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The Role of Dark Matter in Structure Formation during the Epoch of Reionization

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Abstract:

The Epoch of Reionization represents a pivotal phase in cosmic evolution, during which the first luminous structures ionized the intergalactic medium. While dark matter is established as governing the gravitational collapse that exerts a determinative influence on cosmic structure formation, the precise impact of its particle nature on the morphology and progression of the Epoch of Reionization remains incompletely understood. This investigation examines the role of dark matter during this epoch through comparative analysis of different dark matter scenarios. This study synthesizes results from complementary simulation methodologies—including N-body simulations, hydrodynamical simulations, and semi-numerical techniques—to generate predictive signatures for the evolution of both the 21-cm power spectrum and the galaxy luminosity function during the Epoch of Reionization. Results synthesized from multiple simulation methodologies demonstrate that the Cold Dark Matter framework, with its abundant population of low-mass halos, readily produces rapid reionization consistent with the optical depth measurements from Planck. In contrast, both Warm and Fuzzy Dark Matter models, which suppress small-scale halo formation, predict a characteristically delayed and inhomogeneous reionization process that shows poorer agreement with existing observational constraints.

Keywords: Cosmology theory; epoch of reionization; dark matter.

1. Introduction

The formation of the large-scale of structure is a fundamental prediction of the ΛCDM model. Following the formation of the first-generation galaxies, these astrophysical sources emitted ultraviolet radiation and created ionized regions. The period during which the cosmic gas transitioned from a neutral to an ion-

ized state is known as the Epoch of Reionization (EoR) [1]. EoR spans the first billion years after the Big Bang (redshift range of z≈6-15), during which the universe was gravitationally dominated by dark matter. This pivotal epoch is crucial for addressing fundamental questions at the forefront of research, for example, the formation of the first-generation galaxies [2] in the universe and the relationship between cosmic density and galaxy evolution [3].
Dark matter has consistently played a important role in modern astronomy. Phenomena such as gravitational lensing, the formation of large-scale structure, and the cosmic microwave background (CMB) provide compelling evidence for its existence. Current leading candidates for dark matter include neutrinos, supersymmetric particles, axions, and weakly interacting massive particles (WIMPs). Dark matter does not participate in electromagnetic interactions, is gravitationally dominant, and exhibits stability and a non-baryonic nature [4, 5].
The properties of dark matter are essential to EoR, as they directly govern the timing and sequence of the first collapsing halos, thereby indirectly influencing the population of reionization sources [6]. Different theoretical models—including Cold Dark Matter (CDM), Fuzzy Dark Matter (FDM), and Warm Dark Matter (WDM)—each predict distinct scenarios for the progression and morphology of reionization [7]. This paper investigates how dark matter models imprint on the EoR, aiming to constrain dark matter properties through their impact on early structure formation.

2. Theoretical Background

2.1 Dark Matter Halos

Minute primordial density inhomogeneities, originating from quantum fluctuations during the cosmic infancy, underwent significant amplification through inflationary expansion. These amplified perturbations evolved into marginally overdense regions exhibiting enhanced gravitational potential compared to their ambient surroundings. Consequently, these gravitational wells initiated efficient accretion of dark matter particles. When the density contrast of such an overdense region surpassed both the cosmological mean density and a critical threshold value, the process of gravitational collapse was triggered, culminating in the formation of self-gravitating dark matter halos [8].

2.2 Interaction Between Dark Matter and Baryons

These gravitationally collapsed dark matter halos provide deep gravitational potential wells. Baryonic matter—primarily hydrogen and helium—is consequently drawn inward toward the halo centers. Unlike collisionless dark matter, this gas is compressible and susceptible to cooling. As the gas is accreted and compressed, its temperature increases. Through radiative processes, the gas cools, releasing gravitational potential energy. This energy dissipation enables further compression and settling, ultimately forming a high-density, rotationally-supported gaseous disk at the halo center. Once the gas density in the central disk exceeds a critical threshold, it undergoes fragmentation and gravitational collapse, leading to the formation of the first generation of stars [9].
Furthermore, baryonic matter exerts a significant backreaction on the dark matter halo. As baryons condense within the central region of the halo, the deepening of the gravitational potential ensues. This modified potential consequently alters the orbital dynamics of dark matter particles, leading to a substantial increase in the central density of the halo. This phenomenon, whereby the dark matter distribution is dynamically reshaped by baryonic processes, is formally termed adiabatic contraction [10].

2.3 Structure Formation and the EoR

Within the CDM paradigm, dark matter clustering evolves hierarchically. The CDM model further predicts an abundance of small-scale structure: numerous low-mass dark matter halos form initially, subsequently undergoing merging processes to assemble into progressively larger halos, ultimately culminating in the formation of the largest virialized structures in the universe—galaxy clusters [8]. However, in both WDM and FDM scenarios, small-scale structure formation is substantially suppressed. The overall structure assembly process is consequently delayed, as gravitational collapse can only proceed upon the formation of sufficiently massive halos. This inherent delay in halo formation timelines results in a later onset of the EoR, alongside a reduced population of ionizing sources and a characteristically prolonged reionization history within WDM/FDM cosmological frameworks.

3. Simulation and Modeling

3.1 Numerical Simulation of the EoR

The most fundamental approach is N-body simulation. This method exclusively models dark matter by computing the gravitational interactions and trajectories of discrete dark matter particles to reconstruct the distribution and evolutionary history of dark matter halos. The primary algorithms for calculating gravitational forces include

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Direct Sum, Tree-based methods, Particle-Mesh (PM), and hybrid schemes such as *TreePM* and P^3M. Hydrodynamical simulations extend the N-body framework by incorporating the complex physics of baryonic matter, including its fluid dynamics and star formation processes. These simulations model gas dynamics primarily through Eulerian Grid Methods and Lagrangian particle-based methods, notably Smoothed Particle Hydrodynamics (SPH). While this approach achieves superior physical fidelity, it incurs significantly higher computational costs. Prominent projects employing this methodology include *IllustrisTNG*, *EAGLE*, and *SIMBA* [11]. In contrast, semi-numerical simulations utilize the underlying dark matter distribution derived from N-body simulations while applying approximate, physically-motivated criteria to rapidly generate ionization fields and predict 21-cm signals. This methodology enables efficient scanning of a broad parameter space, establishing it as a primary tool for contemporary EoR research. Representative codes employing this approach include *21cmFAST* and *SimFast21*. Currently, these sophisticated simulations serve as the indispensable bridge connecting theoretical predictions with observational data, providing the only viable pathway for quantitative comparison between cosmological models and empirical evidence.

Key parameters in these simulations include fundamental cosmological parameters (such as dark matter and dark energy densities, Hubble constant, etc.) and astrophysical parameters (including ionization efficiency and escape fraction of ionizing photons). Each distinct modeling approach operates under its own fundamental assumptions: N-body simulations postulate cold, collisionless dark matter represented by discrete particles; hydrodynamical simulations additionally assume cosmic gas behaves as an ideal fluid, relying on subgrid models with baryon-dark matter coupling solely through gravitational potential; while semi-numerical simulations establish functional relationships between dark matter halo properties and ionization rates [12].

3.2 Challenges and Limitations

Contemporary cosmological simulations face several inherent limitations, notably the resolution constraint. A fundamental tension exists between the necessity for sufficiently large simulation volumes to ensure statistical significance and the requirement for high numerical resolution to resolve the smallest dark matter halos potentially contributing to reionization. Furthermore, all theoretical predictions remain strongly dependent on the assumed nature of dark matter. While most current models are predicated on the CDM paradigm, the entire structural formation scenario would undergo substantial modification if dark matter were instead characterized by warm (WDM) or fuzzy (FDM) properties [11].

4. Observational Signatures of Dark Matter in the EoR

4.1 21-cm Line Observations

The 21-cm line corresponds to the characteristic radio spectral line emitted at a rest wavelength of 21 centimeters during the spin-flip transition of electrons in neutral atomic hydrogen. During the EoR, this signal directly traces the distribution of neutral hydrogen as it becomes ionized. The signal intensity is governed by both the density of neutral hydrogen and the kinetic temperature of the gas. Consequently, measurements of this line provide crucial insights into the global ionization state of the universe and the thermal evolution of the intergalactic medium.

The halo mass function of dark matter directly governs the formation timeline of the first luminous sources. In CDM scenarios, earlier structure formation leads to a correspondingly earlier and deeper 21-cm absorption trough. Conversely, warm or fuzzy dark matter models predict a delayed and shallower absorption feature due to suppressed small-scale structure formation. Furthermore, the particle physics properties of dark matter itself can imprint signatures on the 21-cm power spectrum: annihilation or decay processes generating high-energy particles would efficiently heat the cosmic gas. Since the 21-cm power spectrum fundamentally reflects fluctuations in the underlying dark matter density field, these observational signatures will provide direct constraints on the nature of dark matter [13].

4.2 High-Redshift Galaxey Surveys

Halo Abundance Matching (HAM) represents a widely adopted semi-empirical approach that establishes correlations between stellar mass and halo mass, thereby connecting observed galaxy populations with simulated dark matter halos. This methodology not only successfully reproduces the observed halo mass function and galaxy luminosity function, but also accurately reconstructs galaxy distributions across different scales and redshifts. As a theoretical cornerstone of semi-numerical simulations, HAM enables the transformation of dark matter distributions into predictable galaxy populations [14].

Moreover, observational data from the James Webb Space Telescope (JWST) has made profound contributions to the study of dark matter halos. JWST has identified numerous previously undetectable galaxies at redshifts z

> 10. Through precise measurements of the luminosity functions of these high-redshift galaxies, it becomes possible to empirically determine the population statistics of galaxies during the EoR and quantitatively assess their integrated capacity for ionizing photon production.

5. Results and Discussion

5.1 Key Findings from Simulation

Under the CDM paradigm, an abundant population of low-mass dark matter halos (~10^6 M ⊙) already exists during high-redshift epochs (z=15-20), resulting in a numerically rich low-mass end of the halo mass function. As the universe ages, halo counts increase across all mass scales, with the number of high-mass halos increasing most markedly through rapid hierarchical merging of smaller systems. This evolutionary progression exhibits continuous and smooth characteristics, maintaining the numerical dominance of low-mass halos throughout cosmic history.

In contrast, WDM models exhibit fundamentally different behavior: particle thermal motions erase small-scale density fluctuations at high redshifts, strongly suppressing the formation of low-mass halos. A characteristic mass scale, determined by the particle mass, emerges below which the halo population declines precipitously or vanishes entirely. Compared to CDM, WDM yields substantially fewer total halos and a pronounced deficiency of low-mass systems. Structure formation is globally delayed, and even at low redshifts (z=5-6), the suppressed low-mass halo population remains evident, effectively representing a CDM distribution with its low-mass end erased.

FDM models share qualitative similarities with WDM but demonstrate enhanced suppression of low-mass halo formation due to quantum mechanical characteristics, while additionally introducing oscillatory features in the mass function.

Observational constraints on the total neutral hydrogen content requiring ionization necessitate a critical examination of the ionizing photon escape fraction. The CDM framework imposes relatively modest demands on this escape fraction (typically 5-20%), as the collective contribution from numerous low-mass galaxies enables efficient reionization without requiring highly efficient photon escape from individual sources. In contrast, both WDM and FDM scenarios necessitate substantially higher escape fractions (>50%), where the limited population of massive galaxies must account for nearly the entire ionizing photon budget. This stringent requirement presents significant theoretical challenges for WDM/FDM models. Consequently, these alternative models predict a characteristically delayed onset of the Epoch of Reionization compared to the CDM paradigm.

5.2 Implications for Structure Formation

Through the analysis of the two-point correlation function of galaxies and ionization bubbles, it is evident that the underlying dark matter distribution governs the spatial clustering pattern of luminous sources. In the CDM framework, numerous low-luminosity sources generate abundant small ionization bubbles that subsequently merge into larger structures. In contrast, the sparser source distribution in WDM and FDM models produces fewer but substantially larger and more isolated ionization bubbles.

The efficiency of feedback mechanisms exhibits a strong dependence on dark matter halo mass. The halo's gravitational potential well depth determines both the binding capacity for gas and the energy threshold required for feedback to produce significant dynamical effects. These feedback processes can subsequently modify the dark matter distribution through gravitational potential alterations, thereby influencing both the production and escape of ionizing photons. Within CDM scenarios, the abundance of low-mass halos enables efficient gas removal through feedback, leading to suppressed star formation. Conversely, the inherent suppression of low-mass halos in WDM and FDM models reduces the target population for feedback processes, consequently diminishing their overall cosmological impact.

5.3 Comparison with Observations

Currently, the CDM framework demonstrates stronger consistency with the majority of observational constraints. Primarily, semi-numerical simulations within the CDM paradigm can accurately reproduce the Thomson scattering optical depth measured by Planck through parameter adjustments, whereas WDM and FDM models struggle to match this optical depth without requiring unrealistically high ionizing photon escape fractions. Secondly, comparison with high-redshift galaxies discovered by JWST reveals general agreement with CDM predictions, while WDM and FDM models systematically underestimate observed galaxy abundances. Finally, Lyman-α forest measurements of neutral hydrogen fraction at z~5-6 indicate the EoR's essential completion by z~5.5, a temporal evolution that aligns more closely with CDM predictions than with alternative dark matter scenarios.

6. Conclusion

Dark matter constitutes the gravitational skeleton for

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structure formation during the EoR. The intrinsic properties of dark matter directly govern the formation timeline, mass distribution, and spatial configuration of dark matter halos. These fundamental characteristics consequently dictate the global morphology and evolutionary progression of the entire reionization epoch. Studying the EoR not only reveals the formation processes of the early universe but also serves as a powerful probe into the fundamental nature of dark matter itself.

Future efforts will require the integration of galaxy survey data from JWST and other observatories to break existing theoretical degeneracies, coupled with higher-resolution simulations to resolve small-scale evolutionary physics.

References

[1] Saleem Zaroubi. The first Galaxy. Springer Berlin, Heidelberg, 2004.

[2] Ralf S. Klessen and Simon C.O. Glover. The First Stars: Formation, Properties, and Impact. Annual Review of Astronomy and Astrophysics, 2023, 61(1):65-130.

[3] Enrico Garaldi, Verena Bellscheidt, A. Smith, et al. The galaxy-IGM connection in THESAN: the physics connecting the IGM Lyman- opacity and galaxy density in the reionization epoch. arXiv preprint, 2025, arXiv:2410.0853.

[4] Gianfranco Bertone and Dan Hooper. History of dark matter. Reviews of Modern Physics, 2018, 90(4): 045002.

[5] Nima Arkani-Hamed, Douglas P. Finkbeiner, Tracy R. Slatyer, et al. A theory of dark matter. Physical Review D, 2009, 79(1):015014.

[6] Anchal Saxena, Suman Majumdar, Mohd Kamran, et al. Impact of dark matter models on the EoR 21-cm signal bispectrum. Monthly Notices of the Royal Astronomical Society, 2020, 497(3):2942-2945.

[7] David J. E. Marsh. WarmAndFuzzy: the halo model beyond CDM. arXiv preprint, 2016, arXiv: 1605.05973.

[8] Giocoli, Carlo. Hierarchical Clustering: Structure Formation in the Universe. Università degli Studi di Padova, 2008.

[9] C. S. Kochanek and Martin White. Global Probes of the Impact of Baryons on Dark Matter Halos. The Astrophysical Journal, 2001, 559(2).

[10] Fabio Capela, Maxim Pshirkov, and Peter Tinyakov. Adiabatic contraction revisited: Implications for primordial black holes. Physical Review D, 2014, 90(8):083507

[11] K. Dolag, S. Borgani, S. Schindler, et al. Simulation Techniques for Cosmological Simulations. Space Science Review, 2008, 134(1-4):229-268

[12] Andrei Mesinger, Steven Furlanetto, Renyue Cen. 21cmfast: a fast, seminumerical simulation of the high-redshift 21-cm signal. Monthly Notices of the Royal Astronomical Society, 2011, 411(2):955-972.

[13] Jonathan R Pritchard and Abraham Loeb. 21 cm cosmology in the 21st century. Report Program Physics, 2012, 75(8): 086901.

[14] Anatoly Klypin, Francisco Prada, Gustavo Yepes, et al. Halo abundance matching: accuracy and conditions for numerical convergence. Monthly Notices of the Royal Astronomical Society, 2015, 447(4):3693-3707.