Chapter 1

Introduction

1.1 Introduction

Although the exploration of our solar neighborhood indicate that most of the mass in the solar system is due to the sun in the form of baryonic matter [2].However, baryonic matter might not be the major contributor of the mass when one looks at the universe at the length scales much larger than the size of the solar system. In the early groundbreaking work of Fritz Zwicky [3, 4] revealed a striking contrast on over the length scales much larger than the solar neighbourhood. By scrutinizing galaxy clusters, particularly the Coma cluster with around a thousand galaxies distributed within a sphere of radius $R \approx 10^6$ light-years, Zwicky discerned that dark matter, referred to as ”dunkle Materie” in German, surpassed luminous matter in abundance. By employing the virial theorem, Zwicky estimated the velocity of galaxies in the Coma cluster, predicting a value of $v \approx 10^5\,\mathrm{m/s}$. Intriguingly, the measured velocity dispersion, approximately $10^6\,\mathrm{m/s}$, presented a notable order-of-magnitude discrepancy. Subsequent investigations [5, 6] has shown that the mass of halo of hot gas is five times larger than the total mass . Although this revelation has mitigated the discrepancy between the observed and predicted values of Coma cluster to some extent. But this still does not rule out the need for the non-luminous (Dark) Matter.

Another crucial evidence for the existence of dark matter emerged through the examination of galactic rotation curves, specifically the rotational velocity (v) of stars in galaxies as a function of their distance (r) from the galactic center. Astrophysicists Vera Rubin, Kent Ford, and their colleagues [7, 8, 9, 10, 11] conducted pioneering observations on numerous galaxies, revealing a significant pattern. Beyond the central concentration of luminous (baryonic) matter the rotation curves exhibited a distinctive flatness: the velocity (v) appeared relatively unaffected by changes in distance (r), as illustrated in Fig. 1.1. This observation sharply contrasts with the expected $\frac{1}{\sqrt{r}}$ dependence of velocity (v) on distance (r), a pattern anticipated if luminous matter alone were responsible for the gravitational pull governing the orbits of outer stars. One of the possible explanation for these rotation-curve phenomena points towards galactic masses being predominantly influenced by a spherical halo of non-luminous dark matter, extending well beyond the observable luminous matter within galaxies.

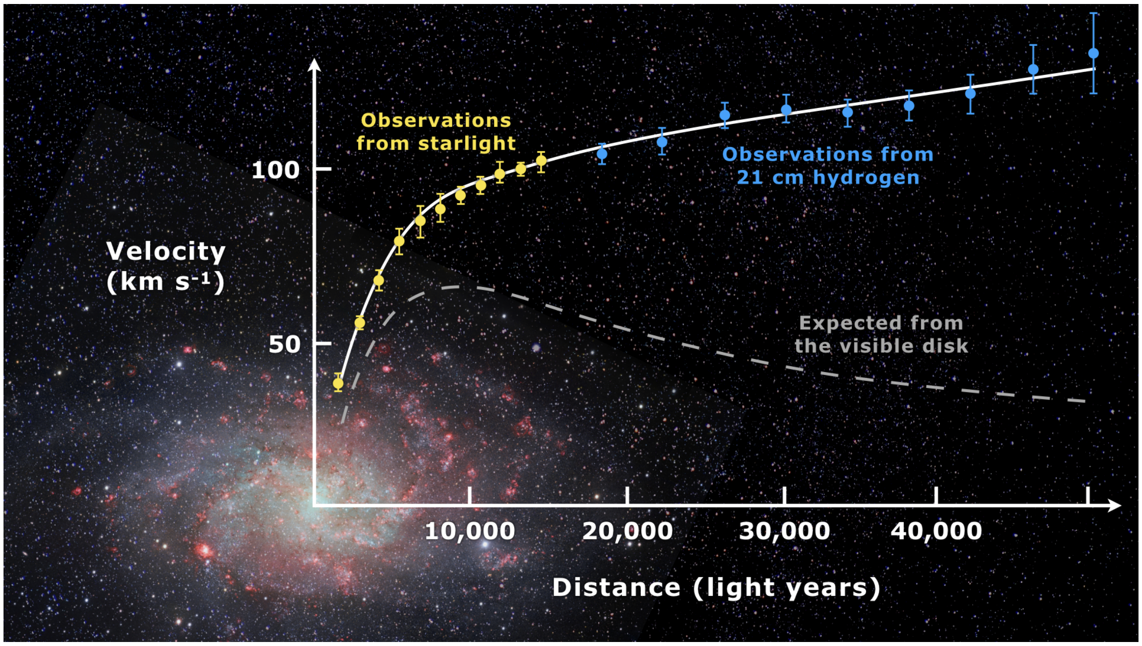

Figure 1.1: The rotation curve of the spiral galaxy Messier 33, depicted with yellow and blue points including error bars, is compared with the predicted curve based on visible matter distribution shown as a gray line. The discrepancy between these curves can be explained by the presence of a dark matter halo surrounding the galaxy .

Another evidence came from gravitational lensing studies of various clusters [12, 13]. These studies indicated that the mass of the clusters, as measured through lensing techniques, far exceeds the mass estimates derived solely from luminosity observations. Furthermore in 2006, Clowe et al. [14] utilized gravitational lensing to investigate the Bullet Cluster (1E0657-558), a pair of galaxy clusters that had collided around 150 million years ago. By comparing gravitational lensing with observations of stars and hot x-ray emitting visible matter, they demonstrated that the mass distribution of the Bullet Cluster does not align with the distribution of baryonic matter (as depicted in Fig. 1.2).

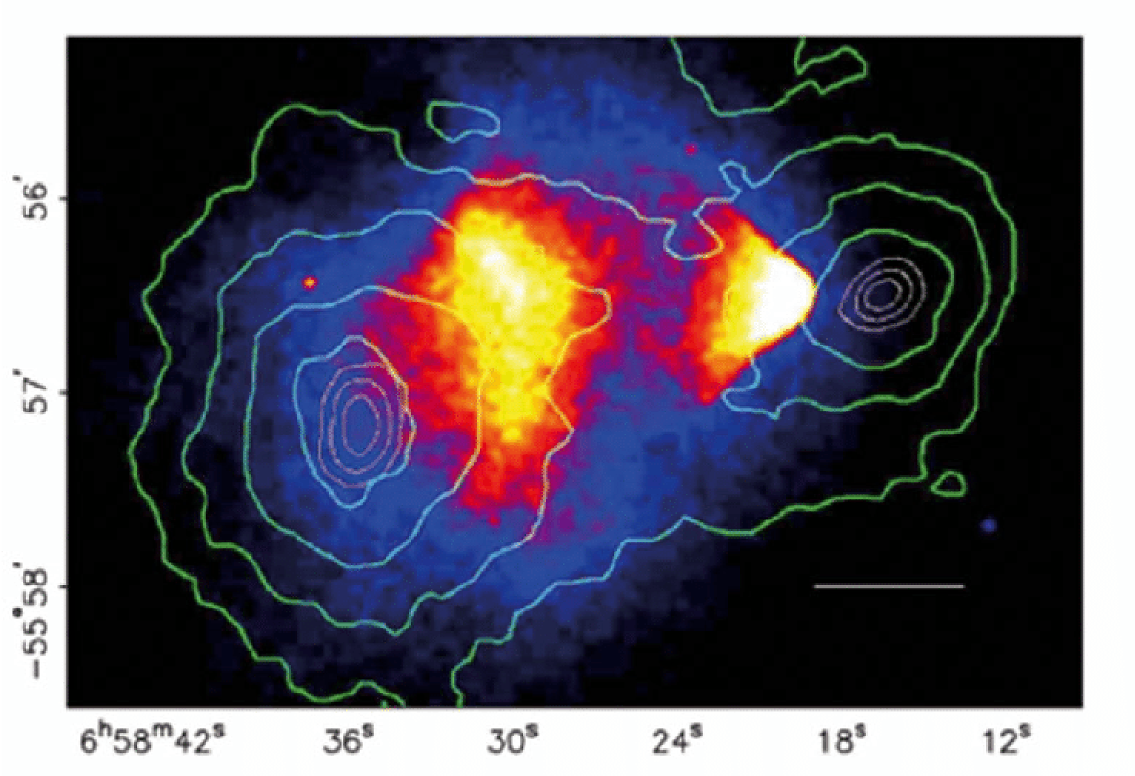

Figure 1.2: Image of the Bullet Cluster (1E0657-558), adapted from [1], compares x-ray emission from hot gas (background color map, with increasing intensity from blue (low) to yellow/white (high)) to the mass distribution inferred from gravitational lensing (green contours, with the outermost contour indicating low mass density and the innermost indicating high density). The white horizontal line in the lower right represents a distance of 200 kpc at the position of the Bullet Cluster. The mass distribution is distinctly different from the gas distribution.

In the figure, the contours represent the mass density distribution from the lensing observations and the background color map represents x-ray intensity. The X-ray intensity is due to baryonic matter and the high intensity X-ray regions appears to be in the central region of the collision. But the high mass density regions appear much further away from the central region of the collision. This clearly shows that the regions of the baryonic (luminous) matter do not coincide with the high mass-density regions as observed by gravitational lensing.

These distributions of luminous and non-luminous matter could suggests that during the merger of the two galaxy clusters, baryonic matter collided and heated up, while dark matter barely interacted, passing through the clusters without observable effects aside from gravitational influence. This shows that dark matter particles may not be having any significant interaction among themselves or with the visible matter.

In addition, the observations of the cosmic microwave background radiation (CMB) have also played a crucial role in supporting the existence of dark matter. The CMB, a photon gas saturating the universe, separated from baryonic matter approximately 400,000 years after the Big Bang during the recombination period, Afterwards, photons largely decoupled from baryonic matter. The uniformity of the CMB observed today, with almost perfect conformity to a blackbody spectrum, But the observed small fluctuations in temperature and polarization, reflects the density distribution of the photon-baryon fluid at the surface of the last scattering[15, 16].

Predictions based on general relativity suggest that matter density fluctuations should grow linearly with the expansion of the universe until a certain point. However, the observed uniformity of the CMB contradicts the expectation that fluctuations in baryon density at recombination would lead to the formation of galaxies. This apparent contradiction is resolved by considering a universe where the mass of baryonic matter is small compared to a gas of nonrelativistic (cold) dark matter particles. These dark matter particles could have begun clumping long before recombination, explaining the observed small fluctuations in the CMB while allowing for the formation of galaxies from the large density fluctuations of dark matter.[17]

The CMB temperature fluctuations, measured by missions like WMAP and Planck, align with theoretical predictions based on a cosmology dominated by cold dark matter. The angular anisotropy spectrum of the CMB, particularly the peaks corresponding to baryon acoustic oscillations, provides insights into the underlying spacetime geometry of the universe and the baryon density distribution. The consistency between CMB measurements and other methods, such as galactic rotation curves and gravitational lensing studies, strengthens the case for the existence of dark matter.[18, 19]

In 1982, Milgrom proposed Modified Newtonian Dynamics (MOND) [20, 21] as an alternative hypothesis to dark matter, suggesting modifications to the laws of physics rather than introducing new particles. MOND posits that the force of gravity behaves differently at very small accelerations, as described by the equation:

$$F = \frac{ma^2}{a_0}$$

where F is the non-relativistic force due to gravity, m is the mass, a is the acceleration, and a_0 is a fundamental acceleration scale ($a_0 \approx 10^{-10}\,\mathrm{m/s}^2$. This modification aims to explain the motion of stars in galaxies without invoking the presence of dark matter.

However, despite attempts to extend MOND, it encounters challenges in fully explaining various observational evidence supporting dark matter. Observations from galactic clusters, gravitational lensing, cosmic microwave background measurements, and Big Bang nucleosynthesis suggest the presence of dark matter. While MOND or its variants may contribute to our understanding of certain observations, the cumulative evidence for dark matter from multiple sources makes it difficult to envision a scenario without its existence [22].

In the thesis, we shall focus on dark matter as the possible explanation for all the phenomena discussed above.

1.2 Characteristics of Dark Matter

In this section, we consider several crucial characteristics of dark matter established by the observational evidence discussed in Section 1.1. Already, we have seen that multiple, independent observations provide a good understanding of the total amount of mass in the form of dark matter in the universe. We also know that dark matter must either be stable or 'long-lived', which means it has decay times larger than the age of universe, as the observations of late time universe shows Dark Matter plays crucial role in structure formation. Furthermore, dark matter:

1. Is not predominantly any of the known Standard Model particles (Thus we need physics beyond Standard Model),
2. Is non-relativistic (cold),
3. Is distributed in halos that extend well beyond the luminous matter of galaxies.
4. Must either be stable or 'long-lived', which means it has decay times larger than the age of universe, as the observations of late time universe shows Dark Matter plays crucial role in structure formation

In the Standard Model of particle physics, fermions constitute the essential building blocks of matter, falling into two main categories: leptons and baryons. Additionally, bosons serve as force carriers responsible for mediating interactions between these fermions. The process of Big Bang Nucleosynthesis suggests that the abundance of light elements is created after the matter-radiation decoupling. However, the evidence for dark matter, as discussed in Section 1.1, relies on observations of any absorption or emission lines in the radiations emanating from galaxies, clusters, and other cosmic structures. The inability to detect such lines associated with known particles suggests that Standard Model particles do not contribute to the dark matter.

Standard Model neutrinos initially appear promising as potential dark matter candidates due to their exclusive engagement through the weak interaction, rendering them effectively "dark," and their emergence as thermal relics from the Big Bang. However, their disqualification arises from their intrinsic relativistic (hot) behavior during the epoch of structure formation in the early universe. This is in stark contrast to the requirements of the cold dark matter (CDM) scenario, which alone establishes a connection between measured density fluctuations at recombination, observed in the Cosmic Microwave Background, and the large-scale structure of the universe. Neutrino mass measurements, both from oscillations and direct experiments, confirm that all Standard Model neutrinos possess masses below 10 eV and exhibit high relativistic behavior incompatible with the characteristics of cold dark matter. Furthermore, the contribution of neutrinos to the overall mass-energy density, as determined from Big Bang Nucleosynthesis and Cosmic Microwave Background measurements, is insufficient to serve as the predominant component of dark matter. This argument extends beyond neutrinos to any fermion with a mass below approximately 10 eV. In essence, Standard Model neutrinos do not meet the necessary criteria to constitute a significant proportion of dark matter in the universe.

The dark matter is expected to be distributed in a halo that extends well beyond the region occupied by luminous matter in galaxies—approximately 6–8 times the distance from the galactic center compared to luminous matter [23]. The prevalent assumption among researchers is that the galactic dark matter distribution is aptly described by the standard halo model (SHM) [24, 25]. While certain disparities exist between the SHM's predictions and observations [26, 27, 28] , it generally aligns well with galactic rotation curves within current uncertainties.

This final characteristic revolves around the extent to which dark matter engages in non-gravitational interactions. Generic upper limits on the strength of these interactions with Standard Model particles and fields can be obtained from various sources, including observations of phenomena such as the Bullet Cluster and similar galaxy cluster mergers [29], measurements of the motion of galaxies and satellites within dark matter halos [30], and constraints on dissipation and thermalization within these halos [31].

As per the available evidence, non-gravitational interactions, encompassing both long-range and contact interactions, between dark matter particles are constrained to exhibit an average scattering cross-section-to-mass ratio denoted as $\sigma_{\mathrm{dm}}/m_{\mathrm{dm}}$, which is approximately $0.5\,\mathrm{cm}^2/\mathrm{g}$ or roughly $1\,\mathrm{barn/GeV}$. Intriguingly, this value closely resembles the ratio of scattering cross-section-to-mass ratios for nuclei. Consequently, astrophysical evidence does not conclusively support the notion that the interaction strength between dark and ordinary matter is inherently "small."

Direct experimental searches focusing on specific classes of dark matter candidates play a crucial role in significantly refining our understanding of the interactions of these particles with Standard Model constituents [32]. Additionally, it is pertinent to note that dark matter particles must be electrically neutral (or possess an infinitesimal charge [33]) to avoid electromagnetic interactions. This characteristic is essential for maintaining the inherently "dark" nature of dark matter, as any substantial electromagnetic interaction would compromise its elusive and non-observable properties.

1.3 Candidates

The nature of dark matter remains a subject of extensive exploration, with a multitude of hypotheses spanning an enormous range of parameter space. These hypotheses encompass a diverse array of potential dark matter particle candidates, ranging from 10^{-22} eV (such as fuzzy dark matter [34, 35]) to 10^{21} eV (WIMPzillas [36]). Additionally, if dark matter particles exhibit significant self-interactions, they have the potential to form composite objects with masses extending up to 10^{50} eV [37]. Numerous review articles delve into the details of these hypotheses (see Refs. [38, 39, 40, 41], and, for a touch of amusement, Fig. 1.3). For brevity, we will underscore general principles and touch upon a few of the most prominent hypotheses along with their current experimental status.

Dark matter hypotheses that are considered "theoretically well-motivated" typically share several key attributes. Firstly, a plausible production mechanism capable of generating an abundance that matches the observed dark matter density in the universe. As mentioned in Section 1.2, to achieve this match, dark matter particles must be stable—long-lived compared to the age of the universe, ensuring their persistence to the present epoch.

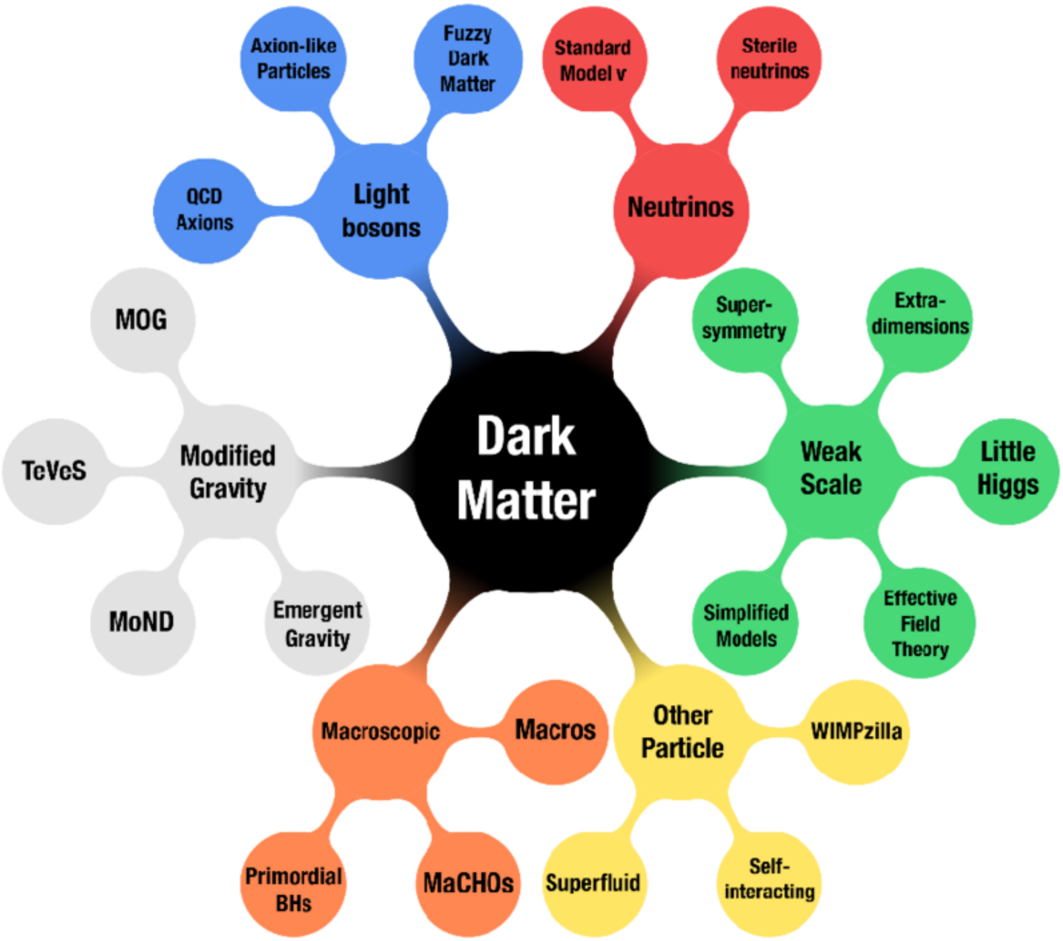

Figure 1.3: Illustration of various dark matter hypotheses.

The hypothesis that has garnered substantial attention over the past several decades and exemplifies the attributes discussed earlier is the notion that dark matter is composed of Weakly Interacting Massive Particles (WIMPs). The development of the WIMP hypothesis stemmed from the observation that particles interacting via the weak force could be created in just the right abundance to match the observed dark matter density, a phenomenon often referred to as the ”WIMP miracle” [42].

In the scenario where dark matter particles were thermally produced in the early universe, meaning they were created in equilibrium with Standard Model particles through collisions at sufficiently high temperatures, the interaction cross-section can be estimated. This estimation follows arguments akin to those used to understand Big Bang Nucleosynthesis. Much like the weak-interaction-maintained equilibrium between neutrons and protons in BBN, a similar equilibrium could exist between Standard Model particles (SM) and dark matter particles (χ) through a process denoted as $\chi\chi \leftrightarrow$ SM in the early universe. As the universe continued to cool after the Big Bang, the dark matter density would decline, governed by the Boltzmann equation [40]:

$$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle\sigma_{\chi v}\rangle n_\chi^2 - n_\chi(eq)^2, \tag{1.3.1}$$

Here, $\langle\sigma_{\chi v}\rangle$ represents the cross-section for $\chi\chi \leftrightarrow$ SM, v is the relative velocity between particles, $n_\chi(eq)$ is the dark matter density in equilibrium, and H is the Hubble constant. The initial term on the right-hand side (RHS) accounts for the dilution of dark matter χ resulting from the expansion of the Universe. The subsequent two terms on the RHS depict the processes of pair annihilation and pair production of χ, respectively.

The solution to this equation yields:

$$\langle\sigma_{\chi v}\rangle \approx 6 \times 10^{-27}\,\mathrm{cm}^3/\mathrm{s}\left(\frac{\Omega_{\mathrm{dm}}}{0.22}\right) \tag{1.3.2}$$

Where $\Omega_{\mathrm{dm}} = \rho_{\mathrm{dm}}/\rho_{\mathrm{crit}} \approx 0.22$ is the ratio of the dark matter density to the critical density for a flat universe. The estimate of $\langle\sigma_{\chi v}\rangle$ from Equation (1.3.2) is on the order of the weak interaction scale if the mass of the dark matter particle $2m_\chi c^2$ lies between 10 GeV and 1 TeV [43, 44]. This characteristic scale, combined with the nonrelativistic nature of WIMPs at the freeze-out temperature, aligns well with the Cold Dark Matter (CDM) scenario, providing an explanation for the observed relic abundance of dark matter. This is the essence of the "WIMP miracle"—weakly interacting particles can be thermally produced with a relic abundance that matches the dark matter density.

Furthermore, many leading theories beyond the Standard Model predict the existence of new physics at the scale of weak interactions. The primary motivation for these theories stems from addressing the hierarchy problem, a puzzle centered on understanding why gravity is remarkably weaker compared to the other fundamental forces, namely the strong and electroweak interactions.

However, experiments have indicated that if WIMPs were the sole constituents of dark matter, with masses $10\,\mathrm{GeV} \lesssim 2m_\chi c^2 \lesssim 1\,\mathrm{TeV}$ and interacting with nuclei via the weak force with unsuppressed couplings, they would have been detected by now. Various cryogenic experiments aimed at detecting WIMPs have been conducted since the 1980s, but despite occasional hints, none has definitively observed WIMP dark matter. Null results from these experiments have led to increasingly stringent constraints on many attractive WIMP theories. Similarly, searches for WIMP candidates at the Large Hadron Collider (LHC) have imposed tight restrictions on numerous WIMP models. Consequently, the WIMP hypothesis has faced challenges, prompting a need to explore alternative explanations for the nature of dark matter.

One such hypothesis related to the WIMP paradigm is the idea that dark matter may consist of sterile neutrinos. This theory suggests the existence of a heavy neutrino species that does not interact via the weak force but could be generated through mixing with standard model neutrinos. The sterile neutrino hypothesis possesses attributes similar to well-motivated dark matter candidates: it provides a production mechanism for a reasonable abundance (mixing with standard model neutrinos) and can address puzzles in neutrino physics, such as generating nonzero standard model neutrino masses. However, searches for x-rays from sterile neutrino decay in nearby galaxies have constrained a substantial portion of the parameter space for sterile neutrinos. Additionally, effects on small-scale structure in the universe have further limited the sterile neutrino parameter space, although some loopholes remain [45, 46, 47, 48].

Another dark matter hypothesis that gained significant attention in the past posited that dark matter might be comprised of Massive Astrophysical Compact Halo Objects (MACHOs). These MACHOs are envisioned as composite baryonic objects—non-luminous entities like planets, brown dwarfs, white dwarfs, neutron stars, and black holes. The term "MACHO" was coined in contrast to "WIMP," and MACHOs had the distinctive advantage of being known to exist. However, subsequent investigations indicated that MACHOs do not exist in sufficient abundance to account for a significant fraction of dark matter in the universe. Consensus today is that MACHOs do not constitute a large portion of dark matter. One of the key arguments against MACHOs as dark matter arises from evidence, as discussed in Sections 1.1 and 1.2, from measurements of the Cosmic Microwave Background (CMB) and Big Bang Nucleosynthesis (BBN), suggesting that dark matter is nonbaryonic. A second argument against MACHOs as dark matter arises from gravitational microlensing studies. If the dark matter halo primarily comprised MACHOs in the mass range of $10^{-7}M_\odot \leq M \leq 10^{2}M_\odot$, gravitational lensing of light from visible stars by these MACHOs would lead to a significant fraction of stars (one in a million) exhibiting transient variations in their apparent brightness. Large-scale microlensing surveys have placed constraints on the contribution of MACHOs to the dark matter mass content, limiting it to 8%. Importantly, these constraints apply not only to MACHOs but also to compact objects composed of nonbaryonic matter [49].

It's worth noting that there are special cases of MACHO dark matter candidates, possibly baryonic, that evade the CMB and BBN bounds—primordial black holes (PBHs). In the early universe, before BBN, regions of space with extremely high energy density might gravitationally collapse into black holes. This contrasts with black holes produced later as the end state of stellar evolution, which are subject to CMB limits on baryon density at recombination and BBN limits at the time of light element formation. The mass of PBHs is constrained to be $10^{-19}M_\odot$ to avoid evaporation via Hawking radiation before the present epoch. Gravitational microlensing surveys have constrained the PBH mass to be $10^{-7}M_\odot$ [50, 51].

In the next section, we will discuss in detail the hypothesis that dark matter primarily consists of ultralight bosons.

1.4 UBDM

Although there are various well motivated candidates for the dark matter, In this thesis, we shall focus on the Ultralight Bosons as potential candidate for dark matter responsible for structure formation. Ultralight bosonic dark matter (UBDM) represents a qualitative departure from the dark matter particles discussed earlier. While WIMPs and sterile neutrinos are envisioned as particles with masses above 10 eV, and search methods are geared towards detecting individual interactions, UBDM consists of bosons with masses below 10 eV (hence ultralight). The search methods for UBDM focus on detecting coherent effects of UBDM waves, treating them as classical fields due to the high mode occupation number of ultralight bosons.

It's worth noting that the distribution of UBDM in the Milky Way may deviate from predictions of the Standard Halo Model (SHM). Various factors like the formation of clumps or streams [52], self-interactions, and topological properties of the UBDM field could lead to the creation of composite structures such as condensates [53], clusters [54], boson stars [55], or domain walls [56, 57]. Although a reasonable assumption is that the motion and distribution of these structures follow the SHM, some fraction of UBDM might become trapped in the local gravitational potential of the Earth or Sun, creating a local halo with enhanced UBDM density [58]. This should be considered in the interpretation of terrestrial experiments searching for UBDM.

One of the most well-motivated candidates for Ultralight Bosonic Dark Matter (UBDM) is the axion[59]. The axion's existence is predicted by a proposal aimed at solving the strong-CP problem in quantum chromodynamics (QCD) [60]. The strong CP problem arises from a CP-violating term in the QCD Lagrangian, represented by a phase $\bar{\theta}_{\mathrm{QCD}}$. Experimental constraints, particularly from the neutron electric dipole moment (EDM), imply that $\bar{\theta}_{\mathrm{QCD}}$ is extremely small, creating a fine-tuning problem. The axion provides a solution to this problem by introducing a pseudoscalar field that evolves dynamically, naturally tending toward a value near zero. Axions, as spin-0 particles, are proposed as the quanta of this field.

Axions are promising UBDM candidate due to their theoretical foundation in addressing the strong CP problem. They have a small mass, with upper limits around 10^{10} meV based on astrophysical observations, and in principle, the axion mass (m_a) can be even smaller than 10^{-12} eV [61, 41]. Apart from their role in solving the strong CP problem, ultralight spin-0 bosons, including axions, are prevalent in theories beyond the Standard Model.

Axions also play a role in a different CDM theoretical framework known as the axion-quark-nugget model. In this model, dark matter consists of ”nuggets” containing quarks held together by an ”axion domain wall.” The model assumes the existence of nuggets and ”anti-nuggets,” balancing quarks and antiquarks to account for the matter-antimatter asymmetry [62].

Another class of UBDM candidates mentioned is spin-1 bosons, particularly hidden photons. These exotic spin-1 bosons could possess nonzero mass, making them potential dark matter candidates. Hidden photons are those that do not directly interact with Standard Model particles, residing in the so-called hidden sector. Theoretical models predict new Z' bosons (hypothetical massive spin-1 bosons), with a broad range of masses and couplings, and these could contribute to the dark matter abundance [62].

Ultralight bosons, encompassing both spin-0 and spin-1 varieties, exhibit diverse interactions with Standard Model particles and fields, offering distinct portals for their potential detection [63]. Spin-0 bosonic field (ϕ) can couple with fermionic field through scalar and pseudoscalar vertices [64, 65, 66, 67]. The nonrelativistic limit establishes scalar vertex interactions as monopoles, while pseudoscalar vertices act as dipoles, introducing spin-dependent energy shifts in fermions. Additionally, these bosons couple to the electromagnetic field, facilitating interactions with photons. Experiments leverage this coupling to explore phenomena such as the conversion of axions into photons within strong magnetic fields. Axions, born out of the Peccei-Quinn solution to the strong CP problem, further exhibit coupling to the gluon field, potentially generating Electric Dipole Moments (EDMs) along the spin direction. Spin-1 bosons, including hidden photons, mirror spin-0 counterparts in generating spin-dependent energy shifts and can intertwine with the electromagnetic field. These diverse interaction channels furnish a rich array of possibilities for experimental detection, each tailored to the specific properties and behaviors of the ultralight bosons under consideration.