From Dark Matter Scaffolding to Obscured Cores: An Integrated View of Galaxy Formation from Theory, Simulation, and Observation

Theoretical Foundations: From Dark Matter Halos to Semi-Analytic Models

The endeavor to understand galaxy formation is built upon a robust theoretical foundation provided by the Lambda Cold Dark Matter (ΛCDM) cosmological paradigm [14]. This model posits that the universe began with small, random density fluctuations imprinted on the fabric of spacetime [8]. Over cosmic history, gravity acted upon these initial perturbations, causing matter to clump together and form structures hierarchically [41] [52]. In this scenario, smaller structures, known as dark matter halos, form first from the dominant component of cosmic mass, cold dark matter (CDM) [9] [41]. These halos then merge and accrete material over time, progressively building up larger and more massive structures, culminating in the formation of galaxy clusters [67]. The gravitational potential wells created by these dark matter halos serve as the scaffolding for all subsequent baryonic processes; ordinary matter, primarily gas, falls into these wells where it can cool, condense, and ultimately form stars and galaxies [8]. The initial conditions for this entire process—the power spectrum of density fluctuations—are now precisely measured from observations of the Cosmic Microwave Background (CMB) [49]. The remarkable success of the ΛCDM model in explaining large-scale cosmic structure across an enormous span of redshift underscores its status as the prevailing framework for modern cosmology [9].

To mathematically describe the statistical properties of this hierarchical growth, astrophysicists have developed powerful analytical tools. The Press-Schechter formalism, and its subsequent extensions, provides a foundational method for calculating the abundance of dark matter halos of different masses at any given time [10] [27]. This approach, often framed within the language of excursion set theory (EST), treats the smoothed density field as a stochastic random walk [11] [12]. A halo of a certain mass is said to form when a random walk crosses a critical density threshold for the first time [10]. This elegant theory yields an analytic expression for the halo mass function, which describes how many halos exist per unit volume for each mass bin [11]. Furthermore, EST provides a means to model the mass accretion history of individual halos, detailing how they grow through smooth accretion and discrete mergers with smaller halos [13] [50]. These accretion histories are encapsulated in what is known as a merger tree, a chronological diagram of a halo's progenitors and descendants that serves as the backbone for most galaxy formation models [28] [70] [77]. While these purely analytical models are computationally inexpensive and provide invaluable insights into the statistics of structure formation, they lack the complexity to track the fate of baryonic matter directly [68].

To bridge the gap between the pure dark matter hierarchy and the observed properties of galaxies, semi-analytic models (SAMs) were developed [44] [90]. SAMs represent a crucial layer of physics applied on top of the pre-calculated merger trees derived from either analytical models or large N-body simulations [2] [51]. Instead of solving the equations of hydrodynamics numerically, SAMs use a set of simplified, physically motivated differential equations to follow the evolution of baryons within each halo [3]. Key processes tracked by SAMs include the cooling of gas onto halo centers, the formation of stars according to a prescribed star formation law, the recycling of gas via supernova-driven winds, the growth of supermassive black holes, and the energy injection from active galactic nuclei (AGN) [1] [44]. The primary strength of SAMs lies in their computational efficiency, which allows them to model the formation and evolution of billions of galaxies across vast cosmological volumes, making them ideal for predicting statistical observables like luminosity functions, Tully-Fisher relations, and galaxy clustering [1] [5]. However, their predictive power relies heavily on tuning free parameters associated with the unresolved physics of baryonic processes, a practice often referred to as calibration [80]. For instance, the EAGLE simulation suite was calibrated to reproduce key low-redshift observables, such as the galaxy stellar mass function and the size-mass relation for disc galaxies, thereby constraining its model parameters before being used to make predictions about the high-redshift universe [93]. This combination of a well-defined dark matter merger tree and a physically motivated set of rules for baryonic evolution makes SAMs a powerful tool for exploring the connections between galaxy properties and their underlying dark matter environment [44].

Computational Laboratories: Cosmological Hydrodynamic Simulations

While semi-analytic models offer a statistical overview of galaxy formation, cosmological hydrodynamical simulations provide a direct numerical experiment, solving the fundamental equations of gravity, hydrodynamics, and radiative processes in a self-consistent manner [16] [97]. These simulations resolve the complex interplay between dark matter, hot ionized gas, cold molecular gas, and newly formed stars within a representative volume of the universe [17]. The evolution from early, less sophisticated codes to modern suites like EAGLE, IllustrisTNG, SIMBA, and FLAMINGO marks a significant advancement in the field [17] [19] [49] [79]. These next-generation simulations achieve unprecedented combinations of resolution, dynamic range, and included physics, leading to a much better agreement with observational data across a wide range of galaxy types and environments [48] [49]. For example, IllustrisTNG builds upon its predecessor by incorporating new physical models for kinetic black hole feedback, magnetohydrodynamics, and revised galactic winds, resulting in more realistic representations of galaxy properties [20] [49]. Similarly, the EAGLE simulations were designed to produce a population of galaxies that closely matches observed properties at redshift zero [17] [93].

A central challenge in these simulations is that the scales relevant for galaxy formation span many orders of magnitude. While simulations may resolve features on the scale of a few parsecs, they cannot resolve the internal physics of individual stars, supernova remnants, or dense molecular clouds where stars form [34] [100]. To account for these unresolved processes, astrophysicists employ subgrid models, which represent the net effect of small-scale physics through simplified prescriptions [74]. Two of the most critical and uncertain subgrid models are those for stellar feedback and AGN feedback. Stellar feedback models aim to capture the energy and momentum injected into the interstellar medium (ISM) by supernovae and stellar winds [31]. Modern implementations often distinguish between thermal and kinetic channels, using both to drive powerful galactic winds with realistic mass loading factors and produce smooth star formation histories [58]. These models are essential for explaining why the overall star formation efficiency in the universe is so low, as feedback prevents runaway collapse and heating of the gas reservoir [34].

AGN feedback represents another crucial, and highly complex, subgrid model. In massive galaxies, the accretion of matter onto the central supermassive black hole releases prodigious amounts of energy, which can heat the surrounding hot halo gas and prevent it from cooling and forming stars—a process known as quenching [45] [57]. Observational evidence strongly suggests that AGN feedback is the primary mechanism responsible for halting star formation in massive galaxies, particularly during the "Cosmic Noon" at z ~ 1-3 [45] [96]. Different simulations implement various forms of AGN feedback. For instance, the SIMBA simulations incorporate three distinct modes: a radiative mode for rapidly accreting black holes, a jet mode for slowly accreting ones, and an X-ray heating mode for gas-poor galaxies [100]. The choice of feedback prescription has profound consequences for the simulated universe. Studies using the Simba simulation show that different feedback models significantly alter the partition of cosmic baryons, with long-range AGN jets increasing the fraction of gas in the large-scale diffuse IGM by approximately 20% compared to weaker feedback models [100].

Despite their sophistication, even state-of-the-art simulations exhibit significant quantitative differences when compared against detailed observational data, highlighting the ongoing challenges in modeling baryonic physics. A comparative study of EAGLE, IllustrisTNG, and SIMBA found that while all three models successfully reproduce the observed galaxy stellar mass function and place galaxies on the star-forming main sequence, they diverge sharply in their predictions for cold gas content [74]. At redshift zero, EAGLE predicts significantly less atomic hydrogen (H I) than SIMBA and IllustrisTNG, while the latter two overproduce H I compared to survey data from ALFALFA [74]. The redshift evolution of the H I mass function also differs qualitatively between the models, with SIMBA and EAGLE predicting an increase in the number density of H I-rich galaxies from z=0 to z=2, whereas IllustrisTNG predicts a decrease [74]. Similar discrepancies are seen for molecular gas (H_2). These divergent results suggest that the precise implementation of feedback mechanisms, particularly AGN feedback, remains a key area of uncertainty [74]. The table below summarizes some of the key characteristics of prominent cosmological simulation suites.

Simulation Suite	Code Used	Box Size (Mpc/h)	Target Baryon Mass ($M_\odot$)	Key Features
IllustrisTNG	Arepo (Moving-mesh MHD)	100 (TNG100), 300 (TNG300)	1.4 x 10^6 (TNG100), 11 x 10^6 (TNG300) [49]	Kinetic black hole feedback, MHD, revised galactic winds, updated dust modeling [20] [49]
EAGLE	GADGET-3 (SPH)	100	~7.7 x 10^5	Calibrated to match z≈0 observables; strong stellar feedback [17] [93]
SIMBA	GIZMO (Meshless Finite Mass)	25, 100	Not Available	Three-mode AGN feedback (radiative, jet, X-ray heating); high-resolution zooms [19] [100]
FLAMINGO	GADGET-3 (SPH)	350	Not Available	Focus on coupling baryonic feedback to cosmology; includes neutrino effects [79] [82]

This comparative analysis demonstrates that while current simulations have achieved a broad success in replicating the general demographics of the galaxy population, their predictive power for more subtle properties hinges on resolving the complexities of feedback physics. The discrepancies underscore that no single model is yet perfect, and continued refinement of subgrid physics is essential for a complete understanding of galaxy formation.

Observational Frontiers: Mapping Galaxies from the Cosmic Dawn to the Present

Observations provide the ultimate ground truth against which all theoretical models and simulations must be tested. The advent of powerful new observatories, particularly the James Webb Space Telescope (JWST) and the Atacama Large Millimeter/submillimeter Array (ALMA), has revolutionized our ability to study galaxy formation across cosmic history [15] [63]. Each instrument probes a unique wavelength regime, revealing different aspects of galaxy physics. JWST excels in the near- to mid-infrared, allowing it to see through dust and detect the light from old stars in distant galaxies, as well as emission lines tracing star formation and AGN activity [15]. ALMA, operating in the millimeter and submillimeter domain, observes the cold dust continuum and spectral lines from molecules like carbon monoxide (CO), which serve as tracers of the total gas mass and star formation rate in dusty, high-redshift systems [15] [61]. The synergy between these two facilities provides an unparalleled view of the structural, obscured, and chemical components of galaxies throughout cosmic time [37] [66].

During the Epoch of Reionization and the subsequent "Cosmic Dawn" ($z > 6$), JWST has made extraordinary discoveries, pushing the observable frontier to redshifts of approximately $z \approx 14$ [14] [35]. These earliest galaxies are surprisingly massive and actively forming stars for their age [14]. For example, spectroscopic confirmation has been obtained for galaxies at redshifts as high as $z = 13.9$ and $z = 14.32$ [14]. The galaxy JADES-GS-z14-0, at $z \approx 14$, has a stellar mass of $\log_{10}(M^*/M_\odot) \approx 8.6$ and a high star formation rate of 19 $M_\odot\ yr^{-1}$, despite the universe being only about 300 million years old [14]. These objects exhibit signs of low metallicity ($\log(Z/Z_\odot) \approx -1.5$), indicating they are among the first generations of stars to enrich the interstellar medium [14]. Morphologically, they display diverse structures; JADES-GS-z14-0 is relatively extended with a half-light radius of 260 pc, while another candidate, JADES-GS-z14-1, is compact [14]. Recent observations have also revealed puzzling spatial offsets between the dust emission traced by ALMA and the UV light from young stars seen by Hubble, a phenomenon observed at z = 5–7 that challenges simple models of galaxy structure [38]. Together, these findings paint a picture of early galaxy assembly that is rapid, efficient, and already producing complex structures like bulges and dense cores, even in the very young universe [62] [101].

The period known as the "Cosmic Noon" (z ~ 1-3) represents the peak epoch of cosmic star formation, during which almost 90% of optical and UV radiation from stars was absorbed by dust and re-emitted in the infrared [15]. This heavy obscuration makes these galaxies invisible to optical telescopes but accessible to IR and submm observatories like JWST and ALMA. The joint analysis of data from these instruments reveals the internal architecture of these massive, dusty starbursts. For instance, studies of z ~ 3 submillimeter galaxies show that they possess a dense, bulge-like core established behind a screen of dust, with a more extended and clumpy outer disk visible at rest-optical wavelengths [37] [101]. This provides direct observational support for the idea that these systems are in a transition phase, rapidly assembling the stellar mass that will eventually become the quiescent elliptical galaxies seen in the local universe [101]. The combined power of JWST and ALMA is therefore providing unprecedented detail on the co-evolution of stellar populations, dust, and gas in the most active galaxies of the past 10 billion years [66]. Predictions based on photo-ionization models suggest that JWST-MIRI will be able to detect key tracers of both star formation (like [Ar II] and PAH features) and AGN activity (like [Ne V] and [Mg IV]) up to redshifts of z~2-3, while ALMA can observe CO and other fine-structure lines to even higher redshifts [15]. However, a major limitation remains the lack of a single instrument that covers all necessary bands simultaneously, requiring a multi-facility approach to fully characterize these complex systems [15].

In the local universe ($z \approx 0$), observations of nearby galaxies serve as a detailed laboratory for testing and calibrating galaxy formation models [59] [74]. Wide surveys provide robust statistical samples for measuring fundamental properties. The HSC-CLAUDS survey, for example, has provided reliable measurements of the star formation rate (SFR) function up to redshift z = 2, covering both the high- and low-SFR regimes [59]. Surveys like ALFALFA and xGASS provide crucial data on the atomic (H I) and molecular (H_2) gas content of galaxies across different morphologies and environments, which are vital for testing the predictions of cosmological simulations [74]. Comparisons between simulations and these local observations reveal both successes and failures. While simulations like EAGLE, SIMBA, and IllustrisTNG broadly reproduce the observed stellar mass function, they struggle with the details of the cold gas mass functions, with EAGLE underproducing H I and IllustrisTNG showing a different redshift evolution for both H I and H_2 compared to observations and the other simulations [74]. These discrepancies highlight the need for further refinement of feedback models in simulations to accurately capture the processes that regulate the cold gas reservoirs that fuel star formation today. The continuous cycle of observation, modeling, and simulation refinement is essential for progressing toward a complete and predictive theory of galaxy formation.

The Physics of Regulation: Gas Accretion, Star Formation, and Feedback

At the heart of the galaxy formation narrative lies a delicate and dynamic interplay between gravity, which drives matter together, and feedback, which injects energy and regulates the conversion of gas into stars [60]. This battle between inflow and outflow determines a galaxy's final mass, size, morphology, and evolutionary path. The process begins with the accretion of gas from the surrounding cosmic web into the gravitational potential well of a dark matter halo [60]. Once this gas is inside the halo, it must cool radiatively in order to lose pressure support and collapse to form stars. The efficiency of this cooling process is a critical first step in galaxy assembly. As the gas cools and condenses, it reaches densities and temperatures suitable for star formation, governed by laws like the Kennicutt-Schmidt law, which links the surface density of gas to the surface density of the star formation rate [34]. Simulations such as the Feedback in Realistic Environments (FIRE) project are specifically designed to model this process with high fidelity, capturing the complex physics of star formation in a realistic interstellar medium [34] [94].

However, star formation does not proceed unchecked. The immense energy released by massive stars and subsequent supernova explosions drives powerful outflows of gas, a phenomenon known as stellar feedback [58]. This feedback plays a crucial regulatory role, preventing runaway star formation and injecting energy back into the interstellar medium [31]. By heating the surrounding gas and driving galactic winds, stellar feedback can expel a significant fraction of a galaxy's baryons, explaining the observed inefficiency of star formation on a cosmological scale [34]. The effectiveness of this process depends on the balance between the thermal and kinetic energy channels of feedback; using both channels together has been shown to produce smooth star formation histories and powerful winds with realistic mass loading factors [58]. The sensitivity of galaxy formation to the details of stellar feedback is demonstrated by studies showing that changes in its strength directly affect the efficiency of baryon cycling and the rates of star formation over cosmic time [31].

In massive galaxies, the dominant feedback mechanism shifts from stellar processes to that of Active Galactic Nuclei (AGN)—the energetic output from accretion onto a central supermassive black hole [47]. During the "Cosmic Noon" at redshifts z ~ 1-3, both star formation and AGN activity reach their peak [15]. In these massive systems, AGN feedback is considered the primary agent for quenching star formation, effectively shutting down the supply of fuel for new stars [45] [57]. This process, known as quenching, transforms blue, star-forming spiral galaxies into red, passive ellipticals [96]. Observational campaigns are working to establish the physical processes that couple AGN energy to the surrounding multi-phase gas, which is a key challenge in the field [47]. Simulations incorporate various AGN feedback models, often distinguishing between a radiative (or quasar) mode, which is effective during periods of rapid black hole growth, and a kinetic (or radio-mode) jet feedback, which operates during slower accretion phases [46] [100]. Detailed analysis within the SIMBA simulation shows that jet feedback is primarily responsible for suppressing the cold gas mass functions at the massive end from z ~ 1 to z = 0, creating the observed anticorrelation between molecular gas fraction and stellar mass [74]. Without this powerful AGN feedback, simulations predict that massive galaxies would continue to form stars at unsustainable rates, contradicting observations of the present-day red sequence [45] [96].

The intricate dance between gas accretion, star formation, and feedback regulation is summarized in the stellar-to-halo mass (SMHM) relation, which plots the stellar mass of a galaxy against the total mass of its dark matter host halo [29]. This relation is a powerful diagnostic of the integrated efficiency of galaxy formation over cosmic time. Observations and simulations show that the SMHM relation peaks for halos with masses around 10^{12} $M_\odot$, corresponding to galaxies like the Milky Way, where the conversion of baryons into stars is most efficient (~20%) [30] [49]. For lower-mass dwarf galaxies, the efficiency drops, while for the most massive clusters of galaxies, it also decreases, reaching only ~10% for MW-mass halos and falling further in the most massive clusters [49]. Remarkably, the shape and location of the SMHM relation exhibit very little evolution between redshift z=1 and today, suggesting that the relationship between stellar mass and halo mass has remained remarkably constant over the last 8 billion years [49]. This stability provides a stringent test for galaxy formation models. The fact that simulations like IllustrisTNG can reproduce this relation indicates a significant level of success in modeling the average outcome of the complex baryonic physics involved [49]. However, the remaining discrepancies in predicting specific gas contents and star formation histories point to the persistent challenge of correctly modeling the sub-grid physics of feedback, which governs the precise balance of this cosmic tug-of-war [74].

A Unified Timeline: Integrating Theory, Simulations, and Observations

By weaving together the threads of theoretical models, computational simulations, and observational data, a cohesive and evolving picture of galaxy formation emerges, spanning from the first light in the universe to the present day. This integrated timeline reveals a process dominated by hierarchical assembly, regulated by complex baryonic physics, and shaped by the interplay between gravity and feedback. The journey begins in the primordial universe, within small dark matter minihalos where the first generation of massive, metal-free stars could form [69]. These Population III stars, whose existence is inferred through detailed semi-analytic models, enriched the surrounding gas with heavier elements, paving the way for the formation of later generations of stars and the first true galaxies [69]. Simulations of this era, such as those from the CoDa II and thesan projects, aim to model the intricate coupling between cosmic reionization and the formation of these first sources of light [23] [71]. Observations from JWST are beginning to probe this epoch directly, identifying high-redshift galaxy candidates at $z > 10$ that challenge expectations of early galaxy properties [14] [35].

As the universe aged, galaxies entered a phase of rapid stellar mass assembly during the "Cosmic Dawn" ($z \sim$ 6-10) and "Cosmic Noon" ($z \sim$ 1-3) [15]. During this period, galaxies were often compact, clumpy, and heavily obscured by dust produced in intense starbursts [15] [62]. Observations from JWST and ALMA have been instrumental in characterizing these systems, revealing that even at these early times, many massive galaxies had already formed a dense, bulge-like core, while still assembling the bulk of their mass in an extended disk or clumps of star formation [66] [101]. Simulations show that this mass buildup occurs through a combination of in-situ star formation and the accretion of stars from smaller, disrupted satellite galaxies [49]. For very massive galaxies, the contribution from accreted ("ex-situ") stars becomes dominant, with over 80% of the total stellar mass in galaxy groups and clusters being acquired through mergers [49]. This hierarchical assembly is the core prediction of the ΛCDM model, with simulations successfully reproducing the general trend of mass growth over time [49] [54].

The evolution of galaxies slows and their character changes as they enter the later stages of cosmic history. For massive galaxies, the cessation of star formation, or quenching, becomes a defining feature [45]. This process is driven overwhelmingly by AGN feedback, which heats the hot halo gas, preventing it from cooling and raining down to form new stars [57] [96]. This transformation from a blue, star-forming spiral to a red, passive elliptical is a key prediction of galaxy formation models. While all modern simulations successfully reproduce the overall decline in the cosmic star formation rate, the precise timing and mechanism of quenching remain areas of active research and debate [74]. Discrepancies between simulations in their predictions for the cold gas content of massive galaxies suggest that the implementation of AGN feedback is still a critical and uncertain ingredient [74]. In contrast, dwarf galaxies remain important laboratories for testing galaxy formation theories and probing the nature of dark matter [89].

The culmination of this evolutionary chain is the population of galaxies we observe in the local universe ($z \approx 0$). Today's galaxies are the end products of billions of years of assembly, feedback, and interaction. The stellar-to-halo mass (SMHM) relation provides a powerful summary of this integrated history, demonstrating that the efficiency of converting dark matter into stars peaks for Milky-Way-mass halos [49]. Despite the successes of current models, significant challenges and open questions remain. One of the most pressing is the "missing baryon problem," where observations indicate that a significant fraction of the universe's expected baryonic matter is unaccounted for at low redshift [100]. This missing material is thought to reside in the warm-hot intergalactic medium (WHIM), a diffuse and difficult-to-observe phase of the cosmic web [100]. Pinpointing its location and physical state is a major goal for future observations, with techniques like Fast Radio Burst (FRB) dispersion measure studies offering a promising new window into the large-scale distribution of baryons [100]. Another major source of uncertainty lies in the translation of simulated gas properties into observable quantities, particularly the H_2-to-CO conversion factor (αCO). The fact that simulations assuming a constant αCO fail to reproduce the observed high-luminosity end of the CO luminosity function highlights that systematic uncertainties in this conversion are a major obstacle to robustly comparing models with observations [74]. Ultimately, the path forward lies in the continued synergy between increasingly sophisticated simulations, which strive to improve their subgrid physics, and ever-more-powerful observations, which provide the detailed constraints needed to guide their development.

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