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The Primordial Black Hole Hypothesis: A Review of a Dark Matter Candidate Without New Physics

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Abstract. The nature of dark matter is an unresolved fundamental problem in physics. Although the exploration of new elementary particles has so far been unsuccessful, primary black holes (PBHs) have become an attractive alternative because of their roots in standard physics. This article comprehensively examines the PBH hypothesis as the ultimate solution to dark matter. We first describe the physical mechanisms that gave rise to PBHs in the early universe, with special emphasis on analyzing the theoretical model of cosmic inflation; then we combed through the observational limitations of multi-messenger astronomy, from the screening effect of Hawking radiation to the distortion of gravitational lensing, from the subtle effects of dynamic effects to the space-time ripples of gravitational waves. This evidence together outlines a narrow window of asteroid mass: only within this interval can all dark matter be composed of PBHs. Finally, we outline the bright future for testing this hypothesis in the future, and emphasize that a new generation of gravitational wave observatories, such as LISA, will play a pivotal role; they may be able to confirm this ingenious and time-honored hypothesis or completely overturn it.

Keywords: Dark Matter, Primordial Black Holes, Cosmology, Muti-messenger Astronomy, Gravitational Waves

1. Introduction

There seems to be something wrong with the universe. Galactic galaxies rotate unbelievably fast, and galaxy clusters distort light far beyond what can be explained by visible matter within them. The cosmic microwave background radiation-the afterglow of the Big Bang-is equally conclusive: about 85% of the matter in the universe is missing [1]. This "dark matter" remains one of the most profound mysteries in modern physics.

For decades, human exploration of dark matter has focused on finding new elementary particles. The mainstream theory "WIMP miracle" once led the way, predicting a weakly interacting massive particle born in the thermal chaos of the early universe. This theory is well-conceived and verifiable. To this end, we have built sophisticated and huge detectors deep underground and designed giant accelerators that can collide particles at extremely high energies. However, after years of searching, these instruments only captured a meaningful silence [2]. The expected signal never came. This dilemma of finding nothing has pushed the academic community to a critical juncture, forcing us to look to unknown territory beyond particle candidates.

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What if the answer is not a new particle at all? An ancient but simple idea is resurfacing: primary black holes (PBHs). They are not the remains of the collapse of stars, but time-space relics forged in the extreme environment of the first second of the birth of the universe [3]. The charm of PBHs is self-evident does not exceed the theoretical framework of the Standard Model and General Relativity, but also inherently has the characteristics of low-temperature, stable, and non-baryonic matter, which is in line with the description of dark matter.

This review explores the PBH hypothesis as a complete solution to the dark matter puzzle. We will first analyze the physical mechanisms that gave birth to them in the early universe, and then sort out the complex network of constraints formed by multi-messenger astronomy observations-constraints that have significantly narrowed the range of possibilities. Finally, we will look to the future and assess the prospects that this fascinating theory, which is different from particle dark matter, will eventually be confirmed or overturned.

2. Formation mechanisms of primordial black holes

Primitive black holes are born in chaos. The core idea is clear at a glance: in the primitive plasma of the early universe, some regions were much denser than elsewhere. If a place is extremely dense, its own gravity can override the expansion of the universe and the outward pressure of the plasma, causing irreversible collapse and eventually forming a black hole [3]. The resulting mass of PBH is closely related to the mass of matter contained in the Hubble horizon at the time of its formation. If a black hole is born during the QCD phase transition period (10-5 seconds), its mass is equivalent to that of the sun; if it is formed during the Planck time (10-43 seconds), it is only as heavy as an eyelash. This interlocking relationship between mass and the moment of formation means that PBH may be spread on eye-popping scales-from as tiny as mustard seeds to as giant as galaxies [4].

The key factor is the source of these initial extreme density perturbations. The theory of cosmic inflation provides the most convincing explanation exponential expansion at the beginning of the universe stretched tiny quantum fluctuations into the seeds of all cosmic structure. However, the traditional single-field slow-rolling inflationary model is too mild. Although it can accurately predict the gentle ripples observed in the cosmic microwave background, it is helpless against the violent density spikes needed to form the primordial black hole [5]. The original power spectrum generated by this model is nearly constant in scale, which means that at the microscopic scale where the original black hole was formed, the fluctuations were negligible.

To breed PBHs, the inflation of the universe must go astray. The most studied mechanism so far is the artificial construction of a special structure in the potential energy field of the inflator, such as a local bulge or near the inflection point. When the inflon field rolls over this structure, it enters a brief "ultra-slow-roll" [6] stage. At this time, the field speed suddenly drops, causing the amplitude of the curvature disturbance to increase exponentially. This process can increase the power spectrum by six to seven orders of magnitude, just meeting the critical condition that triggers the formation of PBH. Although effective, this mechanism often requires careful fine-tuning of the potential energy form, an artificial feature that many theoretical physicists scoff at.

Recent research has taken a different approach and attempted to generate PBHs more naturally without such elaborate adjustments. One promising path involves "spectator fields" [7]. During inflation, there may be other lightweight scalar fields in the universe in addition to the inflaton. Because of their small mass, these spectrometer fields are subject to violent quantum fluctuations, causing their values to change randomly in different regions of the expanding universe. If there is a sufficiently flat region of the potential energy of one such field, quantum transitions can locally push it into it. At this point, the energy density of the spector fields can temporarily dominate, creating the

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large curvature disturbance required for the collapse of PBHs. The whole process can not only not interfere with infaton's main responsibility of generating the large-scale structures observed today, but also avoid the problem of fine adjustment, which can be said to kill two birds with one stone.

In addition to inflation theory, other physical processes in the early universe may have triggered the formation of the PBH. For example, the cosmological phase transition may cause a sudden drop in the pressure of the universe. This softening of the equation of state greatly lowers the threshold for density fluctuations and collapses, making the formation of PBH easier [3]. Among them, the QCD phase transition is particularly eye-catching because it may naturally produce solar mass PBH. More exotic hypotheses, such as the collapse of the strings of the universe, remain a theoretical possibility. In the final analysis, despite multiple approaches, inflation theory remains the most powerful and well-studied framework for the seeds of primitive black holes.

3. The puzzle of observational constraints

If the universe were filled with primeval black holes, they would not escape the trap. Over the past fifty years, astronomers have cast a wide net and exhausted every means to search for traces of its gravity and radiation. This cosmic legal network has pieced together a complex puzzle of layers of constraints, significantly eliminating the possible quality range of PBH. Each puzzle is derived from different observation methods and physical processes that together outline the truth that dark matter is nothing.

3.1. Evaporation constraints: the aftermath of dying black holes

The lightest black holes are unstable. Stephen Hawking's disruptive discovery showed that black holes radiate energy outward, a process now known as Hawking radiation [8]. This radiation has thermal spectral properties, and its temperature is inversely proportional to the mass of the black hole. For black holes of stellar mass, the effect is minimal. But for the original black hole, this is tantamount to disaster. Any PBH with a mass less than about 5×10 ‰ grams (roughly equivalent to the mass of a mountain) has long evaporated to this day.

These microscopic black holes that are about to annihilate suddenly explode like pocket bombs lurking at the birth of the universe. When they decay suddenly, they will burst out a torrent of high-energy particles such as photons, neutrinos, and electron-positrons. This torrential rain of energy particles will surely leave an indelible mark on the vast space [9].For example, those PBH (primordial black holes) that evaporated in the first few minutes after the Big Bang injected additional energy and particles into the primordial cosmic soup where light elements were being formed. This would change the expected abundances of deuterium and helium, undermining the impressive success of the Big Bang Nucleosynthesis (BBN) theory. Then, the PBH that evaporated during cosmic recombination injected energy into the plasma, distorting the perfect blackbody spectrum of the Cosmic Microwave Background (CMB) and obscuring its temperature anisotropies. Eventually, the glow produced by the evaporation of all primitive black holes throughout the history of the universe converged and intertwined, adding to the diffuse gamma ray and cosmic ray background we observe today. These powerful evaporation limits built an iron wall, clearly excluding the possibility that any primordial black hole with a mass less than about 10 μ g would become the main component of dark matter [9, 10]. Any primeval black hole to is dark matter must have a mass higher than that of an asteroid.

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3.2. Gravitational lensing: a cosmic magnifying glass

For PBHs that are massive enough to survive today, their gravity provides us with the most direct detection method. The principle of gravitational lensing is clear: When a dense object passes in front of a distant star, it distorts starlight, causing the star to brighten briefly and uniquely. This "microlensing" phenomenon is a powerful tool for searching for invisible celestial bodies.

Over the past three decades, numerous sky survey projects have monitored hundreds of millions of stars just to capture these fleeting flashing signals. The MACO and EROS teams turned their attention to Magellanic Clouds, while the OGLE Sky Survey focused on the dense clusters of stars in the central bulge of the Milky Way [4]. Recently, Subaru Hyper Suprime-Cam (HSC) conducted extremely sensitive observations of the Andromeda galaxy, with thought-provoking results. Although a few sporadic events have been detected, their number is negligible and far from enough to prove that the entire galactic halo is full of black holes. These fruitless observations set extremely strict limits, almost completely ruling out the possibility that primeval black holes (PBHs) constitute all dark matter in a wide range of about 10^{3} times the mass of the sun (equivalent to the mass of the moon) to 100 times the mass of the sun [1]. The simple hypothesis that dark matter is composed of sun-mass black holes has been basically falsified by these powerful gravitational lens surveys. Other lens techniques, such as Type Ia supernovae light curve distortion observations, detect leaks and fill in gaps, further locking the theoretical space of this critical mass interval [1].

3.3. Dynamical and accretion constraints: gravitational stirring and glowing halos

In addition to the gravitational lensing effect, the massive gravity of a large number of PBHs would have reshaped the galaxy. If galactic halos are filled with massive black holes, they will be like a group of rampaging cosmic hammers, destroying weeds everywhere they go. Those structurally fragile star systems-such as binary stars with broad orbits but thin orbits-will fall apart in an instant if they encounter close contact with massive PBH. The survival of such systems today suggests that the galactic halo cannot be filled with black holes more than 10 times the mass of the sun [1]. Similarly, if PBHs frequently pass clusters in the cores of dwarf galaxies such as Eridanus II, their gravitational disturbances should have caused the clusters to heat and expand, but no such signs have been found in actual observations.

PBHs not only stir up the surrounding environment, but also feast on it. When it travels through the interstellar medium, it uses gravity to devour gas, forming a hot accretion disk around it. The process is not silent-the swallowed gas heats up sharply, bursting with intense X-ray radiation. Such energy gushed out enough to shake the thermodynamics and ionization evolution of the early universe. Planck's precise measurements of the cosmic microwave background radiation (CMB) are extremely sensitive to such energy injections, placing the most stringent limits on PBHs with masses exceeding several solar masses [4]. If the universe is full of primeval black holes, the entire sky will be dazzling.

3.4. Gravitational waves: echoes from the dawn of time

The emergence of gravitational wave astronomy has opened an unprecedented window for us to understand the universe, and also provided two powerful and independent means for testing the PBH hypothesis.

First, if PBHs did exist, they should have formed binary stars in the early days of the universe and merged over time. These collisions send out unique "chirp" signals that have now been

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repeatedly captured by the LIGO-Virgo-KAGRA observatory. Although the masses of black holes discovered so far are consistent with the theory of stellar evolution, the frequency of merger events is a key clue. Theoretical calculations show that if PBHs with 10 times the mass of the sun constitute all dark matter, their merging rate will far exceed the actual observed value. This ironclad evidence, based on the merging rate, fundamentally limits the possible abundance of PBHs at stellar mass levels [1].

Second, and perhaps most exciting, is that the mechanism that forms PBHs (primordial black holes) itself leaves a unique gravitational wave imprint. The huge density fluctuations needed to create PBHs must have violently shaken the structure of spacetime itself. This process creates a random gravitational wave background-a lingering ripple of time and space that originated from the beginning of the universe. The frequency of this background wave is directly related to the mass of the PBHs produced. For PBHs located in the asteroid mass window, the predicted signal falls right in the detection band of the future Laser Interferometric Space Antenna (LISA) [11]. If LISA detects such background waves, it will be tantamount to ironclad evidence. It will not only almost irrefutable confirmation that the early universe experienced a period of violent small-scale structure formation, but also provide a final conclusion for the existence of the original black hole.

3.5. Discussion and future prospects

After decades of unremitting exploration, the parameter space of the original black hole has been greatly compressed. A comprehensive analysis of evidence, such as evaporation effects, gravitational lensing, dynamic characteristics, and gravitational waves, has brought to the surface the only possible area that has not been ruled out-PBHs may still constitute all of dark matter in the asteroid mass range of 1017 to 1023 grams [1]. This window of survival not only confirms the power of multi-messenger astronomy, but also exposes the challenges ahead. Although many existing restrictions are well stated, their theoretical foundation is still controversial. For example, the exact impact of PBH clustering on the confinement of micro-gravitational lenses is still a hot topic of research, and the uncertainty of the gas accretion model makes the constraints based on CMB observations even more confusing.

However, the way forward is gradually becoming clear, and gravitational waves are expected to become the ultimate referee of the original black hole hypothesis. The physical mechanism that bred the original black hole during inflation is inseparable from the generation of the random gravitational wave background [12]. Those huge scalar perturbations that collapse into black holes will inevitably produce tensor perturbations under the second-order effect. This is by no means nonsense, but a definite result in the formation mechanism. For those primeval black holes (PBHs) that still exist in the asteroid mass window, the gravitational wave background they generate will peak in the millihertz band, coinciding with the future Laser Interferometer Space Antenna (LISA) detection range [11].

In my opinion, this test is quite sophisticated. If the surviving PBH in that mass range is indeed dark matter, we can detect raw gravitational wave signals from the early universe through LISA. If nothing is achieved, it will completely overturn a large class of the simplest and most likely inflationary models for PBH formation. Because of this, searching for this specific gravitational wave background has become one of the most anticipated future research directions in cosmology. The next generation of CMB observatories, such as CMB-S4, as well as the fledgling 21-centimeter field of cosmology, will provide us with complementary information-they can detect the raw power spectrum on a smaller scale than before, further constraining the inflationary physical mechanism that causes PBH.

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This story may be more complex than a simple "either-or" story. What if PBHs only account for a small fraction of dark matter and coexist with the dominant particle composition? In this mixed scenario, PBHs will embody gravitational seeds, causing particle dark matter to form extremely dense "peaks" around them in the early days of the universe [13]. The annihilation rate of the particle within these peaks will be greatly increased, and even if the particle's annihilation cross-section is so small that it is difficult to observe elsewhere, it may still produce a detectable gamma ray signal. No such signal has yet been observed, placing strict limits on this fascinating possibility. This highlights the subtle interactions between different dark matter candidates and also shows that the pursuit of primary black holes will affect the entire field of dark matter research.

4. Conclusion

The concept of primitive black holes provides us with a solution rooted in known physics. Over time, a large number of multi-messenger observation data have severely tested this theory, greatly reducing its possible parameter space. Today, there is only one narrow but feasible window left for asteroid mass PBHs, and the possibilities of PBHs as sub-components of dark matter remain vast. The road to exploration is far from over. In the next decade, our ability to detect the early universe will surely undergo earth-shaking changes, especially with the help of gravitational waves. A new generation of observatories, such as LISA, will bring unprecedented precision verification, either capturing the decisive gravitational echo of the formation of PBH or completely rejecting the simplest hypothesis of the origin of inflation. The primitive black hole hypothesis is still vibrant and in the ascendant. It confirms the ancient power of gravity to shape the universe and also demonstrates the continuous expansion of human cognitive boundaries.

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