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# Unraveling the Complex Dynamics of Dark Matter and Dark Energy

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**Abstract:**

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This study examines the dynamics of recent findings related to dark matter and dark energy, beginning with an overview of the theoretical concepts. It assesses various potential dark matter entities such as sterile neutrinos and primordial black holes, alongside a hypothesized exotic variant of hydrogen atoms. Different cosmic simulations are explored; THESAN simulations demonstrate the critical role of dark matter in galaxy formation conditions and galaxy stellar masses, while EAGLE simulations show that Maxwellian distributions are still effective for analyzing dark matter dynamics. The concept of dark energy in cosmic acceleration is discussed through the equation of state parameter. Observations from instruments like WMAP and studies of supernovae are explored; findings suggest that phi cold dark matter model (ϕCDM) aligns more closely to current observations compare to traditional lambda cold dark matter model (ΛCDM). Furthermore, the exploration of early dark energy as a potential approach to mitigate the Hubble tension is highlighted, proposing it as a vital factor in reconciling observed discrepancies in cosmic expansion rates.

**Keywords:** Dark matter, Dark energy, Equation of state parameter

## 1. Introduction

### 1.1 Overview of Theoretical Framework

Dark matter makes up 27% of the universe. Baryonic matter are known as familiar protons, neutrons, and electrons that make up all visible matter, such as stars, planets, and galaxies. These atoms constitute about 5% of the universe's total energy density, which translates to roughly one proton per four cubic meters, Dark matter also constitutes approximately 84% from the mass content in the universe. Unlike baryonic matter which interact with electromagnetic force, dark matter does not. Although it does not emit, absorb, or reflect light, its presence and gravitational effects are inferred from its interactions with visible matter and radiation. It consists likely of one or more types of subatomic particles that do not interact strongly with electromagnetic forces, meaning they cannot be seen with traditional telescopes. Studies of dark matter are crucial for understanding the structure and evolution of the universe. These effects are crucial in binding galaxies together and in forming large-scale structures like galaxy clusters and superclusters. The gravitational pull of dark matter affects the motion of galaxies within clusters, influencing their speed and trajectory in ways that can be measured through gravitational lensing techniques. These measurements methods will further examine the distribution and density of dark matter.

Dark energy is accounting for approximately up 68% of the universe. It is the cause of universe's accelerated expansion. Its discovery came from observations supported by other astronomical data, including measurements from the WMAP satellite [1]. Nature of dark energy presents intriguing questions about the fate of the cosmos. The observations of distant Type Ia supernovae suggests that the universe's expansion is not only continuing but is accelerating. This acceleration implies a repulsive force overcoming the gravitational pull of all matter in the universe. The precise nature of dark energy remains one of the greatest mysteries in astrophysics, with researchers considering various models beyond the cosmological constant.

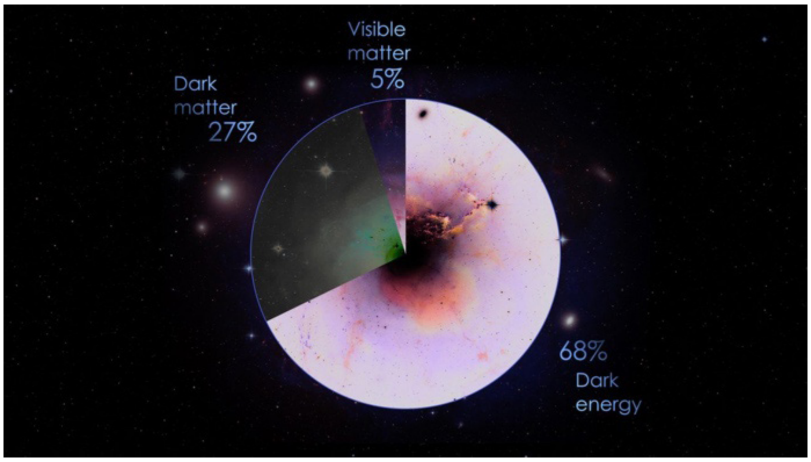


Fig 1 Universe's total energy distribution [1]

## 1.2 Potential candidates for Dark Matter and Dark Energy

Recent investigations have highlighted potential candidates for dark matter such as sterile neutrinos, self-interacting dark matter, and primordial black holes, each proposing unique interactions within the cosmic framework [2]. The study also suggests dark matter may include a previously unknown form of hydrogen atoms. This theory is supported by detailed atomic experiments and astrophysical observations analyzing the 21 cm spectral line. Anomalous results from these studies match the expected characteristics of these novel hydrogen atoms, positioning them as a potential baryonic candidate for dark matter. Further, primordial black holes (PBHs), another candidate for dark matter, are believed to have emerged from intense density fluctuations in the early universe. They are posited as potential dark matter candidates within quantum gravity-inspired models. These models challenge conventional black hole metrics by removing singularities and broadening the conditions for black hole formation. Implies PBHs constitute a significant portion of the universe's dark matter. The cosmological constant (Λ) is widely recognized as a primary candidate for dark energy, characterized by a uniform energy density that pervades space and simplifies the explanation for the expansion of universe. Dark energy's properties and forms can be analyzed from a eqaution, it is the quation of state parameter (ω). This equation is made up by two variables components, they are pressure (p) and energy density (ρ), as expressed in the following term:

$$\omega = \frac{p}{\rho}. \tag{1}$$

The universe's expansion rate is significantly influenced by the equation. The cosmological constant Λ, is characterized by $\omega = -1$, indicating a constant energy density that permeates space uniformly and is responsible for the observed acceleration of the universe. This value implies that dark energy's pressure is negative, counteracting gravitational attraction and driving expansion. Alternative dark energy candidates are explored by considering deviations from it. Quintessence, for instance, is a dynamic scalar field with an equation of state parameter typically in the range of $-1 < \omega < -\frac{1}{3}$. It evolves over time and space, allowing for a varying energy density. In contrast, phantom energy exhibits $\omega < -1$, leading to even stronger repulsive forces than the cosmological constant Λ. This extreme negative pressure will be predicting a future scenario called the "Big Rip", where the accelerated expansion becomes so intense it ultimately tearing apart the

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galaxies, stars, even atomic particles. Eventually tearing apart the fabric of space-time itself. In this scenario, the repulsive force exerted by phantom energy increases without bound over time and overcomes all other forces in the universe.

In the quintessence model, the universe may end in a "Heat Death" scenario, reaching thermodynamic equilibrium. Here, energy is spread so evenly that entropy is maximized, it will prevent any work from being done and eliminating macroscopic energy differences. This state results in a uniform universe where no movement or life can occur due to the consistent temperature and energy levels.

From alternative aspects, research suggests that observed cosmic acceleration might be accounted for by changes in gravitational theory rather than an elusive form of energy. The theories suggesting modifications to Newtonian dynamics and the strong equivalence principle could explain the observed cosmic acceleration [2]. Potentially rendering the concept of dark energy unnecessary in our current understanding of cosmology.

## 2. Empirical Findings and Simulation Results

### 2.1 Dark Matter Discoveries and Insights

A cosmic simulation studies using the THESAN simulation focuses on the relationship between dark matter and baryonic matter, illustrating the processes of galaxy formation and providing insights into their interactive dynamics. The study predicts a positive correlation between the star formation rates and baryonic stellar mass with the galaxy dark matter halo mass, respectively [3]. There is also a positive relationship between absolute ultraviolet (UV) magnitude of a galaxy, which measures its intrinsic brightness in the UV spectrum at 1500 angstroms and their corresponding dark matter halo masses. UV magnitudes are crucial for studying young, hot stars and regions of active star formation within galaxies, as these stars emit strongly in the UV spectrum.The heavier the dark matter halo, the more substantial its gravitational influence on accumulating stellar mass and formation conditions of new galaxy and stars. By mapping UV brightness across different galaxies, astronomers can infer the mass and distribution of dark matter halos, offering a non-intrusive method to study these elusive structures. Studies like these will be enhancing our understanding of the evolutionary stages of galaxies and the role of dark matter in early universe phenomena, including reionization and the formation of the first galaxies. Building on top the findings from the THESAN simulation and UV magnitude mappings, further research could be focusing on how these dark matter halos influence not only the formation but also the evolution and eventual fate of galaxies. Many projects like THESAN and IllustruisTNG are already working towards this direction. Future observational campaigns using advanced space-based telescopes equipped with UV-capable instruments could extend our studies to more distant galaxies, observing how early dark matter distributions set the stage for the formation of galaxy clusters and superclusters. In this approach, it allows for a more nuanced understanding on how dark matter's gravitational effects are tempered by other cosmic forces, influencing everything from star birth to galaxy mergers.

On the otherhand, theoretical models have been validated using cosmic simulations. In a study using EAGLE simulations, researchers explored the impact of dark matter self-interactions in Milky Way-like galaxies using two models: constant and velocity-dependent cross-sections. The findings revealed that local dark matter velocity distributions align closely with Maxwellian distributions, matching predictions from cold collisionless dark matter models with baryons. This consistency across models suggests that Maxwellian distributions are still effective for analyzing dark matter dynamics in direct detection experiments [4].

### 2.2 Dark Energy Discoveries and Insights

On the aspects of dark energy, by analyzing precision data from supernovae and acoustic scales, the equation of state for dark energy consistently registers below -1, aligning towards the concept of phantom energy. However, a study suggest Big Rip singularity might be preventable due to gravitational Schwinger pair-production. This process maintains a high but constant Hubble rate, potentially transitioning the universe into a de Sitter inflationary phase, which could recur in a cyclic manner. These findings suggest an alternative to the Big Rip, proposing a model where the universe undergoes periodic expansions and contractions, although the exact mechanics and implications of phantom energy decay and its cyclical nature require further exploration [5]. In terms of the equation of state parameter itself, an in-depth analysis of CMB, Baryon Acoustic Oscillations (BAO), Supernovae data reinforces a measurement of $\omega = -1.013$. The result slightly deviates from the standard ΛCDM model where $\omega = -1$ [6]. The implications will be further discussed in section 3.1.

Furthermore, a recent review highlights the ongoing Hubble tension, a significant 4-6σ reflecting variations between Hubble constant (H0) values calculated using local distance ladder methods and those data derived from

CMB [7]. The Hubble constant, essential for determining the universe's expansion rate, shows higher estimates from local methods involving Cepheid variables and Type Ia supernovae than from CMB analysis. ΛCDM framework faces challenges in reconciling these variances. This discrepancy has sparked discussions about potential modifications to our understanding of dark energy and dark matter, suggesting a possible need for new gravitational theories. However, no new theories have been definitively proven, primarily due to the absence of decisive observational data, highlighting the importance of more precise and comprehensive future observational studies.

## 3. Theoretical Extensions and Future Prospects

### 3.1 Alternative Models on Dark Energy

The ϕCDM model stands out as a significant theoretical development, dynamically describe dark energy through quintessence and phantom models. The study finds that while the ΛCDM model featuring a constant dark energy component is preferred, ϕCDM models align with current statistical analysis of high-redshift data from Type Ia Supernovae, Quasi-Stellar Objects (QSOs), and gamma-ray bursts. It confirms that the dark energy component is dynamic and evolving in nature. This conclusion was also reached using a novel parametric scheme for the Hubble parameter integrating both quintessence and phantom models. Observational data from the CMB, Supernovae, and BAO were analyzed using the CLASS and Montepython codes to validate this model against empirical data, all supporting ϕCDM model's superiority over ΛCDM [8]. In terms of hubble tension, research states a new dark energy model. It states measurements and local distance-redshift data cannot be explained by systematic errors. The early dark energy model is the most promising for addressing this tension. However, current CMB data are not precise enough to confirm early dark energy's validity over the standard ΛCDM model [9].

### 3.2 Future Prospects on Research

In the search of dark matter's candidate. The ADMX experiment, using SQUID amplifiers, refines the target parameters for future axion-based dark matter searches. The research result has excluded axions with masses between 3.3 and 3.53 microelectronvolts (μeV) as local dark matter with 90% confidence [10]. This finding narrows viable axion mass ranges, guiding future dark matter searches to focus on lighter or heavier axions or alternative particles. Additionally, the axion's potential to bridge gaps in our understanding of dark matter directly supports the ongoing need for highly sensitive detection technologies that can operate at the quantum scale. For dark energy, the reviews pinpoint the potential of other upcoming detailed observations, such as those from CMB Stage 4 telescopes and the James Webb Space Telescope, to provide the necessary precision to either confirm or refute these theories to solve Hubble tension [7]. For early dark energy, future experiments, like those mapping smaller-scale CMB polarization are essential for testing the concept. More precise local H0 measurements are required to cross-check results [9]. These studies are essential for testing theoretical predictions about early dark energy's influence on the structure of the CMB temperature fluctuations. These observations are key to understanding how early dark energy may have affected the rate of cosmic expansion shortly after the Big Bang. Further measurements on the Hubble constant from local astronomical objects will complement these findings, offering a means to cross-verify results from cosmic observations. Ongoing and upcoming cosmological missions promise enhanced precision in cosmological data collection. These comprehensive observations are expected to refine our knowledge of the universe's dynamic, providing new insights into cosmology.

## 4. Summary

The study has discussed recent findings on dark energy and dark matter, including the exploration of potential candidates for dark matter and future axion-based dark matter searches. Empirical results and cosmic simulation models offer significant insights into dark matter's interactive relationship with baryonic matter on a galactic scale which iscrucial for galaxy formation processes, while validating the existing theoretical frameworks. Alongside dynamic models for dark energy, such as the ϕCDM model contrasts with the traditional ΛCDM model. Alternative ending of the universe under phantom energy model is discussed when $\omega < -1$ . Early dark energy is identified as a potential candidate to resolve Hubble tension. These findings underscore the dynamic and evolving nature of current cosmological research. Future prospects involve leveraging various advancements in cosmological surveys and technologies to further explore and refine our understanding of dark matter and dark energy.

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