The Lens Journal
A journal of perspectives for young researchers

Investigating Different Dark Matter Theories

Smriti Pamarati

Abstract

This research paper explores various candidates proposed to explain the nature of dark matter, a fundamental yet elusive component of the universe. The methodology involves a comparative analysis of the strengths and limitations of each theory, with particular focus on Primordial Black Holes (PBHs), which emerge as a leading candidate. By evaluating the evidence and theoretical underpinnings, a logical conclusion is drawn to address the research question: Which theory of dark matter is the most accurate? The findings suggest that PBHs are the strongest contender due to their natural alignment with existing cosmological models and their compatibility with observed phenomena. However, the possibility that dark matter is composed of a combination of different candidates remains open, reflecting the complexity of this unresolved scientific challenge.

Keywords: Dark Matter, Primordial Black Holes, WIMPS, Axions, Hawking Radiation

I. Introduction

One of the most significant questions in physics is “what is the universe made of ?” The standard model of particle physics attempts to explain this by explaining that which is visible. However, visible matter is only a small fraction of what actually exists - there is 6 times more matter than what is visible. This unknown matter is named “dark matter”. To understand what constitutes most of the universe, deductions about dark matter have been made with certain particles likely making up dark matter. However, the research is still ongoing as directly detecting dark matter particles is challenging. This study explores and compares leading theories of dark matter to evaluate which provides the most accurate and scientifically supported explanation of its composition.

DOI: 10.5281/zenodo.14635524

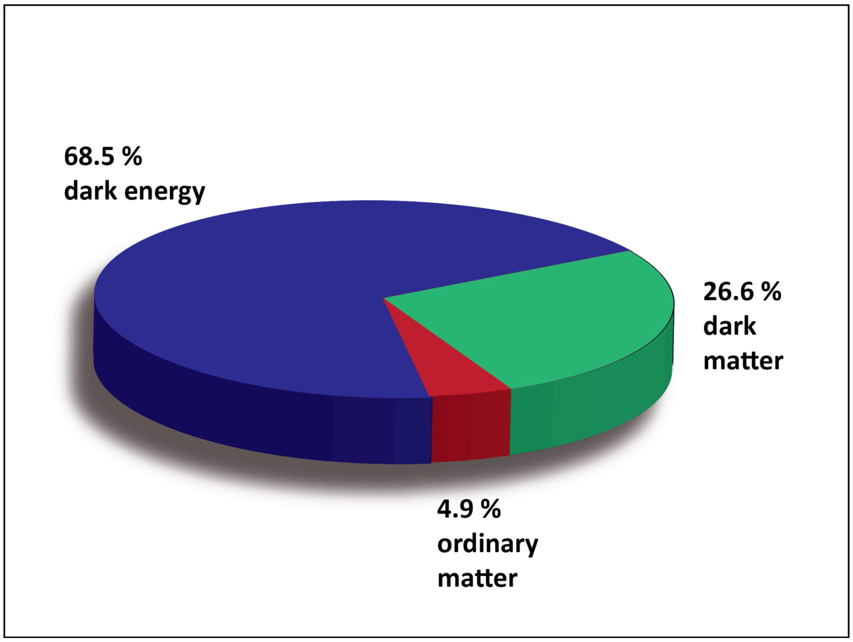

Fig 1.1. *The composition of the universe (Carney, 2020). The universe is fundamentally made up of the following. Baryonic matter comprises a small portion of the universe. A majority of the universe is still unknown.*

Theoretical calculations of the orbital velocity of matter, v, with respect to radius are done based on Keplerian mechanics, given in equation (1),

$$v = \sqrt{\frac{GM}{r}} \text{ — (1)}$$

where G is the Gravitational constant, M represents the mass contained in the orbit of a given star, and r is the orbital radius.

Theoretically, until observational velocities of galaxies were gathered, it was considered that at large radii, the velocity of a galaxy would decrease given the inverse square relationship, $\frac{1}{\sqrt{r}}$. The trend being that at the centre of the galaxy the velocity would be greatest and at larger radii, the velocity would comply with the inverse square relationship as illustrated by the blue line in Fig 1.2.

However, upon analysis of galaxy rotational curves, it was observed that at large radii the rotational curves of high luminosity spiral galaxies are constant or even increasing in some spiral galaxies, which contradicts the inverse square relationship. In the 1930s, Fritz Zwicky was the first to identify the disparity and suggest the existence of more matter in galaxy clusters than visible (Zwicky, n.d.). In the 1980s, Vera Rubin and her team concluded in their paper (Rubin, n.d.) that in high luminosity spiral galaxies, rotation curves are flat to as far as r = 50 kpc. This suggests the existence of unseen mass defined as a dark matter halo that pulls on the edges of the galaxy allowing it to have a rather high velocity even at such large distances from the centre. This discovery led to the hypothesis of dark matter and related investigations.

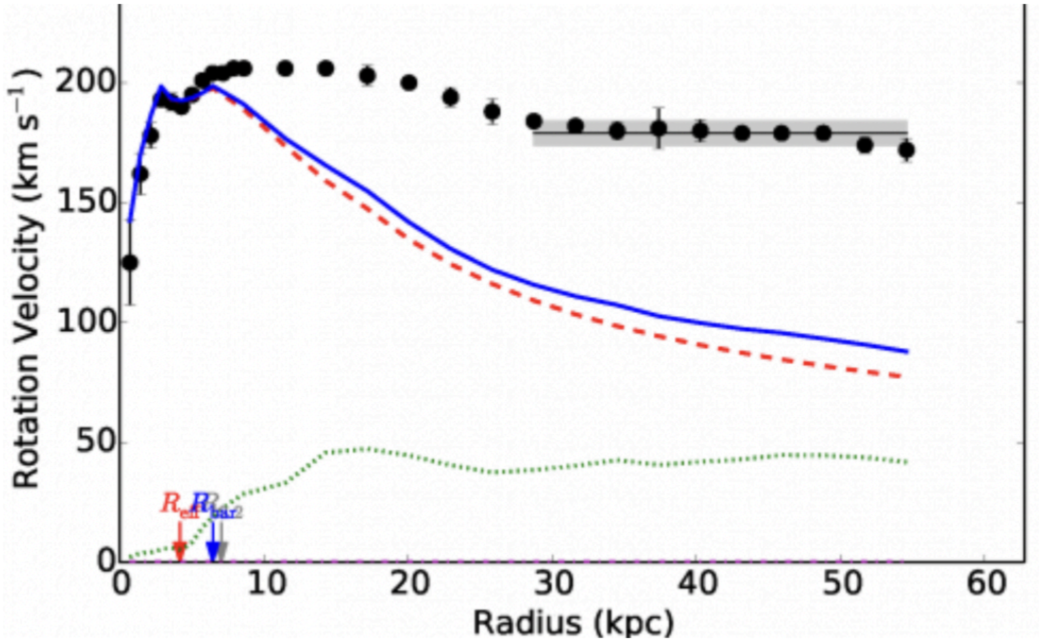

Fig 1.2. *The rotation curves of galaxy NGC5055. The blue curve represents the predicted values with regards to the inverse square relationship that rotational velocity of the galaxy has with the radius from the centre of the galaxy. The Black data points represent the actual values observed (Case Western Reserve University, 2016). The graph was plotted using data from the Spitzer Photometry And Accurate Rotation Curves SPARC database (Federico Lelli, 2020).*

The overwhelming evidence for dark matter's existence - ranging from the cosmic microwave background to galaxy rotation curves and gravitational lensing - has made its detection one of the most pressing topics in modern physics. Understanding dark matter would revolutionize our knowledge of the universe's composition and evolution, with implications for cosmology, astrophysics, and particle physics.

Scientists propose three main methods for detecting dark matter:

- Direct detection: This involves observing interactions between dark matter particles and baryonic matter. If dark matter particles collide with ordinary particles (e.g., electrons or nuclei), their effects could be detected using specialized detectors.
- Indirect detection: In this approach, scientists search for byproducts of dark matter annihilation or decay, such as photons, neutrinos, or antimatter. If dark matter and dark antimatter particles exist and interact, their annihilation could produce observable signals.
- Collider searches: Dark matter particles could be produced in high-energy collisions at facilities like the Large Hadron Collider (LHC). These particles, expected to interact weakly with detectors, might be identified indirectly through "missing" energy and momentum in collision events.

Experiments with the LHC and LEP have already placed constraints on dark matter properties. However, any discovery from collider experiments must be corroborated by findings from direct or indirect detection to confirm the particle's identity as dark matter. This multi-pronged approach ensures the robustness of any potential discovery and its consistency across different detection methods.

The motivation to detect dark matter stems from its critical role in the universe's structure and evolution. This paper evaluates various theories about the nature of dark matter, comparing their strengths and weaknesses to identify the most plausible explanation for this mysterious substance. By doing so, it contributes to the ongoing effort to uncover the universe's hidden composition.

The motivation to detect dark matter comes from historical discoveries that show it must be more prevalent than regular (baryonic) matter. This has driven scientists to search for potential candidates tirelessly, making it one of the hottest topics in modern physics. Understanding dark matter could revolutionise our knowledge of the universe's composition and evolution.

The first understanding is that these particles might bump into ordinary matter particles, much like an electron might bump into another electron. That’s one possible interaction. If dark matter was found this way, it would be called direct detection, because its effects of a dark matter particle hitting a baryonic matter particle could be seen.

Another possibility is that if dark matter exists and it’s basically a particle gas that permeates the galaxy, maybe there are both dark matter and dark antimatter particles. If they exist, then possibly a dark matter and dark antimatter particle might bump into one another and annihilate. Possibly what would come out of that interaction would be matter. If dark matter was found this way, it would be called indirect detection.

Then there’s the third way that one might imagine detecting dark matter and that’s creating it out of energy. Using large particle accelerators, subatomic particles are collided together and the energy is used to create particles that did not exist before the collision. This particular method of searching for dark matter is especially attractive, as the creation and detection and the entire process can be designed and studied very carefully.

An approach to the detection of dark matter particles in nature is to produce them in a laboratory. Experiments with the Large Hadron Collider (LHC) may be able to detect dark matter particles produced in collisions of the LHC proton beams. Because a dark matter particle should have negligible interactions with normal visible matter, it may be detected indirectly as (large amounts of) missing energy and momentum that escape the detectors, provided other (non-negligible) collision products are detected. Constraints on dark matter also exist from the LEP experiment using a similar principle, but probing the interaction of dark matter particles with electrons rather than quarks. It is important to note that any discovery from collider searches must be corroborated by discoveries in the indirect or direct detection sectors to prove that the particle discovered is, in fact, dark matter.

II. Literature Reviews

Dark matter, the enigmatic substance that constitutes most of the universe's mass, presents a fascinating challenge: how do scientists detect what cannot be seen? Understanding this requires exploring over a century of scientific developments, beginning with Lord Kelvin's groundbreaking insights in 1884. While studying the velocity dispersion of stars in the Milky Way, Kelvin investigated whether the galaxy's stability could be explained through the balance of gravitational potential energy and kinetic energy (Ferrell, 2019).

The term “dark matter” was first coined by Henri Poincaré in 1906, who referred to this unobservable mass as “matière obscure” (unknown matter) while discussing Kelvin’s findings. The idea gained further traction in the 1920s when astronomers such as Edwin Hubble, Herber Curtis, and Harlow Shapley expanded our understanding of the universe, demonstrating that the Milky Way was just one of many galaxies. This discovery allowed researchers to investigate the dynamics of other galaxies, deepening the mystery of unseen mass.

In the 1930s, Knut Lundmark contributed to the field by examining the mass-to-light ratios of five galaxies. His work revealed significant discrepancies, with ratios ranging from 6 to 100, implying that much of a galaxy's mass was not luminous. This laid the groundwork for Fritz Zwicky's landmark study in 1933, where he applied similar methods to galaxy clusters. Analyzing the Coma Cluster, Zwicky determined its mass-to-light ratio to be approximately 400. Although later refined due to inaccuracies in early estimates of the universe's expansion rate, his findings strongly supported the existence of dark matter, highlighting that the visible matter constituted only a fraction of the total mass in the cluster.

The 1930s also saw Horage W. Babcock measuring the rotation curves of galaxies - the velocities of stars as a function of their distance from the galactic center. His observations hinted at an anomaly: the expected decrease in velocity with increasing radius did not occur. Decades later, Vera Rubin provided definitive evidence of this discrepancy, identifying flat rotation curves that could not be explained by luminous matter alone. Her work provided strong evidence for the existence of dark matter and introduced the concept of dark matter halos surrounding galaxies (Dr. Becky, n.d.).

This historical progression underscores two critical gaps. Scientifically, the fundamental nature of dark matter remains unknown despite extensive research. Questions about its composition, interaction mechanisms, and implications for cosmology continue to drive inquiry. However, there is also a communication gap: the wealth of scientific insights and theories surrounding dark matter often remains inaccessible to non-specialists. Complex terminology, advanced mathematical models, and fragmented historical accounts can make it challenging for students and the general public to grasp the essence of dark matter research.

This paper seeks to address the communication gap by presenting the scientific history and concepts of dark matter in a simplified, accessible manner, while maintaining accuracy. By demystifying these ideas, this work seeks to bridge the divide between the scientific community and broader audiences, encouraging a deeper appreciation and clearer understanding of one of the most profound mysteries of the universe.

III. Methodology

This study employs a comparative analytical approach to evaluate various theories of dark matter, aiming to address the research question: Which theory most accurately explains the composition of dark matter? To achieve this, the methodology involves systematically comparing these theories by assessing their theoretical foundations, empirical support, and compatibility with established physical phenomena.

Studies and theories were selected based on their adherence to rigorous mathematical frameworks and their compliance with experimentally verified physical laws. To ensure reliability, only studies whose findings did not contradict established phenomena were included in the analysis.

The analysis focused on two primary criteria:

- Empirical Validation: The extent to which a theory is supported by experimental evidence, including particle detection in laboratory environments or astrophysical observations.
- Theoretical Robustness: The degree to which the theory aligns with and extends accepted scientific principles without introducing contradictions or unverified assumptions.

The strengths and weaknesses of each theory were systematically weighed. Strengths were evaluated based on the theory's ability to explain observed phenomena (e.g., galactic rotation curves, gravitational lensing) and provide testable predictions. Weaknesses were identified in terms of reliance on unproven particles, lack of experimental detection, or theoretical inconsistencies.

By employing these methods, the study ensures a systematic and objective approach to determining the most plausible explanation for the nature of dark matter.

IV. Results

Different theories of what dark matter constitutes have been explored leading to the conclusion that the primordial black holes are likely to be the leading candidate.

Dark matter is one of the biggest mysteries in space. It makes up roughly about 25% of the universe (ESA, 2003), yet it cannot be seen or detected with normal tools because it does not emit, absorb or reflect light. Its evidence is only given by its gravitational effects on visible matter, radiation, and how it influences the structure of the universe.

Scientists have come up with various theories to explain what dark matter could be. Some suggest it might be made of hypothetical particles like Weakly Interacting Massive Particles (WIMPs) or axions. Others think it could be something more familiar but hard to see, like Massive Astrophysical Compact Halo Objects (MACHOs) or Primordial Black Holes (PBHs). Each of these theories offers different ideas about what dark matter is and how it behaves.

4.1 Weakly Interacting Massive Particles

The weakly interacting massive particle (WIMP) is a theoretical entity of substantial interest in particle physics. It is postulated to interact primarily through the weak nuclear force, rendering it mostly invisible in astronomical observations due to its weak electromagnetic interaction. It is estimated that approximately 100,000 WIMPs pass through every square centimetre of the Earth's surface each second, primarily interacting through the weak force and gravity.

Theoretical models suggest that the abundance of WIMPs should exceed that of ordinary matter by about fivefold, consistent with the observed prevalence of dark matter in the universe. Detection efforts focus on observing the recoiling charged particles resulting from WIMP collisions, which can emit detectable light. Several experiments have been conducted to indirectly detect this particle (Webmaster, 2011).

WIMPs have attracted considerable attention in scientific research, particularly as they offer a potential explanation for dark matter, a longstanding mystery in astrophysics. Their theoretical prediction, which aligns with independent theoretical frameworks beyond the Standard Model of physics, has been referred to as the "WIMP miracle," highlighting the significance of this hypothetical particle in contemporary physics discourse.

In the following the upsides and downsides of the theory is compared.

DOI: 10.5281/zenodo.14635524

Weakly Interaction Massive Particles	
Pros	**Cons**
Successfully confirming the existence of WIMPs would not only solve the long-standing mystery of dark matter but also significantly enhance our understanding of the universe's composition and evolution. This could lead to breakthroughs in cosmology and astrophysics.	Despite extensive efforts, WIMPs have remained elusive, posing significant challenges for experimental verification. The lack of direct detection thus far raises questions about the validity of the theory and the nature of dark matter.
The existence of WIMPs could provide a unifying framework for particle physics, bridging the gap between the Standard Model and theories of quantum gravity or grand unified theories. This could lead to a deeper understanding of fundamental forces and particles.	The WIMP theory is just one of many proposed explanations for dark matter. Alternative theories, such as axions or modifications to gravity, also have compelling features and remain viable contenders. This diversity of theories complicates efforts to definitively confirm the nature of dark matter.
Research into WIMPs has driven significant advancements in experimental techniques and technologies, pushing the boundaries of particle detection and astrophysical observations. This has practical applications beyond fundamental physics, such as in medical imaging and materials science.	While the WIMP hypothesis fits well with certain theoretical frameworks, there are unresolved issues and uncertainties, such as the "WIMP miracle" coincidence. The lack of consensus on certain aspects of WIMP properties and behaviour introduces ambiguity into the theory's predictions and implications.
	Many versions of the WIMP theory are based on supersymmetry, a theoretical framework that predicts the existence of superpartner particles. However, experimental searches for supersymmetric particles have so far yielded no conclusive evidence, casting doubt on this aspect of the theory.

4.2 Axions

Axions are theorised particles that hold immense promise in explaining dark matter (Sapunar, n.d.). Axions are predicted by scientists to be very lightweight. They are likely to be millions of times lighter than an electron (Quach, n.d.). This makes them hard to detect even by particle detectors. Furthermore, they barely interact with light which is made up of photons and normal matter. This aligns with the nature of dark matter. Axions are theorised to exist throughout space as a field, similar to the recently discovered Higgs field that gives mass to other particles. Strong nuclear force is the force that binds nucleons together in atomic nuclei. The strong force binds quarks together to form protons and neutrons which is what an atomic nucleus is made of. The Standard model of particle physics describes the strong force using specific mathematics. This mathematical model has a hidden symmetry called the PQ symmetry. In physics symmetries often imply a deeper principle (DOE Explains...Symmetry in Physics, n.d.). An imbalance of this could hint at missing physics principles or incomplete theories, Hence, physicists proposed the axion as a solution to the PQ symmetry problem (2207.01068v1 [Hep-Ph] 3 Jul 2022, 2022). As the early universe cooled, the axion field is thought to have become misaligned breaking the PQ symmetry.

Axions	
Pros	**Cons**
Axions were initially purposed to solve a theoretical wrinkle in the Standard model, which is a theory describing most subatomic particles (Prescod, n.d.). They could be a solution to this issue and also a candidate for dark matter.	Axions remain theoretical and their existence remains unproven.
Its characteristics of being lightweight and weakly interacting align with the properties of dark matter.	The theory allows for a rangle of possible axion masses making it challenging to pinpoint a specific type of axion. The theory remains vague.

4.3 Massive Astrophysical Compact Halo Object/ Baryonic Dark Matter

The acronym MACHO, denoting "massive astrophysical compact halo object," initially emerged as a plausible candidate for dark matter, representing entities such as neutron stars, brown dwarfs, and white dwarfs. Despite comprising ordinary matter, MACHOs possess limited or negligible luminosity, rendering them effectively invisible.

Detection strategies have involved scrutinising the luminosity variations of remote stars. Gravitational lensing phenomena, wherein the trajectory of light is altered by the gravitational field of intervening massive objects, offer a means of indirectly identifying MACHOs. Such lensing events result in transient brightenings of distant stellar sources. By quantifying these occurrences, astronomers can infer the distribution of matter, both luminous and dark, within galaxies.

However, subsequent investigations have cast doubt on the viability of MACHOs as a primary constituent of dark matter. The accumulation of these obscured entities appears insufficient to account for the extensive presence of dark matter within cosmic structures.

MACHOs/ Baryonic Dark Matter	
Pros	**Cons**
MACHOs, despite being invisible themselves, can be detected indirectly through gravitational lensing phenomena, offering a means to study their presence and distribution in the cosmos.	Accumulating evidence suggests that MACHOs alone are unlikely to account for the entirety of dark matter. Their combined mass may fall short of explaining the observed gravitational effects attributed to dark matter.
MACHOs are composed of ordinary matter, such as neutron stars, brown dwarfs, and white dwarfs, entities well-understood within astrophysical frameworks.	Current detection techniques primarily rely on gravitational lensing, which may not provide a comprehensive or conclusive assessment of MACHO populations, potentially leading to uncertainties in their contribution to dark matter.
Studying MACHOs provides an avenue for gaining insights into the dynamics and composition of galactic halos, contributing to our understanding of galaxy formation and evolution.	The formation mechanisms and prevalence of MACHOs may impose constraints inconsistent with observed dark matter distributions, challenging their candidacy as the primary constituent of dark matter.

4.4 Primordial Black Holes

Unlike stellar black holes, PBHs wouldn't arise from the collapse of massive stars. Instead, their birth is rooted in the inhomogeneities of the very early universe. Imagine the universe as a hot, dense soup shortly after the Big Bang. Tiny fluctuations in density existed. If, due to these fluctuations, a region became incredibly dense (exceeding the critical density), it could have undergone its own gravitational collapse, bypassing the need for a star's death. General relativity, the theory of gravity, dictates that a collapsing object exceeding the Schwarzschild radius forms a black hole. This radius depends on the object's mass. However, in the denser early universe, the critical density for collapse was much lower, potentially allowing the formation of PBHs much lighter than the Tolman-Oppenheimer-Volkoff (TOV) limit. The TOV limit defines the minimum mass a stellar remnant needs to overcome its internal pressure and collapse into a black hole (Albert Escrivà, 2024).

Primordial Black Holes	
Pros	**Cons**
PBH formation is a natural consequence of standard cosmology, requiring no exotic or new physics beyond what is already known.	While PBH formation is theoretically plausible, the exact mechanism and conditions necessary for their formation remain uncertain, requiring exotic conditions during the early Universe.
They share characteristics with dark matter including its non-baryonic nature and that it is weakly interacting.	A crucial hurdle for PBH dark matter arises from Hawking radiation. Quantum mechanics dictates that black holes emit a faint glow of energy due to their interaction with the quantum vacuum. This radiation causes PBHs to evaporate over time.expand_more For very light PBHs, this evaporation timescale could be shorter than the age of the universe, making them unsuitable as long-lived dark matter constituents.
PBHs offer various potential observational signatures, such as gravitational lensing, microlensing events, and Hawking radiation, which could be detected by current and future observational instruments.	The clustering behaviour of PBHs and their interaction with other cosmic structures are not fully understood, making it challenging to predict their precise observational effects.
PBHs could exist across a wide range of masses, from microscales to supermassive, which allows for diverse observational tests and potential impacts on cosmological structures.	PBHs are not the only proposed candidate for dark matter, and competing theories, such as weakly interacting massive particles (WIMPs) or axions, also have observational support and theoretical motivations.

V. Discussion

Based on research performed, Primordial Black Holes arise as one of the leading candidates for dark matter. Unlike some dark matter candidates requiring entirely new particles or forces, Primordial Black Holes (PBHs) arise naturally from the well-established theory of general relativity with the most compelling factor being that they are a natural fit with existing cosmology. Their formation hinges on the density fluctuations in the very early universe, a concept already used to explain the large-scale structure of the cosmos. This makes PBHs a simpler explanation that doesn't require significant revisions to our current understanding of physics. PBHs form naturally within the framework of general relativity due to these density fluctuations. Furthermore,a crucial characteristic of dark matter is that it's non-baryonic, meaning it's not composed of

DOI: 10.5281/zenodo.14635524

normal matter (protons, neutrons). Normal matter is composed of protons, neutrons, and electrons, and makes up stars, planets, and all visible structures. Dark matter must be non-baryonic, meaning it isn't made of atoms. PBHs, being black holes formed from collapsed matter (singularities), fit this criterion as they are not composed of atoms but are instead regions of extremely dense matter where gravity is so strong that not even light can escape. Additionally, PBHs wouldn't interact much with normal matter or light, aligning with dark matter's elusive nature. Dark matter interacts primarily through gravity. PBHs, due to their nature, would also interact mainly via gravitational forces, aligning with the behaviour expected of dark matter. Since PBHs don't emit light and only affect their surroundings through gravity, they remain elusive and difficult to detect, much like dark matter.

The early universe was extremely hot and dense, and during this time, tiny fluctuations in density could cause certain regions to collapse under their gravity, forming PBHs. The theory of Inflation is a period of rapid expansion in the early universe that stretched out density fluctuations, potentially leading to PBH formation. One possibility is the critical collapse scenario, where a region exceeds a certain critical density threshold, leading to inevitable collapse. Another scenario involves false vacuum decay, where the universe transitioned from a higher-energy state, potentially creating PBHs in the process. The efficiency of PBH formation is highly dependent on the mass range. Smaller PBHs likely formed through different mechanisms compared to their larger counterparts. Understanding the PBH mass function (the distribution of PBHs across different masses) is crucial for their viability as dark matter. Mass function refers to the distribution of PBHs across different masses. Understanding the mass function is crucial to determine how many PBHs could exist and their role as dark matter. Smaller PBHs might form through different processes compared to larger ones, affecting their numbers and distribution.

VI. Addressing Hawking Radiation As A Challenge

Hawking radiation is a theoretical process proposed by physicist Stephen Hawking, where black holes can emit radiation due to quantum effects near their event horizons. This causes them to lose mass over time and eventually evaporate. For large PBHs, this radiation is negligible over the age of the universe, allowing them to remain as potential dark matter candidates. For smaller PBHs, Hawking radiation would cause them to evaporate more quickly. Even so, their existence might leave behind traces or contribute to the formation of supermassive black holes at the centres of galaxies. The main challenge is ensuring there are enough massive PBHs to account for all dark matter without conflicting with observational data.

VII. Limitations

This research is inherently theoretical, as the nature of the problem precludes direct experimental investigation. While indirect evidence from astrophysical observations informs the study, experimental data specific to PBHs or other dark matter candidates remain elusive. Future advancements in detection technologies and observational techniques will be critical for validating or refuting the PBH hypothesis.

VIII. Conclusion

The creation of the universe brought with it fascinating symmetries, such as the existence of equal amounts of matter and antimatter. However, a violation of this symmetry - the matter-antimatter asymmetry - led to the predominance of matter over antimatter (The Matter-Antimatter Asymmetry Problem, n.d.). This imbalance may hold clues about the role of dark matter in the universe's formation and evolution.

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The search for dark matter has been a significant challenge in astrophysics. Evidence of its existence, such as the cosmic microwave background, galactic rotation curves, gravitational lensing, and large-scale structure formation, strongly suggests the presence of an unseen mass influencing the cosmos. While the amount of normal matter in the universe is insufficient to explain these phenomena, dark matter provides a compelling solution. Calculations indicate that dark matter constitutes roughly 84% of the universe's matter content (Dr Becky, n.d.). Since dark matter does not interact with normal matter through electromagnetic forces, it can only be detected indirectly, such as through its gravitational effects (Katherine Garrett, 2011). Despite its elusive nature, understanding dark matter is crucial for unraveling the dynamics of galaxies and the evolution of the universe.

Primordial Black Holes (PBHs) stand out as a particularly compelling candidate for dark matter. Their natural formation within the framework of current cosmological theories, non-baryonic composition, minimal interaction with normal matter, and broad mass spectrum align closely with the expected properties of dark matter. However, challenges remain, including the impact of Hawking radiation on smaller PBHs and ensuring that a sufficient abundance of PBHs exists to account for the observed effects of dark matter.

Other candidates, such as neutrinos, have also been proposed. However, the number of neutrinos is insufficient to explain the vast quantities of dark matter required. While PBHs present a promising avenue, further research is necessary to confirm their viability as dark matter constituents and to address the outstanding challenges associated with their hypothesis.

The discovery of dark matter's composition would revolutionize our understanding of the universe, providing a comprehensive framework to explain phenomena ranging from galactic behavior to the universe’s large-scale structure. As research progresses, the potential confirmation of PBHs - or another candidate - as dark matter could offer profound insights into the fundamental workings of the cosmos.

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