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Possible Causes of Dark Matter Distribution in the Early Universe: Based on Quantum Fluctuations

Shuning Yu*

School of Life Sciences, Yunnan University, Yunnan, 650000, China
*Corresponding author: 20241070037@stu.ynu.edu.cn

Abstract:

Studying the early universe's formation is key to understanding current cosmic structures, especially dark matter distribution—vital for shaping galaxy clusters, filamentary networks, and voids like KBC voids. Existing theories (Big Bang, inflation, Cold Dark Matter) underpin cosmic evolution but lack a clear link between early dynamics and dark matter's specific distribution. Drawing on quantum fluctuation theory and observational data (cosmic microwave background/CMB radiation, early galaxy redshift, dark matter halo observations), this paper hypothesizes: In the extremely short period of time (10^{-36}–10^{-32} seconds) after the Big Bang, the universe's exponential expansion stretched microscopic quantum fluctuations to macroscopic scales. These induced spatial density perturbations: higher-density regions, with stronger gravity, attracted baryonic and dark matter, evolving into galaxy clusters/nodes; lower-density areas, lacking strong gravity and depleted of matter by neighbors, formed voids. Quantum fluctuations' continuity and randomness can explain well the phenomena of dark matter network's branching and galaxies' clustered distribution. The hypothesis accounts for major cosmic structures but faces challenges (e.g., quantifying dark matter filament length/branching, verifying "heavy element drag" in curved network regions). Future research should prioritize measuring primordial gravitational waves, high-resolution galaxy structure observations, curved region element analysis, and quantum fluctuation experiments to complement cosmic evolution theories and clarify early dark matter distribution origins.

Keywords: Early universe; Dark matter distribution; Quantum fluctuations; Cosmic microwave background (CMB); Cosmic structure formation.

1. Introduction

As the direct cause of the microscopic universe's development to its current state, it is imperative to study the early formation process of the universe. However, to date, various hypotheses have emerged endlessly, and there is no completely definitive conclusion regarding this formation process. Therefore, this paper will propose a theoretically relativity feasible hypotheses based on existing observational data and theories and expand upon it.

So far, many hypotheses have been proposed, such as The Big Bang theory, the inflation theory, and the no-boundary condition theory. The hypothesis presented in this article bears some similarities to the inflation theory and The Big Bang theory. Currently, it is known that during The Big Bang, matter and energy were transferred isotropically, but later distributions exhibited significant density differences, resulting in the present-day universe resembling a mesh-like distribution, and the emergence of spaces with low matter content, such as the KBC voids.

In this paper, the author has fully considered the feasibility of exploring the early formation process of the universe based on quantum fluctuations. This paper has tried to avoid unverified content and present the theoretical approach.

The structure of this paper is as follows. In section 2, the author first discussed the development history of the universe from its birth to the present day, focusing on the events that have had a significant impact on the formation of the current network structure of the universe. Next, the author summarized and generalized the information on the evolution of the universe that humans have detected so far. In section 3, this paper will combine the known detection information summarized in section 2 with quantum fluctuations theory to make reasonable hypotheses. At the same time, this paper will point out the urgent problems to be solved in the hypotheses and the new detection information needed. Finally, section 4 will summarize the above article, focusing on conclusions and possible breakthrough directions.

2. Cosmic Evolution Background and Observational Evidence for Early Dark Matter Distribution

2.1 Key Theoretical Foundations

There was a reionization period in the early universe, which can be inferred through redshift and Ly-α rays. Previously, a galaxy with $z \approx 13$ (JADES-GS-z13-1-LA) was detected, and Ly-α emission lines were clearly detected in its spectrum. According to the detected data and constructed models, the galaxy formed 330 million years after The Big Bang. Its Ly-α emission indicates the existence of galaxies in the early universe that could effectively ionize the surrounding medium, supporting the idea that cosmic reionization is an "early and gradual" process, possibly dominated by low-mass galaxies [1].

Based on the information currently detected, scientists assumed that the early universe had uniformity and isotropy. In the early phases of expansion, the radiation density $\rho_R \propto a^{-4}$ and the matter density $\rho_M \propto a^{-3}$ (dark and baryonic). According to Einstein equations and Friedmann-Robertson-Walker (FRW) metric, can have

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3} a_R \frac{g^*(T)}{2} \times T^4 \tag{1}$$

to describe the geometric shape of the universe [2]. This formula is applicable to describing the relationship between the cosmic expansion rate and radiation density. By combining it with the evolution of dark matter density, it can be inferred that after the radiation-dominated phase in the early universe ended, dark matter density gradually became the dominant force in gravity, providing a time window for dark matter clustering induced by quantum fluctuations.

2.2 Observational Data Supporting Dark Matter Distribution Studies

Hubble's Law states that the speed of galaxy regression is proportional to distance, which proves that the universe is constantly expanding. By measuring the redshift of distant galaxies, a three-dimensional distribution map of cosmic matter can be drawn, providing key support for studying dark energy [3].

In addition, studying the cosmic microwave background radiation is also helpful for the study of the early development of the universe. Cosmic microwave background (CMB) is a remnant of thermal radiation from approximately 380000 years after the Big Bang, with a blackbody radiation spectrum and a temperature of around 2.7K, exhibiting very low anisotropy. Its tiny temperature fluctuations reveal the seeds of the large-scale structure of the universe. By analyzing the anisotropy of CMB, the age, density, expansion rate, and proportion of ordinary matter, dark matter, and dark energy of the universe can be inferred.

Dark matter is also one of the very important factors. A type of high-quality dark matter halo is a rare density peak in the early universe, supporting the theory of "quasars born from massive dark matter halos" in the Cold Dark Matter (CDM) cosmological model, and consistent with

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observed phenomena such as Lyman alpha nebulae and cold gas flows [4]. This research result, along with other similar studies, is somewhat related to the distribution of dark matter in the early universe. Someone has suggested that if dark matter does indeed interact with itself, then when dark matter particles collide, they release some energy. In the early universe, the density of star formation sites may have been enough to make annihilated dark matter the energy source for the first stars in the universe, which are called “dark stars” [5].

Observations of the co-distribution of dark matter, galaxies, and diffuse gas further validate the link between quantum fluctuations and large-scale structure. Kou & Bartlett cross-correlated galaxy surveys, gravitational lensing maps, and Sunyaev-Zel’dovich effect data to show that dark matter filaments (traced by lensing) are spatially aligned with galaxies and hot gas—consistent with the hypothesis that quantum fluctuation-induced density perturbations drive co-evolution of all cosmic components. Their results quantify how dark matter’s distribution (shaped by quantum fluctuations) regulates the distribution of visible matter [6].

There are many similar theoretical foundations required, which will not be fully listed here.

3. Reasonable Hypothesis: Based on Quantum Fluctuations Theory

3.1 Theoretical Basis of Quantum Fluctuations and Its Relevance to Dark Matter

In quantum mechanics, the physical quantities of microscopic systems do not always have definite values. Even in the lowest energy “vacuum state” (such as a state without real particles in vacuum), quantum fields still experience transient energy or particle number fluctuations: particle pairs (such as positrons and electrons) can “appear out of thin air” for an extremely short period of time, and then quickly annihilate. Due to the continuity and uncertainty of quantum fluctuations, this theory can be used to explain the random distribution of galaxies and dark matter webs in the current cosmic structure, and it can also provide a certain degree of explanation for the formation of galaxy clusters.

Quantum fluctuation theory can explain the temperature fluctuations of CMB radiation. Quantum fluctuations may also play a direct role in the origin of dark matter particles. Ismail et al. proposed a new mechanism where axion dark matter is produced via an inflation-driven quantum phase transition: quantum fluctuations during inflation trigger symmetry breaking in the early universe, generating a coherent axion field that constitutes dark matter. This model bridges quantum fluctuations (the core of this paper’s hypothesis) with dark matter’s particle nature, suggesting that the same quantum processes driving density perturbations may also account for dark matter’s existence. The minor inhomogeneities in temperature distribution may be caused by quantum fluctuations that were stretched to macroscopic scales during the inflation process. The theory suggests that the influence of quantum fluctuations on gravitational changes can also explain the formation of large-scale structures in the present-day universe [7].

This theory can also explain the origin of the uniformity and isotropy of the universe on a large scale, which is difficult to explain by classical cosmology. All structures in the universe, such as galaxy clusters and superclusters, require “initial density fluctuations” as the starting point for gravitational collapse, which is the theory of quantum fluctuations. It can be explained that these initial fluctuations originate from quantum fluctuations in the vacuum.

The positions of satellite galaxies generally follow the cosmic web and are often arranged in filamentary structures. In the ‘high-mass’ sample, such as the HM-1 and HM-2 regions, the “satellite filamentary structures” formed by companion galaxies are obvious, with an extension scale of up to 0.5 Mpc, which is comparable to the field of view of a single NIRCam imaging channel. This is consistent with the observed satellite filamentary structure of the z=6.6 quasar J0305. In other regions (e.g., HM3), the distribution of satellite galaxies tends to be more isotropic. In addition, the number of companion galaxies varies significantly between different samples, reflecting the changes in the number of bright galaxies in the quasar fields.

3.2 Hypothesis Formulation

In section 2, this paper assumed that during the Big Bang, the transfer of energy and matter was equal in all directions. That is to say, within a very short period of time after the Big Bang (about 10-36 ~ 10-32 or 10-44, a Planck time), the amount of matter and energy contained in a unit space of the same size in all directions is equal. In the extremely short period immediately after The Big Bang, the universe underwent exponential accelerated expansion, which stretched quantum fluctuations to macroscopic scales.

Due to quantum fluctuations, continuous density differences emerge in space, resulting in stronger gravity in areas of higher density and weaker gravity in areas of lower density. This causes matter to be attracted by regions of high density, thereby gathering towards these points. Over time, the densely packed spatial points accumulated more and more matter, further expanding the gravitational force in these regions, gradually forming today's galaxy clusters and galaxies. Due to the randomness of quantum fluctuations, it is highly probable that multiple points with strong gravitational forces are distributed relatively close to each other, which maybe one of the reasons for the formation of today's groups of galaxies. Recent observations of dwarf galaxies further support the role of quantum fluctuation randomness in galaxy clustering. Wang et al. detected an anomalously high clustering of diffuse dwarf galaxies around massive galaxies, which cannot be fully explained by the standard CDM model's 'density peak' mechanism. This 'dark matter halo clustering bias's phenomenon aligns with the hypothesis: quantum fluctuations during the early universe generated random density perturbations, causing dwarf galaxies to preferentially form in regions with correlated gravitational perturbations—resulting in the observed clustered distribution [8].

The magnitude of quantum fluctuations is continuous. Relatively speaking, the gravitational force required to attract regular matter is greater than that required to attract dark matter. Therefore, can speculate that during the early formation of the universe, points with relatively stronger gravitational forces would attract more regular matter and dark matter. Points with relatively weaker gravitational forces could only attract a small point of the remaining dark matter. Meanwhile, if there are two spatial points where quantum fluctuation phenomena are relatively pronounced, their own gravitational forces will affect the space within a certain range around them. This may be the reason for the formation of the dark matter network.

The formation of void regions may be attributed to the absence of points with strong gravitational forces within these areas during the initial formation of quantum fluctuations. With the subsequent expansion of the universe and the attraction of other points with stronger gravitational forces, the region contained less conventional matter, gradually leading to the formation of voids with a large spatial extent today. The root cause of this "gravitational strength difference" lies in the continuous density distribution (from minor to more significant density perturbations) brought about by quantum fluctuations. The evolution of the universe continuously amplifies this difference, ultimately forming a cosmic web where "dark matter-dominated filamentary structures" coexist with "high-density nodes where galaxies are located".

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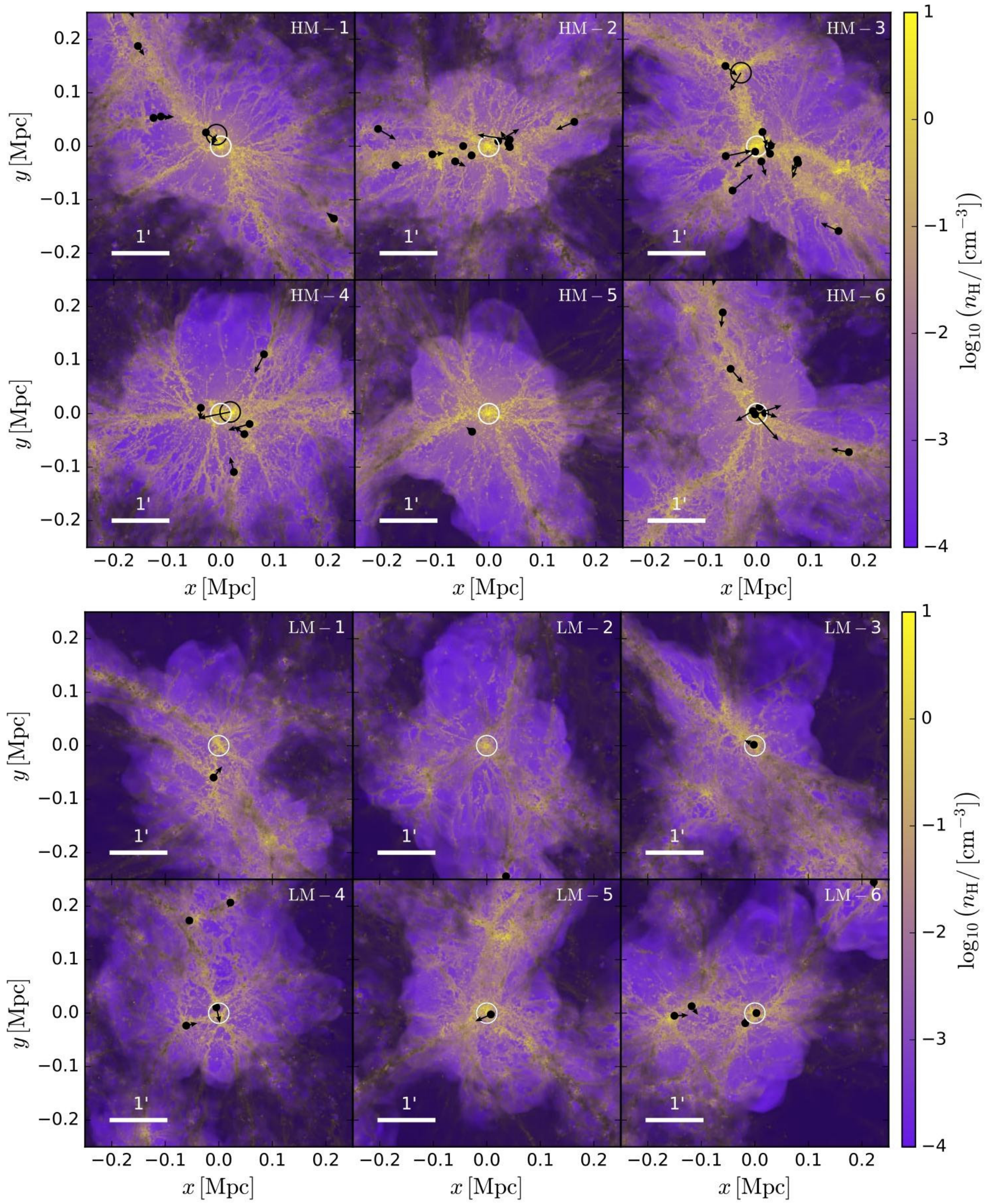

Fig.1 Simulation of dark matter filamentary structure and galaxy distribution [9]

However, in essence, this theory still has many imperfections, which will be elaborated in detail in section 3.3.

3.3 Unresolved Issues and Challenges

Currently, although this theory can explain the formation of many current cosmic structures, there are still some areas that it cannot cover, such as the formation of the shape of the dark matter network between two galaxies. Scientists speculate that the length of the dark matter network between galaxies is much longer than the straight-line distance between them, and there is a large distribution of branches, possibly due to the fact that when quantum fluctuations first appeared in the universe, the space beyond the corresponding points of two galaxies had more pronounced quantum fluctuations, but they were not strong enough to form spatial points where galaxies appeared.

There is another hypothesis that suggests, possibly due to the fact that after the Big Bang, some regions were located far from spatial points where quantum fluctuations were evident, the matter in these regions was either not attracted or was attracted at a slower rate. This matter relied on the energy remaining from the Big Bang to continue nuclear fusion, producing heavier atoms that exerted a certain degree of attraction on their surroundings, thereby dragging the dark matter network to its current position. However, this theory requires subsequent elemental analysis of the regions with greater curvature in the dark matter network (i.e., areas that are clearly potential dragging points) and their surroundings, in search of possible remnants of heavier atoms as evidence to support it. Due to the difficulty in locating the types of elements within the dark matter network and the presence of numerous interfering factors in the region, it may be possible to start with easily detectable celestial bodies such as neutron stars and supernovae.

Currently, scientists still require additional observational data to bolster the theory of quantum fluctuations. For instance, precise measurements of primordial gravitational waves, more refined and detailed observations of large-scale galaxy structures, and CMB observations, direct observations of Hawking radiation from black holes, as well as more experimental verifications of quantum fluctuations at the microscopic scale. Also, the nature of dark matter particles remains a critical open question. Bucko et al. constrained the two-body decaying dark matter model using weak lensing and CMB data, finding that decaying dark matter could affect the growth rate of cosmic structures—including dark matter filaments and galaxy nodes. This suggests that integrating dark matter particle properties (e.g., decay or self-interaction) into the quantum fluctuation framework may resolve unresolved issues, such as the length of dark matter filaments [10].

4. Conclusion

Using observational data (e.g., CMB temperature fluctuations, dark matter halo observations) and theories (FRW metric, quantum fluctuation theory), this study hypothesizes early dark matter distribution: 10^{-36}–10^{-32} seconds post-Big Bang, cosmic exponential expansion stretched quantum fluctuations to macroscopic scales, creating density differences. High-density regions with stronger gravity accumulated dark matter (and some baryonic matter) into galactic nodes and filaments; low-density areas lacking strong gravity formed voids. Quantum fluctuations' continuity explains the dark matter network's branched structure, their randomness accounting for galaxy group distributions.

Unlike the CDM model, which focuses on dark matter halo „density peaks," this hypothesis uses quantum fluctuations' „continuous density perturbations" to explain the network's branched morphology and void origins. It also identifies quantum fluctuations' role in the „gravitational attraction difference"—dark matter needing lower gravity—shedding light on why dark matter accumulated earlier than baryonic matter.

Limitations remain: it can't quantify dark matter network length (e.g., filament lengths exceeding intergalactic distances) without more data; the „drag mechanism in curved network regions" (e.g., heavy element gravitational drag) lacks elemental analysis evidence; and it doesn't address dark matter particle nature (cold vs. warm), requiring integration with particle physics.

Future research will verify via X-ray spectroscopy for heavy elements in curved regions, high-precision primordial gravitational wave measurements, and particle physics models (e.g., Weakly Interacting Massive Particles, WIMPs) to quantify quantum fluctuations' impact on dark matter accumulation. It will also build a quantum fluctuation-driven dark matter distribution model, validated against galaxy surveys like Sloan Digital Sky Survey.

This study offers a new hypothesis for early dark matter distribution origins, clues to quantum mechanics and general relativity's applicability in early extreme conditions, and promotes interdisciplinary research on dark matter nature and large-scale cosmic structures.

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