JOURNAL OF
EMERGING INVESTIGATORS

Unveiling the Cosmic Choreography: Seed, Environment, and the Rise of Supermassive Black Holes

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SUMMARY
This manuscript addresses the formidable challenge of understanding the formation and growth of supermassive black holes (SMBHs) in the early universe, prompted bsolary observational data indicating the existence of SMBHs with masses exceeding 10^9 M masses. The research focuses on unraveling the origins and evolution of these black holes, examining various initial seed scenarios from light to heavy masses. The central hypothesis revolves around the Eddington accretion model, specifically predicting the growth parameters – the e-folding time and fraction. The study employs a theoretical framework and compares heavy seed and light seed models, considering scenarios such as black hole mergers, Lyman-Werner background fluctuations, and conditions in high-redshift quasar host progenitors. Methodologically, the Eddington accretion model is utilized, and the root mean square (RMS) serves as the cost function for robust model evaluation. In conclusion, this study offers valuable insights into SMBH formation and growth, emphasizing the significance of the Eddington accretion model and providing implications for the assembly mechanisms of these enigmatic objects in the early universe.

INTRODUCTION

Supermassive black holes (SMBHs), celestial titans lurking at the hearts of most galaxies, reign supreme with their immense gravity, dictating the flow of matter and energy across galactic realms. Millions, even billions of times heavier than our Sun (for recent reviews, see [1–3]; e.g., SDSS J010013.02+280225.8, a hyperluminous quasar clocking in at ~10^10 solar masses at z ≈ 6.3 [4]), these enigmatic behemoths orchestrate the cosmic ballet of stars and gas, sculpting the interstellar tapestry. Yet, despite their pivotal role in shaping galactic evolution, their genesis and growth mechanisms remain shrouded in obscurity. Unraveling the cosmic choreography of their rise from diminutive seeds poses a captivating challenge in astrophysics, one with profound implications for our understanding of the universe.

Driven by insatiable scientific curiosity and the promise of far-reaching consequences, deciphering the secrets of SMBH growth is paramount. These celestial puppeteers influence the movements of stars and gas through their immense gravitational pull, akin to galactic conductors directing a cosmic symphony [7]. Their accretion-fueled jets, spewing forth searing plasma like celestial fireworks, trigger star formation and sculpt the interstellar tapestry [5]. Furthermore, these enigmatic giants may hold the key to unlocking other cosmic mysteries, potentially bridging the gap between our understanding of dark matter and the very fabric of spacetime itself [6].

However, our quest to illuminate the nascent stages of their growth is hampered by the observational darkness shrouding their early lives. Most observed SMBHs are already cosmic gluttons, nearing or exceeding their maximal feeding rate, known as the Eddington limit. Imagine this limit as a cosmic speed limit, set by the immense pressure generated when a black hole devours matter too quickly. Exceeding this limit would blow away surrounding material, starving the black hole and halting its growth. Theoretical models propose that these behemoths arose from far humbler seeds, such as collapsed massive stars or primordial black holes forged in the cosmic crucible [9]. Charting the trajectory of these seeds into the colossal giants we see today, and predicting their characteristic e-folding times (the rate at which they grow) and accretion rates, is a crucial yet unsolved riddle.

This work delves into this enigmatic realm, wielding the Eddington accretion model as our investigative tool. This model acts as a cosmic telescope, not for light, but for gravity, allowing us to simulate how a black hole grows by swallowing surrounding matter, constrained by the

Eddington limit [8]. By feeding different "seed masses" and "galactic environments" into this model, we aim to unveil the intricate interplay between these factors that dictates the rise of a galactic overlord. Our hypothesis? Both the initial seed mass, like a well-nourished sapling destined for grandeur, and the surrounding galactic smorgasbord, offering a bounty of sustenance, play crucial roles in shaping the accretion trajectory, e-folding time, and ultimately, the final mass of an SMBH.

Through meticulous exploration of these variables within the Eddington model, we seek to not only unveil the recipe for forging a supermassive black hole, but also predict its characteristic growth timescale and determine the fraction of baryonic matter it consumes. By illuminating the pivotal role of seed and environment, our findings could hold profound implications for galactic evolution. They could forge connections between SMBHs and cosmic mysteries like dark matter and the nature of spacetime itself. In essence, deciphering the dance of seed and environment is not just a journey into the heart of galaxies, but a voyage into the very essence of the cosmos.

RESULTS

This section delves into the fascinating story of quasar growth revealed through analyzing figures like Figure 3. , Figure 6. and the heat map results in Table 1. We interpret these observations, weaving together insights from different folding timescales, mass ranges, and redshifts to shed light on the intricate interplay between seed models and quasar evolution.

In our investigation of folding timescales and accretion dynamics in the realm of supermassive black holes (SMBHs), we observe intriguing patterns across different growth scenarios. The Fast Lane, characterized by a rapid 20 Myr pace, reveals that the heavy seed model tends to overestimate quasar growth, pointing to a subpopulation of "cosmic speed demons" exceeding 10^9 solar masses at high redshifts ($z \geq 7$). Conversely, the Slow Burn, operating at an 80 Myr pace, exposes the light seed model's limitations in predicting the more gradual growth of less voracious quasars in the redshift range 6.4-6.0.

Within the Goldilocks Zone, at a 40 Myr timescale, the heavy seed model elegantly mirrors the observed trajectories of hefty black holes (10^8-10^9 solar masses) at redshifts 7.2-6.4, suggesting a strong link between their formation, evolution, and substantial initial mass. Our analysis discerns predilections in different mass ranges, emphasizing the heavy seed model's accuracy in portraying the growth of hefty black holes, tying their evolution to a large initial mass.

The interplay of mass and redshift unfolds as high-redshift convergence becomes apparent. At $z \geq 6.4$, the light seed model gracefully fits the growth of lighter quasars (10^7-10^8 solar masses), while the heavy seed model remains dominant for heavyweights. This hints at potentially distinct formation and growth mechanisms governing different mass-redshift combinations.

Table 1 provides insights into the black hole's gastronomic prowess, revealing that black holes can only devour a limited 5% or 9% of the available baryonic matter within their halo, depending on whether they carry the heft of a heavy seed or the agility of a light seed. The heavy seed model exhibits nearly double the radiative efficiency of its lighter counterpart, underscoring fundamental differences in their accretion mechanisms.

Our study accentuates the importance of folding timescale, mass range, and redshift in shaping the dynamics of quasar growth. The significant disparity in e-folding time between scenarios translates into observable variations in radiative efficiency. At high redshifts, the convergence of growth patterns between light and heavy seeds suggests a shared beginning before their paths diverge into distinct evolutionary trajectories.

This intricate choreography of observations paints a vivid picture of the dynamic forces shaping quasar growth, emphasizing the crucial role of folding timescale in dictating accretion tempo and influencing the efficiency of quasar feasting. The mass range plays a pivotal role in determining the preferred seed model, unveiling potential variations in formation and growth mechanisms. Redshift adds another layer of complexity, influencing the most suitable seed model for different quasar populations. These insights pave the way for future research, urging refinement of seed models, exploration of diverse growth mechanisms, and high-redshift surveys to unravel the captivating tale of light and heavy seeds in the grand narrative of quasar evolution.

DISCUSSION

Our analysis has unveiled a captivating narrative of divergent paths in quasar evolution, woven by the contrasting journeys of light and heavy seed models. Both models, while seemingly adequate in describing these cosmic powerhouses, paint distinctly different portraits of their growth trajectories.

Light seeds, the nimble dancers of the cosmic stage, showcase remarkable efficiency in their accretion. They pirouette through the available material, devouring it with youthful enthusiasm. However, their agility presents a double-edged sword. As they mature, the cosmic larder becomes increasingly bare, potentially hindering their ultimate ascent to supermassive stardom. Material scarcity emerges as their Achilles' heel, casting a long shadow on their future growth.

Heavy seeds, in stark contrast, embark on a more measured waltz. They steadily accumulate mass amidst the ever-present fluctuations of the Lyman-Werner background, demonstrating a patient approach to growth. Interestingly, even with their restrained appetite, these cosmic heavyweights manage to achieve nearly double the radiative efficiency compared to their lighter counterparts. This stark divergence hints at fundamental differences in their underlying accretion mechanisms.

Further illuminating the black hole's appetite, our analysis reveals a surprising disparity depending on its initial heft. Whether equipped with the agility of a light seed or the bulk of a heavy seed, a black hole can only feast on a meager 5% or 9% of the available baryonic matter within its cosmic neighborhood. This differential gastronomic prowess is further amplified by the e-folding time, a crucial parameter dictating their growth rate. The significant difference in e-folding time between the two scenarios translates to distinctly observable variations in their radiative efficiency, adding another layer of complexity to the dance of quasar growth.

However, the cosmic stage takes an unexpected turn at high redshifts. In this distant realm, the growth patterns of both light and heavy seeds exhibit a remarkable convergence. Their trajectories align with expectations from previous studies, suggesting a period of surprising similarity in their early dance with the universe. This convergence offers a unique glimpse into a shared origin story, where the contrasting paths of light and heavy seeds have yet to diverge.

These findings offer valuable benchmarks for future astrophysical models, paving the way for a deeper understanding of the dynamic processes shaping the grand narrative of the universe. As we continue to unravel the secrets of quasars, their growth stories, forever intertwined with the tales of light and heavy seeds, provide captivating chapters in the ongoing saga of cosmic evolution.

In the ongoing pursuit of a more nuanced understanding of quasar evolution, several promising avenues for future research come to the forefront. Firstly, there is a need to refine existing seed models by introducing additional parameterization. This enhancement aims to better accommodate the observed diversity in quasar populations, providing a more comprehensive framework that can capture the subtle variations in their growth patterns.

A second crucial research focus involves exploring the mechanisms responsible for the observed differences in radiative efficiency between light and heavy seeds. By delving into the intricacies of accretion mechanisms, researchers aim to gain a deeper insight into the fundamental physics driving the diverse behaviors exhibited by quasars of varying masses.

Furthermore, the initiation of extensive high-redshift surveys emerges as a valuable strategy. These surveys have the potential to unveil more about the early growth convergence observed in quasars, shedding light on their formative stages. By addressing these questions and pushing the boundaries of our knowledge, researchers aspire to decipher the full score of the cosmic symphony, unraveling the intricate interplay of factors that govern the birth and evolution of these awe-inspiring denizens of the universe.

MATERIALS AND METHODS

1. Data Source and Halo Selection:

Our investigation relies on dark matter halo data generated from sophisticated Monte Carlo merger trees, meticulously crafted by my research mentor, Mr. Scoggins. These merger trees offer a dynamic and realistic representation of the evolutionary trajectories of dark matter halos within the universe. We analyzed the evolutionary tracks of 100 individual halos within this comprehensive dataset, encompassing a diverse spectrum of mass and concentration profiles. This diversity ensured we captured a representative sample of galactic environments encountered by black holes across a range of cosmic conditions.

To establish a standardized galactic context for our simulations, we calculated the median halo based on the mass distribution of the analyzed halos. This median halo, embodying the central tendency in terms of mass and concentration, serves as a quintessential foundation for our black hole growth simulations under the Eddington accretion model (for reference see Figure 4.) .

2. Black Hole Accretion Model:

Our investigation employs the Eddington accretion model. This model, established by the balance between gravitational pull and radiation pressure, suggests that a black hole's luminosity cannot exceed the Eddington luminosity ($Ledd$) due to this equilibrium.

$$L_{\mathrm{edd}} \equiv \frac{4\pi c G \mu m_{\mathrm{p}} M_{\mathrm{bh}}}{\sigma_{\mathrm{T}}} = \epsilon c^2 \dot{M}_{\mathrm{bh}}, \qquad (1)$$

where speed of light c, gravitational constant G, mean molecular weight μ (μ ~ 0.6 for primordial ionized gas), proton mass mp, Thomson cross section σT, and radiative efficiency ϵ. This leads to a black hole mass given by M_bh (t) = M_i exp(t/ τ_fold) with e-folding time τ_fold = (σT$c\epsilon$)/(4$\pi\mu Gm$p) ≈ 450ϵ Myr.

Within this framework, the black hole mass evolves over time. We assume an exponential growth based on the e-folding time (τ_fold). This characteristic time scale indicates how quickly the black hole mass can grow under Eddington-limited accretion.

2.1. Addressing Eddington Model Limitations

Our investigation utilizes the Eddington-limited accretion model as a foundation, but recognizes its limitations in accurately depicting black hole growth observed in Figures 1. These figures demonstrate unrealistic massive accretion exceeding the Eddington limit within a short timescale (~0.8 Gyr). To address this discrepancy, we implement amendments to the model based on the concept of a maximum black hole mass (Mmax) proposed by King (2015). King (2015) argues that black hole growth cannot continue indefinitely due to limitations in disk formation beyond a certain mass threshold. This threshold, Mmax, is expressed in Equation (2) below:

$$M_{\max} = 5 \times 10^{10} M_{\odot} \alpha^{7/3} \eta_{0.1}^{4/13} \left(\frac{L}{L_{\mathrm{Edd}}} \right)^{-4/13} f_5^{-27/26} \qquad (2)$$

α accounts for the viscosity parameter, η reflects the radiative efficiency, $L/Ledd$ denotes the ratio of actual luminosity to Eddington luminosity, and f encompasses additional factors influencing Mmax. Since all other terms are fractions, growth cannot exceed 10^10 solar masses.

2.2. Modified Eddington Model:

To incorporate the Mmax constraint, we modify the standard Eddington model as follows:

1. Growth Capping: Black hole growth is quenched when the simulated mass (Mbh) reaches a prescribed fraction of the baryonic matter in the halo, represented by:

$$M_{\mathrm{bh}} \leq f_{\mathrm{bh}} M_{\mathrm{halo}} \Omega_{\mathrm{b}} / \Omega_{\mathrm{m}} \quad \text{where } \Omega_b = 0.266\,,\ \Omega_m = 0.049$$

f_bh is a parameter defining the fraction limit, taking values of {0.05, 0.1, 0.2, 0.5} in our simulations. This ensures black hole mass remains within realistic bounds related to the available baryonic matter within the halo as prescribed by scoggins et al.

3. Impact on Black Hole Growth:

These modifications significantly impact the predicted black hole growth patterns. By imposing the M_max constraint and applying dynamic adjustments, we prevent the unrealistic mass expansion observed in Figure 1. Instead, black hole growth within our simulations realistically plateaus as it approaches the M_max limit or the prescribed fraction of the halo's baryonic matter as conveyed by Figure 2. This framework allows us to explore more realistic and feasible black hole growth scenarios, particularly in the context of our light and heavy seed simulations.

3. Seed Mass Scenarios:

Our study examined the effect of seed mass by simulating three distinct scenarios:

- Heavy Seed Scenario: We investigated the behavior of black holes with initial masses ranging from 10,000 to million solar masses, representing the upper end of the observed black hole mass spectrum.
- Light Seed Scenario: We probed the growth trajectories of black holes with initial masses as low as 10 to 100 solar masses, potentially representative of primordial black hole candidates.

For each scenario, the selected seed mass values were incorporated into the Eddington accretion model as the initial black hole mass parameter and black holes have been grown as shown in Figure 3.

4. Utilizing Observational Data for Model Verification:

Our investigation leverages the comprehensive quasar dataset compiled by [19], encompassing 203 celestial objects showcasing diverse properties. This rich treasure trove of information, including redshift and black hole mass derived from rest-frame UV magnitude, serves as a critical touchstone for validating the predictions generated by our black hole growth models.

Both Heavy seed and Light seed models operate under the premise of Eddington-limited growth, allowing us to explore the impact of initial mass on the subsequent growth trajectories of these cosmic powerhouses.

This meticulously curated observational data plays a pivotal role in verifying the accuracy and efficacy of our simulated black hole growth. We plan to employ a multifaceted approach to this validation process, encompassing:

- Quantitative Comparisons: Through rigorous statistical analyses, we will quantitatively compare the predicted black hole masses across different redshifts in both our light and heavy seed models with the observed mass distribution within the quasar dataset. Techniques like chi-squared tests will be employed to assess the level of agreement between our simulated and real-world measurements.
- Visual Analysis: We will generate visualizations depicting the predicted growth trajectories of black holes in our models alongside the observed mass distribution as a function of redshift. This visual comparison will offer a readily intelligible interpretation of the agreement or discrepancies between our simulations and the observational data.
- Specific Focus: Our primary focus will be on scrutinizing the overall agreement between the predicted mass distribution and the observed data throughout different redshift ranges. Additionally, we will investigate potential correlations between black hole mass and other quasar properties within the dataset, seeking to identify any noteworthy overlaps or deviations between our simulations and the real-world observations.

By meticulously comparing our simulated black hole growth with the diverse information within the [19] dataset, we aim to achieve the following:

- Validation and Refinement: This comparison process will serve as a rigorous validation check for our black hole growth models, highlighting areas of strong agreement and potentially revealing discrepancies that may necessitate refinements to our theoretical framework.
- Enhanced Understanding: By scrutinizing the interplay between our simulations and real-world observations, we strive to gain a deeper understanding of the complex interplay between initial seed mass, accretion rate, and the overall growth trajectories of black holes across cosmic time.
- Future Research Directions: The insights gleaned from this data-driven validation will pave the way for future research endeavors. We can further refine our models by incorporating additional factors influencing black hole growth or embark on new investigations exploring diverse quasar populations or alternative theoretical frameworks.

In conclusion, leveraging the [19] dataset as a critical validation tool allows us to verify the accuracy and robustness of our black hole growth models. By meticulously comparing simulations with observations and meticulously analyzing the resulting insights, we can embark on a journey of enhanced understanding and pave the way for further exploration within the captivating realm of black hole evolution.

6. Data Analysis and Visualization:

Our simulations generated a wealth of data points, with black hole mass being a key output tracked at various time steps. This meticulous tracking allowed us to reconstruct the intricate evolutionary journey of each black hole throughout its assigned seed mass scenario. To unveil the captivating story lurking within these numerical results, we turned to the power of visualization. Leveraging the versatile Matplotlib library, we crafted insightful plots that vividly capture the growth trajectories and accretion histories of our simulated black holes.

These visualizations transcend mere data points and transform them into compelling narratives. We witness the gradual ascent of black hole masses, their accretion rates rising and falling like cosmic tides, and the distinct growth patterns emerging from the interplay between initial seed mass and the galactic environment. Each plot serves as a window into the dynamic world of black hole evolution, offering a glimpse into the complex interplay of forces shaping these cosmic powerhouses.

Beyond qualitative understanding, we sought to quantitatively assess the agreement between our simulated growth and the observed data. To achieve this, we employed the robust root mean square (RMS) function to evaluate the discrepancy between our predictions and the real-world measurements. Armed with this quantitative metric, we embarked on a systematic exploration, employing heat maps to visualize the RMS values across different combinations of e-folding times and fractional parameters. This systematic search illuminated the optimal combination that most closely mirrors the growth observed in the observational data, bridging the gap between our simulations and the cosmic reality.

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to Mr. Matthew Scoggins, an esteemed Astronomy researcher in the Department of Astronomy at Columbia University. His invaluable guidance and unwavering support played a pivotal role in the realization of this research endeavor. I extend my heartfelt thanks to Mr. Scoggins for generously sharing valuable data, which proved to be instrumental in the comprehensive analysis conducted in this study. Furthermore, I would like to extend my appreciation to the Lumiere Research Scholar Program's team for their support. Their assistance has been crucial in facilitating the successful execution of this study.

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Figures and Figure Captions

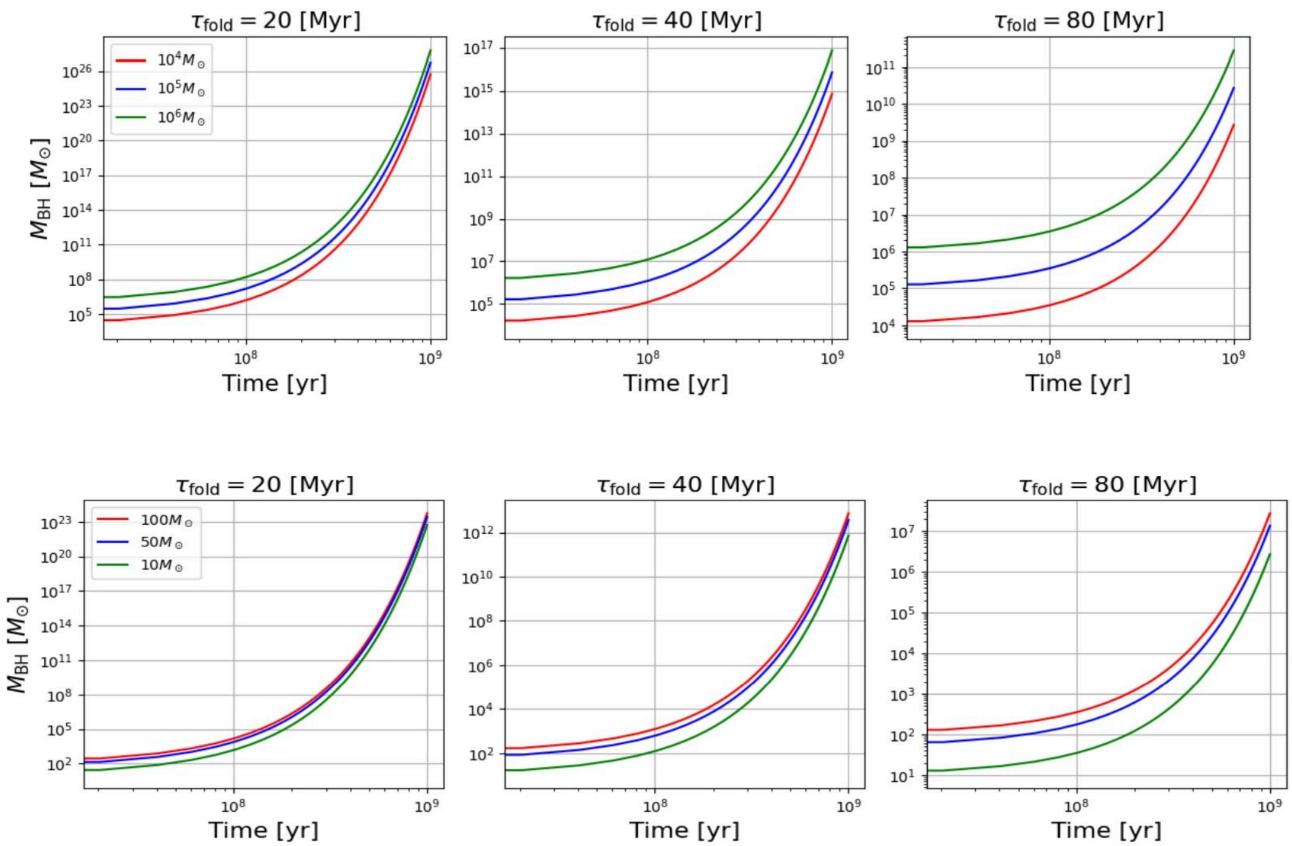

Figure 1. Growth of Supermassive Black Holes (SMBHs) over time, considering the Eddington limit as the governing rate. The analysis encompasses both heavy seed and light seed SMBHs, characterized by initial masses of Mi = {10^4, 10^5, 10^6} solar masses for heavy seeds and Mi = {10^2, 50, 10} solar masses for light seeds, with different e-folding times τ_fold ∈ {20, 40, 80} Myr. The vertical axis represents the SMBH mass in solar mass, and the horizontal axis denotes time in years. The exponential curve illustrates the increasing mass of quasars. However, quasars exhibit unrealistic growth, reaching {10^26, 10^17, 10^11, 10^23} solar masses for heavy seed and light seed, emphasizing the imperative to constrain their growth. Figure clarifies the distinction between heavy seed and light seed initial masses, providing a more precise description of the SMBHs under consideration.

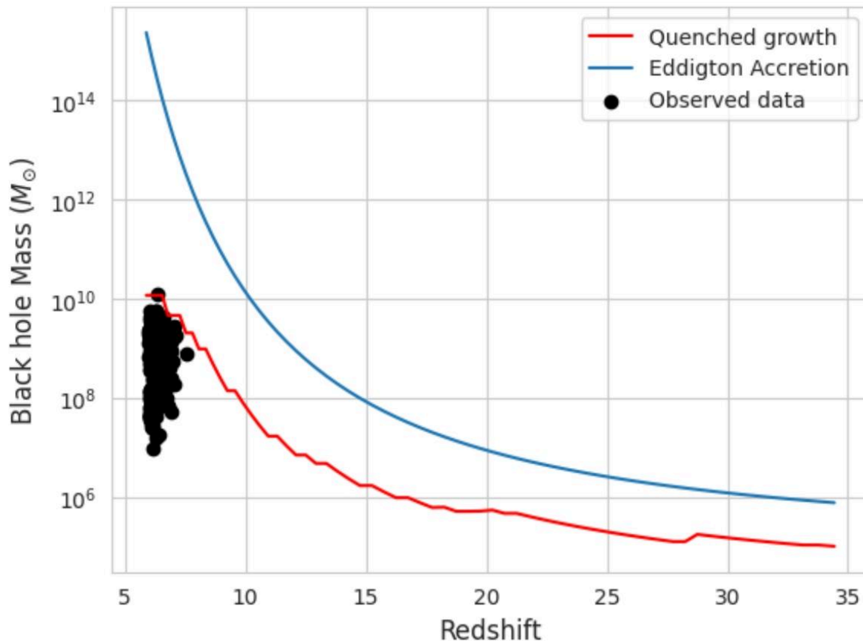

Figure 2. The plot displays two distinct scenarios. Taking the parameters of e-folding time and fraction as examples, the upper plot represents unconstrained Eddington accretion in blue, reaching unrealistic values of 10^14 solar masses. In contrast, the lower plot illustrates the same parameters with constrained Eddington growth. It is evident that the observed data aligns closely with the constrained scenario. This comparison emphasizes the need for constraints in modeling supermassive black hole growth.

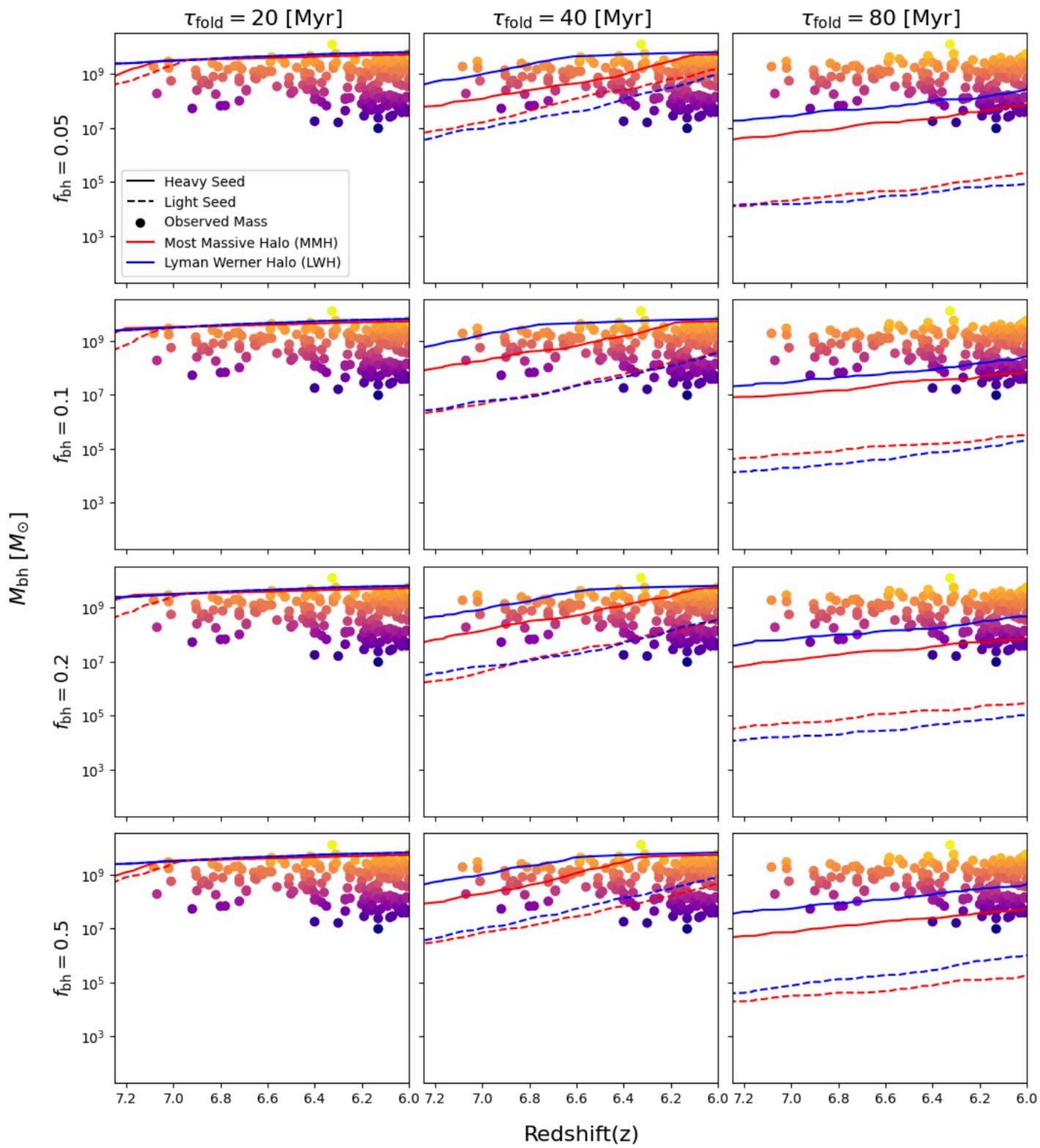

Figure 3. Growth of supermassive black holes (SMBHs) with heavy and light seed masses over a redshift range of $z \in$ [7.1, 6]. The growth rate is assumed to follow the Eddington rate. The heavy seed has a mass of M_bh = 10^5 solar masses, while the light seed has a mass of 50 solar masses. The growth is examined for various fractions of black hole seeds, f_bh, set to {0.05, 0.1, 0.2, 0.5}, and different folding timescales, τ_fold, chosen from {20, 40, 80} Myr. The growth of SMBHs in solar mass units is compared against the observed quasars compiled in

Inayoshi et al. 2020. [19]. This analysis provides valuable insights into the assembly of these massive cosmic objects.

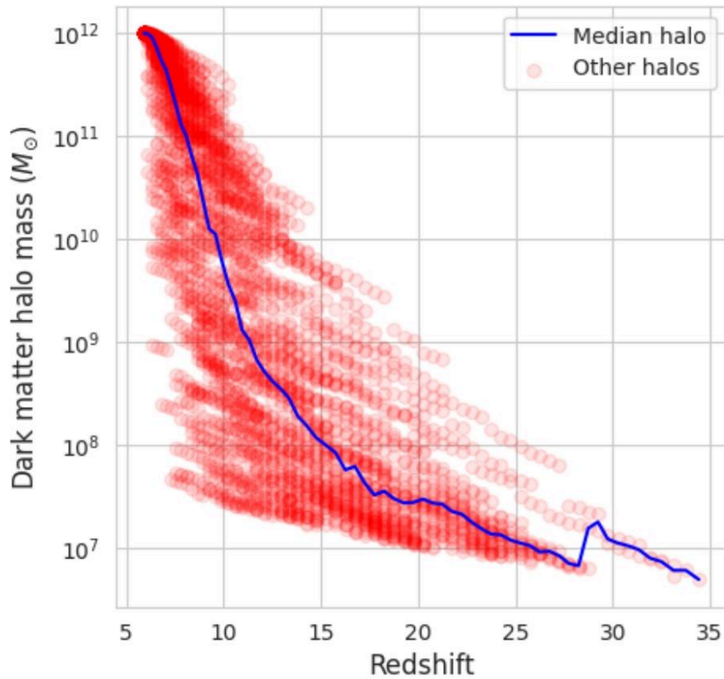

Figure 4. The plot represents 100 branches of data illustrating the dark matter evolutionary track concerning redshift. The solid blue line depicts the median of the data, serving as a generalized halo for the entire study. In the subsequent analysis, this halo is employed to evaluate the optimal set of parameters that closely mimic the expected growth.

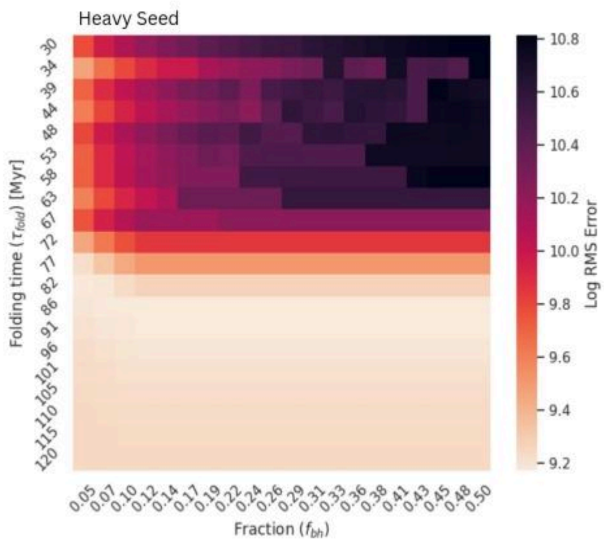

Figure 5(a).

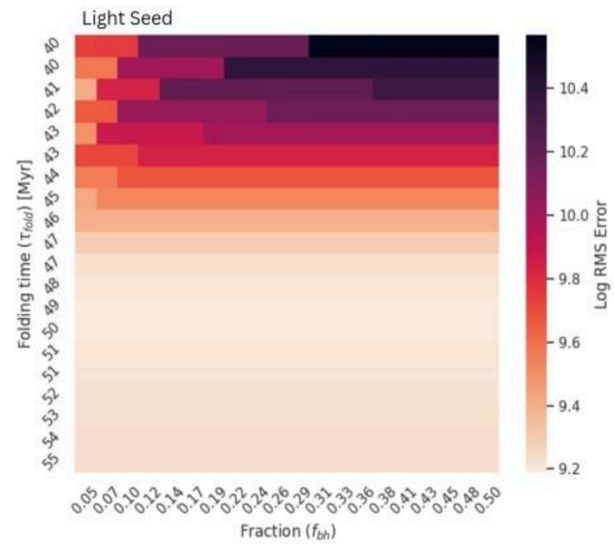

Figure 5(b)

Figure 5. Parameter estimation for supermassive black hole growth. (a) Fractions f_bh = [0.05, 0.5] and e-folding times τ_fold = [30, 120] Myrs are considered, with black holes initiated at [10^5] solar mass (heavy seed scenario). The growth rate follows the Eddington rate. Root mean square is calculated to assess the error between the model and observed data, and a heatmap is plotted. The combination with the least error identifies the appropriate parameters. (b) Similarly, for the same parameters black holes are initiated at 50 solar masses (light seed scenario). The growth rate follows the Eddington rate. Root mean square is calculated to compute the error between the model and observed data, and a heatmap is plotted. The combination with the least error determines the appropriate parameters.

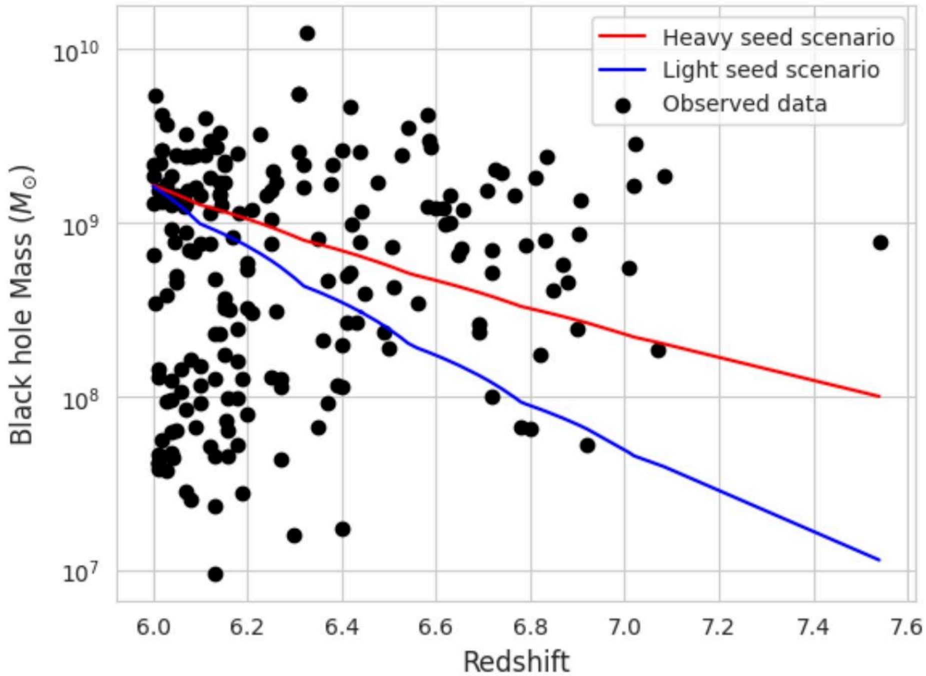

Figure 6. To present a clear compilation of results, both heavy seed and light seed scenarios are plotted. The parameters used to grow these black holes are detailed in Table 1, representing a favorable outcome when compared with observational data according to this study. The growth for both scenarios is illustrated. In the heavy seed scenario, the parameters are as follows: (e-folding-time) τ_fold = 86.84210526315789, (fraction) f_bh = 0.09736842105263158, (initial mass) M_i = 10^5 solar masses. Conversely, in the light seed scenario, the parameters are: τ_fold = 49.473684210526315, f_bh = 0.05, M_i = 50 Solar Masses.

Tables and Table Captions

Parameter	Heavy Seed (10^5 solar mass)	Light Seed (50 solar mass)
f_{bh}	0.09736842105263158	0.05
τ_{fold} (Myrs)	86.84210526315789	49.473684210526315
ϵ	0.192982456	0.10994152
Log RMS	9.17	9.19

Table 1. Summary of the best combination of parameters f_bh and τ_fold yielding the least Root Mean Square error between observed data and black hole growth according to the Eddington accretion rate. Radiative efficiency is also calculated using τfold = (σTc)/(4πμGmp) ≈ 450 Myr.

Appendix

The codebase associated with this research is available on GitHub. To access the code and explore its implementation, please visit the following link: https://github.com/prathamaggarwal7586/Parameter-Estimation-MCMC.git