

The Origin of Supermassive Black Holes in the Early Universe

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Abstract. The discovery of supermassive black holes (SMBHs) in the early universe presents a significant challenge to long-standing models of cosmic structure formation. Their existence after the Big Bang implies extraordinarily rapid growth, which is difficult to reconcile with standard accretion physics. This article investigates the mechanisms enabling such high-growth rates and explains their "overmassive" nature relative to the stellar mass of their host galaxies. By synthesizing theoretical models of seed black hole formation with high-resolution cosmological simulations, such as THESAN-ZOOM, and leveraging new, transformative data from the James Webb Space Telescope (JWST), the author dissects the roles of super-Eddington accretion, Active galactic nucleus feedback, and the unique, gas-rich, dark matter-dominated environments of primordial galaxies. The analysis demonstrates that episodic super-Eddington accretion, occurring in dense, turbulent gas reservoirs, was likely a key driver of this accelerated growth. Crucially, the study finds that the correlation between black hole mass and the host's dynamical mass is more fundamental and tighter in this epoch than the relation with stellar mass. This evidence strongly suggests that early SMBHs are not rare anomalies requiring exotic physics but are instead natural, inevitable outcomes of the primordial conditions, where the total mass of the system, rather than its stellar content, governed initial black hole growth.

Keywords: Supermassive black holes, JWST, Early universe, Super Eddington accretion.

1. Introduction

Supermassive black holes (SMBHs), found at the centers of galaxies, are among the biggest enigmas of modern astrophysics. Their presence in the early universe—in the first billion years following the Big Bang—is a significant problem for standard galaxy formation models. Recent observations using the James Webb Space Telescope (JWST) have revealed that not only were these galactic giants present, but they were regularly "overmassive," i.e., had disproportionate mass relative to the stellar mass of their host galaxies [1,2].

While the local universe exhibits a tight correlation between stellar bulge mass and black hole mass (the $M_{\text{BH}}-M_*$ relation), this is compromised at high redshift. The $M_{\text{BH}}-M_{\text{dyn}}$ relation—between black hole mass and overall dynamical mass (dark and gas)—continues to be strong, however, as recent cosmological simulations have demonstrated [3]. This asymmetry suggests that early black hole accretion is more closely tied to overall host system gravitational potential than to stellar content. Growing numbers of papers have tried to fit these observations by invoking a range of different types of mechanisms. Local analog observations, such as overmassive black holes in dwarf galaxies out to $z \sim 0.9$ [4], have significant implications for long-term evolutionary trends. The revolutionary observations of objects like the quiescent overmassive black hole at GN-z11 and other high-redshift [1], high-energy black holes by JWST gave observational validation to the theoretical model [2]. They are complemented by high-resolution simulations like those of McClymont et al. that demonstrate how gas-rich, dark matter-dominated galaxies can naturally produce overmassive black holes without resorting to exotic physics [3]. Furthermore, blue compact dwarf galaxies observations can provide information about metal-poor environments that contain explosive black hole growth [5].

The aim of this paper is to integrate this theory, calculation, and observation evidence already in hand to explain the early emergence of overmassive SMBHs. The rest of this paper is outlined as follows. Section 2 will recapitulate theoretical seed formation black hole theory and scaling relations. Section 3 will cover cosmological simulation and JWST observation results, including the

paradigmatic case of GN-1001830. Section 4 will discuss accretion mechanisms such as super-Eddington accretion and feedback, and Section 5 will conclude with implications and prospects.

2. Theoretical Background

The formation of supermassive black holes (SMBHs) in the early universe represents a significant challenge to conventional astrophysical models. Theoretical approaches to this problem focus on two fundamental aspects: the origin of initial black hole seeds and the physical mechanisms that enabled their rapid growth to supermassive scales within the first billion years after the Big Bang [6]. Current models propose three primary pathways for seed formation. Population III stellar remnants constitute the lightest seeds, formed from the first generation of massive, metal-poor stars. These primordial stars, with masses reaching 100-1000 solar masses, would collapse into black holes of similar mass through supernova explosions or direct collapse. While theoretically viable, these light seeds face substantial challenges in growing to SMBH proportions within the available time, as they require sustained near-Eddington accretion rates that may exceed physical limits.

Direct collapse black holes (DCBHs) offer a more efficient alternative. Under specific conditions—particularly in pristine gas clouds with low metallicity and strong ultraviolet radiation backgrounds that suppress molecular hydrogen formation—massive gas clouds can collapse directly into black holes of 10^4 – 10^6 solar masses. These heavy seeds significantly reduce the required growth timescale, making them prime candidates for explaining the most distant quasars observed at redshifts $z > 6$.

A third mechanism involves runaway stellar collisions in dense nuclear clusters, where successive mergers of massive stars could produce intermediate-mass black holes of 10^3 – 10^4 solar masses [7]. However, uncertainties remain regarding the frequency and stability of such environments in the early universe. The scaling relations between black holes and their host galaxies provide additional theoretical insights. While the local universe shows a tight correlation between black hole mass and stellar mass (M_{BH} – M_* relation), JWST observations reveal that this relation breaks down at high redshifts. Instead, the M_{BH} – M_{dyn} relation—connecting black hole mass to total dynamical mass including dark matter and gas—remains robust. This suggests that in the early universe, black hole growth was more fundamentally tied to the overall gravitational potential of the host system rather than its stellar content.

The theoretical framework explaining the decoupling of black hole mass from stellar mass incorporates several key factors. Feedback mechanisms play a crucial role, where AGN-driven outflows can suppress star formation while allowing continued black hole growth. Additionally, the different timescales for black hole accretion versus stellar assembly, combined with the gas-rich, turbulent conditions of high-redshift galaxies, create environments conducive to rapid black hole growth without proportional increases in stellar mass. This theoretical foundation provides essential context for interpreting both observational data and simulation results regarding early SMBH formation.

3. Summary

3.1. Cosmological Simulations

Cosmological simulations are nowadays crucial to investigating the formation and growth of supermassive black holes in early epochs. THESAN, combining the Illustris-TNG code with sophisticated gas physics, dust, and radiation transfer treatments, enables modeling of cosmic evolution over the first billion years on a highly detailed scale. The THESAN-ZOOM version achieves extremely high resolution and can capture physical processes on galactic scales that are key to understanding black hole-galaxy co-evolution [8].

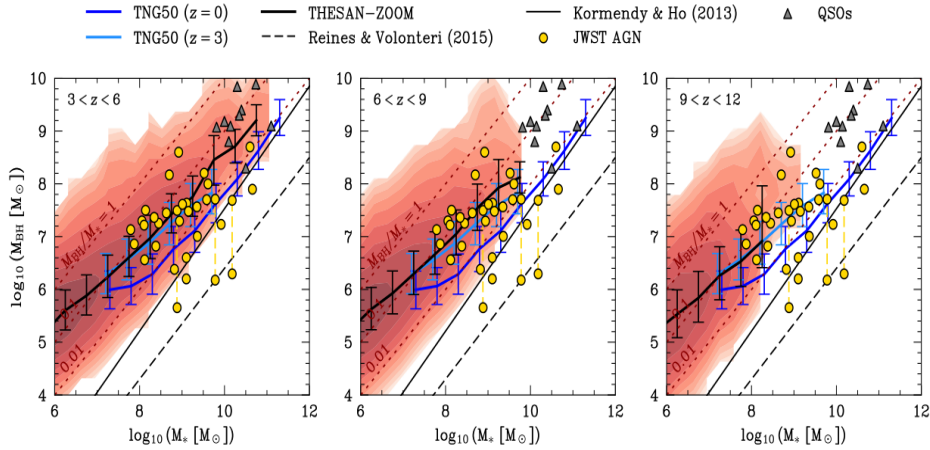


Fig 1. BH masses compared to their host galaxies, with MBH being estimated from M_{dyn} through a universal MBH– M_{dyn} relation [3].

The simulation outputs are also found to demonstrate astonishing agreement with JWST-observed AGN at $z \approx 4$ –11 (golden circles) and high-redshift QSOs at $z \approx 5$ –7 (grey triangles). The simulated galaxies naturally reproduce the ubiquity of "overmassive" black holes in low-stellar-mass systems even without the use of explicit black hole physics within the modeling framework. This simulation-observation consistency strongly suggests that overmassive occurs naturally from the very intrinsic properties of early galaxies rather than requires invoking unusual physical processes.

Comparison with local scaling relations also enhances the evolutionary scenario. While high-redshift systems are quite disparate from local MBH– M_{bulge} relation of early-type galaxies and the MBH– M_* relation of disk galaxies, they are well-comforted in the MBH– M_{dyn} paradigm, as shown in Fig. 1. This correlation makes the argument that black hole evolution in the early universe is more fundamentally connected to the total dynamical mass of the host system, consisting of large dark matter and gas content, than to having an isolated connection with stellar mass evolution [9].

The similar parallel derived from simulations in TNG50, with similar trends at $z = 3$ developing into the local elliptical relation by $z = 0$, reinforces this evolutionary sequence. Together, these simulation results prove that the observed "overmassive" nature of early black holes is a result of different mass assembly routes and environmental conditions in the early universe, where the galaxies were predominantly dark matter-dominated and gas-rich environments, providing the ideal environment for early black hole growth over stellar growth.

3.2. Observational Evidence

The detection of early SMBHs has been completely revolutionized with the advent of JWST. Observations such as JADES and CEERS have detected active galactic nuclei (AGN) at redshifts of over 6, i.e., approximately a little less than one billion years after the Big Bang. These AGN contain black holes much heavier than would be expected by their stellar masses. Black hole-stellar mass diagrams show systematic deviations from the local relations, with clumped galaxies at high redshifts over base lines. Notably enough, however, they behave normally relative to dynamical mass. A good example is galaxy GN-1001830, containing a quiescent overmassive black hole. Its black hole-to-stellar mass ratio is about 1000 times higher compared to nearby galaxies based on JWST observations. The mass of the black hole itself, however, places it on the $M_{\text{BH}}-M_{\text{dyn}}$ relation. This is what ensures these objects are gas-rich but star-poor as evidence in favor of the hypothesis of early black hole accretion being accompanied by cosmological dynamical mass, and not stellar content [10].

3.3. Growth Mechanisms: Super-Eddington Accretion

Even with optimal conditions, the fast SMBH growth requires efficient accretion mechanisms. The Eddington limit sets a theoretical upper bound rate for black holes to accrete matter, balancing

radiation pressure with gravity. Black holes must occasionally surpass this bound through super-Eddington accretion in order to grow from seed to supermassive within a few hundred million years. Several processes enable this to occur. Trapping of radiation in thick accretion flows suppresses escape of photons, reducing outward pressure. Anisotropic emission channels channel radiation into jets or funnels, allowing inflows to run unhampered. Low metal abundance gas reduces opacity, further reducing radiation pressure [11]. Together, these processes enable short episodes of extremely rapid growth. These times are difficult to identify.

Completeness maps of observations are marked by a "purple desert" in the high-mass and high-accretion-rate parameter space. Trapping of photons and survey biases render super-Eddington black holes nearly invisible. Therefore, their contribution to initial black hole growth is known indirectly rather than directly observed. The galaxy GN-1001830 is a great case in point, see Fig. 2 [1].

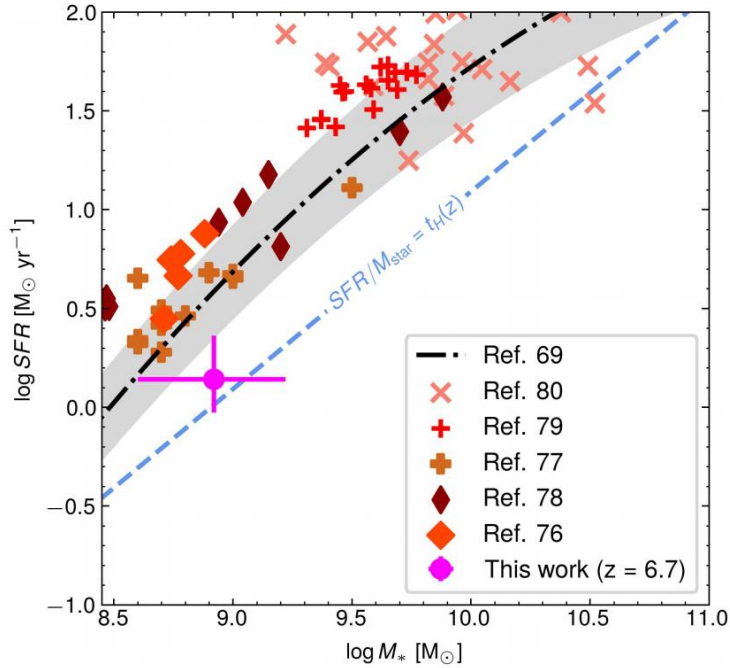


Fig 2. Star-forming rate as a function of stellar mass diagram with position of GN-1001830 with respect to the star-forming main sequence [1].

Quenched star formation, three below main sequence but with sufficient gas. This would require vigorous AGN feedback: energy from the central black hole has been utilized to heat or eject gas and quench effective star formation but allow black hole growth to proceed. Two of these would be capable of explaining the properties of GN-1001830: growth from a compact seed via sub-Eddington accretion, or super-Eddington bursty growth. Simulations indicate that the latter is more likely as heavy-seed models alone cannot be used to explain observed ratios. Thus, GN-1001830 is most likely to have been formed by super-Eddington high-rate flares with extended dormancies in between. It demonstrates that extreme objects do occur naturally in the early universe's environment.

3.4. Feedback and Galaxy Evolution

Black holes, during accretion of matter, release radiation and driving outflows that heat or blow gas away. Feedback quenches star formation by typically strangling it in low-mass galaxies. Feedback makes a gas-rich galaxy like GN-1001830 experience minimal star formation. Feedback strangles stellar growth, allowing the black hole to dominate mass balance and leading to the ultrahigh ratios observed. Semi-analytic codes such as L-Galaxies supplemented by Millennium-II simulations validate these findings. Both have heavy and light seed schemes to simulate populations of more-than-supermassive black holes in low-stellar-mass gas-rich galaxies. Feedback is the leading process consolidating galaxy evolutionary paths and black hole accretion.

4. Conclusion

In summary, the emergence of early, overmassive black holes can be understood as a natural consequence of the primordial conditions of the universe, where galaxies were dominated by dark matter and gas. The evidence indicates that the relationship between black hole mass and dynamical mass ($M_{\text{BH}}-M_{\text{dyn}}$) is more fundamental than the correlation with stellar mass ($M_{\text{BH}}-M_{\text{*}}$), with any departure from the latter highlighting the secondary role of stellar buildup in the initial growth phases. Super-Eddington accretion is posited as a key facilitator of the required high growth rates, although its direct observational signatures remain elusive. Subsequent feedback processes then acted to regulate star formation and set the final black-hole-to-star ratio, as illustrated by systems like GN-z11. Despite the coherence of this scenario, several challenges persist, including the difficulty of confirming AGN in dwarf galaxies due to contamination from stellar activity and observational biases that may obscure super-Eddington events. Fundamental questions regarding seed formation, detailed accretion physics, and early galactic environments remain areas of active debate. Nevertheless, the powerful synergy between advanced simulations and cutting-edge observations from telescopes like JWST is providing unprecedented insight. As future facilities like the ELT and LSST push the observational frontier, people's understanding of these cosmic giants will continue to deepen, solidifying the view that the first supermassive black holes were not anomalies but natural products of the universe's gas-rich youth.

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