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Comparison and Applications for the State-of-art Astrophysics Simulations: Evidence from THESAN and illustrisTNG

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Abstract:

The understandings of the formation of galaxy have been remarkably improved into a new level due to the simulations in astrophysics. Early models using simple N-body simulations were limited due to computational power. Later on, the development of algorithms had enhanced accuracy and scalability. In the modern era (2000s-present), due to the high-resolution simulation supported by projects including the MillenniumTNG and THESAN significantly enhanced the detailed studies of the formation and evolution of galaxy. This study compares the differences of application and comparison between the simulations of the two projects, the MillenniumTNG and THESAN, specific in the concept of high-redshift. While the two projects dive into deep using different methods and taking different angles, they share the same overarching goals of having further understanding of the early universe and the high-redshift galaxies. In particular, the two projects complement each other through their simulations and observations, pursuing better insights into the cosmos at large.

Keywords: MillenniumTNG; THESAN; IllustrisTNG; high-redshift; early universe.

1. Introduction

Galaxy simulations have played a critical role in the cutting-edge scientific research recently, inspiring scientists to test their suspicion and reasoning through high-grade, precision and advanced techniques. By putting their theoretical models and predictions into the models of simulations, scientists are allowed to compare the results with their observational data. The earliest approaches started during 1970s-1980s, with the attempts based on simplified models, usually utilizing N-body techniques to study the relationship between stars and dark matter particles, particularly in the aspects of the dynamics of gravitational interactions. In 1990s, with the development of computing techniques, more and more detailed physics, for example, star formation, gas dynamics, and cooling had been incorporated together, allowing to create a more realistic and more reasonable representation of how dark matter and baryonic matter interplay with each other, opening up a new understanding of formation and evolution of galaxy. When it came to 2000s, as large-scale cosmological simulations appeared, researchers successfully obtained the context of large-scale structure evolving of the universe, using simulated formation of galaxy. The expansion of galaxy and effects of dark energy were incorporated during the simulations, which provided us a more distinct picture than ever. As the development of advanced numerical techniques, like adaptive mesh refinement (AMR) and smoothed-particle hydrodynamics (SPH) increased during 2000s to 2010s, high resolution results of small-scale structures and more comprehensive modeling of fluid dynamics were able to be found. Recently, feedback which came from active galactic nuclei, stellar winds, and supernovae of cosmic scale are trying to focus on details of physical processes incorporating. There are also some ongoing processes, which continuing on the enhance of computational power, create growing complexity and high-resolution simulations of galaxy and provide unprecedented information and precision.

Recent studies have attached their importance on the comparison between simulations and observation results of galaxies in order to get better understanding of their evolution and properties. According to Bravo et al. in 2020 [1], it uses a series of physical action accent the difficulties of reproducing spectral of energy distributions of galaxy. By showing certain models of simulations like shark and prospect [1], researchers demonstrate that optical color distributions can be firmly matched with the observations in surveys. Another studies, Alfaro et al. investigated the analysis of simulated future virialized superstructures and use it to indicate the galaxy occupation in halos of high-density regions [2]. They delve into the relationships and effect between high-density and low-density environment of populations of galaxy within halos, making great efforts on enhancing insights of the distribution of halo occupation. Husko et al. provide evidence showing a fraction between observations and simulations at redshift z=10 mergers up with galaxy in the side of observation [3]. The study emphasizes that in order to find a better understanding of statistic merger results of the galaxy, inconsistencies within different observations and simulations need to be highlighted. By using samples of strong gravitational lensing at galaxy-scale, Liu et al. govern the parameter in the formalism of parametrized post-Newtonian in the area of General Relativity (GR) at galaxy-scale. This illustrates that abundance of potential in the realm of testing GR of strong gravitational lensing. Generally speaking, all of these studies make great efforts in enhancing the understanding between observations and simulations in the aspects of evolution and properties of galaxies as well as the fundamental laws of physics [4]. With these in minds, this study will compare the THESAN and IllustrisTNG projects with descriptions of simulations and give discussions for different simulation results.

2. Descriptions of the Simulations

Astrophysics simulations act as a very important tools in helping scientists better understanding the universe. Recent studies have constantly created models with accurate details based on basic physics laws and different software options in order to have better understanding of complex phenomena in the universe.

Large-ever suite of cosmological simulations have been released recently with a combination of nearly 60 trillion particles, providing unique points of view of the behavior of the cosmos largely. This undoubtedly means a significant advancement in the area of astrophysics simulations. Star formation, dark matter formation and feedback mechanism are incorporated in the simulations to create an exhaustive understanding of the evolution of the galaxy. In the realm of exploring the roles of dark matter and hot holes, researchers use computational constraints to address the limitations and govern the potential of Al to enhance the accuracy [5]. Batziou et al. mention in the paper that it is necessary to integrate non-thermal components, like magnetic fields, to get more reasonable results by using star formation models [6]. Another paper published by Ludlow et al. also discuss how stellar motions, which revealing sensitivity through galaxy properties, can be affected by spurious heat from dark matter [7, 8]. Additionally, an article published by Lozano et. build a bridge between molecular hydrogen formation and star formation rates into a model, aligning complex approaches of simulations with actual observational data [9].

Tools like SIMPUT plays a critical part in the realm of X-ray instrument simulations, creating rational astrophysical objects with varying time variables [10]. Computational astrophysics is a subject which needs researchers, faculty, and students to build simulations in order to complement analytic theories [11]. Discussion within the topic of analytic results of astrophysics simulations provided by Julia is also competitive, for it needs to consider about goals of the courses of its suitability [12].

Projects like CAMELS, based on machine learning simulations, paves the way for projects, which are creative and innovative, and use the simulations to have a better insight into the universe. For example, aim of the DREAMS Project is to build thousands of cosmological hydrodynamic simulations, which cover not only dark matter physics but also astrophysics [13]. The project use machine learning techniques, for instant, Convolutional Neural Network and emulators, to analyze simulation data and disentangle the effects of dark matter and baryonic physics [14]. Machine learning is also applied in building models of astrophysical r-process, in which it simulates nucleosynthesis and predicts nuclear masses [15]. This aligns abundances of observed data with simulations results together. Generative Adversarial Networks also known as GANs are recently being tested to accelerate Monte Carlo simulations [16]. The project has successfully shown their capability in replicating statistical distributions in physical processes [16]. Additionally, astrophysical shock waves, largely enhanced parameter tuning and model convergence with observational data, has been informed in Neural Networks, improving accuracy in complex scenarios in a large sense [17]. Collectively, the parameter tuning and model convergence have been enhanced to another stage, due to the machine learning techniques which are employed in calibrating astrophysical simulations. These studies significantly discover the potential of machine learning in astrophysics simulations. Although there still remain some difficulties like integrating all the innovative methods together with traditional approaches, it is still believed the future of machine learning is full of potential and optimistic.

3. IllustrisTNG

The MillenniumTNG project is an ambitious hydrodynamical simulations that aims to provide a comprehensive understanding of cosmic structure formation, building upon the success of the original IllustrisTNG simulation and incorporates computational techniques advances. The project focuses on several aspects in order to enhance the understanding of the universe. One aspect is the clustering pf galaxies. The project succeeded in reproducing stellar mass of the observed clustering galaxy, due to its computational volume which is approximately 15 times larger than the latter one with available simulation, significantly helping it to produce accurate observed clustering galaxies as a function of stellar mass [18]. A typical simulations results are shown in Fig. 1.

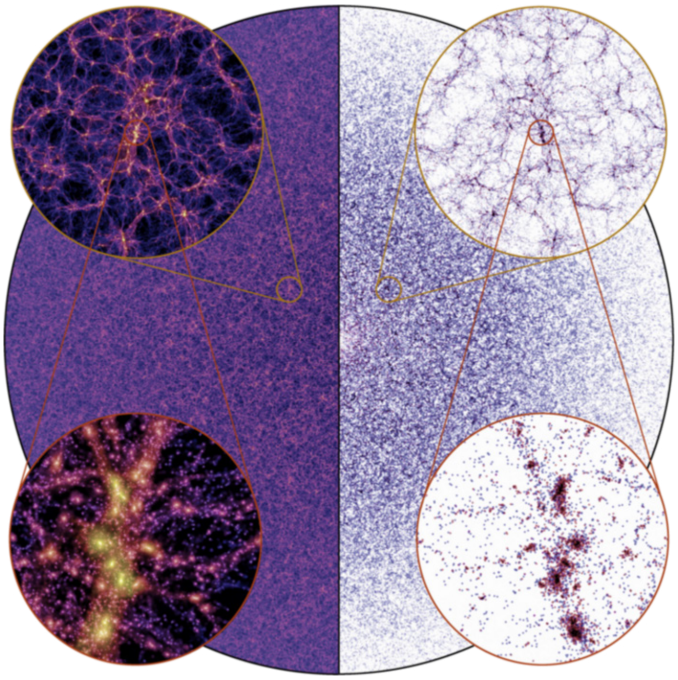

Fig. 1 A typicl results of IllustrisTNG [18].

Another aspect is predicting the galaxy population at high redshifts and making comparisons between the predictive simulations and recent observations from astrophysical instruments like the James Webb Space Telescope (JWST) [19]. The JWST has brought revolutionary progress in the area of early galaxy formation and evolution and, replacing the Hubble Space Telescope (HST) with limited observational capability. JSWT showed the presence of many bright galaxies at high redshift in its early observations, representing inconsistency with current theories of galaxy formation. Additionally, the MillenniumTNG project delves into refining galaxy-halo models for both red and blue galaxies at different redshifts [20]. This helps in understanding deeper about the galaxy-halo connection on small scales and creating a new method to better explain the phenomena of galaxy. The project studies the two galaxies, the luminous red galaxies (LRGs) and star-forming emission-line galaxies (ELGs) at different epochs, and provides new insights into the two-halo model for galaxy population [21]. By utilizing hydrodynamical simulations, the project aligns intrinsic properties galaxies and halos together, measuring the results of the intrinsic ellipticities of galaxies and predicting the intrinsic alignment (IA) signal [22]. The MillenniumTNG project also contributes to the impact of massive neutrinos on cosmic large-scale structure and distribution of galaxies [23]. The paper discuss the cold dark matter plus massive neutrinos simulations using nonlinear structure formation [23]. By using basic statistical measures, the research teams are able to quantify accurately of the impact of neutrinos, revealing several aspects like the impacts of cosmic star formation rate history, the function of galaxy mass, and the strength of the clustering of the galaxy.

To sum up, the MillenniumTNG project utilize several cutting-edge techniques and innovative simulations to push a crucial forward in the studies of the cosmos, for example, the galaxies, halos, and large-scale structure, for which opening up a new angle for us to take a deeper glance in the formation of the galaxy and evolution.

4. THESAN

THESAN project is a state-of-art large-volume radiation-magneto-hydrodynamic simulations focused on the understanding at the Epoch of reionization and the formation of early universe [24]. THESAN project offers unique angles of the changes in reionization dynamics by using different assumptions of dark matter models, numerical convergence, and ionizing escape fractions [24]. Typical results are shown in Fig. 2. The intergalactic medium (IGM), discovered during the Epoch of Reionization, has been connected to galaxies at redshifts z greater than or equal to 5.5 within THESAN project. THESAN has launched a robust fundamental scenario for future analyses at high-redshift galaxies, showcasing their research of ionizing photon escape and dark matter nature [25]. In addition, the study of Lyman-alpha emission and transmission is also an important topic of THESAN, especially during the Epoch of reionization. THESAN has also created a framework, aiming to analyze Lyman-alpha centric data and resolving atomic cooling halos across a significant region of the Universe, by incorporating radiation-magneto-hydrodynamics solvers with galaxy formation models.

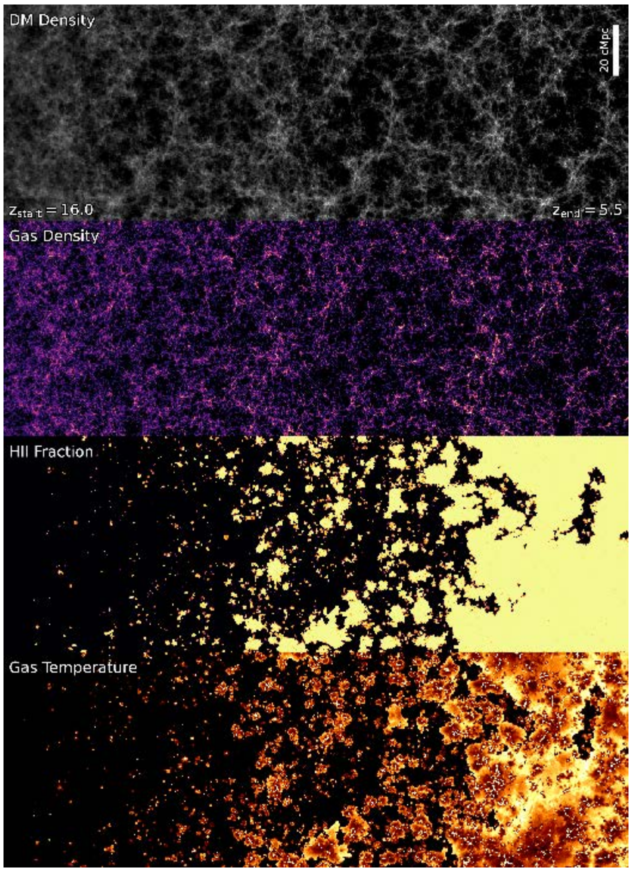

Fig. 2 A typical simulation results of THESAN [24].

Another important contribution that THESAN has made is predictions of line intensity mapping in the Epoch of reionization through multi-tracer. THESAN has achieved significant success in the understanding of galaxy formation and cosmology in the high-redshift universe, estimating line intensities in interstellar medium galaxies as well as 21cm emission from neutral hydrogen gas [25]. This has brought the studies of astrophysics simulations to an instrumental level, especially in calculating the ionizing escape fractions pf reionization-era galaxies. With location of AGN escape fractions is near galaxy gravitational potential wells, the importance of stellar verses AGN has been largely risen due to the simulations provided by THESAN, proving that the locations of AGN is exactly lower than the contributions of reionization [25]. As computational techniques continue to advance, THESAN project will likely to combine more details together and offer a comprehensive view of the formation of galaxy. And the public data release by THESAN simulations will continuously help further studies to enhance their accessibility and collaboration, facilitating difficulty of high-redshift universe studying for further research.

5. Comparison and the State-of-art Simulations

The MillenniumTNG project is an ambitious hydrodynamical simulations that aims to provide a comprehensive understanding of cosmic structure formation, building upon the success of the original IllustrisTNG simulation and incorporates computational techniques advances. While THESAN project is a state-of-art large-volume radiation-magneto-hydrodynamic simulations focused on the understanding at the Epoch of reionization and the formation of early universe. When it comes to galaxy population at z greater or equal to 8, the MillenniumTNG focuses more on hydrodynamical full physics simulations. Comparing to THESAN which provide understanding of the intergalactic medium using a suite of radiation-magneto-hydrodynamical cosmological simulations. For galaxy formation and evolution results, the MillenniumTNG project offers comprehensive details of the formation and evolution of galaxies, which includes formation, history of stars, morphologies, and merger histories. Another simulation of the project is to reproduce the observed galaxy stellar mass function, star formation main sequence, and other scaling relations. Additionally, the MillenniumTNG project simulates the large-scale structure of the universe, which covers areas of the distribution of dark matter halos, galaxies, and the cosmic web. This provides insights into the clustering of galaxies and the development of large-scale structures over cosmic time. Moreover, the project has investigated the impact of massive neutrinos within the large-scale structure and distribution of galaxy. This provides evidence that neutrinos suppress the growth of structure on small scale and delay the formation of galaxies. Machine learning integration has also played a crucial part of the project, which analyzing and interpreting the vast amounts of data provided by the simulation.

On the other side, THESAN provided a deeper insight into the understanding of the EoR, which not only include the timeline if reionization, but also the impact of reionization on the IGM and galaxy formation, reproducing the observed constraints within the background of reionization history, like the Thomson scattering optical depth and the evolution of the neutral hydrogen fraction. THESAN also focuses on the study of the formation and evolution of the first galaxies, including the studies of their star formation histories, morphologies, and feedback processes. In addition, THESAN has successfully incorporated the advanced radiative transfer techniques into the propagation model of ionizing radiation as well as the interaction with the IGM and galaxies. By tracking the chemical enrichment of the universe and producing the distribution of metals, THESANR reveal the impact of chemical enrichment on galaxy formation. Besides, the James Webb Space Telescope (JWST) and the Space Kilometre Array (SKA) provide direct comparisons with observational data, helping THESAN to generate synthetic observation across multiple wavelengths.

On the realm of scale and scope, the MillenniumTNG simulates the universe on a large volume and focuses on the formation and evolution of galaxies across cosmic time. While THESAN focuses on the early universe and the EoR, which provides understanding of reionization process and the formation of the early galaxies. Both two simulations use advanced physics models in order to study dark matter, baryons, and various astrophysical processes. The only difference is that THESAN incorporates additional models including radiative transfer and chemical enrichment, playing a critical role in the study of the EoR. Due to the high aim for high resolution, THESAN uses high resolution to accurately model the small-scale processes relevant to the EoR. In the realm of machine learning, in order to analyze and interpret their data, both projects incorporate machine learning techniques, but focus on different applications.

6. Limitations and Prospects

Although both the two projects represent the highest state-of-art endeavors in the field of cosmological simulations, there are still some limitations. The MillenniumTNG project simulates the universe, requires substantial computational resources, limiting the resolution and the complexity of the physical models. The MillenniumTNG project uses subgrid prescriptions to simulates some astrophysical processes, like star formation, stellar feedback, and black hole growth, causing uncertainties and assumptions. Comparing to THESAN, while using computational resource to simulate the EoR with detailed physics models, limiting the volume and resolution of the simulation. The radiative transfer of ionizing photons also introduces uncertainties in the simulation results. THESAN will benefit from increased computational power in the future iterations, which can provide higher resolution and more details in the simulation of the early universe. By continuously enhance the radiative transfer models, the advanced techniques can lead to more efficient models, which can improve the realism of the simulations and reducing uncertainties. For the future iterations of the MillenniumTNG project, increased computational power can benefit the project and provided higher resolution and more detailed simulations. By improving physical models, such as subgrid models, the physics processes can accurately reduce uncertainties and improve the realism of the simulations.

7. Conclusion

To sum up, both the MillenniumTNG project and THESAN project have contributed a lot to the understanding of the universe, in spite of some limitations, such as computational resources, subgrid physics, and observational constraints, they are facing to. However, with the advances in computational power, physics models, and machine learning techniques, which help to create accurate simulations, the prospects of the projects are promising. As the projects are continuously evolving, they will surely provided deeper insights into the formation and evolution of the universe.

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