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The effect of the extragalactic environment on the evolution of S0-type galaxies

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Abstract. Lenticular galaxies (S0) constitute around 50% of high-mass galaxies in the Local Universe. These galaxies offer insights into their surrounding environment. They also play a pivotal role in tracing galactic evolution, potentially preserving crucial information from the early stages of galaxy formation. Our study investigates the formation mechanisms of S0-type galaxies, with a focus on the role of galaxy mass and the surrounding environment. Utilizing data from the S-PLUS survey, we analyzed 974 lenticular galaxies with mass bins between $\log(M/M_{\odot}) > 9$ and $\log(M/M_{\odot}) < 12$ in the Stripe 82 in 12 bands. The GALFITM code is employed to optimize the signal-to-noise ratio by adjusting the images at a range of wavelengths (3543–9134 Å) simultaneously. We parameterize the light of S0-type galaxies using two Sérsic profiles representing the sum of a bulge and a disk (n=1). From this photometric model, we derive various morphological parameters such as the bulge Sérsic index, the effective radius of the disk and bulge, and the ratio of bulge light to total galaxy light (B/T). Additionally, stellar population properties are obtained by adjusting Spectral Energy Distributions (SEDs) using LePHARE with COSMOS (empirical) and BC03 (theoretical) libraries. We use the measures of the local environment of each galaxy obtained by Baldry et al. 2006, using a K-Nearest Neighbour(KNN) method. Subsequently, we employ these morphological and stellar population parameters to identify analogous galaxies in the IllustrisTNG hydrodynamic simulation. In IllustrisTNG100-1, we retrieved merger trees of galaxies. This analysis allows us to investigate the connection between galaxy formation and various factors such as environment, galaxy mass, stellar population properties, and the presence of an active galactic nucleus (AGN) and its evolution. Finally, by comparing the surrounding environment of our observational data with simulated galaxies, we aim to identify primordial objects and elucidate their role in the evolutionary history of the universe.

Resumo. As galáxias lenticulares (S0) constituem cerca de 50% das galáxias de alta massa no Universo Local. Essas galáxias oferecem insights sobre o ambiente ao seu redor e desempenham um papel crucial no rastreamento da evolução galáctica, potencialmente preservando informações importantes das fases iniciais da formação das galáxias. Nosso estudo investiga os mecanismos de formação das galáxias do tipo S0, com foco no papel da massa da galáxia e do ambiente circundante. Utilizando dados do levantamento S-PLUS, analisamos 974 galáxias lenticulares com massas no intervalo entre $\log(M/M_{\odot}) > 9$ e $\log(M/M_{\odot}) < 12$ na Stripe 82 em 12 bandas. O código GALFITM foi utilizado para otimizar a relação sinal-ruído ajustando as imagens em uma faixa de comprimentos de onda (3543–9134 Å) simultaneamente. Para parametrizar a distribuição de luz das galáxias S0, utilizamos dois perfis de Sérsic representando a soma de um bojo e um disco ($n = 1$). A partir deste modelo fotométrico, derivamos vários parâmetros morfológicos, como o índice de Sérsic do bojo, o raio efetivo do disco e do bojo, e a razão entre a luz do bojo e a luz total da galáxia (B/T). Além disso, as propriedades das populações estelares foram obtidas ajustando Distribuições de Energia Espectral (SEDs) usando LePHARE, utilizando as bibliotecas COSMOS (empírica) e BC03 (teórica). Nós usamos as medidas do ambiente local de cada galáxia obtidas por Baldry et al. (2006), empregando o método de K-Vizinhos Mais Próximos (K-Nearest Neighbours, KNN). Posteriormente, empregamos esses parâmetros morfológicos e de populações estelares para identificar galáxias análogas na simulação hidrodinâmica IllustrisTNG. Na IllustrisTNG100-1, recuperamos árvores de fusão que descrevem todo o histórico de fusões das galáxias. Essa análise nos permite investigar a conexão entre a formação das galáxias e diversos fatores, como ambiente, massa galáctica, propriedades da população estelar, presença de um núcleo galáctico ativo (AGN) e sua evolução. Finalmente, ao comparar o ambiente circundante dos nossos dados observacionais com as galáxias simuladas, buscamos identificar objetos primordiais e elucidar seu papel na história evolutiva do universo.

Keywords. Galaxies: evolution – Galaxies: structure – Galaxies: elliptical and lenticular, cD

1. Introduction

Lenticular galaxies (S0) are hybrid systems that bridge the morphological gap between spiral and elliptical galaxies. They exhibit disk-like structures similar to spirals but lack substantial gas content, which limits active star formation. As a result, their stellar populations are predominantly older, resembling those of elliptical galaxies. This duality in features makes S0 galaxies particularly intriguing for studies of galaxy formation and evolution. Understanding their formation mechanisms can provide significant insights into the interplay between internal processes and external environmental influences on galaxy morphology.

The formation pathways of lenticular galaxies have been widely debated in the literature. One hypothesis suggests that gas-rich spiral galaxies, upon entering dense cluster environments, lose their gas and dust through mechanisms such as ram-pressure stripping, leading to the cessation of star formation (Johnston et al., 2021). Another possibility is that lenticular galaxies emerge from minor or, in a minority of cases, major mergers, where interactions with other galaxies alter their structure and deplete their gas reservoirs (Tapia et al., 2017). A third theory proposes that S0 galaxies are primordial objects, formed at high redshifts (around $z \sim 2$), and have undergone passive evolution (Saha & Cortesi, 2018).

In the Local Universe, lenticular galaxies account for approximately 50% of high-mass systems (Bernardi et al., 2010). Their prevalence in dense environments highlights their significance as probes of environmental influences, such as the role of hot intracluster gas in shaping galaxy evolution. Furthermore, their structural and stellar properties may retain imprints of early galaxy formation processes, making them pivotal in tracing the evolutionary history of the Universe.

2. Methodology

This study utilizes data from the Southern Photometric Local Universe Survey (S-PLUS, Mendes de Oliveira et al. 2019), which covers approximately 9300 square degrees of the sky using 12 optical bands. Observations are conducted with the robotic 0.8-meter T80-South telescope located at Cerro Tololo Inter-American Observatory in Chile. From this survey, we identified a sample of 974 lenticular (S0) galaxies located in Stripe 82. This selection process involved a combination of datasets and methodologies.

We use the probability of being an S0 obtained by Domínguez Sánchez et al. 2018, who applied a deep learning model to the Galaxy Zoo classifications. Next, we refine the selection by excluding objects with a probability ≥ 0.95 of being classified as elliptical or spiral, following the criteria from Bom et al. 2021. Finally, we complement the sample by including objects from DECaLS. We identify lenticular galaxies using the following criteria:

- No spiral arms are present;
- Classified as smooth rather than featured;
- Shows no signs of a recent merger.

2.1. LePHARE and GALFITM properties

First, we applied the GALFITM algorithm (Häußler et al., 2022a) to obtain galaxies' morphological features, such as the bulge and disk component. It performs simultaneous fits on multiple images of the same galaxy across different wavelengths, optimizing the process by minimizing the signal-to-noise ratio. By using a consistent aperture across all bands, we ensure reliable and uniform photometry, which is crucial for deriving morphological parameters accurately.

To characterize the light distribution in lenticular galaxies (S0), we applied the Sérsic law (Sérsic, 1963), which describes how the light intensity $I(R)$ varies with the radial distance R from the galaxy center. The Sérsic index is applied separately to the bulge and disk components, modeling the total light as a combination of these two profiles. The Sérsic equations are:

$$I(R)_{\text{bulge}} = I_e \exp\left\{-b(n)\left[\left(\frac{R}{R_e}\right)^{1/n} - 1\right]\right\}, \tag{1}$$

$$I(R)_{\text{disk}} = I_0 \exp\left(-\frac{R}{R_d}\right),$$

First, we perform the fit using only a single Sérsic fit; afterward, we perform a bulge-to-total light decomposition, fixing the Sérsic index of the disk to 1, allowing the index of the bulge to vary, improving the fit.

2.2. Sample selection: Data Filtering and crossmatch

In the Sérsic law, n represents the Sérsic index, which quantifies the concentration of a galaxy's light profile. Higher n values are indicative of spheroidal galaxies, while lower values are typical of disk-dominated systems. The parameter $b(n)$ is defined by n, while I_n is a free parameter that is fitted.

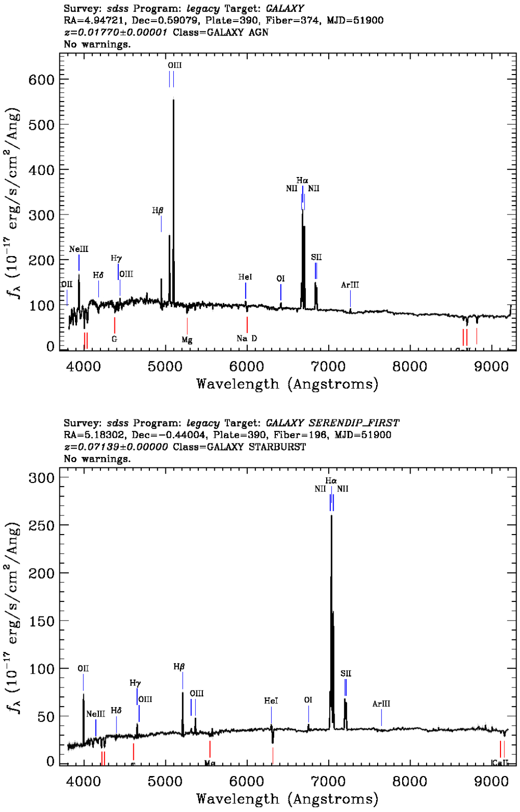

Figure 1. The two SDSS spectra obtained from SDSS website are part of the 100 analyzed galaxies and have a Sérsic index greater than 8. Their values are 8.28 (AGN) and 13.66 (Starburst), respectively. Thus, we can observe that the increase in emission lines might lead to an increase in the Sérsic index.

For our analysis, we focus on galaxies with Sérsic indices below 8 while fitting only one component, as values exceeding this threshold may indicate fitting errors, active galactic nucleus (AGN) activity, or starburst events, as illustrated in Figure 1. Applying this criterion resulted in a sample of 704 galaxies for further study.

For obtaining the properties of stellar populations, we used the code LePhare (Arnouts et al., 1999; Ilbert et al., 2006) , which allows the fitting of Spectral Energy Distribution (SED) in 12 optical bands, taking into account magnitudes and associated errors. This model combines photometric data with empirical and theoretical SED samples, providing parameters such as the Specific Star Formation Rate (sSFR) and the Star Formation Rate (SFR). We utilized the empirical COSMOS library, the theoretical BC03 models, and spectroscopic redshifts obtained from SDSS.

Once we obtained the morphological and photometric properties of the galaxies, we performed cross-matching with the galaxy density catalog by Baldry et al. 2006. Reaching a final sample of 306 objects.

2.3. Analysis in IllustrisTNG Simulations

We utilized the IllustrisTNG100-1 (Pillepich et al., 2018) cosmological simulation, which provides an intermediate-resolution framework for studying galaxy formation and evolution within a 100 Mpc/h cubic volume. This simulation incorporates detailed physical processes, including star formation, supernova and black hole feedback, and gas dynamics, enabling the modeling of realistic galactic structures and environments.

In addition to the parameters obtained from GALFITM, we used the Morfometrika (MFMTK)(Ferrari et al., 2015) software to compute non-parametric asymmetry metrics. By analyzing these asymmetry values alongside Sérsic profiles and stellar population properties derived from LePhare, our collaborators in Argentina cross-referenced the data with IllustrisTNG100-1 to identify S0-like analogs. The selection process involved applying the following properties:

- Star-forming gas fraction: Measures the amount of gas available for star formation.
- Specific Star Formation Rate (sSFR): The star formation rate normalized by stellar mass.
- $\log(M_*)$: The logarithm of stellar mass in solar units.
- Sérsic index in the g-band: Quantifies the light concentration in the g-band.
- Sérsic index in the i-band: Quantifies the light concentration in the i-band.
- Concentration index in the g-band (from MFMTK): Measures the degree of light concentration in the g-band.
- Concentration index in the i-band (from MFMTK): Measures the degree of light concentration in the i-band.
- Gini coefficient and M_{20} statistic in the g-band (from MFMTK): Quantifies the light asymmetries.
  - $G - 0.14 \times M_{20} > 0.80$
  - $G + 0.14 \times M_{20} < 0.33$
- Color indices $g - i$ and $u - r$: Used to trace age, metallicity, and dust content in stellar populations.

Through the reconstruction of merger trees of these analogs, we can better understand the evolution of these galaxies.

3. Results

We fitted 974 galaxies using the GALFITM algorithm, as illustrated in Figure 2, which shows examples of single- and two-component models. This process involves decomposing each galaxy into bulge and disk components using Sérsic profiles.

The figure compares two photometric models for an S0 galaxy, highlighting the outcomes of fitting with a single-component Sérsic profile (first) and a two-component fitting method (second). In the two-component model, GALFITM employs separate Sérsic profiles to account for the bulge and disk contributions. The figure is organized into three rows: the top row shows the original galaxy images derived from the science data, the middle row displays the model images generated by GALFITM, and the bottom row presents the residual images obtained by subtracting the models from the science data. These residuals emphasize discrepancies between the observations and the models, helping assess the adequacy of each fitting approach.

In the first fit of Figure 2, we see that a single Sérsic fit presents more residuals and has a disk-like shape. However, in the second fit, the bulge + disk fit, the residual is almost null. It is important to note that while the two-component (bulge + disk) approach often provides a more detailed characterization of S0 galaxies by separating the centrally concentrated bulge from the extended disk, it is not universally superior. The choice of model depends strongly on the bulge-to-total light ratio (B/T). Galaxies with very high B/T values (bulge-dominated) or very low B/T values (disk-dominated) can often be adequately fitted with a simpler single-component Sérsic model, as these cases lack significant contributions from both components. However, for galaxies with intermediate B/T values, where both bulge and

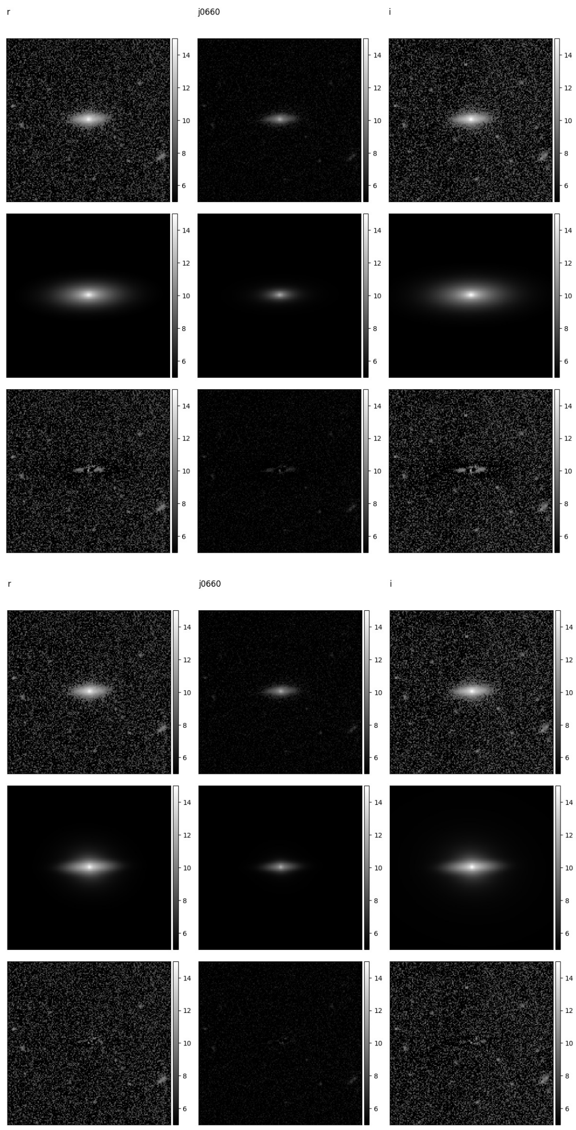

Figure 2. Comparison of photometric models for an S0 galaxy. The first panel shows the result of fitting with a single-component Sérsic profile, while the second panel displays the outcome of a two-component fitting method. Each panel is organized into three rows: (i) the top row shows the original galaxy images derived from the science data; (ii) the middle row presents the model images generated by GALFITM; and (iii) the bottom row depicts the residual images, obtained by subtracting the model from the original data. Although models were created for 12 bands, for simplicity, only the r, Hα, and i bands are displayed here.

disk components contribute significantly to the light distribution, a two-component approach provides a more accurate and comprehensive representation.

Using the single Sérsic model , we determined the Sérsic index n for the galaxies. Figure 3 illustrates how n relates to both color and stellar mass. From this figure, we observe a clear trend: galaxies with lower stellar masses tend to exhibit bluer colors and lower Sérsic indices.

This behavior indicates that lower-mass galaxies are generally less centrally concentrated, as reflected by their smaller Sérsic indices, and possess younger or less evolved stellar populations, resulting in their less redder colors. This trend aligns

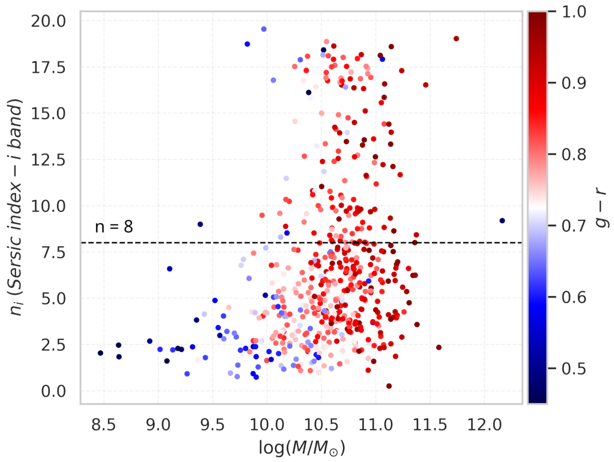

Figure 3. This plot shows the relationship between galaxy mass and Sérsic index. The color bar represents the distribution of points based on (g-r) color.

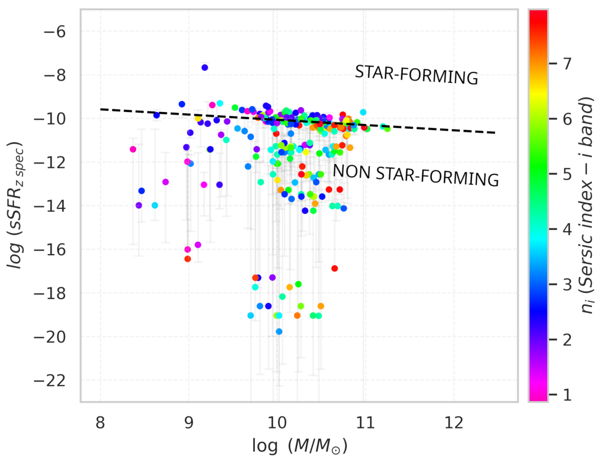

Figure 4. Relationship between Sérsic index, Stellar Mass, and sSFR for the 306 selected galaxies, derived using LePhare. The plot highlights trends in star formation activity, mass, and morphology, revealing the diversity in the evolutionary stages of the sample.

with the expectation that smaller, less massive galaxies typically undergo less significant bulge formation and retain ongoing or recent star formation, distinguishing them from their more massive, redder, and bulge-dominated counterparts.

Subsequently, we utilized the LePhare code to derive the specific star formation rate (sSFR) and other stellar population parameters for these galaxies. These parameters allowed us to analyze the relationship between morphological properties, stellar mass, and star formation activity,as in the Figure 4.

However, S0 galaxies are generally non-star-forming, yet in the Figure 4, many are located above the line defined by Belfiore et al. 2018, deviating from what was initially expected. To address this issue, Haack et al. 2024 corrected magnitudes, improving the deblending process in the SEXTRACTOR tool. This correction significantly refines the photometric extraction specific to the S-PLUS survey data, ensuring more accurate measurements.

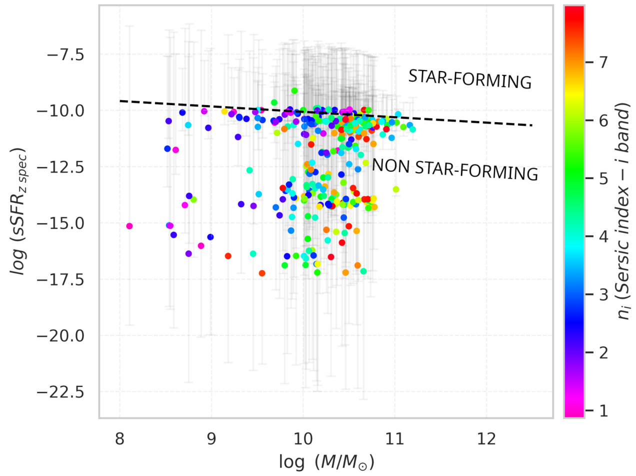

Figure 5. After applying the corrections, this version shows galaxies below the delineation line, where star formation is absent or minimal. However, the uncertainties in the specific star formation rate (sSFR) became much larger, leading us to focus on identifying the causes and improving the data quality.

Figure 5 shows a reduction in the number of galaxies with active star formation, aligning more closely with the expected properties of S0 galaxies, which are typically characterized as non-star-forming (quenched). The updated analysis reveals two distinct families of galaxies: quenched galaxies with specific star formation rates (sSFR) below −12.5 and stellar masses (M_*) exceeding $10^{9.5}\ M_\odot$, and galaxies with higher sSFR (> −10), which are more broadly distributed across the mass bins. This difference may arise because more massive galaxies have been involved in more past mergers and interactions, which might have consumed the galaxy's gas reservoir. However, the challenge lies in understanding and minimizing the errors present in this estimate.

The Sérsic index (n), a structural parameter, appears more closely correlated with stellar mass than with star formation activity, emphasizing its role as an indicator of structural concentration rather than ongoing star formation. This observation reinforces the notion that the Sérsic index reflects intrinsic morphological properties of galaxies.

In the revised photometry estimates, Haack proves to be more consistent with the expected characteristics of S0 galaxies.

In the second phase of the study, in the Figure 6 we examined the correlation between stellar mass, specific star formation rate (sSFR), and environmental density. The results show that galaxies with lower masses tend to reside in lower-density environments, and they exhibit lower star formation rates.

The trend observed in the graph can be interpreted as a reflection of the evolutionary history of galaxies, where massive galaxies in denser environments experienced a last burst of star formation. This pattern suggests that low-mass S0 galaxies are likely to be primordial systems, with a limited capacity for star formation due to their age and evolutionary history. On the other hand, the high sSFR observed in massive galaxies in dense environments points to recent episodes of star formation, possibly triggered by interactions in these regions widely discussed in the literature (e.g. (Coccato et al., 2021)).

The formation of S0 galaxies involves three primary mechanisms: environmental stripping, primordial formation, and galaxy interactions. Environmental stripping processes, such

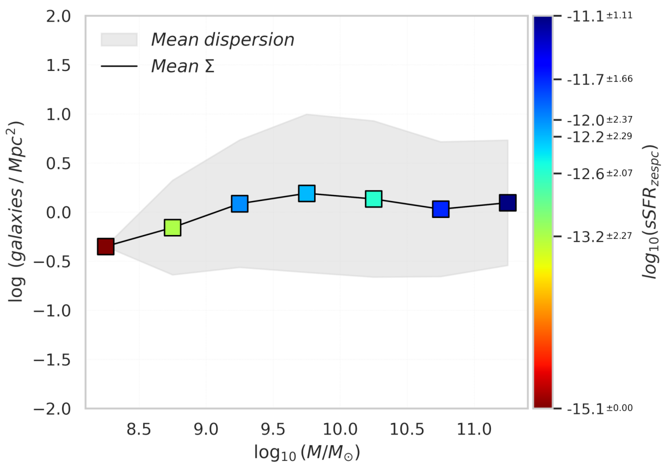

Figure 6. The cross-match results showing the relationship between local density and stellar mass ($\log_{10} M_*$), with the color bar indicating the logarithm of the specific star formation rate ($\log_{10}$ sSFR$_{\rm spec}$). The shaded region illustrates the mean dispersion.

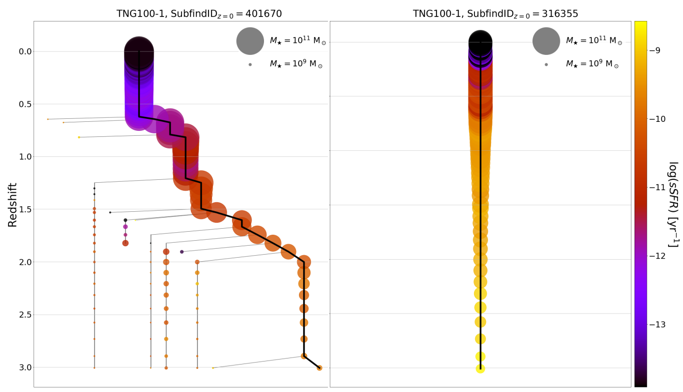

Figure 7. Example of merger trees for two simulated galaxies from the IllustrisTNG100-1 simulation. The left panel presents a schematic representation of a galaxy that experienced merger events, while the right panel corresponds to a system with no mergers in its history, potentially representing a primordial galaxy. Each shift to the left in the tree indicates a merger event. The image below illustrates the evolution of these galaxies from redshift 3 to redshift 0, with the color bar indicating the specific star formation rate (sSFR).

as ram pressure stripping, remove gas from galaxies in high-density environments, leading to a cessation of star formation. Primordial S0 galaxies are thought to form early in the universe's history, remaining as low-mass systems that preferentially occupy low-density environments. Galaxy interactions, particularly in dense regions, can trigger star formation and contribute to the creation of higher-mass S0 galaxies exhibiting recent star-forming activity, as suggested by Tapia et al. 2017.

Our analysis supports these distinctions, showing a close relationship between the properties of S0 galaxies, their stellar mass, and the density of their local environment. Specifically, low-mass S0 galaxies with minimal star formation are likely to be primordial, while high-mass S0 galaxies in dense environments tend to display evidence of interaction-driven star formation.

To further explore the contributions of these mechanisms, we propose a detailed analysis using IllustrisTNG100-1. By categorizing S0-like analogs into bins of stellar mass and local density, we aim to identify patterns that differentiate the formation pathways.

So far, we started from the intermediate mass bin. From this, 51 potential S0 galaxy analogs were identified based on the selected parameters. Following a detailed visual inspection of these candidates, 34 were confirmed to exhibit clear S0-like characteristics, consistent with the morphology and structural properties expected for lenticular galaxies.

Using this approach, we reconstructed the merger trees of these analogs, as demonstrated in Figure 7. For two galaxies, as an example, we can see that the galaxy on the left has gone through a lively merger history, and its star formation activity was quenched at $z \sim 0.5$, after the last merger. This suggests that either the environment or AGN feedback caused the quenching. The galaxy on the right did not go through any merger [1]. In this case, the star formation ceased abruptly at very low z.

Next, we'll integrate the formation histories of simulated objects through all the masses, from high to low, to unravel the impact of environmental factors, mass distribution, and the presence of an active galactic nucleus on the formation of lenticular galaxies.

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[1] We note here that this might depend on the resolution of the simulation