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The Role of Halo Assembly History in Galaxy Evolution

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Abstract:

In the Lambda Cold Dark Matter (ΛCDM) paradigm, dark matter halos serve as the fundamental framework for galaxy formation. Recent studies show that, beyond halo mass, halo assembly history (how and when a halo grows) is a key factor in shaping galaxy properties. This review synthesizes theoretical insights and observational evidence on how assembly time and growth mode influence gas cooling, star formation, feedback, and morphology. Early-forming halos often foster rapid starbursts and spheroidal structures, while late-forming halos sustain prolonged star formation and disk-like morphologies. The role of large-scale environment and cosmic web connectivity further modulates these outcomes, contributing to observable trends such as color bimodality and galaxy clustering. Through comparisons of simulations, semi-analytic models, and observational probes, this paper demonstrates that halo assembly history is a critical secondary parameter in galaxy evolution, beyond mass alone. The implications for feedback processes, halo occupation models, and upcoming surveys are also discussed, emphasizing the need to incorporate assembly bias into future theoretical and empirical frameworks.

Keywords: Galaxy Evolution; ΛCDM Cosmology; Halo Assembly History.

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1. Introduction

In the standard Lambda Cold Dark Matter (ΛCDM) cosmology, galaxies form inside dark matter halos, establishing a close link between galaxies and the large-scale cosmic web. A halo's properties—especially its mass—control gas accretion and star formation, making halo mass the primary determinant of galaxy growth and quenching [1]. Nonetheless, galaxy–halo scaling relations exhibit substantial scatter at fixed halo mass, implying that secondary halo properties also influence galaxy evolution. In particular, questions remain about how a halo's assembly history (the timeline of its mass growth) affects the present-day properties of its galaxies, and how environmental context and large-scale structure feed into this process. Understanding these effects is essential for a complete theory of galaxy formation.

Recent theoretical work has shown that halo assembly history can act as a "second parameter" (beyond mass) governing galaxy evolution. At fixed halo mass, early-forming halos tend to host more massive, redder, and more rapidly quenched galaxies than late-forming halos of the same mass. For example, Xu and Zheng analyzed the Illustris simulation and found that central galaxy star-formation properties correlate most strongly with the host halo's formation time: once the halo's peak circular velocity is fixed, galaxy mass depends mainly on the halo's formation epoch [2]. Similarly, Montero-Dorta et al. used the IllustrisTNG300 simulation to show that halos with rapid early mass accretion build galaxies with higher stellar-to-halo mass ratios and earlier star-formation peaks, while slowly-accreting halos produce lower-mass, later-quenching galaxies at the same final mass [3]. These and related studies demonstrate a clear galaxy assembly bias: galaxy properties and clustering statistics carry imprints of halo growth history at fixed mass. Advanced analyses—for instance using mutual-information metrics—further indicate that the galaxy formation efficiency (stellar-to-halo mass ratio) is a particularly sensitive tracer of halo assembly epoch, especially for low-mass central galaxies [4]. Altogether, recent simulations and models suggest that halo formation time, accretion rate, and related assembly variables significantly influence galaxy evolution beyond the dominant mass dependence.

This review examines the role of halo assembly history in galaxy evolution. It adopts the usual definition of halo assembly time as the lookback time when a halo has assembled half of its present-day mass [1], and explores how variations in this assembly time and other growth history parameters affect observable galaxy properties. The paper summarizes theoretical insights from cosmological simulations and semi-analytic models, as well as efforts to infer halo growth from observations using group catalogs, abundance matching, and machine-learning proxies. After reviewing the theoretical background (Section 2) and the evidence for assembly-related effects in models and data (Section 3), the discussion turns to how assembly history can be incorporated into galaxy–halo models and its implications for interpretation of surveys (Section 4). Throughout, the focus remains on how halo growth history emerges as a crucial parameter for galaxy properties, and highlights open questions and future directions in understanding the halo–galaxy co-evolution.

2. Theoretical Framework

In the ΛCDM cosmological model, structure formation is hierarchical: small initial density peaks collapse first to form dark matter halos that later merge into larger systems [5]. Dark matter dominates the mass budget and provides the gravitational backbone of structure, so baryons fall into these halos, cool, and form the first galaxies. Analytic formalisms (e.g. extended Press–Schechter theory) predict the abundance and growth of halos by mapping linear perturbations to halo collapse statistics [6]. N-body simulations confirm this picture: halos grow through both discrete mergers and smooth dark-matter accretion [7]. Together, these processes assemble the cosmic web of filaments, sheets and voids, setting the large-scale scaffolding on which galaxies form.

Halos that assemble early (high formation redshift) collapse from higher initial overdensities and thus develop higher central densities and concentrations than late-forming halos of the same mass [4]. These differences affect galaxy properties: the oldest halos (earliest assembly) tend to host the reddest, most quenched galaxies, whereas younger halos host bluer, star-forming disks [4]. Halo growth proceeds by a combination of major mergers and smooth accretion [7]. A major merger – in which a halo gains a large fraction of its mass in a single event – can violently reshape the halo and trigger central starbursts or morphological transformation (e.g. building a bulge). In contrast, smooth accretion and minor mergers add material gently, sustaining continuous disk growth without catastrophic disruption.

3. Halo Assembly History and Galaxy Formation

3.1 Gas Accretion and Cooling

Halo assembly history critically affects how gas is accreted and cooled. Early-forming halos collapse at high redshift when the universe is denser, yielding deeper gravitational potentials and higher central densities [8]. In this regime, the radiative cooling time is short because $t_{cool} \propto n^{-1}$ (for fixed temperature) — the cooling rate per unit volume scales as $n^2\Lambda(T,Z)$ [9]. A widely used approximation for the cooling time is:

$$t_{cool} \approx \frac{3k_B T}{n_e \Lambda\left(T,Z\right)} \tag{1}$$

where k_B is the Boltzmann constant, T is gas temperature, n_e is electron number density, and Λ is the cooling function dependent on temperature and metallicity. Thus, higher gas densities in early-forming halos lead to more efficient radiative cooling. Halos below the critical mass threshold $(10^{12} M_\odot)$ often accrete gas via "cold mode" flows, in which gas streams directly into the halo without being shock-heated [8]. This process promotes rapid star formation during early cosmic epochs.

In contrast, late-forming halos typically assemble at lower redshift and reach higher masses. When a halo's mass exceeds the critical threshold, incoming gas is shock-heated near the virial radius to temperatures of 10^{6}¨$C10^{7}K$, forming a stable hot atmosphere. This significantly lengthens the cooling time, suppressing the supply of cold gas [8]. Furthermore, energy injection from AGN and supernova feedback can maintain this high-entropy environment and further inhibit gas condensation [9]. These differences between early and late halo assembly paths help explain the observed diversity in star formation efficiency across galaxies of similar mass but different growth histories.

3.2 Star Formation Histories

Halo assembly history strongly influences the timing and intensity of a galaxy's star formation. In co-evolution models, a central galaxy's star formation rate (SFR) closely tracks the halo's mass accretion rate (MAR): fresh infalling gas fuels star formation as the halo grows [10]. For example, Rodríguez-Puebla et al. demonstrate that for main-sequence galaxies, the in-situ SFR is largely determined by the instantaneous halo MAR [10]. Nonetheless, detailed simulations yield mixed results: Xu & Zheng find in IllustrisTNG that once halo mass is fixed, a galaxy's instantaneous SFR has little correlation with secondary assembly parameters [2]. By contrast, Montero-Dorta et al. report that the shape of the halo's early growth (its specific mass accretion history) strongly imprints on the galaxy's star formation history [3]. Halos that build up mass very rapidly at early times host galaxies with brief, intense starbursts that peak at high redshift and then shut off quickly [9].

In practice, early-forming halos tend to experience rapid gas accretion and a short, powerful star-forming episode, followed by swift quenching. Their galaxies accumulate a large stellar mass early and then exhaust or expel their gas (often via feedback), leading to an early "red and dead" state [9]. In contrast, late-forming halos accrete more slowly, sustaining star formation over longer times. These halos have lower peak SFRs and their central galaxies quench much later, sometimes continuing to form stars to the present epoch. This qualitative trend – early halos → early-quenched galaxies, late halos → extended star-formers – is seen in both semi-analytic and hydrodynamic studies [11,12].

Galaxy quenching can be further categorized as "mass quenching" versus "environmental quenching." Mass quenching refers to internal processes tied to a galaxy's own mass (or host halo mass), such as virial shock heating or AGN feedback. Environmental quenching arises from external influences (e.g., ram-pressure stripping, strangulation) when a galaxy enters a dense group or cluster. Observations indicate these act independently: Peng et al. (2015) showed that the fraction of quenched central galaxies depends only on stellar mass and is independent of environment, whereas satellite quenching depends strongly on local overdensity [11]. In the context of halo assembly, this suggests that at fixed halo mass, an early-assembling halo will quench its central galaxy via internal feedback, while a galaxy in a late-assembling halo that becomes a satellite may additionally lose gas through environmental processes.

3.3 Feedback Processes and Halo Assembly

Feedback from stars and supermassive black holes critically regulates gas accretion and star formation, and its impact depends on halo mass and assembly history. In low-mass or shallow potentials, supernova (SN) feedback can easily drive galactic winds that eject gas and temporarily suppress star formation. In deeper potential wells (often corresponding to early-forming halos), SN-driven outflows are more easily confined, allowing higher SFRs in the early phase [12]. However, in high-mass halos (especially those that formed early and concentrated mass quickly), black hole growth is rapid and AGN feedback becomes dominant. IllustrisTNG simulations show that at high halo mass, concentration (a proxy for early assembly) is anti-correlated with SFR: more concentrated halos host more massive black holes that strongly heat or expel gas, causing a dramatic suppression of star formation [12]. Thus, halo age modulates the relative importance of SN and AGN feedback. An old (early-forming) halo quickly builds a massive central galaxy and black hole; it then experiences powerful AGN feedback that can heat the circumgalactic gas and prevent future cooling. Simultaneously, the intense early starburst means strong SN winds initially, but the deep potential allows much of the gas to remain bound—until AGN-driven heating dominates. By contrast, a late-forming halo grows more gradually: its central BH is smaller for longer, so AGN feedback is weaker or delayed, and star formation can continue for a longer period with weaker regulation.

Assembly-linked feedback also affects how efficiently halos accrete gas. For example, SN feedback can eject gas to large radii, where it may eventually cool and re-accrete ("wind recycling"). Early halos that blew out gas may reincorporate it slowly, especially if AGN heating prevents cooling. Meanwhile, environmental feedback—particularly in satellites—can rapidly strip gas: processes like strangulation or ram-pressure stripping in a rich environment abruptly remove the star-forming fuel when a galaxy falls into a cluster [11]. In aggregate, halos that form earlier tend to see their galaxies lose gas faster and quench sooner due to the interplay of early feedback and rapid growth [9,12], while late-forming halos accrete more steadily and sustain star formation to later times.

4. Impact of Halo Assembly on Galaxy Properties

4.1 Stellar Mass and Star Formation Activity

The stellar-to-halo mass ratio (SHMR) serves as a key indicator of the efficiency with which halos convert baryons into stars. Early-forming halos typically exhibit higher SHMRs, suggesting that their rapid initial growth phases favor intense star formation when gas accretion is most efficient [10]. These systems often experience early starburst activity, depleting their cold gas reservoirs and limiting subsequent stellar mass growth. In contrast, late-forming halos tend to accumulate mass more gradually, leading to extended periods of lower star formation rates and overall reduced stellar mass fractions [13]. This divergence in assembly histories also contributes to morphological differences. Galaxies hosted by early-assembling halos are more likely to develop spheroidal structures, resulting from the compaction induced by major mergers or rapid gas inflow. Meanwhile, galaxies in late-forming halos, having undergone smoother accretion histories, are more prone to maintain disk-dominated morphologies, often supported by ongoing star formation and stable angular momentum retention [4].

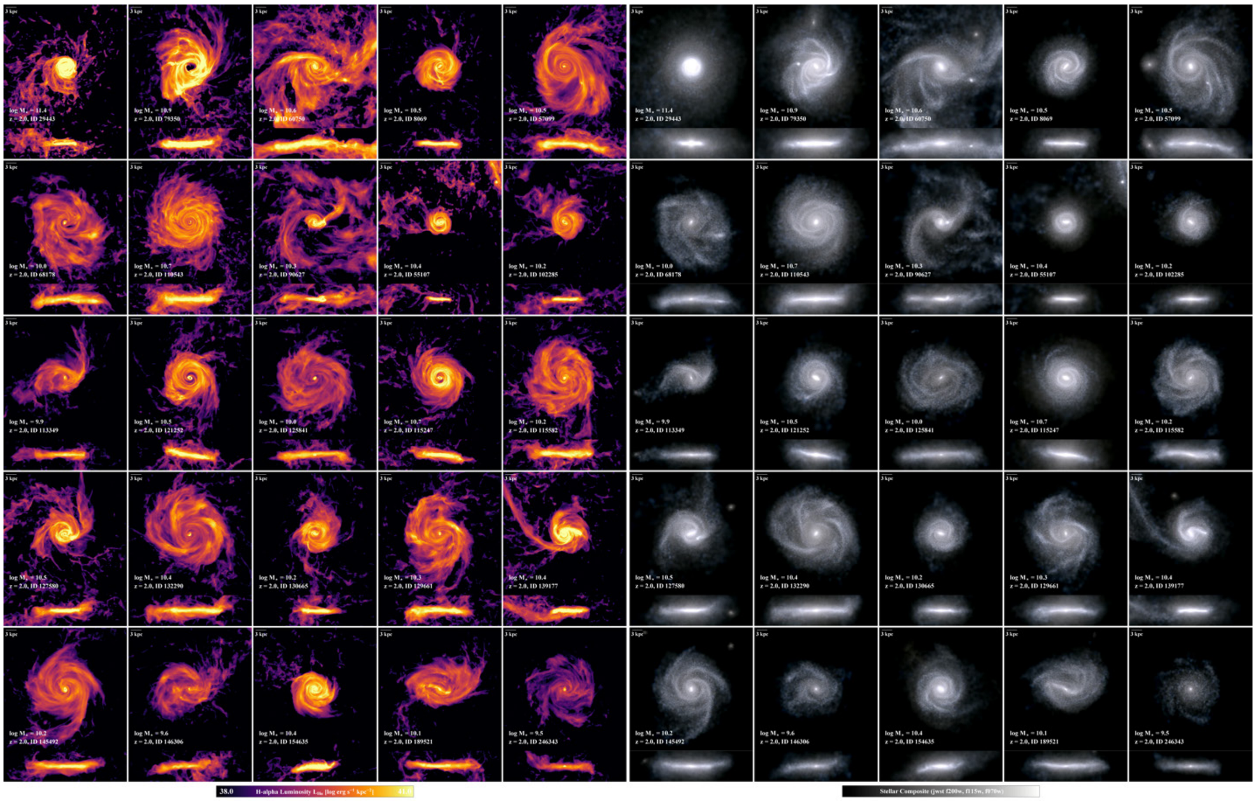

Fig. 1 A sample of 25 disk galaxies from the TNG50 simulation at redshift z = 2. Left panels show Hα emission tracing star formation; right panels display optical light from stellar populations. Each galaxy is also shown edge-on [14].

Figure 1 visually illustrates this diversity by presenting a sample of disk galaxies from the TNG50 simulation at redshift $z = 2$ [14]. The Hα emission traces active star-forming regions, while the optical light distribution highlights the presence of both young and old stellar populations. This snapshot captures how variations in halo growth and assembly modes are reflected in galaxy structure and star formation characteristics.

4.2 Morphology: Mergers vs. Smooth Accretion

Halo assembly mode—whether via violent mergers or smooth accretion—has a dramatic effect on galaxy morphology. Disk-dominated galaxies are found predominantly in halos with calm assembly histories, typically of relatively low mass. Such galaxies form most of their stars in situ and avoid large major mergers, retaining thin, rotationally supported disks [13,15]. In contrast, spheroidals and ellipticals tend to form in more massive halos that experienced multiple major mergers. Mergers drive gas inflows and starbursts, fueling bulge growth and often triggering active galactic nuclei (AGN) feedback, which can quench star formation and puff up the stellar distribution [13]. For example, Rodriguez et al. find that at fixed stellar mass, disk galaxies form in halos 2–10 times less massive than those of ellipticals, and “mergers are less prevalent in the build-up of discs than in spheroidal galaxies” [13]. Similarly, Liang et al. report that larger disks form in halos with active ongoing accretion, while frequent major mergers tend to disrupt disks and produce rounder systems [15]. Thus, a merger-rich assembly history tends to yield red, bulge-dominated galaxies, whereas smooth gas accretion promotes blue, star-forming disks.

4.3 Color Bimodality and Quenching Trends

These assembly-driven processes naturally produce the red–blue (quiescent–star-forming) bimodality of galaxies. Early-forming halos or galaxies that underwent major mergers exhaust or heat their gas in bursts, quenching star formation and moving onto the red sequence. Late-forming halos with mostly smooth accretion retain cold gas, sustaining ongoing star formation and remaining on the blue cloud. Observationally, massive halos with earlier assembly host a higher fraction of quenched galaxies [4]. In massive central galaxies, studies find that the influence of halo assembly on star formation is reduced by internal feedback: AGN and merger-driven winds regulate stellar growth, weakening the direct correlation between assembly time and star formation in these systems [16]. Nonetheless, in low- to intermediate-mass halos the link is stronger: galaxies in early-forming halos tend to form their stars earlier (higher past SFR) and thus exhibit higher stellar-to-halo mass efficiency, reflecting a quasi-linear relation between halo formation time and the integrated star formation history.

5. Environment and Observational Evidence of Assembly Effects

The large-scale environment influences halo formation beyond halo mass alone. In simulations, halos in dense regions—such as filaments and nodes—form earlier than those in underdense voids. Wang et al. show that, at fixed mass, halos more strongly connected to the cosmic web host more galaxies, a signature of galaxy assembly bias [17]. These environmental dependencies, including tidal anisotropy and overdensity, modulate halo growth histories and affect galaxy occupation, especially in highly structured regions.

This bias has been detected in galaxy clustering observations. Using SDSS data, Wang et al. found that central galaxies with similar luminosity and mass cluster more strongly when residing in earlier-forming halos [17]. Specifically, for galaxies with $M_r < -20$, the correlation function revealed stronger clustering in halos with higher concentrations, indicating older assembly times. Satellite assembly bias, by contrast, was weak. These results suggest that halo age influences galaxy clustering and must be included in halo occupation models to accurately match observations.

Further support comes from weak lensing studies. Recent analysis by Paviot et al. using the DESI One-Percent Survey showed that extended models incorporating environment better reproduce lensing and clustering signals [18]. Luminous red galaxies, for example, tend to occupy more anisotropic, dense regions than expected from mass alone. Upcoming surveys like DESI, Euclid, and LSST will allow more precise tests of these trends across redshifts. Discrepancies between galaxy clustering and galaxy–galaxy lensing, if observed at fixed stellar mass, may reveal the imprint of assembly history. Together, theory and observation increasingly support the view that environment regulates halo growth and leaves measurable signatures in galaxy properties [17,18].

6. Conclusion

This review has explored the pivotal role of halo assembly history in shaping galaxy evolution. From a theoretical standpoint, dark matter halos form through hierarchical merging and smooth accretion, with their formation times and growth patterns influencing the thermodynamic conditions under which galaxies form. Early-forming halos, characterized by higher central densities and deeper potentials, tend to promote rapid gas cooling and early star formation. In contrast, late-forming halos often host extended accretion histories and delayed star formation due to heating processes and feedback regulation. The imprint of halo assembly extends to observable galaxy properties. Differences in stellar mass, morphology, star formation activity, and color are all closely linked to when and how a halo assembles. Mergers contribute to the buildup of spheroidal systems and starburst episodes, while smooth accretion fosters disk growth and sustained star formation. Additionally, large-scale environment modulates halo growth pathways, introducing secondary trends—beyond mass—that manifest in galaxy clustering and lensing. Altogether, halo assembly history provides a unifying framework for understanding galaxy diversity. Future developments in high-resolution simulations and deep surveys will further illuminate how the timing and mode of halo formation leave lasting signatures on the galaxies they host.

In the future, there are a couple of things deserved to be studied. The connection between halo assembly history and galaxy evolution remains a frontier in cosmology. As simulations grow more sophisticated, future models will better resolve the fine structure of halos and the multi-phase interstellar and circumgalactic media. This will allow more accurate predictions of how halo growth modes—such as mergers or smooth accretion—impact gas cooling, star formation, and feedback across different environments and mass scales. On the observational side, ongoing and upcoming surveys like DESI, Euclid, and LSST will provide unprecedented data on galaxy properties and spatial distributions across cosmic time. These will enable more precise measurements of assembly bias and its dependence on halo age, environment, and galaxy type. Joint analyses of galaxy clustering, weak lensing, and spectral features will help disentangle the roles of mass and formation history in shaping galaxy properties. Improving empirical models, such as halo occupation distributions and semi-analytic frameworks, will also be crucial. Incorporating secondary halo properties—beyond mass—into these models can bridge the gap between simulations and observations. Ultimately, combining deep observations, advanced simulations, and flexible statistical models will refine people's understanding of how the timing and pathway of halo assembly drive the diversity of galaxy populations observed today.

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