A Comparative Analysis of Illustris TNG and THESAN Cosmological Simulations

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Abstract. Cosmological simulations play a crucial role in understanding the evolution of the universe, offering valuable insights when compared with observational data. With advancements in computational capabilities and data-gathering techniques, simulations have evolved to model larger volumes and finer details of cosmic structures. This review compares two prominent simulations, Illustris TNG and THESAN, focusing on their algorithms and factors considered. Illustris TNG primarily employs smoothed particle hydrodynamics (SPH), while THESAN utilizes moving mesh hydrodynamics (MMH), each offering unique advantages in simulating different aspects of the universe. Furthermore, THESAN incorporates additional factors such as cosmological dust and sophisticated radiation transport algorithms, enhancing its accuracy in predicting early galaxies and stars. The comparison underscores the impact of algorithmic differences and the consideration of various factors on simulation accuracy. This analysis highlights the importance of understanding these specifications in designing simulations that effectively capture the complexities of the cosmos.

Keywords: Cosmological simulations, Illustris TNG, THESAN.

1. Introduction

Cosmological simulations predict how the universe evolves from various initial conditions and physic models, which can then be compared with observational data to provide valuable insights and constraints on cosmological models [1, 2].

In the past few decades, groundbreaking advances occurred in data processing capability, which enabled simulation with larger volume, finer resolution, and more factors involved. Concurrently, data-gathering ability over more portions of the EM spectrum also drastically improved as new telescopes with better light-gathering ability and angular resolution were deployed. These advancements allow for detailed modeling of the early universe and how IGM, galaxies, and other structures develop.

Illustris TNG (The Next Generation) is a simulation primarily focused on galaxy formation. It consists of 18 simulations on 3 different volumes, aiming to decipher galaxy formation by making detailed simulated ones and comparing them to real ones [3].

Theoretical Stellar Astrophysic Network (THESAN) is a simulation primarily focused on stellar interactions' effect on the Epoch of Reionization (EOR). It combines the successful network used in Illustris TNG with self-consistent radiation transport, non-equilibrium heating and cooling, realistic ionizing sources including binary stellar systems and active galactic nuclei, as well as a model for cosmic dust creation, evolution, and destruction.

In this review, comparisons regarding different algorithms and factors involved will be explored, mainly in the context of Illustris TNG and THESAN. This comparison is valuable as it depicts how the difference in specifications affects the effectiveness and accuracy of a model, and such methodology could be useful in designing new simulations that allocate calculation resources more effectively.

2. Computational Scales and Resources

Table 1 is a chart covering key aspects of the computational scale and resources of Illustris TNG and THESAN.

Table 1. Metrics for two simulations [4]

	L_{box}	$N_{particles}$
TNG50	35Mpc/h	$2*2160^3$
TNG100	75Mpc/h	$2*1820^3$
TNG300	205Mpc/h	$2*2500^3$
THESAN-1	95.5cMpc	$2*2100^3$
THESAN-2	95.5cMpc	$2*1050^3$

Table 1 shows how the two simulations are similar in terms of calculation resources and key differences are presented in other aspects of the simulation such as algorithms and factors considered.

3. Algorithms Used

3.1. Subgrid Physics

Subgrid physics refers to the modeling of physics on a scale smaller than the grid resolution of a numerical simulation. As a direct N-body+hydrodynamics approach requires a currently unattainable dynamic range (from subparsec scales to megaparsec scales), subgrid physics is necessary to compensate for activity below the grid size that has a significant impact. For instance, factors such as stellar formation, supernovae, and turbulence in interstellar medium happen on subgrid scales, but they are important factors in EOR and galactic formation [5].

3.2. Hydrodynamics

Hydrodynamics refers to the study of fluid motion and the interactions between different components of a fluid. In the context of cosmological simulations, hydrodynamics principles are applied to model the behavior of gases on cosmic scales. This includes phenomena such as gas pressure, shock waves, turbulence, and the formation of structures like galaxies and galaxy clusters.

3.3. Simulation

Both Illustris TNG and THESAN are hydrodynamics simulations that incorporate subgrid physics. However, their numeric approach is slightly different. IllustrisTNG utilizes APERO, while THESAN utilizes APERO-RT. APERO-RT is based on APERO with the inclusion of radiation hydrodynamics [6, 7].

3.4. Moving Mesh Finite Volume (MMFV)

MMFV was proposed in 2010 to address issues of existing algorithms. Back then, simulations typically used Eulerian hydrodynamics on a Cartesian mesh with (optional) adaptive mesh refinement (AMR) or the Lagrangian SPH (smoothed particle hydrodynamics) technique. AMR's lack of Galilean invariance and overmixing, and SPH's suppression of fluid instability are two flaws in both approaches that hurt simulation accuracy. MMFV is based on an unstructured mesh that is determined by a set of points on a Voronoi tessellation. The mesh is utilized in a finite-volume approach based on a second-order unsplit Godunov scheme with an exact Riemann solver to solve the hyperbolic conservation laws of ideal hydrodynamics. If the points are stationary, the model will be equivalent to a Eulerian model with second-order accuracy. If the mesh moves with the velocity of the local flow, one obtains a Lagrangian formulation of continuum hydrodynamics that is unaffected by the mesh distortion limitations present in other mesh-based Lagrangian schemes. Unlike standard Eulerian codes, this new approach is fully Galilean invariant in this mode, an important feature for cosmological simulations where highly supersonic bulk flows is typical. Furthermore, the novel approach possesses the ability to automatically and continuously modify its spatial resolution, thereby acquiring the primary benefit of SPH for computational structure growth simulations. It also retains

Eulerian models' high accuracy when treating shocks and are more accurate when treating contact discontinuities [8].

APERO-RT is targeted to study the reionization phase of the universe. After the recombination era at z~1200, the universe became transparent to electromagnetic waves. Gas clouds began to form and collapse at z~20-50, dark matter halos from and the first stars ignite, reionizing and heating gas around them [9]. To study this phase, APERO-RT incorporates a series of equations that describe radiation transfer [9-13]. By doing so, simulations using APERO-RT can do advanced radiation simulation, helping simulations such as THESAN calculate the reionization phase. To solve the set of coupled hyperbolic conservation equations for photon number density and photon flux, this set of equations is closed using the M1 scheme. This showed how differences in algorithms can affect the ability of a model to accurately predict a phenomenon.

4. Factors Considered

THESAN and Illustris TNG consider a wide range of different factors, which impacts their simulation results. In comparison to Illustris TNG, THESAN contains a more detailed radiation and cosmological dust process.

4.1. Cosmological Dust

Cosmological dust is an important factor in the early universe as it absorbs light and re-emits them at lower frequencies. THESAN passively advect dust across gas cells during the hydrodynamic step and tracks the amount of dust in five chemical species (C, O, Mg, Si, and Fe) which are produced in two steps (stellar formation and the clumping of ISM (Inter-Stellar Medium)). A wide variety of cosmological processes can destroy dust, such as shocks and sputtering [4].

4.2. Reionization

THESAN incorporates an accurate radiation transport algorithm to model radiation's effect. This enables THESAN to accurately predict how the EOR and IGM are influenced by the first stars and galaxies. On the contrary, Illustris TNG cannot accurately model radiation.

These differences allow THESAN to predict early galaxies and stars with more accuracy. This shows how factors considered impact a simulation's ability to simulate interactions between different aspects of the universe.

5. Comparison of Results

In contrast to Illustris TNG THESAN focused on cosmic reionization down to redshift of z~5, producing high-redshift galaxy populations and the process of reionoization. In THESAN, the reionization phase is simulated in more detail relative to Illustris TNG thanks to the inclusion of a more detailed radiation transfer and cosmological dust model. By utilizing the APERO-RT framework relative to the APERO framework, radiation transfer is solved more realistically.

In the future, models with increasingly fine resolution and/or larger resolution will be deployed to shed light on the mysteries of the universe. Advancements in the differentiation and classification of models will be made to effectively use computational resources, and comparative studies such as this one may help build this structure.

6. Conclusion

In conclusion, this paper reviews cosmological simulations, focusing on the comparison between Illustris TNG and THESAN. Through an examination of their computational scales, algorithms, and factors considered, several key insights emerge. Firstly, the comparison mentions the significance of algorithmic differences in shaping the accuracy and effectiveness of simulations. While both simulations employ hydrodynamics, their numerical approaches vary, with THESAN incorporating radiation hydrodynamics through APERO-RT, enabling more detailed modeling of phenomena like cosmic reionization.

Secondly, the inclusion of various factors, such as cosmological dust and radiation transport algorithms, significantly impacts the predictive capabilities of simulations. THESAN's comprehensive consideration of these factors allows for more accurate predictions of early galaxies and stars, particularly during the epoch of reionization.

However, it's essential to acknowledge the limitations of this study. While it provides valuable insights, it does not include all possible factors influencing simulation accuracy. Additionally, the comparison is limited to Illustris TNG and THESAN, leaving room for exploration of other simulations and methodologies.

Looking ahead, this review highlights the importance of continued advancements in simulation techniques and computational resources. Future studies may leverage comparative analyses like this one to refine models, allocate resources effectively, and deepen our understanding of the cosmos. As simulations evolve with finer resolutions and larger scales, they hold the promise of unraveling the mysteries of the universe and providing invaluable insights into its evolution.

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