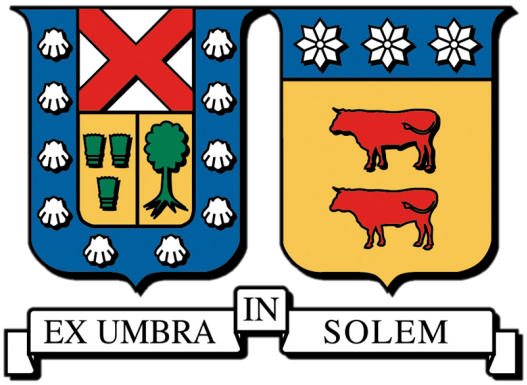
UNIVERSIDAD TÉCNICA FEDERICO SANTA MARÍA

DEPARTAMENTO DE FÍSICA



Mapping Hydrodynamical and Gravitational Effects on Galaxies Around Filaments with Citizen Science

Carolina Dulcien Rojas

MEMORIA PARA OPTAR AL TÍTULO DE LA LICENCIATURA EN ASTROFÍSICA

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Abstract

This thesis explores the application of citizen science via the Zooniverse platform to identify jellyfish galaxies (JF) and mergers within Cluster A1644 at z = 0.0467. Utilizing public classifications obtained through visual inspection, we establish distinct criteria for these identifications and analyze the pre-processing of galaxies to understand the quenching mechanism's variations based on the distance to the cluster center. Our analysis, conducted on a sample of 403 galaxies from the cluster, reveals a 21% overlap between expert classifications and the pure sample for ram pressure stripping candidates. The complete sample for ram pressure stripping (RPS) candidates shows a 60% overlap with expert classifications. For merger candidates, a 15% agreement with the expert sample is observed. Interestingly, Zooniverse-identified merger candidates, on average, have a filament distance 2.10 times closer than that of the average cluster galaxy. This trend reverses when considering expert-classified mergers. No notable disparities in galaxy filament distances are observed between JF galaxies and other galaxies, whether classified by citizen scientists or experts in ram pressure stripping. However, for galaxies beyond $1R_{200}$, JF galaxies exhibit a filament distance approximately 1.20 Mpc greater than that of other cluster galaxies. While the significance of this finding is modest, it may suggest a potential shielding effect for galaxies in close proximity to filaments, a phenomenon observed in simulations. Given the preliminary nature of this study, further exploration could be conducted across additional clusters in the Zooniverse to better understand the influence of filaments.

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Sincerely, Carolina Dulcien Rojas.

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Chapter 1

Introduction

The large-scale structure of the universe reveals a distinctive pattern known as the Cosmic Web. In a λCDM universe, cosmic structures form as dark matter clumps, or "haloes," gradually grow. Galaxies emerge at the centers of these haloes when gas cools and condenses, forming stars as it becomes denser. As haloes combine into larger groups and clusters, they shape the overall structure of the universe (Springel et al. 2006). Galaxy clusters are interconnected by filaments and sheets, with voids dominating its spatial composition (Cautun et al. 2014). Filaments, the most concentrated mass in the universe, exhibit varying connections with clusters based on their respective masses, where more massive clusters have more filaments (Aragón-Calvo et al. 2010). Filaments guide matter to cosmic nodes where galaxy clusters form, creating high-density environments where galaxies interact with each other and with the intra-cluster medium; the clusters, hosting thousands of galaxies, serve as centers for galaxy interactions, for example in dense intra-cluster mediums, star formation in galaxies is rapidly quenched (Lewis et al. 2002). For instance, galaxy's morphology depends in which environment the galaxy lives, more dense regions of the universe are characterized to have elliptical and S0 galaxies (Dressler 1980). Colors also are affected by these factors, being more common that red galaxies live in this dense regions (Peng et al. 2010). The star formation is also influenced by the environment, suggesting that there is a reduced star formation in the clusters than for galaxies of the field. In general, cluster galaxies exhibit significant HI deficiency, lower star formation activity, truncated HI and star-forming disks (Boselli and Gavazzi 2006).

Matter, including galaxies, moves from less dense to more dense areas, undergoing interactions and transformations. This is known to happen in clusters, but can also occur beforehand, termed preprocessing. Preprocessing corresponds to several effects that influence galaxies in cosmic filaments or groups outside clusters, 'transforming' the galaxies before they fall into the cluster (Fujita 2004). Preprocessing could potentially account for the observed suppression of atomic gas content

and star formation activity at considerable distances from the cluster center (Boselli and Gavazzi, 2006; Haines et al., 2015; Bianconi et al., 2018). In this phase, gravitational and hydrodynamic mechanism can impact a galaxy's morphology, star formation, and evolution (López-Gutiérrez et al. 2022). The research of Kotecha et al. (2022), indicate that using simulations with intra-cluster filaments stand out as regions characterized by reduced quenching, enabling cluster galaxies to sustain star formation as they descend further into the cluster, meaning that the filaments protect the galaxy in some region of the cluster, as shown in Figure 1.2, where the 'shielding' happens close to $1R_{200}$ in the filament. However, the study of the influence of filaments in the intra-cluster environment is an unexplored field and hasn't been tested with observations. Exploring the varying influence of filaments on galaxies as they approach contributes significantly to our understanding of the transformation and evolution of galaxies on different environments.

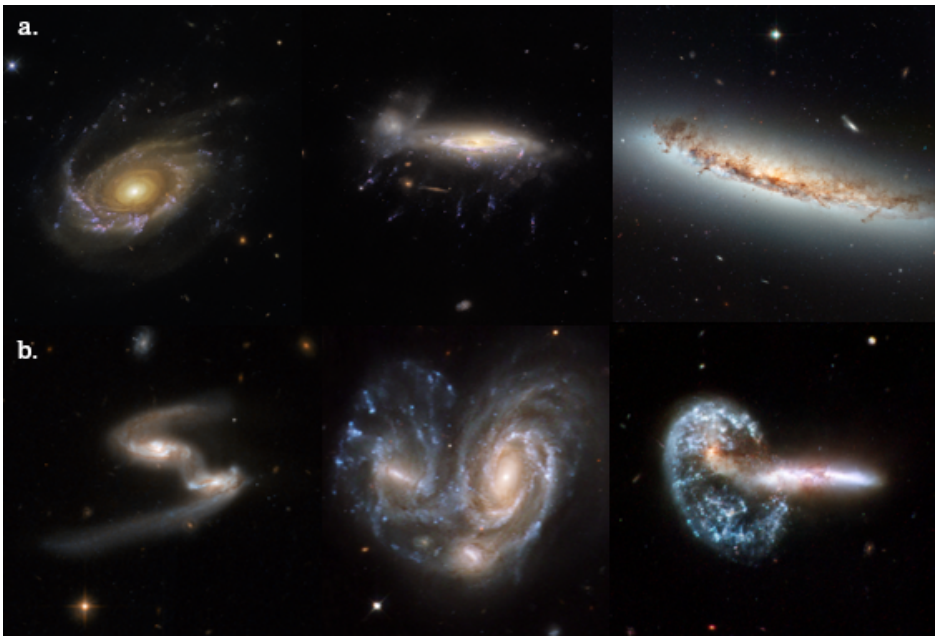


Figure 1.1: Examples of quenching mechanisms, both hydrodynamical and gravitational. (a) JW39, JO204, NGC 4402 (Jellyfish galaxies) (ESA/Hubble & NASA, M. Gullieuszik and the GASP team 2023) (b) Mergers (NASA, ESA, Hubble Heritage Team (STScI/AURA)-ESA/Hubble Collaboration, A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University), K. Noll (STScI), and J. Westphal (Caltech) 2008).

There are two categories of mechanism that can quench galaxies (or preprocess them), this includes gravitational and hydrodynamical effects, as depicted in Figure 1.1. Ram pressure stripping (Gunn and Gott 1972) is among the environmental effects influencing galaxy evolution. When galaxies enter clusters, they frequently undergo gas stripping caused by the ram pressure of the intra-cluster medium, being one of the most efficient mechanisms for affecting the gas reservoir in

cluster galaxies (Vulcani et al. 2022), demostrated with neutral gas (HI) observations of clusters galaxies (Chung et al., 2009; Jaffé et al., 2015). Ram pressure induces the formation of elongated tails of optically luminous stripped material or stars positioned behind galaxies in clusters (McPartland et al., 2015; Smith et al., 2010), commonly referred to as jellyfish galaxies (JF). These JF typically exhibit highly radial orbits as they traverse the dense core of the cluster (Jaffé et al. 2018). Additionally, there is a period during which there is an increase in star formation activity in the disk of these objects, linked to the process that induces disturbed morphologies (Vulcani et al. 2022) to ultimately result in the loss of gas from the galaxy, leading to a decline in star formation activity. The studies affirm that galaxies are found out to 1.5 times the virial radius (Poggianti et al. 2016) but it's worth noting that ram pressure effects may extend beyond this radius, as the search has not explored further distances. Another phenomenon, known as "unwinding galaxies" is being explored as a possible expression of stripped galaxies. These are spiral galaxies with unwound arms displaying a redder hue, heightened brilliance, and increased mass indicative of intensified star formation, also they might enter the cluster at an earlier stage when compared to JF (Vulcani et al. 2022).

Gravitational effects refer to the interactions between galaxies resulting from gravitational forces. Among these effects, tidal interactions manifest when the gravitational forces of one galaxy distort the shape of another, affecting the gas and the stars, leading to the formation of characteristic tidal tails and bridges (Barnes and Hernquist 1992). Mergers, on the other hand, involve the union of two galaxies under the influence of gravity, resulting in a single, often transformed structure (Schweizer, 1982; Toomre and Toomre, 1972). Minor mergers occurs when a larger galaxy absorbs a smaller one, assimilating its stars, gas, and dust (Kaviraj 2015). Harassment involves multiple high-speed close encounters between luminous galaxies (Moore et al. 1996), tends to be more prevalent within galactic clusters or groups. These interactions can have significant consequences on the structure, dynamics, and evolution of galaxies, such as mass, can quenched the star formation and alter the morphology (Darg et al. 2010). For example, mergers induce intense star formation, especially in mergers with spirals (Darg et al. 2010). However, galaxy transformation in clusters is complex, involving factors like cluster mass, X-ray luminosity, dynamical stage, and influx of new spirals from larger structures (López-Gutiérrez et al. 2022). In rich galaxy clusters, tidal interactions between galaxies are intensified. However, due to high relative velocities, these interactions are briefer compared to less crowded areas (Boselli and Gavazzi 2006).

Now that we're aware of interactions that contribute to the quenching of galaxies, the central question guiding our investigation is: What is the function of filaments in the pre-processing of galaxies? Which is the domain mechanism in the quenching of galaxies around filaments? Do filaments shield galaxies and provide better protection from shocks when entering a cluster?

We will devote our attention to the nearby galaxy cluster Abell 1644 (z= 0.0467). We aim to study the different process that can affect galaxy evolution using data from the project called: "Fishing for Jellyfish Galaxies". This is one of the citizen science initiatives of the Zooniverse website to classify galaxies by visual inspection. The impracticality of manually classifying data in extensive surveys necessitates the development of automated methods. To deal with this challenge effectively, it's beneficial to involve the general public in sorting tasks, as demonstrated by Galaxy Zoo (Lintott et al., 2008; Lintott et al., 2011; Willett et al., 2013). Notably, the citizen science for JF project stands as one of the latest projects that extend the search radius to $\sim 2R_{200}$, over other studies as Poggianti et al. (2016). Using the public votes for each galaxy, we use a criteria to find candidates of both type of mechanism, gravitational and hydrodinamical. Once we identify the candidates for each galaxy type, our focus will be on examining their proximity to cosmic filaments to discern the dominant factor (be it gravitational or hydrodynamical) in the process of quenching or influencing galaxies before they reach the core of the cluster. Finally, we study if the preprocesing ocurrs in the vicinity of filaments at large distance from the cluster core, and if the galaxies get protected by the filaments at certain radii ($\sim 1R_{200}$), as mentioned in Kotecha et al. (2022).

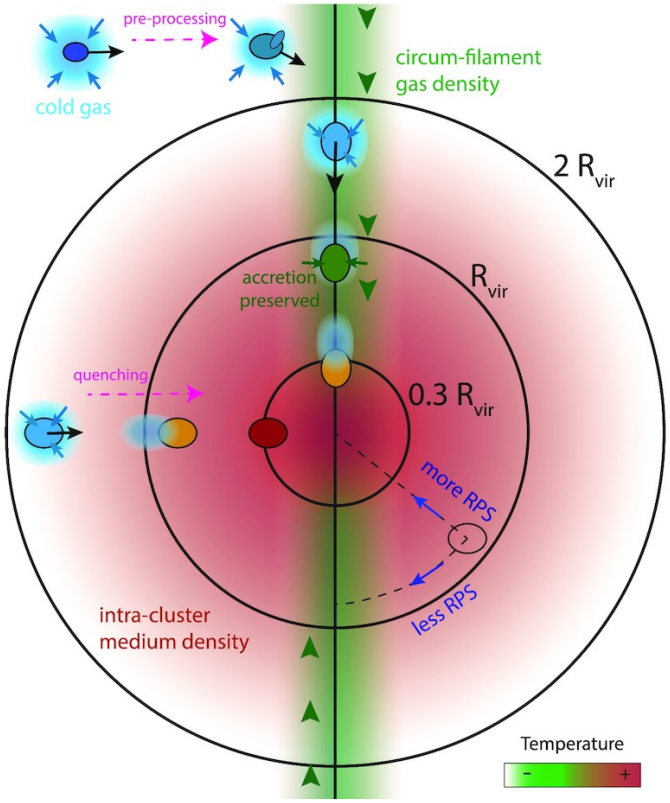


Figure 1.2: Illustration depicting observed trends and proposed mechanisms according to Kotecha et al. (2022). Galaxies outside clusters undergo pre-processing near dense filaments, while inside clusters, proximity to filaments reduces quenching, resulting in a bluer appearance due to decreased strangulation and ram pressure stripping (RPS) in cooler, more coherent filament flows.

The structure of this investigation is outlined as follows: In section 2, we delineate the dataset utilized within the Zooniverse portal and for the large-scale distribution of A1644. In Section 3, we elaborate on the data employed in this project and detail the methods employed to identify jellyfish and merger candidates through public votes. Section 4 presents the result samples for jellyfish galaxies and merger candidates, comparing their distributions of proximity to the filaments with those of other cluster galaxies, including various statistical tests applied to assess their similarity, also the section incorporates the analysis of the distance of jellyfish candidates from the cluster center to explore the influence of filaments. Ultimately, Section 5 provides a summary of our findings and outlines future works.

In this study, we utilize the WMAP9 cosmology (Hinshaw et al. 2013) with a Hubble constant of 69.3 km/s/Mpc and a matter density parameter (Ω_m) of 0.287.

Chapter 2

Data

In this chapter, we present the data utilized in the citizen science project. We also describe the process of creating a catalog through the incorporation of public votes, aiming to identify gravitational and hydrodynamical interactions of the optical images from the Legacy Survey (DR10).

2.1 Zooniverse

We are actively utilizing the Zooniverse platform, specifically engaging with the citizen science project named *Fishing for JF Galaxies*[1]. This project, led by a international group of astronomers[2], aims to enhance the catalog of identified galaxies undergoing ram-pressure stripping, commonly referred to as jellyfish galaxies. In this initiative, participants from the general public are tasked with visually classifying galaxies. The process involves examining two optical images of the galaxy (with different pixel scale) and responding to a series of questions pertaining to their morphology. Figure 2.1 shows the Zooniverse portal, where different questions have representative illustrations in the answers. The project aims to identify galaxies undergoing gas removal (JF), and the questions are specifically designed for this purpose. Figure 2.2 shows the flowchart of the questions present on the web. Please note that if there is a break in continuity of the flowchart, it indicates the conclusion of the survey questions. Additionally, please take into account that the mentioned names essentially represent questions. For instance, 'undisturbed' implies: *Does the galaxy appear to be disturbed and/or asymmetric, in either the close image or the wide image?*, and similarly for the other labels. Also, the voters visiting the site were given a short guide showing examples of different types of galaxies; however, it's important to note that the tutorial is not mandatory.

[1] https://www.zooniverse.org/projects/cbellhouse/fishing-for-jellyfish-galaxies

[2] For more information, please visit https://www.zooniverse.org/projects/cbellhouse/fishing-for-jellyfish-galaxies/about/team

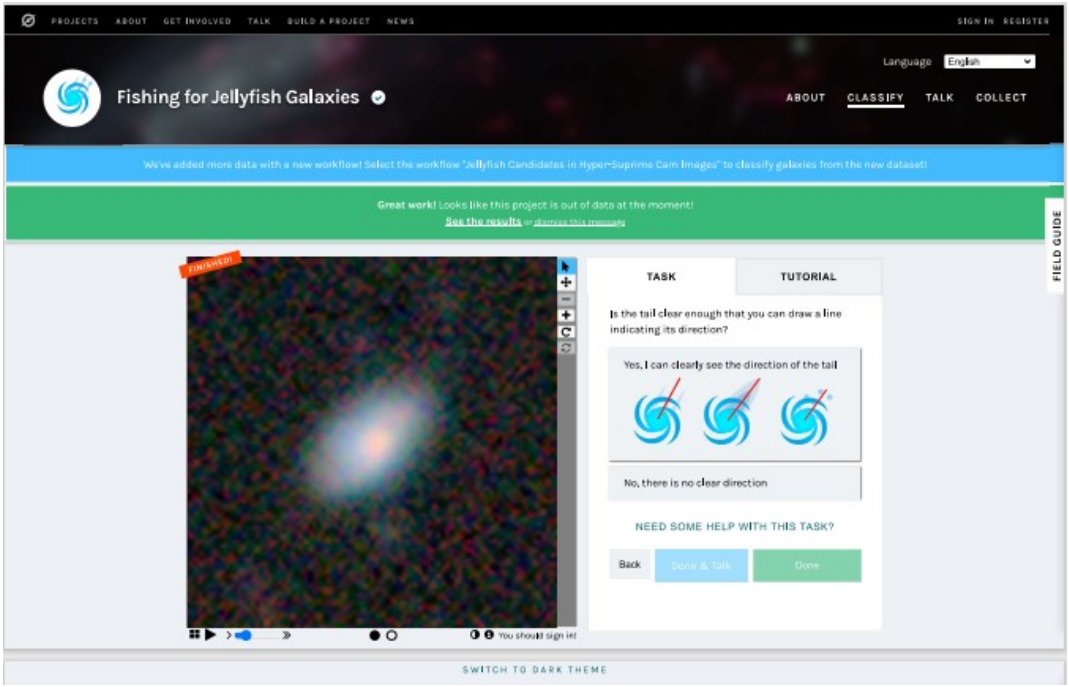


Figure 2.1: Portal for the classification on the citizen project website.

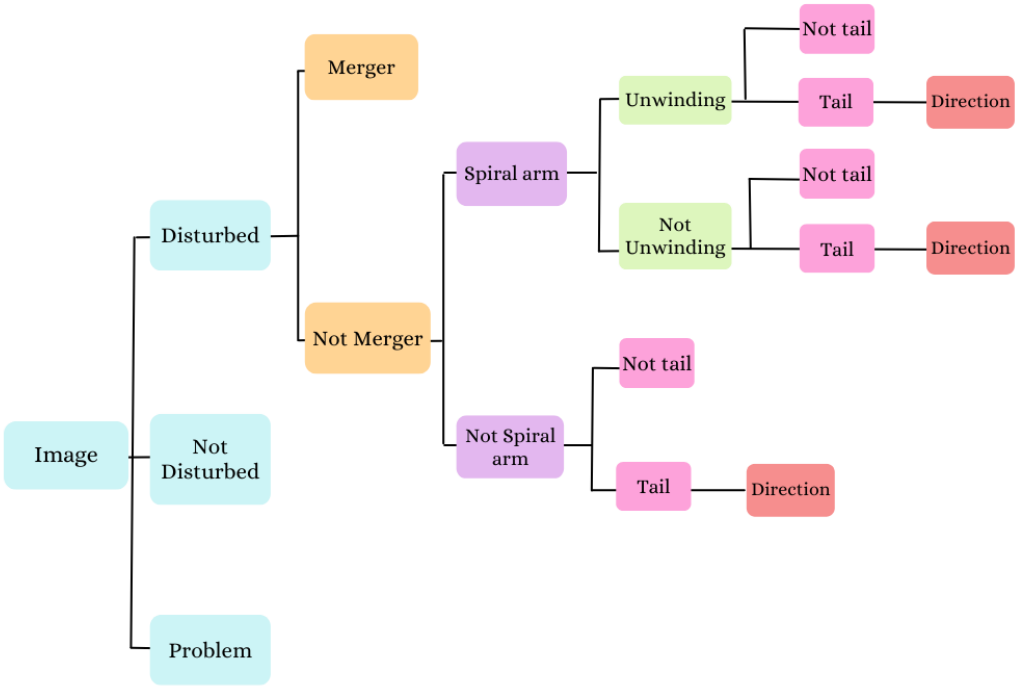


Figure 2.2: Flowchart outlining the series of questions employed in the citizen project for public visual inspection.

The citizen project utilizes a dataset comprising more than 50,000 images sourced from the 9th data release of DECaLS (The Dark Energy Camera Legacy Survey). The dataset specifically features bright spiral galaxies situated within clusters. The galaxies obtained from the portal exhibit a magnitude cutoff ($M_{max} = 19$) in R bands. Also, the source extraction for DECaLS is determined using the exponential disk (EXP), round exponential disk (REX), and modeled by the Sersic profile (SER).

Our research, currently in its pilot[1] phase, is centered around the analysis of the Abell A1644 cluster, which exists at a redshift of 0.0467. The selected galaxies are positioned at distances ranging from the cluster center to $\approx 3R_{200}$[2] . The dataset comprises optical photometry sourced from the public data release (DR10) of the Legacy Survey (LS). DR10 is the tenth public release of Legacy Surveys, comprising three projects: DECaLS, MzLS, and BASS. Covering observations from January 8, 2013, to August 30, 2021, it spans about 14,000 square degrees of the extragalactic sky. Offering imaging data in (g, r, z, i)-bands, including (i)-band observations for the first time, DR10 is publicly accessible for research (Dey et al. 2019).

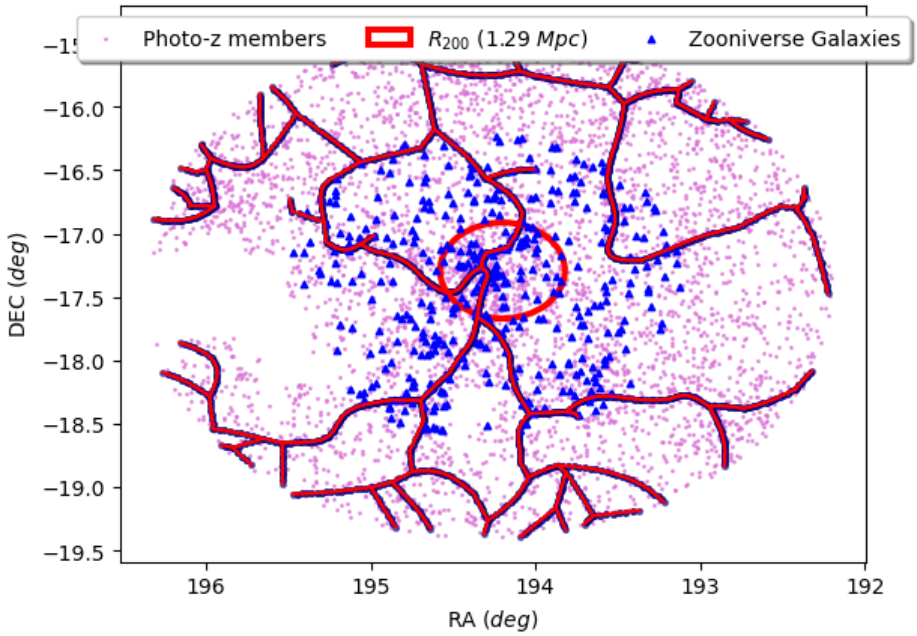


Figure 2.3: Distribution of the galaxies in the cluster A1644. The blue triangles are the galaxies from the citizen science project, from LS DR10. The blue dots are cluster members from S-PLUS. The red circle delineates the approximate boundary of the virial radius. The lines in red/blue are the cosmic filaments.

[1] As our first cluster analysis, it sets the stage for future expansions to explore more clusters.

[2] R_{200} is the virial radius of the cluster. The selected galaxies are positioned at $\approx 3R_{200}$ which corresponds to $\approx$ 3.8 Mpc

2.2 Large-scale environment of A1644

This section explores the cosmic context surrounding Abell 1644. The photo-z (photometric redshift) members featured in Figure 2.3 are derived from the **S-PLUS** (Southern Photometric Local Universe Survey), and ongoing survey that maps the southern sky in 12 optical bands, enhancing photometry and redshift data (de Oliveira C. et al. 2019). The galaxies shown in the Figure 2.3 are employed to delineate the filament structure but are not incorporated in the morphological analysis; their inclusion is solely for visually illustrating the overall large-scale structure of the cluster.

To identify large-scale filaments in and around Abell 1644, DisPerSE was executed on the member galaxies. **DisPerSE**[3] is a program designed for tracing large-scale structures in the universe, specifically focusing on the identification of persistent topological features such as peaks, voids, walls, and filaments in 2D or 3D datasets. Figure 2.3 illustrates the distribution of galaxies along the sky within the cosmic filaments in our cluster, with galaxies classified by participants in the citizen science project marked by green dots. The blue dots indicate galaxies that are cluster members, obtained with S-PLUS.

[3]The analysis was not personally conducted; Lawrence Bilton and Raul Baier mapped the filament structure.

Chapter 3

Methods

In this chapter, we elucidate the methods employed to amalgamate citizen science votes, aiming to categorize galaxies based on their morphology. Additionally, utilizing these candidates, we calculate the distance from each galaxy to the nearest filament to study the pre-processing of galaxies.

3.1 Finding Candidates with Public Votes

We use votes from the citizen science project to determine each galaxy morphology. Each galaxy is assigned 10-11 classifications (disturbed, undisturbed, problem) from different voters, each class linked to a specific number of votes. Within the disturbed class, there are sub-classifications including merger, unwinding, and tail. For clarity, Table 3.1 presents a concise illustration of this data, with each row representing an individual galaxy. Also, the data contains the coordinates for each galaxy, magnitudes, users of voters, pixel scale of the 2 images in the website, etc.

ID	N	Disturbed v.	Undisturbed v.	Problem v.	Merger v.	Unwinding v.	Tail v.
84302108	10	2	6	2	2	0	0
84302416	10	8	1	1	1	3	5

Table 3.1: A short representation of the citizen project vote data, with each column detailing the votes for each class or subclass. 'N' represents the total number of classifications.

To determine which galaxies are disturbed by tidal and/or ram pressure, we establish conditions using the the vote fraction for each class and subclass, as specified in equations (3.1) and (3.2). So, for each galaxy we have different fractions of disturbed, undisturbed, etc. The fractions are given by

$$F_{class} = \frac{N^{\circ}\ votes}{N^{\circ}\ classifications} \tag{3.1}$$

$$F_{subclass} = \frac{N^{\circ}\ votes}{N^{\circ}\ disturbed\ votes} \tag{3.2}$$

Where F_{class} corresponds to the fraction for disturbed, undisturbed or problem and $F_{subclass}$ is the formula for the fraction of merger, unwinding, tail or no tail. Note that $F_{subclass}$ depends on disturbed class fraction, as indicated by the flowchart (See Figure 2.2).

Figure 3.1 shows the distribution of votes in our cluster. The problem fraction is notably high. It's crucial to understand that selecting the 'problem' option in the portal indicates an issue with the image, preventing accurate classification. We examine 'problem galaxies' characterized by a fraction of 0.5 to 0.9 (see Figure 3.2 for examples). Since the real problem galaxies do not necessarily have a high problem fraction, we can infer that the problem fraction is not a relevant factor to consider to produce a catalogue with the votes.

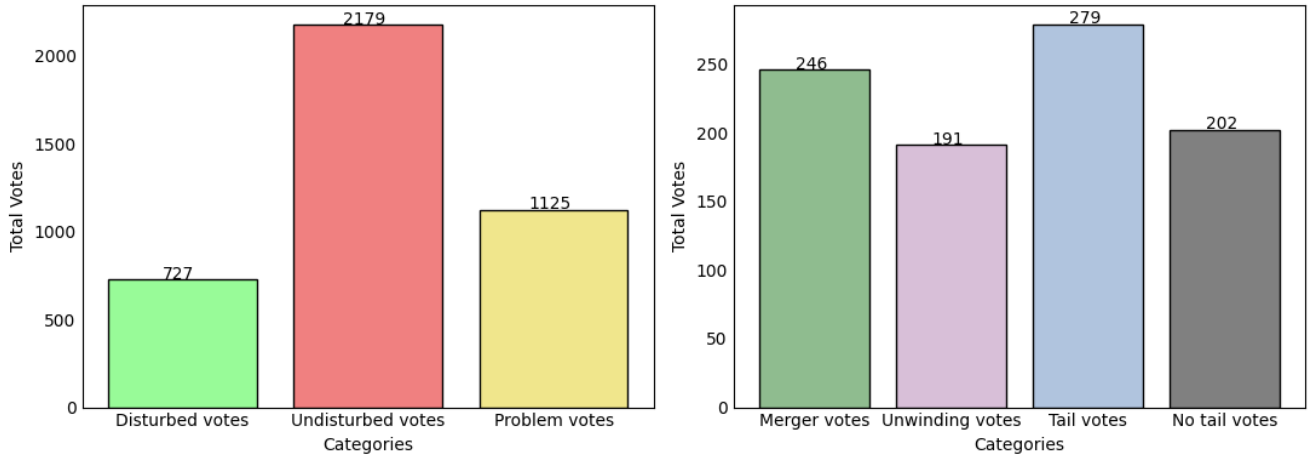


Figure 3.1: Distribution of votes in the A1644 cluster. The plot on the left represents the main categories, while the plot on the right provides the subclassifications within the 'disturbed' class.

As depicted in Figure 3.1, the **votes** have been categorized into seven distinct classes, excluding the spiral arm votes[1]. However, **classifications** are narrowed down to four main categories: undisturbed, problem, merger, or jellyfish. It's important to note that unwinding is not treated as a separate class; rather, it is considered a distinctive feature. This decision was made due to the challenge of distinguishing between unwinding with tails and unwinding without tails[2].

[1]Spiral arm votes were not provided for this analysis.
[2]Not unwinding votes were not provided for this analysis.

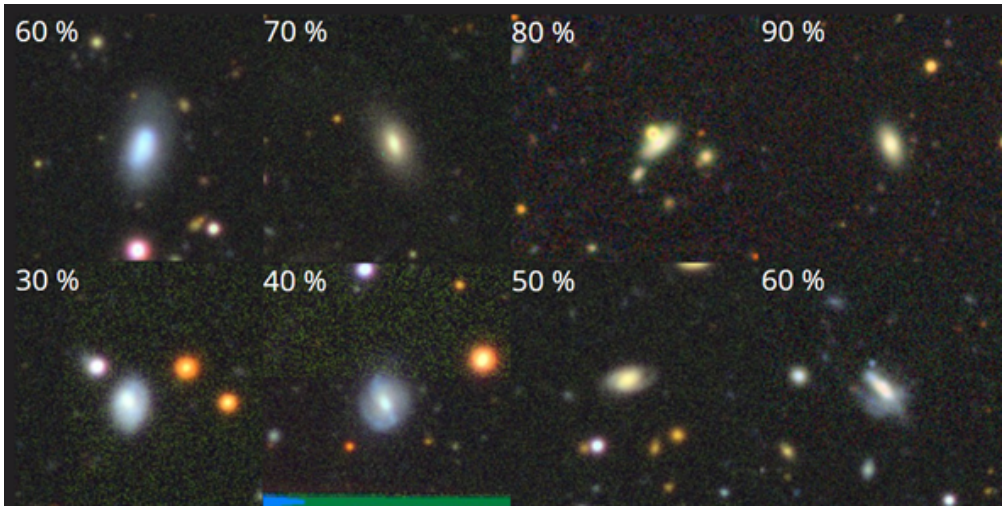


Figure 3.2: Examples of galaxies with high problem vote fractions in cluster A1644, listed from highest to lowest.

3.1.1 Expert sample

In order to evaluate the accuracy and reliability of citizen scientist votes, we have classified by visual inspection[3] the entire sample of galaxies from cluster A1644. This sample exists to confirm the purity and the completeness of the above criteria. Additionalyy, implementing this sample can help us improve the criteria for future works, by applying them to more clusters of the Zooniverse project. On the other hand, the expert classification allows us to include the galaxies that really represent RPS or mergers, in order to make a more precise study of the influence of the filaments in the preprocessing.

The purity and the completeness are given by equations (3.3) and (3.4).

$$\rho = \frac{N^{\circ}_{JF}\ expert\ \ in\ C}{N^{\circ}_{JF}\ C} \tag{3.3}$$

$$\zeta = \frac{N^{\circ}_{JF}\ expert\ \ in\ C}{N^{\circ}_{JF}\ expert} \tag{3.4}$$

Where ρ corresponds to purity of the sample and ζ is the completeness of the sample. C represent the generated samples (Pure, Complete). Note that purity compares galaxies from the expert sample within specific criteria against the citizen science candidates within those criteria, where purity addresses the question: 'How many expert-classified candidates are in the citizen science selected sample?. Conversely, Completeness compares the galaxy candidates from the

[3]Yara Jaffé, Jacob Crosset and Carolina Dulcien, acting independently, individually classified all the cluster sample of Zooniverse.

expert sample, where Completeness answers: 'How many expert-classified candidates are we not considering in citizen science selected sample?'. Figure 3.3 provides a more representative way to comprehend both concepts.

For simplicity, we classified using the categories (1) undisturbed, (2) merger, (3) jellyfish, (5) problem with (-) unwinding as extra feature. We classified 403 galaxies, encountering 20 instances of disagreement. To facilitate this process, we employed a confidence value as shown in Table 3.2.

Confidence	Meaning
1	All disagree
2	2 people agree
3	All agree

Table 3.2: Confidence values for the expert's classifications.

As we see in Table 3.2, each galaxy have a different confidence value based on the agreement of the voters. To generate the expert sample, we only considerate galaxies with confidence 2 and 3. Also, we include a column indicating if the galaxy has unwinding arms.[4]

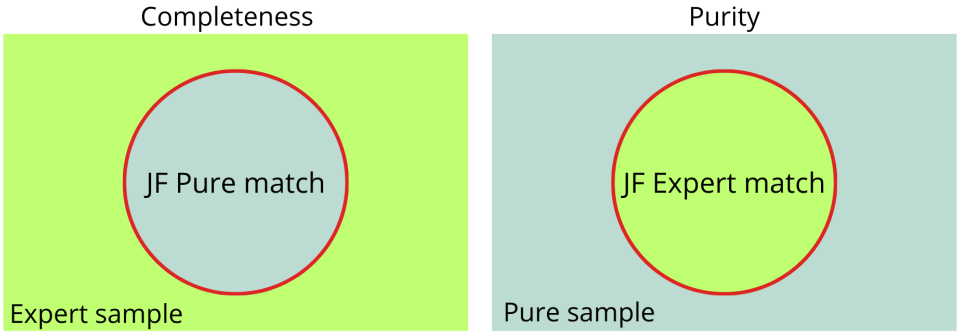


Figure 3.3: Visual representation illustrating the distinction between completeness (left panel) and purity (right panel). For simplicity, the 'pure' sample represents the criteria created, which can be either the complete or the merger sample.

3.1.2 Jellyfish sample

The citizen science project was initiated with the motivation to identify more galaxies experiencing gas removal. The search radius was expanded in comparison to previous studies, such as Poggianti et al. (2016). That's why the flowchart, from disturbed to non-merger options, is designed for the identification of jellyfish galaxies. Tails votes play a significant role in this search, and in some cases, the unwinding effect is considered as a possible phenomenon related to ram pressure stripping (RPS).

[4]Unwinding galaxies may indicate interactions between galaxies or ram pressure stripping.

A *complete* sample

As mentioned earlier, the utilization of the expert sample serves the purpose of validating the number of JF from the pure sample within the generated samples and assessing the overall completeness of the dataset. This criterion aims to maximize the collection of candidates, ensuring a higher level of completeness. Notably, this criterion was established by referencing galaxies from Poggianti et al. (2016), which were previously classified as ram pressure stripping candidates. Our incorporation of conditions is based on the fractions observed in these nine galaxies. Through experimentation with various criteria, we determined that this particular criterion resulted in the highest fraction of completeness, as specified in Section 4 (Table 4.1). The criteria is given by equation (3.5)

$$F_{disturbed} \geq 0.3 \ \& \ F_{notmerger} \geq F_{merger} \tag{3.5}$$

Where $F_{disturbed}$ represents the disturbed fraction, $F_{notmerger}$ is the sum of tail and no-tail fractions, F_{merger} is the merger fraction. Note that the sum of fractions for disturbed, undisturbed, and problem classifications equals 1. As mentioned earlier, the problem fraction is not relevant to consider in the search. Since the majority of the galaxies (all except one) have a higher undisturbed fraction than disturbed, we establish a specific disturbed fraction, approximating the mean disturbed fraction of the nine galaxies of Poggianti et al. (2016). Additionally, since the tails fraction does not exceed 0.2, we do not include it as a condition for identifying jellyfish galaxies. Please refer to Figure 4.6 to view the fractions of each class/subclass.

Additionally, we only consider the non-merger fraction for this purpose. This fraction includes the tail fraction plus the no-tail fractions. If we use '$>$' instead of '$\geq$', we lose 4% of completeness (missing seven galaxies) and gain 1% in purity. Consequently, we would not include two Poggianti Galaxies.

It is crucial to acknowledge that the galaxies undergoing ram pressure stripping within this cluster lack distinctive features. Therefore, dismissing the presence of a tail is not inaccurate. Some galaxies exhibit a jellyfish-like morphology, characterized by a disk with a curved profile on one side, as exemplified in the third case of Figure 1.1. In these scenarios, star formation is concentrated in a specific side of the galaxy, precluding the observation of tails. In conclusion, not considering the tail fraction allows us to include cases of ram pressure stripping that may not be so evident (in other words, a low JClass). Figure 3.4 displays some of the candidates for the complete sample.



Figure 3.4: Examples of ram pressure stripping candidates from the Complete sample generated with the citizen science votes.

A *Pure* sample

The pure sample aims to obtain the least expert non-jellyfish, increasing purity. This criterion is more stringent in the selection of jellyfish galaxies, giving priority to those with a higher disturbed fraction compared to the undisturbed fraction, while excluding cases where the problem fraction is not taken into account. If we were to include the cases where $F_{disturbed} = F_{undisturbed}$ we would gain completeness (+7 galaxies), increasing it by 3% more, but loss purity (-12%).

For the tail fraction, we establish that it must be greater or equal to the half of the votes of the subclasses. The reason behind this is for simple majority[5] where this method typically employs more of the majority to election ('>'), we have chosen to use '$\geq$' to improve the completeness, where we would loss 6% using '>'.

We also include the not merger fraction to avoid mergers in our sample. The decision behind using '$\geq$' instead of $>$ is to include more expert jellyfishes (more purity). The conditions for pure criteria is given by equation (3.6).

$$F_{disturbed} > F_{undisturbed} \;\; \& \;\; (F_{tail} \geq 0.5 \;\; or \;\; F_{notmerger} \geq F_{merger}) \tag{3.6}$$

$F_{disturbed}$ represents the disturbed fraction, $F_{undisturbed}$ denotes the undisturbed fraction, $F_{notmerger}$ is the sum of tail and no-tail fractions, F_{merger} is the merger fraction and F_{tail} is the tail fraction.

In Figure 3.5 is shown some examples of pure jellyfish galaxies .The specific value for purity and completeness is shown and discuss in Section 4.

[5]A simple majority is a voting requirement in which more than half of the total votes ($> 50\%$) cast is needed for a proposal or candidate to be considered approved or elected.



Figure 3.5: Some examples of ram pressure stripping candidates from the Pure sample generated with the citizen science votes.

3.1.3 Merger sample

In the website, the public must identify through visual inspection different types of galaxies, including interactions between galaxies. These interactions incorporate mergers between two or more galaxies, which are characterized by "bridges" or, in some cases, multiple cores or tails.

We create a sample of merging galaxies using citizen science votes from Zooniverse, implementing criteria primarily based on the disturbed and merger fractions. The criterion is defined as follows,

$$F_{disturbed} > F_{undisturbed} \ \& \ (F_{merger} > F_{notmerger} \ \ or \ \ F_{merger} > 0.5) \tag{3.7}$$

Where $F_{disturbed}$ represents the disturbed fraction, $F_{undisturbed}$ denotes the undisturbed fraction, $F_{notmerger}$ is the sum of tail and no-tail fractions, and F_{merger} is the merger fraction.

As we see in equation (3.7), this criterion ensures the exclusion of any undisturbed galaxies, even galaxies that equal votes of disturbed and undisturbed; the gravitational asymmetries associated with disturbances, such as mergers, can manifest in various observable features, including tidal tails, distortions in the galactic morphology, and changes in brightness profiles.

The fraction of merger votes must be greater than the fraction of non-merger votes[6] (See Figure 2.2). This criterion is established to exclude the hydrodynamical interactions. Specifically, the fraction of tails, even though it could be relevant to use in the selection criteria, is not considered within the scope of this identification, because the tail votes are intended for identifying galaxies

[6]Non-merger votes are the sum of tail votes and no-tail votes.

experiencing ram pressure stripping, even the tail votes requests to specify the direction of the tail in order to find that gas removal.

Additionally, we introduce a value of 0.5 for the merger fraction (F'_{merger}), indicating the percentage of disturbed votes attributed to merger events. This helps us understand the proportion of total disturbed votes specifically related to mergers. Without this adjustment, we observe a purity of 50% and completeness of 17.3%, which is relatively low. Additionally, we opt for '$>$' instead of '$\geq$' to enhance purity. Making these changes results in a 13.5% increase in purity and a 7.7% increase in completeness.

The purity and completeness of this selection is specified in Section 4. It appears that there is no list of mergers that aligns with our observations, preventing us from making comparisons with samples from previous studies. Figure 3.6 shows some examples of mergers candidates, with the merger fraction in the upper left.

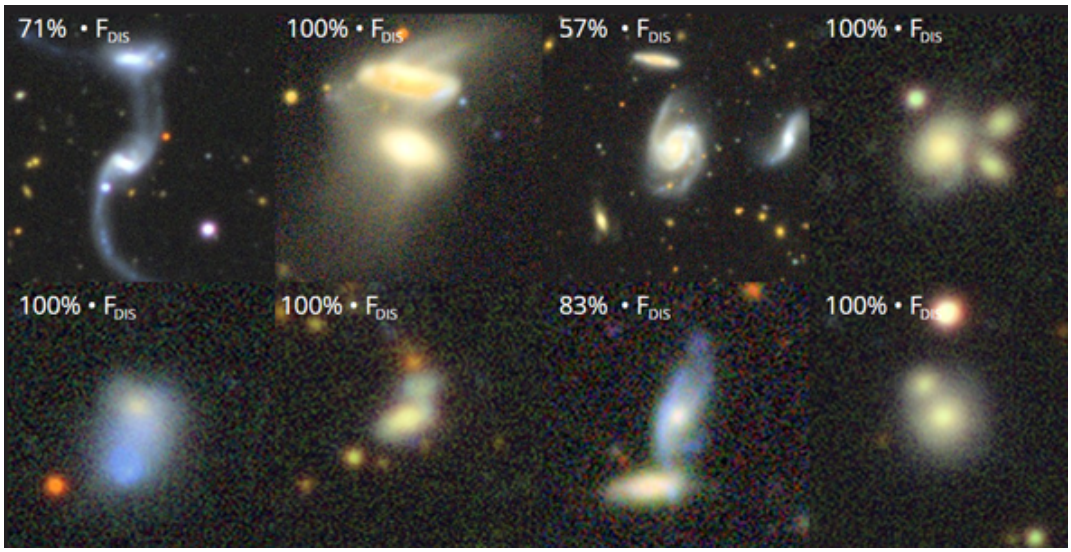


Figure 3.6: Examples of merger candidates generated with the citizen science votes. The upper left in each image indicates the fraction of merger votes.

3.2 Nearest Distances to Filaments

After the candidate selection process, our primary objective is to analyze the specific locations where the pre-processing takes place. In other words, we aim to determine whether the galaxies are close or far away from the filaments. To achieve this, we calculate the distance to the nearest filament for each selected candidate. Note that this calculation is performed in two dimensions, where the redshifts of each galaxy are not being considered.

In general, the code[7] computes the shortest distance from a point to a line segment (filament) defined by two endpoints, as shown in Figure 3.7. Then, finds the closest line segment from an array of segments (filaments) to a given point (galaxy) using the coordinates (ra,dec). The main function converts Cartesian coordinates to polar coordinates, scaling distances from the input file unit to megaparsecs. The function also determines the closest line segment to each galaxy in a catalog and calculates the distance in degrees, and converts it to megaparsecs using the redshift.

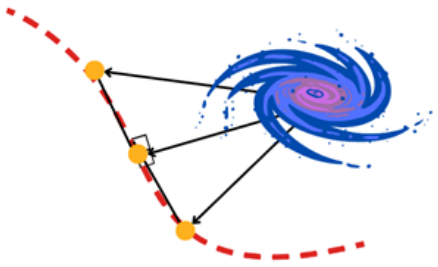


Figure 3.7: Visual representation of the calculation made to compute the perpendicular distance between the candidates and the filaments.

[7]This code was provided by Lawrence Bilton.

Chapter 4

Results

This chapter highlights the main findings from a catalog created through public votes on Zooniverse. The catalog focuses on galaxies experiencing ram pressure stripping (JF) and gravitational effects (mergers). The objective is to establish a criterion characterized by enhanced purity and completeness, laying the groundwork for the expansion of the catalog to more clusters of the Zooniverse in future research works. Using data from these galaxies, we calculate their closest proximity to cosmic filaments to gain insights into the role of filaments in the pre-processing of galaxies. We analyze the identified candidates to discern the predominant mechanisms responsible for quenching galaxies. Additionally, we investigate whether filaments provide protection to galaxies (avoiding quenching) within specific radii, aiming to validate the findings reported by (Kotecha et al. 2022).

4.1 Candidates

The **jellyfish candidates** from the Zooniverse are divided in two groups: Complete and Pure sample. Table 4.1 shows three catalogs of them, along with the corresponding number of galaxies acquired, based on the criteria outlined in Section 2. Additionally, it includes the number of galaxies from the study of Poggianti et al. (2016), purity and completeness based on the Expert sample..

Criteria	$Total_{gal}$	$Total_{\%}$	*Purity*	*Completeness*	$Poggianti_{gal}$
Complete JF	89	22%	43.8%	60.9%	4
Pure JF	19	5%	73.6%	21.8%	1
Expert JF	64	15.8%	-	-	4
Merger	13	4.7%	61.5%	15.4%	-
Expert Merger	52	12 %	-	-	-

Table 4.1: Comparison of different selection criteria: total number of galaxies, sample comparisons, purity, and completeness metrics.

JF Zoo candidates

The Pure sample is established with the objective of including only expert JF, and extending these conditions to additional Zooniverse clusters. Expanding the list of galaxies experiencing ram pressure helps us learn more about how galaxies evolve, and as we will mentioned, it enable us to study in a more robust way the pre-proccesing outside galaxy clusters.

Alternatively, the Complete sample allows us to create a more complete catalog, albeit with the consequence of potentially including non-candidates. The incorporation of a complete catalog may encompass instances of RPS that exhibit less prominent features.

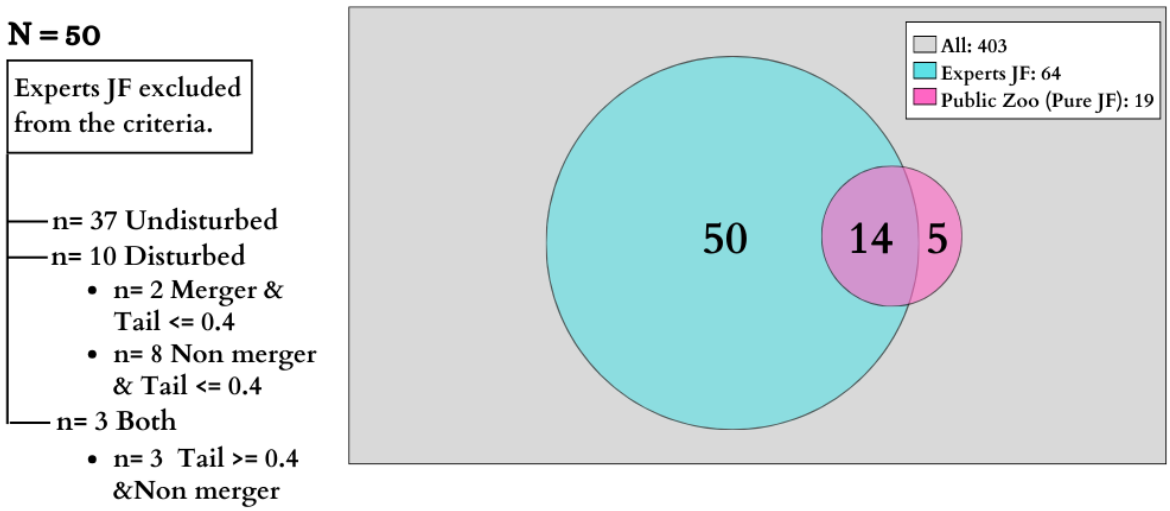


Figure 4.1: Comparison diagram illustrating distinctions among total galaxies, an Expert sample, and a JF Pure sample. The overlapping circles symbolize the matched galaxies between the Expert sample (cyan circle) and Pure sample (pink circle). On the left, the galaxies excluded from the Expert sample are displayed.

As shown in Figure 4.1, 19 JF (pure sample) galaxies were identified as candidates using the public votes by applying the condition 3.6, meaning that 50 expert classified galaxies (out of 64) were not included (as per Equation 3.6). Further details regarding the excluded galaxies are provided below:

- 50 of the excluded galaxies were undisturbed ($F_{disturbed} < F_{undisturbed}$).
- Only 10 galaxies were disturbed ($F_{disturbed} > F_{undisturbed}$), with 2 having a higher fraction of merger and 5 displaying non-merger characteristics but with a low fraction of tail.
- For the 3 cases where $F_{\text{disturbed}} = F_{\text{undisturbed}}$ (In figure, 'both'), a higher non-merger fraction was observed, along with $F_{\text{tail}} \geq 0.4$.

Changing the tail fraction to 0.4 would give as more completeness (+6 galaxies, $\zeta \approx 25\%$) and less purity ($\rho \approx 68\%$).

The public might observe more undisturbed galaxies from the Expert sample; this observation could be related to the possibility that JF galaxies in this cluster do not exhibit prominent features, since we observe that there are candidates identified by experts that do not show tails (See Figure 4.2). Also, it could be due to the public not completing the tutorial (as it was not mandatory) or potential issues with the image. Additionally, there are expert-identified candidates that resemble irregular galaxies, where they are indeed disturbed, but the public may not be familiar with this type of galaxy image, making classification challenging.

Additionally, it's important to consider that the Expert sample is based on assessments from only three experts. If more experts were included ,there is a possibility that the JF sample size could be reduced, potentially leading to increased agreement with the public. Moreover, the inclusion of more experts could help mitigate any potential bias in the sample.

In general, some of the expert JF candidates exhibit asymmetries rather than prominent tails, leading to disagreement with the public's identification of JF. The ideal future scenario would be to confirm these candidates through observations in H-alpha or HI.

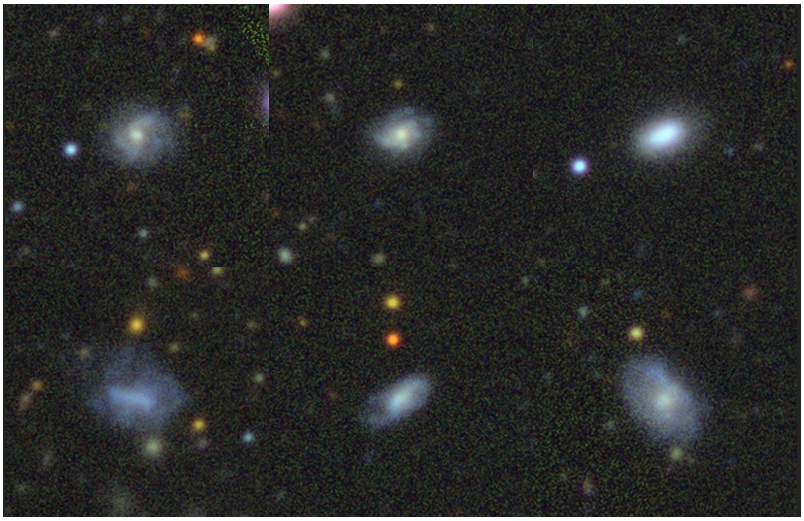


Figure 4.2: Examples of expert JF candidates that went unnoticed by the public, where tails are not prominent.

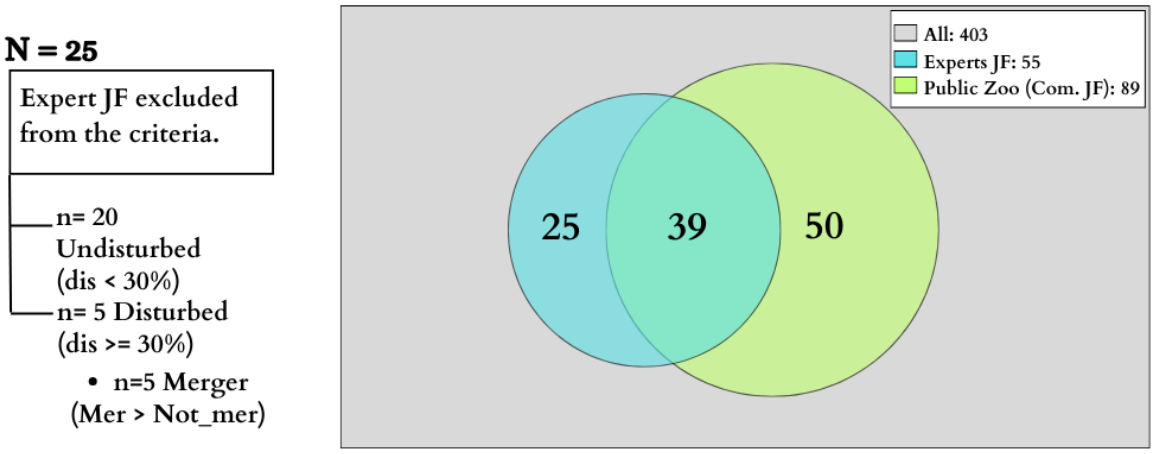


Figure 4.3: Comparison diagram illustrating distinctions among total galaxies, an Expert sample, and a JF Complete sample. The overlapping circles symbolize the matched galaxies between the Expert sample (cyan circle) and Complete sample (green circle). On the left, the galaxies excluded from the Expert sample are displayed.

As shown in Figure 4.3, 89 galaxies were found using the complete sample by applying the condition, meaning that 25 expert classified galaxies (out of 64) were not included. Further details regarding the excluded galaxies are provided below:

- 20 of the excluded galaxies were undisturbed, meaning that $F_{disturbed} < 30\%$.
- Only 5 galaxies were disturbed ($F_{disturbed} \geq 30\%$), having a higher fraction of merger than non-merger.

As we mentioned, this criteria includes the non obvious cases of ram pressure stripping. Despite the fact that the disturbed fraction is low, we obtain more matches than the Pure sample. Also, we see that the disturbed galaxies from the excluded experts are mergers; in these cases there are some objects (probably stars) close to the galaxy that could confused the public.

Mergers Zoo candidates

As the primary objective of the thesis is to focus exclusively on ram pressure, we opt to include only one criterion for the Merger Zoo candidates. Also, the introduction of additional criteria may prove impractical for the establishment of another set of mergers due to limited conditions, having less categories for the identification for mergers in the Zooniverse.

In Table 4.1, 19 mergers candidates are identified by applying the conditions outlined in Equation 3.7, resulting in the exclusion of 44 mergers from the Expert sample. The decision not to include these 44 galaxies in our criteria is based on the following considerations:

- Out of the 44 galaxies, 29 are categorized as undisturbed ($F_{undisturbed} > F_{disturbed}$).
- 12 galaxies are classified as disturbed ($F_{disturbed} \geq F_{undisturbed}$). However, 11 of them do not exhibit a significantly higher fraction of merger votes compared to non-merger votes. Only one displays a merger fraction greater than the non-merger fraction, but it has $F_{merger} = 0.5$, being excluded of the merger sample.

Figure 4.5 visually illustrates the mergers chosen by experts and those meeting the inclusion criteria, encompassing even those that were unable to be included. Opting for the inclusion of '$F_{merger} \geq F_{notmerger}$' instead of '>' results in a 10% decrease in the purity of the sample. However, it leads to a 3% increase in completeness.

We might consider that voters classified the most extreme cases of mergers. Classifying these types of mechanisms is challenging when we lack information about the redshift of all the objects, as there may be no interactions if the galaxy is too far away. Perhaps people find this challenging, or it could be that the citizen science project needs to be more stringent in applying the tutorial before classification. Additionally, it's worth noting that cases involving two nuclei were not identified as mergers by the public, and the post-merger cases were overlooked as well. Furthermore, instances of minor mergers were not identified. Refer to Figure 4.4 to observe examples from the Expert sample that are not immediately apparent as mergers. As mentioned earlier with the JF sample, including more experts in the classification process may generate a different sample for future works.



Figure 4.4: Examples of expert merger candidates that went unnoticed by the public, involving less prominent cases.

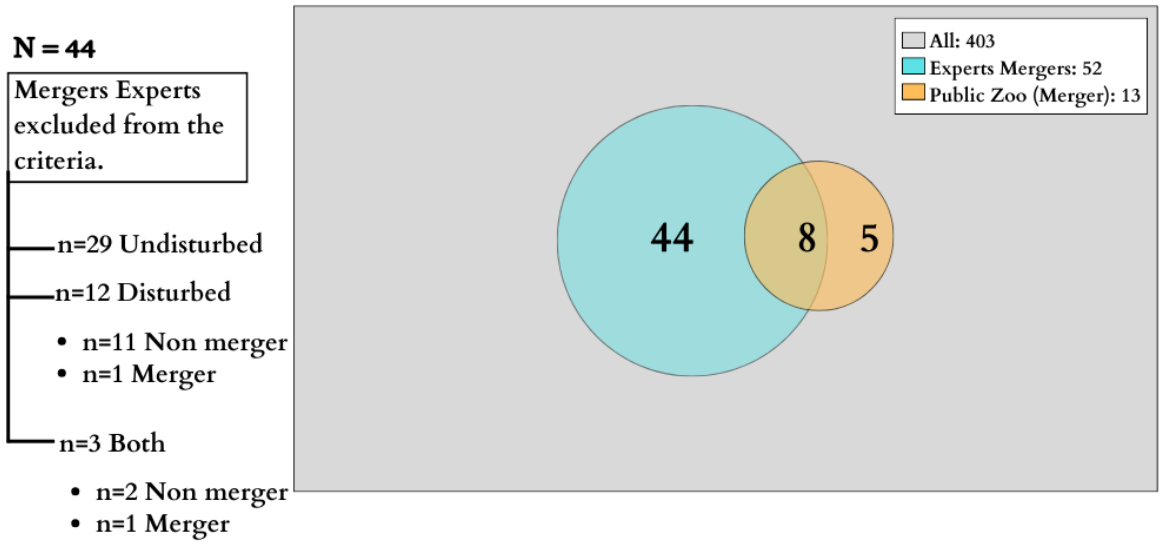


Figure 4.5: Comparison diagram illustrating distinctions among total galaxies, an Expert sample, and a Merger Zoo sample. The upper left section features overlapping circles, symbolizing the matched galaxies between the Expert sample (cyan circle) and Merger Zoo candidates (orange circle).

4.2 Comparison with other samples

Figure 4.6 illustrates the jellyfish galaxies identified in cluster A1644, as cataloged by Poggianti et al. (2016), with the fraction of each class/subclass and the possible category in the top of each image depending on the specified criteria (note that in this case, the subclass fraction is multiplied by the disturbed fraction, implying that the sum of the subclasses corresponds to the disturbed fraction). It is noteworthy that their study focuses on a smaller radius (0.5 R_{200}) compared to our analysis. Additionally, these nine[1] galaxies belong to a lower Jclass of jellyfish morphology (ranging from 1 to 3) where the JClass indicate how evident is the ram pressure stripping. The JClass scale ranges from 0 to 5, with 0 indicating no evident presence or weaker cases and 5 signifying a high level of evident signatures of ram pressure stripping (Poggianti et al. 2016). JClass equals to 1 or 2 indicate tentative cases of RPS only. This distinction may explain if there's deviations from the voters classifications. The referenced paper Poggianti et al. (2016) also utilized high-resolution images and fits files to enhance the visual analysis.

The catalog of Poggianti et al. (2016) serves with the purpose of constructing the 'Complete sample', and serves as a reference to confirm if the public identify the JF galaxies in the portal. It is anticipated that instances with low levels of ram pressure stripping such as $JClass = 1$ and $JClass = 2$ might not prominently exhibit tails, potentially leading the voters to categorize them as undisturbed. This observation is shown in Figure 4.6, which presents three cases, including $JClass = 3$ in two candidate samples. Only three cases of $JClass = 2$ correspond to the undisturbed class, displaying an 'undisturbed' class due to its high fraction greater than the disturbed fraction. However, for the remaining three cases of that JClass, the experts classified them as jellyfish, whereas the public on the Zooniverse did not. The Expert sample identified only four cases of jellyfish galaxies, two of which had a JClass equal to 3. Remarkably, the $JClass = 3$ instances have more than one selection sample, suggesting that the identification process may depend on the degree to which the galaxy appears to undergo gas removal (i.e., the strength of the RPS).

Noting that experts did not classify all galaxies of Poggianti et al. (2016) as Jellyfish, raises the possibility that working with images captured through only three filters might not offer sufficient detail to distinguish all aspects of the galaxy removal process. If viewed in H-alpha or HI (atomic hydrogen), the tails would be more pronounced due to the emission of gas in the radio spectrum.

[1]Initially, there were fifteen galaxies to our cluster, but due to limitations on the Zooniverse platform, 6 galaxies were excluded from the classification process.

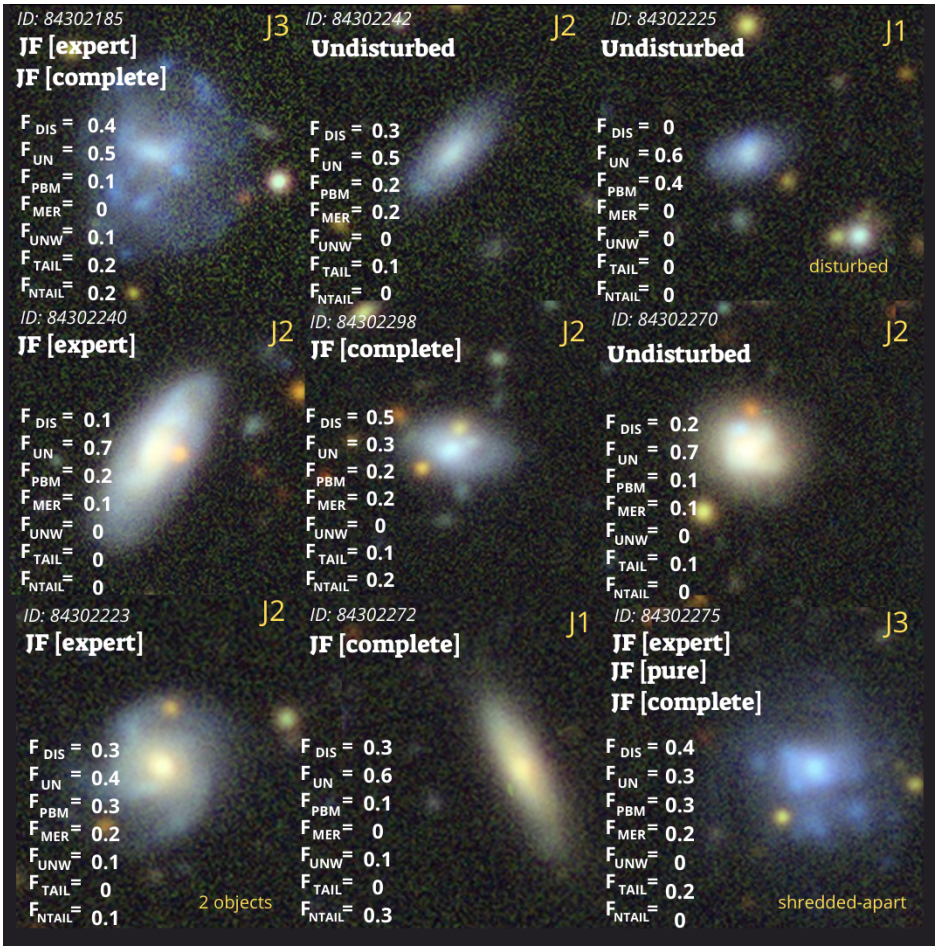


Figure 4.6: Classifications performed to different cluster members (confirmed JF), corresponding to galaxies from Poggianti+16. In the upper left is shown the ID of the galaxy and the final category assigned to each galaxy with the respective criterias. The bottom left displays the vote fraction for each class and bottom right indicate the JClass. The undisturbed class were extracted from the '*object_class*' in the data.

Based on the Expert sample we obtain a total of 15.8% of jellyfish galaxies in our cluster, similar to previous studies, such as Vulcani et al. (2022). They found that 15-20% of blue spiral galaxies, moving towards the center of clusters, undergo ram pressure stripping in a large sample from the WINGS/OmegaWINGS surveys. However, the closest approximation of this fraction, using candidates from Zooniverse is the Complete sample, revealing an approximate 22% prevalence of ram pressure stripping candidates.

The expert-identified merger candidates constitute approximately 12% of the total sample, a proportion consistent with previous studies at higher redshifts ($z \approx 1$) which reported a merger fraction of around 11% (Watson et al. 2019). It's worth noting that the redshift may influence the observed fraction. However, the Merger Zoo candidates show a notably lower prevalence, comprising only approximately 5% of the total sample.

4.3 Pre-processing

This thesis aims to investigate the preprocessing of galaxies around filaments, with the aim of determining whether the findings in Kotecha et al. (2022) align with observations in our cluster. The study indicates a delayed quenching in galaxies closer to intra-cluster filaments, in contrast to established trends for galaxies in outer filaments. Specifically, a decrease in ram pressure stripping is noted in the proximity of intra-cluster filaments, while in the outskirts is more frequent. For this reason in this study we utilize galaxy candidates identified through the public votes on Zooniverse, since we identified candidates for jellyfish galaxies and mergers, both mechanisms of quenching, we analyze which of these effects domains and whether the proximity of filaments hosting these mechanisms is situated farther away from the cluster core or within the core itself.

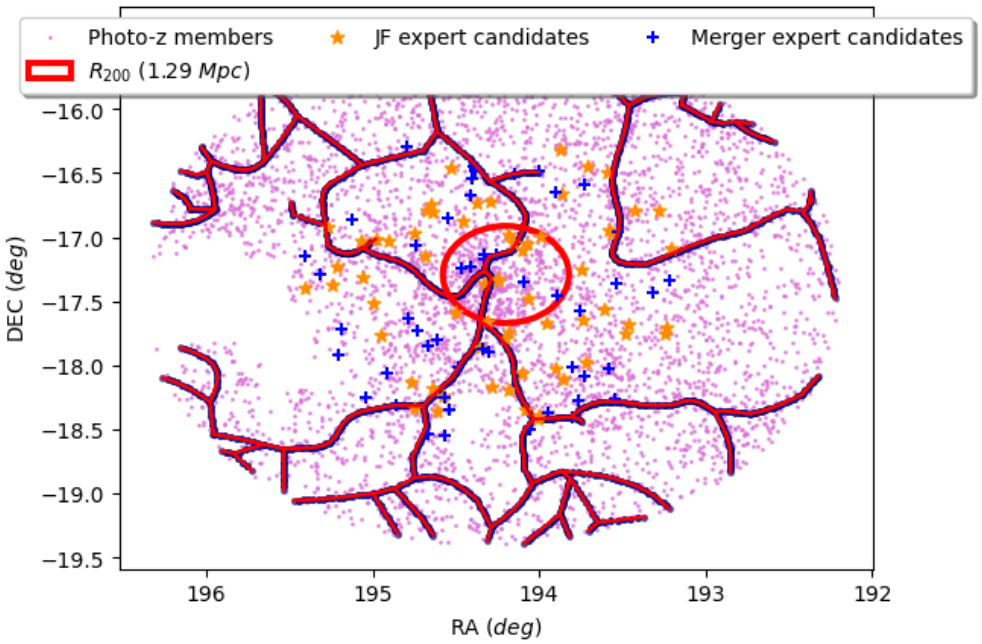


Figure 4.7: Distribution of expert-identified candidates in Cluster A1644. Orange stars represent the Jellyfish expert candidates, while the blue plus symbols indicate the merger Expert candidates.

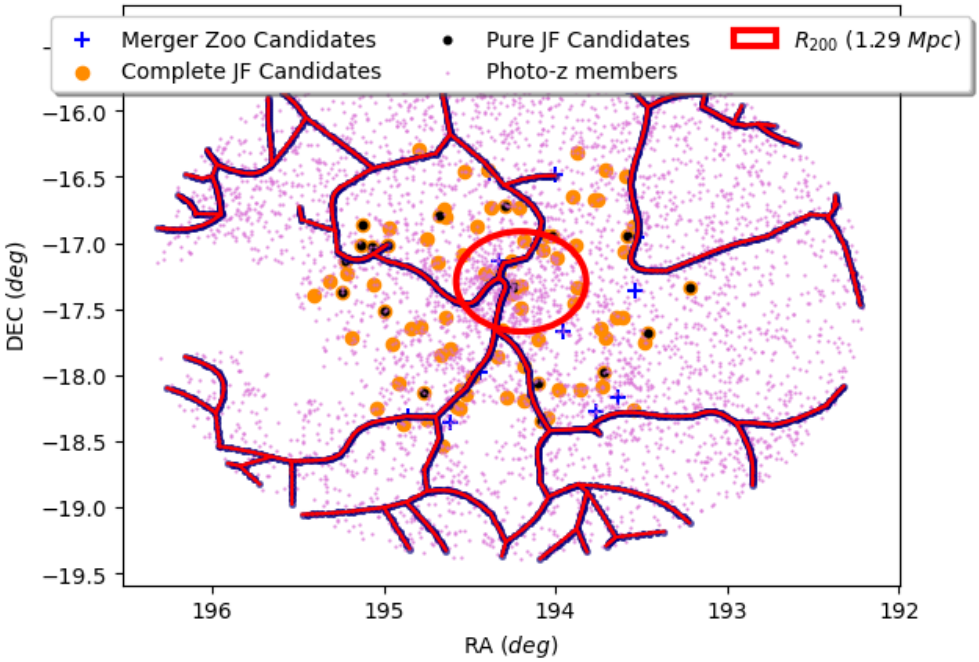


Figure 4.8: Distribution of public-identified candidates in Cluster A1644. Orange dots represent Jellyfish Zoo (JF Zoo) candidates from the Complete sample, black dots correspond to the Pure sample, and blue plus symbols indicate Merger Zoo candidates.

In Figure 4.8, we analyze the candidate distribution within the cluster adjacent to the filaments of Abell 16444, comparing it with the distribution of galaxies in the broader Zooniverse dataset. Additionally, Figure 4.7 illustrates the distribution of expert candidates. Visual inspection poses challenges in discerning a potential preference for candidates to cluster around specific filaments. Therefore, to achieve a more precise evaluation, we calculate the distance from each candidate to the nearest filament within the cluster.

The JF expert galaxy distribution exhibits a distinct slope in the initial bin (Figure 4.9), particularly in close proximity to the filament. To study this distribution, we apply a statistical test. The **Kolmogorov-Smirnov test**, a non-parametric statistical test used to compare the cumulative distribution functions of two samples or a sample against a reference distribution. The result of the KS test applied to the distances of 64 jellyfish candidates and other galaxies within the same cluster does not provide significant evidence to reject the null hypothesis that both samples come from the same distribution. The K-S statistic is 0.1189 with a p-value of 0.3814, suggesting that the distances to the filament in both groups are consistent with each other. Consequently, there is no significant indication that JF candidates have distinct preferences regarding proximity to filaments compared to other galaxies within the considered cluster.

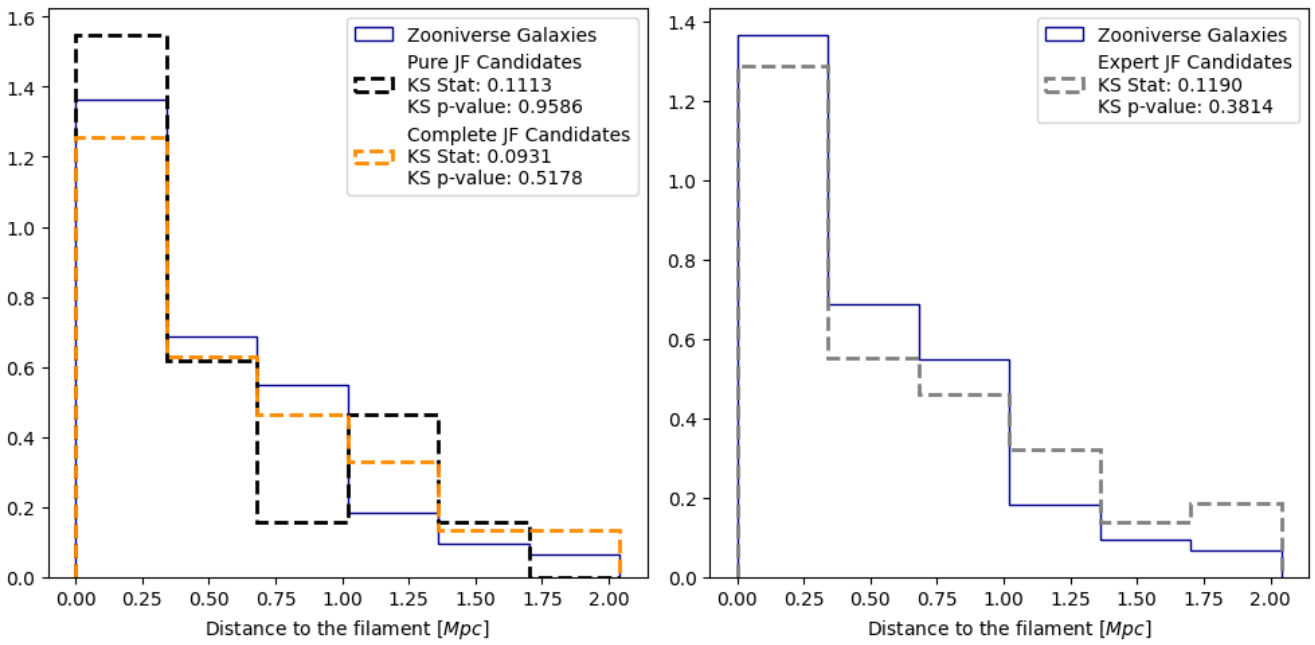


Figure 4.9: Distribution of the JF candidates to the nearest filaments. The left panel displays comparisons between Pure (black), Complete (orange), and all sample galaxies from Zooniverse (blue). In the right panel, we delve into a comparison of the distribution of Expert JF (black) with the entire sample of galaxies from Zooniverse (blue).

Furthermore, both the Pure sample and the Complete sample, assessed using the KS test, exhibit consistency in their distributions. This is supported by the obtained p-values being below the confidence level (0.05), as indicated in the legend of Figure 4.9. However, it is important to note that interpreting these results may be somewhat inaccurate if the analysis does not take into account the entirety of the galaxies in the Expert sample. This is because our criteria do not capture all the jellyfish galaxies of the Expert sample.

Similar to the previous findings, Merger Zoo candidates exhibit a distribution that closely appears similar to the all sample of galaxies in the Zooniverse, as illustrated in Figure 4.10, which displays the distribution of Merger Zoo candidates based on their nearest distances to the filaments. The obtained p-value of 0.81 provides insufficient evidence to reject the null hypothesis, strongly supporting the idea that the two distributions are not significantly different.

However, when considering public votes, the Merger Zoo candidates show a lower p-value of 0.0374. This suggests a significant dissimilarity compared to the overall sample of galaxies in the Zooniverse, indicating evidence to reject the null hypothesis and highlighting a notable difference in the distributions. As we mentioned, 44 experts mergers were not included in this sample since the voters classified them as undisturbed, but it's important to note that the experts also encompass less extreme cases of mergers, where small objects near the galaxies appear to interact,

but recognizing them as mergers becomes challenging due to the absence of redshift knowledge for each galaxy. From this, we can deduce that the voters categorized the most extreme merger cases, suggesting that the mechanism favors filaments only when these extreme cases are included.

Alternatively, these findings may suggest a preference for a filamentary environment in mergers. The filaments can facilitate increased interactions between galaxies.This might suggest that the potential for facilitating mergers to occur by influencing the velocities within that region. This is particularly relevant, as mergers are not as frequent in galaxy clusters, but being close to filaments could create more favorable conditions.

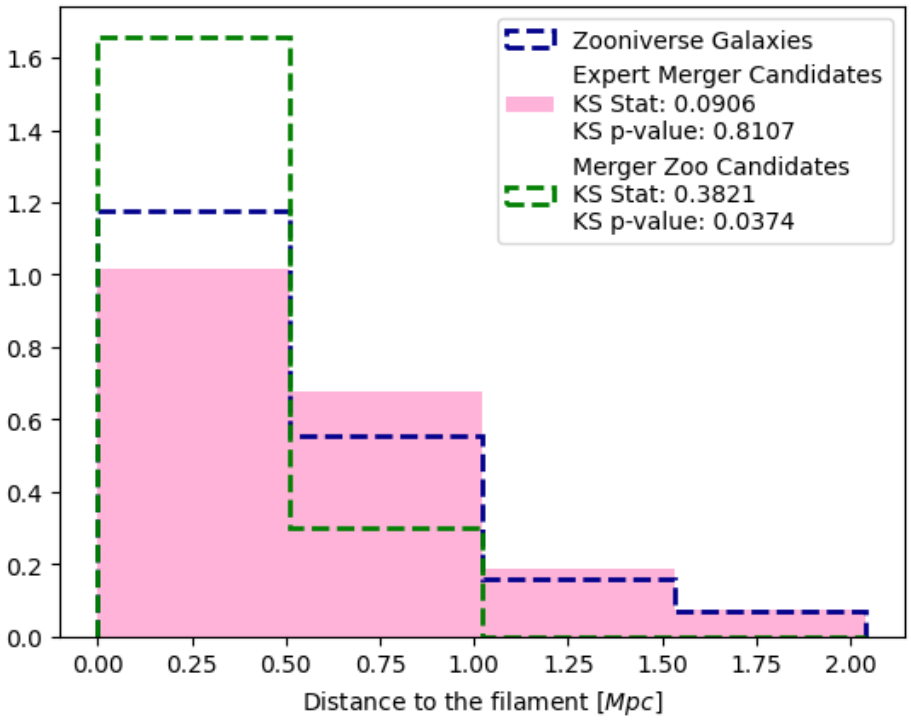


Figure 4.10: Distribution of the Merger candidates to the nearest filaments, displays comparisons between Expert Merger sample (pink), Merger Zoo candidates (green), and all sample galaxies from Zooniverse (blue).

Thus, the pre-processing of galaxies around filaments in cluster Abell 16444 shows no preferences for either gravitational or hydrodynamical mechanisms using the Expert sample. The reason for this may be attributed to the altered dynamics within the cluster. Previous studies indicate that the Abell A1644 cluster reveals a more complex structure than previously known, with three central subclusters and galactic groups falling in the outskirts. Additionally, a new subcluster has been discovered (Monteiro-Oliveira et al. 2020). Exposure to numerous collisions over time likely played a pivotal role in shaping the evolution of the Abell 1644 cluster and, consequently, the constituent galaxies. These events could have influenced the distribution of dark matter, hot gas,

and galaxies within the cluster, impacting their physical and dynamic properties. The observed preference of jellyfish galaxies for specific environments in Abell 1644 may be a consequence of these cluster-altering events. The exposure to various collisional processes throughout the cluster's evolutionary timeline may have created distinct environmental niches, influencing the distribution and behavior of these galaxies. Nevertheless, the correlation between the cluster's dynamical stage and the frequency of ram pressure stripping (RPS) occurrences remains uncertain. Lourenço et al. (2023) suggests an elevated RPS activity in interacting clusters, but the results are inconclusive due to limited data despite a large sample and the complex growth of the cluster.

4.3.1 Cluster Center and Filament Distribution Analysis

We aim to investigate whether galaxies near filaments are adequately distant from the cluster center, potentially shielding them from the extreme environmental conditions prevalent at the center. To achieve this, we compare the distributions of candidate jellyfish galaxies from the Expert sample with the remaining galaxies in the Zooniverse dataset. We delineate three zones: Proximity to the cluster center (from the center to half the virial radius), an intermediate zone (beyond half the virial radius up to the virial radius), and a more distant zone (beyond the virial radius). For each zone, we plot the distribution of distances from the cluster center and the distribution of distances from the filament (See Figure 4.11).

We observe no statistically significant evidence indicating differences in the presented distributions, according to the KS test shown in Figure 4.11. However, upon closer examination of each zone, the first two graphs suggest that for distances close to the cluster, there are more jellyfish galaxies near the center, which is reasonable given the violent intracumular gas, leading to increased ram pressure stripping.

Interestingly, in the zone farthest from the center (beyond 1 virial radius), there are fewer jellyfish galaxies near filaments and more jellyfish galaxies away from filaments; specifically, the JF expert galaxies exhibit a filament distance approximately 1.20 Mpc greater than that of other cluster galaxies. In Kotecha et al. (2022), it was noted that galaxies are 'protected' by filaments up to a certain radius from the cluster center, preventing gas stripping. Therefore, it makes sense to have fewer jellyfish galaxies in this zone. Additionally, Kotecha et al. (2022) indicates that galaxies 'quench' more rapidly away from filaments, explaining the presence of more jellyfish galaxies distant from filaments. However, while this result did not show statistically significant differences, the distribution patterns align with the trends observed in Kotecha, suggesting the need to extend this study to more clusters within the Zooniverse portal. Nevertheless, as per Kotecha et al. (2022), ram pressure stripping would typically dominate in the filaments beyond 2 virial radii from the cluster center; in contrast, our dataset does not exhibit this observed trend.

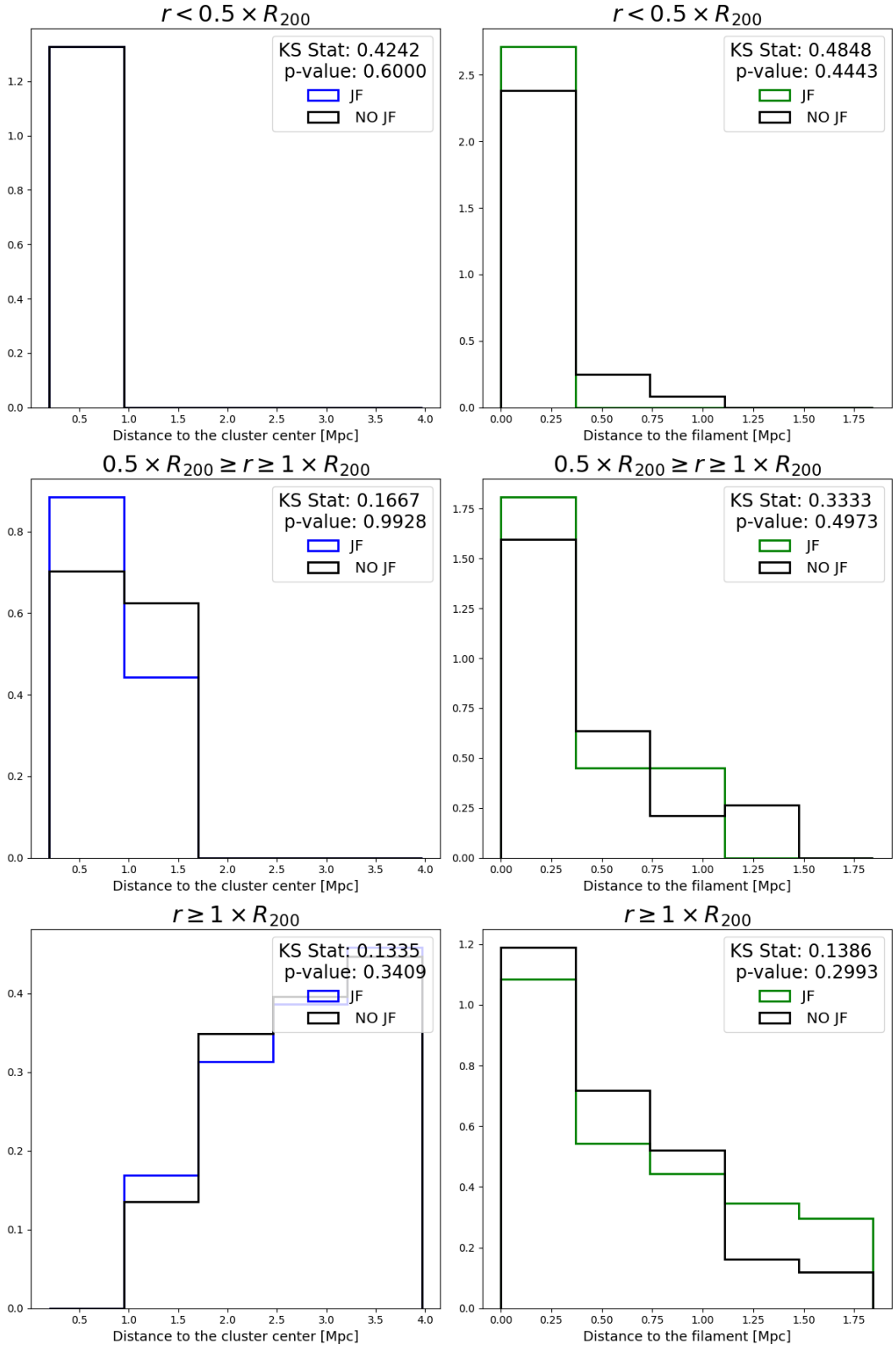


Figure 4.11: Comparison between the distributions of Jellyfish Expert (JF) and No JF. (Left panel) Distributions of Jellyfish Expert candidates (blue) vs. No JF samples (black) based on the distance to the center of the cluster. (Right panel) Distributions based on the distance to the nearest filaments, with Jellyfish Expert candidates in green and No JF samples in black.

Chapter 5

Conclusions

In this preliminary investigation, we utilize citizen science data from Zooniverse to identify potential candidates for jellyfish galaxies and mergers. An expert sample was created to validate the classifications from Zooniverse. The objective is to investigate the pre-processing of galaxies around filaments, particularly in relation to the Abell 1644 cluster. We conduct distance calculations to the cluster center as part of our analysis, aiming to investigate how filaments shield galaxies and to identify any trends analogous to those observed in simulations. Our analysis reveals that:

- The expert sample reveals that approximately 16% of the galaxies within the cluster exhibit jellyfish features, while 4.7% are involved in gravitational interactions.
- Through citizen science votes, we establish a 'complete sample' showing 22% of candidates for ram-pressure stripping (89 in total), with 39 of them aligning with expert assessments, excluding 25 galaxies from the expert JF candidates. Furthermore, we identify a 'pure sample' comprising 5% of ram-pressure stripping candidates (19 in total) within the cluster, excluding 50 galaxies from the expert sample.
- Additionally, the 'merger sample' indicates approximately 5% of candidates, excluding 44 from the expert-identified candidates. The most extreme cases of mergers were identified by the public.

About pre-processing,

- In the study of proximity to the nearest filaments within the cluster, there's no significant statistical difference between the distribution of expert jellyfish candidates and the citizen science candidates.
- The mergers candidates identified through citizen science exhibit a notable disparity in distribution when compared to the expert-selected sample. Specifically, the filament distance

for the citizen science candidates is approximately 2.10 times closer than that of the average cluster galaxy. This difference is statistically supported by the Kolmogorov-Smirnov (KS) test. This suggests that the public commonly categorizes instances of merging based on their extremeness, with these mechanisms exhibiting closer proximity to filaments in more intense cases compared to milder ones.

- Studying the distance to the center of the cluster, it is possible to ascertain that beyond $1R_{200}$, there are fewer ram pressure stripping candidates in proximity to the filaments. This suggests that galaxies may be shielded by the filaments at that radius, preventing gas stripping. However, statistical analysis does not conclusively support these disparate distributions, possibly due to the consideration of a limited sample size. This underscores the need to broaden this study across more clusters within the Zooniverse, enabling a comprehensive exploration of the influence of filaments on shielding galaxies, ultimately validating the findings of simulation studies.

The distribution of jellyfish galaxies around the filaments can be attributed to the dynamic stage of the Abell 1644 cluster, characterized by evident substructures. Further studies could explore how the nature of the cluster correlates with ram pressure stripping (RPS) effects.

Further work will focus on broaden the criteria across additional clusters within the Zooniverse ($\sim$ 50 clusters) and enhance the catalog. Additionally, exploring jellyfish galaxies across various clusters will enable us to investigate the impact of filaments and validate the findings of Kotecha et al. (2022). Moreover, a separate sample need to be created by including unwinding galaxies, and an inclusion criteria will be established based on Zooniverse votes. This approach will enable us to examine the influence of filaments on the quenching process of these galaxies, offering perspectives into whether they align with ram pressure stripping or other mechanisms. Certain details, such as the identification of repeat galaxies, were identified in the entire sample, requiring to remove them. Moreover, analyzing vote fractions will aid in defining JClasses to the jellyfish galaxies. Additionally, having knowledge of the redshifts of the citizen science candidates would enable us to calculate the precise distances to the filaments. Finally, expanding the search radius for clusters will contribute to our understanding of whether quenching occurs even at greater distances from the cluster core.

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