Analysis of the Principle and Simulations for Galaxy Formation

Yuchen Liu[1, *] and Yi Ren[2]

[1]Nanjing International School, Nanjing, China

[2]International Part of Beijing 80 High School, Beijing, China

*Corresponding author: yuchenliu@nanjing-school.com

Abstract. As a matter of fact, the limit to technological advancements seems endless. With the recent launch of the James Webb Space Telescope, cosmological observation has become clearer than ever, allowing us to look deeper into the past. To aid these investigations, simulations have been designed as a way to test the theories and predictions. Despite the fact that simulations have become remarkably precise and accuracy, certain limitations must not be overlooked. We explain the key principles of galaxy formation including dark matter, host halos, and subhalos in this paper. Additionally, the main ideas and models of galaxy evolution including star formation and feedback, along with a deeper analysis into cosmological models especially the IllustrisTNG project. It will help get a better grasp and understanding of potential limitations mainly consisting of large physical calculations. Solutions can be derived from such problems especially with the recent explosion of AI and machine learning related works. By understanding the physical processes, a multilayered perspective can probe and build on the existing methods of cosmological simulations, facilitating for even more detailed and precise data.

Keywords: Astrophysics; simulation; galaxy formation; dark matter; universe.

1. Introduction

Cosmological simulations have become an integral part to understanding and advancing the knowledge of the universe. Although astronomical surveys provide us with enormous amounts of information, a clear picture is only formed with interpretations along with theoretical data. These simulations have become the forefront of understanding galaxy structure and formation [1]. The Millennium Run was one of the first major simulations and represented a major milestone in cosmological simulations. Moreover, the simulated also helped with solving problems faced by many scientists and researchers, one of these was the discovery of very bright quasars from galaxies of high redshift by the Sloan Digital Sky Survey. This challenged the belief of when the first quasars were born, however, the Millennium Run simulation would demonstrate that it was possible [2]. Theoretical simulations require incredibly large amounts of calculation and physics, these problems are solved through computational methods that render high quality simulated data through methods such as N-body, particle-mesh (PM), and particle-particle-particle-mesh (P3M). These techniques reduce the computing power required while still generating reliable and accurate data [3]. Large volumes of high-quality data, along with the ability to surpass conventional time domains has allowed us to observe the universe at high redshifts, letting us into peer into the reionization era. Dark matter is a crucial part when considering structure and formations, it is therefore an essential piece to creating a cosmological simulation. Furthermore, dark matter and energy, despite comprising a significant majority of the matter within the universe, remain enigmatic and mysterious [4]. Dark matter research can be accelerated using simulations. Theoretical data allows us to analyze the robustness and accuracy of the observational data, especially with the recent launch of the James Webb Space Telescope (JWST), observation data of galaxies with z~13 can now be compared with simulated data, by comparing both, additional insights and potential issues and errors can be evaluated through cross checking and corrections.

Illustris is a major ongoing series of cosmological simulations that has received a multitude of spin-off projects each with their own advancements. Recent iterations of the Illustris project has allowed the simulation of much more complex structures and algorithms. IllustrisTNG builds on previous works that use magnetic fields for a more sophisticated and resolute model. 3 physical simulation of cubic volume 50, 100, and 300 megaparsecs (Mpc) are referred to as TNG50, TNG100, and TNG300 respectively, they are distinctly different while complementing each other. Each size focuses on areas, allowing for a solid foundation for data of all volumes and resolutions to be collected [5]. Similarly, the THESAN simulation is one of the latest iterations of the original Illustris project that uses state-of-the-art technology, combined with the implementation of radiation hydrodynamic simulations, it creates for a reliable model of the epoch of reionization (EoR) [6].

We are focusing primarily on newer projects that are currently leading the way in cosmological simulations. Analyzing leading projects and showing their methods allows us for deeper insights into the projects themselves, this allows for evaluation of the various techniques used. Identifying issues is crucial for further innovations in this field, it is important to decide the next steps to take. In Sec. 2, the basic theories of galaxy formation will be discussed including the formation and distribution of dark matter halos, along with an introduction to the behavior of baryonic matter. The Sec. 3 will go deeper into the principles and models behind galaxy formation and evolution. Theoretical data collected through the IllustrisTNG project will also be presented and discussed in Sec. 4. Sec. 5 will display the observation and applications of the IllustrisTNG project, while Sec. 6 discusses the limitations of cosmological observations and potential future outlooks.

2. Theory of Galaxy Formation

The modern theory of galaxy formations falls under the much larger cold dark matter (CDM) cosmological model. It is believed that dark matter halos had a large role in the formation of the universe’s early galaxies. The temperature of baryonic matter was much too high for it to form gravitationally bound materials, the formation of dark matter halos beforehand would have acted as support, enabling for greater gravitational interactions between baryonic material [7]. It is expected that baryonic matter followed the dark matter distribution for values above Jeans length (before the collapse of matter by themselves). This would mean that the deep potential wells of dark matter halos created highly concentrated areas of matter, which would eventually lead to the formation of the first galaxies [8].

A dark matter halo is formed when a linear evolution of density perturbation (expanded to a cosmological scale due to inflation) reaches its critical density, which subsequently causes the gravitational collapse of matter to bind, resulting in a dark matter halo. Even though the nature of linear evolution is rather easy to grasp, nonlinear evolution of dark matter density perturbations are substantially more complex. Nonlinear evolution allows for a hierarchal growth of dark matter halos, regions of overdensity instigates accretion matter from the surrounds to continually collapse into the dark matter halos, cause them to increase in both size and mass over time. Gravitational interactions may also cause smaller dark matter halos to merge into larger halos [8].

The Press and Schechter (1974) equation found the peaks of dark matter in the Gaussian random field, it was derived using of basic statistics from Gaussian random fields. Although it was incredibly accurate given its simplicity, problems would arise when using it in modern N-body functions. A more accurate formula is given by the equation [9]

$$\frac{dn}{dM} = f(\sigma)\frac{\bar{\rho}_m}{M}\frac{\ln\sigma^{-1}}{dM} \tag{1}$$

Where

$$f(\sigma) = A\left[\left(\frac{\sigma}{b}\right)^{-a} + 1\right] exp\left(-\frac{c}{\sigma^2}\right) \tag{2}$$

Here, a, b, and c are parameters determined by N-body simulations, M is the mass, n is the number of halos, and ρ is the density, $\sigma^2(M)$ is determined from the power spectrum of density fluctuations. These equations provide incredibly precise estimates on the mass distribution of dark matter. The formation distributions are given in [10], which finds the rate at which the halos merge, in which a merger tree can be created that traces the formation and evolution of dark matter halos. Dark matter halos explains the movement of early baryonic matter and the formation of galaxies through large ranges of redshift.

3. Simulating Galaxy Formation and Evolution

Cosmological simulations must specific models that have initial conditions which are then built upon. Observations throughout the years have concluded that the universe is made up of ~95% dark matter and dark energy, with only ~5% of the energy density is due to baryonic matter. In §2, we had already discussed the importance of dark matter halos in the formation of galaxies, especially during the early stages of the universe. Cosmological models currently use the ΛCDM model, where CDM is assumed and along with dark energy, is represented by the cosmological constant Λ. CDM assumes that there are no random motions when by itself and that it is collisionless [1].

Following the formation of galaxies through the gravitational collapse of protogalactic clouds, galaxies continually start to evolve due to their immediate surroundings and the perpetual expansion of the universe [11]. Galaxy evolution is shaped by hierarchal structure formation, through interactions, smaller structures merge into larger structures, changing the mass, morphology, and their chemical composition. Similarly, dark matter halo structures supporting the galaxies may also be merged by subhalos [12]. It is now believed that subhalos can persist within their host halos bound by gravity, recent simulations of dark matter halos have shown that there may be layers of subclustering. There may be up to 300,000 gravitationally bound subhalos within a single host halo, subhalos will also directly affect the properties of the galaxies that it is in interactions with [8]. It is believed that many of the largest galaxies were the results of merging, which usually takes an irregular or elliptical shape.

Stars are formed when molecular clouds, formed up of atoms, molecules, and dust experience gravitational collapse. The formation of stars within a galaxy determines structure and luminosity, setting the path for galaxy evolution [13]. The feedback process works with star formation to create a regulated cycle of star formation and to allow the distribution of rich matter throughout the galaxy. The feedback process occurs in phenomena including supernovae explosions. active galactic nuclei (AGN), or stellar winds that release energy and matter into the surrounding [14]. The structure of galaxies are dependent on the formation of new stars, which are bright and blue. This regulated process of recycling stars maintains the observable shape of the galaxy. Moreover, interactions and merges may allow for bulges to form near the center of the galaxy, which also determines the structure of the galaxy. Interactions with the supermassive black holes at the center of the galaxy further regulates the feedback process [14].

The simulation of cosmological structures requires initial conditions and set parameters. Empirical data from measurements and observations constrains the fundamental parameters of the ΛCDM model. The Friedmann-Lemaître-Robertson-Walker space-time is a common cosmological model used for simulations, where the density parameters (dark energy, dark matter, baryons) are predetermined. The generation and simulation of initial conditions and dark matter is given by [1] (refer to [1] for a more in-depth explanation of the simulation process). These processes allows for an accurate simulation that generates reliable and consistent data across multiple simulations.

4. Unveiling the Origins and Evolution of Galaxies Based on IllustrisTNG

IllustrisTNG is a fascinating cosmic simulation project that aims to delve into the formation and evolution of galaxies in the universe. The simulation builds on the success of its predecessor, Illustris, and combines advanced physics and computational techniques to provide a detailed account of galaxy formation and evolution. Below is a brief overview of galaxy formation and evolution structures in IllustrisTNG. Galaxy formation in IllustrisTNG begins with the specification of initial conditions based on the understanding of the early universe. These initial conditions include the distribution of dark matter, gas, and radiation density fluctuations as a starting point for the simulations. Dark matter plays a crucial role in galaxy formation. In IllustrisTNG, dark matter halos first form through gravitational instability. Over time, these halos have grown in size through the accumulation of additional dark matter and gas. As dark matter halos grow, they gravitationally attract surrounding gas. The simulation simulated the cooling and condensation of this gas, allowing it to sink into potential wells in the dark matter halo. This process led to the formation of the first protogalactic structures. In the densest regions of the gas cloud, stars begin to form. IllustrisTNG combines complex physics to model the process of star formation, including the effects of gas density, temperature, and metallicity on star formation rates. Stars are not only born in galaxies, but also influence their evolution. Stellar feedback processes, such as supernova explosions and stellar winds, inject energy and metals into the surrounding gas. These processes can drive outflows of gas, regulate star formation, and affect the chemical composition of galaxies.

IllustrisTNG tracks interactions and mergers between galaxies. These events can dramatically reshape a galaxy's structure and properties, forming larger galaxies through layered growth. The simulation also considered the cosmic web, the large-scale distribution of dark matter filaments and voids. Galaxies are not isolated; they are connected to each other through these structures, and their properties are affected by the geometry of the cosmic web. Supermassive black holes form in the centers of galaxies. In IllustrisTNG, black hole growth is simulated through gas accretion and mergers with other black holes. The energy released by feedback from active galactic nuclei can affect galaxies and their surrounding gas. IllustrisTNG tracks the evolution of galaxies over billions of years, allowing researchers to study how the size, shape and composition of galaxies change as the universe ages. It provides a valuable tool for understanding the properties of galaxies observed during different cosmic epochs. One of the strengths of IllustrisTNG is its ability to generate synthetic observations that allow astronomers to compare simulated universes with real astronomical data. This helps validate simulations and refine the understanding of galaxy formation and evolution. In summary, IllustrisTNG provides a comprehensive and sophisticated model of galaxy formation and evolution in the context of an evolving universe. By integrating physical, cosmological and observational data, it provides valuable insights into the processes that control the emergence and development of galaxies throughout cosmic time, helping to bridge the gap between theory and observation in the field of astrophysics [1].

5. Exploring Galaxy Formation and Evolution through Simulations

Observations of galaxy formation and evolution are not limited to direct observations of the night sky. In fact, simulations have become a powerful tool for understanding the complex process of galaxy birth and evolution. These simulations are complex computer models that simulate the physical and astrophysical processes that govern galaxy formation in a cosmological context. Here, we introduce the main observational methods for simulating the galaxy formation process and discuss the application implications of the research results they provide. These simulations focus on the gravitational dynamics of dark matter in the universe. They track the movement of billions of dark matter particles, allowing researchers to study the formation of dark matter halos, which act as the gravitational scaffolding for galaxy formation. The fluid dynamics simulation builds on the N-body simulation and includes the behavior of gases in addition to dark matter. They incorporate the laws of fluid dynamics to model how gases cool, heat and form structures. This approach allows the study of dark matter halos and baryonic components (gas and stars) within galaxies.

These simulations take into account the evolution of the entire universe, allowing researchers to study the large-scale structure of the universe, including the distribution of galaxies in the cosmic web. They provide insights into how galaxies are distributed in the universe and how their properties evolve over time. Understanding galaxy formation mechanisms: Simulations provide a controlled environment to test the various physical processes involved in galaxy formation, such as gas cooling, star formation, and feedback from supernovae and black holes. By comparing simulation results with observed galaxies, researchers can refine the understanding of these mechanisms. Simulations help test and refine the cosmological models. By comparing simulated large-scale structures of the universe with actual observations, scientists can assess the accuracy of theories such as the Big Bang and the nature of dark matter and dark energy. The simulations allowed the researchers to "rewind" and "play forward" the cosmic clock, watching how galaxies evolved from the early universe to today. This helps us understand the processes that shaped the galaxies we observe today. Simulations can predict observable properties of galaxies, such as their size, shape, color, and distribution of stars within them. These predictions provide important guidance for astronomers in planning observing campaigns and help interpret their results. Simulations allow researchers to test specific hypotheses or scenarios. For example, they could study the effects of mergers, the role of black holes in galaxy evolution, or the formation of specific galaxy types such as elliptical or spiral galaxies. Simulations can explore phenomena that are challenging or cannot be directly observed, such as the formation of the first galaxies shortly after the Big Bang or the dynamics of galaxies in extreme environments such as the centers of galaxy clusters. In conclusion, simulations of galaxy formation are invaluable tools to complement observational astronomy. They provide controlled environments to test hypotheses, refine the understanding of astrophysical processes, and explore the evolution of the universe over cosmic time [15]. Their results have far-reaching applications, enhancing the understanding of the universe and guiding future observational efforts to unravel the mysteries of galaxy formation and evolution.

6. Challenges and Prospects in Galaxy Formation Research

The formation of galaxies involves countless complex physical processes, including gas cooling, star formation, feedback from supernovae and black holes, and the influence of dark matter. Accurately modeling these processes in simulation is challenging and often involves simplifications and approximations. Running high-resolution simulations that capture the large-scale structure of the universe and the intricate details of individual galaxies requires massive computing resources. While technology has advanced, it still limits the size and complexity of simulations that can be performed. the understanding of certain astrophysical processes, such as the nature of dark matter and dark energy, is far from complete. These uncertainties affect the accuracy of simulations and theoretical models. The accuracy of the simulation depends on the quality of the initial conditions provided. Small errors in specifying the initial state of the universe can propagate into major differences in simulation results. Observing the early universe and the formation of the first galaxies is extremely challenging due to the vast distances and timescales involved. This limits the direct observational data and relies heavily on simulations to fill in the gaps. The future of galaxy formation research lies in more complex simulations that can simulate a wider range of physical processes at higher resolutions. Advances in computing power will play a key role in making this happen. The development of exascale supercomputers promises to enable more realistic and detailed simulations. Combining data from a variety of sources, including optical, radio, infrared and gravitational wave observatories, will provide a more complete picture of galaxy formation and evolution. This approach will help validate simulations and provide a more complete understanding of the universe.

Machine learning techniques are increasingly being used in galaxy formation studies. These algorithms can help analyze large datasets, identify patterns and make predictions, potentially revealing new insights into galaxy formation. Upcoming experiments, such as Simons Observatory and CMB-S4, will provide high-resolution maps of the CMB, providing insights into the early universe and the seeds of galaxy formation. These observations will help constrain cosmological parameters and inform simulations. The launch of next-generation telescopes such as the James Webb Space Telescope and the Extremely Large Telescope (ELT) will allow astronomers to peer deeper into the universe and collect detailed data on galaxies at an early stage. These observations will provide key constraints for the simulations [16]. Continued efforts to understand dark matter and dark energy will have a profound impact on the study of galaxy formation. A better understanding of these fundamental building blocks of the universe will lead to more accurate simulations and theoretical models. Galaxy formation research will benefit from interdisciplinary collaborations between astrophysicists, cosmologists, particle physicists and computer scientists. Cross-pollination of ideas and expertise can lead to innovative approaches and breakthroughs. Public interest in astronomy and cosmology is high, and engaging the public in citizen science projects and educational programs can help advance the understanding of galaxy formation. Enthusiastic amateur astronomers and citizen scientists can provide valuable data and insights. In conclusion, although there are limitations to the study of galaxy formation, the future prospects are promising. Advances in computing power, observation, machine learning, and the understanding of fundamental physics will drive progress in this field. As the simulations become more complex and the observations more precise, we will continue to unravel the mysteries of how galaxies, including the own Milky Way, exist and evolve over cosmic time. This research not only expands the knowledge of the universe but also deepens the understanding of the fundamental processes that shape it.

7. Conclusion

The process of galaxy formation has fascinated astronomers for decades, and recent advances have shed light on this complex phenomenon. This abstract provides an overview of the key findings in the field, discusses its limitations and future prospects, and highlights the importance of ongoing research. In recent years, extensive research has revealed the complex process of galaxy formation. Astronomers have pieced together evidence that galaxies, including the own galaxy, are produced by the gravitational collapse of massive clouds of gas and dust. These clouds have undergone a series of transformative events, such as star formation, mergers, and interactions with other galaxies, shaping their eventual structure and characteristics. However, the understanding of galaxy formation remains incomplete. Many questions remain, such as the exact role of dark matter and the interaction of different physical processes as galaxies form. Next-generation telescopes and observatories, coupled with advanced simulations, promise to further solve these mysteries. The study of galaxy formation has profound implications for the understanding of the evolution of the universe. It has provided insights into the origins of stars, planets and even life itself, making it an important area of astronomical research and continues to inspire astronomers around the world.

Author Contribution

All the authors contributed equally and their names were listed in alphabetical order.

References

[1] Vogelsberger M, Marinacci F, Torrey P, et al. Cosmological simulations of galaxy formation[J]. Nature Reviews Physics, 2020, 2(1): 42-66.

[2] Springel V, White S D M, Jenkins A, et al. Simulating the joint evolution of quasars, galaxies and their large-scale distribution. Nature, 2005, 435(7042): 629-636.

[3] Klypin A, Holtzman J. Particle-Mesh code for cosmological simulations. arXiv preprint astro-ph/9712217, 1997.

[4] Somerville R S, Dave R. Physical Models of Galaxy Formation in a Cosmological Framework Annual Review of Astronomy and Astrophysics, 2015, 53(1): 51-113.

[5] IllustrisTNG - Project Description. Retrieved from: https://www.tng-project.org/about/.

[6] THESAN- Project Description. Retrieved from: https://www.thesan-project.com/thesan.html.

[7] Blumenthal G R, Faber S M, Primack J R, et al. Formation of galaxies and large-scale structure with cold dark matter. Nature, 1984, 311(5986): 517-525. DOI:10.1038/311517a0.

[8] Benson A J. Galaxy Formation Theory. Physics Reports, 2010, 495(2-3): 33-86.

[9] Tinker J L, Kravtsov A V, Klypin A, et al. Toward a halo mass function for precision cosmology: the limits of universality. The Astrophysical Journal, 2008, 688(2): 709-728.

[10] Lacey C, Cole S. Merger rates in hierarchical models of galaxy formation. II: Comparison with N-body simulations. Monthly Notices of the Royal Astronomical Society, 1994, 271(3): 676-692.

[11] Pillepich A, Springel V, Nelson D, et al. Simulating Galaxy Formation with the IllustrisTNG Model. Monthly Notices of the Royal Astronomical Society, 2018, 473(3): 4077-4106.

[12] Shi J, Wang H, Mo H, et al. The Formation History of Subhalos and the Evolution of Satellite Galaxies. The Astrophysical Journal, 2020, 893(2): 139.

[13] Mckee C F, Ostriker E C. Theory of Star Formation. Annual Review of Astronomy and Astrophysics, 2007, 45(1): 565-687.

[14] Minniti D, Zoccali M. The Galactic Bulge: A Review. Proceedings of the International Astronomical Union, 2007, 3(S245): 323-332.

[15] Ferreira L de A. The Cosmic Evolution of Galaxy Structure and Morphology at $0.5 < z < 8$[J].

[16] Barreira A, Cabass G, Schmidt F, et al. Galaxy bias and primordial non-Gaussianity: insights from galaxy formation simulations with IllustrisTNG. Journal of Cosmology and Astroparticle Physics, 2020, 2020(12): 013-013.