
Influence of Dark Matter Subhalos on the Formation of the Galaxy Spiral Arms.

Presented by

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Abstract

The dynamical stability of disk galaxies in a Λ CDM cosmology is a fundamental topic in galactic evolution, particularly in the presence of perturbers. In this study, we analyze the structural and kinematic properties of a simulated galactic disk, focusing on the effects of satellite interactions on key dynamical quantities and their influence on the formation of spiral structures. Using high-resolution numerical simulations with the GIZMO multi-physics code, we evaluate the evolution of circular velocity, epicyclic frequency, shear rate, velocity dispersions, and the Toomre stability parameter.

Our simulations incorporate the self-gravity of the stellar disk and gas, along with the full physics of star formation, feedback, and metal cooling in the ISM. Dark matter subhalos interactions are modeled using a population that follows the distribution of mass and orbital parameters observed in cosmological simulations of galaxy formation. The experimental setup includes 30 simulations, ranging from isolated (control) cases to full mergers where the disk interacts with subhalos. To distinguish numerical effects from true dynamical impact, each bombarded simulation is compared to its corresponding isolated counterpart.

Key dynamical tracers show stable behavior, and the overall impact of subhalos on the disk's structure appears minimal. No strong evidence is found that subhalos induce the formation of long-lived spiral arms, especially in simulations that include full baryonic physics. Several factors may contribute to this result. The population of subhalos has relatively low masses and large pericenter distances, limiting their gravitational influence. The string supernova feedback model depletes the gas disk early, preventing sustained spiral structure formation. Additionally, assuming a rigid halo prevents dynamical friction from altering satellite orbits, biasing interactions toward weaker perturbations.

Our findings highlight key aspects of galactic evolution. Feedback modeling plays a crucial role in the longevity of spiral structures, while the mass and orbital properties of subhalos significantly influence their perturbative effects. The assumption of a rigid halo underestimates the impact of minor mergers by preventing subhalos from sinking toward the disk center. Despite these considerations, our results suggest that the bombardment of subhalos could still provide a natural mechanism for generating transient, fragmented spiral structures in galactic disks.

Keywords: Galactic dynamics, disk stability, dark matter subhalos, numerical simulations, velocity dispersion, epicyclic frequency, shear rate, Toomre parameter.

Table of Contents

Table of Contents	iv
List of Figures	v
List of Tables	viii
1 Introduction	1
2 Theoretical framework	3
2.1 General Overview of Galaxies	3
2.1.1 Elliptical Galaxies (E)	3
2.1.2 Spiral Galaxies (S)	5
2.1.3 Lenticular Galaxies (S0)	6
2.1.4 Irregular Galaxies (Irr)	8
2.2 Morphology and structure of spiral galaxies	10
2.2.1 Halo	11
2.2.2 Bulge	13
2.2.3 Disk	14
2.3 Spiral Arms	16
2.3.1 Density Wave	17
2.3.2 Swing Amplification	18
2.4 Dark Matter Subhalos Structures	19
3 Methodology	20
3.1 Isolated Simulations	20
3.1.1 Bulge	21
3.1.2 Stellar Disk	21
3.1.3 Gas Disk	23
3.1.4 Halo	23
3.2 Merger simulations	26
3.2.1 Mass Distribution of Subhalos	27
3.2.2 Spatial Distribution of Subhalos	29
3.2.3 Assignment of Velocities to Subhalos	30

3.3	Star Formation Process	32
4	Implementation	34
4.1	Experimental Setup	34
4.2	Diagnostics of Disk Dynamics	38
4.2.1	Circular Velocity	38
4.2.2	Epicyclic Frequency	40
4.2.3	Shear Rate	40
4.2.4	Toomre Parameter	41
4.3	Numerical Implementation	42
4.3.1	Spatial Discretization and Grid Construction	42
4.3.2	Gravitational Potential Mapping	44
4.3.3	Numerical Differentiation	47
4.3.4	Velocity Dispersion Mapping	51
4.3.5	Surface Density Mapping	53
5	Results and Analysis	55
5.1	Isolated Galaxy VS Merger Galaxy	55
5.1.1	Aq-A-1 Simulation Results	56
5.1.2	GAL1, GAL2, and GAL3 Simulation Results	66
5.2	Simulations with Star Formation	73
5.2.1	Isolated Simulations	74
5.2.2	Merger Simulations	79
6	Conclusion	89
	References	97

List of Figures

2.1	Examples of elliptical galaxies	4
2.2	Examples of spiral galaxies	6
2.3	Examples of lenticular galaxies	7
2.4	Examples of irregular galaxies	9
2.5	Schematic representation of the main morphological components of a spiral galaxy	11
2.6	Comparison of Spiral Galaxy Structures: Grand-Design and Flocculent . . .	16
2.7	Density Wave Motion in Different Reference Frames	17
3.1	Schematic representation of merger galaxy	27
3.2	Illustration of the subhalo mass function, showing the number density of subhalos as a function of their mass	28
4.1	Surface and vertical density profiles for different isolated galaxy simulations	36
4.2	Gravitational potential Φ as a function of radial position R for the simulated galaxy Aq-A-1	46
4.3	Numerical convergence of circular velocity and squared epicyclic frequency for the simulated galaxy Aq-A-1	50
4.4	Numerical convergence of the velocity dispersion mapping for the simulated galaxy Aq-A-1	52
5.1	Circular velocity profile $V_c(R)$ as a function of radius R for different time snapshots in the Aq-A-1 simulation	57
5.2	Radial distribution of satellites (dark matter subhalos) in the Aq-A-1 simulation	58
5.3	Epicyclic frequency squared κ^2 as a function of radius R for different time snapshots in the Aq-A-1 simulation	59
5.4	Shear rate Γ as a function of radius R for different time snapshots in the Aq-A-1 simulation	60
5.5	Radial (σ_R) and vertical (σ_z) velocity dispersion as a function of radius R for different time snapshots in the Aq-A-1 simulation	61
5.6	Toomre factor Q as a function of radius R for different time snapshots in the Aq-A-1 simulation	62

5.7	Density contrast map in the xy-plane at different time snapshots for the Aq-A-1 simulation	64
5.8	Density contrast map in the xy-plane at different time snapshots for the Aq-A-1 simulation	65
5.9	Circular velocity profile $V_c(R)$ as a function of radius R for different time snapshots in the GAL1, GAL2, and GAL3 simulations	67
5.10	Radial distribution of satellites (dark matter subhalos) in the GAL1, GAL2, nad GAL3 simulation	68
5.11	Epicyclic frequency squared k^2 as a function of radius R for different time snapshots in the GAL1, GAL2, and GAL3 simulations.	69
5.12	Shear rate Γ as a function of radius R for different time snapshots in the GAL1, GAL2, and GAL3 simulations	70
5.13	Radial (σ_R) and vertical (σ_z) velocity dispersion as a function of radius R for different time snapshots in the GAL1, GAL2, and GAL3 simulations	71
5.14	Toomre factor Q as a function of radius R for different time snapshots in the GAL1, GAL2, and GAL3 simulations	72
5.15	Densisty contrast profiles in the xy-plane for the GAL1, GAL2, and GAL3 simulations at $t = 2.5$ Gyr	73
5.16	Gravitational potential profiles reconstructed for each simulation at $t = 2.0$ Gyr	74
5.17	Circular velocity profile $V_c(R)$ as a function of radius R for different time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations with and without star formation	76
5.18	Epicyclic frequency squared k^2 as a function of radius R for different time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations with and without star formation	76
5.19	Shear rate Γ as a function of radius R for different time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations with and without star formation	77
5.20	Radial (σ_R) and vertical (σ_z) velocity dispersion as a function of radius R for different time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations with and without star formation	78
5.21	Toomre factor Q as a function of radius R or different time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations with and without star formation	79
5.22	Circular velocity profile $V_c(R)$ as a function of radius R for different time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations with star formation	80
5.23	Radial distribution of satellites (dark matter subhalos) in the GAL1, GAL2, GAL3, and Aq-A-1 simulation with star formation	81

5.24	Epicyclic frequency squared k^2 as a function of radius R for different time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations with star formation	82
5.25	Shear rate Γ as a function of radius R for different time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations with star formation	82
5.26	Radial (σ_R) and vertical (σ_z) velocity dispersion as a function of radius R for different time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations with star formation	83
5.27	Toomre factor Q as a function of radius R for different time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations with star formation . . .	84
5.28	Density contrast profiles in the xy-plane for the GAL1, GAL2, GAL3, and Aq-A-1 simulations at $t = 2.5$ Gyr	85
5.29	Anomalous regions overlaid on density contrast maps in the xy-plane for the GAL3 simulation with star formation and Merger 1 at $t = 2.5$ Gyr. . . .	86
5.30	Density contrast maps in the xy-plane for GAL3 simulation with star formation at different snapshots	87

List of Tables

3.1	Summary of key parameters for the simulated galaxies	24
4.1	Summary of stability experiments for simulated isolated galaxies	35
4.2	Number of particles used in the main structural components of each galaxy model	37
4.3	Number of bins used in the cylindrical grid for each simulation	44
5.1	Values of R_e (effective radius) and $0.2R_e$ for each of the GAL1, GAL2, and GAL3 simulations	67
5.2	Number of gas particles present in each simulation with star formation at different time snapshots	75

Chapter 1

Introduction

Galaxies are fundamental building blocks of the universe, exhibiting a wide variety of morphologies and internal dynamics. Among them, spiral galaxies stand out due to their striking arm-like patterns, which are not only visually prominent but also dynamically rich structures. Understanding the formation and persistence of spiral arms remains one of the most intriguing challenges in galactic dynamics. While classical mechanisms such as the density wave theory and swing amplification have offered partial explanations, the role of external perturbations—particularly those arising from dark matter subhalos—remains an open and actively debated question.

This study investigates the influence of dark matter subhalos on the formation and evolution of spiral structures in disk galaxies through a series of carefully designed numerical simulations. These subhalos, which are relics of hierarchical structure formation and populate the halos of galaxies as predicted by cosmological simulations, can interact gravitationally with the disk and potentially seed non-axisymmetric features. A key novelty of this work lies in evaluating whether these perturbations, under realistic cosmological conditions, are sufficient to trigger or enhance the development of spiral arms. Moreover, the inclusion of the star formation process—rarely considered in similar studies—adds a crucial layer of realism, enabling us to explore how feedback and gas consumption modify the disk’s response to both internal and external influences.

The simulations were conducted using the GIZMO multiphysics code, incorporating a rigorous construction of the galaxy model with components including a spherical bulge, a stellar disk, a gas disk, and a halo implemented as a rigid potential. This setup allowed for high spatial and mass resolution in the baryonic components, keeping computational costs tractable while ensuring numerical stability. The experimental design was meticulously structured to isolate the individual effects of different physical processes: first, by evolving an isolated galaxy to study its natural relaxation and stability; then, by adding star formation to evaluate its self-induced perturbations; and finally, by introducing subhalos to assess their impact in both star-forming and non-star-forming scenarios.

To quantify the system's evolution, the study examines changes in surface density and evaluates key dynamical quantities such as the circular velocity, epicyclic frequency, shear rate, and Toomre stability parameter. These metrics provide a comprehensive view of the disk's structural and kinematic response, enabling a robust interpretation of the role played by each mechanism.

Chapter 2

Theoretical framework

In this chapter, we present the fundamental concepts and theoretical foundations necessary to understand the structure and dynamics of galaxies, which are used in this thesis. We are concerned with a general classification of galaxies, describing their main morphological types and highlighting their distinctive structural components. This overview provides the necessary context for understanding the diversity of galactic forms observed in the universe.

A more detailed discussion is devoted to spiral galaxies; we examine their structural components and explore the mechanisms that govern the formation and persistence of their spiral arms.

2.1 General Overview of Galaxies

Galaxies are vast and complex systems composed of stars, gas, dust, and dark matter, all bound together by gravity. They are the fundamental building blocks of the universe, ranging from small dwarf galaxies with a few million stars (Mateo, 1998) to massive elliptical galaxies containing hundreds of billions of stars (Dressler, 1980). Their structures, compositions, and dynamics provide critical insights into the processes that govern the formation and evolution of the universe. Edwin Hubble's classification scheme, remains one of the most widely used methods to categorize galaxies into four main types:

2.1.1 Elliptical Galaxies (E)

These galaxies are characterized by their smooth, featureless appearance and elliptical shapes, which range from nearly spherical (E0) to highly elongated forms (E7). Elliptical galaxies lack prominent internal structures and are predominantly composed of older, population II stars, which are low in metals and indicative of an early star formation epoch (Mo et al., 2010; Dressler, 1980). These galaxies have minimal interstellar gas and dust, making them sites of little to no current significant star formation.



Figure 2.1: Examples of elliptical galaxies exhibiting distinct structures. From left to right: PGC 42871, NGC 1316 (Fornax A), and NGC 5128 (Centaurus A). All images were obtained from the Astronomy Picture of the Day archive (APOD, 2018, 2015, 2014).

Observations of elliptical galaxies, such as those shown in Figure 2.1, reveal diversity in their structures. Some, like PGC 42871, appear as nearly featureless spheroids, while others, such as NGC 1316, show evidence of interactions or mergers. A particularly striking example is NGC 5128, which, despite being classified as an elliptical galaxy, exhibits a prominent dust lane.

The surface brightness is generally well fit by the Vaucouleurs profile (Mo et al., 2010):

$$I(r) = I_e \exp \left\{ -7.67 \left[\left(\frac{r}{r_e} \right)^{1/4} - 1 \right] \right\}, \quad (2.1)$$

where $I_e = I(r_e)$ is the surface brightness at the effective radius r_e , and r_e is the radius containing half of the total luminosity of the galaxy. This profile highlights the steep decrease in surface brightness with radius, reflecting the highly concentrated stellar mass in the core region (de Vaucouleurs, 1948).

Elliptical galaxies span a wide range of masses and sizes, from giant ellipticals (gE), which are among the most massive galaxies in the universe with stellar masses up to $10^{13} M_\odot$, to dwarf ellipticals (dE), which are less massive and fainter with stellar masses of even $10^7 M_\odot$ (Mateo, 1998). Giants are often found in the central regions of galaxy clusters, where they dominate the cluster’s gravitational potential and may have formed through mergers and accretion processes over cosmic time. In contrast, dwarf ellipticals are commonly found as satellite galaxies in groups or clusters.

The kinematics of elliptical galaxies is primarily governed by “random” stellar motions, resulting in a lack of ordered rotation. Their stellar velocity dispersions are often used to infer their dynamical mass. The presence of supermassive black holes at their centers is common, and their masses correlate with the properties of the host galaxy, such as the stellar velocity dispersion (the $M - \sigma$ relation) (Ferrarese and Merritt, 2000).

Elliptical galaxies are believed to form through multiple channels, including hierar-

chical mergers of smaller galaxies, which disrupt the ordered motions of stars and gas, leading to the smooth, spheroidal morphology observed today. Another formation pathway involves the rapid collapse of gas clouds in the early universe, followed by intense star formation and the depletion of gas reservoirs.

2.1.2 Spiral Galaxies (S)

These galaxies are among the most visually striking galaxies, characterized by their prominent disk structure, spiral arms, and central bulges. Spiral galaxies are rich in gas and dust, which provides the material necessary for ongoing star formation. Star formation predominantly occurs along the spiral arms, where density waves compress the gas, triggering the formation of young, massive stars. These stars illuminate the arms, giving them their bright, bluish appearance (Mo et al., 2010; Lin and Shu, 1964; Roberts, 1969).

They are further classified as Sa, Sb, or Sc, depending on the tightness of their spiral arms, the prominence of the central bulge, and the relative amount of interstellar material (Hubble, 1926):

- **Sa galaxies:** have tight spiral arms, with a pitch angle of about 6° , large bulges ($L_{\text{bulge}}/L_{\text{disk}} \sim 0.3$), with relatively less interstellar gas and star formation.
- **Sb galaxies:** have more open spiral arms than the previous classification, with a pitch angle of about 12° , medium-sized bulges ($L_{\text{bulge}}/L_{\text{disk}} > 0.1$), and an intermediate level of star formation activity.
- **Sc galaxies:** exhibit more open spiral arms with a pitch angle of about 18° , smaller bulges ($L_{\text{bulge}}/L_{\text{disk}} \sim 0.05$), and are gas-rich with significant star formation, often appearing more irregular.

Observations show that the surface brightness in the disk follows an exponential profile, meaning that the brightness decreases exponentially with increasing distance from the galactic center. This profile is well described by the equation:

$$I(R) = I_0 \exp\left(-\frac{R}{R_d}\right), \quad (2.2)$$

where $I(R)$ is the surface brightness at a given radius R (cylindrical radius), R_d is the exponential scale length, $I_0 = L/(2\pi R_d^2)$ is the central surface brightness, and L is the total luminosity. The effective radius enclosing half of the total luminosity is $R_e \approx 1.6R_d$, which characterizes how rapidly the brightness falls off with radius. The exponential profile is a natural outcome of angular momentum conservation and the dissipative collapse of gas during galaxy formation (Mo et al., 2010).

Similar to spiral galaxies, barred galaxies are a subclass of spiral galaxies distinguished by the presence of a central bar structure. The bar is a linear, elongated feature that ex-



Figure 2.2: Examples of spiral galaxies from left to right: NGC 1566, NGC 1232, and NGC 5643, a barred spiral galaxy. All images were obtained from the Astronomy Picture of the Day archive (APOD, 2023, 2024b,c).

tends from the central bulge and connects to the spiral arms. These galaxies are further classified as SBa, SBb, and SBc, analogous to the classification of normal spirals, based on the tightness of the arms and the size of the bulge (Kormendy and Kennicutt, 2004).

The bar structure plays a significant role in the dynamic evolution of the galaxy. It funnels gas from the outer regions of the disk towards the center, potentially fueling bursts of star formation in the central region or feeding a central supermassive black hole (Shlosman et al., 1990). This process can contribute to the buildup of the central bulge and influence the long-term morphology of the galaxy.

Barred galaxies are common in the universe, with approximately two thirds of spiral galaxies exhibiting some form of bar (Eskridge et al., 2000; Athanassoula, 2005). Studies suggest that the presence of the bar may correlate with the galaxy’s environment, mass distribution, and evolutionary stage. Bars are dynamic structures and can evolve over time, with their length, strength, and orientation changing due to interactions with the surrounding disk and dark matter halo (Sellwood, 2014).

Observations of spiral galaxies, such as those shown in Figure 2.2, highlight their diverse morphologies. NGC 1566, is a Seyfert-type spiral galaxy with well-defined arms. NGC 1232 has evidence of interactions, and NGC 5643 is a barred spiral, illustrating the presence of a central bar.

2.1.3 Lenticular Galaxies (S0)

Lenticular galaxies serve as an intermediate class between elliptical and spiral galaxies. They combine features of both types, exhibit a central bulge similar to elliptical galaxies, and also possess a disk component like spiral galaxies. However, their disks lack the characteristic of spiral arms. As a result, lenticular galaxies often have a smooth, lens-like appearance, from which their name is derived (Mo et al., 2010; Sandage, 2005).

These galaxies predominantly contain older, population II stars, indicative of an aging stellar population. They typically exhibit little to no active star formation, as their gas reservoirs have been largely depleted or stripped. The depletion of gas can occur due to several processes, such as ram pressure stripping in cluster environments (Gunn and Gott, 1972), tidal interactions with other galaxies (Moore et al., 1996), or internal dynamical processes (Larson et al., 1980). The absence of significant amounts of gas and dust further contributes to their lack of recent star formation and renders their disk relatively featureless compared to those of spirals.



Figure 2.3: Examples of lenticular galaxies from left to right: NGC 4452, NGC 2787, and NGC 5866. All images were obtained from the Astronomy Picture of the Day archive (APOD, 2010, 2002, 2006).

Observations of lenticular galaxies, such as those shown in Figure 2.3, highlight the variety of structures within this classification. NGC 4452 is an edge-on lenticular galaxy that reveals its disk’s thin, elongated shape. In contrast, NGC 2787 has a faint disk that is less prominent relative to its bulge, and NGC 5866 features a striking dust lane crossing its disk, indicating the presence of some interstellar material.

The luminosity profile of lenticular galaxies can often be modeled as a combination of a Vaucouleurs profile for the bulge and an exponential profile for the disk (Freeman, 1970; Aguerri, 2012):

$$I(r) = I_b \exp \left(-7.67 \left[\left(\frac{r}{r_e} \right)^{1/4} - 1 \right] \right) + I_d \exp \left(-\frac{r}{h} \right), \quad (2.3)$$

where I_b and I_d are the central surface brightnesses of the bulge and disk, respectively, r_e is the effective radius of the bulge (the radius enclosing half of the bulge’s light), and h is the scale length of the disk, which describes how quickly the disk’s brightness declines with radius.

This dual-component structure highlights the coexistence of the bulge-dominated inner region and the disk-dominated outer region in lenticular galaxies. The relative dominance of the bulge or disk varies among lenticular galaxies, leading to a continuum of properties

within the S0 classification.

Lenticular galaxies are frequently found in dense environments, such as galaxy clusters and groups, where interactions with the intracluster medium or neighboring galaxies can remove gas and quench star formation (Dressler, 1980). These environmental effects are thought to play a key role in the evolution of lenticular galaxies, transforming spirals into lenticulars over cosmic time (Poggianti et al., 1999).

From a kinematic perspective, lenticular galaxies exhibit features of both rotation-dominated and dispersion-dominated systems. The stellar orbits in their disks are typically rotationally supported, similar to spirals, while the stars in their bulges show random motions, similar to ellipticals. The balance between these two components varies depending on the galaxy’s specific formation history and environment (Emsellem et al., 2011).

These galaxies are also notable for their wide range of luminosities and sizes, from dwarf lenticulars (dS0), which are low-mass systems often found as satellites in groups, to massive lenticular that can rival the size and brightness of giant ellipticals. Their evolutionary pathways are diverse and may include processes such as the fading of spiral galaxies after gas depletion, mergers, or the accretion of material in cluster environments.

2.1.4 Irregular Galaxies (Irr)

These galaxies are a diverse class of galaxies that lack a well-defined shape or structure, appearing chaotic and asymmetric in morphology. Unlike spirals or ellipticals, irregular galaxies do not possess a prominent central bulge, organized disk, or spiral arms. Their irregular shapes often arise due to gravitational interaction, mergers, or tidal disruptions caused by neighboring galaxies. These interactions can strip or distort material, leading to their disordered appearance (Mo et al., 2010; Toomre and Toomre, 1972; Bournaud et al., 2005).

Irregular galaxies typically contain significant amounts of gas and dust, making them active sites of star formation. Their gas-rich environments support the formation of young, massive stars which illuminate the galaxy and contribute to its often bluish hue (Gallagher, 1984). Many irregular galaxies exhibit bright H II regions -clouds of ionized hydrogen-where intense star formation is ongoing. These regions are often scattered across the galaxy, reflecting its chaotic nature (Hunter, 1997).

Observations of irregular galaxies, as shown in Figure 2.4, illustrate their diverse morphologies. The Large Magellanic Cloud (LMC) is the largest and most massive irregular galaxy in the Local Group, exhibiting faint spiral-like features but lacking a coherent disk. NGC 6822 is a nearby irregular galaxy that is gas-rich and actively forming stars, and



Figure 2.4: Examples of irregular galaxies from left to right: Large Magellanic Cloud (LMC), NGC 6822 (Barnard’s Galaxy), and NGC 1569. All images were obtained from the Astronomy Picture of the Day archive (APOD, 2020, 2008, 2024a).

NGC 1569 is a dwarf irregular galaxy undergoing a starburst event, with intense star formation spread throughout its structure.

Irregular galaxies can often be subdivided into two main types (Hubble, 1926):

1. **Type I (Irr I):** These galaxies retain some semblance of structure, such as faint traces of a disk or remanent of spiral arms. They often appear distorted but still recognizable as galaxies.
2. **Type II (Irr II):** These are more chaotic in appearance, with no discernible structure. They may contain large regions of intense star formation, tidal tails, or disrupted features caused by gravitational interactions.

The stellar populations of irregular galaxies are a mix of older stars and younger, massive stars. The presence of young, blue stars and active star-forming regions distinguishes them from elliptical galaxies (Tolstoy et al., 2009). Their dynamics are also less organized compared to spirals, with random motion and irregular gas flows dominating over coherent rotation (de Blok and McGaugh, 1997).

Irregular galaxies are often smaller and less massive than typical spirals or ellipticals. Many are classified as dwarf irregular galaxies (dIrr), which are among the most abundant galaxy types in the universe (Mateo, 1998). Despite their small size, these galaxies can have a significant impact on their surroundings, serving as building blocks for larger galaxies through hierarchical merging (Kroupa, 2012).

These galaxies provide unique insights into galactic formation and evolution. Their chaotic nature and ongoing star formation make them valuable laboratories for studying the interplay between gas, stars, and feedback processes. Additionally, their prevalence in the early universe suggest that many irregular galaxies may be progenitors of more massive and structured galaxies seen today (Papovich et al., 2015).

From a luminosity perspective, galaxies span a wide range of brightness levels. Their luminosity function can be described by a Schechter function (Schechter, 1976):

$$\phi(L)dL = \phi_* \left(\frac{L}{L_*} \right)^\alpha \exp \left(-\frac{L}{L_*} \right) \frac{dL}{L_*}, \quad (2.4)$$

where $\phi(L)dL$ is the number of galaxies per unit volume in the luminosity interval from L to $L + dL$, L_* is the “characteristic luminosity” marking the transition between bright and faint galaxies, α is the slope of the luminosity function in the plane when $L \ll L_*$, and ϕ_* is a number per unit volume.

2.2 Morphology and structure of spiral galaxies

When we imagine a galaxy, it is often a spiral galaxy that comes to mind, with its iconic swirling arms and bright central bulge. Spiral galaxies are some of the most recognizable and well studied structures in the universe. They are defined by their disk-dominated morphology, with spiral arms that trace the distribution of young, massive stars and regions of active star formation (Lin and Shu, 1964; Roberts, 1969). These galaxies play a significant role in our understanding of galactic evolution and the processes governing star formation, stellar feedback, and interactions with the intergalactic environment (Kennicutt, 1998).

A schematic representation of the main structural components of a spiral galaxy—bulge, stellar disk, gas disk, and halo—is shown in Figure 2.5. This diagram highlights the relative positioning of these components, although their actual proportions vary between galaxies.

Approximately 70% of the galaxies in the nearby universe are spiral galaxies, making them the dominant population in the cosmic landscape (Nair and Abraham, 2010). These galaxies are sites of complex dynamical processes, hosting a variety of stellar population, from young, blue stars in their arms to older, red stars in their central bulge (Gadotti, 2009).

This subsection provides a look at the main structural components of spiral galaxies: the disk, where most of the visible mass and star formation occurs (Freeman, 1970); the bulge, a dense, spheroidal component composed predominantly of older stars (Kormendy and Kennicutt, 2004); and the halo, a diffuse structure extending far beyond the visible limits of the galaxy, containing dark matter (Rubin and Ford, 1970), globular clusters, and a sparse population of stars.

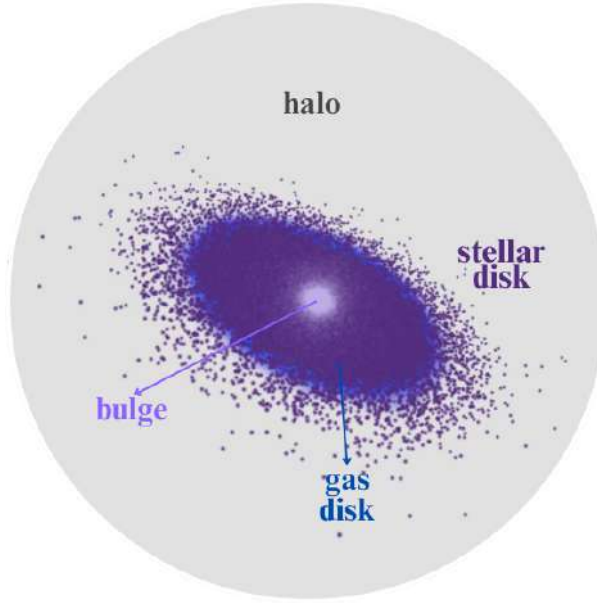


Figure 2.5: Schematic representation of the main morphological components of a spiral galaxy: the bulge, the stellar and gas disk, and the halo. The proportions and spatial extents of these components in this diagram are illustrative and do not necessarily reflect their actual relative sizes in real galaxies.

2.2.1 Halo

The galactic halo is a vast, roughly spherical region that envelops the disk and bulge of a galaxy, extending far beyond the visible boundaries of these components. It plays a critical role in the dynamics, structure, and evolution of the galaxy as a whole. As depicted in Figure 2.5, the halo is composed of two primary components; the stellar halo and the dark matter halo, each with distinct properties and contributions to the galaxy’s mass and gravitational potential (Bland-Hawthorn and Gerhard, 2016).

Stellar halo:

The stellar halo consists of a diffuse population of old, metal-poor stars and globular clusters distributed in a roughly spherical configuration around the galaxy (Mo et al., 2010). These stars are among the oldest in the galaxy, with ages exceeding 10 billion years, and their low metallicity ($[Fe/H] < -1$) reflects the chemical composition of the early universe. The distribution of stars in the stellar halo is often described using a power-law density profile (Helmi, 2008):

$$\rho_{\text{stellar}}(x, y, z) = \rho_0 \left(\frac{x^2 + \frac{y^2}{p^2} + \frac{z^2}{q^2} + a^2}{r_0} \right)^n, \quad (2.5)$$

where ρ_{stellar} is the stellar density as a function of position, $\rho_0 = \rho_{\text{stellar}}(r_0)$ a normalization factor where r_0 is a reference radius generally taken to be the solar radius, n is the

power law exponent, and q and p are the minor- and intermediate-to-major axis ratios (in the axisymmetric case, $p = 1$). Finally a is the scale radius.

The stellar halo extends to distance of up to 100 kpc (depending of the size of galaxy) from the galactic center, far beyond the visible disk. It is populated by stars on eccentric, randomly oriented orbits, which distinguish it from the ordered rotational motion of the disk. These stars are thought to originate primary from the accretion and tidal disruption of dwarf galaxies during the galaxy's formation and evolutionary history (Helmi et al., 1999). The presence of globular clusters in the stellar halo also provides clues about the early stages of star formation and chemical enrichment in the galaxy (Binney and Tremaine, 2008).

Dark matter halo:

The dark matter halo is the most massive and extended component of a galaxy, encompassing and dominating its overall gravitational potential. Composed of non-baryonic matter that does not emit, absorb, or reflect electromagnetic radiation, the dark matter halo is detectable only through its gravitational influence on visible matter and galaxy dynamics. The total mass of the dark matter halo is typically 10 to 100 times greater than the combined mass of the stars, gas and other baryonic components of the galaxy (Wechsler and Tinker, 2018).

The density distribution of the dark matter halo is commonly modeled using the Navarro-Frenk-White (NFW) profile (Navarro et al., 1997):

$$\rho_{\text{DM}}(r) = \frac{\rho_{\text{crit}} \delta_c}{\frac{r}{r_s} \left(1 + \frac{r}{r_s}\right)^2}, \quad (2.6)$$

where $\rho_{\text{crit}} = 3H^2/8\pi G$ is the critical density for closure, δ_c is a characteristic (dimensionless) density, r is the radial distance from the galactic center, and r_s is a scale radius that defines the transition between the inner and outer regions of the halo. This profile predicts a steep increase in density toward the center of the halo, with a gradual decline in the outer regions.

The dark matter halo extends to distances of several hundred kiloparsecs, As illustrated in Figure 2.5, it encloses the entire galaxy, with its influence detectable through galaxy rotation curves (Rubin and Ford, 1970). Observations show that the rotation velocity of stars and gas in the galactic disk remains approximately constant at large radii, rather than decreasing as predicted by the distribution of visible matter alone. The discrepancy provides compelling evidence for the presence of dark matter (Sofue and Rubin, 2001).

The combined gravitational influence of the stellar and dark matter halos determines

the overall gravitational potential of the galaxy, which in turn affects the motion of stars, gas, and globular clusters within the galaxy. The dark matter halo plays a crucial role in stabilizing the disk against gravitational instabilities and sustaining the spiral structure over time (Ostriker and Peebles, 1973). Additionally, the interaction between the halo and the disk influences the accretion of gas, the formation of new stars, and the evolution of the galaxy’s morphology (Dekel et al., 2009).

The stellar halo, although much less massive than the dark matter halo, provides important insights into the galaxy’s assembly history. By studying the chemical compositions, kinematics, and spatial distribution of stars in the stellar halo, it is possible to reconstruct the merger and accretion events that shaped the galaxy over billions of years (Helmi, 2020).

2.2.2 Bulge

The bulge is a nearly spheroidal distribution of stars located at the center of spiral galaxies, as shown in Figure 2.5. It represents one of the primary structural components of spiral galaxies and is integral to their overall morphology and dynamics. The bulge can vary significantly in size and brightness relative to the galaxy as a whole, from the prominent, luminous bulges of early-type spirals (Sa, SBa) to the smaller, less pronounced bulges in late-type spirals (Sc, SBc) (Kormendy and Kennicutt, 2004).

The bulge is predominantly composed of older, population II stars, which are metal-poor and represents some of the earliest generations of stars formed in the galaxy. These stars exhibit low levels of ongoing star formation, as the gas content in the bulge is typically minimal or entirely depleted (Wyse et al., 1997). The lack of significant star formation and the dominance of older stars give the bulge a characteristic reddish color, distinguishing it from the bluish hues of their spiral arms which host younger stellar populations (Gadotti, 2009).

The stars in the bulge are distributed in a manner dominated by random motions rather than the ordered rotation observed in the galactic disk. This results in a pressure-supported system, where the gravitational potential of the bulge is balanced by the random velocities of its stars. The velocity dispersion of stars in the bulge can be used to infer its mass and plays a critical role in determining the gravitational potential of the galaxy’s central region (Binney and Merrifield, 1998).

The bulge significantly influences the dynamics of the inner galaxy, affecting the orbits of stars and the stability of the spiral arms. It is also closely linked to the presence of supermassive black holes at the centers of spiral galaxies. Observations have revealed a strong correlation between the mass of the central bulge (M_b) and the velocity dispersion

(σ) of the stars in the bulge, known as the $M - \sigma$ relation (Ferrarese and Merritt, 2000; Gebhardt et al., 2000). This empirical relation indicates that more massive bulges exhibit higher stellar velocity dispersions, following a power-law dependence of the form $M_b \propto \sigma^p$, where the exponent p is typically found to be between 4 and 5 (Mo et al., 2010). Its significance lies in establishing a direct link between the bulge's structure and the dynamics of its stars.

2.2.3 Disk

The disk is the flattened, rotating component of a spiral galaxy, comprising stars, gas, and dust. It is the most visually striking and active region of spiral galaxies, characterized by its spiral arms, where higher densities of gas and stars give rise to prominent, bright features that extend outward from the central bulge. The disk is the site of most of the galaxy's star formation activity, hosting a wide range of stellar populations from young, massive stars to older, lower-mass stars (Binney and Merrifield, 1998; Kennicutt, 1998).

As illustrated in Figure 2.5, the disk can be divided into two distinct components based on its composition and dynamics: the stellar disk and the gas disk. These components interact dynamically and influence the overall structure and evolution of the galaxy (Freeman, 1970).

Stellar Disk

The stellar disk consists of stars distributed in a relatively thin, flattened structure that rotates around the galactic center. Stars in the disk move in nearly circular orbits within the plane of the disk, although some exhibit slight eccentricities. The thickness of the stellar disk is much smaller than its radial extent, with a vertical scale height of a few hundred parsecs compared to radial sizes that can exceed tens of kiloparsecs (van der Kruit and Freeman, 2011).

The stellar population of the disk is diverse, including both young stars recently formed in the spiral arms and older stars that have orbited within the disk for billions of years. The younger stars, often concentrated in the spiral arms, are typically bright, massive, and blue, whereas older stars are found throughout the disk and exhibit redder colors due to their lower temperatures and metallicities.

The luminosity density distribution can be written as (van der Kruit and Freeman, 2011):

$$L(R, z) = L(0, 0) \exp\left(-\frac{R}{b}\right) \operatorname{sech}^{1/n}\left(\frac{nz}{2h_z}\right) \quad (2.7)$$

where $L(0, 0)$ is the central luminosity density, and h_z is the disk scale length. This

ranges from the isothermal distribution [$n = 1 : L(z) \propto \text{sech}^2(z/z_0)$ with $z_0 = 2h_z$] to the exponential function [$n = \infty : L(z) \propto \exp(-z/h_z)$] and allows for the more realistic case that the stellar distribution is not completely isothermal in the vertical direction.

The stellar disk is dynamically governed by differential rotation, where the angular velocity decreases with increasing distance from the galactic center. This results in a shearing motion that influences the development and maintenance of spiral density waves, as well as the stability of the disk against gravitational collapse (Lin and Shu, 1964).

Gas Disk

The gas disk is the component of the disk composed of the interstellar medium (ISM), which includes molecular clouds, atomic hydrogen (HI), ionized gas (HII regions), and dust. The gas disk is similar in shape to stellar disk but is often more extended and exhibits a lower vertical scale height, making it thinner in comparison (Young and Scoville, 1991).

The ISM serves as the raw material for star formation and is concentrated in the spiral arms, where the gas is compressed by density waves, triggering the collapse of molecular clouds and the subsequent formation of new stars (McKee and Ostriker, 2007). The gas distribution in the disk can be described by an exponential profile similar to the stellar disk, but the scale length of the gas disk is typically larger, indicating that the gas is more extended and less centrally concentrated (Momose et al., 2013).

The kinematics of the gas disk is also governed by differential rotation, with the gas following nearly circular orbits around the galactic center. However, the gas dynamics can be significantly affected by nonaxisymmetric structures such as spiral arms, bars, and interactions with other galaxies. Shock and turbulence within the gas disk are critical for regulating star formation, influencing the efficiency with which gas is converted into stars (Bournaud et al., 2005).

In addition to its role in star formation, the gas disk contains evidence of ongoing processes such as gas accretion from the intergalactic medium, outflows driven by stellar feedback, and the recycling of material ejected by dying stars (Dekel et al., 2009). These processes contribute to the chemical enrichment of the ISM, as heavier elements produced in stars are returned to the gas phase (Tinsley, 1968).

The stellar and gas disk are closely coupled through gravitational interactions and feedback processes. Star formation in the gas disk is influenced by the gravitational potential of the stellar disk, while energy and momentum injected by supernovae, stellar winds, and radiation pressure from young stars regulate the dynamics and thermal state

of the gas disk. Together, these processes shape the evolution of the disk over cosmic time, driving the growth of the galaxy and the redistribution of the baryonic material (Binney and Tremaine, 2008).

2.3 Spiral Arms

Spiral arms are one of the most prominent and dynamically significant structures in disk galaxies. Their formation and maintenance have been extensively studied, leading to multiple theoretical models that attempt to explain their origin. Spiral structures are broadly classified into two categories based on their morphological characteristics (Elmegreen and Elmegreen, 1987):

- **Grand-design spirals:** Exhibit well-defined, symmetric, and continuous spiral arms that extend throughout the disk (e.g., NGC 1566, left panel in Figure 2.6). These arms are often explained by large-scale gravitational instabilities or density wave mechanisms that organize star formation and gas distribution across the disk (Lin and Shu, 1964).
- **Flocculent spirals:** In contrast, have fragmented, patchy spiral arms without a coherent global pattern (e.g., NGC 4414, right panel in Figure 2.6). These structures are typically attributed to local gravitational instabilities, transient features in the disk, or stochastic self-propagating star formation (Elmegreen and Elmegreen, 1987).



Figure 2.6: Comparison of Spiral Galaxy Structures: on the left, NGC 1566, a grand-design spiral galaxy, exhibits well-defined, symmetric spiral arms with prominent star-forming regions. On the right, NGC 4414, a flocculent spiral galaxy, shows a more fragmented spiral pattern, with multiple short arms segments rather than a continuous structure. Both images were obtained from APOD archive (APOD, 2023, 2016).

The mechanisms responsible for spiral arms formation vary depending on the underlying dynamics of the galaxy. In particular, two primary scenarios are proposed for their origin:

- **Spiral arms formed by gravitational torques:** In this scenario, non-axisymmetric perturbation, such as bars or tidal interactions with neighboring galaxies, generate torque induced spiral structures. These arms may be transient and dynamically evolving (Bertin, 1996).
- **Spiral arms as long-lived quasi-stationary structures:** This class includes theories such as the density wave theory and swing amplification, which describe spiral arms as self-sustaining or recurrent features in the galactic disk. The following subsection discuss these two fundamental mechanisms in detail.

2.3.1 Density Wave

The density wave theory was first introduced by Lin and Shu (1964) as a framework to explain the persistence of spiral arms, not material features composed of a fixed set of stars; rather, they represent quasi-stationary density waves, regions of enhanced stellar and gas density that propagate through the galactic disk.

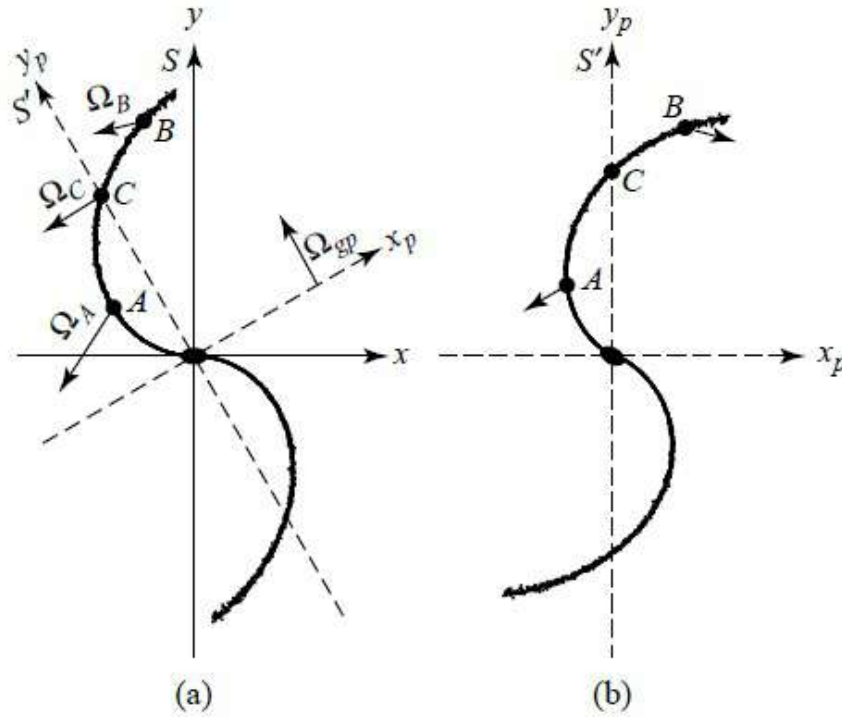


Figure 2.7: (a) Schematic representation of a spiral galaxy with trailing arms, observed in an inertial reference frame S , where a quasi-stationary density wave rotates with an angular pattern speed Ω_{gp} . Stars experience different angular velocities: Star A moves faster than the pattern, Star B moves slower, and Star C co-rotates with the density wave. (b) The same configuration viewed from a rotating reference frame S' , where the density wave appears stationary. Figure taken from Carroll and Ostlie (2017).

In this framework, stars and gas move through the spiral pattern. The density wave

is sustained by self-gravity and differential rotation, where the pattern speed of the spiral arms, Ω_{gp} , differs from the angular velocity of individual stars and gas clouds, $\Omega(r)$. The location where these two frequencies are in alignment defines the corotation radius. As shown in 2.6 (a), stars within the corotation radius move faster than the wave ($\Omega_A > \Omega_{gp}$), while those outside move slower ($\Omega_B < \Omega_{gp}$) (Carroll and Ostlie, 2017; Bertin, 1996). Unlike in the corotation radius, a star moves at the same angular velocity as the wave ($\Omega_C = \Omega_{gp}$), which means it stays within the same region of the spiral pattern over time. This differential motion leads to periodic compression of gas clouds as they enter the high-density areas of the wave, triggering star formation and creating the bright spiral arms observed in galaxies.

To better visualize this effect, 2.6 (b) illustrates the same scenario from a rotating reference frame S' that co-moves with the density wave. In this non-inertial frame, the spiral pattern appears stationary, while the stars follow curved trajectories due to their motion relative to the wave. This perspective highlights how stars interact dynamically with the density wave, reinforcing the idea that the spiral arm is not rigid structures but rather patterns maintained by self-gravity and differential rotation.

The density wave model successfully explains the longevity of grand-design spiral structures and the observed correlation between spiral arms and star formation. However, additional mechanisms, such as feedback from star formation or interaction with galactic bars, are required to sustain the spiral pattern over cosmic timescales (Bertin, 1996).

2.3.2 Swing Amplification

While density waves provides a robust explanation for long-lived spiral structures, another mechanisms known as swing amplification has been proposed to explain transient, recurrent spiral patterns in disk galaxies. This model, induced by Julian & Toomre (1966), describes how leading perturbations in the stellar disk can be amplified as they shear into trailing spiral arms due to differential rotation (Toomre, 1981).

The amplification process occurs when a small leading perturbation in the stellar disk is sheared into a trailing configuration, causing an increase in density contrast due to self-gravitational effects. Swing amplification is particularly effective in generating transient, flocculent spiral arms that appear and disappear over short timescales. Unlike the density wave model, this mechanism does not require an external driver; instead, it relies on the natural evolution of perturbations within the disk (Kawata et al., 2014).

2.4 Dark Matter Subhalos Structures

Dark matter subhalos are smaller gravitationally bound structures embedded within the main dark matter halo of a galaxy. These substructures are a key prediction of the cold dark matter cosmological model (Λ CDM) and formed as a result of hierarchical gravitational collapse in the early universe (Klypin et al., 1999; Moore et al., 1999). Over time, subhalos are incorporated into larger galactic halos during the merger and accretion processes that drive galaxy formation (Diemand et al., 2008).

The subhalos are distributed non-uniformly within the main halo, with a higher density in the outer regions due to tidal effects that disrupt or erode substructures closer to the galactic center (Bullock et al., 2001). Despite their small individual masses relative to the main halo, subhalos collectively contribute to the overall structure and dynamics of the galaxy. Their gravitational influence can perturb the distribution of stars and gas in the galactic disk, potentially triggering features such as spiral arms.

Chapter 3

Methodology

This study explores the influence of dark matter subhalos on the formation and evolution of spiral arms in galaxies through numerical simulations carried out using the GIZMO Multiphysics Code. The first set of simulations is based on the AQ-A-1 halo from the Aquarius project (Springel et al., 2008), serving as the foundation for modeling a Milky Way-like galaxy. The second set consists of three galaxies with different masses, labeled GAL1, GAL2, and GAL3. This second set was introduced to analyze the effect of perturbing subhalos on systems of varying masses.

The methodology focuses on systematically constructing stable host galaxy models, describing their initial conditions and motivations. Consider three main cases: isolated galaxies, galaxies undergoing mergers (where perturbing subhalos are introduced), and analyzing these systems while incorporating star formation processes. Additional physical mechanisms, such as cooling and feedback, were included to enhance the realism of the simulations. Finally, the analysis was extended to galaxies of different masses to evaluate the generality of the results.

3.1 Isolated Simulations

Before analyzing the effects of perturbing subhalos, it is crucial to establish stable and dynamically consistent initial conditions for an isolated galaxy. This step ensures that any structural or kinematic evolution observed in later stages is a direct consequence of external influence rather than numerical artifacts or intrinsic instabilities in the model. Constructing an equilibrium galaxy provides a robust baseline against which the impact of subhalo interactions can be measured, allowing for a clearer interpretation of their role in spiral arm formation and evolution.

In this section, we describe the setup of initial conditions for the isolated galaxy model, detailing the methodology used to generate each of its components: the bulge, stellar disk, gas disk, and halo. For each component 2.5, the initial positions were assigned based

on the corresponding density distribution, while the initial velocities were generated to ensure dynamical consistency with the gravitational potential. This systematic approach guarantees that the simulated galaxy is in a stable equilibrium state before any external perturbations are introduced.

3.1.1 Bulge

The bulge was modeled as a spheroidal distribution of stars, characterized by a Hernquist-like density profile:

$$\rho(r) = \frac{\rho_0}{\left(\frac{r}{a}\right)^\gamma \left(1 + \frac{r}{a}\right)^{3-\gamma}}, \quad (3.1)$$

where r is the radial distance from the center of the galaxy, a is the scale radius, which defines the transition point between the central high-density region and the outer declining density, γ controls the inner slope of the density profile ($\gamma = 1$ results in a cuspy profile), and ρ_0 is a normalization factor that ensures that the total mass of the bulge matches its intended value.

This profile provides a centrally concentrated, spherically symmetric distribution of stars that resembles the observed galactic bulge in massive galaxies.

The initial velocities for the bulge particles were assigned to reflect an isotropic, dispersion-supported structure consistent with the gravitational potential. The process involves the following steps:

- Velocity dispersions and the mean rotational velocity were interpolated from pre-computed grids based on the particle's position in cylindrical coordinates (R, z) .
- Gaussian random values scaled by the velocity dispersions were used to assign the radial (v_r) and vertical (v_z) velocity components. The azimuthal velocity (v_ϕ) was computed as a sum of the mean rotational velocity and a random perturbation. The velocity dispersions were computed using the Jean's equations, which relate the kinematic properties of a stellar system to its underlying gravitational potential.
- The cylindrical velocity components (v_r, v_ϕ, v_z) were transformed to Cartesian coordinates (v_x, v_y, v_z) using the particle's positions (x, y, z) to ensure consistency with the simulation's coordinate system.

3.1.2 Stellar Disk

The stellar disk was modeled as a flattened, rotationally supported component with distinct radial and vertical profiles:

- The radial density profile is exponential and given by:

$$\Sigma(R) = \Sigma_0 \exp(-R/R_a), \quad (3.2)$$

where R is the cylindrical radial distance from the galactic center, R_a is the scale radius of the disk, determining how quickly the surface density decreases outward, and Σ_0 is the central surface density.

- The vertical density profile is described by:

$$\rho(R, z) = \rho_0(R) \text{sech}^2(z/z_0), \quad (3.3)$$

where z is the height above or below the midplane of the disk, z_0 is the vertical scale height, which determines the thickness of the disk, and $\rho_0(R)$ is the density of the midplane at a given radius R .

Together, these profiles describe a disk that is aximmetric and rotationally supported, with stars distributed densely near the center and thinning out both radially and vertically.

The initial velocities for the stellar disk particles were assigned to reflect the rotational support and anisotropic velocity dispersion characteristic of the galactic components. The following approach was adopted:

- The particles in the stellar disk were assigned azimuthal velocities (v_ϕ) based on the rotational velocity profile of the disk. This profiles ensures that the majority of the disk's gravitational support comes from ordered rotational motion. Additionally, a dispersion component was added to the azimuthal velocities to account for random motion within the disk.
- To accurately model the internal dynamics of the disk, random motions were included in the radial (v_r), and vertical (v_z) directions. These motions were assigned based on the velocity dispersion profiles, which vary with the distance from the galactic center and the height above the midplane. The dispersions were chose to reflect an anisotropic velocity distribution, where the random motions are typically stronger in the radial directions compared to the vertical directions.
- The velocity properties (rotational velocities and dispersions) were defined as smooth functions of the particle's positions within the disk. This ensures that the velocity field transitions naturally across different regions of the disk, avoiding abrupt changes that could destabilize the system.
- The assigned velocities were designed to balance the gravitational forces acting on the disk, ensuring that the particles remained bound and the disk maintained a stable configuration during its evolution. The velocity distribution reflects the combined influence of the disk's mass, the gravitational potential of the bulge and halo, an the inherent random motions of the particles.

3.1.3 Gas Disk

For the gaseous components, particles were also used, which in this case are divided into cold and hot gas particles.

- The cold gas follows the same radial exponential profile as the stellar disk but has a vertical profile determined by an interpolated function based on a convenient model. This ensures a realistic stratification of the cold gas, which is primarily confined to the midplane of the disk.
- The hot gas has a radial profile proportional to R indicating that its density decreases linearly with radius in the outer regions. The vertical distribution of the hot gas resembles that of a stellar disk, forming a thicker structure.

The initial velocities of the gas disk particles were assigned to reflect and ordered, rotationally supported configuration with minimal random motion. The process followed these steps:

- The azimuthal velocity (v_ϕ) for each particle was determined from a precomputed grid of rotational velocities. This grid was defined as a function of the particle's radial distance (R) and height above the midplane (z). Bilinear interpolation ensured smooth transitions across the velocity field.
- The radial and vertical velocity components were set to zero for all particles, reflecting the assumption that the gas is initially in a dynamically cold and ordered state.
- Each particle was initialized with a uniform internal energy representing the thermal state of the gas.

3.1.4 Halo

The halo was represented as a rigid potential. This approach allows computational efficiency while maintaining the underlying influence of the halo on the overall galactic dynamics.

For components of the model that follow a granular approach—bulge, stellar disk, and gas disk—particles within each component were assigned equal mass. The choice was made to minimize spurious effects such as two-body relaxation, which can artificially alter the system's evolution over time. It is important to note that while all particles within a given component share the same mass, the mass of individual particles differs between components. The mass of each particle, m_{particle} , was calculated as:

$$m_{\text{particle}} = \frac{M_{\text{total}}}{N_{\text{particle}}}, \quad (3.4)$$

where M_{total} is the total mass of the specific component, calculated as the fraction of the total mass of the galaxy assigned to that component. The number of particles, N_{particle} , is chosen to ensure that the mass of the individual particles remains small enough to maintain a collisionless system while keeping computational costs manageable. This balance is essential to accurately model the large-scale dynamics of the galaxy without introducing artificial collisional effects or excessive computational overhead.

In all cases, center-of-mass corrections were applied to ensure that the initial configurations were dynamically centered and free from spurious drift. This step was critical to accurately model the interactions between the components and maintain numerical stability.

To ensure the stability of the host galaxy models before introducing perturbations, the surface density profiles of the gas particles were monitored over 1 Gyr of evolution in isolation. The convergence of these profiles was used as the primary criterion for establishing a stable galactic configuration.

Sim name	$M_{200} [M_{\odot}]$	$R_{200} [\text{kpc}]$	$M_{50} [M_{\odot}]$	$R_{50} [\text{kpc}]$	C	λ
Aq-A-1	1.839×10^{12}	245.76	2.523×10^{12}	433.48	16	0.04
GAL1	10^{10}	25.01	1.29×10^{10}	43.28	12	0.04
GAL2	10^{11}	53.58	1.31×10^{11}	93.00	11	0.04
GAL3	10^{12}	114.77	1.31×10^{12}	199.20	11	0.04

Table 3.1: Summary of key parameters for the simulated galaxies. The table presents fundamental properties defining the initial conditions of each galaxy model. M_{200} is the virial mass of the halo, defined as the mass enclosed in a sphere with mean density 200 times the critical value. R_{200} gives the corresponding virial radius. We also give the mass and radius for a sphere of overdensity 50 times the critical density, denoted as M_{50} and R_{50} . Finally, we include the concentration parameter (C), and spin parameter (λ).

To provide a comprehensive overview of the initial conditions used in our simulations, Table 3.1.4 summarizes the key properties of the different galaxy models. In contrast to the Aq-A-1 model, whose parameters were directly extracted from the Aquarius Project (Springel et al., 2008), the properties of GAL1, GAL2, and GAL3 were determined using an internal scaling approach. This methodology enables the construction of galaxy models with varying total masses while preserving self-consistent structural and dynamical properties. The process begins with the virial mass and the concentration parameter, and follows these steps:

1. The virial radius R_{200} is determined using an empirical relationship obtained from numerical simulations Macció et al. (2013):

$$\log(C) = a(z)\log(M_{200}/[h^{-1}M_{\odot}]) + b(z), \quad (3.5)$$

where C is a concentration parameter $C = R_{200}/r_s$ and r_s is the scale radius. We can express the virial radius as:

$$R_{200} = h \times 10^{[A \log_{10}(M_{200}) + B]}, \quad (3.6)$$

where h is the Hubble parameter, and A and B are coefficients determined numerically using Brent's method in Python, which combines bisection, inverse quadratic interpolation, and the secant rule to find a root of a continuous function on a closed interval. To ensure consistency, these coefficients were calibrated using real values from Aq-A-1 simulation.

2. From the Navarro-Frenk-White (NFW) density profile, the mass enclosed within a given radius R follows:

$$M(< R) = 4\pi\rho_0 r_s^3 f(x), \quad (3.7)$$

where $x = R/r_s$ and:

$$f(x) = \ln(1+x) + \left(\frac{x}{1+x}\right), \quad (3.8)$$

For the radii corresponding to overdensities 50 and 200:

$$M_{50} = 4\pi\rho_0 r_s^3 f(u), \quad (3.9)$$

$$M_{200} = 4\pi\rho_0 r_s^3 f(C), \quad (3.10)$$

where we defined u as:

$$u = \frac{R_{50}}{r_s}, \quad (3.11)$$

To solve for R_{50} , we introduce a variable s , defined as:

$$s = \frac{R_{50}}{R_{200}}, \quad (3.12)$$

This allows us to express u in terms of s :

$$u = s C, \quad (3.13)$$

By dividing both mass equations:

$$\frac{M_{50}}{M_{200}} = \frac{f(s C)}{f(C)}, \quad (3.14)$$

From the theoretical mass relation at different overdensities:

$$\frac{M_{50}}{M_{200}} = \frac{1}{4}s^3, \quad (3.15)$$

Equating both expressions:

$$\frac{1}{4}s^3 = \frac{f(sC)}{f(C)}, \quad (3.16)$$

These equations is solved numerically using Brent's root-finding method to determine s , which then allows us to compute:

$$R_{50} = sR_{200} \quad (3.17)$$

Finally, using the relation:

$$M_{50} = M_{200} \frac{s^3}{4}, \quad (3.18)$$

we obtain the enclosed mass at an overdensity of 50.

3. For each galaxy model, the halo concentration parameter C and the spin parameter λ were adopted as typical values corresponding to their mass range (Lovell et al., 2011; Onions et al., 2013; Scannapieco et al., 2011).

3.2 Merger simulations

Understanding the role of dark matter subhalos in shaping galactic structures requires not only a stable host galaxy but also a well-defined and physically motivated model for the perturbing subhalos. After construing the galaxy model, it was allowed to dynamically relax for 1 Gyr to ensure stability and eliminate transient effects from the initial setup. This step ensures that any changes observed after the introduction of subhalos are due to their perturbative influence rather than numerical artifacts or initial inconsistencies in the host galaxy.

In this section, we focus on the generation of the initial conditions for the dark matter subhalos 3.1, as they are the only additional component introduced after the isolated galaxy has evolved. The initial conditions of the host galaxy-bulge, stellar disk, gas disk, and halo-remain unchanged from their evolved state. To provide a physically and cosmologically motivated context, several key considerations must be taken into account when assigning the initial conditions of the subhalos.

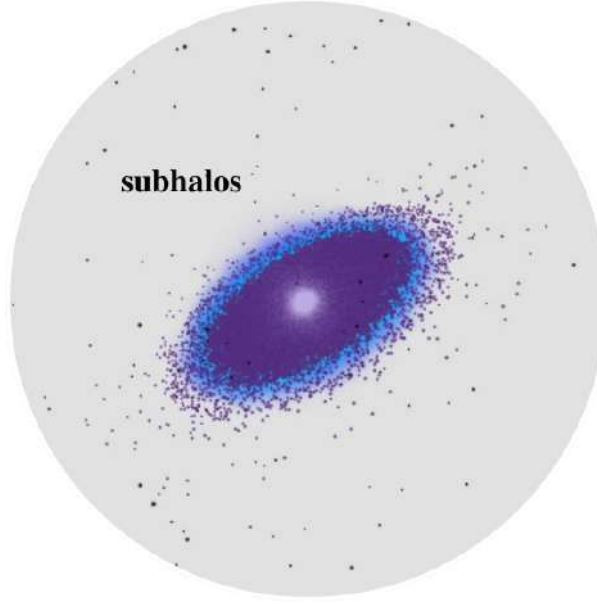


Figure 3.1: Schematic representation of merger galaxy composed by: the bulge, the stellar and gas disk, the rigid halo, and subhalos distribution (black points). The proportions and spatial extents of these components in this diagram are illustrative and do not necessarily reflect their actual relative sizes in real galaxies.

3.2.1 Mass Distribution of Subhalos

The subhalos were assigned masses following a power-law distribution, which is characteristic for dark matter subhalo populations. The number density of subhalos as a function of their mass is given by (Springel et al., 2008):

$$\frac{dN}{dM} = a_0 \left(\frac{M}{m_0} \right)^n, \quad (3.19)$$

where $n = -1.9$, and an amplitude is set to $a_0 = 8.21 \times 10^7 / M_{50}$ with a pivot mass of $m_0 = 10^{-5} M_{50}$. Here, M_{50} is the mass enclosed within a sphere whose overdensity is 50 times the critical density, in these calculations we use this expression for the mass since it is the parameter reported in the references. The normalization of this distribution (a_0) ensures that the total mass in subhalos remains consistent with the fraction of the host halo's mass expected to be contained within the substructure.

The range of subhalo masses was restricted to align with the resolution limits of the simulations, defining a lower bound ($m_{\min}$) and an upper bound ($m_{\max}$). This ensures that only subhalos within the resolution capabilities of the simulation are considered. Consequently, the total expected mass of subhalos with masses above the resolution threshold (m_{res}) is given by:

$$M_{\text{tot}} = \int_{m_{\min}}^{m_{\max}} M \frac{dN}{dM} = \frac{a_0}{n+2} \frac{m_{\max}^{n+2} - m_{\min}^{n+2}}{m_0^n}, \quad (3.20)$$

where $m_{\min}$ is the minimum mass of a subhalo, and $m_{\max}$ represents the upper limit for subhalo masses. Based on the data presented by Springel et al. (2008) for the Aq-A-1 simulation, the extracted values were $m_{\min} = 4.026 \times 10^4 M_{\odot}$ and $m_{\max} = 2.481 \times 10^{10} M_{\odot}$, which led to a total subhalo mass of $M_{\text{tot}} = 3.018 \times 10^{11} M_{\odot}$.

For illustrative purposes, we will use the specific values from Aq-A-1 in the calculations that follow. However, the same procedure was repeated for the other simulations (GAL1, GAL2, and GAL3), using the respective parameter values for each galaxy to ensure consistency across all cases.

Alternatively, if the lower mass limit is relaxed to the scale of the Earth-mass halo (i.e., $10^{-6} M_{\odot}$), the total subhalo mass would increase to $M_{\text{tot}} = 4.005 \times 10^{11} M_{\odot}$. For the Aq-A-1 case, the total halo mass is given by $M_{50} = 2.523 \times 10^{12} M_{\odot}$.

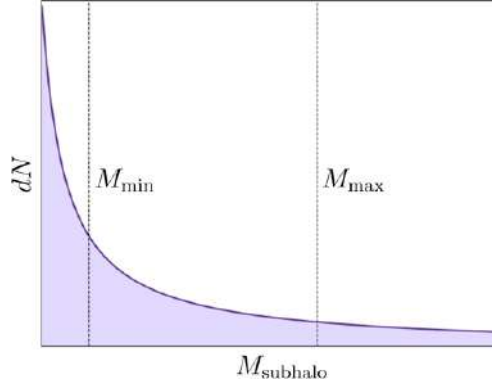


Figure 3.2: Illustration of the subhalo mass function, showing the number density of subhalos as a function of their mass. The curve follows a power-law trend, with the shaded region representing the selected mass range between $M_{\min}$ and $M_{\max}$. This figure is a qualitative representation and is not drawn to scale.

Once the mass distribution was generated-using Monte Carlo rejection sampling-restrictions on $m_{\min}$ and $m_{\max}$ were applied to refine the subhalo population. These constraints ensure that only dynamically relevant subhalos are considered, optimizing both the physical accuracy and computational efficiency of the simulations:

- The lower mass, $M_{\min}$, was set to ten times the mass of the stellar disk particles, ensuring that the subhalos had sufficient mass to exert a significant gravitational influence on the disk particles.
- The upper mass limit, $M_{\max}$, was defined according two merger scenarios:
 - **Merger 1:** $M_{\max} = 0.0001 \times M_{\text{disk}}$.
 - **Merger 2:** $M_{\max} = 0.001 \times M_{\text{disk}}$.

where M_{disk} is the total mass of the disk.

By applying these constraints, subhalos outside the range $[M_{\min}, M_{\max}]$ were excluded from the simulation. This approach ensures that the perturbing subhalos were massive enough to influence the stellar disk dynamics without being so large as to completely disrupt or destroy it. Additionally, it reduces the computational burden by limiting the number of subhalos included in the simulation.

3.2.2 Spatial Distribution of Subhalos

The spatial distribution of subhalos follows the density profile of dark matter halos, which can be well described by the Einasto profile (Springel et al., 2008):

$$\rho(r) = \rho_{-2} \exp \left[\frac{-2}{\alpha} \left\{ \left(\frac{r}{r_{-2}} \right)^\alpha - 1 \right\} \right], \quad (3.21)$$

where r_{-2} is the radius at which the logarithmic slope of density profile equals -2, and $\rho_{-2} = \rho(r_{-2})$. The best-fit values for the index α are typically within the range $0.12 < \alpha < 0.25$, increasing systematically with the halo mass.

For the case of the Aq-A-1 simulations presented by Springel et al. (2008), the parameters are given as $\alpha = 0.678$ and $r_{-2} = 199$ kpc. Expressing the density profile in terms of ρ_{-2} , we obtain the following:

$$\rho(r) = \rho_{-2} \exp \left[\frac{-2}{0.678} \left\{ \left(\frac{r}{199} \right)^{0.678} - 1 \right\} \right], \quad (3.22)$$

To determine ρ_{-2} , we impose the condition that the total mass subhalos satisfy:

$$M_f = \frac{\sum_{i=1}^{N_s} M_i}{M_T}, \quad (3.23)$$

where N_s is the total number of subhalos and M_i is the mass of each subhalo. The total mass enclosed within a given radius R is obtained by integrating the Einasto profile:

$$M_{\text{tot}} = \int_0^R 4\pi r^2 \rho(r) dr, \quad (3.24)$$

Substituting the Einasto profile,

$$\int_0^R 4\pi r^2 \rho_{-2} \exp \left[\frac{-2}{0.678} \left\{ \left(\frac{r}{199} \right)^{0.678} - 1 \right\} \right] dr = M_{\text{tot}}, \quad (3.25)$$

Solving for ρ_{-2} :

$$\rho_{-2} = \frac{M_{\text{tot}}}{4\pi \int_0^R r^2 \exp \left[\frac{-2}{0.678} \left\{ \left(\frac{r}{199} \right)^{0.678} - 1 \right\} \right] dr}, \quad (3.26)$$

Taking $R = r_{50} = 433.48$ kpc and using $M_{50} = 2.526 \times 10^{12} M_\odot$ from Springel et al. (2008), we obtain:

$$\rho_{-2} = \frac{2.526 \times 10^{12}}{\int_0^{433.48} 4\pi r^2 \exp \left[\frac{-2}{0.678} \left\{ \left(\frac{r}{199} \right)^{0.678} - 1 \right\} \right] dr}, \quad (3.27)$$

Evaluating the integral numerically;

$$\rho_{-2} = \frac{2.526 \times 10^{12}}{1.64765 \times 10^8} = 1.533 \times 10^4 M_\odot \text{kpc}^{-3}, \quad (3.28)$$

Thus, the final density profile is:

$$\rho(r) = 1.533 \times 10^4 \exp \left[\frac{-2}{0.678} \left\{ \left(\frac{r}{199} \right)^{0.678} - 1 \right\} \right] M_\odot \text{kpc}^{-3}, \quad (3.29)$$

This distribution predicts the presence of approximately 297791 subhalos within the considered volume.

To assign positions to the generated subhalo masses, we sampled their radial distribution according to the Einasto profile. The probability of finding a subhalo between radii r and $r + dr$ is proportional to:

$$dN(r) = n(r) 4\pi r^2 dr, \quad (3.30)$$

where we assume $n(r) \propto \rho(r)$, giving:

$$dN(r) = 1.533 \times 10^4 \exp \left[\frac{-2}{0.678} \left\{ \left(\frac{r}{199} \right)^{0.678} - 1 \right\} \right] 4\pi r^2 dr, \quad (3.31)$$

The sampling process follows these steps:

1. Generating candidate positions: Radial positions are drawn from the probability distribution $dN(r)$, ensuring that the subhalos follow the Einasto profile.
2. Applying resolution constraints: Any subhalo with $r > r_{50} = 433.48$ kpc is discarded, as it lies outside the interest region.
3. Sorting by mass: The sampled subhalos are sorted from most to least massive.
4. Mass cutoff: Subhalos are included until the total selected mass matches the expected subhalo mass fraction.

This approach guarantees that the spatial distribution of subhalos is consistent with theoretical expectations while ensuring numerical stability and computational efficiency in the simulation.

3.2.3 Assignment of Velocities to Subhalos

In the initial conditions of the simulation, subhalos are assumed to follow circular orbits around the host halo. Under this assumption, the magnitude of the orbital velocity at given

radius r is determined by the balance between gravitational attraction and centrifugal force:

$$v_c = \sqrt{\frac{GM(r)}{r}}, \quad (3.32)$$

where $M(r)$ represents the total mass enclosed within a sphere of a radius r . According to Springel et al. (2008), this enclosed mass is given by:

$$M(r) = \frac{4\pi r_{-2}^3 \rho_{-2}}{\alpha} \exp\left(\frac{3 \ln \alpha + 2 - \ln 8}{\alpha}\right) \gamma\left[\frac{3}{\alpha}, \frac{2}{\alpha} \left(\frac{r}{r_{-2}}\right)^\alpha\right], \quad (3.33)$$

where $\gamma(a, x)$ is the lower incomplete gamma function, and α , r_{-2} , ρ_{-2} are the parameters of the Einasto profile previously determined. This formulation allows for the precise computation of $M(r)$, ensuring that the assigned velocities remain consistent with the mass distribution of the halo.

Once the magnitude of the velocity v_c is determined, the direction of the velocity vector must be assigned. Since subhalos are assumed to move in circular orbits, their velocity vectors must be perpendicular to their position vectors relative to the halo center. To archive this, a random unit vector perpendicular to the position vector is generated.

The procedure for assigning velocity vectors follows the following steps:

1. Normalization of the position vector: The position of each subhalo is given by its Cartesian coordinates (x, y, z) , and the radial distance from the halo center is computed as:

$$r = \sqrt{x^2 + y^2 + z^2}, \quad (3.34)$$

If $r = 0$, a random unit vector is chosen.

2. Construction of a perpendicular vector:

- A reference vector $\vec{a}$ is selected, ensuring that it is not parallel to the normalized position vector $\vec{n}$.
- The component of $\vec{a}$ along $\vec{n}$ is subtracted to create a perpendicular vector $\vec{u}$.
- If $\vec{u}$ is degenerate (that is, very close to zero), a different reference vector is chosen, ensuring numerical stability.

3. Generation of an orthonormal basis:

- A second orthogonal vector $\vec{v}$ is obtained via the cross-product $\vec{n} \times \vec{u}$.
- This result in two mutually perpendicular vectors $\vec{u}$ and $\vec{v}$, which span the plane perpendicular to the position vector.

4. Assignment of a random velocity direction:

- A random angle θ is drawn uniformly from $[0, 2\pi]$.
- The velocity directions is set as a linear combination of $\vec{u}$ and $\vec{v}$:

$$\mathbf{w} = \cos \theta \mathbf{u} + \sin \theta \mathbf{v}, \quad (3.35)$$

5. Scaling by the velocity magnitude: The final velocity components (v_x, v_y, v_z) are obtained by multiplying $\vec{w}$ by the circular velocity v_c :

$$(v_x, v_y, v_z) = v_c \mathbf{w}, \quad (3.36)$$

By following this approach, the assigned velocities ensure that subhalos remain in dynamically consistent orbits, preserving the assumed circular motion within the host halo. Additionally, this method guarantees an even distribution of velocity directions within the allowed orbital plane, preventing artificial anisotropies in the subhalo kinematics.

Once the initial conditions for the subhalos have been generated, these particles are incorporated into the simulation, which has already evolved for 1 Gyr in isolation. The full system of disk galaxy and subhalos is then evolved for 2 Gyr, allowing the subhalos to dynamically interact with the host galaxy and influence its structural and kinematic properties over time.

3.3 Star Formation Process

Star formation is a crucial process in galaxy evolution since it is the mechanism driving the conversion from gas to stars, inducing as side effects, all kinds of astrophysics processes. In our simulations, we included star formation to analyze its impact on the formation and evolution of spiral arms under the influence of dark matter subhalos. To achieve this, we enable the GALSF module in GIZMO, which implements a subgrid star formation model based on the work of Springel and Hernquist (2003).

The star formation prescription in GIZMO follows a density-based stochastic model, where gas particles convert into star particles if they meet specific physical conditions. The criteria for star formation include:

- Gas density threshold: Only gas particles exceeding a given hydrogen number density can form stars.
- Cooling efficiency: The gas must be able to cool efficiently to reach temperatures leading to gravitational collapse. This condition is controlled by the COOLING module, which includes radiative cooling and heating processes (Hopkins et al., 2018).
- Dynamical timescale: The star formation rate is proportional to the local gas density and inversely proportional to the dynamical time of the system. The formulation

follows a Schmidt-Kennicutt law, given by:

$$\dot{\rho}_* = \epsilon \frac{\rho}{t_{\text{dyn}}}, \quad (3.37)$$

where $\dot{\rho}_*$ is the star formation rate per unit volume, ρ is the gas density, t_{dyn} is the local dynamical time and ϵ is the star formation efficiency parameter.

- Gravitationally bound regions: Gas must reside in a region where local self-gravity dominates over turbulent and thermal pressures.

These conditions ensure that star formation is physically motivated and occurs preferentially in dense regions, such as spiral arms.

Once a gas particle transforms into a star particle, it no longer follows the hydrodynamic equation but instead acts as a collisionless N-body particle that trace the gravitational potential. Star formation is coupled with stellar feedback, which injects energy, momentum, and metals into the surrounding gas.

In this work, we conducted two sets of simulations: isolated and merger simulations, both including and excluding star formation. Including star formation and feedback allows us to evaluate how the conversion of gas into stars and the subsequent energy injection affect the morphology and longevity of spiral arms. Previous studies (e.g., Dobbs and Junichi (2014)) suggest that stellar feedback can either enhance or suppress spiral structure depending on the interplay between cooling, turbulence, and self-gravity. By comparing simulations with and without star formation, we aim to quantify its role in maintaining or disrupting spiral arm patterns in the presence of external perturbation from subhalos.

Chapter 4

Implementation

The reliability of any numerical study depends not only on the physical models it employs but also on the rigor with which its computational framework is designed and validated. In the context of galaxy simulations, ensuring that the numerical setup is both physically motivated and computationally robust is essential for extracting meaningful insights into the underlying dynamical processes.

Since simulations approximate continuous systems through discrete representations, their results can be sensitive to choices of resolutions, timesteps, and computational techniques. To guarantee that our conclusions are independent of numerical artifacts, it is necessary to evaluate the stability and convergence of the models employed. Ensuring that our simulations remain consistent across different numerical setups reinforces the reliability of our findings and provides confidence that the observed phenomena emerge from physical mechanisms rather than numerical limitations.

With this in mind, this chapter presents the computational and physical foundation upon which the subsequent analysis is based. By implementing a structured and validated numerical approach, we establish a framework that allows for a rigorous investigation, ensuring that the results presented in this study are both physically meaningful and numerically robust.

4.1 Experimental Setup

The structural configuration of a galaxy plays a fundamental role in determining its dynamical evolution and long-term stability. In particular, the mass fraction of the disk (f_d) and the specific angular momentum retained by the disk (j_d) are key parameters that influence both the radial and vertical structure of the system. The interplay between the two quantities directly affects the rotational support of the disk, the efficiency of angular momentum transport, and the ability of the system to maintain a dynamically stable configuration over cosmological timescales.

To ensure that the simulated galaxies were both physically realistic and numerically stable, we performed an initial set of experiments designed to evaluate the effect of different structural configurations on the long-term evolution of the system. The purpose of this experiment was to assess how variations in f_d and j_d impact the convergence of the surface and vertical density profiles, which are critical indicators of a well-balanced equilibrium state, and to identify the configuration that best preserved its structural integrity over time.

Sim name	f_b	f_d	f_g	j_d	n_b	n_d	n_g
isolated_sim1	0.01	0.05	0.1	0.05	5×10^4	2×10^5	10^5
isolated_sim2	0.01	0.08	0.1	0.05	5×10^4	2×10^5	10^5
isolated_sim3	0.01	0.10	0.1	0.05	5×10^4	2×10^5	10^5
isolated_sim4	0.01	0.08	0.1	0.08	5×10^4	2×10^5	10^5
isolated_sim5	0.01	0.10	0.1	0.10	5×10^4	2×10^5	10^5

Table 4.1: Summary of stability experiments for simulated isolated galaxies. The table presents key parameters defining the initial conditions of each simulation, including the mass fractions of the bulge (f_b), disk (f_d), and gas (f_g). The fraction of the specific angular momentum retained by the disk is given by j_d . The resolution of each component is represented by the number of particles in the bulge (n_b), disk (n_d), and gas (n_g). The number of particles for the halo is not reported, as it is modeled as a rigid potential in all simulations.

The experiment was conducted specifically for the Aq-A-1 simulation, serving as a reference model to calibrate the structural parameters before extending the analysis to other galaxy models. Five simulations were performed keeping the bulge fraction $f_b = 0.01$ and the gas fraction ($f_g = 0.1$) fixed, following the typical values adopted in previous studies (Scannapieco et al., 2011). In addition, the same resolution was maintained for the entire set of experiments. Table 4.1 summarizes the parameters explored in these simulations.

Gas particles were chosen for this analysis because, unlike stars, gas is a collisional component that responds more dynamically to gravitational instabilities, shocks, and angular momentum redistribution. Although stars retain their orbital properties over long timescales, gas can experience compression, dissipation, and turbulence, making it a more sensitive tracer of structural evolution.

Among the five tested configurations, isolated_sim1 was selected as the optimal model due to its superior structural stability. The surface density profile shown in the left panel of Figure 4.1 suggests that the mass distribution in the disk is not subject to significant radial migration, a key indicator of numerical stability. In contrast, other configurations exhibit more substantial deviations over time, particularly those with higher disk mass fractions and the same specific angular momentum. Although in the case of isolated_sim4

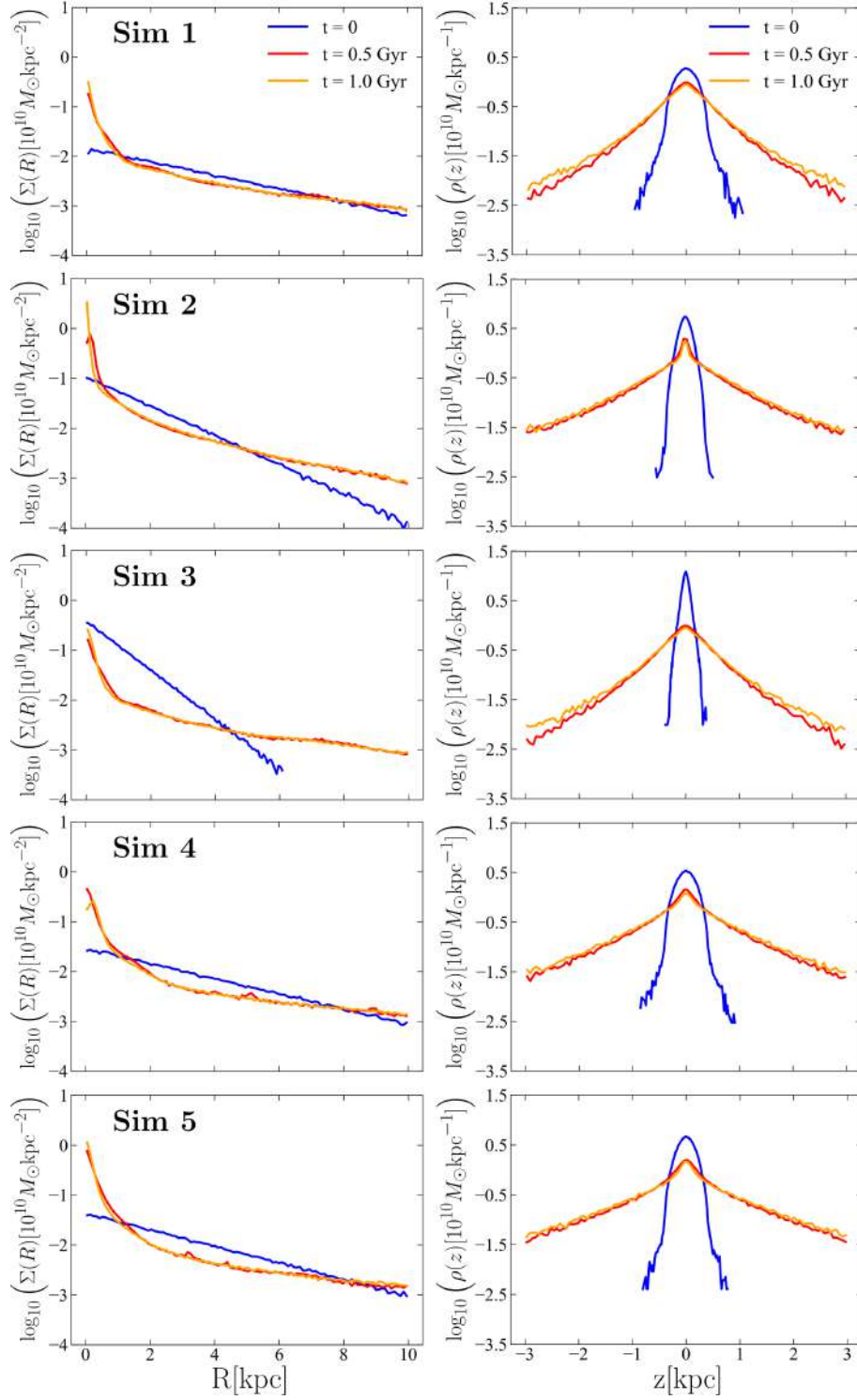


Figure 4.1: Surface and vertical density profiles for different isolated galaxy simulations. Each row corresponds to different simulations, ordered from sim1 to sim5, as described in Table 4.1. The left column presents the surface density profile as a function of the cylindrical radius, while the right column displays the vertical density profile as a function of height.

and `isolated_sim5`, radial migration does not appear to be a significant issue, their surface density profiles still show noticeable deviations from the initial conditions. This effect must be carefully considered, as the profiles are displayed on a logarithmic scale, meaning that even small changes in the distribution can reflect non-negligible structural evolution. These deviations suggest that while the disk remains dynamically coherent, it undergoes more substantial long-term modifications compared to `isolated_sim1`, reinforcing the choice of the latter as the most stable configuration.

The right panels of Figure 4.1 present the vertical density profile as a function of z . A dynamically stable disk should maintain a relatively thin vertical structure over time, as excessive vertical expansion suggests heating effects that can disrupt the disk’s equilibrium. In `isolated_sim1`, the vertical profile remains well-constrained across different time steps, indicating that the system does not experience significant heating. This contrasts configurations such as `isolated_sim2` and `isolated_sim3`, where the vertical expansion is more pronounced, leading to a decrease in central density over time.

Another important consideration in selecting `isolated_sim1` is its alignment with established models in the literature. The chosen values of $f_d = 0.05$ and $j_d = 0.05$ are consistent with those used in previous studies (Scannapieco et al., 2011), ensuring that the model is physically motivated and numerically comparable to previous studies.

With the results of this experiment confirming the stability of `isolated_sim1`, we adopt its structural parameters as the standard configuration for all subsequent simulations. The values of $f_d = 0.05$ and $j_d = 0.05$ are thus fixed for GAL1, GAL2, and GAL3, ensuring consistency across different mass regimes while maintaining a dynamically stable disk structure. In addition, to improve the accuracy of our analysis, we increase the resolution of the simulations.

Sim name	n_b	n_d	n_g
GAL1	100000	400000	200000
GAL2	100000	400000	200000
GAL3	100000	400000	200000
Aq-A-1	200000	800000	400000

Table 4.2: Number of particles used in the main structural components of each galaxy model. The GAL models share the same resolution across disk, gas, and bulge components, while the Aq-A-1 model employs a higher resolution in the disk and gas to improve dynamical accuracy and statistical sampling.

Table 4.1 summarizes the number of particles used for each structural component of the galaxy models implemented in this study. For the GAL1, GAL2, and GAL3 models, we adopt a consistent resolution of $n_d = 400000$, $n_g = 200000$, and $n_b = 100000$, provid-

ing a balanced and sufficiently fine sampling of the disk, gas, and bulge components. In contrast, for the Aq-A-1 model—which is the most physically motivated in our sample, being directly derived from the cosmological Aquarius Project—we employ a substantially higher resolution. This includes $n_d = 800000$, $n_g = 400000$, and $n_b = 200000$, enabling a more robust statistical description of the system’s internal dynamics and the influence of external perturbations analyzed in subsequent sections.

It is important to note that in all models, the dark matter halo is implemented as a rigid, analytic potential rather than as a particle-based component. Additionally, simulations that include mergers and star formation retain the same resolution as their corresponding isolated galaxy models, ensuring a consistent basis for comparative analysis.

4.2 Diagnostics of Disk Dynamics

The dynamical state of a galactic disk is shaped by a complex interaction between self-gravity, differential rotation, velocity dispersion, and external perturbations. Understanding these interactions requires a set of well-defined dynamical diagnostic that provide insight into the mass distribution, stability, and kinematic structure of the system. These diagnostics not only allow us to assess the long-term evolution of the disk but also help identify the mechanisms driving the formation of non-axisymmetric structures, such as spiral arms.

A key challenge in studying galactic dynamics is distinguishing between intrinsic properties of the system and evolutionary changes introduced by internal processes or external interactions. By analyzing the relevant dynamical quantities, we can quantify the degree of rotational support, the susceptibility to gravitational instabilities, and the impact of differential motion on large-scale structures. These properties determine whether the disk remains kinematically stable, undergoes secular evolution, or becomes susceptible to fragmentation and structural reorganization.

This section introduces the fundamental diagnostics used to characterize the global and local dynamical properties of the disk. Their theoretical foundation and physical motivation provide a quantitative framework for interpreting the stability and evolution of the system, serving as the basis for assessing how external perturbations influence the structure of the galaxy.

4.2.1 Circular Velocity

The circular velocity, $V_c(R)$, is a fundamental dynamical quantity that characterizes the gravitational potential and mass distribution of a galaxy. It describes the velocity that a test particle would have if it were in a perfectly circular orbit around the galactic center,

assuming that the only force acting on it is gravity. This quantity provides a direct measure of the total enclosed mass within a given radius, making it an essential diagnostic for analyzing the structure and stability of disk galaxies.

Physically, the circular velocity is derived from the balance between the centrifugal force and the gravitational attraction in a rotationally supported system. For a particle moving in a circular orbit at a radius R from the center of the galaxy, the equation of motion is given by:

$$\frac{d^2 R}{dt^2} = -\frac{\partial \Phi}{\partial R}, \quad (4.1)$$

where $\Phi(R, z)$ is the gravitational potential of the system. Setting this acceleration equal to the centripetal acceleration due to circular motion, we obtain the expression for the circular velocity:

$$V_c(R) = \sqrt{R \left. \frac{\partial \Phi}{\partial R} \right|_{z=0}}, \quad (4.2)$$

where the radial derivative of the potential is evaluated at the midplane of the disk ($z = 0$), ensuring that $V_c(R)$ accurately represents the equilibrium rotational motion of the stellar and gas components in the disk.

The shape of the circular velocity curves carries valuable information about the mass distribution in the galaxy. In an idealized self-gravitating exponential disk, the velocity initially rises steeply and then gradually declines at large radii. However, observations of real galaxies often reveal flat or even rising rotation curves extending well beyond stellar disk (Rubin and Ford, 1970), suggesting the presence of an extended dark matter halo that dominates the gravitational potential in the outer regions.

Beyond its role in probing the total mass profile, the circular velocity is also a key parameter in assessing disk stability. Variations in $V_c(R)$ can be used to identify non-axisymmetric perturbations, such as spiral arms. Significant fluctuations in the velocity curve may indicate gravitational interactions, secular evolution, or numerical artifacts that can influence the galaxy's long-term dynamics.

In the context of this study, the circular velocity serves as a primary tool for evaluating the dynamical consistency of the simulated galaxies. A well-defined and stable rotation curves suggest that the mass distribution remains dynamically coherent over time, whereas deviations may signal external perturbations or internal instabilities.

4.2.2 Epicyclic Frequency

The epicyclic frequency, $\kappa(R)$, is a fundamental quantity that describes the radial oscillations of stars or gas parcels in a galactic disk. It characterizes how a test particle deviates from a perfectly circular orbit when perturbed, playing a crucial role in disk stability, spiral structure formation, and resonances within the galaxy. The behavior of $\kappa(R)$ determines whether a disk can support long-lived spiral arms, as well as the location of key dynamical resonances (Binney and Tremaine, 2008).

Physically, the epicyclic frequency is derived from the small perturbation theory of orbital motion in a differentially rotating disk. If a star initially moving on a circular orbit experiences a small radial displacement, it undergoes harmonic oscillations around its equilibrium radius. The frequency of these oscillations is given by:

$$\kappa^2 = R \frac{d\Omega^2}{dR} + 4\Omega^2, \quad (4.3)$$

where Ω^2 is the angular velocity of the disk, defined as:

$$\Omega(R) = \frac{V_c(R)}{R}, \quad (4.4)$$

where $V_c(R)$ is the circular velocity. The first term in the equation for κ^2 accounts for the radial shear in the rotation curve, while the second term represents the stabilizing effect of the centrifugal force.

In the context of this study, the epicyclic frequency is a crucial diagnostic for assessing the dynamic response of the galaxy to perturbations. By analyzing its profile before and after the introduction of dark matter subhalos, we gain insight into how these interactions modify the stability and resonance structure of the disk. Since the frequency profile directly influences the formation and persistence of spiral structures, changes in $\kappa(R)$ provide a clear signature of secular evolution and external perturbations affecting the system.

4.2.3 Shear Rate

The shear rate, $\Gamma(R)$, quantifies the differential rotation of a galactic disk and describes how the angular velocity $\Omega(R)$ changes with radius. This quantity plays a crucial role in understanding the stability, structure, and kinematics of the galactic disk, as it directly affects the formation of spiral arms, bars, and large-scale non-axisymmetric features (Sellwood, 2014).

Physically, the shear rate measures the extent to which neighboring fluid elements or stellar orbits experience differential motion. In a system with rigid-body rotation, where all material rotates with the same angular velocity, the shear rate is zero. However, in a differentially rotating disk, which is the case for spiral galaxies, $\Omega(R)$ varies with radius,

leading to a non-zero shear. The shear rate is defined as:

$$\Gamma(R) = -\frac{d \log \Omega(R)}{d \log R} = -\frac{R}{\Omega(R)} \frac{d \Omega(R)}{d R}, \quad (4.5)$$

where $\Omega(R)$ is the angular velocity.

The shear rate is particularly important in the context of gravitational instabilities and spiral structure formation. It appears explicitly in the swing amplification mechanism, which describes how perturbations in a stellar or gaseous disk can be amplified by differential rotation to form spiral arms (Michikoshi and Kokubo, 2018). Higher values of $\Gamma(R)$ correspond to stronger differential rotation, which can either stabilize the disk against fragmentation or enhance the formation of spiral structures, depending on the disk's local conditions.

In this work, the shear rate serves as a key diagnostic for assessing the dynamic response of the disk to perturbations. Changes in $\Gamma(R)$ over time provide insight into how the introduction of dark matter subhalos modifies the internal kinematics of the galaxy. An increase in shear can indicate disk heating or an enhancement of differential rotation due to external interactions; the shear rate provides a critical measure of how external perturbations reshape the global structure of the galactic disk.

4.2.4 Toomre Parameter

The Toomre parameter, Q , is a fundamental criterion for assessing the gravitational stability of a differentially rotating disk. It quantifies the competition between self-gravity, pressure support, and differential rotation, determining whether a galactic disk is stable against local gravitational collapse and the formation of large-scale structures such as spiral arms. First introduced by (Toomre, 1964), this parameter remains one of the most widely used diagnostics in the study of galactic dynamics. The Toomre parameter is defined for a collisionless fluid as:

$$Q(R) = \frac{\sigma_R(R) \kappa(R)}{3.36 G \Sigma(R)}, \quad (4.6)$$

where $\sigma_R(R)$ is the radial velocity dispersion, which represents the level of random motion in the disk and provides kinematic support against gravitational collapse, κ is the epicyclic frequency, G is the gravitational constant, and $\Sigma(R)$ is the surface density of the disk, representing the local mass available for self-gravitating collapse.

The value of Q determines whether a galactic disk is stable or unstable to axisymmetric perturbations (Binney and Tremaine, 2008):

- $Q < 1$: The disk is gravitationally unstable, meaning that small perturbations can grow exponentially, leading to fragmentation and star formation. This regime is

characteristic of gas-rich disks and regions where spiral arms trigger local collapse.

- $Q \sim 1$: The disk is marginally stable, meaning that perturbations are suppressed by pressure and differential rotation, but local instabilities can still develop under favorable conditions.
- $Q > 1$: The disk is gravitationally stable, meaning that self-gravity is not strong enough to overcome pressure support and differential rotation. In this regime, perturbations decay rather than grow into large-scale structures, and the disk remains kinematically hot with suppressed fragmentation.

In this work, the Toomre parameter is used as a key diagnostic for disk stability, allowing us to track how external perturbations (such as interactions with dark matter subhalos) affect the susceptibility of the disk fragmentation. Variations in $Q(R)$ over time indicate whether the galaxy remains stable or transitions into an unstable regime.

By analyzing the Toomre parameter before and after introducing perturbing subhalos, we assess how these interactions modify the local stability properties of the disk. If perturbations induce regions where $Q < 1$, they could lead to enhanced mass clumping and the formation of transient spiral arms. In contrast, an increase in Q could indicate disk heating and suppression of large-scale instabilities.

4.3 Numerical Implementation

Quantifying the dynamical properties of a galactic system requires a robust computational framework capable of processing and analyzing the vast amount of data produced by numerical simulations. In this section, we describe the implementation for extracting and computing the relevant dynamical variables from the simulation outputs, ensuring accurate and physically meaningful results.

The available simulation data consist of particle-based information, where each individual particle represents a discrete element of the system. For every particle in the simulation, we have access to its spatial coordinates (x, y, z) , velocity components (v_x, v_y, v_z) , and gravitational potential (Φ) . These quantities serve as the foundation for computing key kinematic and structural parameters, which provide insight into the stability, mass distribution, and dynamical evolution of the galactic disk.

4.3.1 Spatial Discretization and Grid Construction

In numerical simulations of galactic dynamics, the system is represented as a collection of discrete particles that sample the underlying mass and kinematic distribution of the galaxy. However, analyzing the global and local dynamical properties of the system requires transitioning from this particle-based representation to a structured framework of continuous

functions that allows for the computation of derivatives, averages, and statistical properties in a well-defined manner. This is accomplished by discretizing the simulation domain into a computational grid, where physical quantities are evaluated within well-defined spatial bins.

For this study, a cylindrical grid (R, ϕ, z) was constructed, reflecting the natural geometry of the galactic disk, which is predominantly axisymmetric and rotationally supported. This choice ensures that radial, vertical, and azimuthal variations are captured efficiently, aligning with the dominant structure of the disk. Within this grid, a binning strategy was implemented to partition the data into discrete elements, allowing for local averaging and the computation of derivatives with minimal noise.

Binning methods

The binning approach determines how the simulation data is spatially grouped within the grid. For this study, the vertical (z) and azimuthal (ϕ) coordinates were linearly binned, ensuring a uniform resolution in these directions. However, for the radial coordinate (R), two distinct binning schemes were explored:

1. **Linear binning:** The radial range was divided into evenly spaced bins, ensuring constant spatial resolution throughout the disk. Linear binning ensures uniform spatial resolution, which is beneficial for capturing large-scale structures such as spiral arms. However, depending on the spacing, it may under-sample the central vs the outer regions of the disk, where the mass concentration is highest and dynamical variations are most pronounced.
2. **Logarithmic binning:** The radial range was divided into bins that increase in size with logarithmic radius, providing higher resolution in the inner region where dynamical timescales are shorter and variations are more significant. Logarithmic binning provides higher resolution at smaller radii, making it particularly advantageous for studying inner disk dynamics where gravitational instabilities are stronger. However, this approach leads to coarser resolution at larger radii, which may obscure details of the outer disk's evolution.

Each of these binning strategies was tested with different bin counts (25, 50, and 100 bins) to evaluate their impact on the numerical accuracy and stability of the computed quantities, we assess their impact on the convergence of the numerical results and select the configuration that best balance spatial resolution, computational efficiency, and physical accuracy.

The binning configurations selected for each simulation are summarized in Table 4.3.1. These values were chosen based on a systematic exploration of different bin counts, as described previously, and were found to provide a suitable compromise between spatial

Sim name	R_{bins}	ϕ_{bins}	z_{bins}
GAL1	20	25	25
GAL2	50	25	25
GAL3	50	25	25
Aq-A-1	25	25	25

Table 4.3: Number of bins used in the cylindrical grid for each simulation. The radial coordinate R was logarithmically binned according to the surface density profile of each galaxy, while the azimuthal (ϕ) and vertical (z) coordinates were linearly binned. For all cases, the z -coordinate spans from -1 to 1 kpc and the azimuthal coordinate covers the full domain from 0 to 2π . For simulations including mergers and star formation, the same binning scheme as the corresponding isolated case was applied.

resolution and computational efficiency. The chosen binning schemes demonstrated a consistent and accurate reconstruction of the underlying physics for each galaxy model, ensuring that the numerical calculations remained stable and physically meaningful across all the analyses presented in this work.

The radial extent of the cylindrical grid was defined based on the surface density profiles of each simulated galaxy. In all cases, the radial range was chosen to be greater than the effective radius of the corresponding galaxy, ensuring that the grid captures the full dynamical behavior of the disk and includes the outer regions where structural and kinematic features may still be relevant.

4.3.2 Gravitational Potential Mapping

To transition from the discrete particle-based representation of the simulation to a structured cylindrical grid, it was necessary to assign physical properties to each grid cell. The gravitational potential, Φ , was mapped onto the grid by determining which particles belonged to each spatial bin and aggregating their potential values. This process ensured that the gravitational field of the galaxy was well-represented at all radii, capturing the large-scale structure while minimizing numerical artifacts.

Each particle in the system carries information about its position and gravitational potential. The assignment process consists of the following steps:

1. Determining the grid cell for each particle:
 - The cylindrical coordinates (R, ϕ, z) of each particle were computed.
 - Using the predefined binning scheme, the corresponding grid cell was identified.
 - If a particle was outside the grid limits, it was excluded from the mapping process.
2. Accumulating potential values in each cell:

- Once the grid cell was determined, the gravitational potential values Φ of that particle was stored in a list associated with the corresponding bin.
- A counter tracked the number of particles per cell, ensuring proper statistical treatment.

3. Statistical aggregation using the median:

- Instead of computing a simple sum or average, the median value of Φ was assigned to each cell. This approach provides a more stable and physically meaningful representation of the local gravitational potential.

The assignment of the median gravitational potential to each cell of the grid offers significant advantages in minimizing numerical artifacts and preserving the physical integrity of the system. The median effectively captures the dominant potential value within each bin, reducing distortions caused by transient effects or numerical noise. This approach leads to a smoother representation of the potential field, ensuring that the derived dynamical properties remain reliable.

Moreover, the median's resilience to extreme values is particularly beneficial in complex astrophysical environments. Particles experiencing temporary numerical artifacts or residing in regions with strong dynamical interactions can exhibit outlier potential values that do not represent the bulk distribution. By assigning the median potential to each grid cell, these statistical anomalies are effectively suppressed, offering a robust estimate of the gravitational potential and preventing distortions in the analysis. This method ensures that local structures within the galaxy are preserved, maintaining accurate spatial gradients essential for understanding orbital dynamics and stability. Such robustness against outliers has been highlighted in studies focusing on the gravitational potential distribution and its influence on large-scale matter clustering.

To further illustrate the methodology used to map the gravitational potential onto the computational grid, Figure 4.2 presents the reconstructed gravitational potential Φ , as a function of the radial position R for the simulation Aq-A-1 at $t = 1.0$ Gyr. In order to obtain a two-dimensional representation, the vertical coordinate was fixed at $z = 0$, ensuring that the potential was evaluated within the midplane of the galactic disk. Additionally, the azimuthal coordinate was collapsed by averaging, reducing the three-dimensional data to a radial profile that facilitates direct comparison between different binning schemes.

The logarithmic binning scheme (left panel) provides a more detailed reconstruction, particularly in the inner regions of the galaxy where the gravitational potential varies rapidly. By assigning a higher density of bins at small radii, the logarithmic approach captures the steep potential gradient near the galactic center with greater precision compared to the linear binning scheme. This finer resolution allows for a more accurate

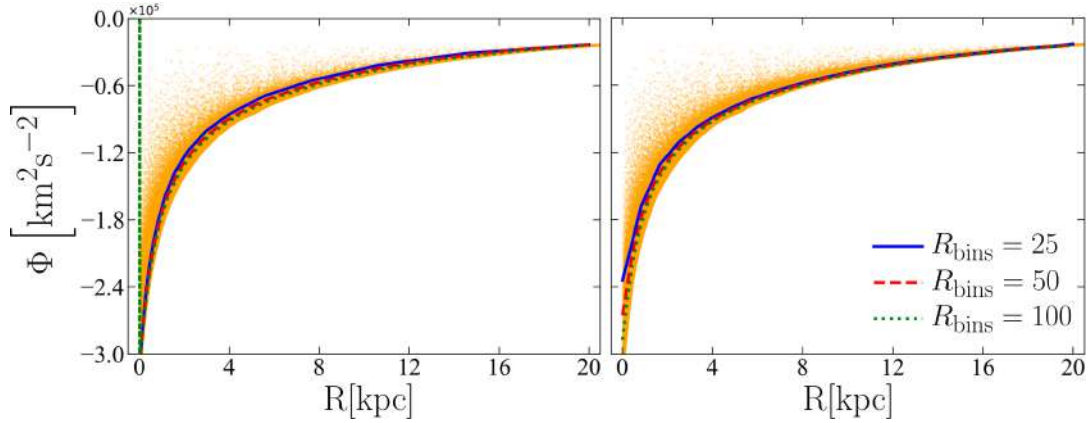


Figure 4.2: Gravitational potential Φ as a function of radial position R for the simulated galaxy Aq-A-1. The orange points represent the individual particle values extracted from the simulation, while the solid blue, dashed red, and dotted green lines correspond to the reconstructed profiles using 25, 50, and 100 radial bins (R_{bins}), respectively. The left panel shows the reconstruction using a logarithmic binning scheme, whereas the right panel presents the results for linear binning.

representation of the central gravitational field, which is essential for analyzing orbital structures and inner disk dynamics.

However, while the logarithmic binning approach improves resolution in the central regions, it also presents a notable limitation: some central bins may not contain a sufficient number of particles to robustly represent the true distribution of the potential field. This effect can be observed in Figure 4.2, in which some central intervals deviate by taking values of the potential much smaller in magnitude than the expected smooth trend of the profile. This is a consequence of the low particle density in these refined bins, leading to increased statistical noise in their assigned values. Such fluctuations may introduce artificial variations in derived dynamical quantities, particularly in the calculation of gradients and higher-order derivatives of the potential.

In contrast, the linear binning scheme (right panel) distributes bins evenly across the radial domain, ensuring that each bin accumulates a more consistent number of particles throughout the disk. This approach results in a smoother and more statistically stable profile, reducing the effects of low-number statistics at small radii. However, its uniform resolution means that it may under-resolve the sharp potential gradient in the central region, potentially leading to a slight loss of accuracy in the description of the inner galactic dynamics.

Given the considerations discussed above, a logarithmic binning scheme was adopted for the radial coordinate in all evaluated scenarios, as it provides a better match to the underlying mass distribution of the simulated galaxies and allows for a more accurate

reconstruction of the gravitational potential in the inner regions of the disk. However, the benefits of the linear binning approach—particularly its statistical stability and uniform sampling—are leveraged by applying linear binning in the azimuthal and vertical directions. This hybrid strategy, summarized in Table 4.3.1, ensures an optimal balance between resolution and numerical robustness across the cylindrical grid.

4.3.3 Numerical Differentiation

In numerical simulations of galactic dynamics, the computation of derivatives of the gravitational potential is fundamental for obtaining key dynamical quantities. The accurate estimation of these derivatives allows us to quantify forces, assess stability criteria, and derive orbital properties that influence the evolution of spiral arms and disk structure. Given the importance of these calculations, we require a robust numerical differentiation scheme that maintains consistency with the underlying physics while minimizing numerical artifacts.

A crucial application of numerical differentiation in our study is the computation of the circular velocity, which requires the evaluation of the radial partial derivative of the gravitational potential, $\frac{\partial\Phi}{\partial R}$, at each point in the computational grid. To achieve high precision while maintaining stability, we employed five-point finite difference formulas. This approach ensures a high order of accuracy and effectively reduces truncation errors compared to lower-order schemes, making it suitable for resolving the smooth gravitational field of galactic disks.

Finite Difference Method for Radial Derivatives

To compute the radial gradient of the potential $\frac{\partial\Phi}{\partial R}$, we applied a five-point central difference formula for points that are not near the boundaries. This method approximates the derivative as:

$$\frac{\partial\Phi}{\partial R} \approx \frac{-\Phi(R + 2\Delta R) + 8\Phi(R + \Delta R) - 8\Phi(R - \Delta R) + \Phi(R - 2\Delta R)}{12\Delta R}, \quad (4.7)$$

This scheme provides fourth-order accuracy, minimizing numerical dispersion and improving the representation of radial forces across the grid. However, near the edges of the computational domain, where a five-points stencil is not available, a different approach is necessary to maintain accuracy.

For boundary points (the first and last two radial bins), we employed forward and backward finite difference formulas, ensuring that numerical stability is preserved at the domain limits. These are given by:

- Lower boundary (smallest radial bins):

$$\frac{\partial \Phi}{\partial R} \approx \frac{-25\Phi(R) + 48\Phi(R + \Delta R) - 36\Phi(R + 2\Delta R) + 16\Phi(R + 3\Delta R) - 3\Phi(R + 4\Delta R)}{12\Delta R}, \quad (4.8)$$

- Upper boundary (largest radial bins):

$$\frac{\partial \Phi}{\partial R} \approx \frac{25\Phi(R) - 48\Phi(R - \Delta R) + 36\Phi(R - 2\Delta R) - 16\Phi(R - 3\Delta R) + 3\Phi(R - 4\Delta R)}{12\Delta R}, \quad (4.9)$$

These one-sided finite difference formulas provide consistent estimates of the radial gradient while ensuring numerical stability at the boundaries. The derivation and implementation of these high-accuracy finite difference schemes follow the methodology outlined in Burden et al. (2015).

By definition, the radial partial derivative of the gravitational potential should always be non-negative, as it represents the direction of increasing potential towards the center of the system. However, due to numerical artifacts introduced by discretization, some computed derivatives may appear negative, which is physically inconsistent in a gravitational field. To correct this issue, we applied a post-processing step:

1. For each grid point where the computed derivative was negative, the value was replaced by the average of the previous and next radial points to smooth out numerical fluctuation.
2. If, after this correction, the derivative remained negative, it was set to zero to prevent the introduction of artificial, nonphysical forces.

This approach ensures that the computed gravitational field remains physically meaningful, preventing numerical inconsistencies from propagating into the derived dynamical properties, such as circular velocity and epicyclic frequency.

Differentiation in a Logarithmic Grid

Since our study also incorporates a logarithmic radial binning scheme, it is necessary to adapt the differentiation procedure accordingly. When radial coordinates are spaced logarithmically, the variable transformation $R = \exp(u)$, where $u = \log_{10}(R)$, modifies the differentiation process. Using the chain rule, we obtain:

$$\frac{\partial \Phi}{\partial R} = \frac{\partial \Phi}{\partial u} \cdot \frac{\partial u}{\partial R}, \quad (4.10)$$

Since $u = \log_{10}(R)$, we have:

$$\frac{\partial u}{\partial R} = \frac{1}{R \log(10)}, \quad (4.11)$$

Thus, the radial derivative in logarithmic coordinates is given by:

$$\frac{\partial \Phi}{\partial R} = \frac{\partial \Phi}{\partial u} \cdot \frac{1}{R \log(10)}, \quad (4.12)$$

This formulation allows us to compute derivatives efficiently in a logarithmic grid by first applying finite differences on uniform u -space and then rescaling the result accordingly. Since the spacing in u is constant, the same finite difference formulas used for the linear grid can be applied in logarithmic space, ensuring consistency across different binning schemes.

Second-Order Derivatives

In addition to first-order derivatives, the computation of second-order derivatives is essential for accurately determining the epicyclic frequency (κ). Following the methodology outlined in Burden et al. (2015), we employed five-point finite difference formulas to ensure high precision in the estimation of second derivatives.

For second derivative of the gravitational potential with respect to z , we used the following finite difference scheme for points that are not near the boundaries:

$$\frac{\partial^2 \Phi}{\partial z^2} \approx \frac{-\Phi(z + 2\Delta z) + 16\Phi(z + \Delta z) - 30\Phi(z) + 16\Phi(z - \Delta z) - \Phi(z - 2\Delta z)}{12(\Delta z)^2}, \quad (4.13)$$

This formula provides fourth-order accuracy, reducing truncation errors while maintaining numerical stability. However, for grid points at the edges of the domain, where a five-point stencil is unavailable, we implemented forward and backward finite difference formulas to maintain accuracy:

- Lower boundary (first two bins):

$$\begin{aligned} \frac{\partial^2 \Phi}{\partial z^2} \approx & \quad (4.14) \\ & \frac{35\Phi(z) - 104\Phi(z + \Delta z) + 114\Phi(z + 2\Delta z) - 56\Phi(z + 3\Delta z) + 11\Phi(z + 4\Delta z)}{12\Delta z^2}, \end{aligned}$$

- Upper boundary (last two bins):

$$\begin{aligned} \frac{\partial^2 \Phi}{\partial z^2} \approx & \quad (4.15) \\ & \frac{35\Phi(z) - 104\Phi(z - \Delta z) + 114\Phi(z - 2\Delta z) - 56\Phi(z - 3\Delta z) + 11\Phi(z - 4\Delta z)}{12\Delta z^2}, \end{aligned}$$

The numerical differentiation framework described here was consistently applied to all

quantities requiring derivative computations. Whether computing the vertical derivative of the gravitational potential, the radial derivative of dynamical variables such as angular velocity, or any other physically relevant quantity, the same finite difference schemes were utilized. This uniform implementation ensures consistency across all calculations, minimizing numerical artifacts and preserving the physical accuracy of the derived properties.

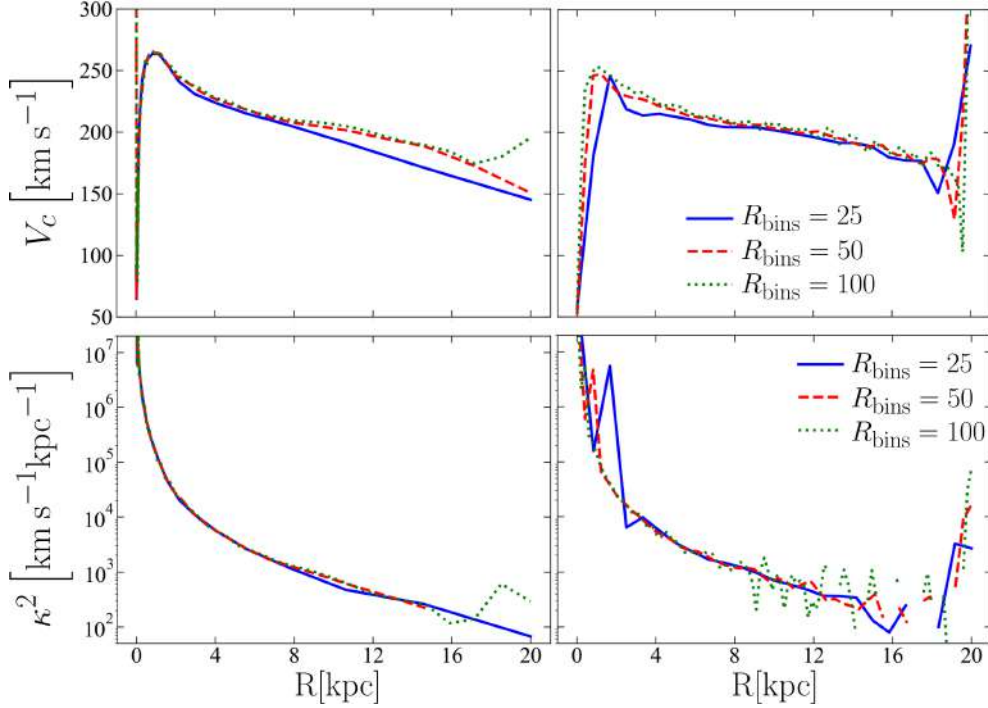


Figure 4.3: Numerical convergence of circular velocity and squared epicyclic frequency for the simulated galaxy Aq-A-1. The top row shows the circular velocity (V_c), and the bottom row represents the squared epicyclic frequency (κ^2). The left column presents results obtained using a logarithmic binning scheme, while the right column shows results using linear binning. The different curves correspond to reconstructions with 25 (solid blue), 50 (dashed red), and 100 (dotted green) radial bins (R_{bins}).

Figure 4.3 presents a comparison of the numerical convergence of the circular velocity and the squared epicyclic frequency for the Aq-A-1 simulation under two different radial binning strategies: logarithmic (left column) and linear (right column). The top panels display the circular velocity profiles, while the bottom panels show the corresponding κ^2 profiles. Each curve in the figure corresponds to a different number of radial bins—25, 50, and 100—allowing us to assess how the resolution of the binning affects the reconstruction of key dynamical quantities.

Overall, all the reconstructions we can see in Figure 4.3 exhibit physically meaningful trends, consistent with the expected dynamical properties of the galactic disk. The circular velocity follows a typical rotation curve peaking at small radii before decreasing gradually. The epicyclic frequency squared follows a declining trend, as expected, re-

flecting the underlying gravitational potential structure. Notably, the logarithmic binning approach reconstructs the profiles with greater smoothness at large radii and better detail, particularly at small radii, where the increased resolution captures finer variations in the computed gradients.

However, the circular velocity profile with the finest binning (50 and 100 radial bins) exhibits inconsistencies near the galactic center, where numerical fluctuations introduce small deviations from the expected smooth profile. This suggests that an excessively refined binning may amplify numerical noise in regions with fewer particles contributing to the differentiation process. On the other hand, the reconstruction with 25 bins provides more stable and physically consistent velocity profiles.

For the epicyclic frequency squared, the logarithmic binning produces a smoother and well-resolved profile, whereas the linear binning scheme exhibits more abrupt variations, particularly in the outer regions where fewer particles contribute to the differentiation. This highlights the advantages of logarithmic binning in capturing dynamical quantities with higher accuracy while maintaining numerical stability.

4.3.4 Velocity Dispersion Mapping

Velocity dispersion is a fundamental property in galactic dynamics, it provides insights into the stability of the system, the level of turbulence, and the degree of thermal and dynamical support against gravitational collapse. In particular, the radial (σ_R), azimuthal (σ_ϕ), and vertical (σ_z) velocity dispersions are crucial for assessing the stability of the disk (e.g., via the Toomre parameter), identifying kinematic heating processes, and understanding the impact of external perturbations, such as interactions with dark matter subhalos.

From a computational perspective, mapping velocity dispersion across the galactic disk requires an efficient strategy for binning the velocity distribution within each cell of the cylindrical coordinate grid. The velocity data extracted from the simulation are initially in Cartesian coordinates (v_x, v_y, v_z) , which must be transformed into cylindrical components (v_R, v_ϕ, v_z) to match the natural symmetry of the disk. Each particle is then assigned to a corresponding grid cell based on its spatial position, allowing the statistical computation of velocity dispersion within each bin.

To ensure a physically meaningful and unbiased measurement, the velocity dispersion were calculated using the sample standard deviation formula, which accounts for finite-sample corrections:

$$\sigma_i = \sqrt{\frac{1}{N-1} \sum_{j=1}^N (v_{i,j} - \bar{v}_i)^2}, \quad (4.16)$$

where $v_{i,j}$ is the velocity of the j -th particle component i , $\bar{v}_i$ is the mean velocity of that component within the grid cell, and N is the number of particles in the cell. If a grid cell contained only a single particle, the dispersion was set to zero, as a meaningful standard deviation cannot be computed from a single value.

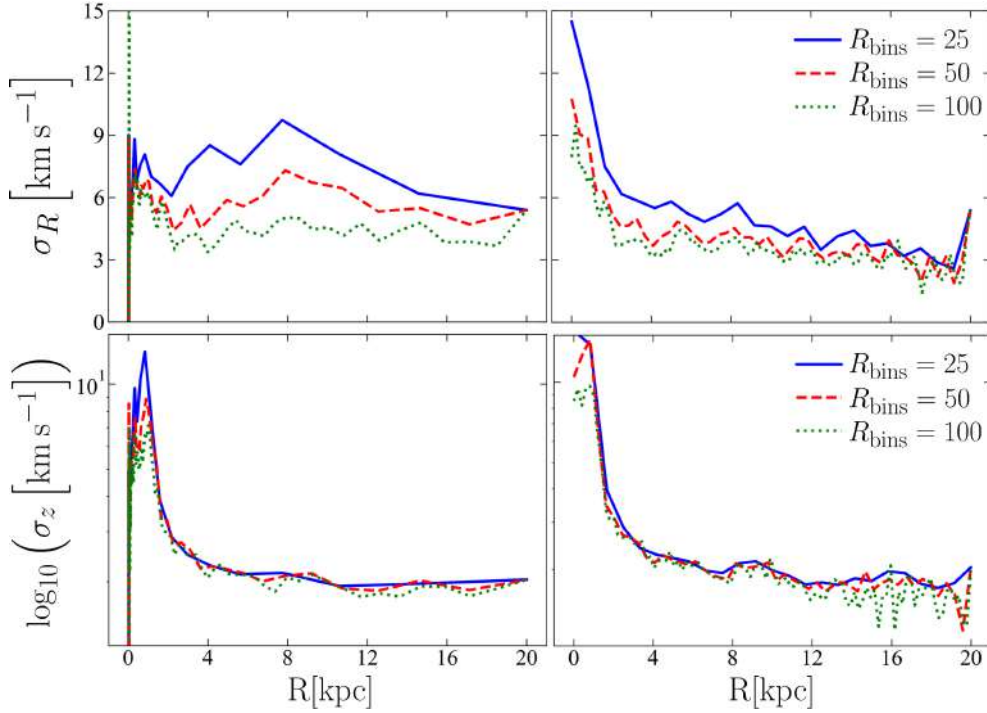


Figure 4.4: Numerical convergence of the velocity dispersion mapping for the simulated galaxy Aq-A-1. The top row shows the radial velocity dispersion (σ_R), while the bottom row represents the vertical velocity dispersion (σ_z). The left column corresponds to the logarithmic binning scheme, and the right column to the linear binning scheme. The different curves correspond to reconstructions with 25 (solid blue), 50 (dashed red), and 100 (dotted green) radial bins (R_{bins}).

Figure 4.4 displays the numerical convergence of the radial and vertical velocity dispersion profiles for the Aq-A-1 simulation, reconstructed using two different radial binning strategies. The upper row presents the dispersion of the radial velocity (σ_R), and the lower row shows the dispersion of the vertical velocity (σ_z). The left column corresponds to the logarithmic binning scheme, while the right column shows results using a linear binning scheme. For each configuration, the profiles are computed with 25, 50, and 100 radial bins, represented by solid blue, dashed red, and dotted green lines, respectively. This figure allows for a direct comparison of how binning choices affect the fidelity and smoothness of the reconstructed velocity dispersion profiles.

The numerical convergence analysis of the velocity dispersion mapping reveals distinct behaviors for the radial and vertical components. The radial velocity dispersion (σ_R) shown in the upper panel of Figure 4.4 exhibits the expected decreasing trend with radius; however, the choice of binning method significantly impacts the mapped magnitudes. The logarithmic binning scheme provides higher resolution in the central regions, capturing more detailed variations, but induces noticeable differences in the overall amplitude compared to the linear binning. This suggests that while the general trend is robust, the numerical resolution can influence the precise values obtained. The radial velocity dispersion is a key diagnostic of the disk's dynamical state, as it reflects the level of random motion of stars and gas within the disk plane. Higher values of σ_R indicate stringer heating mechanisms, such as gravitational interactions or secular evolution, while lower values suggest a dynamically colder and more rotationally supported disk.

In contrast, the vertical velocity dispersion (σ_z) shown in the lower panel of Figure 4.4 follows a well-defined profile that stabilizes to a contrast value at large radii, consistent with theoretical expectations for dynamically relaxed disk systems. Unlike σ_R , σ_z remains largely unaffected by the binning strategy, showing minimal variations across different resolutions. This indicates that the mapping of vertical velocity dispersion is numerically stable, reinforcing the reliability of this quantity in our analysis regardless of the chosen binning method. The vertical velocity dispersion is crucial for understanding the disk's thickness and vertical stability, as it quantifies the random motions perpendicular to the plane. A high σ_z can indicate vertical heating due to interactions with perturbers, such as dark matter subhalos, whereas a lower dispersion suggests a thin, dynamically cold disk with minimal external perturbations.

4.3.5 Surface Density Mapping

The surface density of a galactic disk ($\Sigma(R)$) is a critical quantity for understanding its mass distribution, gravitational stability, and response to external perturbations. It directly influences the rotational support of the disk and plays a fundamental role in defining the Toomre stability criterion, which quantifies the susceptibility of a disk to gravitational instabilities and spiral arm formation.

The numerical implementation follows a binning procedure where particles are assigned to radial bins based on their cylindrical radius R . The density values extracted from the simulation are grouped into discrete bins, and the mean surface density is computed within each bin as:

$$\bar{\Sigma}(R) = \frac{1}{N} \sum_{i=1}^N \Sigma_i(R), \quad (4.17)$$

where $\Sigma_i(R)$ represents the density contribution of each particle within the bin, and N is the number of particles in that radial interval. This averaging process ensures a smooth representation of the density distribution while reducing numerical noise.

The resulting surface density profile serves as a fundamental diagnostic tool for analyzing disk structure and stability. It allows us to evaluate the evolution of mass distribution over time, track radial migration effects, and assess whether the simulated disk maintains its expected density profile over long dynamical timescales.

To ensure the physical consistency and numerical robustness for our computed dynamical quantities, the mapping procedures and convergence tests were systematically applied to each of the dynamical variables evaluated in this study. This thorough verification process allowed us to assess the accuracy and stability of the computed profiles, identifying the most suitable binning scheme for each specific case.

By testing multiple binning strategies for the reconstruction of the gravitational potential, velocity dispersion, and derived dynamical quantities, we ensured that our methodology and implementation remains reliable across different galactic configurations. The final binning selection was carefully tailored for each system under consideration; Aq-A-1, GAL1, GAL2, and GAL3, both in their isolated and merger configurations, as well as in the presence of star formation. This approach guarantees that the derived profiles remain free of artificial numerical artifacts while preserving the fundamental physical properties of each galactic model.

Chapter 5

Results and Analysis

Understanding the dynamical response of galactic disks to perturbations from dark matter subhalos requires a comprehensive analysis of how structural and kinematic properties evolve under different scenarios. Building upon the robust framework established in the implementation chapter, this section presents the results of a series of controlled numerical experiments designed to isolate the physical mechanisms that govern spiral arm formation, disk stability, and mass redistribution. By systematically comparing isolated galaxies, merger simulations, and star-forming systems, we aim to disentangle the role of external gravitational perturbations and internal processes in shaping the large-scale morphology of disk galaxies.

This chapter is organized to provide both a global and local perspective on the evolution of simulated systems. We begin by analyzing the impact of subhalo perturbations on models of isolated galaxies. We then assess how the inclusion of star formation alters the system in the absence of mergers, allowing us to distinguish their effects independently. Finally, we introduce mergers in galaxies with active star formation, quantifying how the presence of perturbing subhalos influences the persistence of structure formation.

5.1 Isolated Galaxy VS Merger Galaxy

In this section, we present a detailed analysis of the differences between isolated galaxies and galaxies under the influence of mergers, focusing on simulations of Aq-A-1, GAL1, GAL2, and GAL3. For each galaxy, we compare the behavior of the system in its isolated state with its dynamics when subjected to the presence of perturbing subhalos in the context of mergers. Importantly, all these simulations were conducted without the inclusion of star formation, allowing us to isolate the effects of gravitational interactions and mergers without the complexity introduced by baryonic processes.

The aim of this analysis is to assess how different galaxy masses, represented by Aq-A-1, GAL1, GAL2, and GAL3, respond to the presence of subhalos and the associated gravita-

tional perturbations. By comparing the isolated and perturbed states of each galaxy, we seek to understand the impact of these external perturbations on key dynamical quantities, such as circular velocity, epicyclic frequency, shear rate, and Toomre stability parameter, across different systems. This enables a direct evaluation of the role of subhalos in modifying the dynamical structure of the galactic disk.

The results from both the Aq-A-1 simulations and the GAL suite of simulations provide valuable insights into how subhalos, in galaxies with different masses, influence the stability and evolution of disk galaxies. By focusing on profiles of dynamical variables and subsequently exploring local variations to identify subtle perturbations that may not be apparent in averaged profiles, we provide a more nuanced understanding of the interaction between galaxies and their subhalo populations.

5.1.1 Aq-A-1 Simulation Results

In this section, we focus on the Aq-A-1 simulation, which does not include star formation, to investigate the dynamical behavior of the galactic disk under different conditions. We consider three distinct scenarios: the isolated galaxy, Merger 1, and Merger 2, as previously defined in earlier sections (see Section 3.2). By comparing the results from the isolated case with those of the simulations involving subhalo interactions, we aim to isolate the physical effects from potential numerical artifacts, ensuring a clearer understanding of the true dynamical impact.

All the profiles presented in this section correspond to averaged quantities. For their graphical representations, the computed values were azimuthally averaged to reduce local fluctuations and highlight the underlying radial trends. Additionally, all profiles are shown at the midplane of the disk ($z = 0$), where the gravitational and kinematical effects are most prominent. This averaging strategy ensures a clearer and more robust comparison across different scenarios, minimizing the impact of local irregularities or transient features.

The circular velocity profile $V_c(R)$ is a fundamental diagnostic for evaluating the dynamical stability of galactic disks and identifying perturbations induced by external influences, such as mergers. Figure 5.1 presents the evolution of $V_c(R)$ over time for the Aq-A-1 simulation, comparing the isolated case with simulations that include perturbing subhalos. The solid lines represent the isolated simulation, while the dashed lines correspond to the simulation of presence of perturbing subhalos. The left panel shows the results for Merger 1, while the right panel presents the results for Merger 2.

A key observation from this analysis is that the presence of subhalos does not include deviation in the circular velocity profile across most of the disk. The inner regions ($R < 10$ kpc) remain largely unaffected, with both the isolated and perturbed cases following nearly

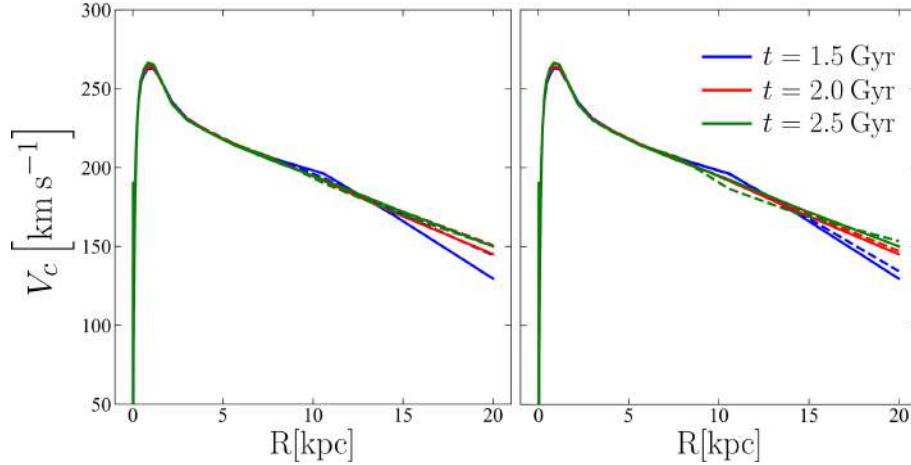


Figure 5.1: Circular velocity profile $V_c(R)$ as a function of radius R for different time snapshots in the Aq-A-1 simulation. The solid lines represent the isolated simulation, while the dashed lines correspond to the simulation in the presence of perturbing subhalos. The left panel shows the results for Merger 1, while the right panel presents the results for Merger 2.

identical trends over all time snapshots. This suggest that any gravitational interactions with subhalos are either too weak or too transient to induce noticeable changes in the rotational support of the disk.

At larger radii ($R > 10$ kpc), slight differences between the isolated and perturbed profiles emerge. However, these variations are confined to regions where numerical inconsistencies are expected to be more prominent due to the lower density of particles and the increased sensibility to discretization effects in the potential gradient. Given that these outer regions are also the most susceptible to numerical artifacts, it is plausible that the observed differences stem primarily from numerical noise rather than from actual dynamical perturbations induced by subhalos.

Moreover, since Merger 2 is a subset of Merger 1, any physical effect induced by subhalo interactions in Merger 1 should also be present in Merger 2. However, the nearly identical behavior of both cases further supports the hypothesis that the minor variations seen at larger radii are numerical rather than physical origin. If subhalos were effectively disturbing the disk's gravitational equilibrium, we would expect systematic shifts in $V_c(R)$ across all radii and an accumulation of deviations over time, which is not observed.

To further investigate the impact of subhalos on the stability of circular velocity profiles, we examine the radial distribution of these perturbers, as shown in Figure 5.2. This figure presents the spatial distribution of the dark matter subhalos within the Aq-A-1 simulation, distinguishing between Merger 1 and Merger 2. Notably, our simulations consider a rigid halo, which prevents dynamical friction from acting on the satellites and altering

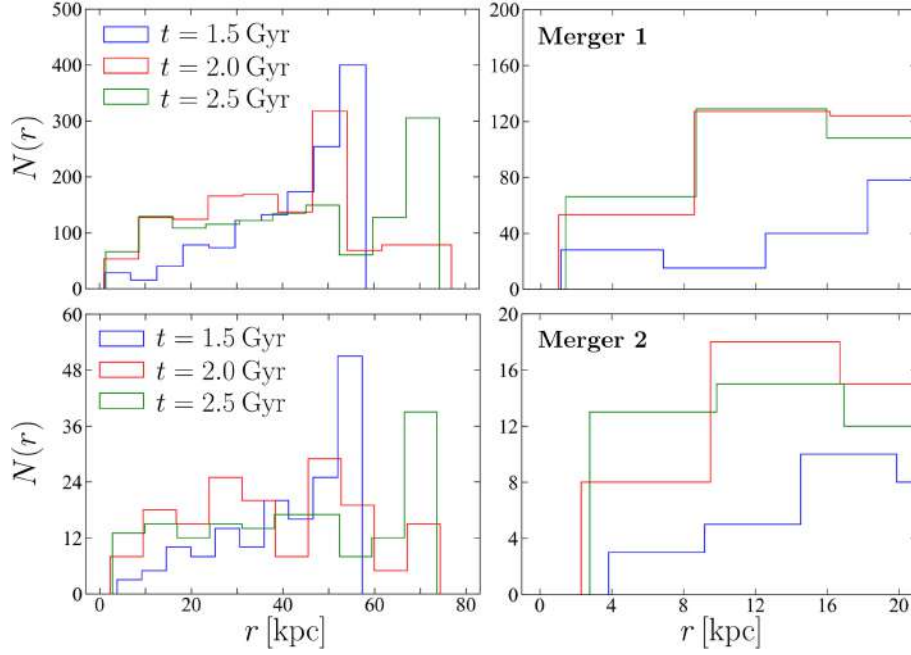


Figure 5.2: Radial distribution of satellites (dark matter subhalos) in the Aq-A-1 simulation. The histograms show the number of satellites $N(r)$ at a given radius r for different time snapshots. The first row corresponds to Merger 1, while the second row represents Merger 2. The left panels display the full radial distribution of satellites, while the right panels are truncated at the region of the disk that is relevant to our analysis. Different colors represent different time snapshots.

their orbits, thus ensuring that they remain at a relatively large radial distance from the galactic center throughout the simulation.

The presence of subhalos within the host galaxy can cause gravitational perturbations that alter the disk structure, potentially inducing fluctuations in the velocity profiles. However, the results in Figure 5.2 suggest that most of the satellite remains at relatively large radii throughout the simulation, with a significant fraction distributed beyond 40 kpc. This distribution shows little evolution in time, which further supports the idea that the subhalos in our simulation do not move inward due to the rigid halo assumption. Since the observed discrepancies in the velocity profiles arise predominantly in the outer regions of the disk, the population of subhalos at these distances may contribute to the numerical fluctuations or also introduce genuine dynamical perturbations.

Focusing on the right panels of Figure 5.2, which highlight the subhalo distribution within the galactic disk, we note that the number of satellites in the inner regions remains relatively small at all time steps. This reinforces the idea that the stability of the circular velocity profile is not significantly affected by the presence of subhalos, as there are no substantial concentrations of these structures within the radii where major deviations in the velocity profile are observed. Thus, the rigid halo assumption leads to the satellites

maintaining the orbits at large radii, unable to significantly perturb the disk's dynamics.

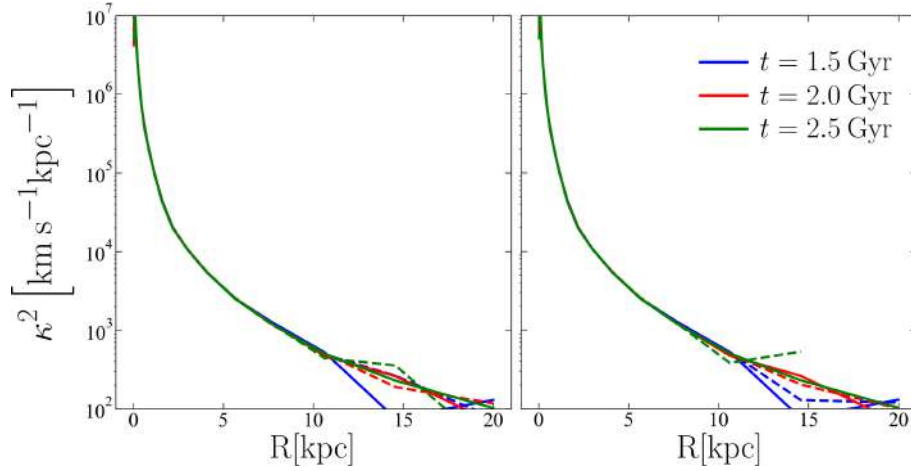


Figure 5.3: Epicyclic frequency squared κ^2 as a function of radius R for different time snapshots in the Aq-A-1 simulation. The solid lines represent the isolated simulation, while the dashed lines correspond to the simulation in the presence of perturbing subhalos. The left panel shows the results for Merger 1, while the right panel presents the results for Merger 2.

To further assess the dynamical stability of the system, we analyze the squared epicycle frequency, κ^2 , as a function of radius in Figure 5.3. Similarly to the analysis of the circular velocity, we compared the isolated simulation with the cases including perturbing subhalos, distinguishing between Merger 1 and Merger 2. The solid lines represent the isolated simulation, while the dashed lines correspond to the simulation in the presence of perturbing subhalos. The left panel shows the results for Merger 1, while the right panel presents the results for Merger 2.

The overall trend of κ^2 exhibits a smooth decline with increasing radius, which is characteristic of disk galaxies, where differential rotation governs the orbital dynamics. Notably, in the central regions ($R < 10$ kpc), the profiles remain stable over time, showing no significant deviations between the isolated and perturbed cases. This suggests that the inner disk retains its structural integrity despite the presence of subhalos, reinforcing the conclusion that the mass distribution in this regions is not significantly altered by external perturbations.

However, beyond $R > 10$ kpc, we observe an increase in fluctuations among the profiles, particularly in the outermost bins. The behavior mirrors the trends seen in the circular velocity profiles (Figure 5.1), where discrepancies are most pronounced at large radii. Given that these deviations arise in regions with fewer particles and lower surface densities, it is likely that they are driven by numerical fluctuations rather than genuine dynamical instabilities.

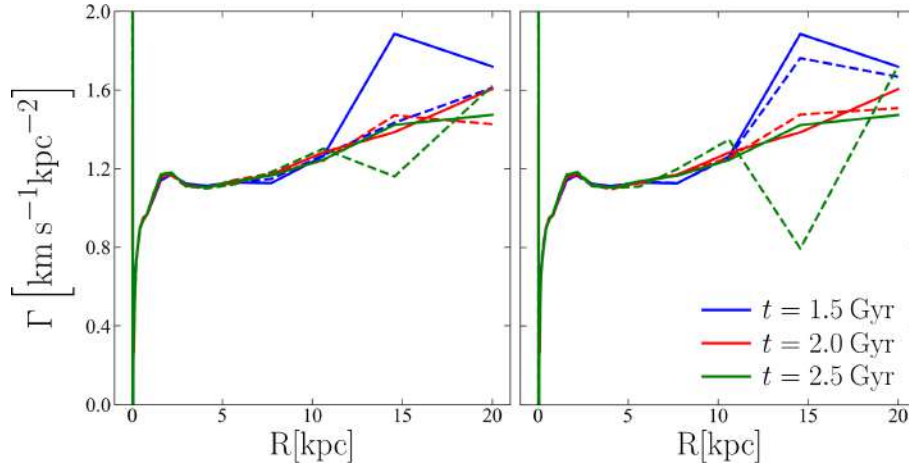


Figure 5.4: Shear rate Γ as a function of radius R for different time snapshots in the Aq-A-1 simulation. The solid lines represent the isolated simulation, while the dashed lines correspond to the simulation in the presence of perturbing subhalos. The left panel shows the results for Merger 1, while the right panel presents the results for Merger 2.

To further reinforce the stability analysis of the disk, we examine the shear rate $\Gamma(R)$ in Figure 5.4, which quantifies the differential rotation within the galaxy. In the inner disk region, the shear rate remains largely stable across different time snapshots, showing minimal deviations between the isolated and perturbed cases. This consistency suggests that the differential rotation of the disk is not significantly affected by the presence of subhalos, supporting the earlier conclusions drawn from the circular velocity and epicyclic frequency analysis. The stable shear rate in the regions implies that the disk retains its kinematic structure.

However, in the central region of the disk, we observe some noticeable variations in the shear rate profile. These abrupt changes could be attributed to the logarithmic binning used for data analysis, as well as to the influence of the bulge. The central regions are particularly susceptible to the gravitational effects of the bulge, which can introduce additional perturbations in the dynamics. These variations, although evident in the inner regions, do not significantly disrupt the overall stability of the disk, and are confined to areas where the disk's mass distribution is influenced by the central structure.

Beyond $R > 10$ kpc, we observed an increase in variability, with fluctuations becoming more pronounced at large radii. These variations are consistent with the trends identified in Figures 5.1 and 5.3, where discrepancies in the outer disk were attributed to numerical limitations rather than physical perturbations. The greater sensitivity of $\Gamma(R)$ to small fluctuations in the velocity field further amplifies these variations, particularly in low-density regions where fewer particles contribute to the estimation of dynamical quantities.

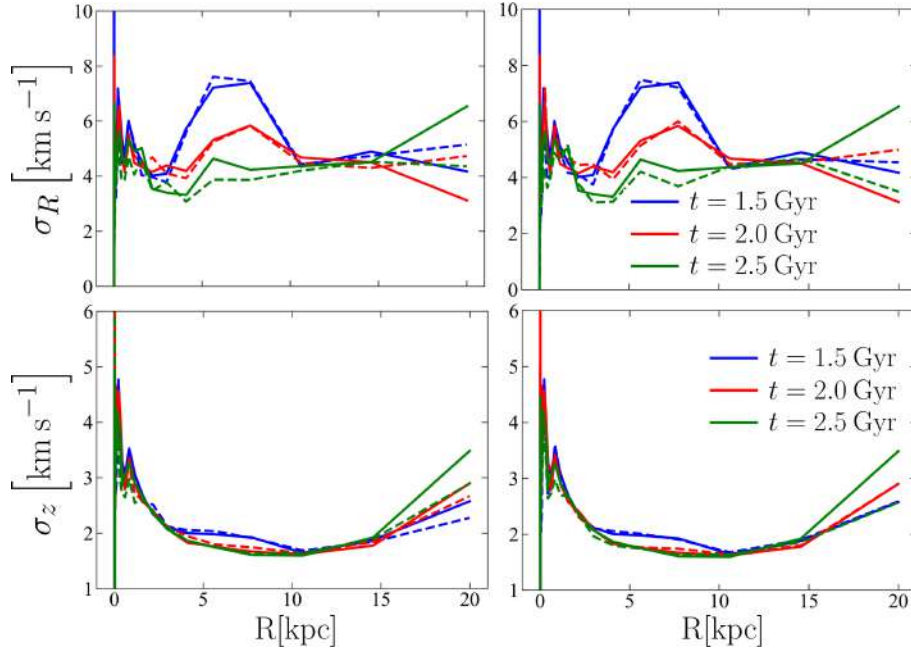


Figure 5.5: Radial (σ_R , top row) and vertical (σ_z , bottom row) velocity dispersion as a function of radius R for different time snapshots in the Aq-A-1 simulation. The solid lines represent the isolated simulation, while the dashed lines correspond to the simulation in the presence of perturbing subhalos. The left panel shows the results for Merger 1, while the right panel presents the results for Merger 2.

Figure 5.5 displays the radial (σ_R) and vertical (σ_z) velocity dispersion profiles as a function for the Aq-A-1 simulation. The figure compares the isolated case with the simulations influenced by two different merger scenarios: Merger 1 and Merger 2.

The analysis of the velocity dispersion profiles presented in 5.5 provides further confirmation of the stability of the system and the limited influences of perturbing subhalos on the galactic dynamics in the Aq-A-1 simulation. The radial velocity dispersion exhibits a clear trend where the profiles remain consistent between the isolated and perturbed cases across different time snapshots. Although some fluctuations appear at larger radii, they are within the expected range of numerical variations and do not indicate significant structural perturbations induced by subhalos. This consistency suggests that the disk remains dynamically stable and does not experience strong radial heating due to interactions with satellites.

On the other hand, the vertical velocity dispersion, shows an even stronger agreement across different scenarios. The profiles exhibit a well-defined decline toward larger radii, converging to a relatively constant value, as expected in a dynamically relaxed system. The absence of substantial deviations between the isolated and merger cases reinforces the conclusion that subhalo interactions do not induce significant vertical disturbances in the disk structure. This finding is particularly relevant, as vertical heating is a key indicator of

dynamical instability and can lead to thickening of the galactic disk over time. The results confirm that the simulated system maintains its vertical structure even in the presence of perturbing subhalos.

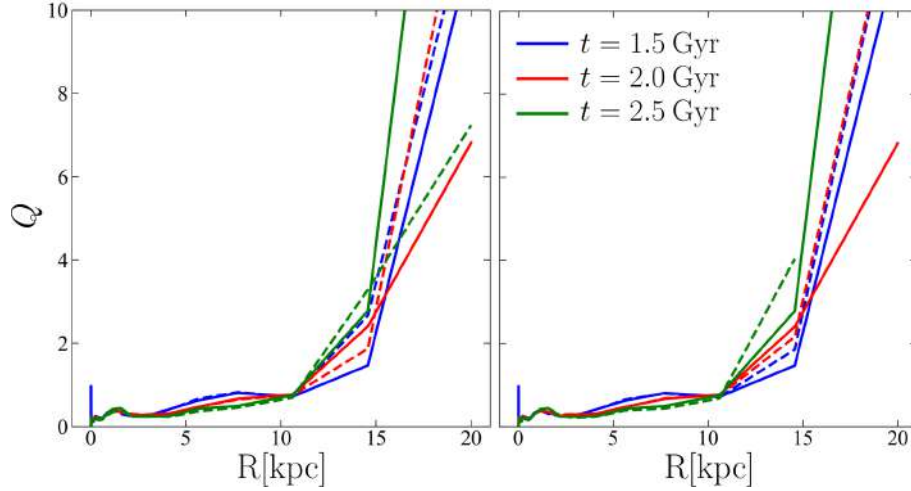


Figure 5.6: Toomre factor Q as a function of radius R for different time snapshots in the Aq-A-1 simulation. The solid lines represent the isolated simulation, while the dashed lines correspond to the simulation in the presence of perturbing subhalos. The left panel shows the results for Merger 1, while the right panel presents the results for Merger 2.

In the analysis of the Toomre stability parameter (Q), shown in Figure 5.6, we explore the gravitational stability of the disk against local axisymmetric perturbations. The figure illustrates the evolution of Q as a function of radius (R) for different time snapshots in the Aq-A-1 simulation. The solid lines represent the isolated simulation, while the dashed lines correspond to the simulation in the presence of perturbing subhalos. The left panel displays the results for Merger 1, while the right panel presents the results for Merger 2.

As seen in the figure, for the inner regions of the disk ($R < 10$ kpc), the Toomre parameter Q tends to take values close to 0, suggesting that gravitational effects are predominant in the system. As the radius increases, we observe that Q also increases, indicating that pressure forces begin to dominate the disk's dynamics at larger radii.

It is important to remember that the Q parameter is inversely related to the surface density (Σ), meaning it is only well-defined in regions where Σ is sufficiently large. In the outer regions of the disk, where surface density decreases, Q becomes increasingly sensitive to these variations. The significant increase in Q at larger radii reflects the growing influence of the pressure in these regions.

In both the velocity dispersions and the Toomre parameter we note that close to zero there are significant variations in the profiles, which again can be attributed to the nu-

merics of the binning as well as the influence of the galactic bulge.

Until now, we have focused on the analysis of average profiles for various dynamical quantities, which provide a general understanding of the system's behavior. These mean profiles, however, may not capture local variations of perturbations that could be present within the disk. To gain a deeper understanding of these local variations, we introduce the concept of density contrast, which quantifies the relative deviation of the local density from the average density of the system at each radial position R :

$$\delta(\Sigma(R)) = \frac{\Sigma(R) - \bar{\Sigma}(R)}{\bar{\Sigma}(R)}, \quad (5.1)$$

here, $\Sigma(R)$ represents the local surface density, and $\bar{\Sigma}(R)$ is the mean surface density, computed across the disk. A density contrast value of zero indicates that the local density equals the mean density, while negative values suggest underdense regions (where the local density is lower than the average), and positive values indicate overdense regions (where the local density exceeds the average).

This approach allows us to examine local deviations from the mean profile that may not be apparent when analyzing the averaged quantities alone, providing insight into how substructures and other small-scale effects might influence the galaxy's dynamics. By incorporating the density contrast, we can identify regions of the disk where gravitational interactions, such as those induced by subhalos, may be causing disturbances that have not yet been captured.

As shown in Figure 5.7, the density contrast maps provide an important diagnostic of the gravitational influence of subhalos on the galactic disk. These maps highlight the contrast between the local density at each point and the average density. The maps cover three different galaxy configurations: the isolated galaxy (top row), Merger 1 (middle row), and Merger 2 (bottom row). Each column corresponds to different time snapshots, starting from $t = 1.5$ Gyr in the first column and progressing to $t = 2.5$ Gyr in the last column.

Upon examining the density contrast maps, we observe the presence of both overdense and underdense regions throughout all the scenarios presented, including the isolated and merger cases. The consistent appearance of these features suggests that they are intrinsic to the evolutionary process of the galaxy rather than being induced by external perturbations. Notably, these regions do not exhibit significant variations or amplifications under the influence of the mergers, indicating that the presence of subhalos does not introduce substantial perturbations to the disk's density structure. This stability in the contrast patterns further supports the conclusion that the mergers, despite introducing external mass distributions, do not play a dominant role in altering the large-scale density mor-

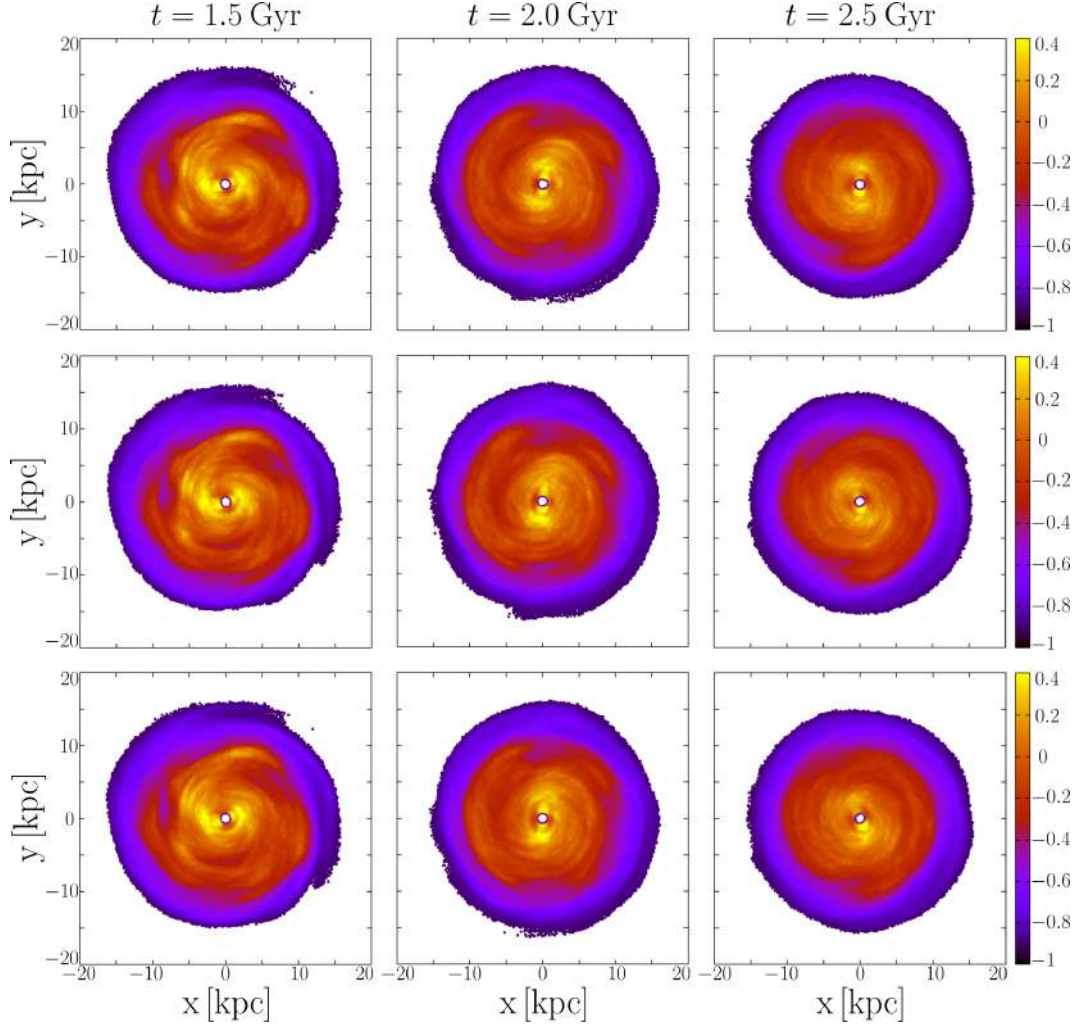


Figure 5.7: Density contrast map in the xy -plane at different time snapshots for the Aq-A-1 simulation. The first row represents the isolated galaxy, the second row shows the results for Merger 1, and the third row corresponds to Merger 2. Each column displays the density contrast at different time snapshots: the first column at $t = 1.5$ Gyr, the second column at $t = 2.0$ Gyr, and the third column at $t = 2.5$ Gyr. The color map illustrates the density contrast.

phology of the galactic disk.

Moreover, the time evolution of the density contrast maps shows little change, further suggesting that the overall stability of the disk is maintained throughout the simulation, regardless of the merger scenario or the presence of perturbing subhalos.

To further explore the behavior of the dynamic variables, we present the visualization shown in Figure 5.8. This figure was constructed using a linear binning process, with 100 radial and 100 vertical bins to provide a clearer view of the system's behavior. The goal of this visualization is to analyze whether the dynamic variables align with the density contrast and to detect any local perturbations that may not have been observable through

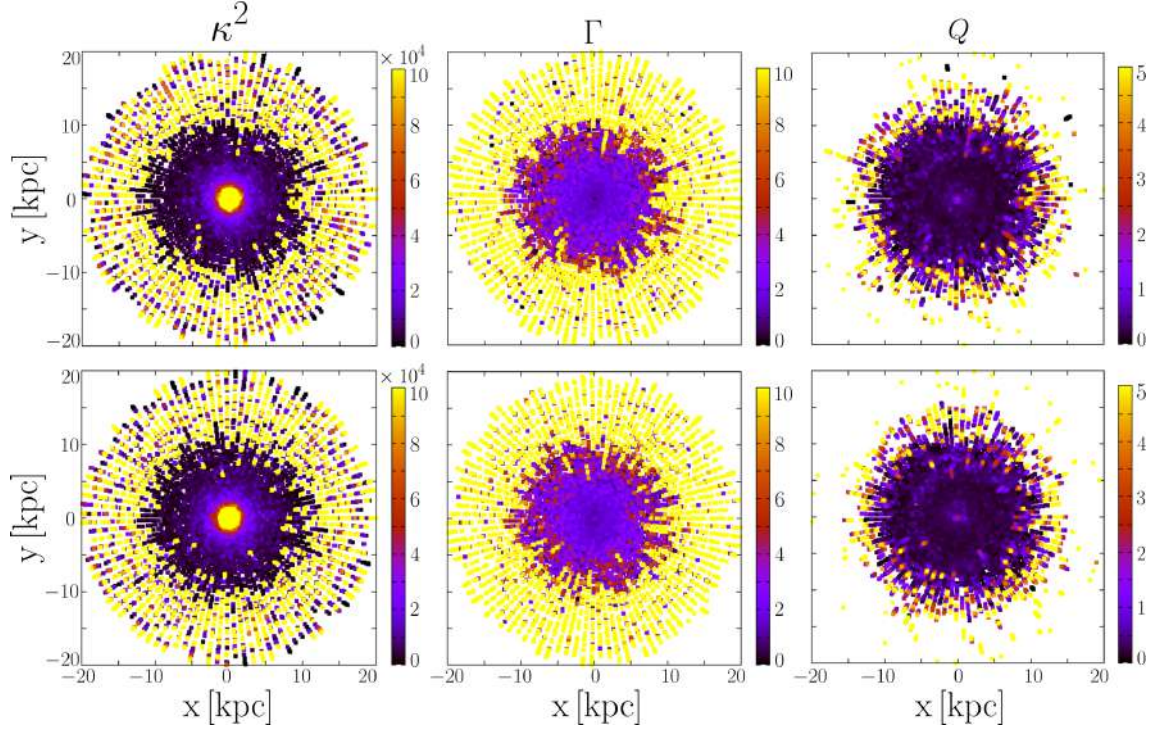


Figure 5.8: Visualization of dynamic variables in the xy -plane at $t = 2.0$ Gyr for the Aq-A-1 simulation in the midplane ($z = 0$). The first column shows the squared epicyclic frequency κ^2 , the second column displays the shear rate Γ , and the third column presents the Toomre parameter Q . The first row corresponds to the isolated galaxy, while the second row presents the results for the galaxy under the influence of Merger 1. The color maps illustrate the respective values of each variable.

the mean profile analysis. Only Merge 1 is considered in this analysis since its subhalo population also contains the subhalos of Merger 2.

Upon examining the results, the dynamic variables show behavior consistent with the trends observed in the density contrasts. Specifically, the regions identified as overdense in Figure 5.7 are reflected in the dynamic variables as regions where the disk is more strongly influenced by gravitational effects and exhibits more stability. These regions also correspond to the inner parts of the disk. On the other hand, for radii $R > 10$ kpc, we observe the dominance of pressure in the system, coinciding with the regions that exhibited a mass underdensity, where the disk's dynamics are more influenced by pressure forces than gravitational ones. We can however observe a mild correlation between Q low values and spiral features in the simulations.

Importantly, no significant local variations are observed in the dynamic variables, suggesting that the information extracted from the mean profiles is a good representation of the system's overall behavior. This observation reinforces the stability of the disk as the lack of large fluctuation supports the idea that the disk remains in a stable state despite

the presence of perturbing subhalos.

Overall, the results from this analysis indicate that the system’s behavior is well captured by the mean profiles, and the dynamic variables align with the general trends observed in the density contrast analysis, without revealing any significant local perturbations that would disrupt the overall stability of the system.

5.1.2 GAL1, GAL2, and GAL3 Simulation Results

In this section, we will extend the analysis performed for the Aq-A-1 simulation to a new set of simulations, namely GAL1, GAL2, and GAL3. We will focus on analyzing the dynamics of these galaxies in the presence of Merger 1, as this population of subhalos also encompasses the subhalos from Merger 2.

The primary motivation for this analysis is to investigate how subhalo interactions influence galaxies of different masses. This set of simulations allows us to extend our study across a mass spectrum, ranging from a galaxy with a very low mass, GAL1, which has a total mass of $10^{10} M_{\odot}$, to a typical galaxy like GAL3 with a mass of $10^{12} M_{\odot}$. By comparing galaxies of varying mass, we aim to assess how the galaxy’s mass affects its response to subhalo interactions and whether there are any mass-dependent trends in the dynamics of the galactic disk.

It is important to note that, similar to the previous analysis of Aq-A-1, the impact of star formation is excluded from this first analysis to isolate the effects of the subhalos on the galaxy’s dynamics. In this way, we will focus solely on the gravitational perturbations caused by the subhalos, providing a clearer understanding of their influence on the stability and structure of galaxies with different masses.

As in previous sections, the profiles analyzed here represent azimuthally averaged quantities, allowing for a more reliable characterization of the radial structure by smoothing out local variations. All measurements were taken at the disk midplane ($z = 0$), where the relevant dynamical features are most clearly defined.

The circular velocity profile $V_c(R)$ as a function of radius R for different time snapshots in the GAL1, GAL2, and GAL3 simulations is presented in Figure 5.9. The solid lines represent the isolated galaxies, while the dashed lines correspond to the galaxies under the influence of Merger 1. Each color represents a different time snapshot, from $t = 1.5$ Gyr to $t = 3.0$ Gyr. From left to right, the panels show the results for GAL1, GAL2, and GAL3.

The circular velocity profiles of the three galaxies show behavior consistent with expectations for a galactic disk. The velocity decreases in the central regions due to the

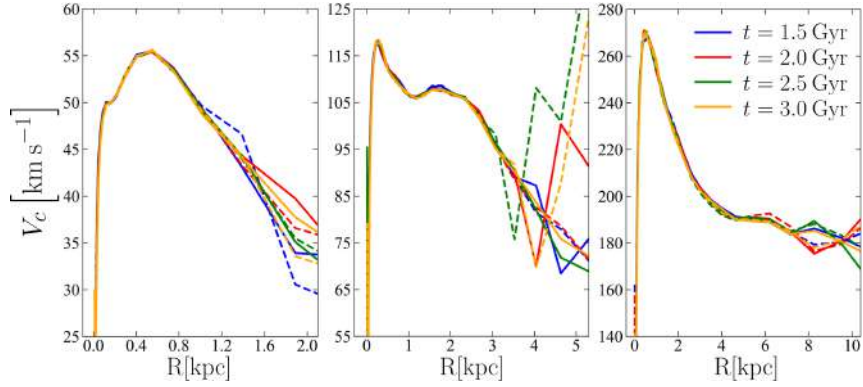


Figure 5.9: Circular velocity profile $V_c(R)$ as a function of radius R for different time snapshots in the GAL1, GAL2, and GAL3 simulations. The solid lines represent the isolated galaxies, while the dashed lines correspond to the galaxies under the influence of Merger 1. Each color represents a different time snapshot. From the left to right, the panels show the results for GAL1, GAL2, and GAL3.

gravitational dominance of the galactic nucleus, followed by an increase as we approach the outer regions and decaying again. This trend is observed in all three galaxies, although with differences in the velocity scale.

Sim name	R_e [kpc]	$0.2R_e$ [kpc]
GAL1	2.09	0.42
GAL2	4.87	0.97
GAL3	10.43	2.07
Aq-A-1	15.36	3.07

Table 5.1: Values of R_e (effective radius) and $0.2R_e$ for each of the GAL1, GAL2, and GAL3 simulations. These values represent the initial and final radii within which the profiles of the dynamical variables were analyzed for each simulation.

The upper limit of the radial distance R is defined as an effective radius R_e , calculated using the relation $R_e = R_{200}/C$, where R_{200} is the virial radius and C is the concentration parameter of the halo, as listed in Table 3.1.4. This effective radius corresponds to the scale radius of the Navarro-Frenk-White (NFW) profile, representing the distance at which the logarithmic slope of the halo density profile transitions from a steep central decline to a slower outer falloff. Defining R_e in this way allows the analysis to focus on the region where the disk's contribution to the galactic dynamics is most significant while ensuring a consistent and meaningful radial cut-off across different galaxy models. The resulting values of R_e for each simulation are summarized in Table 5.1.2, allowing for a fair and coherent comparison of the internal dynamical properties of the systems.

When analyzing the impact of subhalos, we observe that they do not induce significant changes in the circular velocity profile. The galaxy profiles under the influence of Merger 1 closely match those of the isolated galaxies, suggesting that the subhalos exert minimal

dynamical influence on the disk. The only noticeable effect occurs in the outer regions, where slight fluctuations can be observed.

Interestingly, GAL3, the most massive galaxy in the set, appears to have a more well-behaved profile compared to GAL1 and GAL2. The circular velocity in GAL3 is more stable across the entire radius, with fewer fluctuations in the outer regions, indicating that the galaxy's larger mass helps maintain a more regular velocity profile. This trend suggests that the mass of the galaxy plays a role in mitigating the impact of subhalos on the overall dynamics of the galaxy.

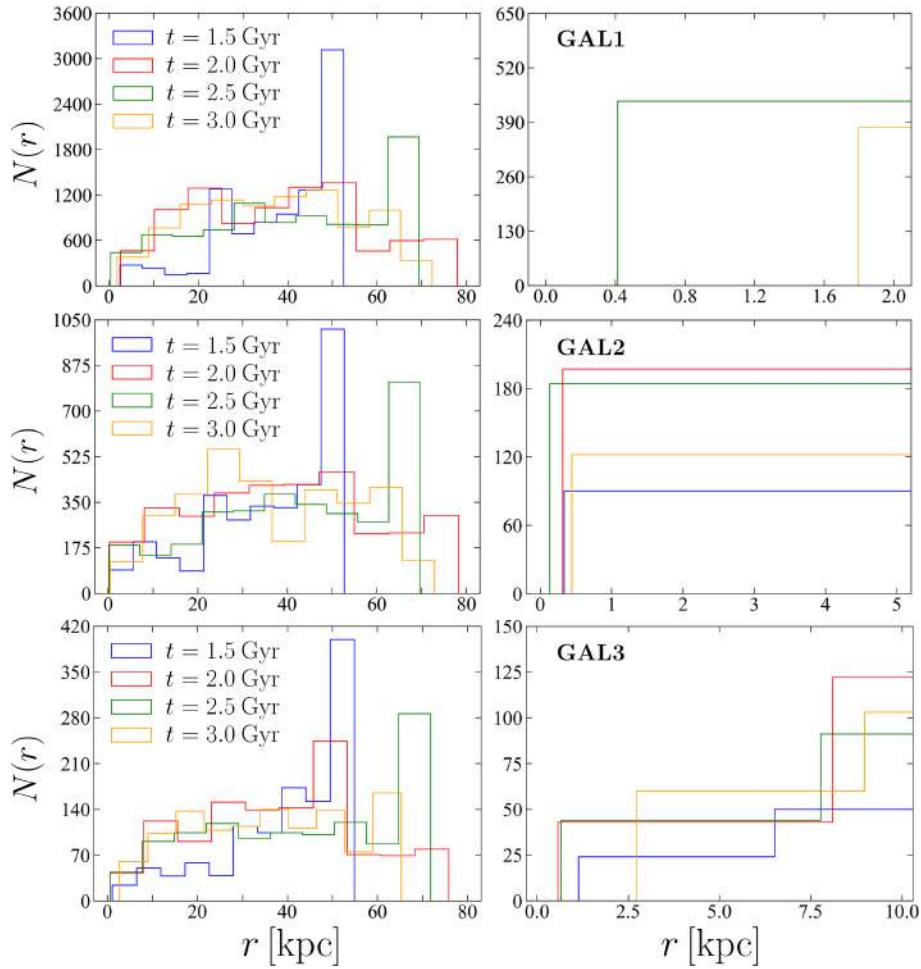


Figure 5.10: Radial distribution of satellites (dark matter subhalos) in the GAL1, GAL2, and GAL3 simulation. The histograms show the number of satellites $N(r)$ at a given radius r at different time snapshots. From top to bottom, GAL1, GAL2 and GAL3 are shown. The left panel displays the full selected range, while the right panel is truncated at the effective radius of the host galaxy in which simulation. Different colors represent different time snapshots.

Figure 5.10 shows the radial distribution of satellites (dark matter subhalos) for the GAL1, GAL2, and GAL3 simulations. The histograms display the number of satellites

$N(r)$ at a given radius r at different time snapshots, from $t = 1.5$ Gyr to $t = 3.0$ Gyr. The left panels show the full selected radial range, while the right panels are truncated at the effective radius of the host galaxy in each simulation.

Upon analyzing the spatial distribution of subhalos, we observe that the distributions for all three galaxies do not change significantly over time. This indicates that the overall distribution of subhalos is largely unaffected even if the mass of the galaxies varies.

It is also important to note that the criteria for selecting satellites are based on the disk mass and the mass per particle of the disk. Since lower-mass subhalos are more likely to be present in the system, it is not surprising that the less massive galaxies, such as GAL1, host a greater number of subhalos.

One interesting finding in the case of GAL1 is that subhalos only appear in the regions of interest after $t > 2$ Gyr, which suggests that before this time, the galaxy continues with an isolated disk. This result indicates that the subhalos, with relatively large orbital radii compared to the disk, only begin to perturb the disk at later times. Thus, the early evolution of the galaxy is dominated by the isolated disk, with the subhalos having little effect until later stages.

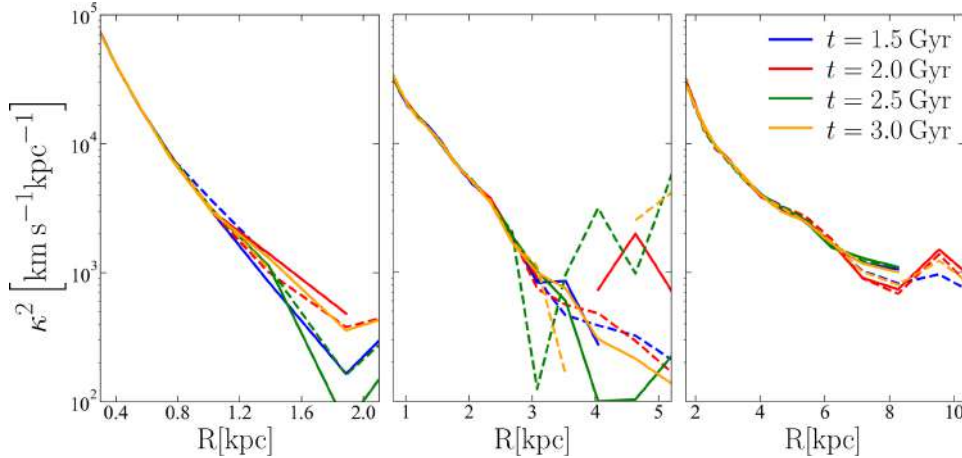


Figure 5.11: Epicyclic frequency squared κ^2 as a function of radius R for different time snapshots in the GAL1, GAL2, and GAL3 simulations. The solid lines represent the isolated galaxies, while the dashed lines correspond to the galaxies under the influence of Merger 1. Each color represents a different time snapshot. From the left to right, the panels show the results for GAL1, GAL2, and GAL3.

Figure 5.11 shown the evolution of the epicyclic frequency squared κ^2 as a function of radius R for the GAL1, GAL2, and GAL3 simulations. The solid lines represent the isolated galaxies, while the dashed lines correspond to the galaxies under the influence of Merger 1. Each color represents a different time step, ranging from $t = 1.5$ Gyr to $t = 3.0$

Gyr.

For the analysis of the dynamical variable profiles, we set the lower limit at $0.2 \times R_e$. This decision is based on our previous analysis of Aq-A-1, where the central region showed noise associated with numerical effects and the presence of the bulge. By excluding the inner 20% of R_e , we avoid the influence of these artifacts and focus on more reliable data that reflects the true dynamics of the disk.

The analysis of the k^2 reveals that, as expected, the perturbations caused by the subhalos are most noticeable in the outer regions of the disk. The most massive galaxy, GAL3, shows a more stable and well-behaved profile, the curve for these galaxy remain relatively smooth and no not exhibit significant variations compared to the less massive galaxies. This suggest that the larger mass galaxies are better able to maintain their dynamical structure despite the influence of the perturbing subhalos.

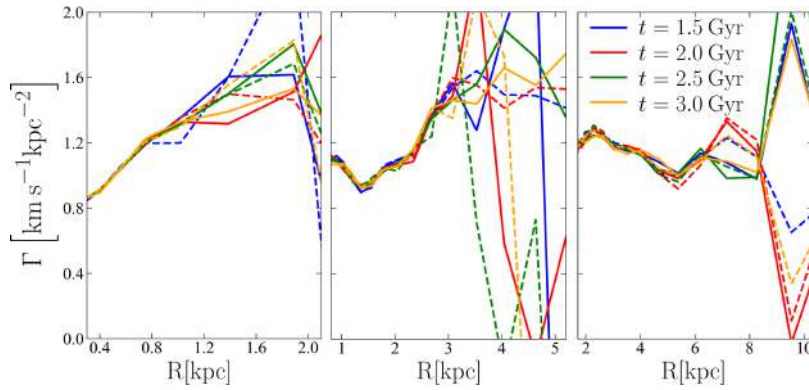


Figure 5.12: Shear rate Γ as a function of radius R for different time snapshots in the GAL1, GAL2, and GAL3 simulations. The solid lines represent the isolated galaxies, while the dashed lines correspond to the galaxies under the influence of Merger 1. Each color represents a different time snapshot. From the left to right, the panels show the results for GAL1, GAL2, and GAL3.

Figure 5.12 displays the shear rate Γ as a function of radius R for the GAL1, GAL2, and GAL3 simulations. The solid lines represent the isolated galaxies, while the dashed lines correspond to the galaxies under the influence of Merger 1. Each color represents a different time snapshot, ranging from $t = 1.5$ Gyr to $t = 3.0$ Gyr.

The analysis of the shear rate shows a pattern consistent with the trends observed in the over-dynamical variables. For most of the disk, up to approximately $R_e/2$, the shear rate behaves smoothly and predictably, reflecting the stable dynamics of the disk. Beyond this point, however, the profile becomes unstable and shows more fluctuations, indicating that the subhalos' influence is more pronounced at larger radii, as expected.

Overall, the shear rate analysis follows the same trends as the other dynamical variables, with more massive galaxies like GAL3 exhibiting a stable behavior and the less massive galaxies showing more pronounced fluctuations as the subhalos exert a stronger influence. This further emphasizes the role of galaxy mass in determining the stability of the system under the influence of perturbing subhalos.

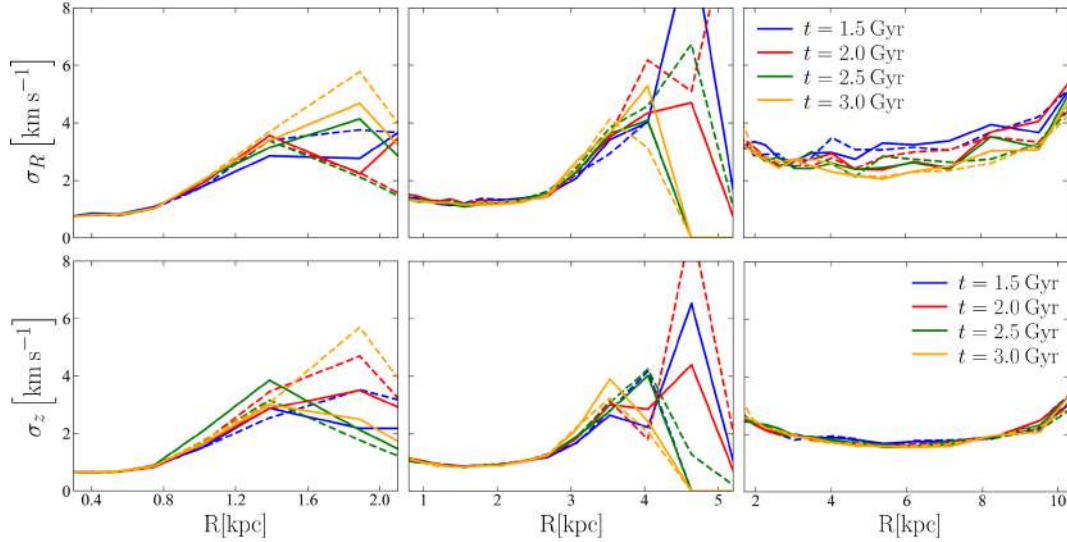


Figure 5.13: Radial (σ_R , top row) and vertical (σ_z , bottom row) velocity dispersion as a function of radius R for different time snapshots in the GAL1, GAL2, and GAL3 simulations. The solid lines represent the isolated galaxies, while the dashed lines correspond to the galaxies under the influence of Merger 1. Each color represents a different time snapshot. From the left to right, the panels show the results for GAL1, GAL2, and GAL3.

Figure 5.13 shows the radial and vertical velocity dispersion (σ_R and σ_z) as a function of radius R for the GAL1, GAL2, and GAL3 simulations. The solid lines represent the isolated galaxies, while the dashed lines correspond to the galaxies under the influence of Merger 1. Each color represents a different time snapshot, ranging from $t = 1.5$ Gyr to $t = 3.0$ Gyr.

As seen in the analysis of the previous dynamical quantities, the velocity dispersion profiles follow a similar trend across all three galaxies. Both the radial and vertical velocity dispersions exhibit a smooth increase as we move outward from the center, with the most substantial variations occurring in the outer regions of the disk.

In general, the velocity dispersion profiles for the different time snapshots remain relatively consistent, indicating that the subhalos do not induce significant long-term dynamical changes in the velocity structure of the disks. This behavior reinforces the observations made earlier, where it was shown that the subhalos primarily affect the outer regions of the disk, with more massive galaxies being less influenced by the perturbations.

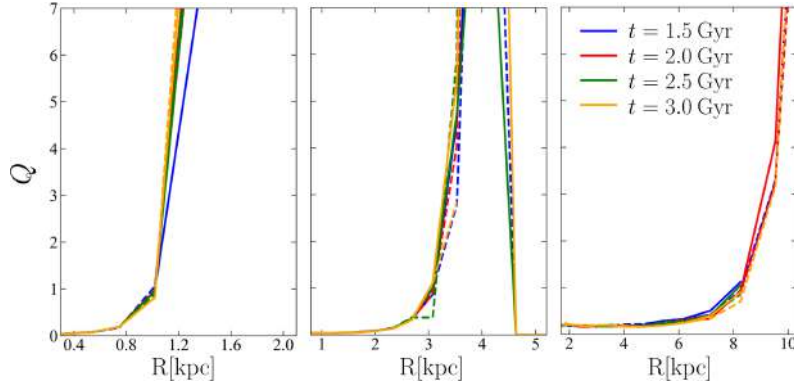


Figure 5.14: Toomre factor Q as a function of radius R for different time snapshots in the GAL1, GAL2, and GAL3 simulations. The solid lines represent the isolated galaxies, while the dashed lines correspond to the galaxies under the influence of Merger 1. Each color represents a different time snapshot. From the left to right, the panels show the results for GAL1, GAL2, and GAL3.

Figure 5.14 shows the Toomre parameter as a function of radius R for the GAL1, GAL2, and GAL3 simulations. The solid lines represent the isolated galaxies, while the dashed lines correspond to the galaxies under the influence of Merger 1. Each color represents a different time snapshot, ranging from $t = 1.5$ Gyr to $t = 3.0$ Gyr.

In the analysis of these simulations, we observe that the presence of Merger 1 does not induce significant changes in the Q -profiles of the galaxies.

All three galaxy models show that gravitational effects dominate the system, with a tendency for pressure to become the dominant force as the distance from the center increases. This shift to pressure dominance appears later for the more massive galaxy (GAL3). Once Q begins to increase, it does so rapidly, indicating a swift transition to pressure-driven dynamics in the outer regions of the galaxy. In comparison, the less massive galaxies (GAL1 and GAL2) show an earlier onset of this transition, with pressure forces becoming dominant at smaller radii.

In Figure 5.15, we present the density contrast profiles in the xy -plane for the GAL1, GAL2, and GAL3 simulations at $t = 2.5$ Gyr. The top row shows the isolated galaxies, while the bottom row displays the galaxies under the influence of Merger 1. From left to right, each column corresponds to GAL1, GAL2, and GAL3. The color bar represents the density contrast.

Upon analyzing the density contrast maps, we can assess the non-local effects that are not visible in the mean profiles. Similar to the analysis in the Aq-A-1 case, we observed that the presence of the merger does not induce significant local perturbations in the den-

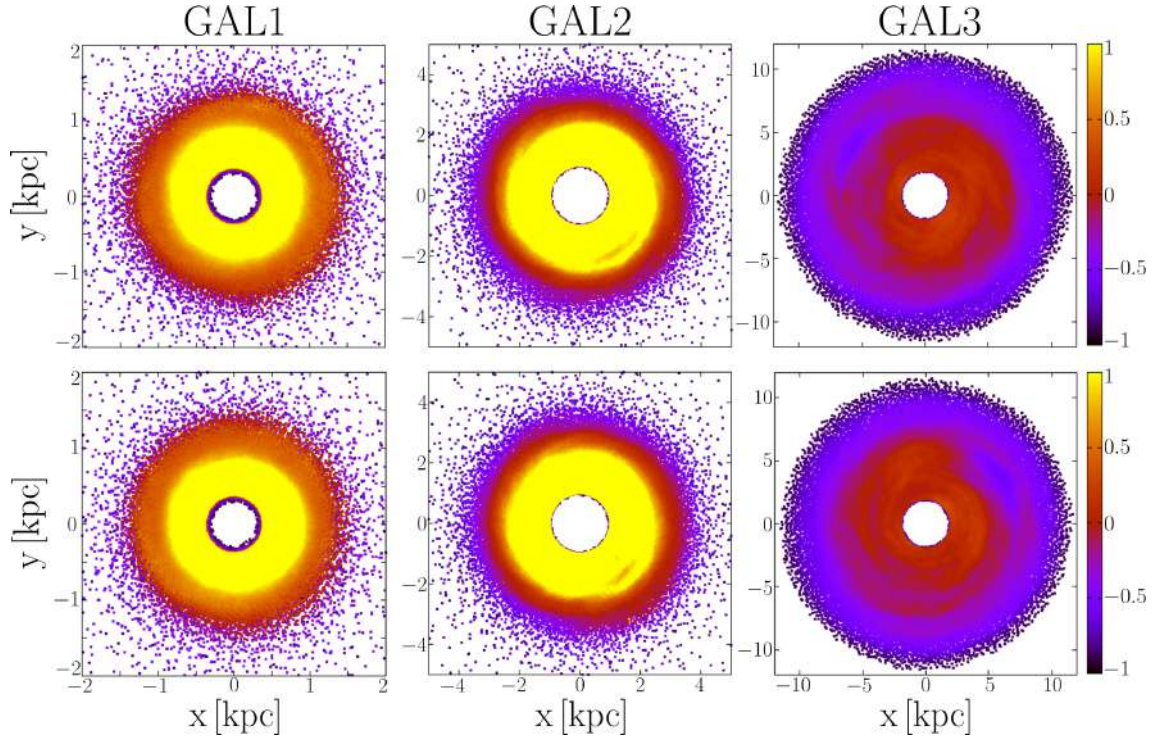


Figure 5.15: Density contrast profiles in the xy -plane for the GAL1, GAL2, and GAL3 simulations at $t = 2.5$ Gyr. The top row shows the isolated galaxies, while the bottom row shows the galaxies under the influences of Merger1. From left to right, each column corresponds to GAL1, GAL2, and GAL3. The color bar represents the density contrast.

sity contrast. In all cases, the profiles appear well-behaved, with no substantial variations compared to the isolated galaxy profiles.

For the low-mass galaxies GAL1 and GAL2, we observe more pronounced overdensities with higher contrast; however, the behavior remains similar in both the isolated and merger scenarios. In the case of GAL3, the mass distribution shows more subtle overdensities. While these regions seem to suggest some structures, they appear similarly in both the isolated and merger cases, indicating no significant influence of the merger on the density contrast.

5.2 Simulations with Star Formation

In this section, we analyze the effects of star formation on the dynamical evolution of galactic gas disks across our simulation set. We begin by comparing the isolated versions of the GAL1, GAL2, GAL3, and Aq-A-1 simulations with and without star formation, aiming to identify how the inclusion of this physical process modifies the structure and stability of the systems. This comparative approach allows us to isolate the specific dynamical signatures introduced by star formation alone.

Subsequently, we extend our analysis to examine how these star-forming systems respond to external perturbations by incorporating the influence of Merger 1. As previously established, Merger 2 represents a subset of the subhalo population contained in Merger 1 and does not introduce distinct dynamical effects; therefore, only Merger 1 is considered in this stage. This two-step exploration enables us to disentangle the individual and combined impacts of star formation and external interactions on the morphology and stability of galactic disks.

5.2.1 Isolated Simulations

To better understand how the inclusion of star formation affects the simulated galaxies, we start by analyzing the reconstructed potential profiles for the isolated galaxies with star formation. The results are shown in Figure 5.16, where the yellow points represent the real values extracted from the simulation, and the blue points correspond to the reconstructed potential using a grid. We used a binning approach that was best suited to each case, and the same binning was maintained for both star formation and no star formation simulations, as outlined in Table 4.3.1.

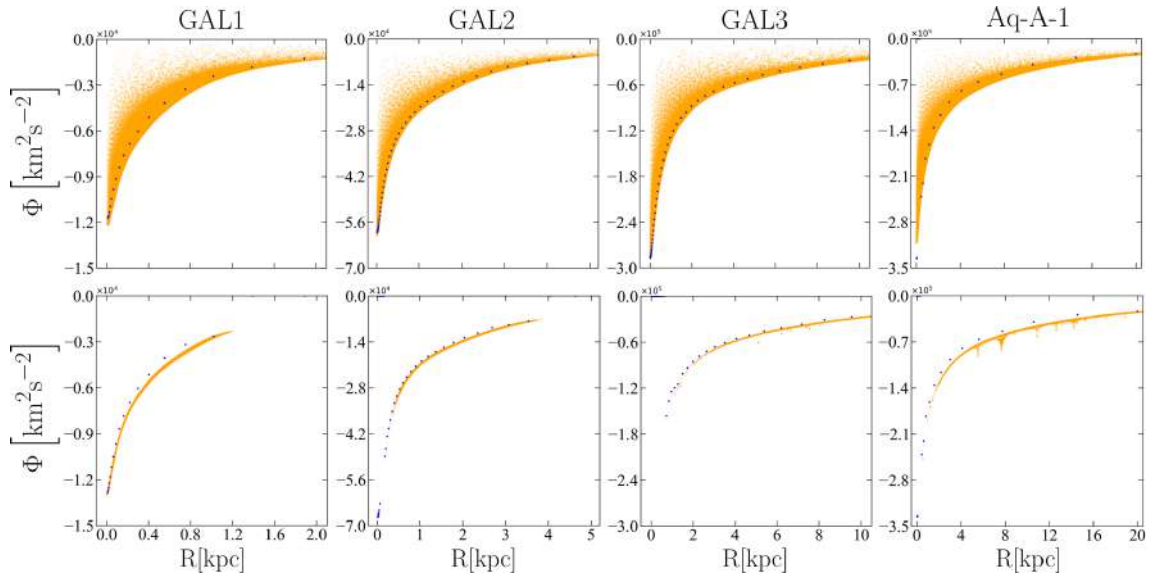


Figure 5.16: Gravitational potential profiles reconstructed for each simulation at $t = 2.0$ Gyr. The yellow points represent the real values extracted from the simulation, while the blue points correspond to the reconstructed potential using a grid. The top row shows the reconstructed profiles for isolated galaxies without star formation, while the bottom row displays the reconstructions for isolated galaxies with star formation. From right to left, the columns correspond to GAL1, GAL2, GAL3, and Aq-A-1.

The reconstructed potential profiles demonstrate a good recovery of the general potential behavior. However, in the cases of star formation, it is clear that there is a reduction in the number of gas particles, which complicates the reconstruction of the potential. This is expected because the process of star formation transforms gas particles into stars. To

quantify how many gas particles remain in each simulation, we refer to Table 5.2.1.

Sim name	0.5 Gyr	1.0 Gyr	1.5 Gyr	2.0 Gyr	2.5 Gyr	3.0 Gyr
GAL1	59693	59251	59054	58936	58902	58880
GAL2	31436	30485	30157	29976	29907	29847
GAL3	15304	11758	10730	10007	9692	9421
Aq-A-1	49004	35409	29807	27096	24991	23616

Table 5.2: Number of gas particles present in each simulation with star formation at different time snapshots. All simulations begin with 400000 gas particles at $t = 0$.

As shown in Table 5.2.1, the star formation process is very efficient. Initially, each GAL simulation starts with 200000 gas particles and Aq-A-1 starts with 400000 gas particles as can be seen in Table 4.1. After 3 Gyr, between 70.56% (for GAL1) and 95.29% (for GAL3) of the available gas has been converted into stellar material.

The results presented in Table 5.2.1 also suggest a trend in which more massive galaxies exhibit higher star formation efficiency. This is evident from the decreasing number of gas particles in GAL1, GAL2, and GAL3 over time, with GAL3—being the most massive—showing the largest percentage of gas converted into stars. However, Aq-A-1 appears to deviate from this trend. This discrepancy may be attributed to the fact that Aq-A-1 was initialized with a higher concentration and modeled with a significantly higher resolution compared to the GAL simulations. These differences imply that a direct comparison between Aq-A-1 and the GAL models under these conditions may not be entirely fair, as they do not share the same initial setup or numerical treatment.

Although the reconstructed potentials capture the overall behavior of the gravitational potential, they lack sufficient resolution to identify the potential wells visible in the case of Aq-A-1 with star formation. These wells may also appear in other simulations at different time steps. These potential wells are indicative of gravitational instabilities in the disk, which may be associated with spiral arms.

To begin analyzing the changes in the system’s dynamic variables when considering the star formation process, we start with the analysis of the circular velocity, as shown in Figure 5.17. This figure presents the circular velocity profile $V_c(R)$ as a function of radius R for different time snapshots across the GAL1, GAL2, GAL3, and Aq-A-1 simulations with and without star formation (dashed and solid lines).

We observe that, in general, the cases with star formation show much noisier profiles, even when using the same binning as the cases without star formation. This suggests that the star formation process introduces instabilities into the system, which seem to persist over time. These instabilities are more pronounced in the simulations of lower-mass

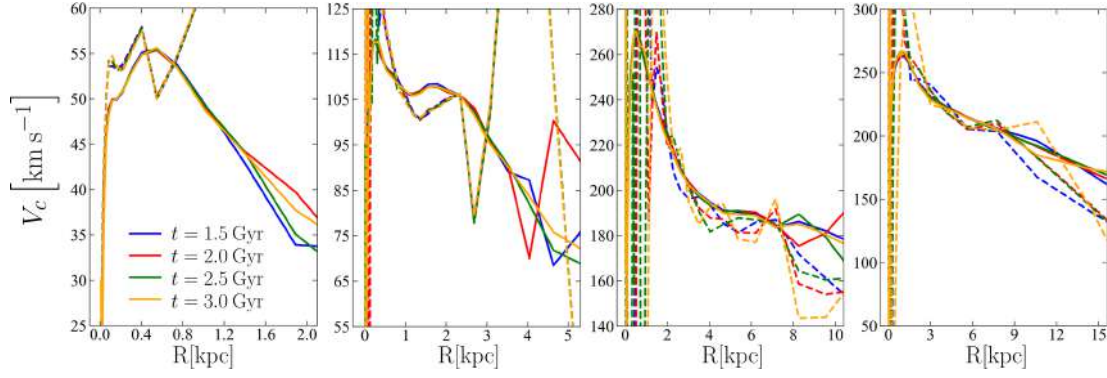


Figure 5.17: Circular velocity profile $V_c(R)$ as a function of radius R for different time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations with and without star formation. The solid lines represent the isolated galaxies without star formation, while the dashed lines correspond to the galaxies with star formation. Each color represents a different time snapshot. From right to left, the panels show the results for GAL1, GAL2, GAL3, and Aq-A-1.

galaxies such as GAL1 and GAL2 and appear less significant in the higher-mass galaxies like GAL3 and Aq-A-1. However, the worst profile reconstruction occurs in the central regions, which makes sense given that our reconstruction of the gravitational potential profiles showed the most significant loss of gas particles in the central part of the disk, making reconstruction more challenging in this area.

The inner limits for each profile were set based on the effective radius values for each simulated galaxy, as shown in Table 5.1.2. This allows for a fairer comparison between our models.

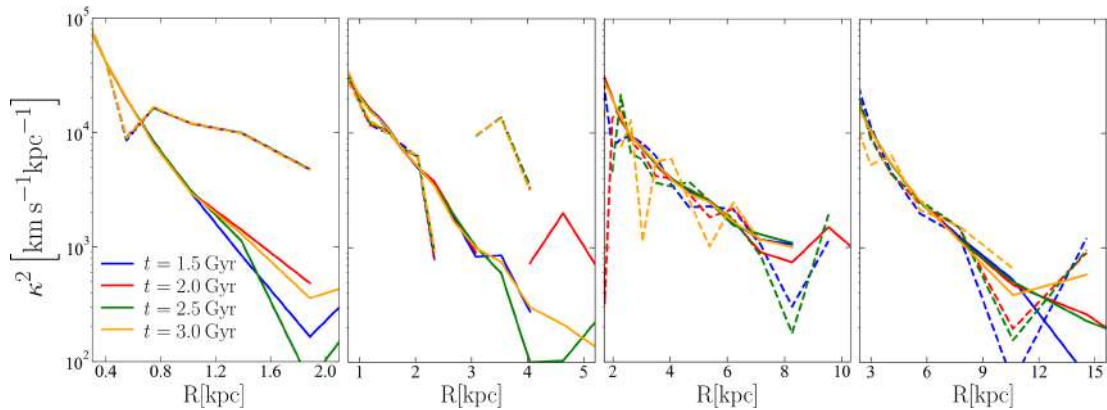


Figure 5.18: Epicyclic frequency squared k^2 as a function of radius R for different time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations with and without star formation. The solid lines represent the isolated galaxies without star formation, while the dashed lines correspond to the galaxies with star formation. Each color represents a different time snapshot. From right to left, the panels show the results for GAL1, GAL2, GAL3, and Aq-A-1.

The Figure 5.18 shows the epicyclic frequency squared k^2 as a function of radius R for different time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations with and without star formation. The solid lines represent the isolated galaxies without star formation, while the dashed lines correspond to the galaxies with star formation. Each color represents a different time snapshot, from right to left, showing the results for GAL1, GAL2, GAL3, and Aq-A-1.

We can observe that the results are consistent with what was seen in the previous circular velocity profiles, with a better reconstruction for the more massive galaxies and noisier profiles for the lower-mass galaxies. Additionally, it is evident that the star formation process introduces instabilities into the system, which appear to persist in the same regions throughout time.

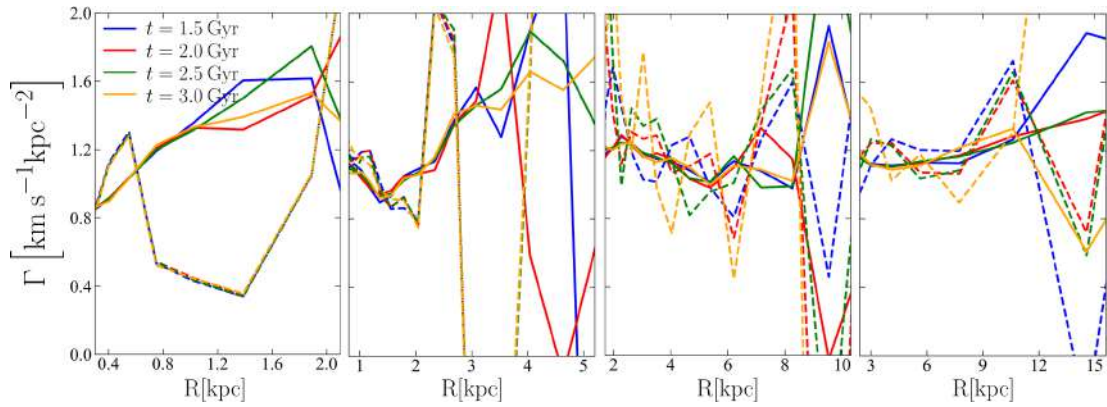


Figure 5.19: Shear rate Γ as a function of radius R for different time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations with and without star formation. The solid lines represent the isolated galaxies without star formation, while the dashed lines correspond to the galaxies with star formation. Each color represents a different time snapshot. From right to left, the panels show the results for GAL1, GAL2, GAL3, and Aq-A-1.

The figure 5.19 shows the shear rate Γ as a function of radius R for different time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations, with and without star formation. The solid lines represent the isolated galaxies without star formation, while the dashed lines correspond to the galaxies with star formation. Each color represents a different time snapshot, from right to left, the panels show the results for GAL1, GAL2, GAL3, and Aq-A-1.

The behavior observed with the shear rate is consistent with the previous findings. The profiles are noisier in the presence of star formation, suggesting regions of instability in the disk that persist over time. These instabilities appear to be a direct consequence of the star formation processes occurring in the galaxy simulations.

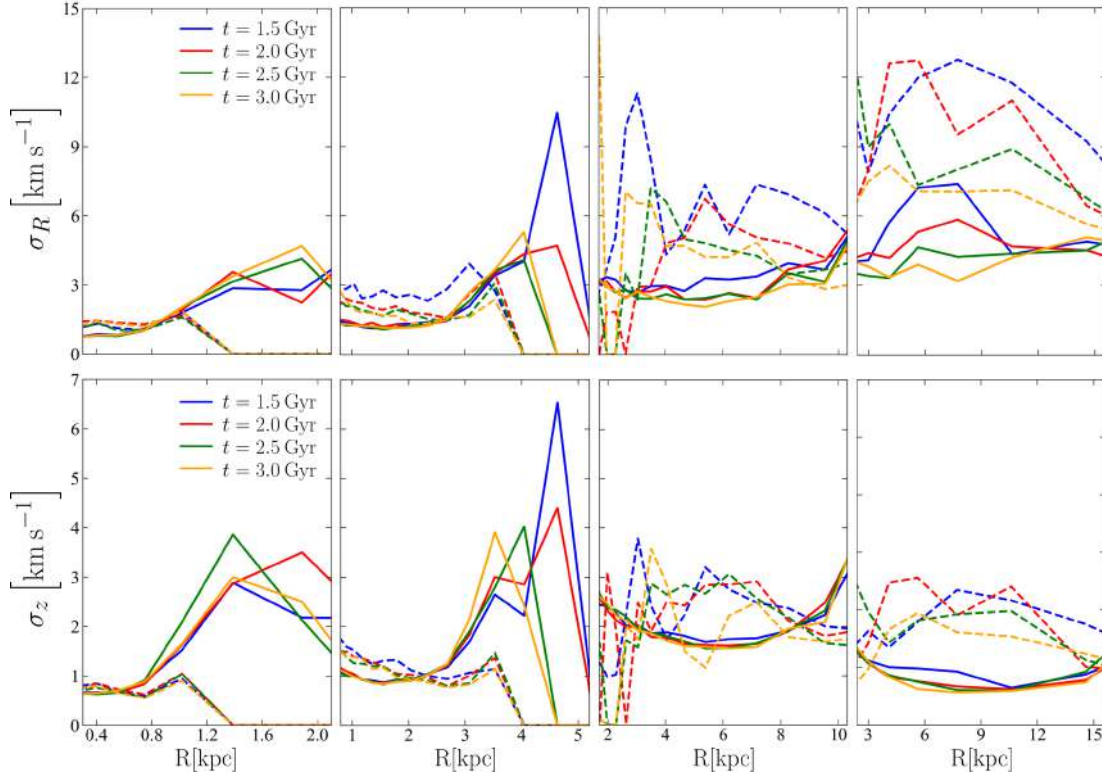


Figure 5.20: Radial (σ_R , top row) and vertical (σ_z , bottom row) velocity dispersion as a function of radius R for different time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations with and without star formation. The solid lines represent the isolated galaxies without star formation, while the dashed lines correspond to the galaxies with star formation. Each color represents a different time snapshot. From right to left, the panels show the results for GAL1, GAL2, GAL3, and Aq-A-1.

Figure 5.20 presents the radial (σ_R , top row) and vertical (σ_z , bottom row) velocity dispersion profiles as a function of radius R for different time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations, both with and without star formation. The solid lines represent the isolated galaxies, while the dashed lines correspond to the galaxies with star formation. Each color represents a different time snapshot. From right to left, the panels show the results for GAL1, GAL2, GAL3, and Aq-A-1.

It is important to note that the lack of gas material in the outer disk regions for low mass galaxies (GAL1 and GAL2), which was observed in the gravitational potential profiles, is also evident in the velocity dispersion profiles, where the values are equal to zero. For the more massive galaxies, which retain gas material throughout the analyzed regions, we observe that both radial and vertical dispersion values increase when star formation processes are included. This indicates that the star formation process imparts greater pressure to the system.

In Figure 5.21, we analyze the Toomre factor Q as a function of radius R for different

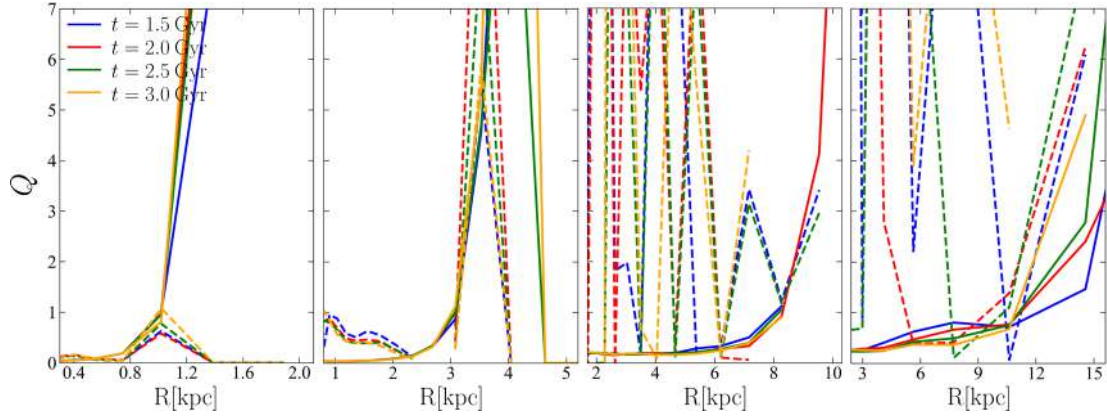


Figure 5.21: Toomre factor Q as a function of radius R or different time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations with and without star formation. The solid lines represent the isolated galaxies without star formation, while the dashed lines correspond to the galaxies with star formation. Each color represents a different time snapshot. From right to left, the panels show the results for GAL1, GAL2, GAL3, and Aq-A-1.

time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations, with and without star formation. The solid lines represent the isolated galaxies, while the dashed lines correspond to the galaxies with star formation. Each color represents a different time snapshot.

For GAL1, the system behaves similarly to the case without star formation. However, the values of Q do not continue to increase as in the other simulations, since the gas material depletes before this trend can fully emerge. In GAL2, the disk appears to be marginally stable in the central region but shows a tendency to decay, indicating gravitational instability. Subsequently, similar to the case without star formation, there is a tendency for Q values to increase, but they rapidly decrease again.

For the more massive galaxies, GAL3 and Aq-A-1, the Toomre factor consistently shows an increasing and decreasing trend with respect to radius. This pattern persists throughout the simulation, suggesting that the star formation process is inducing radial instabilities within the system.

5.2.2 Merger Simulations

In this section, we focus on analyzing the dynamics of galaxies with active star formation in the presence of Merger 1. We use Merger 1 for the analysis since it contains the same subhalo population as Merger 2, and previous results have shown no significant difference in the effects between these two mergers. The goal is to examine how the dynamics of the galaxies evolve with the active star formation process when subjected to perturbations from Merger 1.

This analysis will be carried out for the four simulation sets we have been working with so far, using the same binning strategy defined in Table 4.3.1. The results will help us understand the combined effects of star formation and the gravitational interactions caused by the merging subhalos.

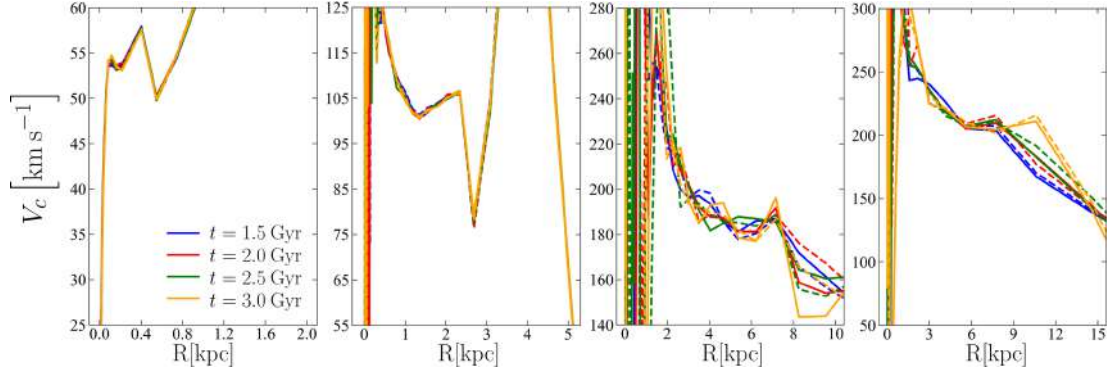


Figure 5.22: Circular velocity profile $V_c(R)$ as a function of radius R for different time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations with star formation. The solid lines represent the isolated galaxies, while the dashed lines correspond to the galaxies under the influence of Merger 1. Each color represents a different time snapshot. From the left to right, the panels show the results for GAL1, GAL2, GAL3, and Aq-A-1.

Figure 5.22 shows the circular velocity profile $V_c(R)$ as a function of radius R for different time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations with star formation. The solid lines represent the isolated galaxies, while the dashed lines correspond to the galaxies under the influence of Merger 1. Each color represents a different time snapshot. From left to right, the panels display the results for GAL1, GAL2, GAL3, and Aq-A-1. This figure allows us to observe the changes in the velocity profiles in response to the mergers.

Here, we observe something interesting. While we were already familiar with the behavior of the profiles from the analysis in the previous section, we now note that the effects of the perturbing subhalos do not cause significant changes in the circular velocity profiles for the low-mass galaxies (GAL1 and GAL2). However, these perturbations do appear to introduce slight changes in the circular velocity profiles for the more massive galaxies. This suggests that the low-mass galaxies are more resilient to the gravitational effects of the subhalos while the higher-mass galaxies exhibit more noticeable responses to the mergers. This behavior may be attributed to the fact that, in more massive systems, the satellites themselves tend to possess higher gravitational energy, which enhances their capacity to perturb the disk and induce dynamical disturbances when interacting with the host galaxy.

In Figure 5.23 shows the radial distribution of satellites (dark matter subhalos) in the GAL1, GAL2, GAL3, and Aq-A-1 simulations with star formation. The histograms show

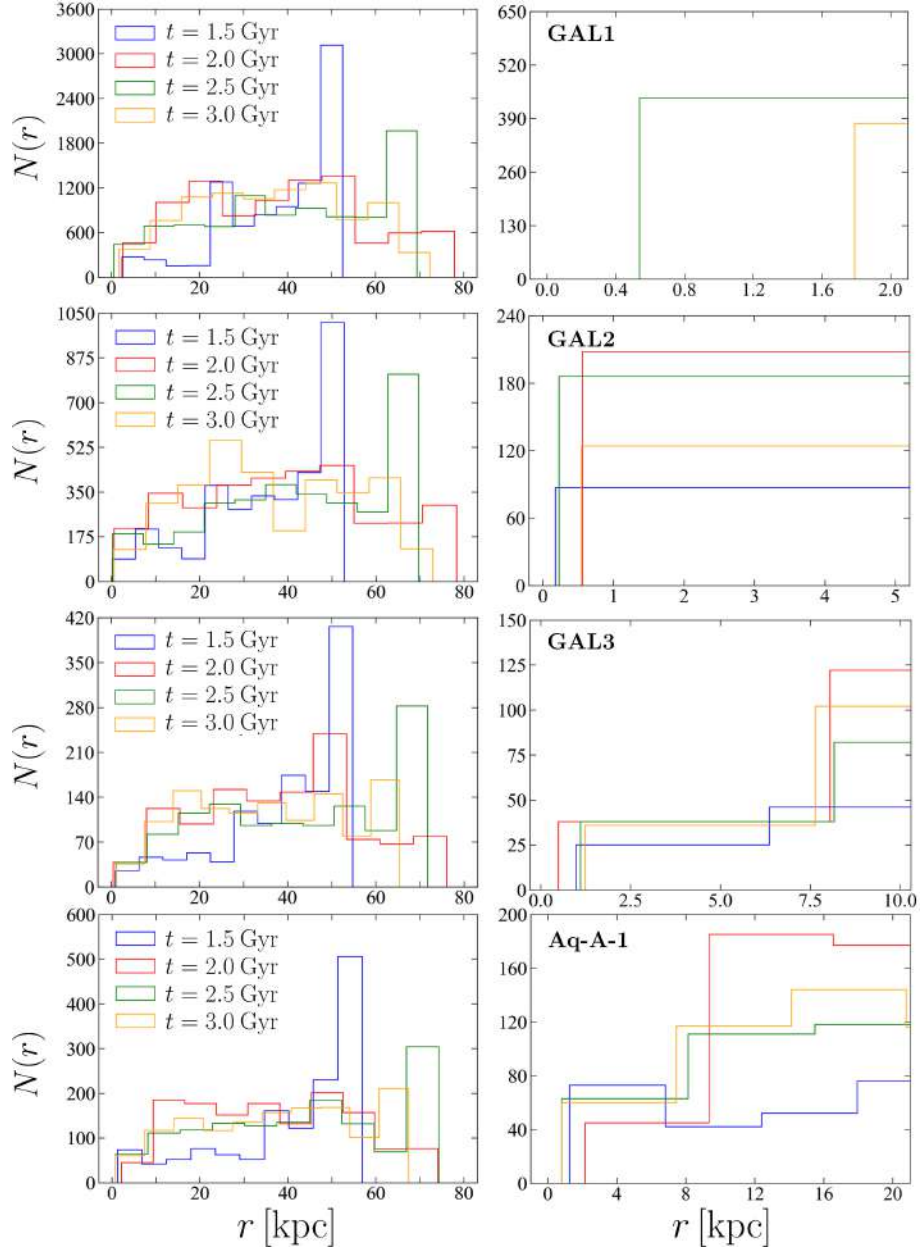


Figure 5.23: Radial distribution of satellites (dark matter subhalos) in the GAL1, GAL2, GAL3, and Aq-A-1 simulation with star formation. The histograms show the number of satellites $N(r)$ at a given radius r at different time snapshots. From top to bottom, GAL1, GAL2, GAL3, and Aq-A-1 are shown. The left panel displays the full selected range, while the right panel is truncated at the effective radius of the host galaxy in the simulation. Different colors represent different time snapshots.

the number of satellites $N(r)$ at a given radius r at different time snapshots. From top to bottom, the panels display GAL1, GAL2, GAL3, and Aq-A-1. The left panel displays the full selected range, while the right panel is truncated at the effective radius of the host galaxy in each simulation. Different colors represent different time snapshots.

In this figure, we observe the radial distribution of satellites with star formation. This allows us to ensure that, in the simulations with star formation, subhalos are able to enter the disk region, showing a behavior similar to the distributions we analyzed in Figures 5.2 and 5.10 for the cases without star formation. This verifies that in all the simulations, subhalos are interacting with the gas disk.

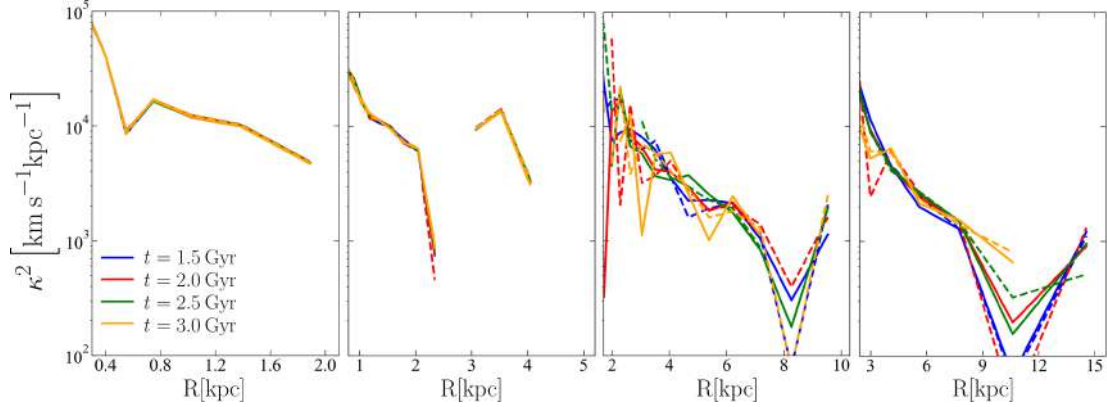


Figure 5.24: Epicyclic frequency squared κ^2 as a function of radius R for different time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations with star formation. The solid lines represent the isolated galaxies, while the dashed lines correspond to the galaxies under the influence of Merger 1. Each color represents a different time snapshot. From left to right, the panels show the results for GAL1, GAL2, GAL3, and Aq-A-1.

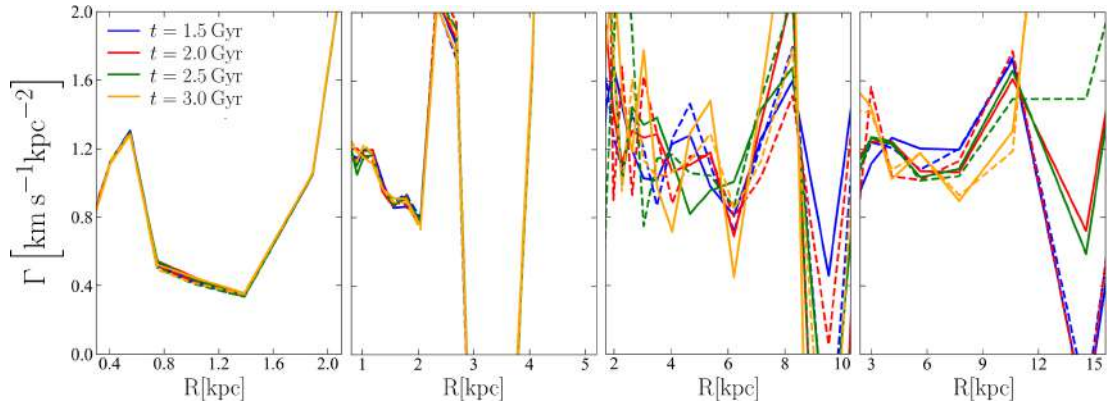


Figure 5.25: Shear rate Γ as a function of radius R for different time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations with star formation. The solid lines represent the isolated galaxies, while the dashed lines correspond to the galaxies under the influence of Merger 1. Each color represents a different time snapshot. From the left to right, the panels show the results for GAL1, GAL2, GAL3, and Aq-A-1.

Figures 5.24 and 5.25 present the squared epicyclic frequency (κ^2) and shear rate (Γ) as a function of radius for different time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations with star formation. The solid lines represent the isolated galaxies, while the dashed lines correspond to the galaxies under the influence of Merger 1. Each color

represents a different time snapshot.

Upon examining both figures, we see that the trends align with what we observed in the circular velocity profiles. For the low-mass galaxies (GAL1 and GAL2), the perturbing effects of the merger do not significantly affect the profiles of κ^2 and Γ , which remain relatively stable (compared to the galaxy without merger). In contrast, for the higher-mass galaxies (GAL3 and Aq-A-1), the presence of the merger does lead to noticeable changes in these profiles, although these changes are not organized in a clear pattern (i.e., not a straightforward increase or decrease in values). This suggests that while the merger is having some dynamic effect on the system, its influence does not manifest in an orderly way, yet still indicates the importance of the merger's presence.

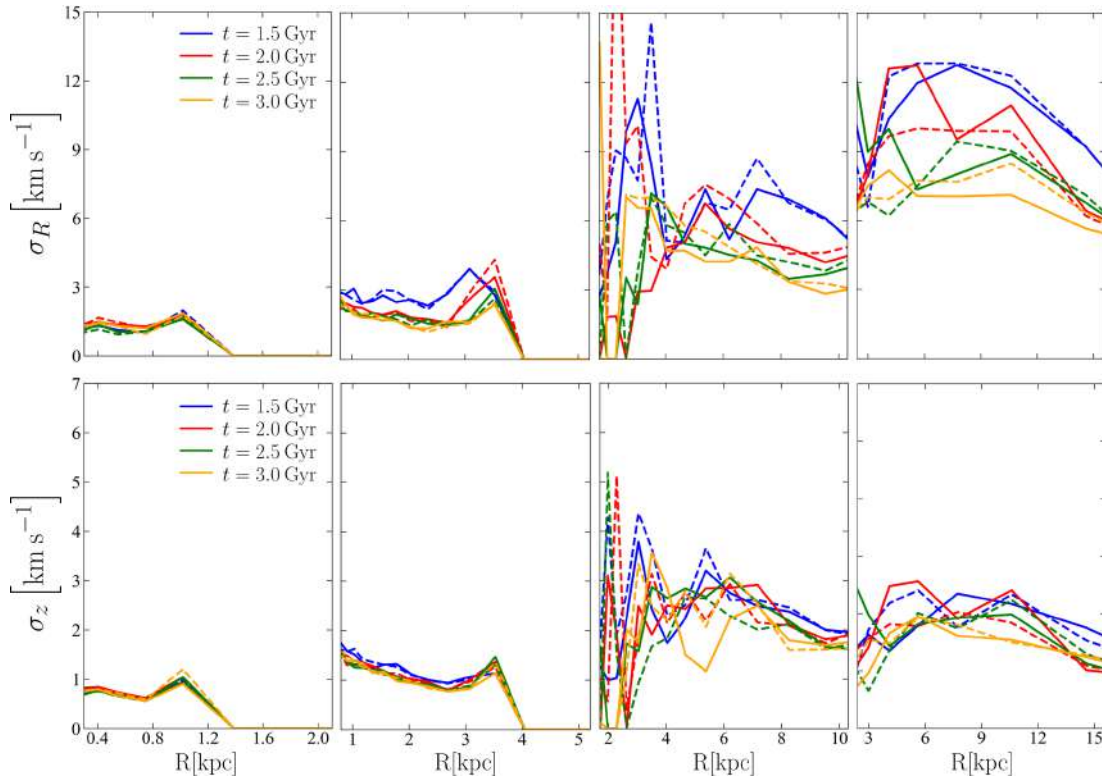


Figure 5.26: Radial (σ_R , top row) and vertical (σ_z , bottom row) velocity dispersion as a function of radius R for different time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations with star formation. The solid lines represent the isolated galaxies, while the dashed lines correspond to the galaxies under the influence of Merger 1. Each color represents a different time snapshot. From the left to right, the panels show the results for GAL1, GAL2, GAL3, and Aq-A-1.

In Figure 5.26 we present the radial (σ_R) and the vertical (σ_z) velocity dispersion profiles as functions of radius for the GAL1, GAL2, GAL3, and Aq-A-1 simulations with star formation. The solid lines represent the isolated galaxies, while the dashed lines correspond to the galaxies under the influence of Merger 1. Each color represents a different

time snapshot, and the panels show the results for GAL1, GAL2, GAL3, and Aq-A-1 from left to right.

As seen in the figure, significant changes in the velocity dispersion profiles are observed only in the higher-mass galaxies (GAL3 and Aq-A-1). In these cases, both the radial and vertical velocity dispersions show an increasing trend when the effects of the merger are considered. This increase is likely due to the gravitational interactions between the galaxies and merges, which induce random motions in the stars, effectively heating the disk and causing the velocity dispersions to rise. In contrast, the low-mass galaxies (GAL1 and GAL2) do not show such significant changes, as their smaller gravitational potential limits the merger's impact.

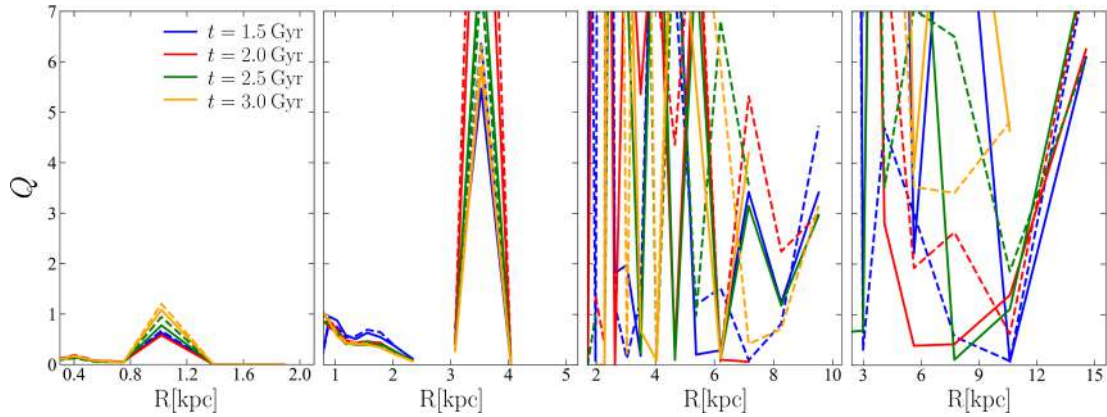


Figure 5.27: Toomre factor Q as a function of radius R for different time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations with star formation. The solid lines represent the isolated galaxies, while the dashed lines correspond to the galaxies under the influence of Merger 1. Each color represents a different time snapshot. From the left to right, the panels show the results for GAL1, GAL2, GAL3, and Aq-A-1.

In Figure 5.27, we present the Toomre factors Q as a function of radius R for different time snapshots in the GAL1, GAL2, GAL3, and Aq-A-1 simulations with star formation. The solid lines represent the isolated galaxies, while the dashed lines correspond to the galaxies under the influence of Merger 1. Each color represents a different time snapshot, and the panels show the results for GAL1, GAL2, GAL3, and Aq-A-1 from left to right.

As seen in the figure, the Toomre factor profiles for the low-mass galaxies (GAL1 and GAL2) remain almost identical with and without the presence of the merger. This suggests that the merger has a negligible impact on the stability of these galaxies. However, significant variations are observed in the higher-mass galaxies (GAL3 and Aq-A-1). In these cases, the presence of the merger leads to notable fluctuations in the Toomre factor, but no clear trend emerges in terms of increasing or decreasing Q values. This lack of a definitive trend indicates that the merger introduces a level of dynamical complexity that

does not manifest in a simple, predictable manner in the stability of the disk.

Up to this point, we have analyzed the mean profiles of the dynamic variables across our simulations. While these profiles give us a general overview of the system's behavior, they do not fully capture the underlying spatial variations and local instabilities present in the galaxies. To gain a deeper understanding of the real changes occurring in the system, we now turn our attention to the density contrast profiles in the mid-plane ($z = 0$) of each galaxy. These profiles provide a more detailed and spatially resolved view of the distribution of mass within the galaxies, highlighting regions of overdensity that may be indicative of significant structural features, such as spiral arms or gravitational instabilities.

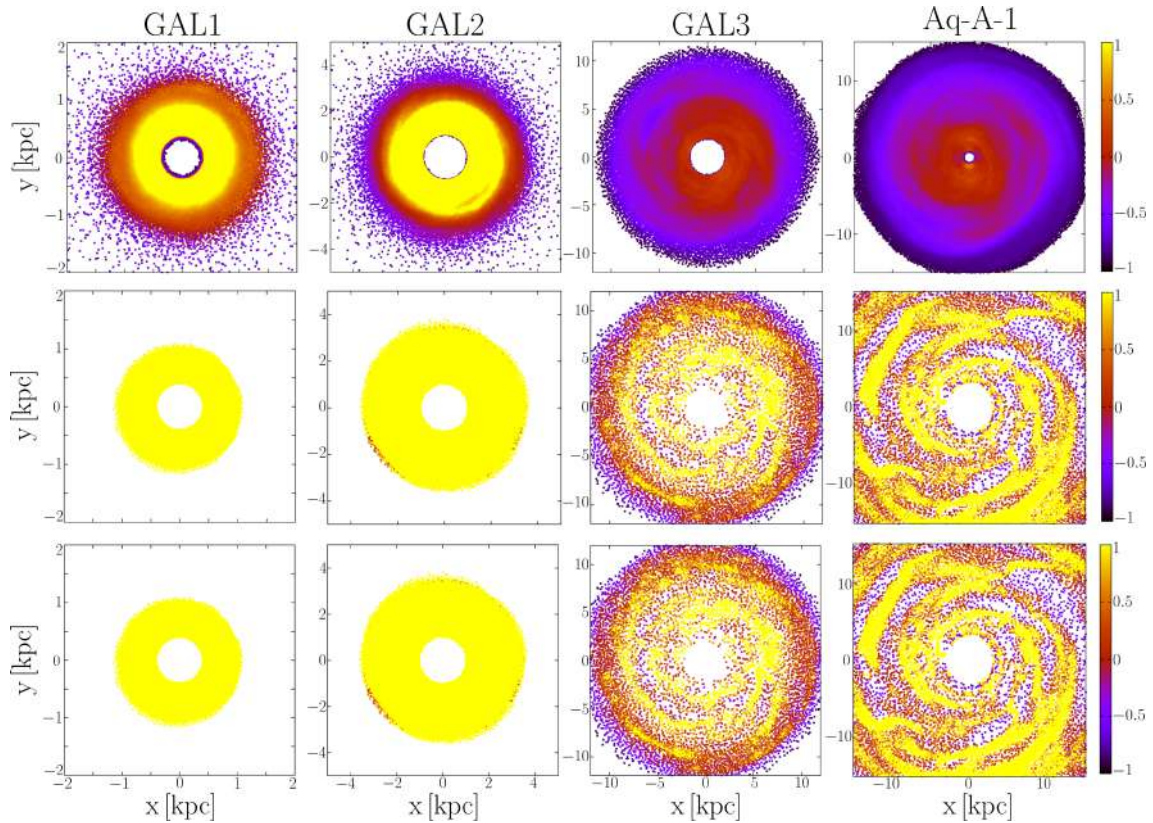


Figure 5.28: Density contrast profiles in the xy -plane for the GAL1, GAL2, and Aq-A-1 simulations at $t = 2.5$ Gyr. The top row shows the isolated galaxies without star formation, the second row shows the galaxies without the presence of mergers but with active star formation, and the bottom row displays the galaxies with star formation and under the influence of Merger 1. From left to right, each column corresponds to GAL1, GAL2, GAL3, and Aq-A-1. The color bar represents the density contrast.

Here we present Figure 5.28, which shows the density contrast profiles in the xy -plane for the GAL1, GAL2, and Aq-A-1 simulations at $t = 2.5$ Gyr. The top row shows the isolated galaxies without star formation, the second row shows the galaxies without the presence of mergers but with active star formation, and the bottom row displays the

galaxies with star formation and under the influence of Merger 1. From left to right, each column corresponds to GAL1, GAL2, GAL3, and Aq-A-1. The color bar represents the density contrast.

From the detailed analysis we have conducted thus far and the results shown in 5.28, it is evident that the star formation process significantly influences the dynamics and structure of the simulated galaxies. Specifically, the density contrast profiles illustrate that star formation induces noticeable structural changes in the gas distribution within the disks. In the cases of the more massive galaxies, GAL3 and Aq-A-1, these structural modifications manifest clearly as coherent overdensity regions, strongly suggestive of spiral arm formation. Such spiral-like features are less distinct or absent in the lower-mass galaxies, GAL1 and GAL2, where star formation affects the distribution of gas but does not produce equally prominent or organized structures. These results emphasize the crucial role that star formation plays in shaping galactic disks and their spiral features, particularly in galaxies with sufficiently high mass to support strong gravitational instabilities.

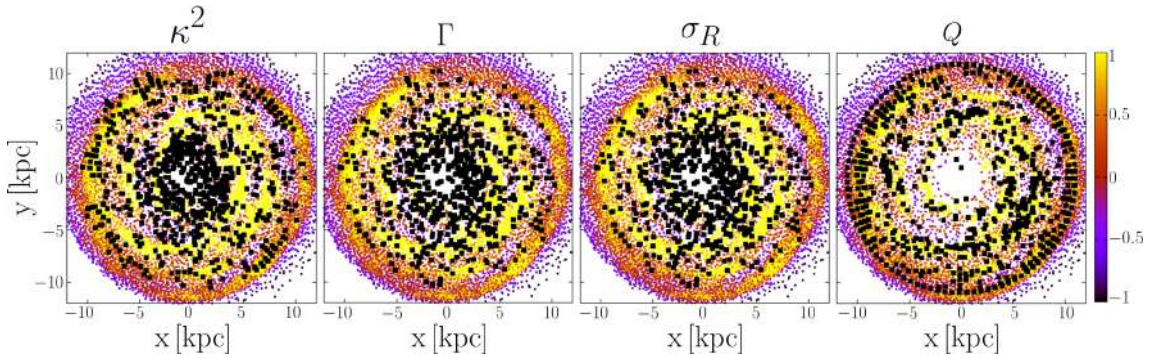


Figure 5.29: Anomalous regions overlaid on density contrast maps in the xy -plane for the GAL3 simulation with star formation and Merger 1 at $t = 2.5$ Gyr. Each panel shows the spatial distribution of the density contrast, with black points indicating locations where anomalies were detected in key dynamical quantities. From left to right, the panels correspond to the squared epicyclic frequency (κ^2), shear rate (Γ), radial velocity dispersion (σ_R), and the Toomre parameter (Q). The color bar represents the density contrast.

To complement the interpretation of the density contrast distributions, Figure 5.29 presents a comparative spatial analysis between the density contrast and the key dynamical quantities in the disk for the GAL3 simulation with star formation and under the influence of Merger 1 at $t = 2.5$ Gyr. In each panel, the background color represents the density contrast, while the black points indicate locations where anomalous values were detected in the squared epicyclic frequency, shear rate, radial velocity dispersion, and the Toomre parameter.

The results show a clear tendency for these dynamical anomalies to spatially overlap with regions of overdensity within the disk. This spatial correlation reinforces the idea that

the dynamical behavior of the system is closely tied to the underlying mass distribution, particularly where spiral-like overdensity features are present. The consistency between the identified overdense regions and the locations of anomalous dynamical quantities suggests that these structures are not merely visual artifacts but are dynamically relevant. This further supports the interpretation that the formation of spiral features in the GAL3 disk is accompanied by significant dynamical responses in the system.

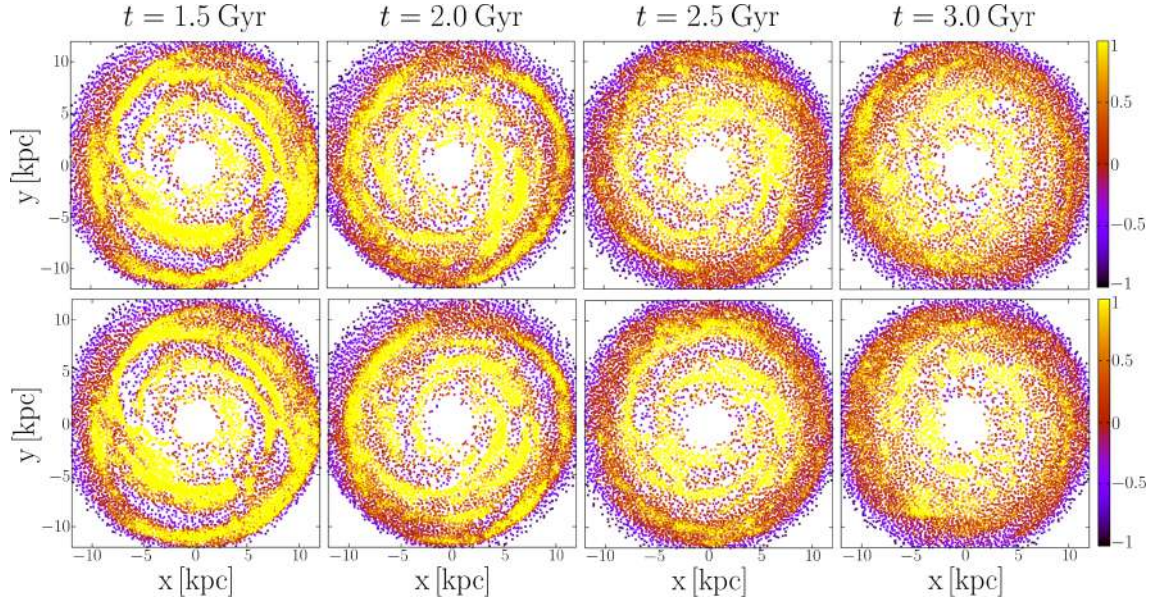


Figure 5.30: Density contrast maps in the xy -plane for GAL3 simulation with star formation at different snapshots. The top row shows the isolated galaxy with star formation and without mergers, while the bottom row displays the galaxy with star formation under the influence of Merger 1. From left to right, each column corresponds to a different time: $t = 1.5$, $t = 2.0$, $t = 2.5$, and $t = 3.0$ Gyr. The color bar represents the density contrast.

To further explore the persistence and evolution of spiral-like overdensity structures in our simulations, we introduce Figure 5.30, which shows the density contrast in the xy -plane for the GAL3 simulation with active star formation across different time snapshots. The top row corresponds to the isolated galaxy without mergers, while the bottom row includes the influence of Merger 1. Each column represents a different time step: $t = 1.5$, 2.0 , 2.5 , and 3.0 Gyr, from left to right.

These maps reveal that the overdense structures, which are suggestive of spiral arms, persist over time in both the isolated and perturbed cases. This temporal continuity indicates that once formed, these features remain coherent for extended periods, reinforcing the idea that they are stable dynamical structures rather than transient fluctuations.

Additionally, the presence of mergers appears to mildly reinforce these spiral arm structures in the more massive simulations, GAL3 and Aq-A-1. As evident in the bottom

row of Figure 5.28, the density contrasts show slightly more pronounced and well-defined overdensities when mergers interact with disks already affected by star formation. Although this effect is subtle, it clearly suggests that interactions with subhalos can enhance gravitational instabilities in galaxies of higher mass, potentially contributing to a more defined spiral pattern. This indicates that mergers play a supporting role, reinforcing the structural features induced primarily by star formation.

To assess whether the population of subhalos associated with Merger 1 introduces noticeable differences in the development or enhancement of these structures, we compared the isolated and merger cases at each snapshot. While visual inspection reveals no obvious systematic changes, a statistical analysis was carried out by constructing cumulative distribution functions (CDFs) of the density contrast values at each time. The results indicate that the distributions remain broadly similar between the isolated and perturbed configurations, with no consistent shift toward higher contrast values in the merger case. This suggests that the presence of subhalos in Merger 1 does not systematically amplify the contrast of overdense regions, and thus, their role in strengthening or triggering spiral structures.

Chapter 6

Conclusion

This study has explored the dynamical influence of dark matter subhalos on the formation and evolution of spiral arms in disk galaxies, using a controlled numerical framework built on high-resolution simulations with a rigid halo potential. The methodology adopted here—simulating galaxies with a static dark matter halo—proved to be a particularly effective approach for isolating disk dynamics and enabling high spatial resolution in the stellar and gaseous components. This setup allowed us to conduct computationally demanding experiments with relatively low numerical cost, making it a suitable strategy for systematically probing the effects of various perturbative mechanisms on galactic structure.

A key finding of this work is that the star formation process itself acts as a significant source of internal perturbation. Even in the absence of mergers, the inclusion of star formation induced non-axisymmetric features in the disk, such as spiral arms, as clearly in Figures 5.28 and 5.30, and more broadly discussed throughout Section 5.2. These results underscore the importance of treating star formation not merely as a background process, but as an active driver of morphological evolution. The experimental design—comparing isolated galaxies, isolated galaxies with star formation, and galaxies undergoing mergers with active star formation—was important in disentangling the individual effects of each mechanism, allowing for a clearer interpretation of their roles.

Additionally, the simulations revealed that the feedback associated with star formation significantly alters the structural evolution of the disk. Without varying the star formation parameters, the prescribed model triggered widespread star formation and strong gas evaporation, leading to the disruption of the disk gas. This highlights the sensitivity of the results to the adopted feedback model and suggests that the treatment of star formation and its coupling to the interstellar medium can critically influence the global dynamics and observable features of the galaxy.

Although the subhalo population was generated using cosmologically motivated spatial and mass distributions, as presented in section 3.2, the specific implementation-

particularly the mass range and orbital parameters led to a negligible impact on the disk structure. Under the conditions selected for this experiment, the perturbations produced by the subhalos were insufficient to alter the disk or induce strong spiral features significantly. This result is supported by Figures 5.2, 5.10, and 5.23, which show that the number of subhalos within the region of interest remains relatively low. While this does not rule out the possibility that inter-satellite interactions may induce spiral features under different conditions, it highlights the limited effectiveness of such perturbations under the assumptions made in this setup.

Finally, the rigid halo approximation, while computationally advantageous, played a central role in suppressing the effectiveness of subhalo interactions. Since the orbits of the subhalos remained largely distant from the galactic disk and dynamical friction was not included, these objects failed to penetrate the inner regions where they could effectively inject energy and trigger morphological changes. More realistic simulations incorporating a live halo and dynamical friction could result in stronger and more frequent disk-subhalo interactions, potentially enhancing the role of substructure in shaping galactic morphology.

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