Dark Matter and Its Role in the Universe: Cosmological and Entropic Perspectives

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Abstract

Dark matter remains one of the most compelling and elusive components of the universe, accounting for nearly 27% of its total mass-energy content. While its gravitational influence is well established through galactic rotation curves, gravi- tational lensing, and cosmic microwave background (CMB) anisotropies, its fun- damental nature continues to evade direct detection. This paper presents a com- prehensive overview of dark matter within the framework of modern cosmology, emphasizing its role in structure formation and universal evolution. Further, the discussion extends to the thermodynamic implications of dark matter in the con- text of black hole entropy and spin dynamics, highlighting potential connections between dark matter, gravitational entropy, and dark energy.

Keywords: Dark Matter, Cosmology, Entropy, Black Holes, Spin Parameters, Struc- ture Formation

Introduction

The universe, as understood through the standard cosmological model (ΛCDM), con- sists of approximately 5% ordinary (baryonic) matter, 27% dark matter, and 68% dark energy. The concept of dark matter was first introduced by Fritz Zwicky (1933) to ex- plain discrepancies between visible mass and gravitational effects in galaxy clusters. Subsequent studies, particularly of galactic rotation curves and the CMB power spec- trum, have solidified dark matter's role as the dominant form of matter in the cosmos. However, its composition remains unknown, suggesting the existence of non-luminous, weakly interacting particles or exotic compact objects.
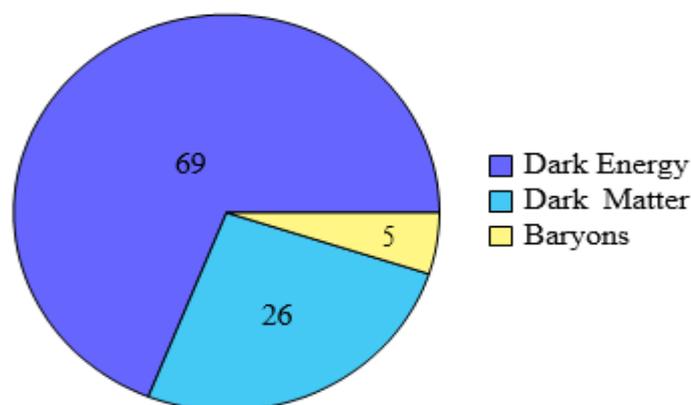

Figure 1: Approximate composition of the Uni- vers in the Λ*CDM model* (*Planck* 2020 *baseline*): 69 %*dark energy*, 26 %*dark matter*, 5 %*baryons*.

In the early universe, dark matter played a critical role in seeding the growth of cosmic structures. Observations of CMB anisotropies ($\Delta T/T \approx 10^{-5}$) reveal that dark matter perturbations gravitationally enhanced the density contrast, allowing baryonic matter to collapse into galaxies and clusters. The cosmological principle of isotropy and homogeneity leads to the Friedmann-Lemaître-Robertson-Walker (FLRW) metric, which governs universal expansion through the Friedmann equations:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}(\rho_m + \rho_r + \rho_\Lambda) - \frac{k}{a^2} \tag{1}$$

where $a(t)$ is the scale factor and ρ_m includes both baryonic and dark matter densities. In the matter-dominated epoch, the density perturbations grow linearly as $\delta_m \propto a(t)$, forming the scaffolding for galaxy and cluster formation.

Observational Evidence

Evidence for dark matter arises from multiple astrophysical and cosmological observa- tions:

Galaxy Rotation Curves: The flatness of stellar velocity profiles at large galactic radii implies an unseen mass halo, consistent with $\rho(r) \propto r^{-2}$.

Gravitational Lensing: The bending of light around massive clusters exceeds predictions from visible matter alone, confirming additional mass components.

Cosmic Microwave Background: Planck satellite data provide precision con- straints on dark matter density, supporting the ΛCDM model.

Bullet Cluster Observations: Separation between baryonic gas (via X-rays) and gravitational potential (via lensing) reveals the collisionless nature of dark matter.

Particle Candidates and Theoretical Models

Several dark matter candidates have been proposed, including Weakly Interacting Mas- sive Particles (WIMPs), axions, sterile neutrinos, and primordial black holes (PBHs). WIMPs, predicted in supersymmetric extensions of the Standard Model, naturally yield the observed relic density through thermal freeze-out with an annihilation cross-section
$\langle \sigma v \rangle \approx 6 \times 10^{-26}$ cm^{3}s^{-1}. Alternatively, axions—arising from the Peccei-Quinn mech- anism—offer a solution to the strong CP problem and may form Bose-Einstein conden- sates behaving as cold dark matter.
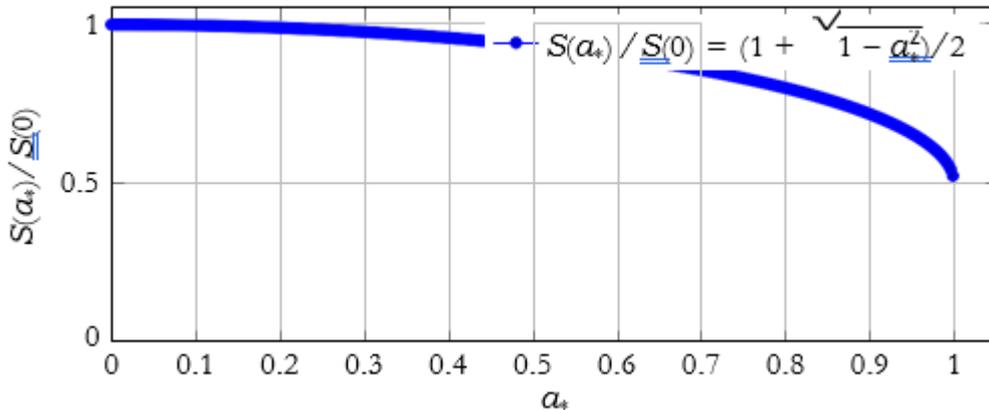
Dark Matter and Entropy in Black Hole Physics

Figure 2: Normalized Kerr black hole entropy as a function of dimensionless spin pa- rameter $a_* = Jc/(GM^2)$. Higher spin reduces the horizon area and hence the entropy for fixed mass.

Recent research has suggested potential links between dark matter, gravitational en- tropy, and black hole dynamics. The entropy S of a black hole, given by the Bekenstein- Hawking formula $S = \frac{k_B c^3 A}{4 G \hbar}$, is proportional to the event horizon area A. When con- sidering spinning (Kerr) black holes, entropy varies with mass M and spin parameter $a_* = Jc/GM^2$. In astrophysical contexts such as X-ray binaries (XRBs) and active galactic nuclei (AGNs), variations in entropy may be influenced by surrounding dark matter halos, modifying the energy exchange and accretion efficiency.

Furthermore, modeling dark matter as a weakly interacting fermionic or bosonic field introduces entropy corrections associated with non-standard spin states (e.g., $\pm 1/4$, $\pm 3/4$). Such spin-dependent entropy perturbations may contribute to the local dark energy density or modify Hawking radiation rates. These effects hint at a deeper thermodynamic interplay between dark matter, quantum spin statistics, and black hole entropy.
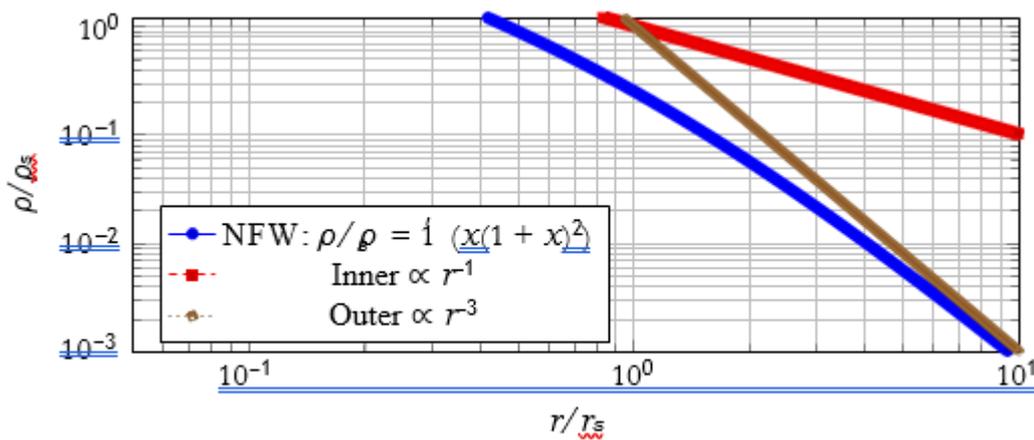

Figure 3: Characteristic shape of the Navarro–Frenk–White (NFW) halo density profile and its inner/outer asymptotes.

accurately reproduce the large-scale cosmic web structure observed in galaxy sur- veys. On cosmological scales, dark matter's clustering opposes the repulsive influence of dark energy, maintaining a dynamic equilibrium in the universe's expansion.

Conclusion

Dark matter serves as the invisible backbone of the universe, shaping its structure and dynamics from the earliest moments after the Big Bang to the present cosmic web. Its gravitational influence is indispensable in explaining galactic stability and large- scale structure formation. The possible thermodynamic links between dark matter, entropy, and black hole spin parameters open an exciting interdisciplinary frontier, bridging cosmology, particle physics, and black hole thermodynamics. Further ex- perimental searches—through direct detection, collider experiments, and cosmological probes—remain vital for unraveling its true nature.

Acknowledgements

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