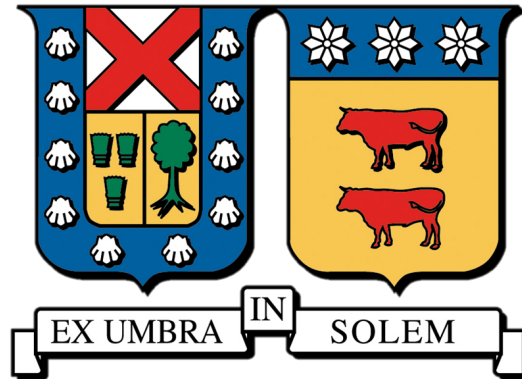


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A STUDY OF JELLYFISH GALAXIES
IN COSMOLOGICAL SIMULATIONS

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Abstract

Galaxy transformations in cluster environments represent one of the key processes driving galaxy evolution. Among these transformations, ram pressure stripping (RPS) plays a crucial role in shaping galaxies and their gas content as they fall into clusters. However, we still don't fully understand the efficiency and consequences of RPS in galaxy evolution.

This study investigates the evolution of jellyfish galaxies in cluster environments using IllustrisTNG simulations and citizen science classifications. Our sample is divided into two distinct populations: high-confidence and medium-confidence jellyfish galaxies, based on their morphological features as classified by volunteers. Jellyfish galaxies, characterized by their distinctive gas tails shaped by RPS, provide unique insights into environmental processes affecting galaxy evolution. Through the analysis of high-confidence galaxies, we find these systems are predominantly recent infallers within R_{200} , exhibiting ongoing star formation and broad color distributions indicative of early quenching. In contrast, medium-confidence galaxies show lower gas masses, redder colors, and more advanced quenching, reflecting prolonged gas depletion.

The temporal evolution of gas mass reveals rapid stripping in high-confidence galaxies, with up to 37% of their gas removed within 0.5 Gyr post-infall. Our results demonstrate that citizen science enables efficient identification of jellyfish morphologies across large datasets, highlighting its value in addressing challenges posed by big data in modern astrophysics while advancing our understanding of environmental processes in galaxy evolution.

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Chapter 1

Introduction

Galaxies are complex structures composed of stars, gas, dust, and dark matter, whose understanding has been fundamental to the development of modern astronomy. In the early 20th century, Edwin Hubble demonstrated that galaxies extend beyond the Milky Way, revolutionizing our view of the cosmos and initiating an era of research focused on these vast stellar systems. Since then, a morphological classification has been developed that distinguishes between spiral, elliptical, and lenticular galaxies—a distinction that not only describes their external shapes but also fundamental aspects of their evolution ([Boselli and Gavazzi, 2006](#); [Yun et al., 2018](#)).

Galaxies exhibit diverse physical and morphological characteristics. Spirals, like the Milky Way, are distinguished by their arms filled with gas and dust, which allow continuous star formation. In contrast, elliptical galaxies lack gas, so their star formation is limited, and they exhibit a homogeneous structure. Lenticular galaxies are intermediate between spirals and ellipticals, with prominent disks but without visible arms. These characteristics depend not only on the initial conditions of formation but also on the evolutionary processes to which galaxies have been exposed over time. In this context, the star formation rate (SFR), gas content, and stellar mass are some of the fundamental parameters that vary considerably among different types of galaxies and reflect the physical and dynamic processes that affect them ([Peng et al., 2010](#); [Salinas et al., 2024](#)).

Similarly, evolutionary studies allow us to glimpse the origin and endpoint of different phenomena. In the case of galaxies, we mainly refer to two types of evolutionary mechanisms: Secular (internal) and environmentally driven (external). Secular mechanisms refer to processes that occur due to the inherent properties of a galaxy, such as AGN feedback or star formation regulation. Environmentally driven mechanisms, on the other hand, arise from interactions between a galaxy and its surroundings or with other galaxies. Examples of external evolutionary mechanisms include mergers ([Toomre and Toomre, 1972](#)), harassment ([Moore et al., 1996](#)), and starvation or strangulation ([Larson et al., 1980](#)). However, the most significant environmentally driven mechanism is Ram Pressure Stripping (RPS) ([Gunn and Gott, 1972](#)), which occurs due to the interaction between the interstellar medium

(ISM) of galaxies and the intracluster medium (ICM) present in galaxy clusters. This interaction causes galaxies falling into these clusters to develop a kind of "tail," giving rise to the term Jellyfish galaxies.

Ram Pressure Stripping becomes effective when the ram pressure exerted by the intracluster medium exceeds the restoring gravitational pressure of the galaxy's disk. The ram pressure, given by:

$$P_{\text{ram}} = \rho_{\text{ICM}} v_{\text{gal}}^2, \quad (1.1)$$

where ρ_{ICM} is the density of the intracluster medium and v_{gal} is the velocity of the galaxy relative to the cluster medium, must overcome the restoring force per unit area of the galaxy's disk. This balance is expressed as:

$$P_{\text{ram}} > 2\pi G \Sigma_{\text{star}} \Sigma_{\text{gas}}, \quad (1.2)$$

where G is the gravitational constant, Σ_{star} is the surface density of the stellar component of the galaxy, and Σ_{gas} is the surface density of the gas in the galaxy. In turn, the surface densities are defined as:

$$\Sigma_{\text{star}} = \frac{M_{\text{star}}}{2\pi r_d^2}, \quad \Sigma_{\text{gas}} = \frac{M_{\text{gas}}}{2\pi r_d^2}, \quad (1.3)$$

where M_{star} and M_{gas} are the stellar and gas masses of the galaxy, respectively, and r_d is the scale length of the galaxy's disk.

Jellyfish galaxies are a clear example of how external interactions, specifically RPS, affect the gas content of a galaxy. The study of these galaxies is particularly important because it allows us to observe in real-time how the environment influences galactic evolution, contributing to our understanding of the processes of formation and transformation of galaxies (Yun et al., 2018).

While we have learned extensively about RPS from observations (see Cortese et al. (2021) for a review), we still haven't managed to fully reproduce these processes in simulations —particularly in cosmological simulations capable of modeling environmental quenching—remains a challenge. Nevertheless, cosmological simulations have proven to be an essential tool for analyzing galaxies experiencing processes like RPS. Since the first studies in the 1980s, the development of these simulations has revolutionized our understanding of the evolution of cosmic structures in nonlinear environments, which are difficult to address through conventional analytical methods (Angulo and Hahn, 2022). Current simulations have enabled significant advances in modeling complex phenomena, including the interactions between galaxies and their environment, as well as internal processes like feedback from supernovae and black holes. IllustrisTNG (Nelson et al., 2019b), for example, has successfully replicated properties such as the stellar mass function, star formation

rates, and gas dynamics in and around galaxies. These simulations achieve a remarkable balance between reproducing observational data and providing insights into the physical processes shaping galaxy evolution. Despite relying on subgrid models to treat unresolved physical processes, their calibrated parameters ensure consistency with observations, making them indispensable tools for exploring interactions like Ram Pressure Stripping and their impact on galaxy clusters (Crain and van de Voort, 2023).

However, the analysis of these complex simulations presents its own challenges, particularly in identifying and classifying specific phenomena across vast datasets. In this context, citizen science initiatives have emerged as a powerful complement to computational methods, exemplified by the "Cosmological Jellyfish" collaboration. This innovative project combines IllustrisTNG simulations with the collective effort of thousands of volunteers who visually classify simulated galaxies for evidence of RPS-induced jellyfish morphologies (Zinger et al., 2024; Yun et al., 2018). Recent studies utilizing this collaborative approach have yielded significant insights: Rohr et al. (2023) quantified cold gas loss in jellyfish galaxies and demonstrated their contribution to cluster gas reservoirs, while Göller et al. (2023) revealed crucial relationships between RPS and star formation rates. These findings highlight how the integration of citizen science with advanced simulations can accelerate our understanding of complex astrophysical phenomena while simultaneously fostering public engagement with cutting-edge research.

Building upon these computational and collaborative foundations, our work aims to analyze a sample of Jellyfish galaxies identified through the "Cosmological Jellyfish" project within the IllustrisTNG simulations. This study will focus on understanding the processes that determine their formation and characteristic properties, allowing us to bridge the gap between simulated predictions and observational evidence. Through detailed comparison with recent observations, we will evaluate how effectively the model reproduces the conditions and physical processes observed in galaxy clusters. This analysis promises to contribute to a more comprehensive understanding of environmental interactions and their fundamental role in galactic evolution.

Chapter 2

Methods and data

2.1 Illustris TNG

The IllustrisTNG project¹ (Marinacci et al., 2018; Naiman et al., 2018; Nelson et al., 2017; Pillepich et al., 2018; Springel et al., 2018) represents a suite of cosmological simulations that builds upon its predecessor, *Illustris*, by incorporating a significantly improved galaxy formation model. These simulations include both gravitational and magnetohydrodynamical (MHD) processes within the framework of the Λ CDM cosmological model. The cosmological parameters adopted are consistent with the Planck 2015 results: total matter density $\Omega_m = \Omega_{dm} + \Omega_b = 0.3089$, baryonic density $\Omega_b = 0.0486$, cosmological constant $\Omega_\Lambda = 0.6911$, Hubble constant $H_0 = 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$ with $h = 0.6774$, normalization $\sigma_8 = 0.8159$, and spectral index $n_s = 0.9667$.

The suite consists of three principal simulations: TNG300, TNG100, and TNG50. These simulations span comoving cubic volumes of approximately 300 Mpc, 100 Mpc, and 50 Mpc on a side, respectively. The resolution of each simulation varies depending on the targeted scientific goals. TNG300 is designed to capture large-scale structures and cosmic evolution with a baryonic mass resolution of $1.1 \times 10^7 M_\odot$, while TNG100 strikes a balance between resolution and volume, achieving a baryonic resolution of $1.4 \times 10^6 M_\odot$. TNG50, the highest-resolution simulation of the suite, resolves baryonic particles to a mass of $8.5 \times 10^4 M_\odot$ and includes 2×2160^3 resolution elements, enabling the study of fine-scale processes within galaxies (Nelson et al., 2019a; Pillepich et al., 2019).

This work focuses exclusively on TNG50, which offers a spatial resolution of approximately 50 – 200 pc in star-forming regions, sufficient to resolve individual star-forming clumps, gas clouds, and feedback-driven outflows. It also accounts for gravitational interactions across all cosmic scales, down to fractions of the gravitational softening length (Nelson et al., 2019a). Gas hydrodynamics and magnetic field evolution are modeled using the moving-mesh code AREPO (Springel, 2010),

¹<https://www.tng-project.org>

which employs a Voronoi tessellation for spatial discretization of the gas.

2.2 Cosmological Jellyfish Project

As stated earlier, citizen science is a key tool for processing large amounts of data, such as in the case of the visual classification of galaxies. Hence, we used the "Cosmological Jellyfish" catalog (CJF from now on), which is available in the Supplementary Data Catalogs² section inside the IllustrisTNG web page. All details of the jellyfish identification process are described by Zinger et al. (2024) and summarized here.

The authors used data from the TNG50 and TNG100 simulations to construct a sample spanning a wide range of stellar masses ($10^{8.3} - 10^{12.3} M_{\odot}$) and host halo masses ($10^{10.4} - 10^{14.6} M_{\odot}$), covering redshifts from $z = 0$ to $z = 2$. To identify jellyfish galaxies, the authors selected galaxies based on their position within host halos and their potential environmental interactions. Specifically, the sample includes satellites residing within $2 R_{200,c}$ of their host, enabling the study of ram pressure stripping both within and outside the virial radius.

The identification process utilized the Zooniverse platform, where citizen scientists examined composite images showing gas-density distributions overlaid with stellar contours. To ensure classification consistency, volunteers underwent training with representative examples of both jellyfish and non-jellyfish galaxies. The final classification implements a weighted scoring system that the authors called *Adjusted Score*, that can be expressed mathematically as:

$$\text{score} = \frac{\sum w_i v_i}{\sum w_i}, \quad (2.1)$$

where w_i represents the weight assigned to a given volunteer i reflecting their reliability based on their consistency with expert classifications and performance in training exercises, and v_i represents their binary classification response ('Do you think that the galaxy at the centre looks like a JF?' yes: 1, no: 0). The Adjusted Score serves as a critical parameter for determining the classification confidence of each galaxy. Galaxies with high scores (e.g., score > 0.8) are classified as high-confidence jellyfish candidates, as they received consistent "yes" votes from most volunteers. Conversely, galaxies with low scores (score < 0.4) are identified as unlikely to exhibit jellyfish features. Galaxies with intermediate scores (e.g., $0.4 \leq \text{score} \leq 0.6$) represent ambiguous cases. Figure 2.1 presents exemplar jellyfish galaxies identified through this process in both TNG50 and TNG100 simulations. The images shown span a range of redshifts, allowing the identification of jellyfish features at different cosmic times.

²https://www.tng-project.org/data/docs/specifications/#sec5_3

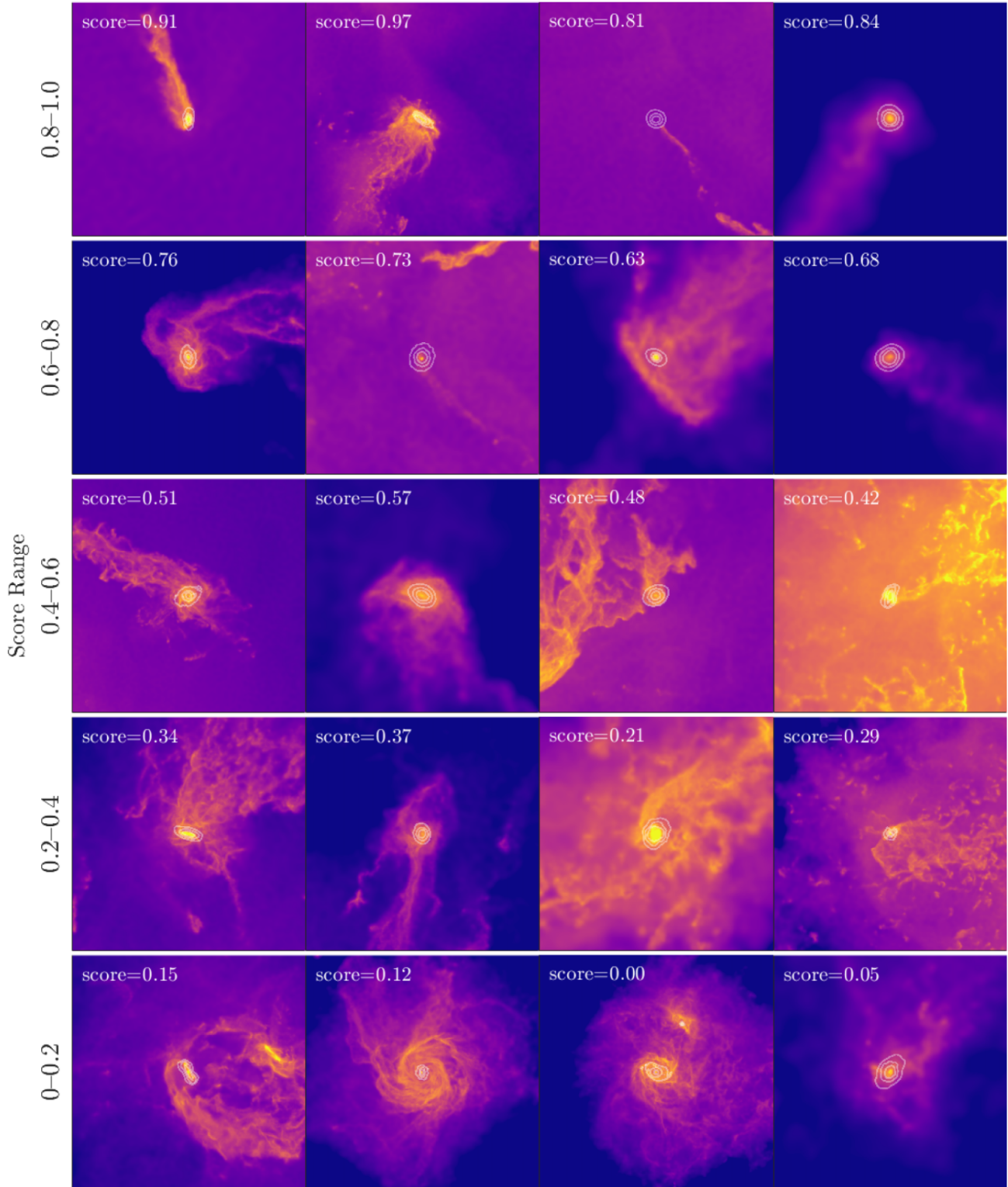


Figure 2.1: Examples of galaxies from both the TNG50 and TNG100 simulations with different JF scores, obtained from the CJF project. The top rows show galaxies with high JF scores and the bottom rows showing objects of progressively lower scores. Figure retrieved from [Zinger et al. \(2024\)](#).

2.3 Data

To systematically analyze jellyfish galaxies, we established two distinct populations, with masses $> 10^7[M_\odot]$ based on the JF scores (hereafter score) from the CJF project:

High-Confidence Sample (score > 0.8)

This population comprises galaxies with unambiguous jellyfish characteristics, as validated by Zinger et al. (2024). These galaxies exhibit definitive morphological signatures of RPS, including pronounced asymmetric gas tails and distinct structural distortions. The high classification consensus among citizen scientists confirms the reliability of these identifications.

Medium-Confidence Sample ($0.6 < \text{score} < 0.8$)

This secondary population encompasses potential jellyfish galaxies whose classification carries greater uncertainty. The morphological features in these systems are typically more subtle or ambiguous, attributable to various factors:

- Viewing angle limitations (particularly in edge-on orientations)
- Evolutionary phase of the stripping process
 - Early-stage cases where ram pressure effects are nascent
 - Late-stage instances where stripped gas has dispersed

The inclusion of this intermediate-confidence sample serves two crucial purposes: it enables the investigation of a more comprehensive jellyfish population and facilitates the study of transitional states in the ram pressure stripping process. This broader sample coverage provides insights into the evolutionary continuum between strongly stripped and minimally affected systems (See top rows of Fig 2.1).

Chapter 3

Results

3.1 Physical properties of the Cosmological Jellyfish

3.1.1 Mass distribution

The stellar mass distributions of jellyfish galaxies are shown in Figure 3.1 to determine whether the masses differ between the two confidence populations. Both high- and medium-confidence galaxies predominantly occupy the range $\log_{10}(M_{\star}/M_{\odot}) = 9.5 - 10.5$, indicating that the differences between these populations are related purely to their evolutionary state and not their stellar mass. Medium-confidence galaxies, however, include a subset of higher-mass systems, extending up to $\log_{10}(M_{\star}/M_{\odot}) = 11.0$.

This analysis highlights that the additional high-mass component in medium-confidence galaxies may reflect either a difference in stripping intensity or an observational bias in classification. High-mass galaxies are generally more resistant to ram pressure stripping (RPS) due to their deeper gravitational potentials (Boselli and Gavazzi, 2006). Additionally, many massive galaxies do not have sufficient gas content to exhibit prominent stripping signals, as they are more likely to have undergone significant quenching through internal processes. This lack of available gas may contribute to weaker morphological features that lower their classification confidence. On the other hand, intermediate-mass galaxies ($\log_{10}(M_{\star}/M_{\odot}) = 9.5 - 10.5$) are more likely to develop visible jellyfish features. These galaxies have substantial gas reservoirs for RPS to produce noticeable tails, but their gravitational binding is not strong enough to entirely prevent gas stripping. This alignment with theoretical predictions supports the efficiency of RPS in transforming galaxies within this intermediate-mass range, while reinforcing that differences in classification confidence are primarily driven by evolutionary state and gas content rather than stellar mass.

Interestingly, Zinger et al. (2024) note that galaxies in this stellar mass range are most susceptible to environmental interactions, which aligns well with our findings. Their study highlights that

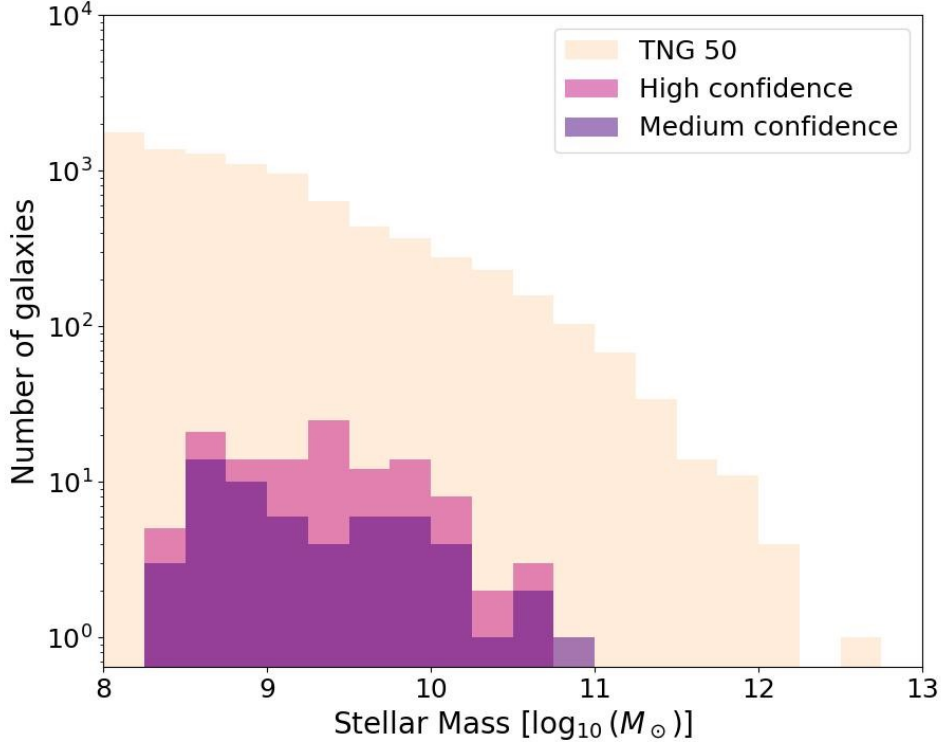


Figure 3.1: Histogram of stellar mass for galaxies in the TNG50 simulation (light orange bars), highlighting the two populations of jellyfish galaxies: High and medium confidence. High-confidence galaxies (pink bars) and medium-confidence galaxies (purple bars) have a broader distribution, the only difference being that the medium confidence ones have galaxies up to $10^{11} M_{\odot}$.

galaxies around $\log_{10}(M_{\star}/M_{\odot}) = 10$ are most likely to experience efficient gas stripping, supporting our observed morphological transformations within this mass regime. Medium-confidence galaxies, which extend to higher masses, align with the notion proposed by [Yun et al. \(2018\)](#) that massive galaxies might show less dramatic stripping due to their deeper gravitational potential but still participate in the RPS process.

3.1.2 Galaxy colors

The $g - r$ color index is a crucial diagnostic tool for studying the evolutionary state of galaxies, as it provides insights into their star formation activity and quenching processes. Bluer colors typically indicate ongoing star formation, while redder colors suggest quiescence and reduced gas content. By analyzing the $g - r$ color distributions of jellyfish galaxies, we aim to identify patterns that link their morphological features to their evolutionary stages.

The $g - r$ color index distributions reveal that high-confidence galaxies span a wide range of colors, from blue to red ([Figure 3.2](#)). This broad distribution suggests that these galaxies represent a

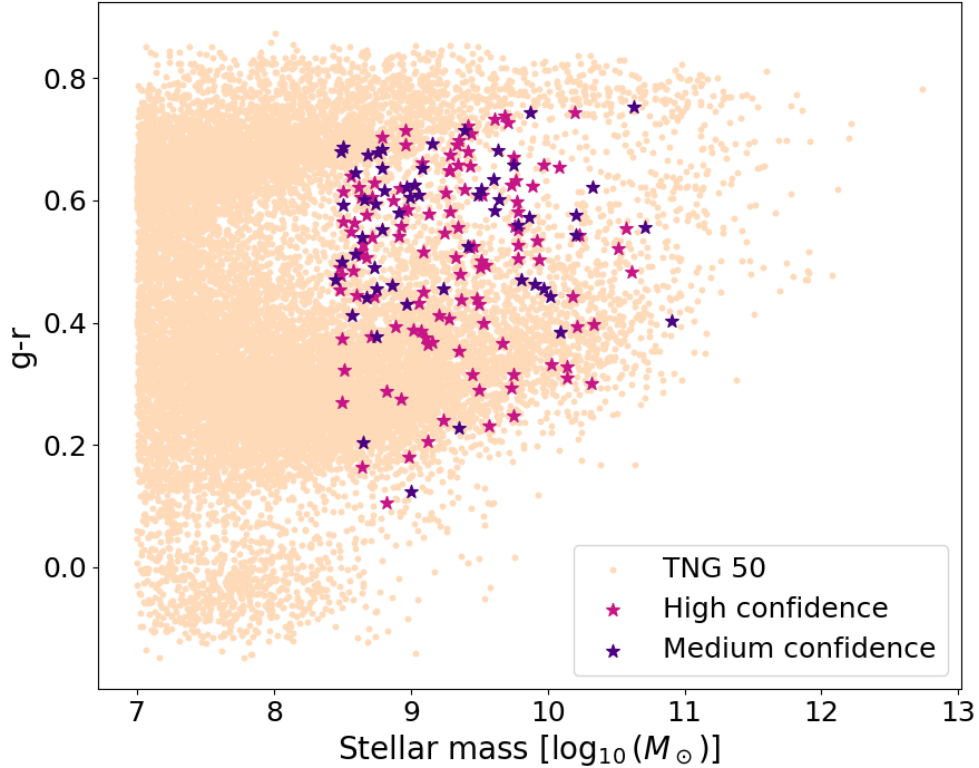


Figure 3.2: Relation between $g - r$ color index and stellar mass (M_*) for high-confidence and medium-confidence galaxies compared to the full TNG50 sample (light orange dots). Medium-confidence galaxies (purple stars) appear redder than high-confidence galaxies (pink stars), suggesting that RPS is actively removing gas, reducing star formation, and quenching these galaxies.

diverse set of evolutionary states. Many high-confidence galaxies are likely recent infallers into their host clusters, as their blue colors indicate ongoing star formation despite the early effects of ram pressure stripping (RPS). Conversely, medium-confidence galaxies display a broader distribution skewed toward redder colors, indicative of more advanced quenching stages. As shown in Figure 3.2, the relation between the $g - r$ color index and stellar mass for high- and medium-confidence galaxies highlights these distinctions compared to the rest of the TNG50 catalog. The redder colors of medium-confidence jellyfish galaxies suggest they are at a more advanced stage of environmental interaction, where significant amounts of gas have already been stripped, slowing star formation and pushing them toward the red sequence. Conversely, high-confidence galaxies, with their blue colors, may represent earlier stages of evolution, where ongoing star formation persists despite the onset of RPS.

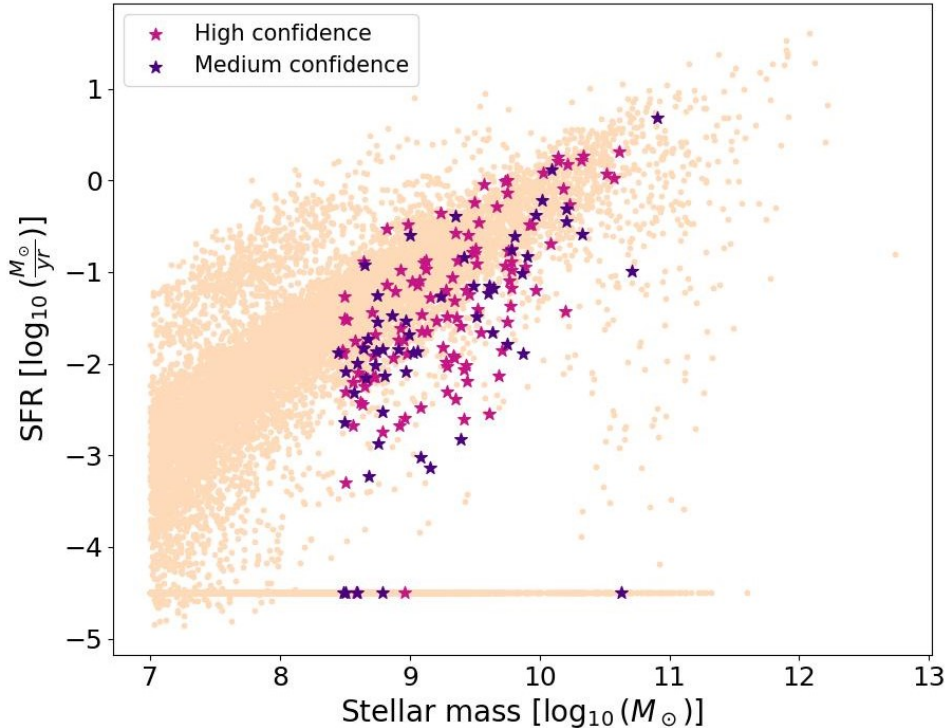


Figure 3.3: Relation between stellar mass and star formation rate (SFR) for high-confidence galaxies and medium-confidence galaxies.

3.1.3 Star formation activity

The star formation rate (SFR) distributions reveal the diverse evolutionary stages of jellyfish galaxies (Figure 3.3). High-confidence galaxies maintain significant star formation activity, with SFRs ranging from $\log_{10}(\text{SFR}/M_{\odot} \text{ yr}^{-1}) = -2$ to 0, predominantly following the linear M_{\star} -SFR relation of the general TNG50 population. This suggests ongoing star formation, likely sustained in their stripped tails. In contrast, medium-confidence galaxies exhibit a broader distribution in the M_{\star} -SFR plane, including fully quenched systems with $\log_{10}(\text{SFR}/M_{\odot} \text{ yr}^{-1}) < -4$. The presence of galaxies with SFR = 0 indicates the final stages of RPS-induced quenching, where gas reservoirs are completely depleted. The greater dispersion toward lower star formation rates in medium-confidence galaxies suggests they may be in a transitional phase of environmental quenching, consistent with their color distribution (Figure 3.2). This pattern reinforces a scenario where high-confidence galaxies represent earlier phases of the stripping process, while medium-confidence cases capture later evolutionary stages as galaxies transition toward quiescence.

Rohr et al. (2023) emphasize that galaxies experiencing strong RPS can sustain elevated SFRs in their tails, consistent with the active star-forming regions we observe in high-confidence systems. Meanwhile, the broader SFR distribution in medium-confidence galaxies aligns with their findings of varied quenching timescales in galaxies experiencing weaker environmental interactions. Also,

Göller et al. (2023) highlight that galaxies undergoing RPS show distinct color gradients as star formation ceases, which is consistent with the redder colors observed in medium-confidence galaxies shown in Figure 3.2.

3.2 Gas stripping and temporal evolution

3.2.1 Infall times and morphology

Figure 3.4 illustrates the temporal distribution of jellyfish galaxies categorized by their confidence levels. The x-axis represents the time since infall into the cluster environment, while the y-axis indicates the fraction of galaxies within each temporal bin. High-confidence galaxies (pink) are primarily concentrated within the first 2 Gyr after infall, whereas medium-confidence galaxies (purple) are more evenly distributed across all time bins. This visualization allows us to immediately discern differences in evolutionary timing between the two populations.

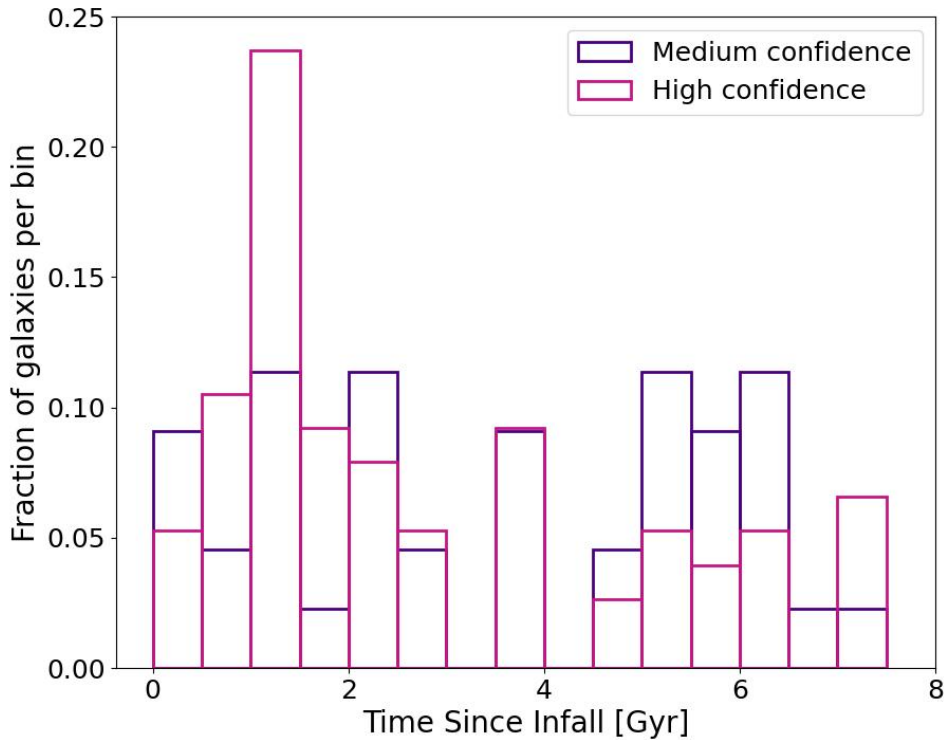


Figure 3.4: Distribution of jellyfish galaxy scores as a function of time since infall. High-confidence galaxies (pink bars) are primarily located near infall times (< 2 Gyr), whereas medium-confidence galaxies (purple bars) are more uniformly distributed over time. This suggests that morphological features of jellyfish galaxies are most prominent shortly after infall.

The temporal distribution reveals that more than 50% of high-confidence galaxies have lookback times (LBT) below 2 Gyr, consistent with the notion that these galaxies are recent infallers experiencing the initial effects of ram pressure stripping (RPS). Medium-confidence galaxies, by contrast, are evenly distributed across the temporal bins, suggesting they encompass a broader range of evolutionary stages, from early interactions to fully quenched systems. These trends are also reflected in Figure 3.2, where high-confidence galaxies exhibit bluer $g - r$ color indices indicative of ongoing star formation, aligning with their classification as recent infallers. Meanwhile, medium-confidence galaxies, with their redder colors, likely represent systems at more advanced quenching stages.

Interestingly, jellyfish features, including stripped tails, become apparent at approximately $1 R_{200}$, as observed in our sample. This finding agrees with Salinas et al. (2024), who reported similar trends at $\sim 1.16 R_{200}$. The slight difference can be attributed to the distinction between temporal and spatial measurements; while our analysis focuses on time since infall, Salinas et al. explore spatial distances. Additionally, Pallero et al. (2022) observed analogous environmental quenching trends in the EAGLE simulation, further reinforcing the consistency of these results across different simulations and methodologies.

This alignment of temporal and spatial findings highlights the crucial role of RPS in shaping jellyfish galaxy features, particularly during early cluster interactions. Beyond cluster entry ($t = 0$), high-confidence galaxies exhibit dramatic morphological changes and gas loss, consistent with their earlier evolutionary phase. Medium-confidence galaxies, however, represent later stages of interaction, where prolonged stripping has resulted in less pronounced features and advanced quenching processes. This distinction provides a comprehensive view of jellyfish galaxy evolution as a dynamic and multi-stage process driven by environmental interactions.

3.2.2 Gas mass and stellar mass relation

Figure 3.5 shows the relation between stellar mass and gas mass for galaxies classified as high-confidence and medium-confidence, compared to the full TNG50 galaxy sample. While both populations show lower gas content than the general TNG50 population (indicating active gas removal), there is a clear hierarchical pattern in gas retention. High-confidence galaxies, while showing reduced gas masses compared to the general population, retain more gas than medium-confidence galaxies at fixed stellar mass. This aligns with a scenario where high-confidence cases represent earlier stages of ram pressure stripping, where dramatic gas stripping creates prominent jellyfish morphologies but significant gas reserves remain.

Medium-confidence galaxies exhibit systematically lower gas masses and greater scatter in the relation, suggesting they represent later evolutionary stages where prolonged stripping has removed more of the original gas content. The reduced gas content in these systems may explain

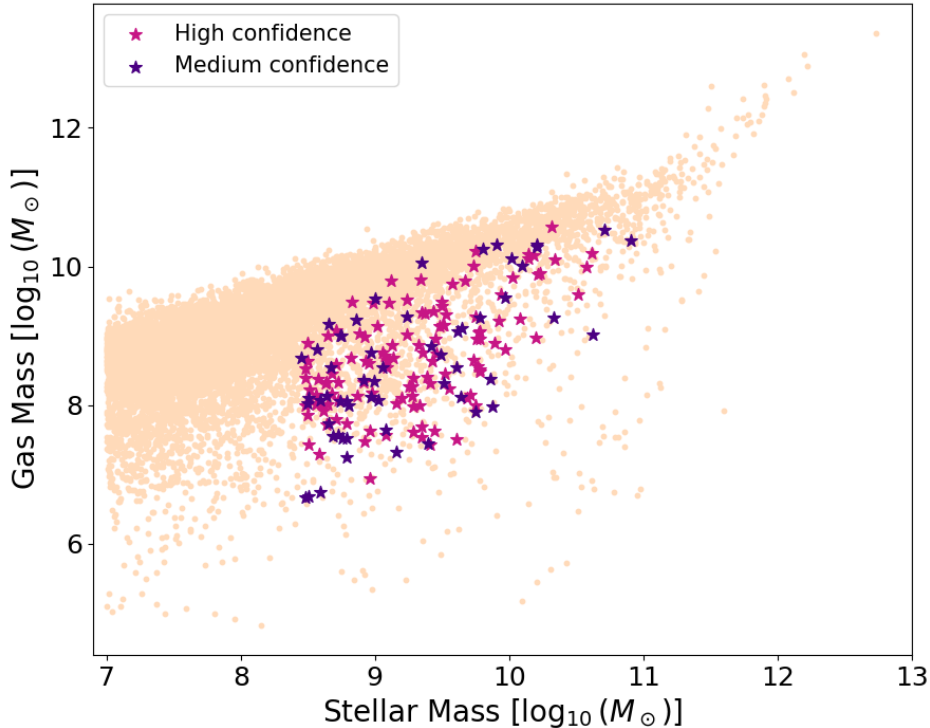


Figure 3.5: Relation between stellar mass and gas mass for high-confidence and medium-confidence galaxies, compared to the full TNG50 sample. High-confidence galaxies tend to have slightly higher gas masses for a given stellar mass compared to medium-confidence galaxies. This may reflect ongoing gas removal through Ram Pressure Stripping, where the remaining gas is concentrated in specific regions such as the galaxy’s tails.

their less prominent jellyfish features, as less gas remains to form the characteristic stripped tails. This hierarchical pattern of gas content (TNG50 > high-confidence > medium-confidence) provides strong evidence for the temporal evolution of galaxies undergoing RPS, from gas-rich high-confidence jellyfish galaxies to more gas-poor medium-confidence systems.

This interpretation aligns well with our other findings about star formation rates and time since infall, supporting a coherent picture of jellyfish galaxy evolution through different stages of Ram pressure.

3.2.3 Gas mass evolution

Figure 3.6 presents the temporal evolution of the normalized gas mass fraction, i.e., the gas mass per snapshot normalized by the maximum gas mass of the galaxy, as a function of their infall time. Negative (positive) values on the x-axis represent times before (after) their infall. The infall time ($t = 0$) is defined as the moment when the galaxy crosses the R_{200} of its final host for the first time.

Both high- and medium-confidence jellyfish galaxies exhibit similar gas content prior to infall

($t < 0$), with minimal variation as indicated by the narrow dispersion bands. Upon entering the cluster environment ($t = 0$), high-confidence galaxies experience an immediate and pronounced decline in gas mass, losing approximately 37% of their initial gas content within the first 0.5 Gyr. Medium-confidence galaxies, in contrast, undergo a more gradual depletion, reflecting a slower stripping process.

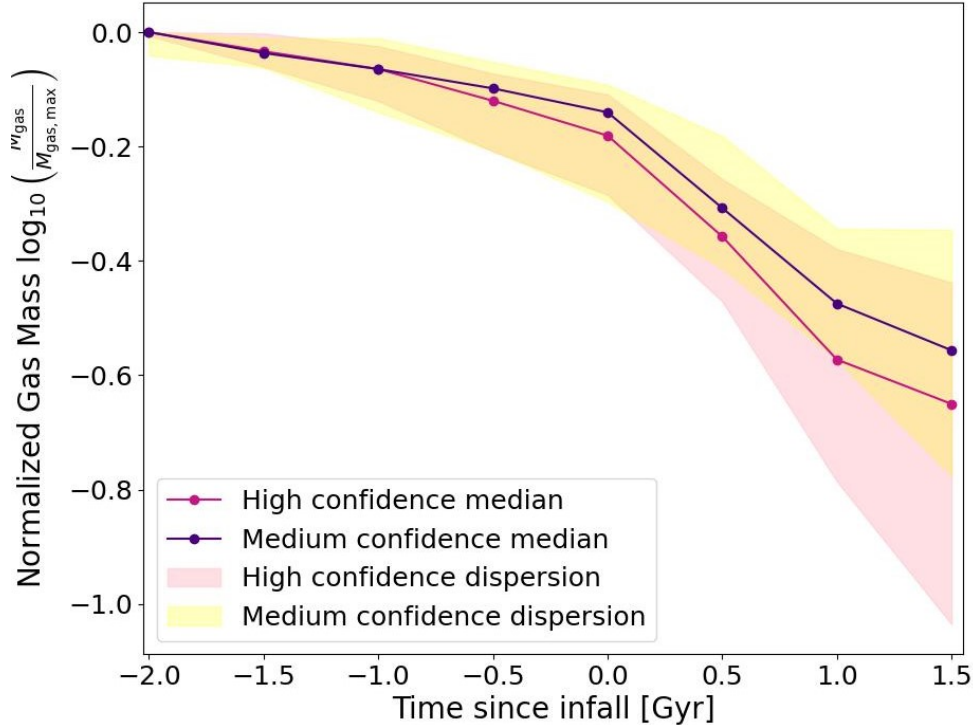


Figure 3.6: Evolution of normalized gas mass as a function of time since infall. Median curves and dispersion regions are shown for high (pink line) and medium-confidence (purple line) galaxies. High-confidence galaxies exhibit a steeper gas loss immediately after infall, consistent with stronger RPS. Medium-confidence galaxies show a slower decline, indicating less efficient stripping. Median curves and their corresponding 25 and 75 percentile (shaded regions) are shown for high (pink shading)- and medium-confidence galaxies (yellow shading).

The dispersion in gas content increases significantly after infall for both populations, reaching its maximum during the intermediate phase (1.0 - 1.5 Gyr). This variability suggests diverse evolutionary pathways influenced by orbital parameters, local intracluster medium conditions, or intrinsic galaxy properties. High-confidence galaxies retain approximately 32 - 40% of their initial gas mass by 1.5 Gyr post-infall, while medium-confidence galaxies show a slower decline, retaining more gas over the same period. This trend aligns with the idea that medium-confidence galaxies are at later evolutionary stages and may have infall histories involving repeated crossings of R_{200} , which gradually stripped their gas over time.

Although the large dispersion bands highlight significant variability within each population, the

overall trends remain consistent with the hypothesis that ram pressure stripping has an immediate and sustained impact on gas removal. High-confidence galaxies exhibit more efficient gas stripping during their early cluster passage, aligning with their more prominent jellyfish morphologies. On the other hand, the gradual stripping observed in medium-confidence galaxies could be attributed to softer interactions due to weaker environmental forces or longer orbital timescales. These results reinforce the significance of the cluster environment in driving galaxy transformation.

Chapter 4

Conclusions and future work

This work has provided insights into the evolution of jellyfish galaxies in cluster environments, leveraging high-resolution IllustrisTNG simulations and the classifications from the Cosmological Jellyfish Project by [Zinger et al. \(2024\)](#). Their dataset enabled the efficient identification of galaxies with distinct jellyfish features, demonstrating the importance of collaborative efforts to tackle the challenges posed by big data in astronomy.

Our analysis shows that high-confidence jellyfish galaxies are predominantly recent infallers into the cluster environment, with their morphological features, such as stripped tails, becoming prominent at approximately R_{200} . This finding aligns with the $\sim 1.16R_{200}$ radius reported by [Salinas et al. \(2024\)](#), highlighting the consistency between our simulations and observational results. These galaxies retain blue colors and significant star formation rates (SFRs), indicative of early stripping stages, whereas medium-confidence galaxies exhibit redder colors and lower SFRs, consistent with advanced quenching. The evolution of normalized gas mass further illustrates a clear progression driven by ram pressure stripping, with high-confidence galaxies losing gas more rapidly than their medium-confidence counterparts.

By addressing the broader question of how RPS shapes galaxy evolution, this work has shown that jellyfish galaxies represent a dynamic evolutionary sequence. High-confidence galaxies reflect the early phases of RPS, while medium-confidence systems capture later stages of interaction, where prolonged gas stripping leads to advanced quenching. These results align with previous findings from [Pallero et al. \(2022\)](#) and [Salinas et al. \(2024\)](#), reinforcing the role of RPS as a key driver of morphological and star formation changes in cluster galaxies.

For future work, a key objective will be to compare these results with observations, particularly the findings of [Salinas et al. \(2024\)](#), to validate the spatial and morphological predictions of the simulations. A detailed study of tail orientations and their relation to cluster centers will further constrain the orbital dynamics of RPS, bridging the gap between simulations and observations.

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