A Survey of Galaxy Dynamics and Dark Matter Phenomena

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Abstract

This survey comprehensively examines the intricate dynamics of galaxies and the pivotal role of dark matter in their formation and evolution. Emphasizing the significance of dark matter's gravitational interactions, the survey explores phenomena such as weak lensing, galaxy-halo alignments, and the core-cusp issue, which challenges current models by highlighting discrepancies in dark matter density profiles. The study delves into spiral structures in disk galaxies, the evolution of star formation rates, and the challenges of accurately determining dark halo virial masses, especially in dwarf galaxies. The impact of stellar feedback, including winds and supernovae, is analyzed for its role in regulating star formation and influencing galaxy morphology. Advanced computational models and galaxy simulations are highlighted for their contributions to understanding galaxy dynamics and dark matter distribution. Gravitational lensing, particularly microlensing, emerges as a crucial tool for probing dark matter and extrasolar planets, offering insights into mass distribution and cosmic evolution. The survey underscores the necessity of integrating observational data with sophisticated models to address persistent challenges in galaxy dynamics and dark matter research. By synthesizing diverse research domains, this survey lays a foundation for future investigations into the universe's structure and evolution, advocating for enhanced observational capabilities and refined models to advance our understanding of these complex phenomena.

1 Introduction

1.1 Focus of the Survey

This survey investigates the intricate dynamics of galaxies and the pivotal role of dark matter in their formation and evolution. Understanding these dynamics is essential for elucidating cosmic structure formation and interpreting phenomena such as weak lensing and galaxy-halo alignments [1]. The survey challenges misconceptions in fluid mechanics related to gravitational structure formation, which have historically resulted in inaccuracies in estimating baryonic and non-baryonic matter [2].

A primary focus is the formation and stability of spiral structures in disk-shaped galaxies, crucial for studying galaxy dynamics [3]. The evolution of the star formation rate (SFR)-density relation over cosmic time is also examined, as it is vital for understanding galaxy formation and evolution [4]. Additionally, the survey addresses the challenges in accurately determining the dark halo virial mass (Mvir) of galaxies, particularly in the dwarf galaxy regime where traditional methods are less effective [5].

The role of ultra-diffuse galaxies (UDGs) in challenging existing galaxy formation models, especially regarding dark matter content, is explored [6]. Techniques for interpreting faint galaxy data to trace the evolution of galaxy luminosity density over cosmic time are reviewed [7]. The impact of cosmic voids on galaxy properties, highlighting the significance of environmental interactions in galaxy dynamics, is also discussed [8].

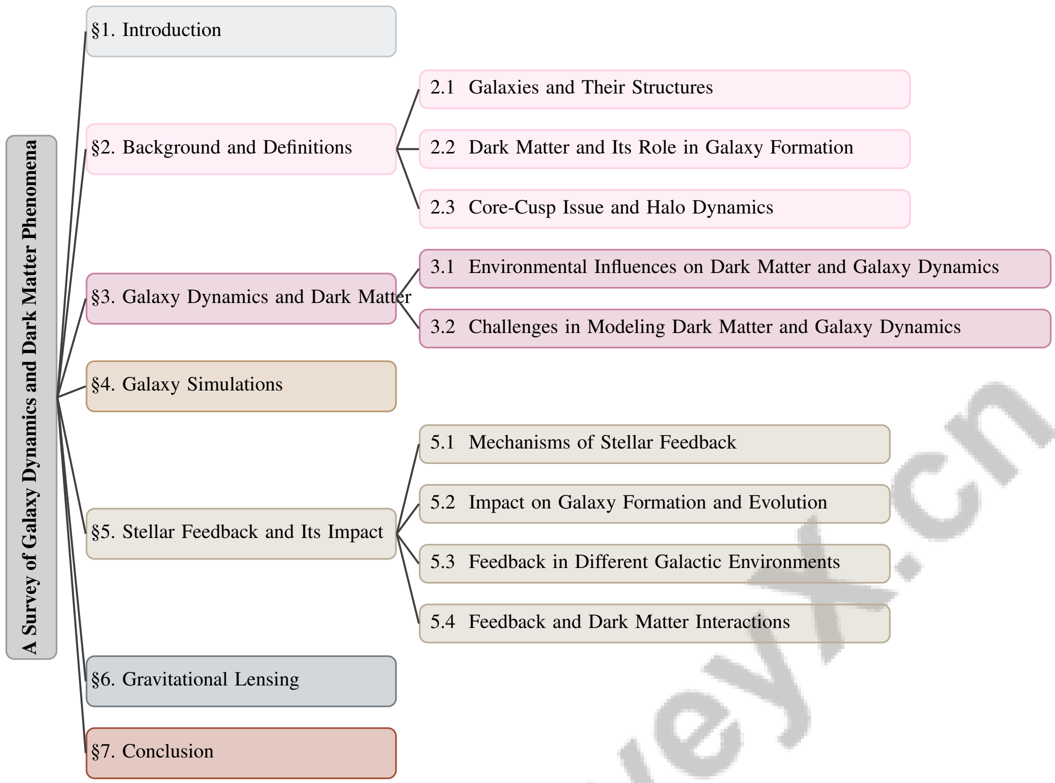

Figure 1: chapter structure

An in-depth examination of star-forming galaxies during the cosmic noon era, particularly around redshift z 2, is provided [9]. The necessity of benchmarks for evaluating the consistency between cosmological simulations and deep submillimeter galaxy surveys is emphasized, focusing on dust emission properties critical for understanding galaxy evolution [10]. Furthermore, the interconnection of vertical HI structures in the Milky Way Galaxy with large-scale blow-outs from clustered supernova explosions is analyzed, underscoring the importance of large-scale structures like supershells in galactic evolution [11].

The survey also addresses the challenge of obtaining reliable metallicity values for globular clusters (GCs) around early-type galaxies (ETGs), notably M87, illustrating the importance of studying galaxy dynamics and dark matter phenomena [12].

By synthesizing findings from diverse research areas, the survey underscores the essential role of galaxy dynamics and dark matter in enhancing our understanding of galactic structures, star formation processes, and the historical evolution of galaxies. This is particularly facilitated by advancements in precision astrometry from missions like Gaia and insights into the effects of gas outflows on galaxy formation and chemical enrichment [13, 14]. These investigations not only advance our comprehension of the universe's structure and evolution but also lay the groundwork for future research in astrophysics and cosmology.

1.2 Structure of the Survey

The survey is systematically organized to provide a comprehensive examination of galaxy dynamics and dark matter phenomena, structured into key sections that address the complexities of this field. The initial section, "Background and Definitions," establishes essential concepts such as galaxy structures—including the halo, disc, and bulge/bar [14]—the critical role of dark matter in galaxy formation, and the core-cusp issue, which is fundamental for understanding dark matter halo dynamics.

The section "Galaxy Dynamics and Dark Matter" delves into the intricate interplay between dark matter and galaxy dynamics, focusing on environmental influences and the challenges of accurately

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modeling these interactions [15]. It also discusses the dynamics of atomic, molecular, and hot gas in small galaxy groups, offering insights into their unique interactions [16].

In "Galaxy Simulations," the role of computational models in simulating galaxy formation and evolution is highlighted, providing insights into dark matter distribution and evaluating various simulation techniques [17]. This section includes benchmarks for comparing different models of galaxy evolution and understanding the relationship between simulated and observed dust properties in galaxies [10].

The "Stellar Feedback and Its Impact" section investigates how stellar feedback affects galaxy dynamics and formation, analyzing the life cycle of star clusters from their formation in molecular clouds to their eventual dispersal [18], along with the impact of stellar feedback across different galactic environments and its interactions with dark matter [19].

The "Gravitational Lensing" section examines gravitational lensing as a tool for studying mass distribution in galaxies, emphasizing its role in detecting dark matter and providing insights into galaxy dynamics [20]. It also considers the implications of gravitational lensing for understanding galaxy mass assembly and evolution [21].

The survey concludes with a synthesis of key findings and a discussion on the current state of research in galaxy dynamics and dark matter phenomena, setting the stage for future studies in this dynamic field. Each section builds upon the previous one, ensuring a cohesive and comprehensive examination of the topic.The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Galaxies and Their Structures

Galaxies, composed of stars, gas, dust, and dark matter, follow intricate formation and evolutionary trajectories. The Milky Way serves as a central model, comprising the bulge, disc, and halo—each playing a pivotal role in galactic dynamics. The bulge's diverse stellar populations offer insights into morphological, kinematic, and chemical properties essential for unraveling galactic evolution [22]. Dwarf galaxies, especially dwarf spheroidals, are key to understanding the Cold Dark Matter (CDM) framework, despite detection challenges due to their faintness [23]. Both dwarf and larger galaxies exhibit spiral arms, with structures linked to stellar mass and star formation rates [21].

Disk-shaped galaxies' dynamics are critical for understanding stability and evolutionary processes under gravitational influences [3]. Environmental interactions, like tidal forces, can induce vertical breathing motions in disc galaxies, impacting stability and star formation [24]. Stellar velocity distribution functions in various galactic components offer insights into dynamical equilibrium and structural evolution [25]. Large-scale phenomena, such as supershells and HI shells driven by supernova explosions, further influence galactic structures [11]. Isolated galaxies provide unique perspectives, though modeling them in hydrodynamic simulations requires careful boundary condition management to avoid gas dynamics misrepresentations [26]. Unique galactic forms, including prolate shapes with limited rotation, highlight the diversity of structures, necessitating comprehensive classification frameworks [27].

Star-forming galaxies' properties during the cosmic noon period are crucial for understanding galaxy formation [9]. Void galaxies, influenced by local and large-scale environments, exhibit distinct evolutionary traits that enhance comprehension of galactic structures [8]. Examining these structural components and their interactions enriches our understanding of galactic evolution across cosmic time.

2.2 Dark Matter and Its Role in Galaxy Formation

Dark matter, comprising around 27

Challenges to the CDM model include the core-cusp issue and the missing satellites problem. The core-cusp issue involves discrepancies between observed flat density profiles in galaxy centers and steep profiles predicted by simulations [28]. Significant dark cores in dwarf galaxies challenge the standard CDM model's cuspy density profile predictions [29]. Ongoing investigations explore galaxy mergers' role in stellar mass growth and star formation rates at high redshifts [30].

Dark matter influences larger cosmic structures, such as galaxy clusters, integral to phenomena like the Fingers-of-God effect, driven by galaxy motion within clusters [31]. The interplay between dark matter and baryons is evident in accretion processes onto galaxies, crucial for mass growth and significantly affected by environmental factors [32]. Discrepancies in angular momentum between galaxies and their dark matter halos underscore dark matter's significant role in galaxy formation [33].

The persistence of disc morphology in massive galaxies, despite expected elliptical shapes due to mergers, further highlights dark matter's complex role in maintaining these structures [34]. The mass-metallicity relation observed in globular clusters, such as the blue tilt in NGC 5170, suggests a nuanced role of dark matter in galaxy evolution [35]. Additionally, vertical breathing motions in disc galaxies, influenced by tidal interactions, underscore dark matter's intricate impact on galactic dynamics [24].

Galaxies' properties depend on local density and cosmic void influences, affecting their formation and evolution [8]. Challenges in determining globular clusters' metallicity in extragalactic systems, such as M87, highlight the complexities of studying dark matter's role in galaxy formation [12]. Dark matter's significant role in galaxy formation and evolution is also pertinent to understanding the gravitational slip parameter PPN and its implications for cosmological models [36].

Dark matter is indispensable in galaxy formation and evolution, influencing processes from baryonic matter's initial collapse to galaxy clusters' dynamics and galactic structures' maintenance. Understanding these interactions is vital for comprehending the universe's structure and evolution over cosmic time [37].

2.3 Core-Cusp Issue and Halo Dynamics

The core-cusp issue challenges the CDM framework, predicting cuspy density profiles at dark matter halos' centers, while observations in dwarf spheroidal galaxies often reveal flatter core-like profiles, indicating a discrepancy between theoretical models and empirical data [28]. This discrepancy has led to investigations into alternative dark matter models and baryonic feedback's impact on these profiles [38]. Self-interacting dark matter models propose that interactions among dark matter particles could naturally lead to core-like structures [19]. Baryonic processes, such as supernova-driven and AGN feedback, are crucial for redistributing mass and energy, altering gravitational potential and flattening dark matter density profiles [39]. Photoionization effects also influence gas cooling within halos, affecting the thermal and dynamic state of baryonic matter [40].

Understanding dark matter halo dynamics is pivotal for galaxy formation and evolution. Traditional models may overlook complexities such as dark matter halos' triaxial nature and observational biases distorting perceived versus actual dark matter column densities [41]. Galaxy formation involves hierarchical assembly, with major mergers and smaller systems' accretion contributing to complex formation history, particularly for elliptical galaxies [42]. The distribution of merging orbital parameters of satellites accreted by central galaxies significantly impacts growth dynamics and scaling relations [43].

Accurate halo dynamics modeling is hampered by limited observational data and selection biases in surveys, complicating efforts to constrain dark matter halo shapes and properties [5]. Simulations often struggle to capture dwarf galaxies' dynamic processes and morphological diversity, especially at high redshifts, necessitating sophisticated models incorporating a broader range of physical processes [44]. The shape of dark matter halos, particularly in galaxies like the Milky Way, has been extensively studied, with new models introducing highly flattened galaxy structures exhibiting asymptotically constant rotation curves [45]. These models provide insights into potential variations in halo shapes and their implications for galaxy dynamics.

Addressing the core-cusp issue and understanding dark matter halo dynamics require comprehensive models integrating diverse physical processes influencing galaxy dynamics. Efforts to unravel the complexities of galaxy formation and evolution are crucial for enhancing our understanding of the universe's structure and behavior over cosmic time. Advanced observational techniques, such as precision astrometry from the Gaia mission, enable researchers to map the Milky Way and other galaxies in three dimensions, revealing intricate relationships between stellar motion, chemical composition, and galactic structures. Theoretical models, like the semi-analytic framework used in the Mentari project, simulate galaxy spectral energy distributions, integrating star formation and

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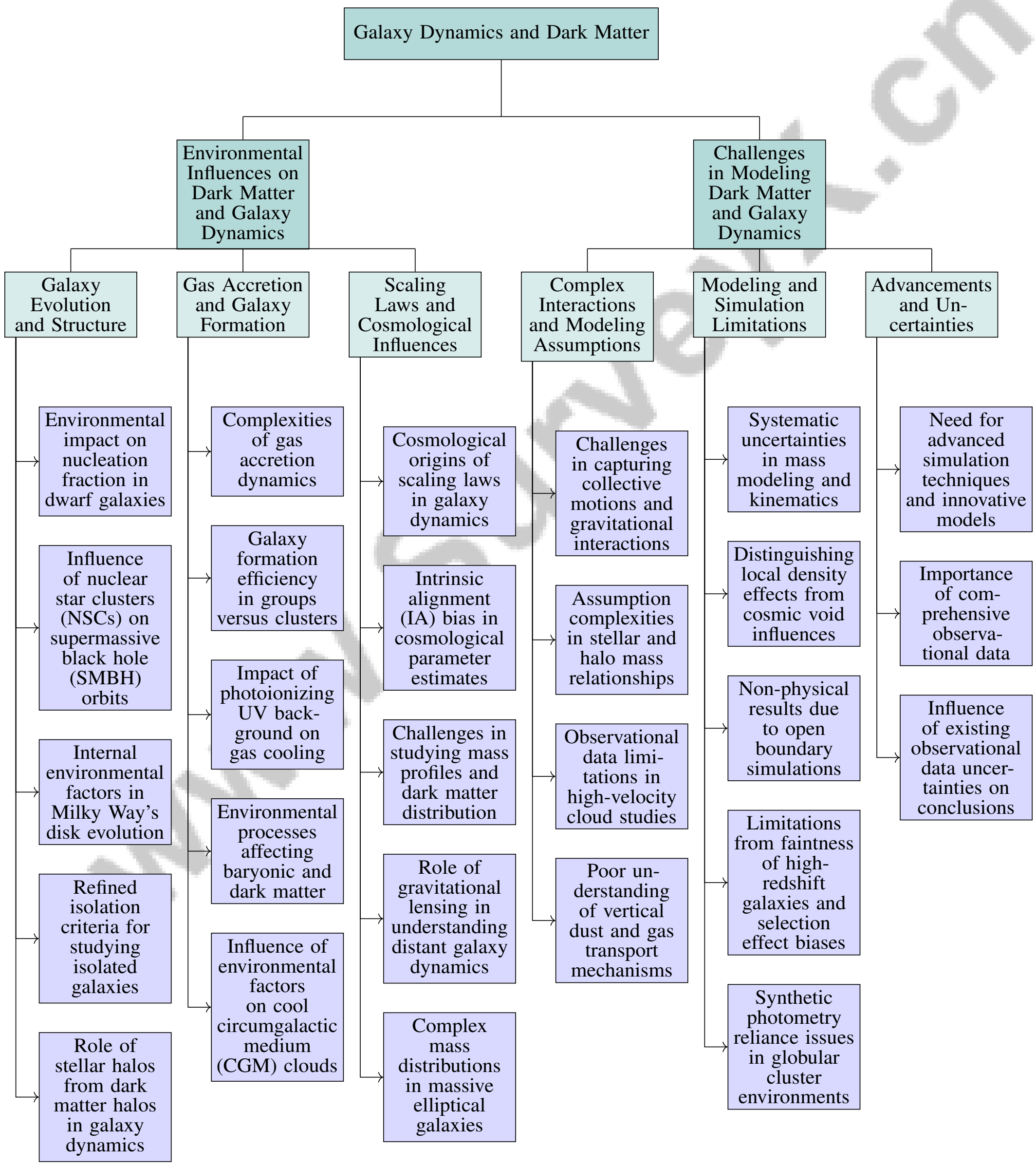
metal enrichment histories to provide insights into the physical processes governing galaxy evolution. Furthermore, studies employing Principal Component Analysis have demonstrated how cosmic web environments significantly influence correlations between various galaxy properties, shedding light on the mechanisms shaping their formation and evolution. Collectively, these approaches contribute to a comprehensive understanding of the universe's dynamic history [46, 47, 13, 14].

In recent studies of galaxy evolution, understanding the dynamics of galaxies and the role of dark matter has become increasingly critical. Figure 2 illustrates the key aspects of galaxy dynamics and dark matter, highlighting environmental influences on galaxy evolution and structure, gas accretion dynamics, and cosmological scaling laws. Furthermore, this figure addresses the challenges in modeling these dynamics, including complex interactions, modeling assumptions, and the limitations of current simulations and observational data. By integrating these insights, we can better comprehend the intricate processes that govern galaxy formation and evolution.



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3 Galaxy Dynamics and Dark Matter

3.1 Environmental Influences on Dark Matter and Galaxy Dynamics

The evolution and structure of galaxies are significantly shaped by their environments, affecting both baryonic and dark matter components. The nucleation fraction in dwarf galaxies, closely linked to cluster density, highlights the environmental impact on nuclear star clusters (NSCs) [48]. NSCs, in turn, stabilize supermassive black hole (SMBH) orbits, influencing core dynamics [49]. Within the Milky Way, internal environmental factors drive disk evolution, as shown by chemical evolution models and cosmologically consistent simulations [50]. Studies of isolated galaxies, refined by new isolation criteria, further elucidate environmental influences on galactic evolution [51]. Stellar halos, originating from massive, dwarf irregular-type dark matter halos, underscore the historical role of environmental factors in galaxy dynamics [52].

Gas accretion dynamics, crucial for galaxy formation, are intricately tied to environmental contexts. The multi-zoom method captures these complexities, emphasizing the need for understanding gas accretion across varied environments [53]. Galaxy formation efficiency is notably higher in groups than in clusters, necessitating dynamic models [54]. The photoionizing UV background critically influences gas cooling efficiency in low-mass halos, impacting galaxy dynamics [40]. The cosmic web environment also significantly affects galaxy properties, highlighting the environmental dependency of galaxy formation [55]. Environmental processes, such as gas stripping, profoundly affect galaxy evolution, impacting both baryonic and dark matter [56]. The fate of cool circumgalactic medium (CGM) clouds, essential for star formation, is influenced by environmental factors like the hot corona [15].

Scaling laws in galaxy dynamics suggest cosmological origins, underscoring the importance of environmental influences [32]. Intrinsic alignment (IA) between galaxy shape and large-scale structure can bias cosmological parameter estimates, highlighting the need to consider environmental effects [1]. Limited known galaxy-galaxy lenses challenge the study of mass profiles and dark matter distribution [20], but gravitational lensing aids in understanding dynamics and properties of distant galaxies, especially at high redshifts [57].

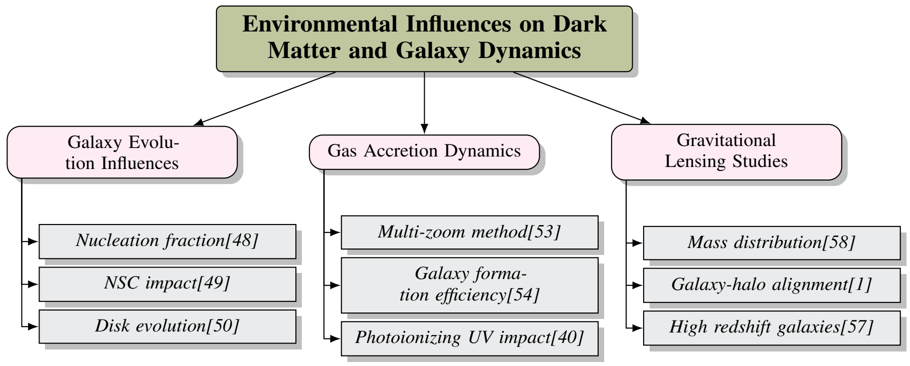
This figure illustrates the hierarchical structure of environmental influences on dark matter and galaxy dynamics, categorizing key studies into galaxy evolution influences, gas accretion dynamics, and gravitational lensing studies. It highlights the nucleation fraction, NSC impact, and disk evolution as primary factors in galaxy evolution, while gas accretion dynamics are explored through methods like multi-zoom and the impact of photoionizing UV backgrounds. Gravitational lensing studies focus on mass distribution, galaxy-halo alignment, and observations of high redshift galaxies, as shown in Figure 3.

Incorporating environmental influences into galaxy dynamics models is essential for understanding dark matter distribution and dynamics within cosmic structures. Strong gravitational lensing analyses reveal complex mass distributions in massive elliptical galaxies, providing precise measurements of stellar and dark matter components, crucial for testing galaxy formation models. The cosmic web's influence on galaxy properties, as shown through Principal Component Analysis, illustrates its effect on relationships among galaxy characteristics. Studies of dark matter halo substructures offer insights into interactions and evolutionary processes governing dark matter behavior relative to visible matter. These findings collectively enhance our understanding of galaxy formation and dark matter's role in the cosmos [58, 47, 59].

3.2 Challenges in Modeling Dark Matter and Galaxy Dynamics

Modeling dark matter and galaxy dynamics is fraught with challenges due to complex baryonic and dark matter interactions. Prior methods often fail to capture collective motions and gravitational interactions in collisionless disk systems, crucial for understanding galaxy dynamics [3]. The assumption of a direct relationship between stellar and halo mass, especially at low masses, complicates modeling, as many halos exhibit diverse stellar masses or lack stars [23], notably in dwarf galaxies [6].

Observational data limitations exacerbate these challenges. Accurately determining distances and masses of high-velocity clouds is hindered by their indistinct nature and previous observational constraints [60]. The mechanisms behind vertical dust and gas transport above the galactic plane,



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particularly subsonic shell dynamics, remain poorly understood [11]. Systematic uncertainties in mass modeling and kinematics affect the inference of gravitational dynamics and mass profiles [36].

Distinguishing local density effects from cosmic void influences on galaxy properties further complicates modeling [8]. Simulations often rely on open boundaries, which may act as infinite gas reservoirs, leading to non-physical results [26]. The faintness of high-redshift galaxies and selection effect biases limit observational data, impacting simulation accuracy [9]. Synthetic photometry reliance may overlook complexities of individual globular cluster environments and metallicity distributions, limiting model accuracy [12].

Addressing these challenges requires advanced simulation techniques, innovative theoretical models, and comprehensive observational data. Overcoming these obstacles can enhance understanding of galaxy dynamics and dark matter's role in shaping cosmic structures, leading to more accurate models of the universe's structure and evolution. However, existing observational data, with inherent uncertainties, continue to influence conclusions about halo shapes [45].

4 Galaxy Simulations

4.1 Galaxy Simulations and Computational Models

Galaxy simulations and computational models are pivotal in elucidating the dynamics, formation, and evolution of galaxies. Utilizing advanced computational frameworks and sophisticated algorithms, these models analyze baryonic and dark matter interactions, providing insights into their evolutionary trajectories across cosmic epochs. Incorporating data on star formation, chemical enrichment, and environmental influences, these models offer a comprehensive view of galaxy properties over time [47, 61, 46, 52, 62]. High-resolution simulations, especially those using the N-body and smoothed particle hydrodynamics (SPH) code ChaNGA, enable detailed modeling of galactic structures via zoom-in techniques.

A significant advancement in simulation methodologies is the Selective Boundary Condition (SBC) approach, which refines hydrodynamic simulations by adjusting boundary conditions based on fluid velocity, thus enhancing accuracy and reducing non-physical results. This is particularly crucial for modeling isolated galaxies, where improper boundary settings can distort gas-loss processes and star formation histories. For instance, simulations with open boundaries smaller than ten times the characteristic radius of a galactic dark-matter halo can act as infinite gas reservoirs, leading to misleading outcomes after about 0.6 billion years. In contrast, selective boundary conditions using velocity thresholds minimize issues like reversed shocks, yielding reliable results at lower computational costs [46, 26].

N-body simulations have greatly advanced our understanding of the orbital parameters of satellite galaxies accreted by central galaxies (CGs), revealing their dynamics under dark matter's influence. These simulations highlight CGs' unique growth histories within galaxy groups and clusters, emphasizing early mass assembly and subsequent mass accretion through galactic cannibalism, affecting CG structure and kinematics. Insights into merging dynamics and stellar mass evolution enhance our comprehension of galaxy formation mechanisms across cosmic time [46, 43, 13, 30]. The direct integration of equations of motion for numerous stars in disk galaxies allows exploration of their collective dynamics, revealing the impact of stellar interactions on galactic structures.

Theoretical models utilizing potential theory have been developed to describe disky dark halos, integrating gravitational dynamics and kinematics to provide insights into dark matter halo properties [45]. Bayesian inference in joint analyses of lensing and dynamical data exemplifies the role of computational models in simulating galaxy formation and dynamics, enhancing predictive power and understanding dark matter distribution.

By synthesizing theoretical insights, observational data, and advanced computational methodologies, galaxy simulations continue to evolve, deepening our understanding of the universe's structure and behavior. These models enhance comprehension of galactic dynamics by integrating star formation, metal enrichment, and gas accretion processes, enabling precise predictions of cosmic phenomena such as galaxy evolution and star formation rates. This contribution enriches astrophysics and cosmology, leveraging data from contemporary surveys like the Gaia mission to provide a detailed 3D representation of the Milky Way and its complexities [46, 13, 14].

4.2 Simulations of Specific Galaxy Types

Simulations tailored to specific galaxy types yield critical insights into their evolutionary pathways and structural characteristics. For massive disk galaxies, tracing merger histories and morphological evolution unveils the significant role of mergers in shaping galaxy dynamics [34]. The Three Hundred project provides a comprehensive analysis of 324 galaxy clusters using Gadget-X and Gizmo-Simba simulations, comparing various physical processes and feedback mechanisms to enhance our understanding of cluster dynamics and the challenges in modeling such complex systems [63].

As illustrated in Figure 4, the hierarchical structure of galaxy simulation insights categorizes findings into massive disk galaxies, galaxy clusters, and dwarf spheroidal galaxies, highlighting key aspects such as merger histories, cluster dynamics, and gas-loss rates. This visual representation complements the textual analysis by providing a clear framework for understanding the relationships among different galaxy types.

In dwarf spheroidal galaxies, the impact of boundary conditions on gas-loss rates has been rigorously assessed through hydrodynamic simulations employing open, closed, and selective boundary conditions. These experiments reveal how simulation parameters critically influence outcomes, offering insights into gas dynamics and evolutionary processes [26].

These tailored simulations emphasize the importance of diverse methodologies and datasets in capturing the unique characteristics of specific galaxy types. By employing sophisticated computational techniques and exploring various evolutionary scenarios, these simulations enhance our understanding of galaxy formation and evolution. They provide insights into processes governing galaxy dynamics across scales, including spectral energy distributions (SEDs), star cluster population dynamics, and the regulation of star formation through environmental factors and feedback mechanisms. Such analyses bridge theoretical models with observational data [64, 46, 65].

4.3 Advanced Simulation Techniques

Recent advancements in galaxy simulations stem from integrating novel computational techniques, significantly enhancing our understanding of galaxy dynamics and evolution. The integration of numerical simulations with semi-analytic models within the CDM framework improves mass and luminosity relation predictions, combining the strengths of both approaches for a comprehensive understanding of galactic properties [66]. The incorporation of machine learning (ML) techniques represents a significant evolution from traditional methods. Hybrid approaches that blend traditional modeling with ML have emerged, improving model performance by leveraging non-linearities in high-

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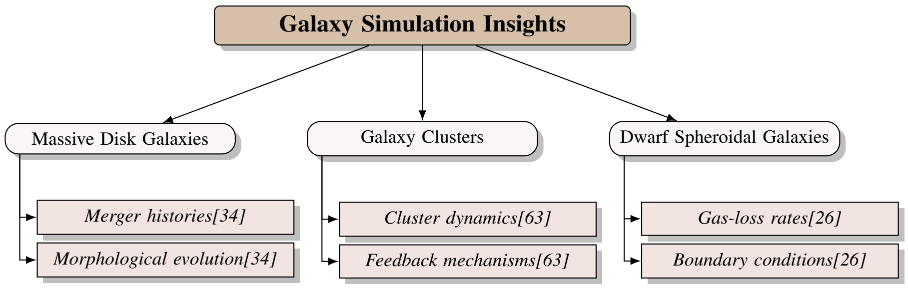


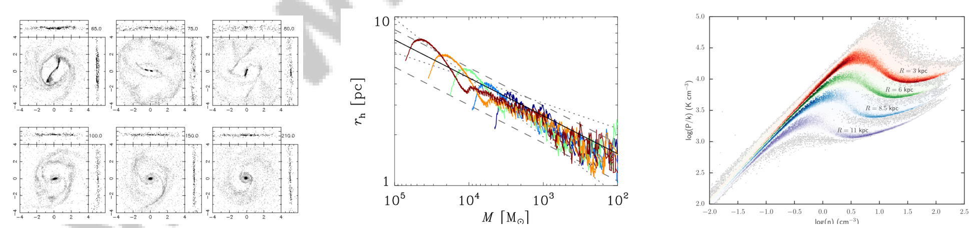
Figure 4: This figure illustrates the hierarchical structure of galaxy simulation insights, categorizing them into massive disk galaxies, galaxy clusters, and dwarf spheroidal galaxies, highlighting key aspects such as merger histories, cluster dynamics, and gas-loss rates.

dimensional data. Probabilistic neural networks trained with summary statistics and spatially-resolved maps of observable quantities enhance the robustness of ML applications in galaxy simulations [61].

Graph Neural Networks (GNNs) have been employed to predict stellar masses by connecting subhalos based on their distances and incorporating features from their relationships, highlighting GNNs' potential in capturing complex cosmic interactions [62]. Advanced techniques now include detailed physical processes, such as thermal conduction and gravitational effects, creating a robust framework for studying galaxy dynamics [15]. These enhancements facilitate accurate modeling of gas dynamics and star formation processes, addressing limitations of previous simulations.

Moreover, dynamic allocation of computational resources based on data characteristics signifies a substantial improvement in simulation efficiency. This approach employs advanced machine learning to predict resource requirements, optimizing processing time and resource allocation, thus enhancing simulation efficiency and enabling precise modeling of galaxy formation and evolution through diverse data sources, including integral-field spectroscopic maps and semi-analytic models [46, 62, 61].

Future research should refine these models to align more closely with observational data, exploring the roles of gas dissipation, mergers, and disc instabilities in galaxy evolution [67]. By integrating cutting-edge computational techniques and observational insights, galaxy simulations will increasingly elucidate the complex processes driving galaxy dynamics and evolution.



(a) Time-lapse of a star's orbit in a binary system[68]

(b) Logarithmic plot of the ratio of half-light radius (r$_h$)$tomass(M)fordifferentstellarpopulations.$[64]

(c) Logarithmic plot of pressure (P/k) against number density (n) for different radii (R) of a galaxy.[65]

Figure 5: Examples of Advanced Simulation Techniques

As shown in Figure 5, the study of galaxy simulations has advanced significantly through sophisticated techniques, illustrated by three distinct examples. The first depicts a time-lapse of a star's orbit in a binary system over six panels, providing insight into dynamic interactions. The second features a logarithmic plot examining the relationship between half-light radius and mass across stellar populations, anchored by a power-law fit that underscores scaling laws. The third explores the interplay between pressure and number density within galaxies, revealing the balance of forces shaping galactic structures. Together, these examples highlight the power of advanced simulation techniques in unraveling galactic complexities [68, 64, 65].

5 Stellar Feedback and Its Impact

5.1 Mechanisms of Stellar Feedback

Stellar feedback encompasses key processes such as stellar winds, radiation, and supernovae, which redistribute energy and matter within galaxies, thus regulating galaxy dynamics and evolution. These processes shape the interplay between baryonic matter and galactic structures, influencing star formation rates, metal enrichment, and overall galaxy evolution. The PESPH method, with its refined timestep criterion, enhances simulation accuracy by mitigating energy conservation violations during feedback processes [38].

Stellar winds and supernovae expel gas from galactic centers, impacting star formation rates and interstellar medium dynamics. The minimalist regulator model highlights supernova feedback's role in maintaining galactic atmosphere equilibrium. Tidal interactions, akin to stellar feedback, significantly influence disc galaxy dynamics, particularly through vertical breathing motions [24]. Incorporating radiation and supernova feedback into galaxy models is essential for depicting star-environment interactions accurately, as demonstrated in cosmological hydrodynamics simulations like the EAGLE project, which explore variations in supernova and AGN feedback effects on galaxy properties [46, 69, 70, 71].

The Dust and Stellar Evolution Effect Analysis (DSEAA) method combines N-body simulations with radiative transfer analysis to compute velocity dispersion measurements, providing nuanced insights into stellar feedback's impact on galactic dynamics. These comprehensive approaches underscore feedback's role in regulating star formation and interstellar medium chemical enrichment, shaping galaxy characteristics across mass scales. Understanding these mechanisms enhances comprehension of galaxy formation and evolution processes, as stellar feedback shapes both immediate stellar environments and broader cosmic structures [17, 70, 69, 72].

5.2 Impact on Galaxy Formation and Evolution

Stellar feedback is crucial in galaxy formation and evolution, significantly influencing star formation rates and interstellar medium dynamics. Supernova feedback, in particular, modulates the circumgalactic medium (CGM), maintaining equilibrium between gas inflows and outflows, thereby controlling star formation rates [69]. In small galaxy groups, feedback processes such as gas stripping and cold gas clump formation highlight feedback's operational dynamics in diverse environments [16].

Robust feedback mechanisms, including supernovae and AGN, suppress early star formation, resulting in flatter star formation histories and higher gas fractions, which enhance disc formation likelihood. Late-time gas accretion, characterized by higher specific angular momentum, promotes disc structures while reducing overall galaxy formation efficiency [52, 13, 70, 72]. While mergers contribute to galaxy evolution, their role in stellar mass growth is limited, with feedback processes dominating star formation and galaxy morphology regulation [30].

Incorporating cosmic rays into simulations significantly alters properties such as star formation rates and stellar mass functions, highlighting their role in feedback processes [73]. Studying stellar velocity distribution functions provides insights into the contributions of different stellar populations to galaxy formation and evolution [25]. Understanding these mechanisms is essential for unraveling galactic dynamics complexities and broader cosmic structures, as feedback influences processes from star formation regulation to structural and chemical evolution.

This is further illustrated in Figure 6, which depicts the key elements influencing galaxy formation and evolution. The figure highlights the roles of stellar feedback, galaxy dynamics, and galaxy characteristics, categorizing significant processes and relationships derived from various studies. It emphasizes feedback mechanisms, dynamics such as gas stripping and mergers, and characteristics including the stellar mass-halo mass (SMHM) relationship and globular clusters. Unique evolutionary paths, such as those of galaxy ID44, illustrate feedback's diverse impacts on galaxy formation and evolution [27]. Additionally, the Selective Boundary Condition (SBC) provides a more accurate representation of gas-loss processes in isolated galaxy simulations over extended timescales [26].

Understanding the stellar mass-halo mass (SMHM) relationship at low mass scales is critical, as benchmarks emphasize the need for individual assessments of faint dwarf galaxies rather than relying on extrapolated models from higher masses [23]. Accurately determining metallicities for globular clusters (GCs) can lead to better constraints on galaxy formation models and a deeper understanding of early-type galaxy evolution [12].

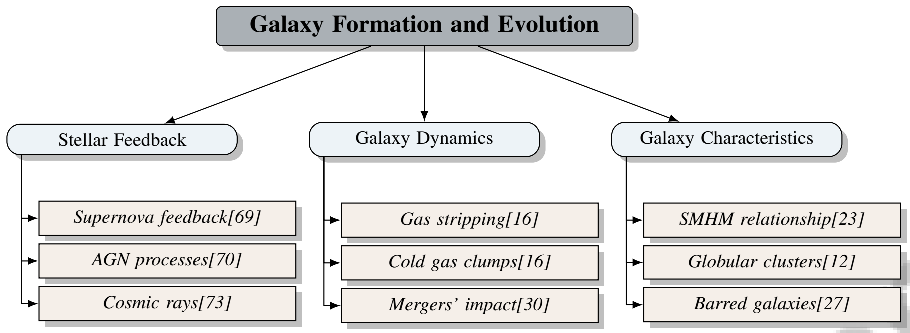


Figure 6: This figure illustrates the key elements influencing galaxy formation and evolution, highlighting the roles of stellar feedback, galaxy dynamics, and galaxy characteristics. The categories reflect significant processes and relationships derived from the studies, emphasizing feedback mechanisms, dynamics such as gas stripping and mergers, and characteristics including the SMHM relationship and globular clusters.

5.3 Feedback in Different Galactic Environments

Stellar feedback processes vary significantly across galactic environments, influencing galaxy dynamics and evolution in distinct ways. The complexity of baryon physics, coupled with the interconnected evolution of dark matter and baryons, complicates accurate modeling and measurement of feedback effects [70]. Feedback processes, including stellar winds, supernovae, and radiation, regulate star formation rates and shape the circumgalactic medium (CGM).

In diverse galactic environments, the equilibrium states of galactic atmospheres are influenced by varying feedback mechanisms. Algebraic solutions for these equilibrium states demonstrate how different feedback processes impact star formation rates and CGM properties [69]. In high-density environments like galaxy clusters, feedback from AGN and supernovae significantly alters gas dynamics, leading to variations in star formation efficiency and morphological transformations.

The adaptability of feedback processes to changing galactic conditions is crucial for maintaining equilibrium. This adaptability is enhanced by improved resource utilization and responsiveness to shifting workloads, as demonstrated in computational models integrating advanced techniques for simulating feedback effects [74]. Such models provide insights into feedback's diverse impacts across environments, from isolated galaxies to dense cluster regions.

The diverse nature of stellar feedback across galactic environments underscores the need for sophisticated models that incorporate intricate interactions between baryonic matter and dark matter components. Different dark matter frameworks, such as Self-Interacting Dark Matter (SIDM) and feedback-influenced Cold Dark Matter (CDM), yield distinct galaxy formation outcomes and rotational dynamics. This variability necessitates a comprehensive understanding of how feedback mechanisms influence star formation and structural evolution, particularly concerning dark matter halos and the resultant abundance patterns observed in stellar populations [75, 52, 69]. Understanding these interactions is essential for unraveling the intricate processes governing galaxy formation and evolution, offering deeper insights into the universe's structure and behavior over cosmic time.

5.4 Feedback and Dark Matter Interactions

The interactions between stellar feedback and dark matter are pivotal in shaping galaxies' structural and dynamical evolution. Stellar feedback mechanisms, including supernova explosions, stellar winds, and radiation, redistribute baryonic matter within galaxies, altering gravitational potential and influencing dark matter halo dynamics. This interplay is critical for galaxy evolution, as demonstrated by the minimalist regulator model, which emphasizes the importance of outflow energy in regulating star formation [69]. The redistribution of baryonic matter due to stellar feedback can significantly affect dark matter halo inner density profiles, indicating a complex interaction between baryonic processes and dark matter [37].

Stellar feedback notably promotes disc formation in galaxies, regulating star formation efficiency and angular momentum distribution [72]. This regulatory effect is crucial for maintaining equilibrium between gas inflows and outflows, controlling star formation rates and overall interstellar medium dynamics. Observations indicate that the baryonic density in the universe is predominantly dark, significantly impacting galaxy formation and evolution [16].

Interactions between dark matter and stellar feedback are further highlighted by tidal streams, providing nuanced insights into substructure effects on debris distribution and coherence [76]. The gravitational dynamics of high-velocity clouds, possibly dominated by dark matter, underscore the complex relationship between baryonic feedback and dark matter [60].

Moreover, gravitational lensing interactions with galactic dynamics offer insights into dark matter's role in shaping cosmic structures [36]. These interactions can inform our understanding of dark matter, particularly regarding decaying neutrinos as a candidate [45]. Utilizing small-scale measurements to improve constraints on cosmological parameters and model galaxy assembly bias further underscores the significance of feedback and dark matter interactions in galaxy evolution [77].

Future research should prioritize enhancing feedback process models and implementing higher resolution simulations to comprehensively understand accretion dynamics, particularly regarding the complex interactions between supernova and AGN feedback mechanisms, critical for regulating star formation and shaping galaxy properties. By refining these models and simulations, researchers can better quantify feedback processes' impacts on galaxy evolution, including effects on star formation efficiency, gas accretion, and metal enrichment, ultimately leading to deeper insights into the dynamics governing galaxy formation and growth [70, 72, 46, 17, 71]. Delving deeper into these interactions will provide a clearer picture of the processes governing galaxy formation and evolution, enriching our understanding of the universe's structure and dynamics.

6 Gravitational Lensing

6.1 Gravitational Microlensing and Dark Matter Detection

Gravitational microlensing is a pivotal method for exploring dark matter and detecting extrasolar planets, utilizing the gravitational deflection of light by massive objects to temporarily enhance brightness. This technique is particularly effective in identifying compact dark matter objects and analyzing mass distributions within galaxies [78]. Microlensing's ability to detect lensing anomalies linked to substructures within dark matter halos refines dark matter distribution models and enhances understanding of cosmic dynamics [79]. It also reveals complex magnification patterns from misaligned disks in dark matter halos, highlighting intricate interactions between baryonic and dark matter components [80].

The versatility of microlensing extends to exoplanet detection, underscoring its role in addressing fundamental astrophysical questions [78]. Recent studies employing advanced metrics, such as the Janis-Newman-Winicour metric, have refined microlensing models, enhancing constraints on dark matter halo properties [81]. Microlensing also aids in exploring dark matter in galaxies like Andromeda through pixel lensing, analyzing unresolved stars, and assessing Macho candidates' mass distribution. This technique enriches understanding of dark matter's role in galaxy formation and structure while contributing to stellar dynamics exploration through high-precision observations. Future space-based telescopes are expected to further illuminate stellar mass functions and dark matter distribution [78, 20, 82].

6.2 Weak Lensing and Galaxy Dynamics

Weak gravitational lensing is crucial for investigating galaxy dynamics and dark matter distribution within cosmic structures. It results in subtle shape distortions of background galaxies, offering statistical measures of mass distribution in intervening structures and facilitating galaxy formation and evolution analysis. This technique provides insights into dark and baryonic matter interactions, contributing to understanding cosmic structure formation within cosmological models like Lambda Cold Dark Matter (CDM) [80, 83, 58, 84, 85].

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Weak lensing reveals that misaligned disks in galaxies can mimic substructure presence in dark matter halos, leading to complex image configurations [80]. This emphasizes the intricate interplay between baryonic and dark matter components. A primary challenge in weak lensing research is the degeneracy of lens parameters, necessitating sophisticated models to accurately infer lensing system dynamics [78]. Isolated clumps or substructures significantly influence lensing signals, underscoring the need for comprehensive models capturing mass distribution complexity [79].

Advanced models employing metrics like the Janis-Newman-Winicour metric enhance the precision of weak lensing measurements [81]. Weak lensing remains a powerful method for studying galaxy dynamics and dark matter distribution, complementing strong lensing and satellite dynamics. It offers critical insights into mass distribution, dark matter halo characteristics, and galaxy formation processes, significantly advancing understanding of galaxy formation and the large-scale structure of the cosmos [83, 14, 58, 20, 86].

6.3 Gravitational Lensing in Galaxy Clusters

Gravitational lensing in galaxy clusters is essential for investigating mass distribution and dynamics within these massive cosmic structures. By analyzing lensing effects, researchers derive insights into stellar mass profiles and dark matter halo masses of individual galaxies, enhancing understanding of galaxy formation and evolution. Lensing affects observed flux of background sources, such as dusty star-forming galaxies and the Cosmic Microwave Background, providing information on mass distribution and implications for large-scale structure formation [58, 83]. Lensing in clusters results in distorted and magnified images, instrumental in studying dark matter content.

Sophisticated ray-tracing methods applied to models with misaligned disks and halos generate datasets of lensing configurations and magnification maps, essential for understanding complex interactions between baryonic and dark matter components [80]. Anomalous flux ratios in specific strong lens systems, such as B1422+231 and PG 1115+080, indicate substructures within dark matter halos, providing insights into the hierarchical nature of dark matter distribution [79]. Time delays between multiple images produced by strong lensing offer constraints on mass distribution within clusters, with negative time delays suggesting strongly naked singularities [81].

Gravitational lensing in galaxy clusters enhances understanding of dark matter distribution and serves as a critical tool for investigating fundamental gravity properties and cosmic structure. Analyzing mass distribution of massive elliptical galaxies through lensing yields insights into stellar mass profiles and inner dark matter halo mass, vital for testing galaxy formation models. Studies reveal a persistent excess of galaxy-galaxy strong lensing in clusters, surpassing CDM model predictions, indicating potential gaps in understanding galaxy formation and cosmological frameworks. This multifaceted approach to gravitational lensing deepens comprehension of dark matter and informs the evolution of cosmic structures across various Hubble types [58, 83, 63].

6.4 Galaxy-Galaxy Lensing and Mass Profiles

Galaxy-galaxy lensing is a powerful technique for probing mass distribution around galaxies, providing insights into their mass profiles and underlying dark matter halos. This method involves measuring the mean excess surface density profile, (r), around foreground lensing galaxies, correlating to mass profile understanding [87]. By analyzing weak lensing signals induced by foreground galaxies on background sources, researchers infer radial mass distribution and gain insights into dark matter halo properties.

Misaligned disks within dark matter halos significantly influence lensing properties, leading to unusual magnification ratios and complex image geometries [80]. Such configurations underscore intricate interactions between baryonic structures and dark matter. While substructure halos dominate lensing optical depth contributions, the cumulative effect of isolated halos should not be neglected, as it can substantially influence lensing data interpretation within the Cold Dark Matter (CDM) model [79].

Advanced lens equations, such as the Virbhadra-Ellis lens equation, allow for computation of time delays and image positions due to strongly naked singularity lensing, yielding new insights into mass distribution and potential anomalies within galaxy halos [81]. These methodologies enhance galaxy-galaxy lensing analyses' precision and deepen understanding of complex galaxy mass profiles.

Galaxy-galaxy lensing is crucial for examining galaxy mass profiles, offering significant insights into dark matter distribution and cosmic structure characteristics. By leveraging strong gravitational lensing, researchers decompose galaxy mass distribution, revealing distinct baryonic components and their contributions to overall mass profiles. This approach enables precise measurements of stellar mass distributions and inner dark matter halo masses, crucial for testing galaxy formation and evolution models. Recent surveys identifying new galaxy-galaxy lenses enhance the ability to measure dark matter properties and contribute to understanding cosmological parameters such as matter density and structure growth in the universe [58, 87, 20]. By leveraging subtle gravitational effects of foreground galaxies on background sources, this technique significantly contributes to understanding galaxy formation and evolution.

7 Conclusion

The exploration of galaxy dynamics and dark matter phenomena reveals the intricate relationship between baryonic processes and dark matter, which is crucial for deciphering the universe's structure and evolution. Dark matter significantly influences galaxy formation by aiding in the accretion of baryonic matter, star formation, and the development of galactic structures. A linear correlation between the number of globular clusters and virial mass provides a method for estimating halo masses, especially in massive galaxies, though challenges persist in accurately assessing halo masses in dwarf galaxies.

Gravitational lensing, particularly strong lensing, plays a vital role in verifying galaxy structures and measuring dark matter halo masses. However, the presence of substructures can lead to inaccuracies in mass estimates, highlighting the need for advanced modeling techniques to enhance our understanding of star cluster populations as indicators of galaxy evolution. Future research should focus on refining models with more comprehensive data from forthcoming surveys.

The cosmic web's impact on galaxy evolution and interactions underscores the importance of aligning simulation predictions with observational data. Although simulations can replicate the Tully-Fisher relation's slope and scatter, discrepancies in the zero-point suggest that current Cold Dark Matter models may require adjustments to better match observations of disk galaxies.

Enhanced observational capabilities are essential, particularly through the ongoing analysis of Gaia data and the integration of novel technologies to bridge existing knowledge gaps. Future studies should examine the influence of dark matter on stellar populations, improve measurement techniques for stellar properties, and consider these findings' implications on galaxy formation theories. Additionally, spectroscopic confirmation of the blue tilt and the study of globular cluster systems in other spiral galaxies could further substantiate these results.

The small-scale crisis in fossil groups raises broader questions about galaxy formation and the Cold Dark Matter model's validity. Experimental findings suggest that the proposed method accurately predicts dense molecular gas behavior in response to stellar feedback, providing insights into star formation efficiencies. Moreover, a substantial portion of massive disc galaxies maintains their morphology due to relatively quiet merger histories or specific merger conditions that favor disc preservation.

Future investigations should refine delay-time distribution models based on observational data and explore alternative sources of r-process elements to support these conclusions. Notably, extremely flattened halo models fail to replicate the Milky Way's observed kinematics, implying that the dark halo must be rounder than previously thought. Key insights include identifying a main sequence of star formation and the role of internal processes in regulating star formation rates, which are vital for comprehending galaxy evolution. Additionally, new color-metallicity relations for globular clusters around M87 reveal significant deviations from earlier studies, particularly for blue globular clusters, indicating they are more metal-rich.

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