What insights can be gained into the formation and growth of supermassive black holes by comparing and contrasting heavy seed light seed models?

Pratham Aggarwal[1]

***Abstract* — Black holes, enigmatic cosmic entities, have fascinated astronomers and astrophysicists for decades. In this study, we delve into their intricate behavior, focusing on the Eddington accretion model. This model, named after Sir Arthur Eddington, provides a theoretical framework for understanding how these gravitational giants interact with matter. Our investigation explores a range of initial seed scenarios, considering both light and heavy seeds. These seeds represent the origins and evolution of black holes, from the remnants of massive stars to primordial entities formed in the early universe. By examining these diverse scenarios, we aim to unravel the complex accretion processes that govern black hole growth. To ensure the robustness of our analysis, we employ a root mean square approach, a statistical tool that helps us predict crucial parameters. This method allows us to quantify the dynamic nature of black hole accretion and gain valuable insights into the underlying mechanisms driving these cosmic phenomena. Our study ultimately aims to provide well-informed conclusions about the behavior of black holes within the Eddington model and try to predict important parameters involved in accretion. By expanding our understanding of these cosmic enigmas, we try to contribute to the ongoing quest to unravel the mysteries of the universe, shedding light on one of its most captivating phenomena.**

I. Introduction

Observational data from high-redshift quasars, with redshifts z ≳ 6, corresponding to an age of the universe of about 0.917 Gyrs (~ 6.64% of the age of the universe), suggest the existence of quasars with masses exceeding $\geq 10^9 M_\odot$ (for recent reviews, see [1–3] (e.g. SDSS J010013.02+280225.8, a hyper luminous quasar located near the border of the constellations Pisces and Andromeda, with a mass of ~ $10^{10} M_\odot$ at z ≈ 6.3, as reported by [4].) a supermassive black hole (SMB poses a significant challenge for theories explaining the formation and growth of black holes. According to current understanding, black holes are believed to form as the end result of massive stars. Specifically, black holes that originate from the first generation of massive stars, known as Population III (PopIII) stars, are expected to have initial seed masses that are similar to their final stellar masses (as suggested by studies such as [5]). However, it is expected that these PopIII remnant black holes are initially starving for accretion material (as indicated by previous studies conducted by [6–12]). Here we apply the eddington accretion model on light seed and heavy seed scenarios and gain important insight on quasar's growth.

II. Methods

Dark matter halos used in the study are obtained from Monte Carlo merger trees. Median is computed from data of 100 different halos and then used in the study.

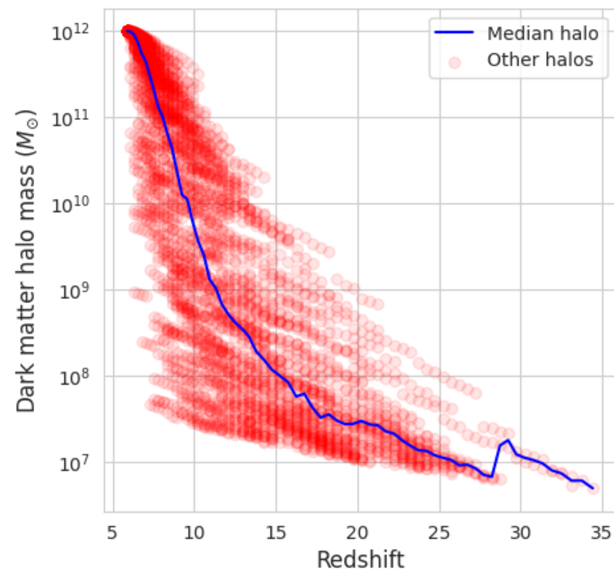

Figure 1 Shows 100 different dark matter halos plotted against redshift. halo in solid blue is median of all the halos analyzed in the study

Black hole accretion rate is assumed to be eddington.Here M_i is seed mass and τ_{fold} is e-folding time

$\tau_{fold} = (\sigma_T c\epsilon)/(4\pi\mu G m_p) \approx 450\epsilon\ Myr$ where ϵ is radiative efficiency

$$M_{bh}(t) = M_i\, exp(t/\tau_{fold}) \quad (1)$$

constraints are applied growth to quasars in our study due to the inherent limitation that these celestial objects cannot grow beyond a certain threshold. In order to prevent unrealistic accretion, an assumption is introduced that quasars are restricted from growing beyond a certain fraction (f_{bh}) of the available baryonic matter within their host halo (see [13] for more detail). This constraint is implemented to ensure that the growth of quasars remains within a physically plausible and observationally supported range, thereby enhancing the realism of our modeling and analysis.

$$M_{bh} \leq f_{cap} M_{halo} \Omega_b / \Omega_m \quad (2)$$

[1]Pratham Aggarwal from Sidhhartha Public School (e-mail: prathamaggarwal7586@ gmail.com).

where $\Omega_b = 0.266$, $\Omega_m = 0.049$ *and* f_{cap} is fraction

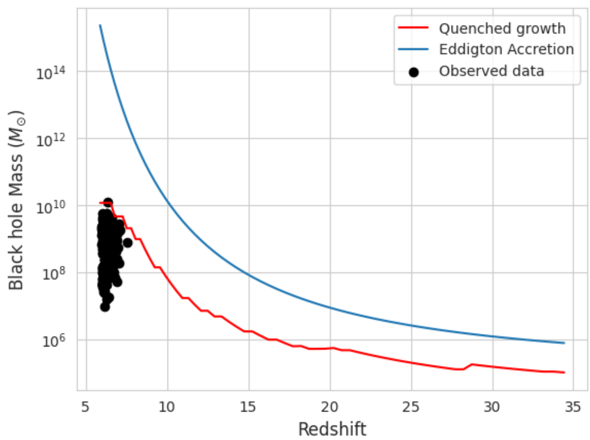

Figure 2 Consists of two different growths. Unconstrained Eddington Growth: This scenario shows galaxy growth without limitations, resulting in astronomically unrealistic values (e.g., $10^{10} M_\odot$), inconsistent with observed data. Quenched Growth with Constraints: Here, growth is constrained by a random fraction cap, yielding values that align with observable data, providing a more realistic representation of galaxy growth.

study is conducted involving the growth of black holes from different initial masses, specifically $50 M_\odot$ (referred to as the "light seed") and $10^5 M_\odot$ (the "heavy seed"). Additionally, we explored various combinations of fractions (f_{bh}) and e-folding times (τ_{fold}). To assess the accuracy of our predictions, we compared the simulated growth to observed data at high redshifts. This evaluation is performed by computing the root mean square error (RMSE).The objective of our analysis is to identify the most suitable combination of parameters, namely the fraction (f_{bh})) and e-folding time (τ_{fold}), that minimizes the RMSE between the predicted growth and observed data. This optimal combination provides the best fit to the observed data and enhances the accuracy of our predictions.To present our findings effectively, we utilized a heat map visualization technique. The heat map visually represents the results, allowing for easier interpretation and a clearer understanding of the relationships between different parameter combinations and the corresponding RMSE values. This graphical representation aids in identifying the parameter set that yields the least RMSE and, therefore, the most accurate predictions in our study.

III. Results

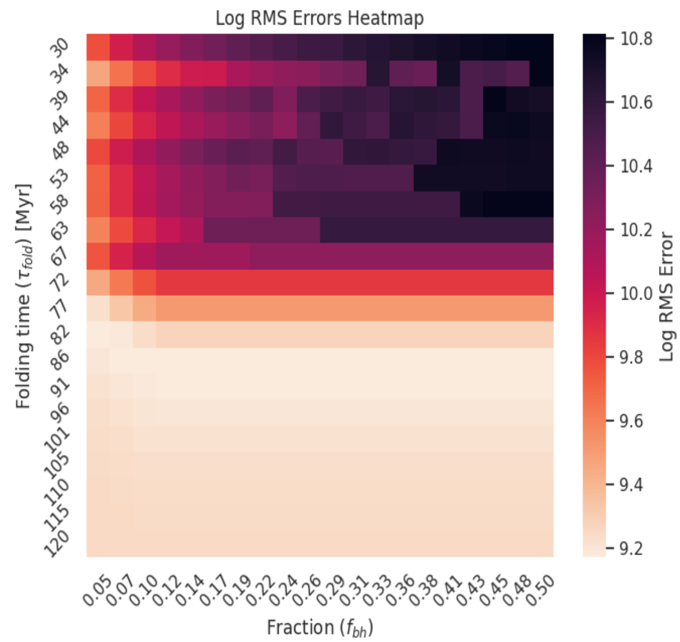

Figure 3. .Parameters to estimate are fractions $f_{bh} \in (0.05, 0.5)$ and e-folding times($\tau_{fold} \in (30, 120)\ Myr$. For different parameters black holes are grown with initial mass $10^5 M_\odot$ (heavy seed scenario). Growth rate is assumed to be eddington rate .Root mean square is calculated to compute error between the model and observed data and then heat map is plotted.Combination with least error will be the appropriate parameters.

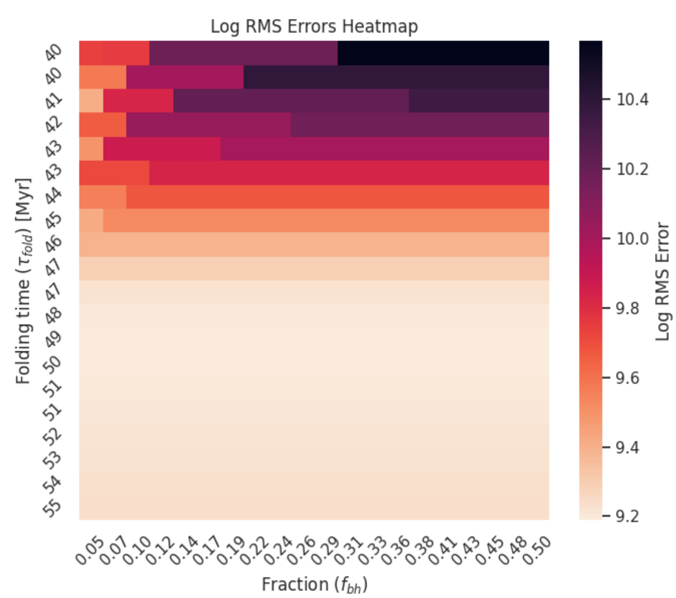

Figure 4.Parameters to estimate are fractions $f_{bh} \in (0.05, 0.5)$ and e-folding times($\tau_{fold} \in (40, 55)\ Myr$. For different parameters black holes are grown with initial mass $50 M_\odot$(light seed scenario). Growth rate is assumed to be eddington rate .Root mean square is calculated to compute error between the model and observed data and then heat map is

plotted.Combination with least error will be the appropriate parameters.

TABLE I. RESULTS

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

Figure 5. Above panel summarizes the best combination of parameters (f_{bh} and τ_{fold}) which yields the least error between observed data and black hole grown according to the eddington accretion rate. We also calculate the radiative efficiency using $\tau_{fold} = (\sigma_T c\epsilon)/(4\pi\mu G m_p) \approx 450\epsilon\ Myr$

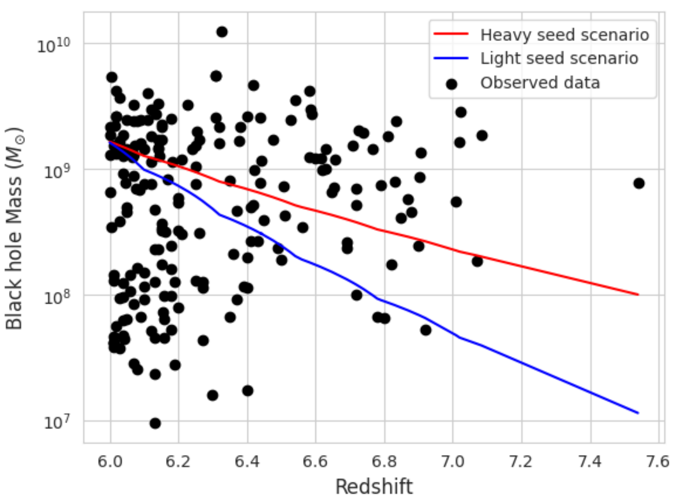

Figure 6. Fig.6 illustrates the plotted data for both the heavy seed scenario and the light seed scenario, as specified in Fig.5. In the heavy seed scenario, the parameters are as follows: $\tau_{fold} = 86.84210526315789$, $f_{cap} = 0.09736842105263158$ and seed $M_i = 10^5 M_\odot$ Conversely, in the light seed scenario, the parameters are $\tau_{fold} = 49.473684210526315$, $f_{cap} = 0.05$ and seed $M_i = 50 M_\odot$

The results presented in Table 1 indicate that black holes can only accrete 5% or 9% of the available baryonic matter within the halo, with the specific percentage depending on whether the seed is heavy or light. Furthermore, the e-folding time exhibits a significant disparity between the heavy seed and light seed scenarios, leading to observable differences in radiative efficiency. Additionally, at high redshifts, it becomes apparent that the growth patterns of both scenarios look remarkably similar at high redshift, aligning with the expectations set forth by previous studies [5].

ACKNOWLEDGMENT

I would like to express my heartfelt gratitude to Mr. Matthew Scoggins, PhD student in the Department of Astronomy at Columbia University. His guidance and unwavering support were instrumental in making this research possible. I extend my sincere thanks to Mr. Scoggins for generously providing valuable data, which significantly contributed to the thorough analysis conducted in this study.

REFERENCES

[1] Xiaohui Fan, Michael A Strauss, Gordon T Richards, Joseph F Hennawi, Robert H Becker, Richard L White, Aleksandar M Diamond-Stanic, Jennifer L Donley, Linhua Jiang, J Serena Kim, et al. A survey of z¿ 5.7 quasars in the sloan digital sky survey. iv. discovery of seven additional quasars. The Astronomical Journal, 131(3):1203, 2006.

[2] Daniel J Mortlock, Stephen J Warren, Bram P Venemans, Mitesh Patel, Paul C Hewett, Richard G McMahon, Chris Simpson, Tom Theuns, Eduardo A Gonzales-Solares, Andy Adam- ´ son, et al. A luminous quasar at a redshift of z= 7.085. Nature, 474(7353):616–619, 2011.

[3] Ji-Jia Tang, Tomotsugu Goto, Youichi Ohyama, Chichuan Jin, Chris Done, Ting-Yi Lu, Tetsuya Hashimoto, Ece Kilerci Eser, Chia-Ying Chiang, and Seong Jin Kim. Rapid black hole growth at the dawn of the universe: a super-eddington quasar at z= 6.6Monthly Notices of the Royal Astronomical Society, 484(2):2575–2586, 2019.

[4] Xue-Bing Wu, Feige Wang, Xiaohui Fan, Weimin Yi, Wenwen Zuo, Fuyan Bian, Linhua Jiang, Ian D McGreer, Ran Wang, Jinyi Yang, et al. An ultraluminous quasar with a twelve billion-solar-mass black hole at redshift 6.30. Nature, 518 (7540):512–515, 2015.

[5] Stanford E Woosley, Alex Heger, and Thomas A Weaver. The evolution and explosion of massive stars. Reviews of modern physics, 74(4):1015, 2002.

[6] Daniel Whalen, Tom Abel, and Michael L Norman. Radiation hydrodynamic evolution of primordial h ii regions. The Astrophysical Journal, 610(1):14, 2004.

[7] Brian W O'Shea, Tom Abel, Dan Whalen, and Michael L Norman. Forming a primordial star in a relic h ii region. The Astrophysical Journal, 628(1):L5, 2005.

[8] Jian-Min Wang, Yan-Mei Chen, and Chen Hu. Feedback limits rapid growth of seed black holes at high redshift. The Astrophysical Journal, 637(2):L85, 2006.

[9] Jarrett L Johnson and Volker Bromm. The aftermath of the first stars: massive black holes. Monthly Notices of the Royal Astronomical Society, 374(4):1557–1568, 2007.

[10] Milos Milosavljevi ˇ c, Sean M Couch, and Volker Bromm. Accretion onto intermediate-mass black holes in dense protogalactic clouds. The Astrophysical Journal, 696(2):L146, 2009.

[11] Marcelo A Alvarez, John H Wise, and Tom Abel. Accretion onto the first stellar-mass black holes. The Astrophysical Journal, 701(2):L133, 2009.

[12] Myoungwon Jeon, Andreas H Pawlik, Thomas H Greif, Simon CO Glover, Volker Bromm, Milos Milosavljevi ˇ c, and´ Ralf S Klessen. Black hole feedback on the first galaxies. In AIP Conference Proceedings, volume 1480, pages 325–328. American Institute of Physics, 2012.

[13] Matthew T Scoggins, Zolt´an Haiman, and John H Wise. How long do high redshift massive black hole seeds remain outliers in black hole versus host galaxy relations? Monthly Notices of the Royal Astronomical Society, 519(2):2155–2168, 2023.