Exploring the Connection Between Dark Matter Candidates and Primordial Black Holes Through Gravitational Lensing

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In this literary review, we explore the connection between Primordial Black Holes (PBH) and gravitational lensing to investigate the potential role PBHs play as dark matter candidates in the early universe. The concept of PBHs first came about in 1967 by academics Yakov Borisovich Zel'dovich and Igor Dmitriyevich Novikov, explaining that they hypothetically formed shortly after the Big Bang. Gravitational lensing, predicted by general relativity, allows researchers to investigate far-off objects like galaxies and black holes. This study compares the effects of gravitational microlensing with other pieces of evidence such as dynamical and accretion evidence and uses various methods such as analyzing surveys to find evidence of microlensing effects to investigate dark matter and rule out certain ranges of PBH masses and abundances as dark matter candidates if they do not match the data from galaxy surveys. The findings will guide future investigations and shed light on the fundamental role gravitational lensing has on the link between PBHs and dark matter candidates.

Introduction

Primordial Black Holes (PBHs) have been thought to have formed in the early stages of our universe's creation, moments after the Big Bang, presumably making them some of the oldest known objects within our universe. They range from the size of subatomic particles to hundreds of kilometers[1].

In 1916 Albert Einstein formulated his theory of general relativity, proposing the first-ever theoretical concept of a black hole. It has now been almost 51 years since physicist Stephen Hawking released his paper "Black Holes in the Early Universe," first introducing the concept of a primordial black hole[2]. He suggested that variations in the distribution of matter, known as density fluctuations, during the inflationary period—a rapid expansion phase in the early universe—could have given rise to the formation of tiny black holes during the Big Bang.

Hawking and Carr advanced a theory suggesting that in the radiation-dominated era, marked by high-energy radiation driving rapid expansion and extreme temperatures in the early universe, regions with slightly higher masses would collapse, giving rise to a range of black holes differing in sizes, ranging from between 10 μg to $10,000\odot$ (solar masses). As early as 1975, other physicists began to ponder the nature of primordial black holes, concerned about whether PBHs larger than 1011 kg had not completely evaporated (it can give off tiny particles as light and heat, getting smaller and smaller until they vanish, otherwise known as Hawking Radiation) or if they have the potential to explain the difference between the visible matter in our universe and how galaxies and stars move, which is currently attributed to the presence of unseen dark matter. The theory gained particular attention in the 1990s, coinciding with the development of cosmic inflation theory, which offered an explanation for the origin of the universe's density fluctuations. Additionally, the notion gained renewed interest after the first-ever gravitational waves were observed from a binary black hole merger by LIGO-Virgo in 2016[3]. The sizes of those black holes were larger than anticipated, ranging from 10 to 50 solar masses, leading some physicists to speculate that they were of primordial origin (regular black holes are formed from the collapse of massive stars, while primordial black holes are thought to have originated from the intense density fluctuations in the early universe).

On the other hand, dark matter remains one of the most enigmatic and pervasive mysteries in modern astrophysics. Its existence has been inferred from its gravitational effects on visible matter, but its true nature remains elusive (as further mentioned in the following sections). Although various dark matter candidates have been proposed, including weakly interacting massive particles (WIMPs)[4], axions[5], and sterile neutrinos[6], the possible existence of primordial black holes as dark matter candidates has intrigued researchers for decades. Through a plethora of observational data collected in the past, we gauge that dark matter evidence has not been observed directly, but rather through its influence on astronomical phenomena in our universe, especially the gravitational influences it possesses, such as its effects on the galactic rotation curve[7].

The relationship between dark matter and PBHs stems from the fact that a PBH, if present, contributes significantly to the total mass of the universe and may constitute some or all of the elusive dark matter. Gravitational lensing plays an important role in investigating this intriguing hypothesis. Predicted by Einstein's theory of general relativity, gravitational lensing occurs when the gravitational field of a massive object such as a galaxy or black hole bends the path of light passing near it. This diffraction of light can distort the appearance of distant objects, magnify their image, or create multiple images of the same object, depending on the light source, lens, and orientation of the observer.

By studying the gravitational lensing effects caused by massive celestial bodies such as galaxies, astronomers have gained valuable insight into the distribution and properties of dark matter in the universe. Similarly, studying the potential effects of PBHs using gravitational lensing, such as microlensing, magnification, and distortion of light, and identifying the constraints of the mass and abundances of PBHs based on the absence of lensing in specific regions of the universe, allowing researchers to study their existence, mass, and abundance.

Gravitational lensing is chosen as the main focus of this paper due to its unique ability to provide a direct observational tool to study the existence of PBHs. Direct detection of PBHs is often difficult for conventional astronomical observations, as they are elusive and may not emit significant electromagnetic radiation. However, gravitational lensing provides an indirect but powerful method to detect and characterize PBHs. By analyzing the distortion and magnification of background objects in the light caused by the PBH's gravitational effects, researchers can derive valuable information about these mysterious objects and extrapolate their potential as dark matter candidates.

In this paper, I explore conclusions and links made between PBHs and dark matter, using a comparative analysis between theoretical predictions and previously collected observational data. By examining the relationship between PBHs and gravitational lensing, this paper hopes to reveal the fundamental role that PBHs may have played in the formation of the early universe.

Dark Matter

Our universe is made up of 27% dark matter, the observable matter we know makes up only 5% of it[8]. The elusive nature of dark matter is a prevalent mystery, consisting of non-baryonic particles[9](a hypothetical form of matter that does not contain baryons—that is, without any protons or neutrons) that have not yet been detected in laboratories or through various detection efforts[10]. However, early studies have revealed evidence for dark matter via the gravitational impact it has through astronomical observations including substantial movements of galaxies and stars within clusters, large-scale structures, gravitational lensing, as well as cosmic microwave background radiation11. Evidence collected so far has revealed the possible distribution, mass, and abundance of dark matter within the parameters of our observable universe. The data that suggests that dark matter is non-baryonic and exhibits "cold" characteristics indicate the relatively slow motions of particles and celestial bodies during the early stages of the universe's development, where their speeds were lower than that of the speed of light. Furthermore, its interaction with other matter is predominantly governed by gravity, exhibiting weak interactions concerning the other fundamental forces.

The Lambda Cold Dark Matter (λCDM) cosmological model[11] offers a direct, yet peculiar explanation. The model involves a cold, flat, dark matter universe, governed by a cosmological constant known as λ. The six fundamental parameters that encompass this constant include the following: the density of matter and baryons, the amplitude and scale dependence of initial mass fluctuations, and the age of the universe and the first stars. Remarkably, this (λCDM) cosmology aligns exceptionally well with the collective astronomical data obtained so far.

The main question arises: What exactly is dark matter? The concept plays an integral role in understanding the origins and fate of our universe, the phenomena that take place within it, its shape, vastness, and other characteristics. The term dark matter can be broken down into two parts, "dark" and "matter". Matter refers to anything that possesses mass and occupies space. Visible matter is composed of baryonic matter[12], and interacts with the electromagnetic spectrum, therefore being mass that we can observe and interact with. However, we use the term "dark" to describe a form of matter that exists but does not interact with the electromagnetic spectrum. Physicists believe dark matter to be composed of non-baryonic matter, undetectable even at the Large Hadron Collider, possibly escaping without any notice[13].

Primordial Black Holes as Dark Matter Candidates

Physicist Bernard Carr, who initially had doubts about the existence of primordial black holes in the early 1970s, now believes that there is a strong possibility that they exist. Hawking and Carr did early calculations on how the universe in its early stages could have produced black holes, as previously mentioned in the introduction. Today, Carr asserts a 50% or higher likelihood of the existence of PBHs, as other dark matter particle searches have been unsuccessful, and gravitational wave experiments support the evidence of PBHs[14].

While dark matter is commonly believed to consist of elementary particles, an alternative source, primordial black holes, could also contribute to developing a PBH, serving as a potential dark matter candidate. However, certain limitations narrow down the potential mass ranges for PBHs to $(10)^{16}g$, to $(10)^{17}g$, $(10)^{20}g$ to $(10)^{24}g$, and 10 to $10M\odot 15$. The possibility of PBHs with masses larger than $(10)^{3}M\odot$ is a subject of debate, but it has gained significance due to recent observations of black-hole mergers by LIGO/Virgo.

Even if PBHs made up a small portion of the dark matter density, they could have significant implications for cosmology. Larger PBHs could play a role in generating cosmological structures[15], mitigating issues associated with the standard cold dark matter model. Larger PBHs can mitigate the small-scale issues in the (λCDM) model[16] by contributing to the dark matter content of the universe and forming varying types of halos, or regions of space where the gravity of a PBH causes dark matter to accumulate, compared to standard cold dark matter particles. Additionally, they can address large-scale issues by acting as the seeds for structure formation, growing into massive black holes, attracting surrounding matter, and eventually forming galaxies. Furthermore, the formation and properties of PBHs are intricately linked to early universe conditions, such as the equation of state (the relationship between the pressure and the energy density of the universe) during inflation, making the study of their evolution valuable for understanding the early universe's physics. Moreover, sufficiently larger PBHs might serve as the seeds for the formation of supermassive black holes found in galactic nuclei. Additionally, there are several intriguing possibilities with exotically massive PBHs, such as remnants from PBH evaporation at Planck-mass or immensely large black holes exceeding $(10)^{12}M\odot$, which could contribute as interesting dark matter candidates[17].

The most commonly proposed theory for the formation of a PBH is the idea of inflationary fluctuations[18]. Shortly after the Big Bang had occurred, the inflationary period took place, where primordial density fluctuations were stretched out, seeding the growth of structure formation. The theory of inflation fluctuations suggests that the seeds for the formation of the primordial black hole (PBH) were sown during the rapid expansion of the universe after the Big Bang. Fluctuations in quantum density that expanded during cosmic-scale inflation led to the creation of hyperdense regions. When the density exceeded a critical threshold, gravitational collapse occurred, creating PBHs of different masses.

In this scenario, gravity is dominated by the denser regions if they were larger than the Jeans mass, which is the critical mass above which gravity's influence becomes more significant, causing collapse against the pressure. To view this proposed theory mathematically, we consider the horizon-scale fluctuations to have a Gaussian distribution with dispersion σ and the fraction of horizon patches collapsing into a black hole to be[14]:

$$\beta \approx \mathrm{Erfc}\left(\frac{\delta_c}{\delta\sqrt{2}}\right)$$

In this context, 'Erfc'[19] represents the complementary error function, and δc is the density contrast, indicating the fractional excess above the mean necessary for the formation of PBHs, the horizon-scale fluctuations have a Gaussian distribution with a dispersion of σ and β is the PBH mass fraction. The second theory that suggests PBH formation is the theory of scale-invariant fluctuations – with constant amplitude at the horizon epoch, their mass spectrum should have the power-law form, where λ specifies the equation of state $(p = w\rho C^2 g)$ at PBH formation[14]:

$$\frac{dn}{dM} \propto M^{-\alpha}$$

with

$$\alpha = \frac{2(1+2w)}{1+w}$$

The exponent in this form -α arises due to a difference in redshift dependencies, the connections between how much light from faraway objects has shifted to the red end of the spectrum and their other properties like distance, speed, age, or size, between the background density and PBH density. M represents the mass of a PBH, w represents the ratio of pressure to density and n is the number density of a fixed PBH mass, It was once even argued that primordial fluctuations would be of an invariant scale[20], but this was inapplicable in the inflationary scenario. As mentioned previously, PBHs could have even arisen from a collapse in a matter-dominated era. If the universe transitions into a pressureless state, mainly dominated by matter, there is a higher likelihood of PBH formation. This situation can occur during a phase transition when mass converts into non-relativistic particles or during a gradual reheating phase following inflation. A recent study by Hidalgo et al.[21] explored the formation of PBHs in a scenario where an oscillating scalar field behaves like dust during an extended period of preheating. While various other studies explore different formation theories of primordial black holes (PBHs), the main emphasis of this paper is to analyze lensing phenomena to provide evidence for PBHs as potential candidates for dark matter.

Gravitational Lensing

Gravitational lensing, also termed a "cosmic magnifying glass," is a phenomenon by which the path of light in outer space is influenced by the gravitational effects[22] of varying mass concentrations present throughout our universe. Gravitational lensing occurs when there is a source of a single mass concentration present, such as the core of a dense galaxy. When light from distant galaxies approaches this point of mass concentration, the photons that are traversing through these mass distributions are redirected around the point, producing multiple images of the background galaxy. If the lensing phenomena end up being completely symmetrical, an almost complete circle of light is formed, otherwise known as an "Einstein Ring". However, if lensing were to occur in a massive distribution of galaxies, it would be more complex. This is because galaxy clusters do not have a center, and are significantly "lumpy". The cluster's gravitational influence causes background galaxies to be distorted, resulting in the formation of frequently observed, slender "lensed arcs" typically found in the cluster's outer regions.

Researchers commonly distinguish between three types of lensing regimes: strong, weak, and micro. Strong lensing arises when the observer perceives multiple images of the source, which necessitates the presence of a perturber generating a potent gravitational field and a remarkably precise alignment between the lens and the source. In contrast, the gravitational field of the deflector in weak lensing is typically insufficient to yield multiple images; instead, it induces a generic distortion in the observed images, detectable only in a statistical sense. The term 'microlensing' denotes instances of strong lensing where the angular separations between the multiple images are extremely small. This name originates from the angular separation that is produced by the gravitational field of a star, which is usually on the order of microarcseconds. Gravitational lensing is still a considerably new field—strong, weak, and microlensing observations only being a few decades old. However, in this brief time span, it has transcended its status from being a mere mathematical uncertainty to becoming a potent instrument for studying astronomical phenomena such as galaxies and star clusters, dark matter, and black holes.

Multiple observations investigate the population of primordial black holes and set limits on the range of masses in which they could serve as plausible dark matter candidates[23]. Various observations have been made to study PBH populations and establish constraints on their weight range. These constraints are key to understanding whether PBHs can explain the elusive dark matter that makes up much of the universe's mass. Constraints on mass ranges arise from a combination of theoretical considerations and observational data. Theoretical models for the formation of PBHs suggest that their masses can range from microscopic scales, such as the Planck mass, to astronomical scales comparable to the masses of stars. The significance of identifying these black holes remains crucial, even if they contribute to a small fraction of cosmological dark matter in our universe. As a result, future observations will allow researchers to probe into the scenarios where PBHs are present in much smaller quantities. As discussed earlier, the presence of mass and energy causes space-time to curve. In the case of dark matter, gravitational lensing reveals its distribution as we further analyze and study the gravitational effects on visible matter. Using microlensing, we can detect the mass and abundance of primordial black holes directly.

As of yet, there have been a few varying techniques to gather observational evidence of the existence of a PBH: gravitational microlensing, gravitational waves, electromagnetic signatures from evaporation, accretion, and dynamical effects[24]. Microlensing has proven to be the most reliable constraint for high-mass objects, whereas gravitational waves have provided more potential for further discoveries in this field alongside the electromagnetic signatures providing constraints for the lower mass ranges.

The earliest known record of the lensing of a massive object has been mentioned in the 1704 paper, Newton's Opticks[25]. Although Newton's query upon this observation had not specified whether the phenomena was that of gravitational light bending or conventional optical phenomena, in 1784, John Mitchell was able to use Newton's Opticks to argue that light would be redshifted after traversing through a gravitational medium[26]. Researchers continued to investigate this matter until 1924, when Chwolson's work demonstrated the potential for lensing to create multiple images of a distant source, a phenomenon now referred to as strong lensing[27]. However, this occurrence relies on the precise alignment of the source and deflector, making it reasonable to infer that observing such events would be highly improbable. Reflecting the prevailing thoughts of that era, Einstein, influenced by Mandl, explored what Paczynski later termed "microlensing," which involves the temporary brightening of a star caused by the magnification from a foreground object passing in the observer's line of sight. In a concise and overlooked article from 1937, Fritz Zwicky expresses his belief that galaxies and galaxy clusters could serve as valuable lenses, envisioning how lensing through such systems could facilitate detailed examinations of otherwise faint distant systems and also provide insights into the total masses (including dark and visible matter) of the lenses. The mathematical understanding of multiply imaged geometries was further advanced independently by Klimov, Liebes, and Refsdal. Refsdal demonstrated that if a background lensed source, such as a quasar, exhibits variability in its light output, the time delay in the arrival of light observed in its multiple images could be used to determine an absolute distance scale. This approach provides a geometric means to measure the rate of expansion of the universe.

The concept of galaxies being surrounded by dark matter haloes had become widely accepted by the early 1980s. However, quantifying the distribution of dark matter around galaxies and verifying its influence in galaxy formation poses a challenge, considering its invisible nature. To address this, elliptical galaxies, being compact and dense, offer an excellent opportunity as gravitational lenses.

In a notable study, the SLACS[28] team utilized spectroscopic data from the Sloan Digital Sky Survey and identified 98 elliptical galaxies that strongly lens background blue star-forming galaxies at moderately high redshift. The known redshifts of both the lens and the background source allowed for determining the lensing geometry using the Hubble Space Telescope images[29]. This geometry defines the total mass within the critical line, also known as the "Einstein radius," regardless of whether the material emits light. By combining this information with the dynamically based mass derived from the dispersion of stellar velocities within the lensing galaxy on a smaller physical scale, the total mass density as a function of galactocentric distance $\rho(r)$ can be derived. Remarkably, across various cosmic times and lens masses, the total mass distribution exhibits a consistent isothermal distribution. This spatial extension is greater than that of visible baryons, providing clear evidence for the existence of dark matter.

Furthermore, the total mass distribution appears to align with the ellipticity and orientation of the light. These significant findings confirm that the early formation of massive dark matter haloes played a crucial role in facilitating the rapid formation of the cores of massive galaxies. In his insightful work, Zwicky proposed the utilization of galaxy clusters as natural telescopes to explore magnified images of remote galaxies, thereby extending the reach of our existing observational capabilities.

Over the past five years, this approach has proven highly effective in locating and comprehending the characteristics of the earliest galaxies visible during the universe's early stages, accounting for only 10–15% of its current age. Clusters of galaxies present significantly larger cross-sections to the background population compared to individual galaxies, leading to a higher likelihood of encountering magnified images; indeed, many clusters exhibit numerous multiple images. However, the mass distribution within a cluster is less uniform than that of an individual galaxy, necessitating careful modeling to understand the locations of critical lines and derive associated magnifications. Notably, some of the most distant galaxies known have been detected by focusing on the critical lines of massive clusters, where typical magnifications range from 20 to 30 times.

These distant systems would have remained undetected without the signal boost provided by gravitational lensing. Given that early galaxies are likely less massive and luminous than their later counterparts, this technique offers the sole means to assess their abundance. Beyond enhancing the integrated brightness of sources and making them more easily observable with telescopes, gravitational lensing also enlarges the apparent angular size of distant sources, facilitating the determination of their internal properties.

The most distant galaxies are physically diminutive, approximately ten times smaller than our Milky Way, posing a challenge for resolution using instruments like the Hubble Space Telescope and ground-based telescopes equipped with adaptive optics—a method correcting for atmospheric blurring. Nevertheless, the combination of adaptive optics and gravitational magnification provides exceptional opportunities. For instance, a distant galaxy with a redshift of 3 typically spans only 0.2 - 0.3 arcsec, but when magnified by a factor of 30×, it becomes feasible to secure spectroscopic data point-by-point across its enlarged image and reveal features such as rotating discs[30]. From these and related studies, a tentative picture of early galaxy evolution emerges.

During a time when the universe was approximately 5% of its current age, a substantial population of feeble low-mass galaxies emerged from slowly cooling clumps of hydrogen gas. The energetic ultraviolet radiation from young stars in these early galaxies ionized the surrounding hydrogen gas, and they continued to evolve, accumulating through mergers and the ongoing accretion of hydrogen gas.

Gravitational Microlensing to Measure a PBH

We can observe two features from microlensing: photometric microlensing (temporary brightness changes) and astrometric microlensing (apparent shifts in the source's centroid position)[31]. The photometric signal characteristics of a basic point-source, point-lens (PSPL) model, as observed from the center of the solar system, exhibit symmetry and lack chromatic aberration. The timescale and maximum amplification of this signal are dependent on the mass of the lens involved. Nevertheless, astrophysical complexities, such as the velocity distribution of sources and lenses, galactic dust extinction, blending in densely populated stellar fields, stellar and planetary companions, and the perspective shift caused by Earth's orbital motion around the Sun, add intricacy to this straightforward PSPL model. However, these complications can be effectively addressed and disentangled to determine the gravitational lens mass and enable dark matter detection through microlensing. Of particular significance for extended microlensing events is the alteration in the geometric configuration of the source-lens-observer system due to the Earth's orbital motion around the Sun. Researchers have found a promising way to detect PBHs with masses around or greater than 1 solar mass. By measuring the duration and parallax, the apparent shift or change in the position of a star or other astronomical object due to the motion of the observer, of the microlensing event, we can distinguish black hole lenses from other astrophysical sources.

Observations involving the use of the Subaru HSC have provided strong limits on PBHs in different mass ranges[32]. Additionally, strong lensing of fast radio bursts and gamma-ray bursts offers unique opportunities to probe PBH dark matter. In a reassessment of the OGLE data, several candidate events were identified with masses approximately equal to $\sim 10_{\text{-}5} M\odot$. OGLE-GAIA observations also detected black holes of around $1M\odot$, which fall within the mass gap region and could have originated from primordial sources[33].

By using microlensing constraints derived from HSC data, researchers can limit potential stochastic gravitational wave background signals, such as those reported by NANOGrav[34]. The primary source of systematic uncertainty lies in the distribution of dark matter in the Milky Way halo, which also has implications for other dark matter experiments. While microlensing constraints are not influenced by small-scale primordial black hole (PBH) clustering, they are significantly affected by large-scale PBH clustering.

Beyond galactic microlensing surveys, lensing of supernovae at cosmological distances and lensing of quasar light curves are also considered for studying PBH dark matter. In the future, high-resolution imaging with telescopes like the James Webb Space Telescope, the Roman Space Telescope, or an Extremely Large Telescope could enhance our understanding of PBH constraints using gravitational lensing.

Dynamical and Accretion Evidence

When considering the density (symbol p) and velocity dispersion (V) of PBHs, along with a system's mass (M_c), radius (R_c), velocity dispersion (V_c), and survival time (t_L), we find the following constraints (limitations on the values of the parameters mentioned above)[35]:

$$f(M) < \begin{cases} M_c V/(G M \rho t_L R_c) & [M < M_c(V/V_c)] \\ M_c/(\rho V_c t_L R_c^2) & [M_c(V/V_c) < M < M_c(V/V_c)^3] \\ M V_c^2/(\rho R_c^2 V^3 t_L) \exp[(M/M_c)(V_c/V)^3] & [M > M_c(V/V_c)^3] \,. \end{cases}$$

In the PBH mass function above, the three limits correspond to different disruption scenarios: multiple encounters, one-off encounters, and non-impulsive encounters. These scenarios potentially indicate the presence of primordial black holes (PBHs). However, we specifically focus on the three effects that have been claimed to show positive evidence. These effects include the heating of the Galactic disk, peculiar characteristics of ultra-faint dwarf galaxies (UFDGs), the cusp/core problem in dwarf galaxies, recent observations by JWST of galaxies at higher redshifts than predicted by standard galaxy formation models, and the triggering of white-dwarf explosions[36].

Numerous constraints and potential signatures are associated with primordial black holes (PBHs) arising from their accretion luminosity (the brightness produced when matter falls onto a massive object due to gravity, emitting light as it heats up in the process)[37]. These signatures involve observations of point sources for individual PBHs, the generation of cosmic background radiation[38], and effects on the thermal history of the universe due to a population of PBHs[39]. However, these signatures are subject to uncertainty, as they rely on astrophysical assumptions and the environment surrounding the black holes, such as gas density and temperature.

PBHs residing in galactic nuclei or halos will accrete local gas and stars, while those outside galaxies will still accrete intergalactic gas, with consequences depending on the uncertain state of the intergalactic medium. Additional indirect constraints arise from μ-distortions[40] in the cosmic microwave background spectrum, linked to the dissipation of density fluctuations that give rise to PBHs[41]. Although these effects are typically considered as constraints, they also hold potential as signatures.

We see signs of different forms of matter, such as gas or dust, falling into big black holes in the centers of galaxies, and also some hints from X-rays and infrared light, showing that there might be clouds of particles around earlier than usual. We also notice radio signals, and during this time, even mysterious dark matter could be getting pulled in.

Silk has also raised similar points, proposing that intermediate-mass PBHs might have been prevalent in early dwarf galaxies, exhibiting mostly inactive behavior today but having been active during their gas-rich past[42]. Current observations of active galactic nuclei support the possibility of such intermediate-mass PBHs, and their early feedback could potentially offer a unified explanation for various anomalies observed in dwarf galaxies. These PBHs could serve multiple roles, including contributing to early galaxy formation, acting as seeds for supermassive black holes at high redshifts, and:

1. Suppressing the number of luminous dwarf galaxies.
2. Generating cores in dwarf galaxies through dynamical heating.
3. Intermediate PBHs could fix the ”too big to fail” problem by shaping small galaxy formation.
4. Facilitating the formation of bulgeless disks (flattened galaxies).
5. Playing a role in the creation of ultra-faint dwarf galaxies (UFDGs) and ultra-diffuse galaxies.
6. Lowering the normal matter ratio in galaxies like the Milky Way.
7. Explaining ultra-luminous X-ray sources found in the outskirts of galaxies.
8. Triggering star formation in dwarf galaxies through active galactic nuclei.

Additionally, the presence of intermediate-mass PBHs would lead to the microlensing of extended radio sources[43].

Gravitational Wave Evidence

This section presents a brief analysis of the evidence for primordial black holes (PBHs) based on gravitational wave (GW) observations. In 2015, the initial detection of GWs[44] resulted from the merging of surprisingly large black holes (around $30M_\odot$), differing from those typically observed in X-ray binaries. This discovery reignited interest in PBHs, not just as merger sources, but also as a potential explanation for the elusive dark matter problem. Subsequently, over the span of seven years, around 90 detections have been cataloged in the third Gravitational-wave Transient Catalog (GWTC-3)[45], with intriguing properties of the GW sources.

A unifying PBH scenario is considered, which could account for various features observed in GW events, including merging rates, the distribution of black hole masses, events occurring in high- and low-mass gaps for stellar remnants, mergers with highly asymmetric masses, reported low spins, and specific subsolar black hole candidates. Additionally, PBHs in the stellar-mass range might contribute to a GW background at nanohertz frequencies, arising from both PBH binaries and waves generated through density fluctuations that lead to PBH formation. This GW background may already have been detected by Pulsar Timing Arrays (PTAs), such as the North American Nanohertz Observatory for Gravitational Waves (NANOGrav)[46], the European Pulsar Timing Array (EPTA)[47], the Parkes[48], and the International Pulsar Timing Array (IPTA)[49] collaborations. Nevertheless, further observations are required to confirm this potential discovery.

Opportunities and Implications in Primordial Black Hole (PBH) Research

In the domain of PBH (primordial black hole) physics, the progress made possible by current and forthcoming observational facilities stands unparalleled in its sensitivity. However, for effective PBH searches, it is imperative that these facilities not only possess extraordinary sensitivity but also gather data with well-timed cadence and comprehensive sky coverage. A path to amplify PBH sensitivity rests in the synergy of data from multiple observational powerhouses such as the Rubin Observatory, Roman Space Telescope, and Euclid. A collaborative endeavor, integrating joint processing and analysis methods, will undoubtedly magnify the possibilities of detecting these enigmatic entities.

While gravitational wave facilities situated on the ground such as LIGO and Cosmic Explorer, along with those based in space like LISA and AEDGE, present an exceptional opportunity to directly observe PBHs through their gravitational effects, the backing of the High Energy Physics (HEP) community becomes pivotal in propelling these facilities forward. Collaborative scientific teams, addressing the intricacies of PBH analyses within present and upcoming datasets, stand as paramount. These teams will meticulously construct robust tools to conduct exhaustive and sensitive PBH searches, with the computational requirements aligning effectively with the capabilities of HEP scientists and facilities.

Theoretical exploration remains a pivotal foundation in advancing our understanding of various facets of PBHs, encompassing their production mechanisms, clustering behavior, and spin properties. This theoretical underpinning not only informs us about the anticipated prevalence of phenomena like black hole microlensing and gravitational wave events but also assists in mitigating systematic uncertainties inherent in cosmic surveys. Moreover, the intricate connections between PBHs and primordial physics are unearthed through theoretical inquiries. Enhanced simulations that capture PBH merger rates and PBH-specific accretion rates contribute substantial insights that provide a foundation for constraints derived from observations.

Conclusion

In summary, this literature review examines the link between PBHs and gravitational lensing and their potential as dark matter candidates in the early universe. By focusing on gravitational lensing as a primary research tool, this paper investigates its unique ability to indirectly explore the existence, mass, and abundance of PBHs. The constraints identified from lensing observations provide valuable information, surpassing the challenges posed by the elusive nature of PBHs, which often evade conventional detection methods. As the search to understand dark matter continues, gravitational lensing is emerging as a promising avenue that offers a different and direct approach to exploring the connection between dark matter and PBH and their potential role in shaping our understanding of the early universe.

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