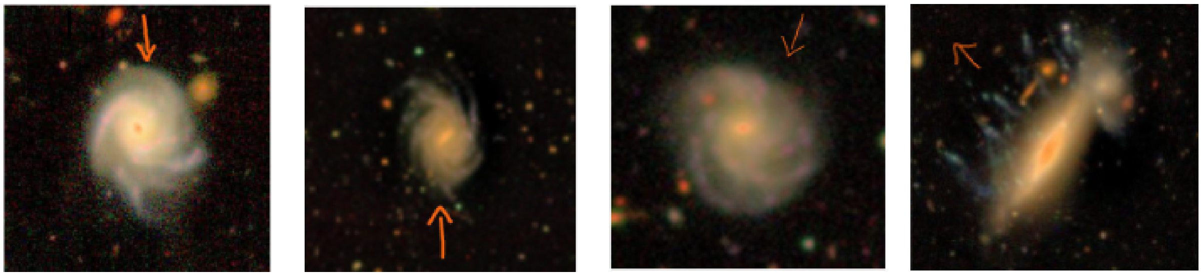
clusters. The details of these questions are provided in Table 3.1. Each question guides the classifiers in identifying the general morphological characteristics of the galaxy. The recorded votes are then collected and analyzed to identify combinations of feature-based votes that correspond to Jellyfish galaxies.

## 3.1 Jellyfish candidates in Hyper Suprime Cam Images workflow

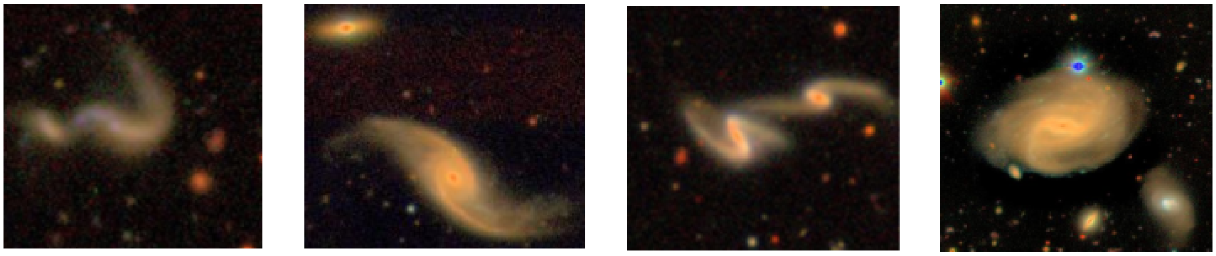
The main objective is to select a reliable Jellyfish candidates sample by using the morphological classification results on images from the Public and Expert zoo. For this purpose, we utilized the expert Zoo as a calibration in the confirmation process. The Galaxy Zoo classification survey consists of various questions about the most notorious morphological features,



(a) *Left:* Spiral arms unwinding & material leaving. *Center:* Sharp edge on opposite side to unwinding. *Right:* Bright blue leading edge of disk, unwinding and material leaving.



(b) More examples of asymmetry and spiral arms unwinding, far right: example of edge-on disk undergoing stripping



(c) Merger and tidal interactions are characterized by their typical strong disruptions on the shape of galaxies

Figure 3.2: Array of galaxy candidates displaying various features discussed in each question, including a guessed ram pressure wind direction and a concise description of the main characteristics observed in the galaxies.

which are listed in Table 3.1 and figure 3.1. Based on these responses, selection criteria were applied to confirm the jellyfish galaxies by creating combinations of the answers provided for each question in each image. Statistical analysis was conducted to examine the percentages of ”agreement” or ”disagreement” by counting the number of ”Yes” or ”No” responses and dividing by the total number of votes for each respective question. This analysis was performed using both the expert and public Zoo data-sets. To visualize the differences, we investigated the distribution of votes for each question in all images, aiming to evidence the dispersion in responses and evaluate the accuracy of agreement for each galaxy image sets. The ultimate goal is to find a reliable method for identifying the best Jellyfish candidates in the public Zoo data-set based on the reliability of expert votes.

We initiated our study by focusing only the expert sample, which offers higher credibility due to its evaluation by 11 individuals who has expertise in the field. This sample comprises a subset of 333 galaxies, carefully selected from massive clusters and groups within the RXGCC catalog, all details discussed in section 2.4.

## 3.2 Confirming according combination of features

The confirmation of Jellyfish candidates depends entirely on the voted features observed in the galaxy images. Therefore, establishing criteria to obtain the best candidates is fundamental. As mentioned earlier, we first analyze the expert zoo images results. In this initial stage, we define a level of credibility for the results, which essentially sets a reliability percentage for each specific question. This serves as a distinctive flag for each question. We then combine different feature-based questions with a fixed flag level for each question. This combination allows us to extract specific objects that agree the desired criteria. After extracting the best Jellyfish galaxies from the expert zoo data-set, we compare them with galaxies voted on by both experts and non-experts. This comparison aims to identify the main differences observed during the visual inspection and provides insights for calibrating the results from the public zoo in the future.

### 3.2.1 6 features combined: Most strict version

The resulting candidates are extracted based on the combination of features voted, in this case we focused on the features **Yes-Tail displaced**, **Yes-Unwinding**, **Yes-Sharp edge**, and **Yes-Tail direction**, each one with a majority vote credibility level greater than 50%. Additionally, to avoid confusion with other types of interactions, such as tidal interactions or harassment, which can produce similar features as mentioned above in galaxies, two fixed features are included, they are **Not-merger** and **Yes-Disturbed** (both with vote credibility lever greater than 50% too), aiming to exclude interactions that are not primarily related to Ram Pressure Stripping and eliminate individual galaxies that do not exhibit asymmetric blue gas disks due to RPS. The only one feature not considered was spiral arms due to there are Jellyfishes that could have a projection edge on and this feature would bias the selection.

After selecting 6 features to identify this sample of Jellyfish candidates, we obtained 43 promising candidates distributed among high-mass groups and clusters, as presented in the table below and a collage with all images selected are shown in A.1 and a few examples of

| **Question on the galaxy features** | **Focused answer** |
|---|---|
| Does the galaxy appear to be **disturbed** and/or asymmetric, in either the close image or the wide image? | Yes - Disturbed/Asymmetric |
| Does the galaxy appear to be **merging**, colliding or interacting with another galaxy? | No - Not merging, colliding or interacting |
| Does the galaxy have visible **spiral arms**? | Yes, the galaxy has spiral arms |
| Do some of the spiral arms appear to be extending, or **unwinding**, compared to others? | Yes, unwinding arms appear |
| Does the galaxy appear to be **compressed**/flattened or brightened along one edge? | Yes, the galaxy looks compressed/flattened/brightened on one side |
| Does the galaxy have a distinct tail or **displaced material** to one side? | Yes, the galaxy has a distinct/displaced tail |
| Is the tail clear enough that you can draw a line indicating its **direction**? | Yes |
| Does the **tail extend from** the centre of the galaxy, elsewhere on the disc, or from the whole disc? | Centre or the whole disc or elsewhere |
| **Draw** a line along the length of the tail, starting from where it joins the galaxy and ending at the tip of the tail. | Draw |

Table 3.1: Questions on the description of morphological features in galaxy images. This table displays the questions voted by classifiers on the Galaxy Zoo portal for morphological classification. In the case of the public sample, the last requirement of drawing the line on the galaxy's tail was not included.

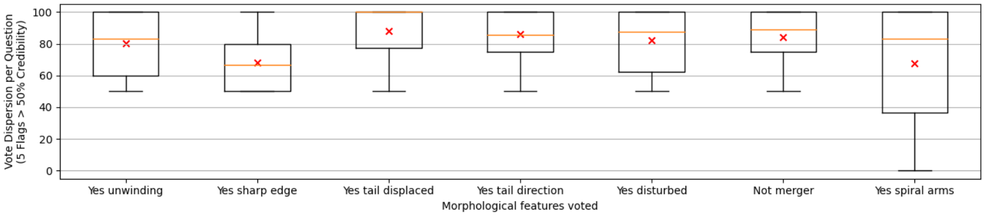


Figure 3.3: Box plot showing a statistical description about dispersion of vote percentages per feature for all the resulting galaxies after applying the 6-feature selection criterion method in the expert sample. The red cross represents the average vote percentage for each feature in all the chosen galaxies, while the orange horizontal line represents the median vote percentage. The first six box-plots are considered to filter the Jellyfish selection, while spiral arms flag are not considered.

Jellyfish galaxies extracted by this method are shown in 3.4. A statistical description is shown in Figure 3.3, the majority of the morphological features voted by experts for these galaxies exhibit a low dispersion of votes within this sample and they have high box-plots due to our strict reliability greater 50%. As a summarize of the choice method, this confirmed Jellyfish sample represents the most strict version in terms of the total number of selected features and the low dispersion of votes by constraining much the reliability of votes, imposing a high level of agreement for each question about the morphology.

### 3.2.2 5 features combined: Intermediate strict version

Similar to the previous section, we proceeded with the selection of galaxies exhibiting Jellyfish characteristics by combining three features: **Yes-Tail displaced**, **Yes-Unwinding**, **Yes-Sharp edge**, and **Yes-Tail direction**, all with a credibility level exceeding 50% as last one method. Additionally, two fixed features were included, **Not Merger** and **Yes-Disturbed**, both with a credibility level exceeding 50%. However, it is important to note that these two additional flags are not combined with each other. They are an additional set of flags added to avoid different interaction than RPS. Please refer to table 3.2 for a visual representation where Not Merger and Yes Disturbed are shown as separate from other flags. Actually, only three features were combined, while the two extra fixed features were included separately. Using these flags combination we obtained an amount of 101 galaxies located in clusters and high-mass groups, as it is shown in a table below and a collage with all images selected are shown in A.2and a few examples of Jellyfish galaxies are shown in figure 3.5. In table 3.2 we have different combinations of features that the galaxy selection shown, we can note that most of this sample has a sharp edge or unwinding arms separately and galaxies showing both unwinding arms and sharp edge together are not common for this selection. On the other hand the box plot figure 3.6 for this version in comparison with box plot figure 3.3 we can notice that the combination of 5 features (this case) has a little more dispersion in each voted feature compared to the previous one, but the sharp edge feature does not have a high box plot, which means that in some selected combinations this feature does not had a significant agreement unlike the rest and also with the previous case, which only for the fact of setting a level of confidence in the vote had a high box plot, this was not the case here.

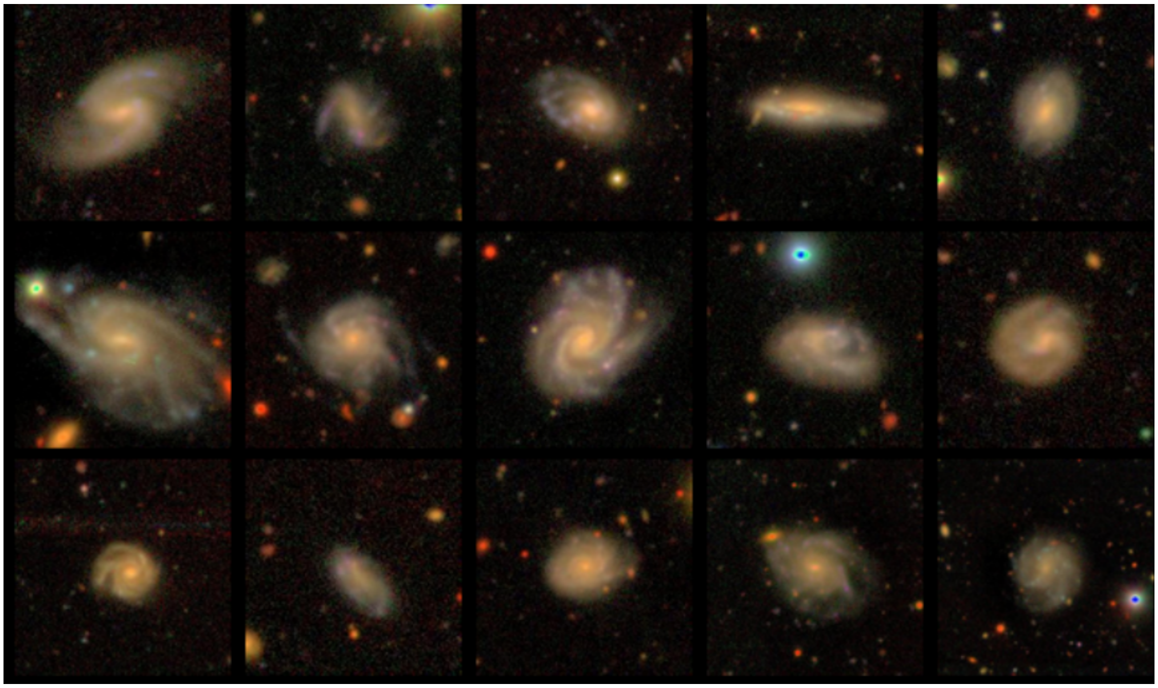


Figure 3.4: A few Jellyfish galaxies selected by using the most strict version of 6-features combined discussed on section 3.2.1.

The features spiral arms was also not considered in this combination but it is the one that shows the most dispersion.

| 3 Feature Combination + 2 extra flags | Galaxy Count |
|---|---|
| Yes tail direction and Yes displaced tail and Yes sharp edge + Not merger and Yes disturbed | 50 |
| Yes tail direction and Yes displaced tail and Yes unwinding + Not merger and Yes disturbed | 49 |
| Yes tail direction and Yes sharp edge and Yes unwinding + Not merger and Yes disturbed | 1 |
| Yes displaced tail and Yes sharp edge and Yes unwinding + Not merger and Yes disturbed | 1 |

Table 3.2: Table showing the number of galaxies provided by each feature combination.

### 3.2.3 4 features combined: A permissive version

To identify more different types of Jellyfish galaxies, a combination approach was employed by selecting two flags from the set of **Yes-Tail displaced**, **Yes-Unwinding**, **Yes-Sharp edge**, and **Yes-Tail direction**. All possible pair combinations were considered, similar to the approach used in the previous section. To ensure the focus on Ram Pressure effects and exclude other interactions, two fixed flags were included: **Not Merger** and **Yes Disturbed**. However, it was important to increase the credibility level for the pair combinations to

Figure 3.5: A few Jellyfish galaxies selected by using the intermediate strict version of 5 features combined discussed on section 3.2.2.

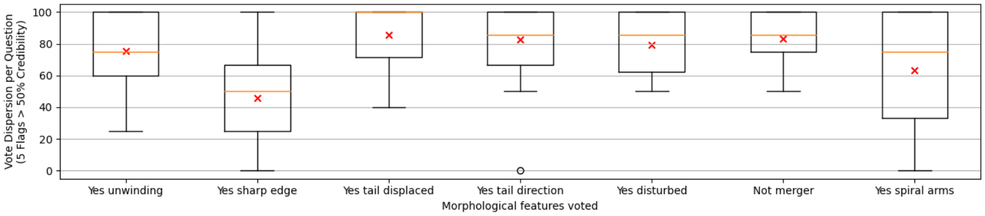


Figure 3.6: Box plot showing measures of the dispersion of vote percentages per feature for all the resulting galaxies after applying the 5-feature selection criterion in the expert sample. The red cross represents the average vote percentage for each feature in all the chosen galaxies, while the orange horizontal line represents the median vote percentage. Spiral arms flag are not considered in the selection criterion.

70% agreement, while maintaining a 50% credibility level for the two additional flags. This adjustment aimed to account for the potential misclassification of objects and to capture a stronger signal of Ram Pressure effects that could be less prominent in only a pair combination of features. We obtained from this combination an amount of 85 galaxies.

The process of selecting Jellyfish candidates using this combination method exhibits higher dispersion compared to previous cases. Specifically, the morphological features of Unwinding, Sharp edge, tail displaced, and tail direction show a greater range of votes. However, due to the increased credibility level until 70% for these features, many of the reliable objects identified in the previous combinations are also included in this selection. As a result, this approach provides a broader range of sub-classes within the Jellyfish category, capturing a greater diversity of galaxy morphologies associated with Ram Pressure effects. In table 3.3 we can see different combination of features, the most common is those galaxies with a displaced tail with a distinguishable tail direction, then galaxies with unwinding arms and also a displaced tail or a clear tail direction and finally a sharp edge with displaced tail galaxies were the least common, and again galaxies with sharp edge and unwinding arms

| **2 Feature Combination + 2 extra flags** | **Galaxy Count** |
|---|---|
| Yes tail direction and Yes displaced tail + Not merger and Yes disturbed | 63 |
| Yes displaced tail and Yes unwinding + Not merger and Yes disturbed | 10 |
| Yes tail direction and Yes unwinding + Not merger and Yes disturbed | 7 |
| Yes tail direction and Yes sharp edge + Not merger and Yes disturbed | 4 |
| Yes displaced tail and Yes sharp edge + Not merger and Yes disturbed | 1 |

Table 3.3: Table showing the number of galaxies provided by each feature combination.

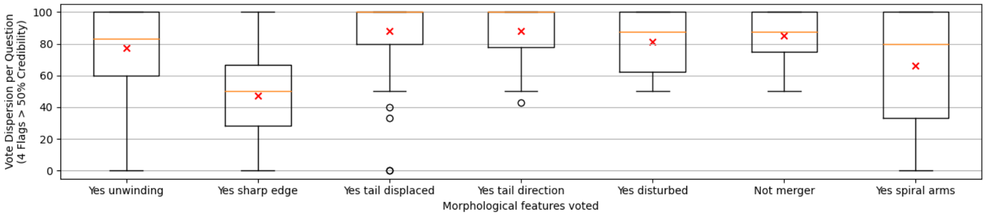


Figure 3.7: Box plot showing measures of the dispersion of vote percentages per feature for all the resulting galaxies after applying the 4-feature selection criterion in the expert sample. The red cross represents the average vote percentage for each feature in all the chosen galaxies, while the orange horizontal line represents the median vote percentage. Spiral arms flag are not considered in the selection criterion.

don't appear by using this selection criterion.

Regarding the box plot shown in 3.7 comparison with the two last ones examples, this box plots have more dispersion due to the combination of features could include a less agreement in those features not combined, however the general dispersion of votes is really similar to the method of 5 features combined (the last one) but this one method has more outliers indicating the fact the agreement decreases when less features are combined.

|  | Clusters | High mass groups | Features combined |
|---|---|---|---|
| Number of JF | 29 | 14 | 6 |
| Number of JF | 65 | 36 | 5 |
| Number of JF | 58 | 27 | 4 |

Table 3.4: A simple table showing the mass-range distribution where Jellyfish galaxies were confirmed using the method of 6, 5 and 4-combined features

To conclude this section, the following facts are obtained, in the first place, combining the voted features allows the candidates to be Jellyfish galaxies to return and when testing with different versions we realize that the strictest versions reduce the sample and the categorization of Jellyfish galaxies too much . However, when combining fewer features we can refine, categorize and better understand the distribution of Jellyfish types according to their morphology as we can see in tables 3.2 or 3.3. It must be taken into account that the level of confidence in the votes also depends on the number of votes for the image, therefore the more expert votes an image has, the better its confidence. And although there is no absolute way to vote whether or not it is a Jellyfish, we can take advantage of a statistical agreement using box-plots to give permissiveness but also quality to the selection, at least for the expert sample, since the case of public votes must be calibrated using these statistics results from the votes of the experts. We also learned that reliability level and number of features combined affects the host's mass-range where Jellyfish were confirmed, as shown in table 3.4, the number of Jellyfish galaxies inside cluster is always greater than they inside galaxy groups even when the number of targets for groups and clusters are very similar, as figure 2.5 shown.

## 3.3 Expert and Public zoo results comparison

In this section, our primary objective is to compare and highlight the differences between the votes based on morphological features for galaxies selected by expert classifiers and those voted by the public through visual inspection. To achieve this, we will compare the same set of galaxies obtained from 6-combined features selection, as discussed in the previous sections, see figure 3.8. Additionally, we will compare galaxies from the expert zoo that were also voted by the public classifiers, allowing us to demonstrate the initial data dispersion between the two sets of votes. This comparison is presented in figure 3.9.

To reduce noise in the comparison, we have selected galaxies voted by the public with more than five votes each. We then create box plots for both the expert and public votes, focusing on understanding the differences in the dispersion of votes for each morphological feature of the galaxies. From our analysis, we observe that for the comparison using the 6-combined features, there is generally low dispersion in the expert votes for the majority of the features questions, expect the feature spiral arms where both dispersion in expert and public results are similar. However, we notice a broader range of dispersion in the votes from the public classifiers, mainly in spiral arms, sharp edge, displaced tails and tail direction. On the other hand a less dispersion is present in not merger, disturbed disk and unwinding arms. This discrepancy indicates that the expert classifiers had better agreement and less dispersion of votes (which means, more accurate votes) in identifying the morphological features than the public classifiers. This observation is expected, given that the expert sample is smaller and classifiers are experts.

Furthermore, the most significant difference emerges in the feature "Not Merger" and "Yes disturbed disc" responsible for distinguishing the distinctive signs of Ram Pressure Stripping (RPS) and avoid tidal interactions or harassment. The public classifiers often identified processes of galaxy merger or tidal interactions features where the experts identified potential Jellyfish galaxies and RPS effects. As we note in those 'Not merger' and 'Yes disturbed Disc' between experts and public, they public have selected with less dispersion (accurate votes) merger galaxy process and undisturbed discs where the experts have selected RPS effects and disturbed disc. However tail directions and unwinding arms features were the best agreement between experts and the public because both box-plots in expert and public have similar position and less dispersion.

We also conducted a comparison with galaxies voted by the public classifiers within the expert zoo, shown in figure 3.9. Here, we observed minimal vote dispersion in the features responsible for ”Disturbed Disk” and ”Not Merger” as before 6-combined features comparison, providing evidence that the most galaxies in the expert zoo were identified by the public classifiers as galaxies in the process of merger or as undisturbed disc galaxies.

These significant differences reveal valuable insights, indicating that the combined features that served to extract Jellyfish galaxies from the expert sample may not necessarily work as effectively for extracting Jellyfish galaxies from the entire sample. These intrinsic differences in the detected features for galaxies provide vital clues for the future calibration steps of the public sample. The calibration process will involve studying the vote differences to find an optimal way of combining the features in the public zoo to extract as many Jellyfish galaxies as possible from the total sample of 5254 galaxies.

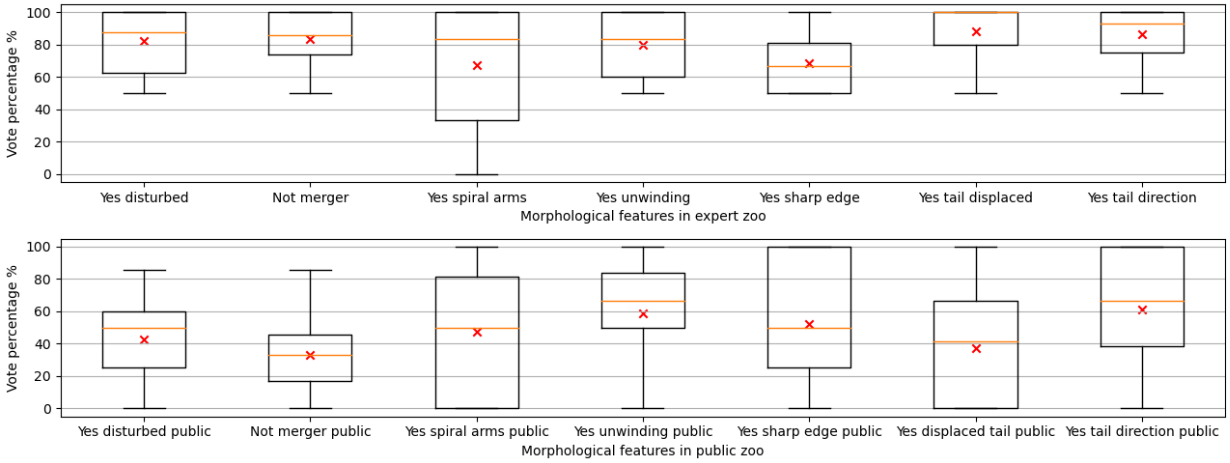


Figure 3.8: Box-plot comparisons showing the dispersion of votes among expert classifiers in the Expert Zoo and public classifiers in the Public Zoo. Each box-plot displays the spread of votes for individual questions based on the observed features in all selected galaxy images by criterion based on 6-combined features. The orange horizontal line is the median, and the red cross indicates the mean of the votes for the galaxy images. *Top panel* shows the comparison for galaxies selected based on 6 combined features for expert zoo results. *The bottom panel* shows the box-plots for public results from all galaxies in expert Zoo that were voted on by expert classifiers.

To conclude this section we can conclude that as expected there would be a difference in the nature of the votes between expert and public votes, we can note that the extraction methods employed for expert votes might not necessarily return the same objects with the same quality when done on the public results. We noted strong differences in what people identified as RPS and galaxy mergers processes, but the unwinding arms and tail directions at least for the selection of 6 features combined showed better agreement than the rest. One option to calibrate the public votes would be to use the statistical evidence of the differences in the votes for those galaxies that we know (from expert votes) have certain features and then use that difference (could be to find the difference between the average agreement) to find the confidence percentage of each voted feature and calibrate it for the public, and then in a larger population of galaxies to see if this calibration can improve the type of Jellyfish

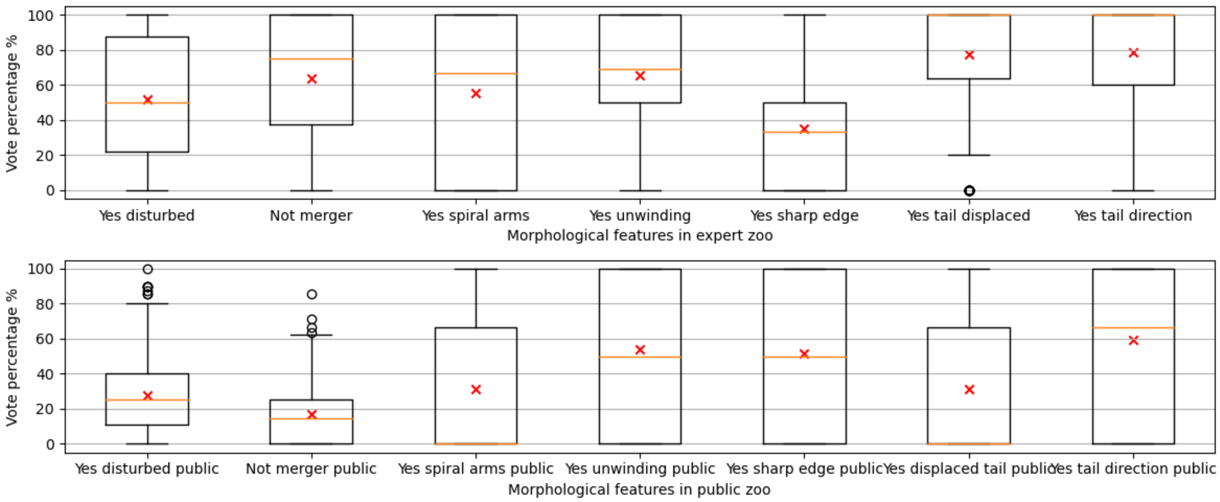


Figure 3.9: Box-plot comparisons showing the dispersion of votes among expert classifiers in the Expert Zoo and public classifiers in the Public Zoo. Each box-plot displays the spread of votes for individual questions based on the observed features in all selected galaxy images. The orange horizontal line is the median, and the red cross indicates the mean of the votes for the galaxy images. *Top panel* shows the comparison for all galaxies selected for expert zoo sample. *The bottom panel* shows the box-plots for galaxies in public zoo that were on expert zoo sample also.

found, being very strict in the combination but with a previous calibration of the percentage of agreement for the public, since the goal is to know how people voted, whether good or bad, and after the calibration to use the appropriate percentage to filter the Jellyfish from the public votes, will be tested soon.

# Chapter 4

# Results and discussion

In this section, we present the main results derived from the confirmation of Jellyfish galaxies using the methods discussed in the previous section. We focus on three key components. First, we examine the fraction of confirmed Jellyfish galaxies within their respective groups or clusters to determine if there is any correlation between the host mass and the Jellyfish fraction in this sample. Secondly, we investigate the properties of X-rays provided by RXGCC to explore any correlation between the extension and density profile of X-rays and their distance from the cluster center. This analysis allows us to gain insights into the effects of Ram Pressure Stripping, considering different models for the density of the hot gas present in galaxy clusters and groups. Finally, we aim to characterize the distribution of tail directions by studying the relative positions of the tails with respect to the cluster.

## 4.1 Investigating the Influence of Host Mass-Range on Jellyfish Fraction

One straightforward way to study and characterize the population of confirmed Jellyfish galaxies is by examining their relation to the mass of their host, as it is shown on table 3.4 by each Jellyfish confirmation method. This approach allows us to understand the occurrence of Jellyfish galaxies in different environments according the hosts mass. To conduct this study, we simply count the number of confirmed Jellyfish hosts and divide it by the total number of targets detected in those hosts, thereby representing the frequency of Jellyfish galaxies. We expected that Ram Pressure is more effective in denser environments because $P = \rho v^2$, thus in those more massive structure with a high galaxy density there's more gas and high velocity dispersion, so an interesting correlation between the mass of host and the Jellyfish fraction could be studied and expected. As shown in Figure 4.1, there is a trend but not strong of increasing Jellyfish frequency as the host mass increases, which is in qualitative agreement with previous studies on ram pressure stripping in different mass ranges for radii continuum at least Roberts et al. (2021), but in our visible Jellyfish study.

It is important to note that the confirmation rate in 4.1 exhibits a slight increase. This can be attributed to several factors. Firstly, the expert Zoo represents only 20% of the targets identified by the HSC coneSearch algorithm in all clusters present in this sub-sample (In Roberts et. al there are $\sim$ 100 radio continuum galaxies, so our sample size is quite similar). Inherent variations in the number of detected targets among different hosts can weaken the statistical signal and increase the dispersion in the measurement of Jellyfish frequency. Secondly, potential measurement uncertainties in the mass properties derived from the RXGCC survey can also influence the observed trend. It is acknowledged in the survey false detection or errors in determining the properties may occur. Additionally, despite the reliable nature of our galaxy selection based on expert sample votes, there is still a possibility of misclassifications or imperfect combinations of flags that may result in non-genuine Jellyfish identifications. In fact, there's no an absolute method to extract Jellyfish confirmations in a perfect way. However, despite these considerations, the observed increasing trend is sufficiently robust to conclude that Jellyfish galaxies become more frequent as the mass of the host increases, agrees with previous studies but in visible observations instead radii continuum, as Roberts et al. (2021).

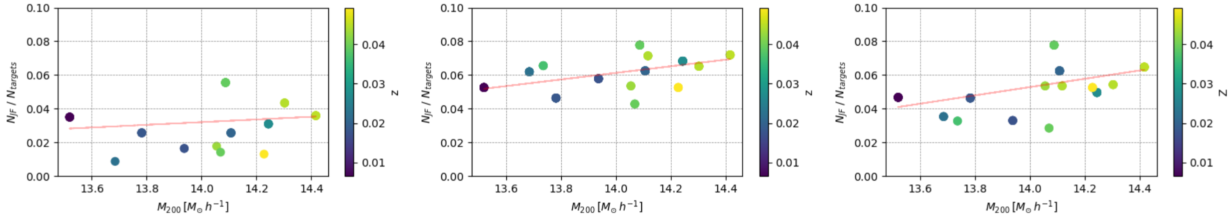


Figure 4.1: The plot illustrates the occurrence of Jellyfish galaxies in different mass ranges of hosts, the red line shows the slight trend of measurements to increase by fitting a simple lineal interpolation. In the *left panel*, we present the occurrence based on the method utilizing 6 features, as discussed in Section 3.2.1. *The center panel* displays the occurrence derived from the method utilizing 5 features, as discussed in Section 3.2.2. Finally, *the right panel* presents the occurrence based on the method utilizing 4 features, as discussed in Section 3.2.3.

## 4.2 Characterizing Jellyfish Galaxies According to Density-Based Host Subset

We also present a characterization of Jellyfish galaxies in relation to the estimated gas density of their hosts. To achieve this, we consider different subsets that allow us to separate hosts based on the extent and compactness of the intracluster medium (ICM) gas (so far mixing groups and clusters from expert zoo sample).

We know that both the beta and core radius parameters are related together with the concentration and also the extent of the gas density in the host, therefore we can study hosts with concentrated or extended gas density, which determines a way how the Ram Pressure stripping could be distributed in the host, therefore studying how this physical mechanism affects the distance where the Jellyfish is is an interesting correlation to explore.

### 4.2.1 Separation based on X-ray central compactness using the $\beta$ profile

Firstly, we employed a separation criterion that describes the compactness of the X-ray emission in the host. This is done by studying the $\beta$ profile estimated by the RXGCC survey. We select hosts with a $\beta$ value lower than 0.7, indicating a steeper increase in density at close radii, implying a concentrated X-ray density nearby centre. Conversely, we also select clusters with $\beta$ values greater than 0.7, representing clusters with a more flatter and continuous decrease in density as the radius increases, indicating a more distributed X-ray density also is shown a set of plots displaying those sub-sets created to separate using $\beta$ and $r_{core}$, see both bottom and top panels of figures A.5, A.6 and 4.2 to see beta sub-sets. This analysis is performed on hosts containing galaxies confirmed as Jellyfish using the feature combination methods discussed in the previous section. The density profiles are calculated using the ecuation2.1 mentioned in previous studies, King (1962) and are represented by a set of plots (A.4, 4.6, and A.7), which show the density distribution in the clusters where Jellyfish galaxies are found. Some density profile plots are in appendix because are too large, but most representative are on main paper.

Using each cluster density subset, we calculated the projected distance on the sky between the center of the cluster and the Jellyfish galaxies. We then utilized the angular diameter size information, which was calculated to convert physical measurements and angular distances in the clusters considering their redshift and the standard cosmology, to convert this angular distance into a physical distance in megaparsecs (Mpc), then we normalized that distance by their respective host radius $r_{200}$ to standardize the comparison between Jellyfish-Host centre distances in different hosts. We created histograms that considered all the Jellyfish galaxy-host normalized distances in the high-beta and low-beta subsets to analyze the distribution of distances in clusters with low and high gas density central compactness, respectively.

The results are shown in Figure 4.3, where we observe that hosts with high and low $\beta$ values have a similar distance range, however hosts with lower beta values, which corresponds more central concentrated gas density does indeed show Jellyfish galaxies at smaller distances than hosts with higher beta values, whose gas density is flatter and more uniform and shows Jellyfish galaxies at greater distances, see both bottom left and bottom right panels on 4.2. The histogram itself shows significant variations in its behavior, there are fewer host galaxies with high beta values, which means that these samples have fewer host galaxies with extended gas density and that there is a preference for more concentrated density profiles. On the other hand, beta profile significantly affects the distribution of angular distances compared to $r_{core}$ (see histograms 4.4). But the most important result is that concentrated densities (low beta) have Jellyfish signal at short distances from the center, which is expected.

### 4.2.2 Separation based on X-ray extension using the and $r_{core}$

To study the compactness of the gas density of the ICM as it was studied in the previous section with the beta profile, we are going to include a study on extension of density profile to understand how is the concentration including the $r_{core}$. In this sense, we are going to separate two subsets using the median of their distribution of $r_{core}$, that is, using to separate a subset with the highest 50% for the measurement and another with the 50% with the lowest

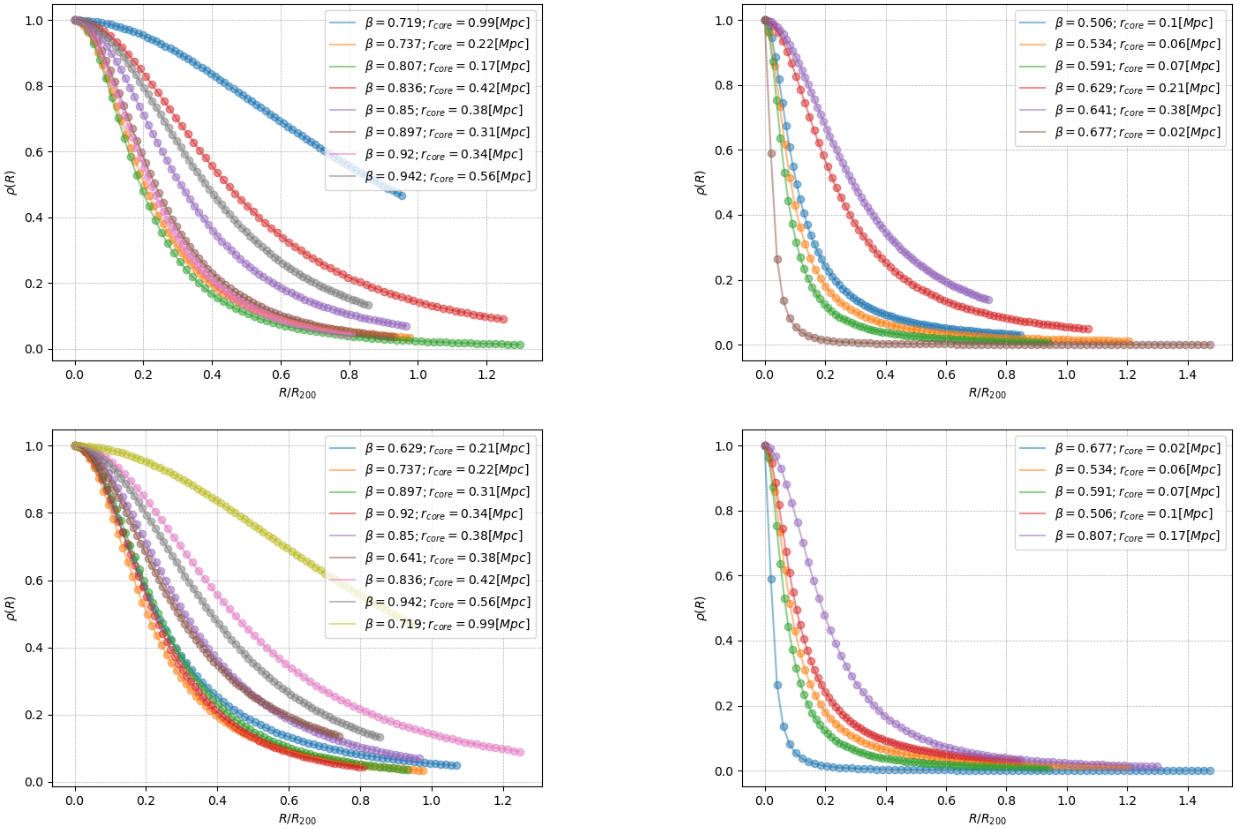


Figure 4.2: Set of plots showing the density gas distribution for hosts that contains inside confirmed Jellyfish galaxies selected by 4-combined features, hosts are separated by each $\beta$ and $r_{core}$ sub-sets discussed on sections 4.2.1 and 4.2.2 respectively. *Bottom left panel* shows high $\beta \geq 0.7$ and *Bottom right panel* displays low $\beta < 0.7$ subsets. *Top left panel* shows 50% of highest values of core radius and *Top right panel* displays 50% lowest values of core radius..

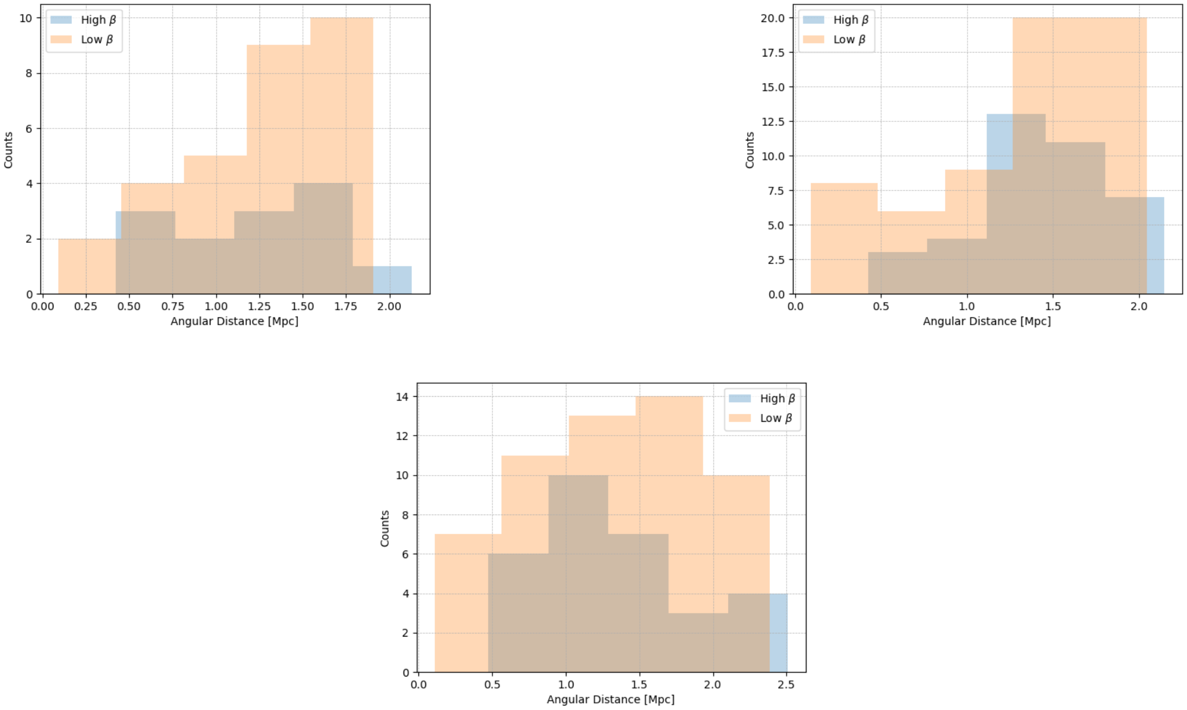


Figure 4.3: Plot showing a distribution of angular distances in Mpc units measured by a separation angle for each of the three Jellyfish confirmation methods by low and high-$\beta$ host subsets. The *left panel* displays the separation distances distribution for Jellyfish galaxies confirmed using the combination of 6 features. The *central panel* represents the distribution for Jellyfish galaxies confirmed with 5 combined features, and finally, the *right panel* shows the distribution for the case of 4 combined features. The plot gives information about the correlation between x-ray density subsets and the distance when RPS affects the galaxies

measurements, see top panel on figures 4.2,A.6 and A.5. The results are shown in the graph 4.4, we can notice that the distribution of angular distances is not much affected in its shape by the parameter core radius compared to the sensitivity of beta in the angular distances distribution, figure 4.3. However, an important result is the fact that the smaller the core radius, that is, the more concentrated in the center, there are Jellyfish at close distances. Although the distribution is similar, but at least we found indications that there are RPS closer to the center compared to hosts with more widespread distribution where there is no evidence.

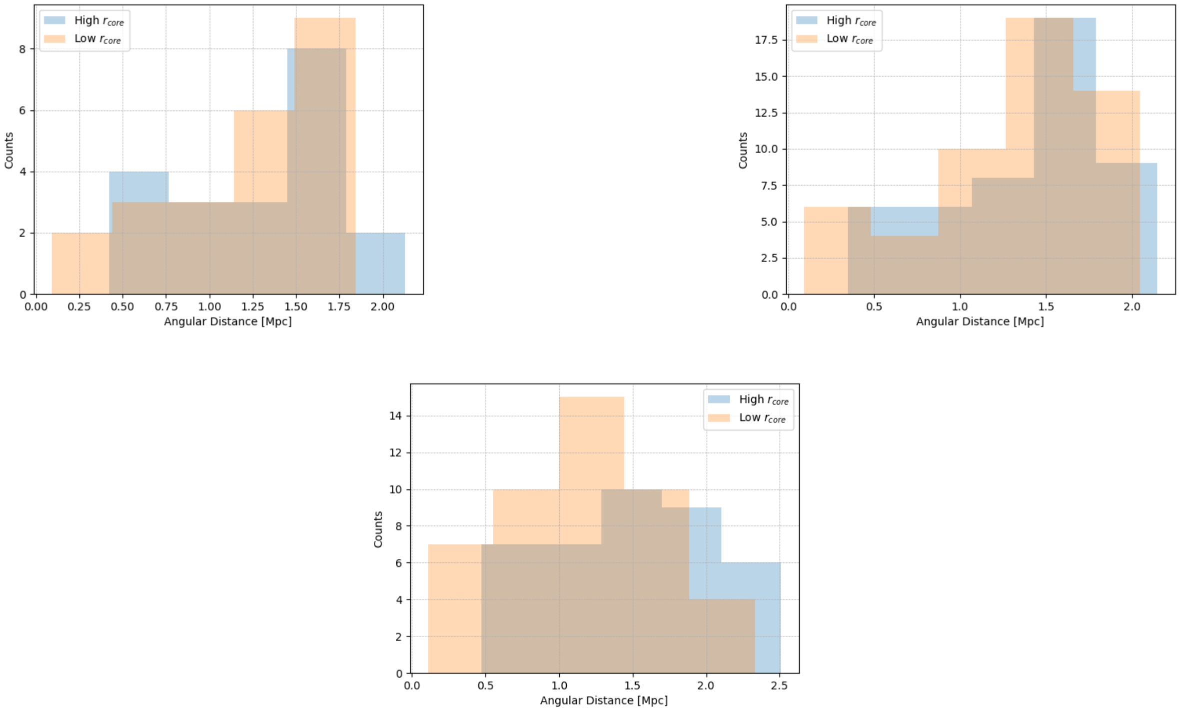


Figure 4.4: Plot showing a distribution of angular distances in Mpc units measured by a separation angle for each of the three Jellyfish confirmation methods by low and high-$r_{core}$ host subsets. The *left panel* displays the separation distances distribution for Jellyfish galaxies confirmed using the combination of 6 features. The *central panel* represents the distribution for Jellyfish galaxies confirmed with 5 combined features, and finally, the *right panel* shows the distribution for the case of 4 combined features. The plot gives information about the correlation between x-ray density subsets and the distance when RPS affects the galaxies

### 4.2.3 Separation based on both $r_{core}$ and $\beta$

Finally, in this section we study the effect that both parameters have together in modelling the extension and compactness of the gas density present in the host because in this way we can make a full description of density profile model. As in the previous cases, we seek to separate the hosts based on the reported values of Beta and Core radius, we separate high and low beta using the value $\beta = 0.7$, and for the value of $r_{core}$, the median of the distribution is chosen, as in the previous case. The results are shown in 4.5.

As we can see in the figure 4.5, for the three Jellyfish cases confirmed using the parameters, we have those hosts low beta and low core radius in green, that is, those with a more centre-concentrated density gas distribution (low beta) and with less extension of gas with low core radius, they show Jellyfish galaxies at lowest distances than other compactness and extension subsets, although also have a wide distances range it is the only subset showing galaxies at centre, due to the nature of its compactness and extension nature. On the other hand, those with low beta but the larger core radius value in black, show longer average distances of Jellyfishes from host centre compared to the previous case, due to high core radius effect, although with some galaxies nearby to the centre due to the low beta nature. Regarding those hosts that have a lower concentration in the center (high beta means more flatter distribution) and smaller extension (low core radius) in red, they have a wider distances range of Jellyfish to the host centre, as expected. Finally, those hosts with flatter gas distribution (high beta) and greater core radius are the least present in this sample, being very weak statistically to establish conclusions.

According to the last two results, those with low beta description and low core radius, that is, those hosts with more concentrated densities, have Jellyfish closer to the center for all confirmed Jellyfish cases, while in the case from a extended distribution such as High beta and high core radius also show a wide angular distance range, but no jellyfish at close distances to th centre. Which is to be expected since RPS is radially distributed from the host and may spawn Jellyfish closer to the center in case the galaxy able to get close enough as in the case of galaxy groups, where the galaxy could advance through the environment because is less dense and extended, while in massive clusters the density could act earlier and more efficiently from the center. This also depends on other things such as the self-gravity of the galaxy, since those with greater selg-gravity will be more complex to extract their gas, therefore it is natural to think that the distribution of distances is wide since RPS will act in different radii depending on the density, but the findings of galaxies near the center will occur whenever the galaxy can get close to the center and when the RPS is effective in those regions.

## 4.3 Tail directions representation

Another study employed for our Jellyfish galaxies is to represent the direction of the stripped material due to Ram Pressure Stripping. To achieve this, we calculate using an astropy python-modulus tool called `position_angle` to determine the preferred tail direction pointing with respect to the center of the host. This analysis provides valuable information about the physical processes involved in the interaction between the galaxy and the host environment, shedding light on the mechanisms of Ram Pressure Stripping and its impact on galaxy morphology and gas distribution.

To accomplish this, we use the central coordinates of the cluster, provided by RXGCC, and the galaxy coordinates, provided by HSC. Then, we use the astropy position angle algorithm and represent the results in the plot 4.7. In this plot, we observe a distribution of preferred tail directions relative to the hosts, ranging from 0 to 180 degrees, where 0 degrees indicates

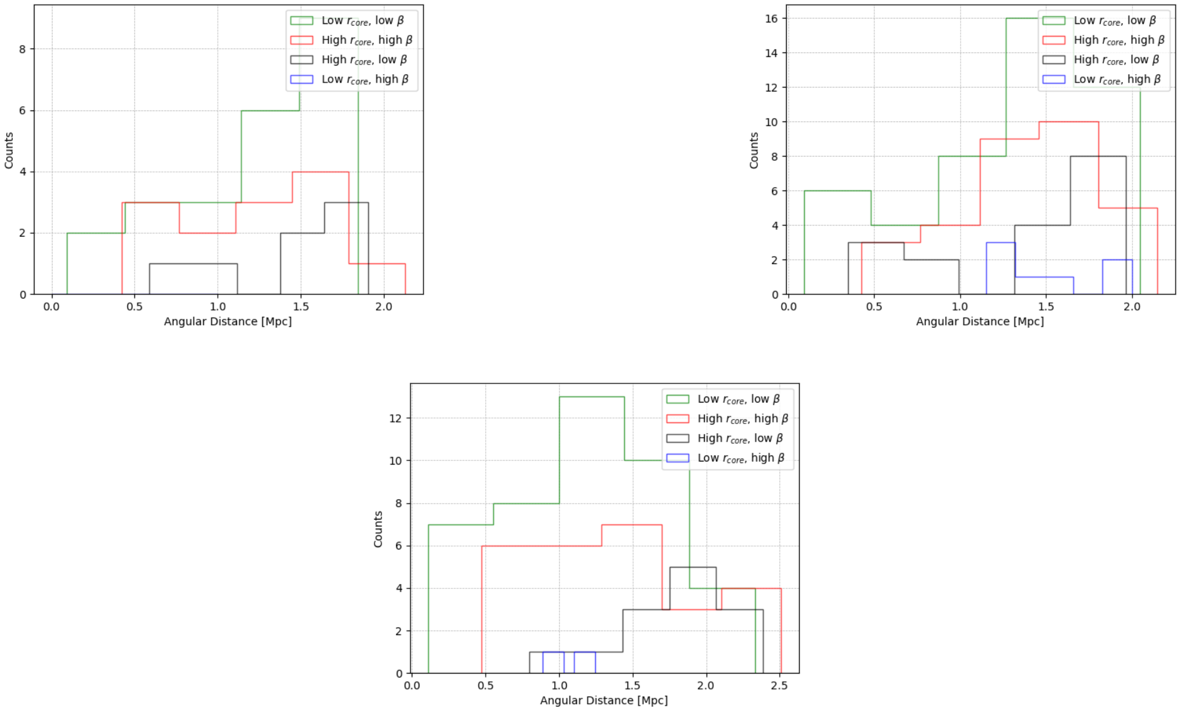


Figure 4.5: Plot showing a distribution of angular distances in Mpc units measured by a separation angle for each of the three Jellyfish confirmation methods by both low and high-$\beta$, $r_{core}$ host subsets. The *left panel* displays the separation distances distribution for Jellyfish galaxies confirmed using the combination of 6 features. The *central panel* represents the distribution for Jellyfish galaxies confirmed with 5 combined features, and finally, the *right panel* shows the distribution for the case of 4 combined features. The plot gives information about the correlation between x-ray density subsets and the distance when RPS affects the galaxies

the tail direction pointing aligned at host position while 180 degrees indicates the tail points away from the host position. We note that for those Jellyfish galaxies selected for the 5 and 4 features combined two peaks corresponding to the preferred direction of the tails are shown. The peak near 180 degrees indicates that a population of Jellyfish galaxies tends to have tails that point away from the host, implying that RPS is favoring the material stripped from the galaxy that points away from the host's position. On the other hand, values close to 0 degrees indicate tails pointing aligned with the position of the host. Because in this selection of galaxies we include those hosted in clusters and groups of galaxies we must consider two effects, first, those galaxies that are falling into massive clusters and with extended density, the tail appears early and in the opposite direction to the cluster due to the fact that the pressure is contrary to the infall motion of the galaxy, this originates the peak close to 180 degrees. On the other hand, the galaxies located in less massive and less dense groups, there is a possibility that the galaxy survive the RPS effect, passing the center and resulting the tails aligned to the direction of the cluster, therefore this phenomenon is present in the second peak close to 0 degrees, and statistically we find more galaxies in groups at near redshift, so it makes sense to find more galaxies in this sector, and the physical explanation comes from the nature of the host environment, but also from the characteristics of the galaxy, since it is possible that RPS is more effective in those less massive galaxies whose self-gravity is less and allows material to be easily removed.

It is important to note that this measurement is a general approach to determine the tail direction, serving as a first visualization of the environment affects in tails. Several factors may contribute to the wide range of tail directions. Firstly, whether the host or galaxy positions used for this calculation could have measurement errors. The cluster positions measured by RXGCC might suffer from inaccuracies or even false detections, as discussed in Xu et al. (2022) in section 4.2. Secondly, the galaxy positions provided by the HSC coneSearch algorithm may sometimes be slightly offset for targets located within the host. Additionally, as discussed in section 2.2, there were cases of blended sources, which could coincide with some Jellyfish galaxies having slightly off-center detections when cataloged as blended sources.

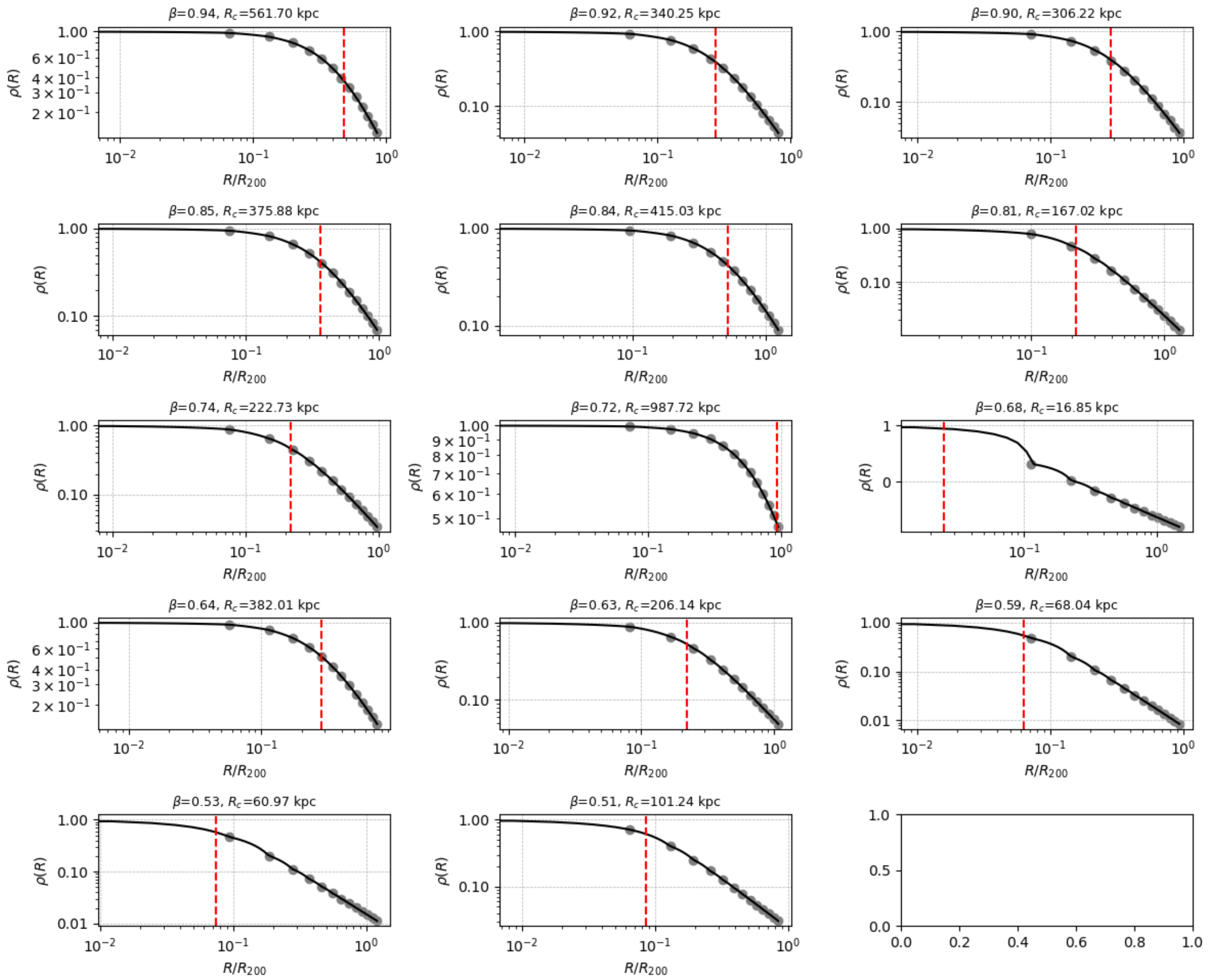


Figure 4.6: Set of plots displaying the density profile for clusters containing Jellyfish galaxies. The plots are arranged in descending order of the Beta value and show a vertical line indicating the position of the core radius. The density is normalized between 0 and 1, as a common central density value is used for all clusters. The cluster radii are also normalized with respect to the virial radius calculated for each cluster. This set of clusters corresponds to the galaxies extracted using the 5-feature combination discussed in Section 3.2.2.

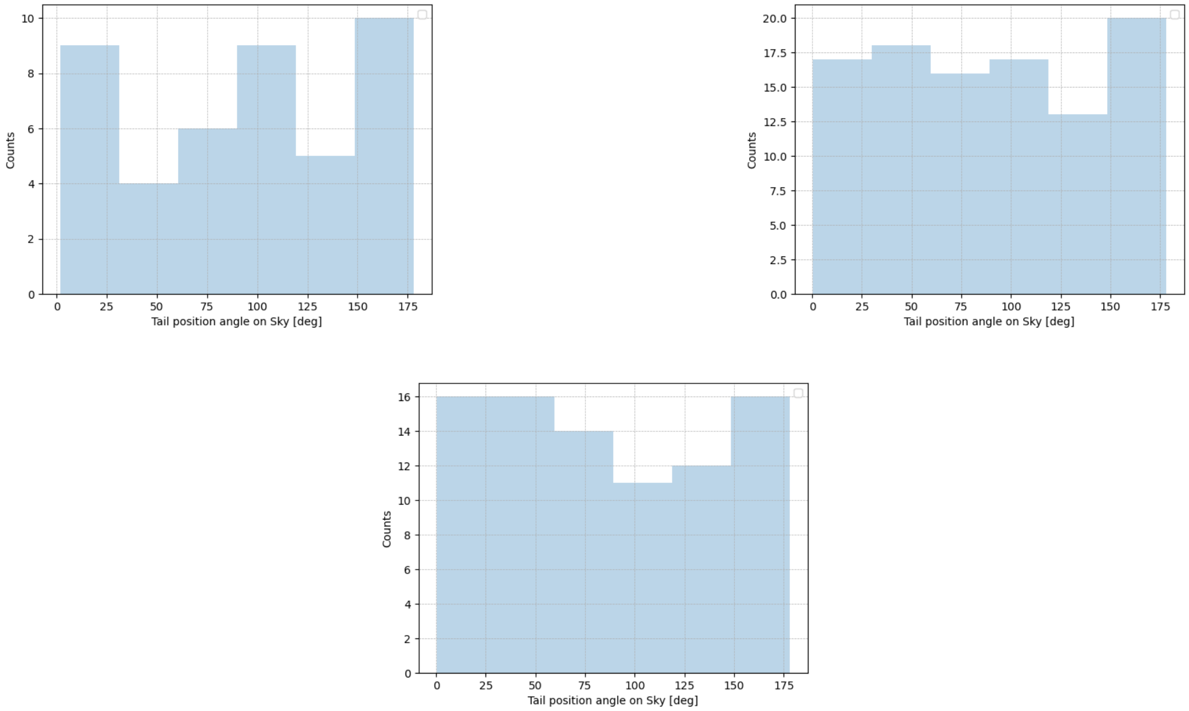


Figure 4.7: Plot showing a distribution of tail directions of Jellyfish galaxies measured by position angle on the sky for each of the three Jellyfish confirmation methods. The *left panel* displays the tails direction distribution for Jellyfish galaxies confirmed using the combination of 6 features. The *central panel* represents the distribution for Jellyfish galaxies confirmed with 4 combined features, and finally, the *right panel* shows the distribution for the case of 5 combined features. The angle position values range from 0 (aligned to host position) to 180 degrees (pointing away of host position), indicating the orientation of the tails with respect to the central cluster position. Peaks in the distributions reveal preferred tail directions for different subsets of Jellyfish galaxies, suggesting variations in the effects of Ram Pressure Stripping in different morphological scenarios.

# Chapter 5

# Conclusions

In this work we focused to characterize a population of Jellyfish galaxies from the properties of the environment in the X-ray that can be measured from the ICM, through optical detection and RGB image processing with which an visual inspection visual to the candidates to be Jellyfish galaxies that suffer the effects of Ram Pressure Stripping can be carried out. With our analysis we were able to identify that Jellyfish galaxies are correlated to the measured X-ray properties of the environment surrounding them in their main host, we show that the fraction of Jellyfish galaxies increases slightly with the mass of their host, which means that mass of the host affects the environment density and thus affects Ram Pressure too and this was a complement to the increase signal found by Roberts et al. (2021) but using a visible sample of Jellyfish galaxies. On the other hand, we show a connection with the properties of the X-ray measurements, we find a relationship between the compactness of density gas distribution parameters beta and core radius , with the angular distance at which the Jellyfish is detected or that RPS is affecting the galaxy, evidencing that in hosts whose gas density is central-concentrated using sub-sets with low beta and/or low core radius we find Jellyfish galaxies at nearby angular distances to the centre and also a range of distances but in comparison with distribution of gas more extended using high beta and/or high core radius there's no evidence of Jellyfish galaxies at nearby centre distances. This is in agreement with the fact that Ram Pressure Stripping, by definition, is related to the density of gas present and their distribution. We also show that the Jellyfish population has a direction of the tails strongly linked to the environment in which it is moving through, since depending on whether it is a massive and dense cluster, it will be more likely to find Jellyfish whose tail direction will be in the opposite direction, while the less massive and less dense groups can be found Jellyfish galaxies whose tail directions are aligned with the main host. The above being consistent with studies of the directions of the tails and showing that our Jellyfish population is mostly in the near redshift groups.

Our study may have some dispersion in the measurements because we are working with 20% of the targets detected within some hosts selected based on a mass and redsfhit criteria, therefore some studies may lack robust statistical measurements. This will be worked on and improved with the inclusion of the approximately 5000 galaxies from the public zoo calibrating their results by using a statistical studies about the difference of votes to figure it out a link between the expert criteria and the public results at the moment to return most Jellyfish galaxies as possible. As well as by improving the photometry, it will be possible to improve the measurement in the selections of the candidates by cutting in a color magnitude diagram instead of just color cut. Also better statistical performance in angular distance or tails direction histograms will be included due to the large of data. Also the actual density profile for hosts will be computed, not only a normalised version that we did here because there was no central density information available in RXGCC that limited our density description. We will vary the tail direction histograms by host-mass, galaxy-mass and concentrated X-ray properties as well. We will study more in details how many unwinding features could be explained by ram pressure stripping and others by tidal interactions using simulations to determine the tail direction produced by both effects and compare them. As well as incorporate simulations that allow to study in better detail the time scale of the tails and their direction to understand how will evolve the galaxy moving through a dense environment considering hydrodynamics effects but also with dark-matter simulation, painting a tail, as Smith et al. (2022) did in population but now using visual jellyfish galaxies sample. And finally will work on a sub-population of galaxies present in our images identified as Break BRD galaxies, which would correspond to an intermediate state between the red sequence and blue cloud galaxies, being a type of 'ancient' jellyfish galaxies.

# Appendix A

# Appendix

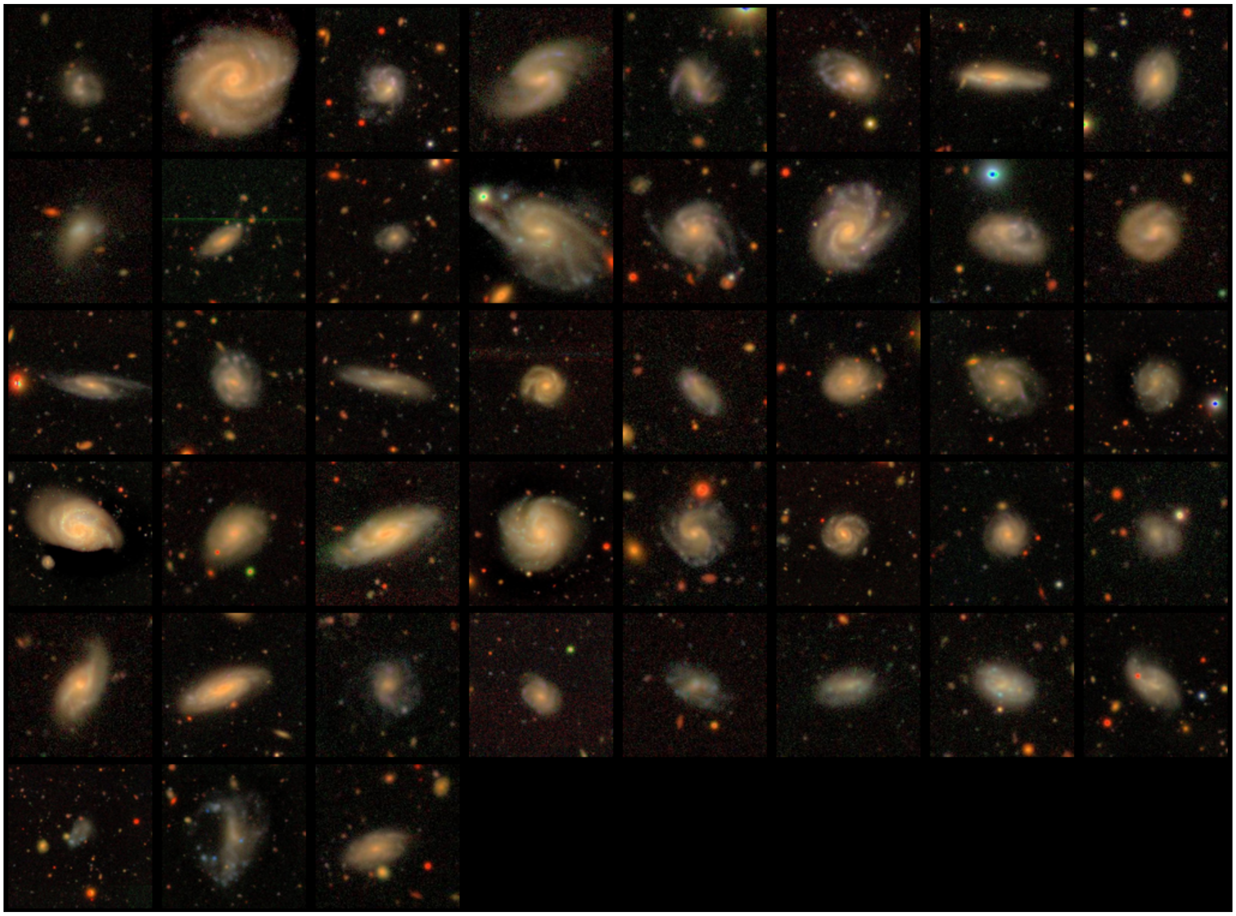


Figure A.1: This collage montage showcases a collection of selected Jellyfish galaxies. These galaxies were identified based on a combination of 6 combined features, as discussed in section 3.2.1. The collage provides a visual representation of the diversity among the selected Jellyfish galaxies and highlights the distinctive features observed in each case.

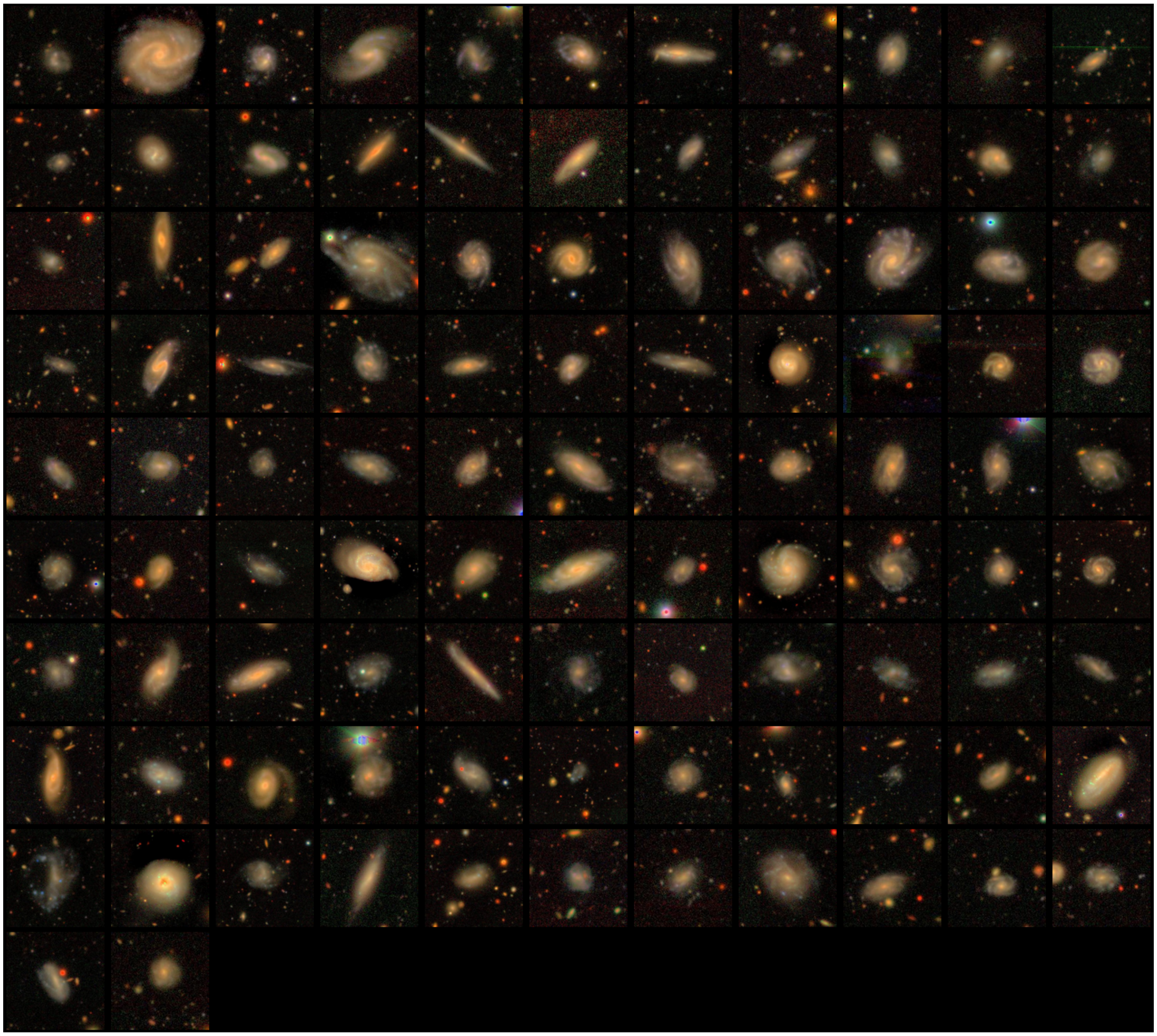


Figure A.2: This collage montage showcases a collection of selected Jellyfish galaxies. These galaxies were identified based on a combination of 5 combined features, as discussed in section 3.2.2. The collage provides a visual representation of the diversity among the selected Jellyfish galaxies and highlights the distinctive features observed in each case.

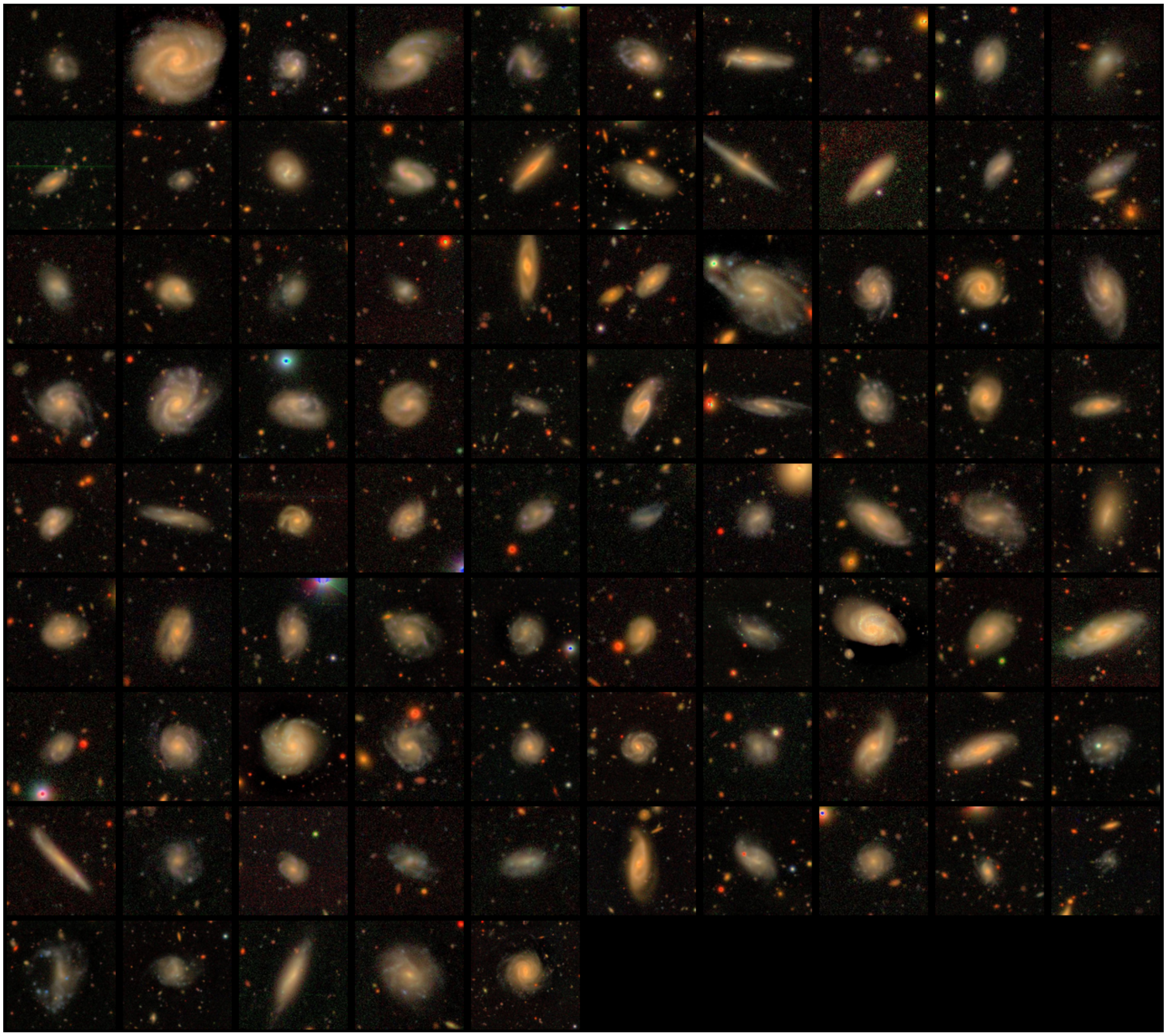


Figure A.3: This collage montage showcases a collection of selected Jellyfish galaxies. These galaxies were identified based on a combination of 4 combined features, as discussed in section 3.2.3. The collage provides a visual representation of the diversity among the selected Jellyfish galaxies and highlights the distinctive features observed in each case.

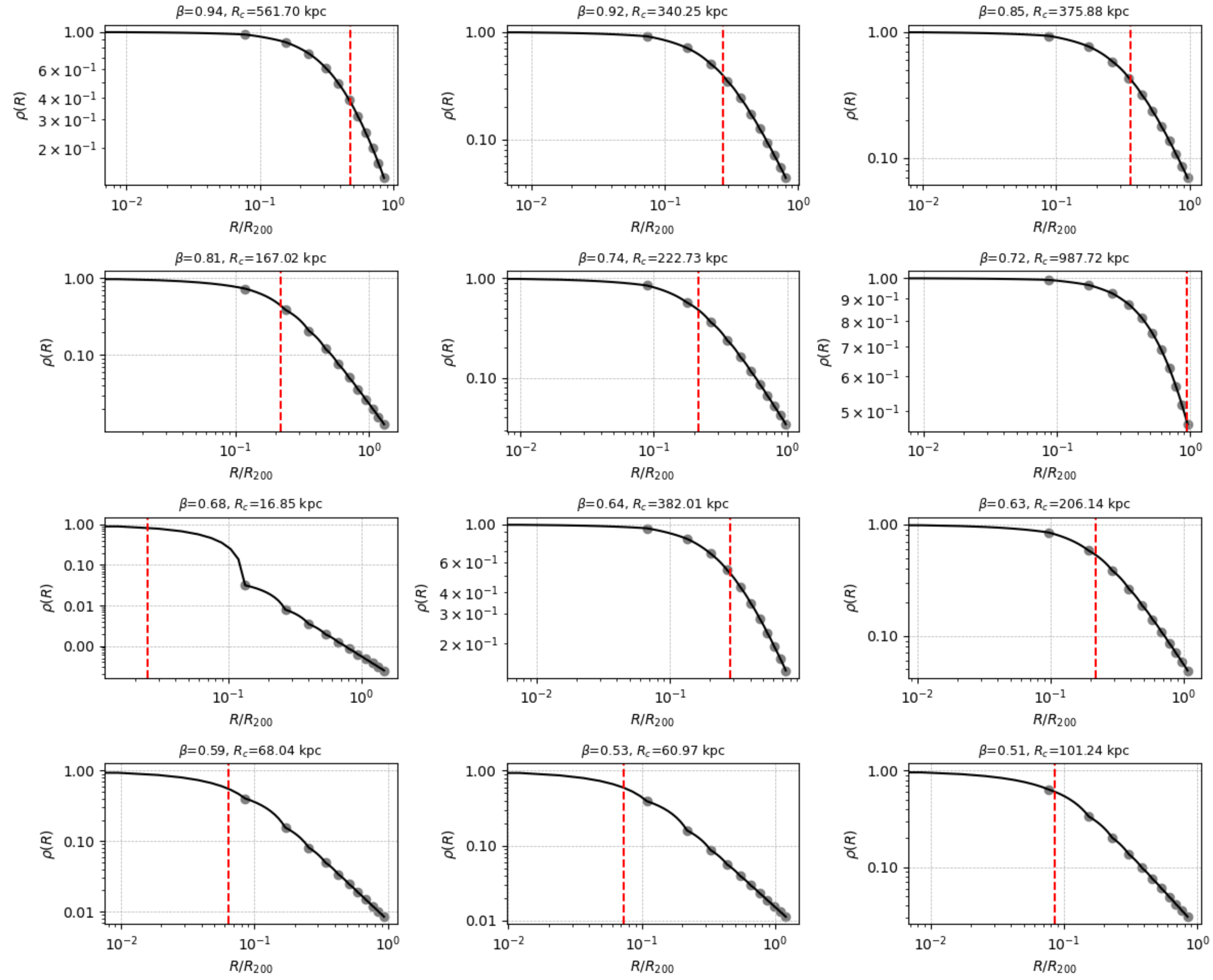


Figure A.4: Set of plots displaying the density profile, see eq. 2.1, for hosts containing Jellyfish galaxies. The plots are arranged in descending order of the Beta value and show a vertical line indicating the position of the core radius. The density is normalized between 0 and 1, as a common central density value is used for all hosts. The host radii are also normalized by using virial radius $r_{200}$ calculated for each cluster. This set of clusters corresponds to the galaxies extracted using the 6-feature combination discussed in Section 3.2.1.

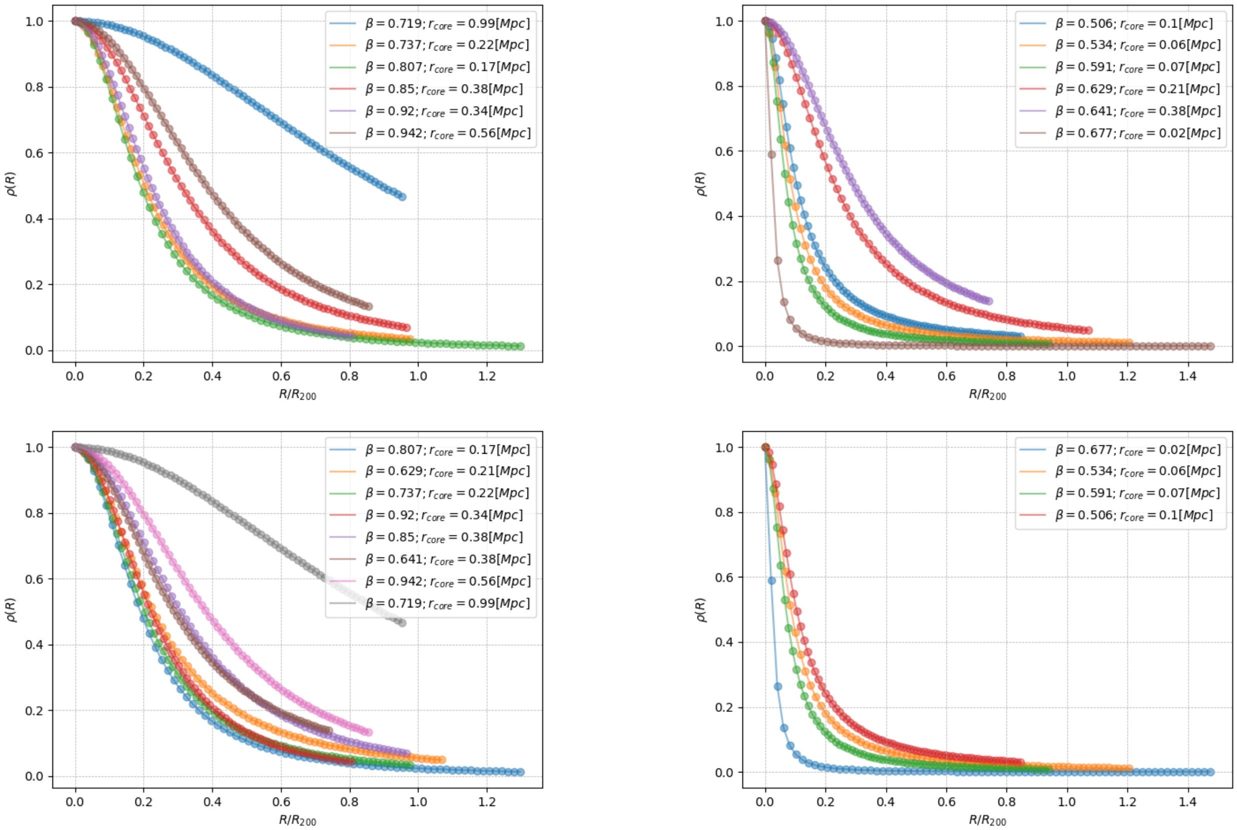


Figure A.5: Set of plots showing the density gas distribution for hosts that contains inside confirmed Jellyfish galaxies selected by 6-combined features, hosts are separated by each $\beta$ and $r_{core}$ sub-sets discussed on sections 4.2.1 and 4.2.2 respectively. *Bottom left panel* shows high $\beta \geq 0.7$ and *Bottom right panel* displays low $\beta < 0.7$ subsets. *Top left panel* shows 50% of highest values of core radius and *Top right panel* displays 50% lowest values of core radius.

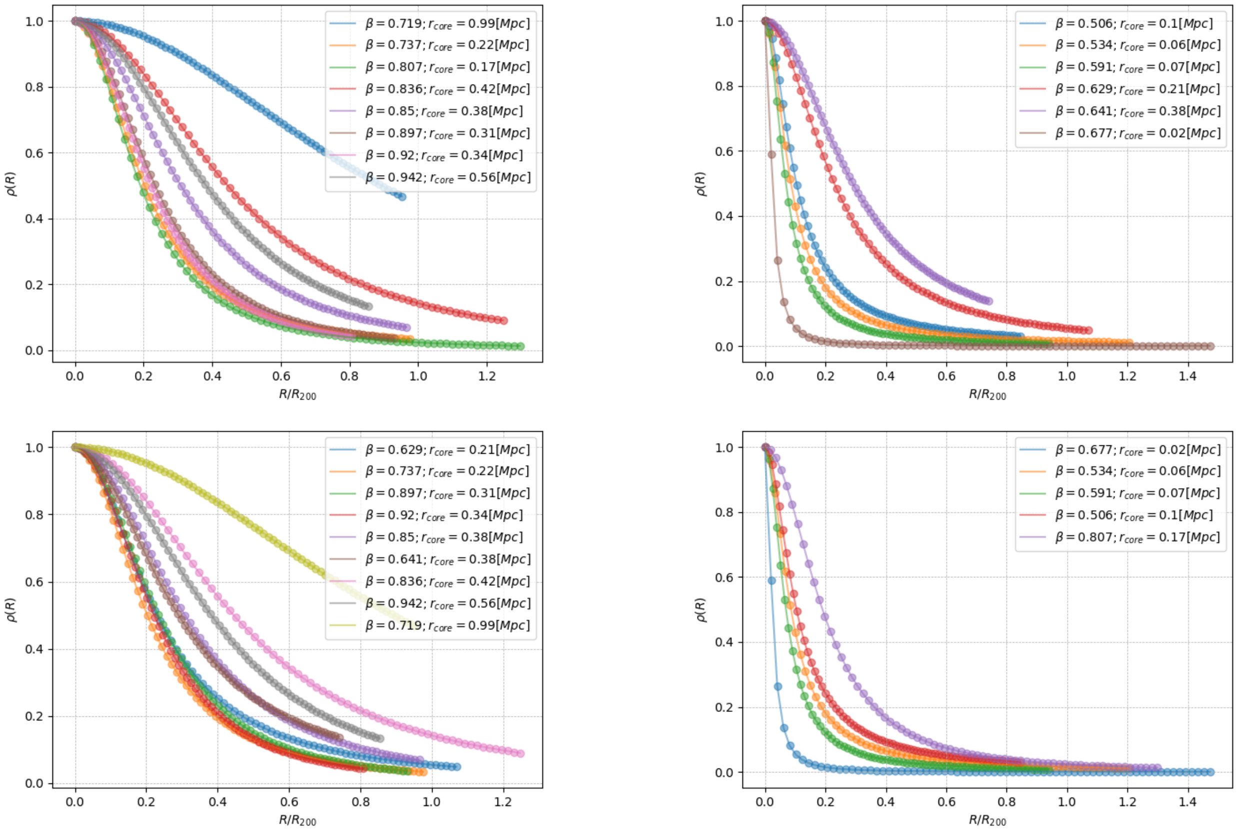
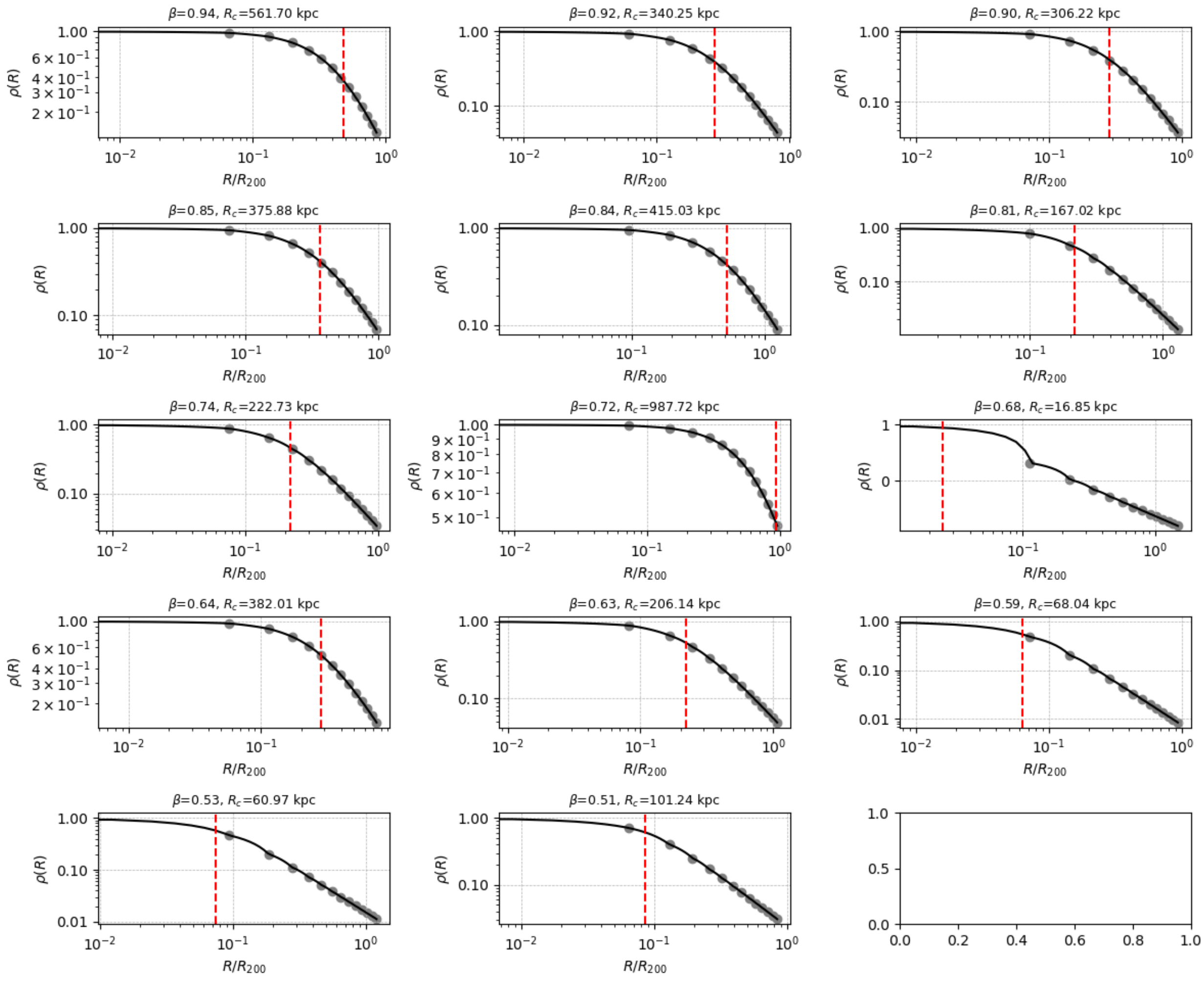


Figure A.6: Set of plots showing the density gas distribution for hosts that contains inside confirmed Jellyfish galaxies selected by 5-combined features, hosts are separated by each $\beta$ and $r_{core}$ sub-sets discussed on sections 4.2.1 and 4.2.2 respectively. *Bottom left panel* shows high $\beta \geq 0.7$ and *Bottom right panel* displays low $\beta < 0.7$ subsets. *Top left panel* shows 50% of highest values of core radius and *Top right panel* displays 50% lowest values of core radius.



$\beta$=0.94, $R_c$=561.70 kpc

$\beta$=0.92, $R_c$=340.25 kpc

$\beta$=0.90, $R_c$=306.22 kpc

$\beta$=0.85, $R_c$=375.88 kpc

$\beta$=0.84, $R_c$=415.03 kpc

$\beta$=0.81, $R_c$=167.02 kpc

$\beta$=0.74, $R_c$=222.73 kpc

$\beta$=0.72, $R_c$=987.72 kpc

$\beta$=0.68, $R_c$=16.85 kpc

$\beta$=0.64, $R_c$=382.01 kpc

$\beta$=0.63, $R_c$=206.14 kpc

$\beta$=0.59, $R_c$=68.04 kpc

$\beta$=0.53, $R_c$=60.97 kpc

$\beta$=0.51, $R_c$=101.24 kpc

Figure A.7: Set of plots displaying the density profile, see eq. 2.1, for hosts containing Jellyfish galaxies. The plots are arranged in descending order of the Beta value and show a vertical line indicating the position of the core radius. The density is normalized between 0 and 1, as a common central density value is used for all hosts. The host radii are also normalized by using virial radius $r_{200}$ calculated for each cluster. This set of clusters corresponds to the galaxies extracted using the 4-feature combination discussed in Section 3.2.3.

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