Exploring Population III Stars through Cosmological Simulations

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Abstract

Population III stars are considered to be the earliest generation of stars formed in the universe. By studying their formation process, we can better understand the structure of the early universe and the subsequent formation process of galaxies. In order to effectively address the practical difficulty that Population III stars are not easily observed directly, cosmological numerical simulations have become a major method for understanding their formation process. In this paper, the cosmological simulation methods for Population III stars are discussed in detail. The main body of the paper primarily introduces the SMUGGLE model used for calculating star formation and stellar feedback. The remaining sections mainly discuss the FOF and SUBFIND-HBT methods used for dark matter halo and galaxy structure detection. On this basis, combined with the corresponding program flowcharts, this paper explains the roles of these methods in analyzing the structure of the early universe and the formation of Population III stars. Through the systematic organization and summary of the relevant simulation methods, the application of numerical simulations in the early universe and galaxy formation can be better understood.

Keywords

Population III stars, cosmological simulations, star formation, SMUGGLE model, structure detection.

1. Introduction

Population III stars are the universe's first stars, forming from metal-free gas just hundreds of millions of years after the Big Bang. Unlike modern stars, they're massive which have tens to hundreds of solar masses, short-lived, and their feedback shapes later galaxy formation. But observing them is really hard, so scientists need to use some methods to figure out its characteristics, especially simulations. Cosmological simulations are crucial approaches to infer and speculate the cosmological and galaxy population properties (Moreno et al. 2025)[4]. The structure of cosmology is triggered by gravity, which can reflect the distribution of matter in the universe. Thus, measuring some important and indispensable cosmological parameters comes to be an important task. One of the steps is to determine the location of the haloes and the galaxies (Moreno et al. 2025)[4]. The two prominent approaches the researchers used in The THEZSAN-ZOOM Project can be concluded into two parts, the SMUGGLE-Model and Structure Detection [1].

2. SMUGGLE Model

The first method is called SMUGGLE-Model, which means to analyze the star formation and stellar feedback. Researchers in The THESAN Project said that they provide an evolved version (Zier et al. 2025)[1]. According to Federico Marinacci, he interpreted the SMUGGLE model as the Stars and MUltiphase Gas in GaLaxiEs (Marinacci, 2019)[2]. This is an advanced framework for simulating star formation and stellar feedback and also addresses key challenges in modeling the interstellar medium at high resolution [2]. SMUGGLE integrates multiple physics:

star formation thresholds, radiation transport, and feedback from winds and supernovae. Its design specifically alleviates numerical artifacts like artificial collapse and overcooling. One of the significant parts of THESAN-ZOOM is that it largely decreases the inflowing and lowering star formation rates[1].

3. Structure Detection and Simulation Analysis

Another section is about how to analyze the simulation files, it has three steps. In the first part, they conducted high-resolution cosmological simulations and generated 189 snapshot files, covering a time span from redshift z=16 to z=3, with a time resolution of 10 Million years[1]. These files comprehensively recorded the physical properties of gas, dark matter, and stellar particles, laying the foundation for subsequent research. During the data processing stage, people first use the FOF algorithm to identify dark matter halos, which is based on the spatial proximity of particles. Subsequently, the SUBFIND-HBT algorithm is used to further analyze the substructures, defining the most inner halo as the central galaxy and the rest as satellite galaxies[4]. This step is important for researchers to know the hierarchical structure of galaxies. FOF is a spatial clustering method that groups particles based on proximity. If two particles are closer than a defined linking length (b), they're assigned to the same structure. This creates a series of connections. The critical parameter is b, typically set to 0.2× the average particle separation[3]. For example, if particles are 1 Mpc apart on average, b = 0.2 Mpc. Smaller b yields finer structures, while larger b merges halos (Li et al, 2018)[3]. However, FOF is fast and scalable which is ideal for large datasets. It also isn't influenced by geometry, unlike spherical-overdensity methods. Moreover,, FOF provides a simple yet powerful way to map cosmic structures. Its efficiency makes it a staple in astrophysics, though users must carefully tune b.

4. Conclusion

Those two methods provide profound influential on the discussion to Population III star formation, and those two also give people an insight to know what is the prevalence approaches in cosmology to comprehend the diverse phenomenon.

References

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