Massive Early Seeds as a Phenomenological Framework for the Origin of High-Redshift Supermassive Black Holes

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Abstract

Supermassive black holes (SMBHs) with masses of 10^8–10^9 $M_\odot$ are observed at redshifts z > 7– 10, corresponding to cosmic times less than 700 Myr after the Big Bang within ΔCDM cosmology. Recent JWST discoveries, including Little Red Dots (LRDs), compact galaxies hosting overmassive SMBHs, and dust-obscured AGN (e.g., CAPERS-LRD-z9 at z ≃ 9.3), challenge light-seed models that rely solely on Eddington-limited accretion from stellar-mass remnants (Kocevski et al., 2025, Maiolino & et al., 2024, Rusakov et al., 2026).

While heavy-seed scenarios such as direct collapse partially alleviate growth timescale issues, they often require finely tuned initial conditions or episodic super-Eddington accretion to match the observed abundance and mass distribution of high-z SMBHs.

Unlike existing heavy-seed models, this work proposes a phenomenological framework in which massive early seeds ($M_{seed} \geq 10^5$–$10^6\, M_\odot$) are treated as an effective macroscopic population constrained by observations, without invoking a single specific formation channel. Forming preferentially in highly biased overdense environments at $z \geq 15$, these seeds act as gravitational centers that accelerate galaxy and quasar assembly, reducing the required growth from ≃18–20 e-folds to ≥10 while remaining consistent with realistic duty cycles and feedback physics. The model naturally explains the elevated M_{BH}/M_* ratios observed in compact high-redshift systems without extreme dust obscuration or feedback fine-tuning.

We outline viable parameter ranges and present multiple independent observational tests, including an enhanced central SMBH occupation fraction in compact galaxies (testable with JWST programs such as GLIMPSE and PRIMER), relic intermediate-mass black hole populations, and elevated early merger rates detectable by LISA Consortium (2025). The framework is fully consistent with ΔCDM cosmology and does not modify global cosmological observables. It can be decisively tested or falsified with ongoing JWST deep fields, ngEHT observations, and future gravitational-wave measurements. In particular, the absence of an enhanced SMBH occupation fraction in the most compact high-redshift galaxies would directly falsify the model.

Keywords: *supermassive black holes, high-redshift galaxies, JWST, direct collapse, gravitational waves, LISA*

1. Introduction

Supermassive black holes (SMBHs), with masses ranging from 10^6 to 10^{10} $M_\odot$, reside at the centers of massive galaxies and play a fundamental role in their evolution through feedback processes such as outflows, jets, and radiative heating (Fabian et al., 2012, Kormendy & Ho, 2013). Understanding their origin remains one of the central challenges in modern astrophysics, particularly given the rapid assembly of billion-solar-mass SMBHs within the first billion years after the Big Bang (z > 6–10).

Recent observations from the James Webb Space Telescope (JWST) have significantly sharpened this problem by revealing a growing population of SMBHs at z > 7, many of which appear overmassive relative to their host galaxies (M_{BH}/M^* significantly exceeding local scaling relations). Notable examples include dust-obscured active galactic nuclei (AGN) in compact systems known as Little Red Dots (LRDs), as well

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as broad-line sources such as CAPERS-LRD-z9 at z $\simeq$ 9.3 and the Virgil galaxy at a cosmic age of ~800 Myr (Kocevski et al., 2025, Maiolino & et al., 2024, Naidu et al., 2025, Rusakov et al., 2026, Taylor & et al., 2025). These findings suggest that SMBH seeds must have formed early and grown efficiently under extreme conditions, placing strong constraints on theoretical models.

Standard formation scenarios include: (i) growth from light stellar-remnant seeds ($\sim$ 10–100 $M_\odot$) via prolonged Eddington or super-Eddington accretion (Madau & Rees, 2001, Volonteri, 2010), (ii) direct collapse of pristine gas clouds into heavy seeds ($\sim 10^4$–$10^6 M_\odot$) under intense Lyman–Werner radiation (Bromm & Loeb, 2003, Inayoshi et al., 2020) (iii) runaway stellar mergers in dense nuclear clusters (Portegies Zwart & et al., 2023), (iv) primordial black holes formed from early density fluctuations (Carr & et al., 2021), and (v) more speculative mechanisms involving dark matter or other new physics.

Each of these scenarios encounters difficulties when confronted with recent JWST data. Light-seed models typically require sustained high accretion rates and large duty cycles, while heavy-seed formation channels often rely on rare environmental conditions that may not reproduce the observed abundance (De Graaff et al., 2025, Latif & et al., 2022). Primordial black hole scenarios are additionally constrained by limits from the cosmic microwave background, microlensing, and evaporation (Inayoshi et al., 2020, Ziparo et al., 2025).

In this work, we propose a phenomenological framework in which massive early seeds ($M_{seed} \geq 10^5$–10^6 M_{odot}) form preferentially in highly biased overdense regions at z > 15. These seeds act as early gravitational centers that accelerate the hierarchical assembly of galaxies and quasars, naturally accounting for elevated M_BH/M* ratios without invoking extreme accretion histories or finely tuned feedback.

We review the limitations of standard models in Section 2, derive physical constraints and parameter ranges for the proposed framework in Section 5, and outline testable observational signatures using current JWST surveys (e.g., GLIMPSE, PRIMER), next-generation interferometry (ngEHT), and the future LISA mission (Sections 6–7). This framework provides a consistent and testable pathway to reconcile early SMBH observations with theoretical growth limits.

Throughout this work, "massive early seeds" refers to black holes with initial masses $\geq 10^5$–$10^6\,M_\odot$ formed at very early cosmic epochs (z > 15) in rare and extreme environments. Their origin may involve enhanced gas collapse, rapid protostellar mergers, or the collapse of dense protocluster structures under metal-poor conditions. Rather than assuming a single formation channel, we treat these seeds as an effective initial condition compatible with a range of processes within standard cosmology.

2. Review of Standard Formation Scenarios for Supermassive Black Holes

We briefly review the principal proposed mechanisms for supermassive black hole (SMBH) seed formation at high redshifts, highlighting their strengths and key limitations, particularly in light of recent JWST discoveries of overmassive SMBHs in compact systems at z > 7.

2.1. Light Seeds from Stellar Remnants

The standard scenario assumes that SMBHs grow from stellar-mass seeds ($\sim$ 10–100 $M_\odot$) formed in the first Population III stars via core collapse or pair-instability supernovae. Subsequent growth occurs through Eddington-limited or super-Eddington accretion (Madau & Rees, 2001, Volonteri, 2010).

The mass growth under Eddington-limited accretion follows the exponential form:

$$M(t) = M_0 exp[(1{-}\epsilon)/\epsilon \times t/t\_Edd], \quad (1)$$

where M_0 is the initial seed mass, $\epsilon \simeq 0.1$ is the radiative efficiency and $t_{Edd} \simeq 45$ Myr is the Salpeter timescale (Inayoshi et al., 2020, Salpeter, 1964).

Even under ideal conditions, this corresponds to a mass growth timescale of $\simeq$ 0.45 Gyr for 10 e-foldings, leaving little room for interruptions in the accretion history. Reaching 10^9 $M_\odot$ from $\sim 100\,M_\odot$ in less than 700 Myr remains challenging under realistic early-Universe conditions due to strong feedback, rapid gas depletion, and low average accretion rates (Johnson & Bromm, 2007). JWST observations of overmassive SMBHs in compact systems (e.g., LRDs with $M_{BH}/M*$ significantly exceeding local scaling relations) further strain this model, requiring extreme and potentially difficult-to-sustain assumptions about prolonged super-Eddington phases (Kocevski et al., 2025, Maiolino & et al., 2024).

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2.2. Direct Collapse Black Holes (Heavy Seeds)

In metal-poor, pristine gas clouds exposed to intense Lyman-Werner UV flux from nearby star-forming regions, gas can cool nearly isothermally and collapse directly into $\sim 10^4$–$10^6\,M_\odot$ seeds, bypassing the need for prolonged super-Eddington growth (Bromm & Loeb, 2003, Inayoshi et al., 2020).

Recent JWST candidates include compact objects in merging systems and LRDs interpreted as possible direct-collapse remnants (Rusakov et al., 2026, Taylor & et al., 2025). However, the required conditions — pristine gas and a strong, sustained UV background — are extremely rare. Detailed simulations and abundance estimates indicate that direct collapse may struggle to reproduce the observed number density of high-z SMBHs and quasars without fine-tuning (De Graaff et al., 2025, Latif & et al., 2022).

2.3. Runaway Collapses in Dense Stellar Clusters

Dense nuclear star clusters can undergo runaway mergers driven by dynamical friction and stellar collisions, potentially producing intermediate-mass black hole seeds ($\sim 10^2$–$10^4\,M_\odot$) (Portegies Zwart & et al., 2023, Vergara et al., 2025).

While efficient in dense environments, this channel faces uncertainties at z > 15 due to limited protocluster assembly timescales and early metal enrichment. JWST has not yet provided clear evidence for a widespread population of IMBHs in high-redshift systems, and the mechanism is not expected to dominate under current constraints.

2.4. Primordial Black Holes (PBHs)

PBHs could form from high-density fluctuations in the early Universe, with masses potentially spanning $10^{-16} M_\odot$ to $10^5 M_\odot$ (Carr & et al., 2021, Ziparo et al., 2025).

Strong observational constraints severely limit their contribution:

- CMB anisotropies and μ-distortions exclude significant PBH fractions in the 10–100 $M_\odot$ range (Inomata et al., 2021, Planck Collaboration et al., 2020).
- Lensing (HSC, OGLE) and microlensing surveys constrain f_PBH < 0.01–0.1 in relevant mass ranges.
- Hawking evaporation excludes PBHs with masses below $\sim 10^{15}$ g.

Although PBHs could seed some high-z SMBHs, current bounds make them unlikely to dominate the observed population without extreme fine-tuning, although they remain an active area of theoretical investigation (Carr & et al., 2021, Green & Kavanagh, 2021).

2.5. Alternative and Speculative Scenarios

Models involving self-interacting dark matter, axion miniclusters, or other speculative physics remain poorly constrained and lack robust observational support (no confirmed signatures in CMB, GW, or JWST data).

2.6. Summary

Taken together, these limitations suggest that no single standard formation scenario appears to simultaneously reproduce the observed abundance, masses, and early appearance of SMBHs revealed by JWST without invoking rare environmental conditions, prolonged super-Eddington growth, or additional physics. Light-seed models primarily struggle with growth timescales and duty cycles, heavy-seed mechanisms (direct collapse, runaway mergers) are limited by environmental rarity, and PBH scenarios are tightly constrained by multiple independent observations. These limitations motivate the exploration of complementary or extended seeding pathways that relax growth constraints while remaining fully consistent with ΔCDM cosmology. The phenomenological massive early seed framework introduced here provides such a pathway, treating massive seeds ($M_{seed} \geq 10^5$–$10^6 M_\odot$) as an effective initial condition in biased overdense regions at z > 15.

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Table 1. Comparison of Standard SMBH Seed Formation Scenarios

Scenario	Seed Mass	Advantages	Key Limitations
Light seeds	10–100 $M_\odot$	Common formation in Pop III stars	Slow growth, requires extreme duty cycles
Direct collapse	10^4–10^6 $M_\odot$	Large initial seeds, bypasses Eddington limit	Extremely rare conditions
Cluster mergers	10^2–10^4 $M_\odot$	Dynamical channel in dense clusters	Limited efficiency at z > 15
PBHs	Broad range	Early formation	Strong observational constraints (CMB, lensing,evaporation)

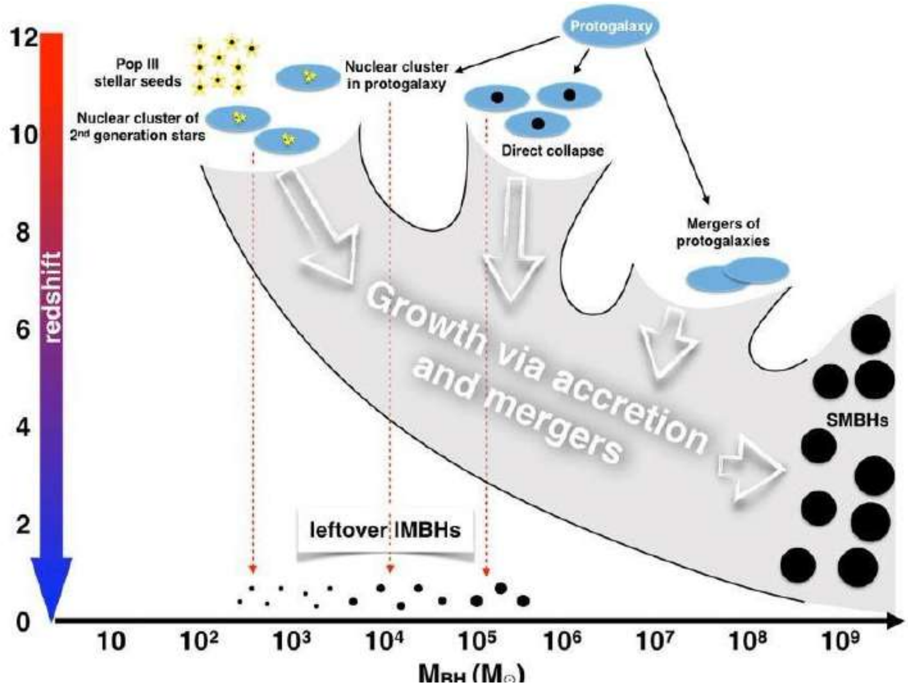

Figure 1. Schematic overview of standard SMBH seed formation and growth pathways from z ≥ 12 to the present. The diagram illustrates the main channels (Pop III stellar seeds, direct collapse, nuclear cluster mergers, Lyman-Werner radiation effects) and their temporal evolution.

3. Constraints on Growth

Black hole growth is limited by the Eddington accretion rate, governed by the Salpeter equation 1. For light seeds with initial masses of order 10–100 $M_\odot$, reaching the observed SMBH masses of 10^8–10^9 M_{odot} at z > 7 (corresponding to cosmic times t ≤ 700 Myr) requires approximately 18–20 e-folding growth phases. For example, growing from 10 $M_\odot$ to 10^9 M_{odot} demands $\ln(10^8) \simeq 18.42$ e-folds, equivalent to roughly 9–10 e-folding times ($\simeq$ 405–450 Myr for $\epsilon \simeq 0.1$) of near-continuous Eddington or super-Eddington accretion. This corresponds to an effective duty cycle approaching unity ($f_{duty} \geq 0.8$–1), which is difficult to sustain under realistic early-Universe conditions due to strong radiative feedback and limited gas supply (Pacucci & et al., 2023, Volonteri, 2010). See Figure 2 for a direct comparison of growth curves for light and heavy seeds.

Black hole mergers can supplement mass growth, but gravitational wave energy losses typically remove 5–10% of the total system mass per merger (Abbott et al., 2016, Baker et al., 2006). While hierarchical mergers contribute to the final mass budget, they are insufficient to fully bridge the gap for stellar-mass seeds without prolonged super-Eddington phases — which remain observationally rare and theoretically constrained at high redshift due to feedback-driven outflows (Inayoshi et al., 2020, Wang & et al., 2021).

Adopting heavy initial seeds with masses $M_{seed} \geq 10^5$–$10^6 M_\odot$ (as proposed in this work) dramatically alleviates these constraints. Starting from $M_0 = 10^5 M_\odot$, reaching 10^9 requires only ∼9.21 e-folds ($\ln(10^4) \simeq$ 9.21), equivalent to roughly 4–5 e-folding times ($\simeq$ 180–225 Myr) at $\epsilon = 0.1$. This timescale is comfortably accommodated within the available ∼700 Myr (∼15 e-folding times), even when allowing for intermittent

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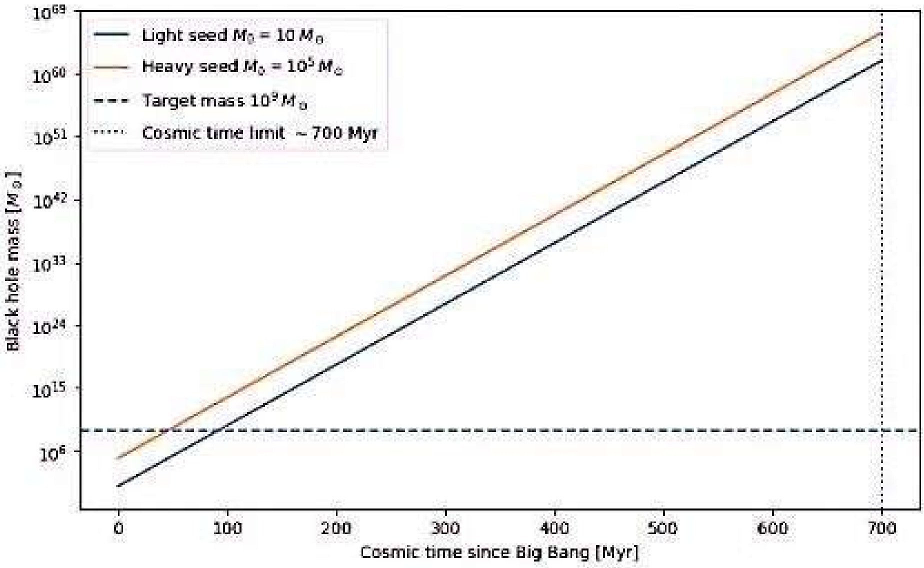

Figure 2. Eddington-limited growth curves for light seeds ($M_0 = 10 M_\odot$) and heavy seeds ($M_0 = 10^5 M_\odot$) as a function of time since the Big Bang. The horizontal dashed line indicates the available cosmic time at z $\simeq$ 7 ($\sim$ 700 Myr). Heavy seeds reach $10^9\ M_\odot$ well within the limit, while light seeds require prolonged and potentially difficult-to-sustain accretion histories.

accretion and feedback effects. This effectively relaxes the growth-time tension inherent to light-seed models.

Hawking evaporation has negligible impact on such objects. The evaporation timescale is given by:

$$t_{evap} \simeq 5120\pi G^2 M^3/(\hbar c^4), \tag{2}$$

which exceeds the current age of the Universe by many orders of magnitude. For example, a black hole with $M \simeq 10^5\ M_\odot$ has an evaporation timescale $t_{evap} \geq 10^{90}$ yr. Consequently, heavy early seeds remain stable and can serve as dynamically significant gravitational centers throughout cosmic history.

These growth constraints are particularly relevant for the compact, overmassive systems revealed by JWST, such as Little Red Dots (LRDs), where elevated M_{BH}/M_* ratios suggest rapid and efficient black hole assembly in biased environments (Maiolino & et al., 2024, Rusakov et al., 2026, Taylor & et al., 2025). Our model of massive early seeds naturally explains these observations by reducing the required accretion duty cycle and enabling early seeding in overdense regions.

4. The Massive Early Seed Hypothesis

We propose a phenomenological scenario in which heavy black hole seeds with initial masses $M_{seed} \geq 10^5$–$10^6 M_\odot$ form preferentially in extremely overdense environments at redshifts z $\geq$ 15. These environments correspond to the high-δ tails of the primordial density field — strongly biased regions where the local overdensity δ exceeds typical collapse thresholds, corresponding to rare high-δ fluctuations (3σ peaks; Bromm & Loeb, 2003, Inomata et al., 2021, Lodato & Natarajan, 2006).

Several physical pathways may plausibly contribute to the formation of such seeds. One possibility is enhanced direct collapse in atomic-cooling halos where molecular hydrogen cooling is suppressed by strong Lyman–Werner radiation fields produced by nearby star-forming regions (Inayoshi et al., 2020, Latif & et al., 2022). Another pathway involves dynamical processes in dense proto-clusters or mini-halos, where runaway stellar collisions or gas fragmentation can produce intermediate-mass black hole seeds that subsequently merge rapidly (Freitag & et al., 2006, Portegies Zwart & et al., 2023).

In this framework, the resulting heavy seeds act as dominant gravitational centers that accelerate gas infall and baryonic collapse on timescales comparable to or shorter than the effective baryonic collapse time within the surrounding dark matter halo. As a consequence, the growth of the black hole becomes less dependent on prolonged super-Eddington accretion phases, which are energetically demanding and observationally constrained in the high-redshift Universe (Pacucci & et al., 2023, Wang & et al., 2021). Importantly, the model remains agnostic regarding the precise microphysical mechanism responsible for

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seed formation and instead focuses on the macroscopic dynamical consequences. In this picture, massive seeds serve as preferred centers for early galaxy and quasar assembly.

Quantitatively, a seed with mass $M_{seed} \simeq 10^5 M_\odot$ embedded within a halo of virial mass $M_{halo} \simeq 10^8$–$10^9 M_\odot$ at redshifts z ≃ 15–20 can significantly shorten the gas-collapse timescale compared with models in which collapse is driven solely by the halo potential. In such systems, the enhanced gravitational potential near the seed can drive efficient early gas accretion. Order-of-magnitude estimates based on Bondi–Hoyle-like accretion in dense environments suggest that the initial growth phase can proceed at near-Eddington rates for approximately 100–200 Myr without requiring sustained super-Eddington accretion (see also Section 3).

This scenario is fully consistent with the standard ΔCDM cosmological framework and does not require modifications to fundamental physics or exotic mechanisms. Instead, it shifts the emphasis toward rare initial conditions and environmental bias as key drivers of early SMBH formation. It complements existing seed formation channels — including light Population III remnants, direct collapse black holes, and primordial black holes — by providing a pathway for rapid early supermassive black hole growth in the rarest overdense regions of the early Universe. In this way, the model naturally explains the elevated black hole–to–stellar mass ratios observed in compact high-redshift systems discovered by JWST, including the class of objects known as Little Red Dots (Maiolino & et al., 2024, Rusakov et al., 2026, Taylor & et al., 2025).

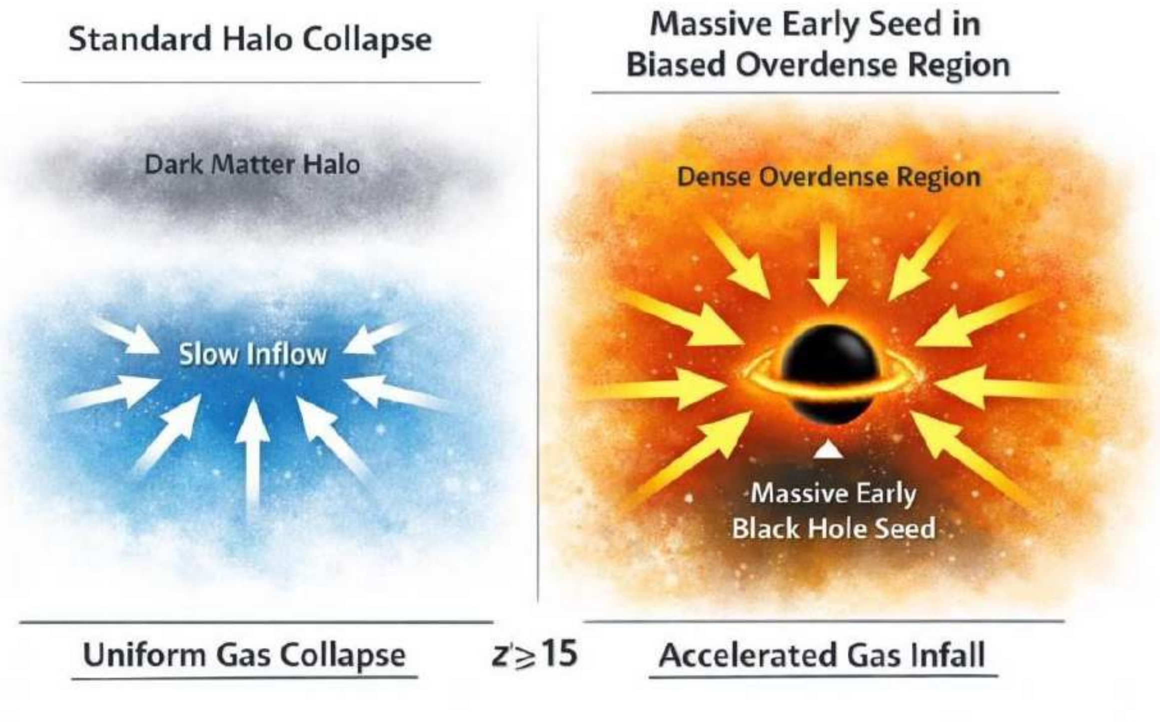

Figure 3. Schematic illustration of a massive early seed embedded in a biased overdense region at z ≥ 15, illustrating accelerated gas infall toward the seed compared with a uniform halo collapse scenario. The diagram highlights how extreme overdensity can facilitate rapid baryonic collapse and reduce the required accretion duty cycle for early supermassive black hole growth.

5. Model Constraints and Parameter Estimates

Any viable model for the formation of supermassive black holes must remain consistent with existing observational data and with the standard cosmological framework. In this section, we outline the principal physical constraints and characteristic parameter ranges of the proposed massive early seed model.

5.1. Seed Mass Scale

Observations of high-redshift quasars reveal black holes with masses $MBH \simeq 10^8$–$10^9 M_\odot$ at redshifts z > 7, corresponding to cosmic ages of less than 700 Myr (e.g. Bañados & et al., 2018, Mortlock et al., 2011). Explaining the existence of such massive objects within this limited time window places strong constraints on the initial mass of black hole seeds.

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In the proposed framework, the initial seed masses are assumed to lie well above the stellar-mass regime. A conservative lower bound for massive early seeds is $M_{seed} \geq 10^5$–$10^6 M_\odot$. Such masses significantly reduce the number of required e-folding times needed to reach the observed quasar masses under Eddington-limited accretion. Consequently, the model alleviates the need for prolonged super-Eddington growth phases, which are limited by radiative feedback and gas supply (Maiolino & et al., 2024, Pacucci & et al., 2023). Observations of compact JWST sources such as Little Red Dots at z $\simeq$ 8–10 suggest seed masses above $\sim 10^4 \, M_\odot$ to explain their rapid assembly (Rusakov et al., 2026, Taylor & et al., 2025). Upper bounds are expected to be comparable to the characteristic collapse mass scale in metal-free atomic-cooling halos ($\sim 10^6$ Bromm & Loeb, 2003).

5.2. Growth-Time Constraints

The mass growth of a black hole accreting at the Eddington limit (see Eq. 2). Starting from stellar-mass seeds ($M_0 \simeq 10 M_\odot$), reaching $10^9 \, M_\odot$ within 700 Myr requires nearly continuous accretion at or above the Eddington limit, corresponding to roughly 18–20 e-foldings with duty cycles approaching unity. Such a scenario is difficult to reconcile with observational indications of intermittent AGN activity in the early Universe (Wang & et al., 2021). In contrast, seeds with initial masses $M_0 \simeq 10^6 M_\odot$ require substantially fewer e-folding times ($\sim$ 7–9), making the observed early SMBHs achievable within standard accretion scenarios even with moderate duty cycles ($\sim$ 0.1–0.5) (Volonteri, 2010).

Higher radiative efficiencies ($\epsilon \geq 0.15$), expected for rapidly spinning black holes, would further increase the growth timescale under Eddington-limited accretion. Since the e-folding time scales as $\epsilon/(1-\epsilon)$, even moderate increases in spin can significantly slow mass growth. This further strengthens the argument that massive initial seeds may be required to reproduce the observed high-redshift SMBH population within the available cosmic time.

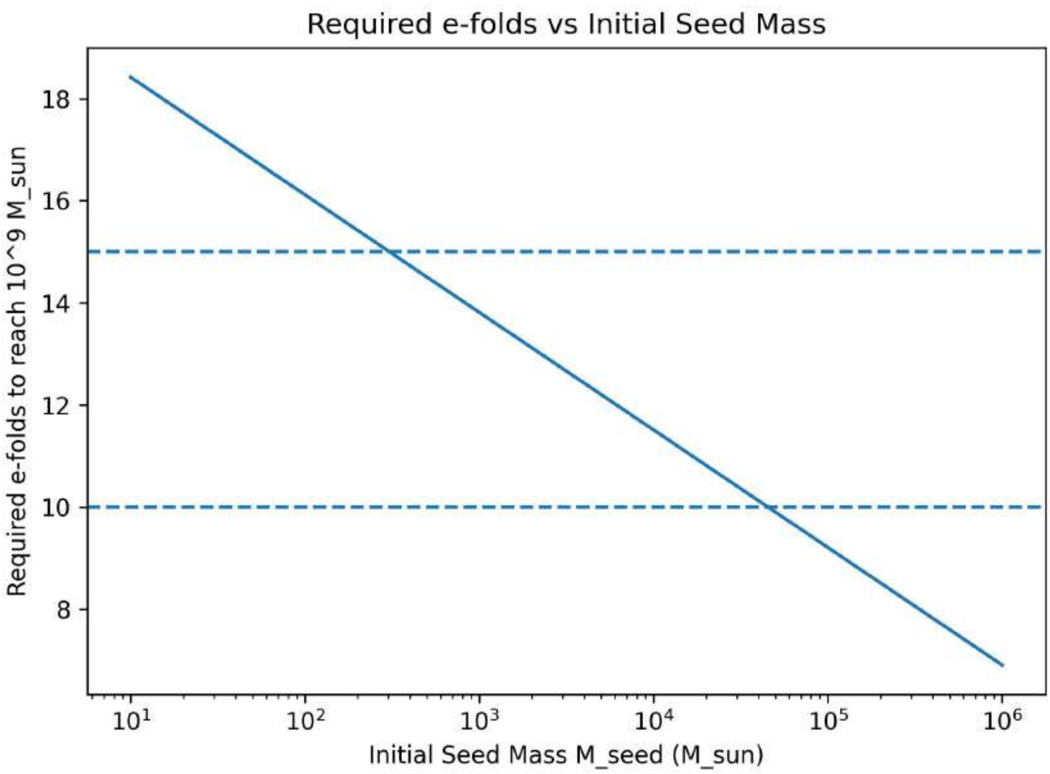

Figure 4. Required number of e-foldings to reach $10^9 \, M_\odot$ under Eddington-limited accretion as a function of the initial seed mass, $M_{\rm seed}$. The horizontal dashed line indicates the maximum of approximately 14–15 e-foldings available within $\sim$ 700 Myr. Seeds with $M_{\rm seed} \geq 10^5 \, M_\odot$ easily satisfy this constraint, whereas light seeds require an unphysically large number of e-foldings.

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5.3. Stability and Survival

Black holes with masses exceeding $\sim\ 10^5 M_\odot$ are effectively stable over cosmological timescales. The Hawking evaporation time, given by Eg. 2, greatly exceeds the age of the Universe ($\sim 10^{10}$ yr) for massive seeds and supermassive black holes (Hawking & Ellis, 1975). Consequently, once formed, massive early seeds can persist throughout cosmic history and remain dynamically relevant during the earliest stages of galaxy formation.

5.4. Number Density and Environmental Constraints

The observed comoving number density of luminous quasars at high redshift is relatively low $\sim 10^{-6}$–$10^{-7} Mpc^{-3}$ at z > 6 (e.g., Shen & et al., 2020, Willott et al., 2010) . Massive early seeds must therefore represent a rare population rather than a ubiquitous component of the early Universe.

The model therefore requires: (i) a low initial number density of massive seeds ($n_{seed} \leq 10^{-4}$–$10^{-5} Mpc^{-3}$) to avoid the overproduction of SMBHs, (ii) preferential formation in highly biased overdense regions (bias parameter b ≥3–5, corresponding to rare peaks in the primordial density field), and (iii) association with the most massive early dark matter halos ($M_{halo} \simeq 10^9$–10^{10} $M_\odot$ at z ≃ 15–20). These conditions remain compatible with constraints from large-scale structure formation, including halo mass functions derived from cosmological N-body simulations (e.g., Jenkins et al., 2001, Reed et al., 2007).

5.5. Consistency with Standard Cosmology

The massive early seed model does not modify the global expansion history of the Universe and remains fully compatible with the ΔCDM cosmological framework. The seeds act only as localized gravitational centers and do not contribute significantly to the total matter density of the Universe. Even at peak abundance, their contribution to Ω_m is negligible ($< 10^{-5}$).

Any observable deviations from standard cosmological predictions would therefore appear primarily at small scales and high redshifts, affecting the earliest stages of galaxy and quasar formation. Current constraints from the cosmic microwave background and large-scale structure surveys do not exclude this scenario, as it operates within the allowed parameter space for rare seed formation in the early Universe.

Table 2. Summary of parameter ranges for the massive early seed model

Parameter	**Range**	**Justification / Observational Constraint**
Seed mass (M_{seed})	10^5–$10^6 M_\odot$	Lower bound from growth constraints (Sec. 3); upper from Jeans mass in metal-free halos (Bromm & Loeb, 2003)
Formation redshift (z_{form})	z > 15	Early biased regions; compatible with reionization timelines (Planck Collaboration et al., 2020)
Number density (n_{seed})	$< 10^{-4}$–10^{-5} Mpc^{-3}	Matches quasar luminosity function at z > 6; avoids overproduction (Shen & et al., 2020, Willott et al., 2010)
Bias parameter (b)	3-5	Rare peaks ($\sigma > 3$); from Gaussian field statistics (Jenkins et al., 2001)
Halo mass at formation	10^9–10^{10} $M_\odot$	Most massive early halos; from N-body simulations (Reed et al., 2007)

6. Observational Implications and Testability of the Model

The proposed model of massive early seeds generates several robust and independently testable observational signatures that can be probed with current and upcoming astronomical facilities. These predictions differentiate the scenario from standard light-seed and direct-collapse models and provide clear pathways for empirical verification. A key strength of the massive early seed framework is that it produces multiple independent and quantitatively testable predictions across both electromagnetic and gravitational-wave observations.

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One of the most distinctive predictions of the model is the combination of a relatively high black hole occupation fraction in early galaxies together with elevated merger rates at very high redshift — a combination that is difficult to reproduce simultaneously in conventional seeding scenarios.

Enhanced fraction of compact galaxies hosting central black holes. The model predicts a significantly higher incidence ($\simeq$30–50%) of central black holes in compact high-redshift galaxies compared with uniform light-seed models, which typically predict occupation fractions below $\sim$10%. This prediction can be tested using deep-field observations from the James Webb Space Telescope, including surveys such as GLIMPSE, PRIMER, and COSMOS-Web, which are already identifying large samples of compact galaxies at z > 7 (Maiolino & et al., 2024, Taylor & et al., 2025). Detection of black hole signatures — such as broad emission lines or X-ray counterparts — in a substantial fraction of these systems would strongly support the proposed scenario.

Reduced duration and duty cycle of super-Eddington accretion phases. Because massive seeds require only approximately 4–5 e-foldings of Eddington growth (Sec. 3), the model predicts shorter or more intermittent super-Eddington accretion episodes with duty cycles of roughly 0.1–0.5. Observationally, this should manifest as lower average Eddington ratios or weaker large-scale outflow signatures in high-redshift active galactic nuclei compared with predictions from light-seed growth models. Spectroscopic observations of compact sources such as Little Red Dots using JWST NIRSpec and MIRI instruments can constrain these accretion properties (Pacucci & et al., 2023, Rusakov et al., 2026, Wang & et al., 2021).

Relic population of intermediate-mass black holes. The model naturally predicts a population of relic intermediate-mass black holes (IMBHs) with masses of approximately 10^3–10^5 $M_\odot$that fail to grow efficiently due to limited gas supply or strong feedback. Such objects could appear as off-nuclear compact sources in dwarf galaxies or ultra-compact stellar systems. The detection of these relic IMBHs through dynamical mass measurements with JWST or future extremely large telescopes would support the model, while stringent upper limits on their abundance would constrain the seed mass function.

Elevated early merger rates and gravitational-wave background. Rapid hierarchical assembly in the early Universe implies enhanced black hole merger rates at redshifts z > 10. This should generate a distinct stochastic gravitational-wave background in the millihertz frequency band accessible to the future Laser Interferometer Space Antenna mission. Characteristic amplitudes of $\Omega_{GW} \simeq 10^{-11}$–$10^{-10}$ are expected for merger-driven scenarios involving massive early seeds (Klein & et al., 2024, LISA Consortium, 2025). Detection of a stronger-than-expected high-redshift signal would provide strong support for the model.

Overmassive black hole–to–stellar mass ratios. The massive early seed framework naturally explains the elevated black hole–to–stellar mass ratios observed in compact high-redshift systems. Ratios of $M_{BH}/M_* \geq 10^{-3}$–10^{-2} inferred in Little Red Dot galaxies can arise without invoking extreme dust obscuration or finely tuned feedback processes (Maiolino & et al., 2024, Taylor & et al., 2025). Future JWST imaging and spectroscopic surveys of larger LRD samples can test whether these ratios correlate with galaxy compactness and local overdensity — a key prediction of the model.

Falsifiability of the scenario. The massive early seed model is directly falsifiable through several observational tests. In particular, the model would be strongly disfavored if: • JWST surveys detect central black holes in fewer than $\sim$30% of compact high-redshift galaxies. • The LISA mission measures a gravitational-wave background fully consistent with predictions from light-seed scenarios without evidence for enhanced early merger activity. • Observational searches fail to identify relic populations of intermediate-mass black holes in dwarf galaxies or compact stellar systems.

Such null results would significantly constrain or potentially rule out the massive early seed formation scenario.

7. Discussion and Conclusions

The massive early seed model provides a physically motivated, self-consistent, and observationally testable framework that complements existing scenarios of supermassive black hole (SMBH) formation, such as light Population III remnants, direct collapse, and prolonged super-Eddington accretion. By positing heavy seeds ($M_{seed} \geq 10^5$–10^6 $M_\odot$) forming preferentially in strongly biased, overdense environments at z $\geq$ 15, the model naturally alleviates the severe timing tension revealed by JWST observations of overmassive black holes in compact systems at z > 7 (Maiolino & et al., 2024, Rusakov et al., 2026, Taylor & et al., 2025). It requires no invocation of new fundamental physics, relying solely on plausible variations in the initial conditions of the early Universe — specifically, the rare high-σ peaks of the density field where

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Table 3. Summary of quantitative observational tests distinguishing the massive early seed scenario from standard seeding models

Prediction	**Observable Signature**	**Instrument**	**Expected Signal**	**Falsification Condition**
Enhanced BH fraction in compact galaxies	Central BH signatures in LRDs	JWST (GLIMPSE/ (GLIMPSE/PRIMER)	>30–50%	$< 10\%$
Reduced super-Eddington phases	Lower Eddington ratios, weaker outflows	JWST NIRSpec / MIRI Duty cycle	Persistent high duty cycles	occupation <10% fraction
Relic IMBH population	Off-nuclear compact sources	JWST / ELT	10^3–10^5 $M_\odot$ BHs	No detectable population
Elevated merger rates	Stochastic GW background	LISA	$\Omega_{GW} \sim 10^{-11}$–$10^{-10}$	Standard light-seed amplitude
Over-massive ratios	$M_{BH}/M_* > 10^{-3}$–10^{-2}	JWST NIRCam	Correlation with compactness	No correlation

atomic-cooling halos and rapid collapse can occur under intense Lyman-Werner backgrounds or proto-cluster dynamics (Inayoshi et al., 2020, Latif & et al., 2022).

Compared to light-seed models, the scenario dramatically reduces the required number of e-folding growth phases (Section 3), lowering the growth burden from ∼18–20 e-folds to ≤10 for seed masses ≥ $10^5\ M_\odot$. This allows observed SMBH masses to be reached with realistic duty cycles and without extreme fine-tuning of feedback or accretion physics. Relative to standard direct-collapse models, it broadens the viable parameter space by relaxing the need for perfectly tuned pristine environments, instead emphasizing preferential formation in the most overdense regions. The model remains fully consistent with ΔCDM cosmology (Section 5.5 and does not contribute significantly to the matter budget or large-scale structure.

A key strength of the massive early seed scenario lies in its predictive power and falsifiability (Section 6). Multiple independent observational signatures — enhanced BH fractions in compact galaxies, reduced super-Eddington phases, relic intermediate-mass black holes, elevated merger rates, and overmassive M_{BH}/M_* ratios — can be probed with existing JWST data and will be decisively tested by future ultra-deep surveys (GLIMPSE, PRIMER, COSMOS-Web), next-generation radio interferometry (ngEHT), and the LISA gravitational-wave mission (launch ∼2035). These facilities will provide decisive constraints and potentially resolve one of the most pressing puzzles of the high-redshift Universe: the rapid emergence of supermassive black holes.

The main uncertainty of the model lies in the poorly constrained abundance of high-σ peaks at $z > 15$, which future surveys and cosmological simulations will clarify. If confirmed, the scenario would highlight the critical role of rare, biased environments in shaping the first quasars and massive galaxies, implying that the earliest stages of galaxy formation were governed primarily by rare initial conditions rather than by average cosmological evolution.

In conclusion, the massive early seed model offers a simple yet powerful framework that reconciles JWST's surprising discoveries with theoretical expectations while remaining firmly rooted in established physics. Future observations will ultimately determine whether this scenario or an alternative mechanism best describes the dawn of supermassive black holes in the early Universe. Regardless of the outcome, the massive early seed model highlights the potential role of rare environmental conditions in driving the rapid emergence of the first supermassive black holes, offering a new perspective on early galaxy formation. Further theoretical development and high-resolution cosmological simulations will be essential to quantify the expected abundance of such massive seeds in high-σ regions.

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