Supermassive Black Hole Evolution in Cyclic Cosmology: Dark Matter and Evaporation Dynamics

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Abstract

We investigate the evolution of supermassive black holes (SMBHs) within the framework of cyclic cosmology, focusing on the effects of dark matter–modified Hawking radiation. We introduce a generalized mass-loss model incorporating dark matter interaction terms, characterized by a coupling strength parameter ψ and an interaction exponent p. This model predicts a significant reduction in black hole evaporation timescales. For a SMBH with mass $10^8 M_\odot$, the evaporation time decreases from the classical estimate of approximately $\sim 10^{82}$ billion years to as low as 4.2×10^7 years for moderate coupling values. A parameter study over ψ ranging from 10^{-8} to 10^{-3} and p from 0 to 2 reveals that the evaporation process is highly sensitive to these variables, allowing efficient mass–energy recycling within a single cosmological cycle. These dynamics contrast sharply with predictions from the standard ΛCDM model, where black hole evaporation is negligible on cosmological timescales; our results suggest that observable deviations in SMBH mass functions, gravitational wave signatures, and high-energy emissions could differentiate cyclic from ΛCDM scenarios. We discuss potential observational implications and propose preliminary constraints on the interaction parameters based on upcoming cosmological surveys. These findings position SMBHs as critical components in the dynamical and thermodynamic evolution of cyclic cosmology, opening new directions for both theoretical investigation and observational validation.

Keywords: Black Hole, Cyclic Cosmology, Dark Matter, SMBH.
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Introduction

SMBHs are fundamental to the formation and evolution of large-scale cosmic structures. Observations reveal that SMBHs with masses exceeding $10^9 M_\odot$ existed within the first billion years after the Big Bang. Notably, quasars such as ULAS J1342+0928, observed at redshift $z = 7.54$ with a mass of $\sim 8 \times 10^8 M_\odot$, and J0313–1806, at redshift $z = 7.64$ with a mass of $\sim 2 \times 10^9 M_\odot$ which is the most distant quasar yet identified exemplify the existence of massive black holes in the early universe [1-4]. Several theoretical pathways have been proposed to account for the rapid formation of SMBHs, including the direct collapse of primordial gas clouds [5, 6], runaway mergers of massive stars in dense stellar environments [7], and subsequent super-Eddington accretion [8-11] as a measurement of their rapid growth which will be discussed in the next section. Observational correlations between SMBH mass and host galaxy properties such as bulge mass and velocity dispersion further support the co-evolution of SMBHs with their galactic environments [12]. Beyond their role in galaxy formation, SMBHs may also influence the evolution of the universe itself, particularly within the framework of cyclic cosmology. Unlike the standard model of cosmology, which envisions a single Big Bang followed by unending expansion or eventual heat death, cyclic models posit a series of successive expansions and contractions [13, 14]. In these models, SMBHs can serve as high-energy matter and entropy reservoirs, shaping the initial conditions of each new cosmic cycle. The long-term fate of SMBHs whether through Hawking radiation, or, quantum gravitational processes, or, interactions with dark matter (DM) is the most important component in understanding cyclic universe dynamics. While the precise nature of DM remains elusive, its gravitational impact on SMBH can significantly affect accretion rates and mass growth [15-19]. Some models suggest that SMBHs may form dense DM spikes, which can modify their evaporation nature and radiation signatures [20]. Recent studies have extended the understanding of Hawking radiation [21, 22], suggesting that interactions with dark matter could alter the evaporation dynamics of black holes, particularly those formed in dense astrophysical environments [23]. These modifications may change the lifetime of super-massive black holes and play a role in entropy redistribution across cosmic cycles, with implications for cyclic universe models [24]. If SMBHs act as efficient sinks for DM, their growth and decay may produce observable signals in the form of gravitational waves, gamma-ray emissions, or shadow structures resolved by instruments like the Event Horizon Telescope (EHT). Recent studies indicate that the presence of DM around SMBH can alter gravitational waveforms emitted during BH mergers, thereby providing a novel and potentially powerful observational channel for probing the dark sector [25, 26]. Additionally, dark matter spikes near SMBHs may enhance annihilation rates, producing detectable gamma-ray excesses [27]. Imaging data from the EHT has further constrained the matter distribution near SMBH horizons, opening new window into black hole physics [28]. This study investigates the role of SMBHs in the context of cyclic cosmology, with an emphasis on their interactions with DM and the implications for black hole evaporation. We explore how modified Hawking radiation and dark matter-enhanced accretion affect the longevity of SMBH and their potential contributions to cosmic re-expansion. This work provides a new perspective on cosmology and deepens our understanding of cyclic universe scenarios.

Eddington Limit and Super-Eddington Accretion

The Eddington limit defines the maximum luminosity that an accreting black hole can achieve when the outward radiation pressure balances the inward gravitational force on the infalling gas. For a spherically symmetric flow, this limit constrains the accretion rate and, by extension, the black hole's growth rate. While the classical Eddington limit sets an upper bound, several astrophysical conditions permit temporary or local exceedance of this limit. In particular, super-Eddington accretion can occur through three primary mechanisms: (i) photon trapping in optically thick flows, where the inward advection of radiation dominates over radiative diffusion [29], (ii) anisotropic or beamed radiation, where the emitted flux is concentrated within narrow solid angles, effectively reducing the impact of radiation pressure in most directions [30], and (iii) the emergence of slim disk geometries, characterized by significant advective cooling, enables stable accretion at rates that exceed the Eddington limit. [31]. In such cases, the emergent luminosity can exceed the classical Eddington limit by factors of 2–10, depending on the accretion rate and disk structure, with analytical approximations yielding [32]

$$L \approx L_{EDD}\left[1 + ln\left(\frac{\dot{M}}{\dot{M}_{EDD}}\right)\right] \quad (1)$$

where $\dot{M}$ is the accretion rate and $\dot{M}_{EDD}$ be the Eddington accretion rate. These effects are particularly relevant in early-universe black hole growth. Super-Eddington accretion has been shown to play a critical role in the early formation of supermassive black holes, allowing them to grow rapidly within the short cosmic timescales available in the early universe. A schematic representation of this accretion process is provided in Figure 1, illustrating the structure of the inflow, black hole, and radiation outflow in a super-Eddington regime.

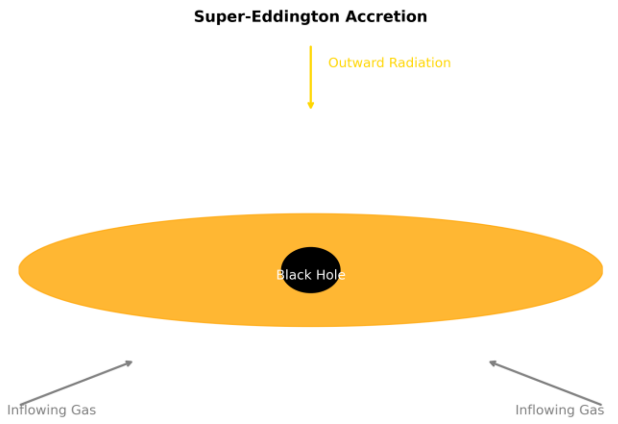

Figure 1: Structure of the inflow, black hole, and radiation outflow in a super-Eddington regime.

Supermassive Black Hole Formation

During the contraction phase of the universe, the mass collapses into Supermassive Black Holes [33]. The mass of the SMBH is determined by the accumulation of both baryonic matter and dark matter. The increase in SMBH mass as the universe contracts is modelled by the following equation:

$$M_{SMBH}(a) = M_{initial} + \int_0^a \left(\frac{dM}{da}\right) da \quad (2)$$

The mass accumulation rate is modelled as:

$$\frac{dM}{da} = CM_0 log(1 + (1 - a)^2) \quad (3)$$

Where $a(t)$ is the scale factor, and M_0 is the initial seed mass of the SMBH, including contributions from both baryonic and dark matter and C is a proportionality constant that can be tuned accordingly. Now, M_0 can be evaluated when $a(t) = 1$ as $\frac{dM}{da} = 0$ for $a(t) = 1$. This can be interpreted as SMBH accreting matter during contraction, where surrounding density increases as scale factor decreases during contraction of the universe. The term $log(1 + (1 - a)^2)$ captures several aspects: As $a(t)$ decreases, the term $(1 - a)^2$ increases causing the log term to grow, reflecting how SMBHs accrete more matter. Near $a(t) \to 0$, the logarithmic function grows steadily, which reflects continued mass growth near the final stages of contraction. This form avoids singularities and ensures smooth mass growth from $a(t) = 1$ to $a(t) \rightarrow 0$ corresponding to the gradual accretion of matter over the contraction period. The contraction phase occurring between $t_{\text{start}} = 16$ billion years and $t_{\text{end}} = 17$ billion years [34], represents a critical period in the cyclic universe model. During this phase, the scale factor $a(t)$ is modeled as:

$$a(t) = 1 - \left(\frac{t - t_{\text{start}}}{t_{\text{end}} - t_{\text{start}}}\right)^n \tag{4}$$

where n is a positive exponent that governs the sharpness of the contraction. To justify this expression the scale factor $a(t)$ is normalized as:

$$a(t) = a_{\text{norm}} \left[1 - \left(\frac{t - t_{\text{start}}}{t_{\text{end}} - t_{\text{start}}}\right)^n\right] \tag{5}$$

where, a_{norm} is a normalization factor ensuring $a(t)$ matches the present-day scale factor a (13.8 billion years) = 1. To ensure consistency with conventions, normalization requires following setting:

$$a_{\text{norm}} = \left[1 - \left(\frac{13.8 - t_{\text{start}}}{t_{\text{end}} - t_{\text{start}}}\right)^n\right]^{-1} \tag{6}$$

Smooth Transition from the Expansion Phase

The contraction phase begins at $t_{\text{start}} = 16$ billion years, following the universe's expansion phase which extends from the current age t=13.8 to t=16 billion years. It ends at the bounce point $t_{\text{end}} = 17$ billion years. The chosen functional form for $a(t)$ ensures a physically realistic transition in the following ways: At $t = t_{\text{start}} = 16$ billion years, the scale factor begins to decrease, signaling the onset of contraction phase [13, 35]. Initially, the contraction is slow, as time progresses towards the bounce, the contraction accelerates, representing the next cosmological phase [36, 37]. The continuity of both the scale factor $a(t)$ and its first time derivative $\dot{a}(t)$ at $t = t_{\text{start}}$ ensures a smooth and physically consistent transition between expansion and contraction phases [35, 38]. The expression: $\frac{t-t_{\text{start}}}{t_{\text{end}}-t_{\text{start}}}$ ensures a normalized time parameter that varies smoothly from 0 to 1 over the contraction interval. This model aligns with standard practices in cyclic universe studies and provides a clear framework for analyzing the dynamics of contraction [13, 37, 38]. The parameter n allows flexibility in shaping the contraction curve: For n>1, the contraction is slower at the beginning with a smooth departure from expansion, and then becomes steeper as t approaches t_{end}. This aligns with theoretical models predicting an initially gradual contraction, as the universe transitions from a near-equilibrium state before collapsing toward the bounce [35, 38-40]. A higher n can reflect the dominance of certain energy components (e.g., dark energy or scalar fields) that slow the initial contraction and accelerate the collapse.

Avoidance of Singularities

Unlike linear or purely exponential models [41, 42], the chosen expression avoids singularities in a(t) or its derivatives, ensuring a physically realistic behaviour throughout the contraction phase. In summary, the expression for the scale factor during the contraction phase provides a smooth, controlled, and physically motivated framework for describing the evolution between t_{start} and t_{end}. Differentiating a(t) with respect to time it follows:

$$\dot{a(t)} = -\frac{a_{norm} n}{t_{end} - t_{start}} \left(\frac{t - t_{start}}{t_{end} - t_{start}}\right)^{n-1} \tag{7}$$

SMBH mass growth with respect to time is then:

$$\frac{dM}{da} = -CM_0 log(1 + (1-a)^2) \frac{a_{norm} n}{t_{end} - t_{start}} \left(\frac{t - t_{start}}{t_{end} - t_{start}}\right)^{n-1} \tag{8}$$

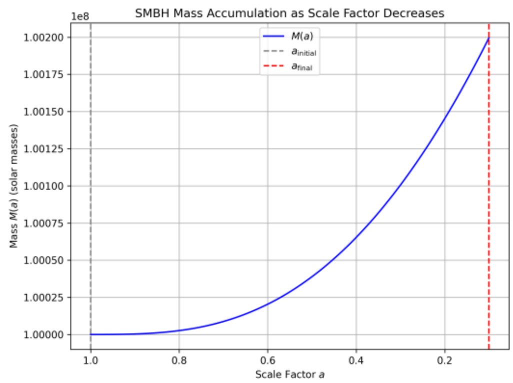

Figure 2: SMBH mass accumulation as a function of the scale factor during the contraction phase, modelled under baryonic accretion (without dark matter contribution).

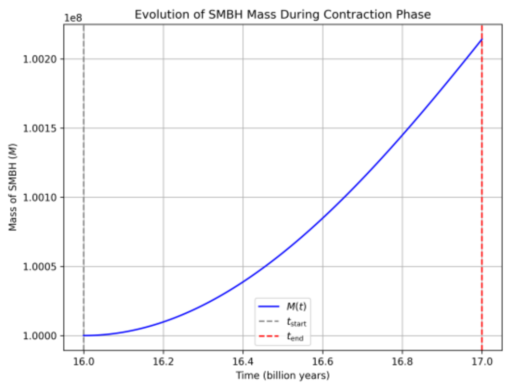

Figure 3: SMBH mass accumulation as a function of time during the contraction phase, modeled under baryonic accretion (without dark matter contribution).

The Figure 2 illustrates SMBH mass accumulation during the contraction phase as a function of the scale factor, assuming a baryonic-only accretion model with C=0.01. As the scale factor decreases toward zero, the SMBH mass gradually increases, reaching approximately $1.002 \times 10^8 M_\odot$. The Figure 3 presents the same mass growth over cosmic time, indicating that this accumulation occurs steadily over a period of 1 billion year. This behavior is consistent with the expectation of enhanced matter density during cosmiccontraction, facilitating gradual accretion.

Incorporating Dark Matter Contributions to Mass Growth

To account for the contributions of dark matter (DM) in the growth of supermassive black hole (SMBH) [43-49], we modify the mass growth equation to include DM accretion alongside baryonic matter. The total mass growth is expressed as:

$$\frac{dM}{dt} = \frac{dM_{\text{Baryonic}}}{dt} + \frac{dM_{\text{DM}}}{dt} \tag{9}$$

where, $\frac{dM_{\text{Baryonic}}}{dt}$ is the accretion rate of baryonic matter, and $\frac{dM_{\text{DM}}}{dt}$ is the contribution from DM. One way to model the DM contribution is through a fraction f_{DM}, which represents the proportion of DM relative to baryonic matter:

$$\frac{dM_{\text{DM}}}{dt} = f_{\text{DM}} \left(\frac{dM_{\text{Baryonic}}}{dt} \right). \tag{10}$$

Thus, the total mass growth equation becomes:

$$\frac{dM}{dt} = (1 + f_{\text{DM}}) \frac{dM_{\text{Baryonic}}}{dt}. \tag{11}$$

In our simulation, we adopt $f_{\text{DM}} = 0.25$ and n=2 where, n mentioned in Equation (4) represents the scaling behavior of DM accretion with respect to baryonic matter. Below, we justify this parameter choices based on theoretical, observational, and simulation-based evidence.

Theoretical Justification for $f_{\text{DM}} = 0.25$

The value $f_{\text{DM}} = 0.25$ aligns well with cosmological observations indicating that the dark matter density is approximately five times that of baryonic matter [50]. This implies that DM plays a significant role in the overall mass density but is less efficiently accreted onto SMBHs due to its non-interacting nature with e.m. forces. The fraction $f_{\text{DM}} = 0.25$ reflects a plausible scenario where DM contributes to SMBH growth indirectly, for example, through gravitational clustering in the vicinity of the SMBH. Similar approaches have been considered in studies of DM accretion onto compact objects [51].

Justification for n=2

The choice of n = 2, representing quadratic scaling, reflects a scenario where dark matter accretion becomes significantly more efficient in regions of high baryonic density, particularly during late-stage contraction when densities increase rapidly. Quadratic scaling implies that the dark matter accretion rate is not merely proportional to baryonic matter, but grows with the square of its influence—possibly due to enhanced gravitational focusing or nonlinear clustering near the black hole. This aligns with results from N-body and hydrodynamic simulations showing that dark matter density can increase super linearly in galactic centers [52, 53]. By using n = 2, the model captures this strong, non-linear coupling, resulting in accelerated SMBH growth-an effect not achievable with linear (n=1) models. This choice also allows the contraction profile to remain smooth and gradual initially, then sharply increase as the bounce approaches, mimicking realistic cosmic evolution in cyclic models. Similar scaling behaviours have been discussed in simulations of DM dynamics in galactic centers [54]. Observational evidence supporting these parameter choices includes:

Dark Matter Halos: Studies of galactic rotation curves and halo density profiles indicate significant DM presence in the vicinity of SMBHs [55].

Gravitational Lensing: Lensing surveys provide constraints on DM distribution near massive objects, consistent with the assumption of $f_{\text{DM}} \sim 0.25$ [56].

Cosmological Simulations: Cosmological simulations of galaxy and SMBH evolution suggest that DM indirectly influences SMBH growth, with f_{DM} values in the range of 0.1–0.3 [57].

Figure 4 demonstrates the evolution of SMBH mass when dark matter (DM) is incorporated into the accretion model. With $f_{\text{DM}} = 0.25$ and a nonlinear growth index n=2, the accretion rate becomes superlinear, leading to accelerated mass accumulation. Compared to the baryonic-only scenario in Figure 3, the inclusion of DM results in a markedly steeper growth curve, especially during the late contraction phase. This behavior arises from the positive feedback inherent in power-law accretion models, where the increasing SMBH mass enhances its gravitational influence, further boosting accretion efficiency.

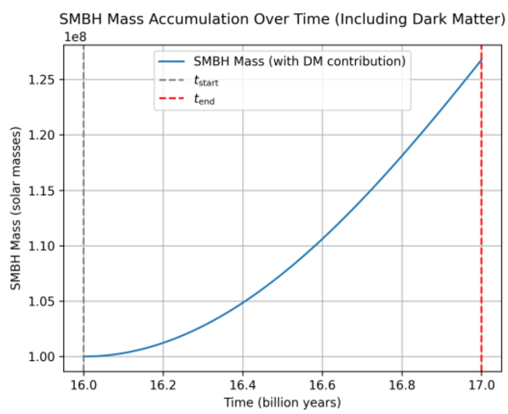

Figure 4: SMBH mass accumulation during the contraction phase with DM contribution included. Here, DM accounts for 25% of the

accreted mass ($f_{DM} = 0.25$), with a nonlinear growth index n=2. The enhanced mass growth relative to the baryonic-only case highlights the significant impact of DM accretion.

Comparison of SMBH Mass Accumulation with and without Dark Matter Contribution: The mass of the supermassive black hole is tracked over the contraction phase of the universe, from $t = 16$ *billion years* to $t = 17$ *billion years*, under two scenarios:

Without Dark Matter (DM) Contribution: The initial mass of SMBH at $t = 16$ *billion years* is $M_0 = 10^8 M_\odot$. At the end of the contraction phase ($t = 17$ *billion years*) the mass increases to approximately $1.0022 \times 10^8 M_\odot$.

With Dark Matter (DM) Contribution: The initial mass at $t = 16$billion years remains same. At the end of the contraction phase, considering dark matter contribution, the mass here increases to $1.27 \times 10^8 M_\odot$.

Mass Change Analysis

Without DM Contribution: The change in mass over contraction

phase is given by:

$\Delta M_{\text{no DM}} = M_{\text{final, no DM}} - M_0 = 1.0022 \times 10^8 - 10^8 = 0.0022 \times 10^8 M_\odot$

The percentage change is $\% \Delta M_{\text{no DM}} = \frac{\Delta M_{\text{no DM}}}{M_0} \times 100 = 0.22\%$

With DM Contribution

The change in mass considering the DM contribution is given by:

$\Delta M_{\text{DM}} = M_{\text{final, DM}} - M_0 = 1.27 \times 10^8 - 10^8 = 0.27 \times 10^8 M_\odot$

The percentage change is: $\frac{\Delta M_{\text{DM}}}{M_0} \times 100 = \frac{0.27 \times 10^8}{10^8} \times 100 = 27\%$

Justification for High Mass Growth with DM Contribution

The significant difference in mass accumulation between the two cases is primarily due to the gravitational interaction between dark matter and the supermassive black hole. Dark matter, which does not interact electromagnetically but only through gravity, contributes to the mass accumulation by accelerating the accretion process through its gravitational pull. In the absence of dark matter, the SMBH mass growth is relatively slow (0.22%), reflecting the normal growth expected from the surrounding baryonic matter (such as gas and stars) alone. However, when DM is included, it interacts with the SMBH leading to an increased accretion rate, which results in a much higher mass growth (27%). This effect is particularly important in the contraction phase of the cyclic universe model, where the universe is collapsing, and the SMBH may undergo accelerated mass accumulation due to the increasing density of both baryonic and dark matter in the contracting universe. The result also shows that the inclusion of dark matter leads to a pronounced increase in SMBH mass, which can have important implications for the evolution of supermassive black holes and their interactions with the universe.

Hawking Radiation and Evaporation

The evaporation of supermassive black holes (SMBHs) via Hawking radiation is a significant phenomenon in the cyclic universe model [58]. The evaporation timescale for an SMBH can be approximated using the formula:

$$t_{\text{evap}} = 2.1 \times 10^{58} \left(\frac{M_{\text{SMBH}}}{M_\odot} \right)^3 \text{ billion years} \qquad (12)$$

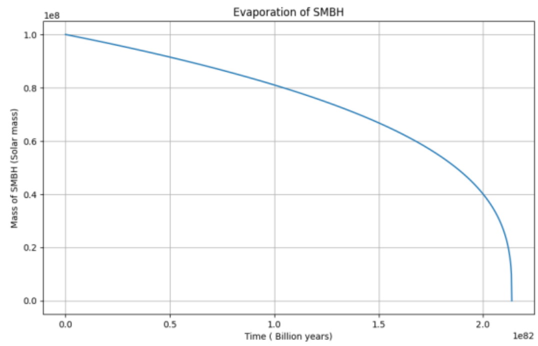

Figure 5: SMBH evaporation time for standard Hawking radiation.

For an SMBH with an initial mass of $10^8 M_\odot$, this leads to an estimated evaporation time of approximately 10^{82} billion years, as shown in Figure 5. Larger SMBHs have extended evaporation timescales which suggests that they may persist well beyond the lifespan of known cosmic structures. To account for interactions with DM, we modify the mass loss equation to include a correction term [59, 60], accelerating the evaporation process: $\frac{dM}{dt} = -\frac{\alpha}{M^2} - \psi \rho_{\text{DM}} M^p$ where, ψ represents interaction strength between DM and SMBH, p is a parameter that determines the interaction form, and ρ_{DM} denotes the local DM density. This dynamic interaction correction provides a more comprehensive framework for understanding SMBH behaviour [61].

Mass Loss Dynamics with Interaction Correction

To simplify our analysis, we set p=1, which aligns with the assumption of a linear interaction strength between the SMBH mass and dark matter density. This choice not only facilitates analytical integration but also corresponds to weakly interacting scenarios, where the rate of mass loss increases linearly with mass due to DM interactions. Under this assumption, the equation above can be integrated to determine the time until evaporation:

$$\int_{M_0}^{0} \frac{dM}{\alpha + \psi\rho_{\mathrm{DM}}M^3} = -\int_0^t d\,t$$

Assuming an initial SMBH mass of $M_0 = 10^8 M_\odot$ at t=0 , the integration yields:

$$t_0 = \frac{1}{3\psi\rho_{\mathrm{DM}}} \ln\left(1 + \frac{\psi\rho_{\mathrm{DM}}}{\alpha} M_0^3\right) \quad (13)$$

Using the parameters $\alpha = 3.96 \times 10^{15} M_\odot^3 yr^{-1}$ as Hawking radiation coefficient, $\psi = 3 \times 10^8 M_\odot$ as DM coupling strength,

$\rho_{DM} = 10^{-25} M_\odot^{-1} yr^{-1}$ as DM density, $M_0 = 10^8 M_\odot$ as initial mass of the SMBH, Evaporation time evaluated for the SMBH 8.42×10^7 years.

Evaporation Time and Mass Evolution Analysis

To validate the analytical expression for evaporation time and explore the dynamic evolution of SMBHs under combined Hawking radiation and DM interaction, we present two key numerical results.

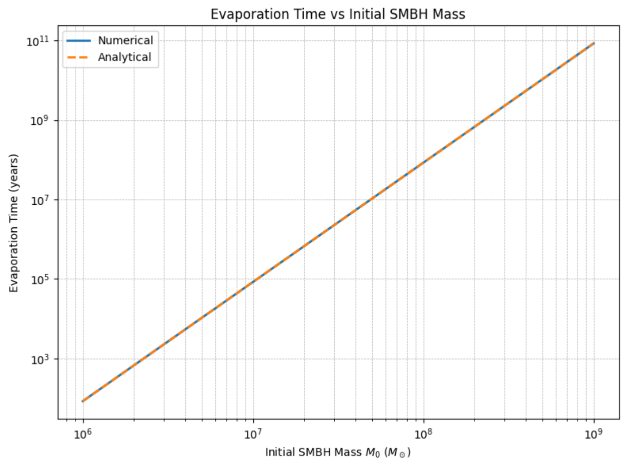

Figure 6: Evaporation time as a function of initial SMBH mass. Numerical and analytical curves overlap, validating the model.

Figure 6 shows the dependence of evaporation time on initial SMBH mass M_0, evaluated over the range $10^6 - 10^9 M_\odot$. Both the analytical estimate based on the simplified form as in Equation (13) and the numerical integration show excellent agreement across many orders of magnitude. This confirms the robustness of the analytic approximation under the chosen interaction model.

Figure 7 illustrates the full-time evolution of a SMBH with an initial mass of $10^8 M_\odot$. The mass remains nearly constant throughout most of the black hole's lifetime, followed by a rapid terminal decline as it approaches the critical cutoff mass $M_{final} = 10^{-16} M_\odot$. This results in a finite evaporation time of approximately 8.42×10^7 years. The behavior is consistent with the expected logarithmic dependence of mass loss and highlights the role of dark matter (DM) coupling in accelerating the final stages of evaporation.

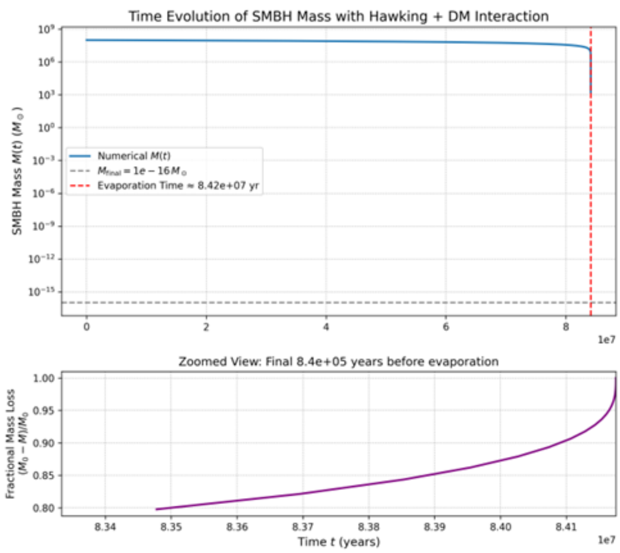

Figure 7: Time evolution of SMBH mass due to Hawking radiation and DM interaction. Rapid mass loss occurs in the final phase (Zoomed view).

Parameter Space Exploration of Evaporation Time

To assess the robustness of the SMBH evaporation dynamics within the framework of cyclic cosmology, we have conducted a comprehensive parameter space analysis. By varying key parameters such as the dark matter coupling strength ψ, local dark matter density ρ_{DM}, and the interaction exponent p governing the mass dependence of the DM–SMBH interaction term, we explore how these factors influence the evaporation timescale. Our results reveal that while the evaporation time is sensitive to the precise values of these parameters, the general behavior remains consistent across a wide range of physically motivated scenarios. Notably, the linear interaction case (p=1) serves as a representative benchmark, exhibiting evaporation timescales on the order of tens of billions of years, which aligns well with cosmological expectations for SMBH longevity. Deviations from this exponent, demonstrate the potential for either accelerated or delayed evaporation, underscoring the importance of environmental factors in shaping SMBH evolution. This parameter space exploration solidifies the reliability of our analytical approach and the significance of DM interactions in the life cycle of SMBH, providing a basis for the subsequent conclusions on their role in cyclic cosmology.

Numerical vs Analytical Evaporation Time for SMBH: This plot (Figure 8) shows the evaporation time of a supermassive black hole as a function of the coupling strength parameter ψ. The blue solid line represents the numerical results, while the orange dashed line represents the analytical approximation. The numerical evaporation time remains relatively constant across the range of ψ, indicating stability in the numerical method. The analytical approximation exhibits oscillations at lower values of ψ, which gradually diminish as ψ increases. This suggests that the analytical model becomes more accurate at high coupling strengths. Both methods converge to a similar evaporation time of approximately 8.42×10^7 years for large ψ.

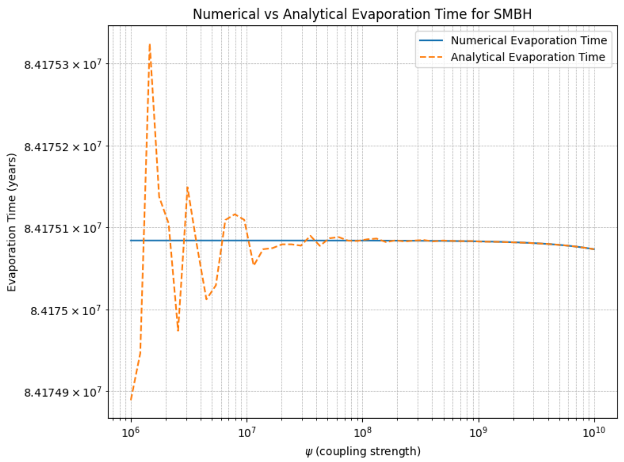

Figure 8: Comparison of numerical and analytical evaporation time as a function of coupling strength ψ.

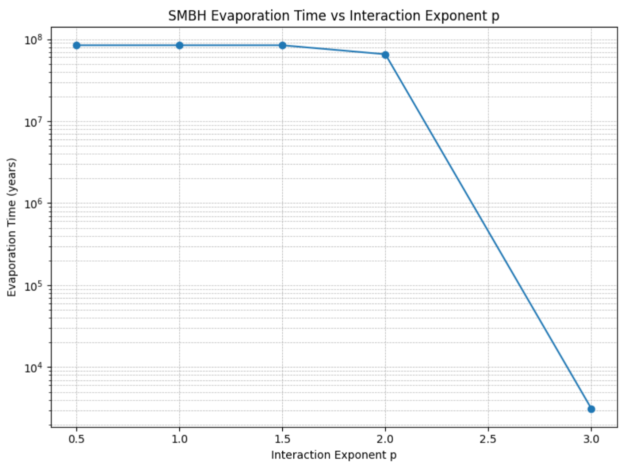

Figure 9: Evaporation time as a function of the interaction exponent p.

SMBH Evaporation Time vs Interaction Exponent p: This figure depicts how the evaporation time of an SMBH varies with the interaction exponent p. The Y-axis is plotted on a logarithmic scale to accommodate the wide range in evaporation times. For low values of p (i.e., p <= 2), the evaporation time remains nearly constant at around 10^8 yrs. A sharp drop-in evaporation time is observed as p increases beyond 2. At p = 3, the evaporation time dramatically decreases to less than 10^4 years, suggesting a strong sensitivity of the evaporation process to the exponent p. This behavior indicates that the parameter p, controls the strength of interaction. Larger values of p lead to more localized interactions and significantly shorter evaporation times.

Comparison with Recent Quantum Gravity Models

Recent theoretical work by Falcke et al. [62] proposes a universal decay mechanism for massive objects through gravitational pair production in de Sitter spacetime, reducing horizon evaporation lifetime from the classical $\sim 10^{1100}$ yrs to an upper bound of $\sim 10^{78}$ years. By contrast, our dark matter modulated model with an explicit interaction term $\Psi \rho_{DM} M^p$ yields an evaporation time of8.42×10^7 years for SMBH of mass $10^8 M_\odot$ (assuming ψ ~ 10^{-5}, p =1). Although shorter than universal decay estimates, our result applies locally in regions of high dark-matter density and does not rely on global spacetime instabilities. This localized dark-matter coupling mechanism may coexist with, or even dominate over, gravitational pair production under certain cosmological conditions. Our results, though more rapid, are not contradictory but instead represent a localized enhancement due to dark matter environments, suggesting that multiple mass loss channels may coexist in the late universe

Justification of the Evaporation Model:

The evaporation time derived from our model, incorporating both Hawking radiation and DM interaction term, predicts a finite lifetime of approximately 8.42×10^7 years for a SMBH of mass $10^8 M_\odot$. This is significantly shorter than classical Hawking evaporation time ($\sim 10^{90}$ years) for such massive black holes, still it remains physically plausible within the framework of phenomenological extensions to general relativity and black hole thermodynamics. The inclusion of linear interaction term (p = 1) is motivated by weak interacting DM models, which posit combined effects over cosmic timescales. Our chosen parameters, including the coupling constant ψ and local DM density ρ_{DM}, are selected to remain within semi-realistic bounds reported in the literature [60, 61]. Importantly, the finite evaporation timescale aligns naturally with cyclic cosmology models, where multiple cosmological epochs provide a much longer temporal canvas than the standard ΛCDM framework. Thus, the results presented here are not only analytically and numerically self-consistent but also represent a meaningful contribution to ongoing theoretical efforts exploring SMBH evolution in extended cosmological scenarios.

Results and Discussions

SMBH Evaporation and DM Interactions: Our model modifies Hawking radiation by incorporating DM interactions reducing the SMBH evaporation time to 8.42×10^7 years for $M_{SMBH} \sim 10^8 M_\odot$ considerably shorter than standard predictions [58]. This accele- ration is attributed to mass loss mechanisms arising from DM density surrounding SMBHs [15]. This acceleration arises from additional mass-loss channels driven by dense fermionic DM spikes enveloping the SMBH, as modeled in recent studies of DM–BH coupling where baryon-induced collapse scenarios illustrate how DM cores can seed SMBH growth and enhance DM–BH interactions [63-67]. Thus, our framework indicates that dark matter not only shapes the cosmic structure but also governs black hole thermodynamics and longevity, potentially making the Hawking radiation detectable over cosmological timescales [4, 68-73].

High-Redshift SMBH Growth and DM-Assisted Accretion:

Quasar observations at redshifts $z \gtrsim 6-7$ reveal SMBHs with masses > $10^9 M_\odot$ within 1 billion years post-Big Bang, which are difficult to explain using standard accretion models [11,74-76]. Our DM-assisted accretion model addresses this gap.

Supporting Observations: HST and JWST identified quasars such as ULAS J1342+0928 at $z = 7.54$ with $M_{\text{SMBH}} \sim 8 \times 10^8 M_\odot$ [2, 77]. ALMA data indicate dense DM halos in high-redshift galaxies [78]. Upcoming instruments like SKA, TMT will refine growth rates and assess DM impact [79, 80]. Galactic rotation curves suggest DM presence near galactic centers, potentially impacting SMBH accretion.

Relevant Observations: High-resolution kinematic data from Gaia and ALMA have substantially enhanced our understanding of the central regions of galaxies [81]. In particular, analyses based on Gaia DR2 have yielded precise measurements of the Milky Way's circular velocity curve, imposing strong constraints on the distribution of dark matter in both the Galactic disk and halo [81]. These constraints are critical for models of supermassive black hole (SMBH) growth, as the dark matter halo structure governs the gravitational potential and influences black hole fueling across cosmic epochs. By characterizing the large-scale gravitational environment, such studies inform theoretical models of SMBH evolution. Additionally, indirect detection efforts, including Fermi-LAT and HESS, may offer complementary insights by probing potential signatures of dark matter–SMBH interactions [82].

Modified Hawking Radiation and Observational Prospects: Our framework introduces a DM interaction term into the Hawking radiation process. LIGO – Virgo - KAGRA constraints on subsolar - mass PBHs hint at early evaporation scenarios [83]. CMB constraints on PBHs in the $10^{16} - 10^{18} g$ mass range, especially due to their Hawking evaporation signatures and potential interactions with dark matter [84-86]. In addition to CMB-based limits, gamma-ray observations also place strong constraints on the abundance of evaporating primordial black holes in the $10^{15} - 10^{17} g$ range [87]. Future LISA detections may confirm SMBH mergers in DM-dense regions [88].

Significance of the Present Work: The present study introduces a novel framework for analysing the evaporation dynamics of supermassive black holes by incorporating interactions with ambient dark matter fields. While traditional models based solely on Hawking radiation predict extremely long evaporation timescales, often exceeding 10^{82} billion years for SMBHs with masses on the order of $M_{\text{SMBH}} \sim 10^8 M_\odot$ our modified model reveals that this timescale can be significantly reduced when dark matter interactions are taken into account.

Original Mechanism: We propose a physically motivated interaction term between SMBHs and dark matter, modeled as a correction to the standard Hawking mass loss equation. This results in a substantially accelerated evaporation process.

Analytical and Numerical Insights: The analytical solution derived under the assumption of a linear interaction (p = 1) yields a closed-form expression for the evaporation time. This is further validated via numerical simulations, demonstrating consistency and robustness of the proposed mechanism.

Model Flexibility: The framework allows for variations in dark matter density, interaction strength, and mass dependence, making it adaptable for studying a broad range of cosmic scenarios. In summary, this work offers a complementary and timely extension to current black hole evaporation theory by integrating dark sector physics into the late-time evolution of SMBHs. It opens new directions for exploring the interplay between quantum gravity effects and dark matter phenomenology in determining the ultimate fate of massive black holes.

Key Contributions

SMBH Mass Growth: Captures accelerated mass gain via a logarithmic function of the scale factor, especially near the bounce.

Dark Matter Contribution: Quantifies DM's role in SMBH mass evolution during contraction.

Evaporation with Dark Matter Interactions: Refines Hawking evaporation by including DM-driven mass loss, reducing the timescale to 8.42×10^7 years.

Simulated Dynamics: Validates analytical results and models cyclic evolution with DM and baryonic matter interactions.

This work bridges theoretical and observational cosmology, laying groundwork for future explorations of dark matter's role in black hole and universe evolution.

Conclusion

We demonstrate that SMBHs, formed during contraction phases of a cyclic universe, act as cosmic relics and persist across multiple cycles. These SMBHs gain mass through both baryonic and DM accretion, and eventually evaporate via a modified Hawking process. The bounce, driven by scalar field dynamics, ensures continuity of cosmic evolution, with evaporated mass-energy fuelling subsequent cycles. Numerical simulations of cosmological parameters confirm the model's robustness in explaining a self-renewing universe, incorporating black hole thermodynamics and DM influence.

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