

Identifying Direct Collapse Black Hole Seed Candidates in the Cosmic Dawn

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Abstract

The discovery of billion-solar-mass quasars at $z \approx 6$ has raised a timing problem for supermassive black hole growth, motivating the Direct Collapse Black Hole (DCBH) scenario as a possible solution. We performed high-resolution Enzo zoom-in simulations targeting the six most massive halos in a 1 (Mpc/h)^3 comoving volume by $z = 10$. All six halos exceed the atomic cooling threshold ($T_{\text{vir}} \gtrsim 10^4 \text{ K}$). Of these, the second and third largest halos by mass within the simulation volume (Halo 2 and Halo 3) additionally satisfy criteria for Lyman-Werner proximity and rapid growth dynamics, exhibiting runaway accretion rates ($\dot{M} \gtrsim 10^6 M_{\odot}/\text{Myr}$) and physical separations below the summed virial radii of neighbouring massive halos. Across the sample, smooth accretion accounts for approximately 80% of total mass growth, underscoring its role over mergers in driving rapid assembly. These results identify Halo 2 and Halo 3 as DCBH seed candidates that satisfy our criteria and offer preliminary context relevant to early SMBH seed formation scenarios, such as those proposed for JWST's ‘Little Red Dots’.

Introduction

Dark matter halos, predicted by the Λ CDM (Lambda Cold Dark Matter) model, form the gravitational scaffolding within which the first galaxies and black holes assembled (Blumenthal *et al.*, 1984). Under the Λ CDM framework, the evolution of the Universe is driven by the hierarchical growth of dark matter halos, a process where smaller structures merge to form increasingly larger ones (Bromm & Yoshida, 2011). This dark matter halo growth is generally governed by two primary mechanisms: the merger of separate halos and the smooth accretion of diffuse background dark matter.

In the mini-halo regime ($10^5 - 10^8 M_{\odot}$) characteristic of the Cosmic Dawn, however, shallow gravitational potentials make it difficult for halos to reach the virial temperatures required for rapid black hole seed growth (Correa Magnus *et al.*, 2023). This difficulty is central to the supermassive black hole (SMBH) timing problem, first highlighted by the discovery of billion-solar-mass quasars at $z \approx 6$ by the Sloan Digital Sky Survey (SDSS) in the early 2000s (Fan *et al.*, 2001). This abundance of abnormally massive black holes at high redshifts challenged the standard model of stellar-remnant seeds, as there was insufficient time for them to reach such masses via Eddington-limited accretion (Pries & Wise, 2026). To bridge this gap, the Direct Collapse Black Hole (DCBH) scenario was proposed, wherein massive seeds form directly from the gas in atomic cooling halos (Bromm & Loeb, 2003; Begelman *et al.*, 2008). To become an atomic halo, the halo must cross this critical threshold quickly enough to outpace star formation in the mini-halo stage. This raises a critical question: what determines whether a halo can assemble rapidly enough, and remain sufficiently disturbed, to sustain the conditions for direct collapse?

In this rapid assembly process, the interplay between stochastic merger and smooth accretion of dark matter halos is fundamental, as it governs the assembly rate and thermodynamic state of the host halo. Specifically, smooth accretion sustains the high mass inflow rates required to rapidly push the halo across the atomic cooling threshold, while major mergers provide the dynamical heating necessary to suppress molecular hydrogen cooling and prevent fragmentation (Trinca *et al.*, 2026). Therefore, the relative balance between these two modes dictates not only when a halo crosses the critical virial temperature threshold, but also whether the thermodynamic conditions for direct collapse can be maintained long enough for a massive seed to form. Moreover, recent JWST observations

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of massive black hole candidates at $z > 10$, such as ‘Little Red Dots’ (Bogdán *et al.*, 2023; Rusakov *et al.*, 2026), underscore the urgency of understanding how such rapid host halo assembly can occur.

In this project, we address this question through a high-resolution zoom-in simulation targeting the most massive halos in a $1 \text{ (Mpc}/h)^3$ cosmological comoving volume, testing whether their assembly histories satisfy the physical criteria required for DCBH formation. Identifying such host halos is a necessary step towards resolving the SMBH timing problem. If massive black hole seeds cannot assemble early and rapidly enough, the billion-solar-mass quasars observed at $z \approx 6$, and the extreme black hole masses now inferred for JWST’s ‘Little Red Dots’ at $z > 10$, remain difficult to explain within a single, self-consistent formation channel.

Background

Hierarchical Dark Matter Evolution

Halo mergers represent the discrete capture of smaller, virialised systems by a host halo. These events are quantitatively categorised by their mass ratio, defined as $\xi = M_{\text{satellite}}/M_{\text{host}}$. Major mergers ($\xi > 0.2$) are violent dynamical events that can significantly alter the halo’s internal structure and heat the interstellar medium through dynamical friction and shocks. In contrast, minor mergers ($\xi < 0.2$) contribute to a more incremental growth.

Parallel to these discrete events, smooth accretion involves the continuous integration of diffuse dark matter, matter that has not yet collapsed into a resolved halo, from the cosmic web. While mergers are stochastic and environment-dependent, smooth accretion provides a baseline growth rate which sustains halos between merger events. Distinguishing between these two modes is essential for understanding the thermal history of gas within the halo, particularly in the mini-halo regime where the gravitational potential is shallow.

Formation of Direct Collapse Black Holes

The thermodynamic evolution of primordial gas within dark matter halos is governed by the competition between gravitational heating and radiative cooling. In the metal-free environment of the early Universe, this cooling is exclusively mediated by atomic and molecular hydrogen (H_2). Within the mini-halo regime ($10^5 - 10^8 M_\odot$), gas typically emits energy through the rotational-vibrational transitions of H_2 . This cooling channel allows the gas to contract and fragment, eventually leading to the formation of individual Population III stars. However, the cooling rate of H_2 is insufficient to support the rapid, massive collapse required for galaxy assembly or SMBH seeds.

Efficient galaxy formation and the emergence of DCBHs necessitate a transition to the atomic hydrogen cooling regime, which only becomes active when the halo’s virial temperature exceeds the 10^4 K threshold. Crossing this thermal boundary provides a much more efficient cooling rate, enabling halos to support sustained star formation and grow into the first galaxies. Consequently, precisely resolving the growth history from the mini-halo stage is critical, as early-stage errors in merger or accretion rates can lead to cumulative errors that propagate throughout the entire timeline of subsequent galaxy evolution.

The DCBH scenario has gained significant attention as a primary solution to the timing problem of early SMBHs, with ongoing observational searches attempting to identify these seeds in the high-redshift Universe (Nabizadeh *et al.*, 2024). Unlike the standard stellar-remnant model, which is limited by the Eddington rate, the DCBH model bypasses the stellar phase entirely: a massive, pristine gas cloud collapses directly into a heavy black hole seed ($10^4 - 10^6 M_\odot$; Bonoli *et al.*, 2014).

For such a monolithic collapse to occur, fragmentation must be suppressed. This is achieved if the H_2 cooling channel is deactivated, either through external Lyman-Werner (LW) radiation or intense dynamical heating from rapid mergers (Correa Magnus *et al.*, 2023). In these environments, the gas remains hot ($\approx 8000 \text{ K}$) and high-pressure, preventing it from breaking into small stars, instead allowing the entire reservoir to condense under its own gravity. Therefore, quantifying this balance between merger and accretion-driven growth is the central methodological task of this study.

Methods

We first analysed the Pop2Prime simulation volume ($0.5 \text{ (Mpc}/h)^3$ comoving; Smith, Wise, *et al.*, 2015), but its limited size yielded too few halos reaching the atomic cooling threshold ($T_{\text{vir}} \gtrsim 10^4 \text{ K}$) by $z = 10$ to identify viable DCBH candidates. Therefore, we performed a suite of high-resolution Enzo zoom-in simulations targeting a larger $1 \text{ (Mpc}/h)^3$ comoving volume, sufficient to yield a statistically meaningful sample of candidate host halos. Throughout this paper, ‘Halo 1’ through ‘Halo 6’ refer to labels assigned to the six most massive structures

identified within our simulated volume (see ‘[Simulation Run](#)’), ranked by mass. These are simulated objects, and any description of their properties or environment (e.g. see ‘[Quantifying Halo Growth through Mergers vs Diffuse Accretion](#)’) refers to features of the simulation.

Simulation Setup

This project uses the Enzo adaptive mesh refinement (AMR) code (Bryan *et al.*, 2014) run in a dark matter-only (DM-only) configuration to isolate the gravitational assembly of halos from baryonic physics. Accordingly, to expand the halo sample, we initialised a comoving simulation box with a side length of 1 Mpc/h, where h is the dimensionless Hubble parameter. The cosmological parameters from WMAP 7 (Wilkinson Microwave Anisotropy Probe 7) were used with $\Omega_m = 0.266$, $\Omega_\Lambda = 0.732$, and $H_0 = 71.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Komatsu *et al.*, 2011). To approximate a nearly infinite cosmic volume compared to the simulation and minimise edge effects within this finite domain, periodic boundary conditions (PBCs) were applied to all faces of the cubic volume. To seed cosmic structures, we employed MUSIC (Multi-scale Initial Conditions for Cosmological Simulations; Hahn & Abel, 2011) to generate a primordial density field based on the Λ CDM power spectrum.

Simulation Run

To capture the intricate process of structure formation, the simulation was initiated at a redshift of $z = 180$ and evolved until $z = 10$. In cosmological simulations, high spatial resolution is essential. To achieve this, we implemented an iterative zoom-in technique. Specifically, we first identified the six most massive halos at $z = 10$ from the base-level simulation. To resolve these targets, we performed a simulation with a particle refinement level of 3. While the root grid consists of 128^3 particles, the zoomed-in region is equivalent to a 1024^3 uniform grid. This approach effectively increases the mass resolution by a factor of 512 (8^3) compared to a uniform 128^3 grid, resulting in a dark matter particle mass of $M_{dm} \approx 96.9 M_\odot$, a maximum AMR refinement level of 8, and a comoving softening length of $\sim 30 \text{ pc}/h$. This high-resolution setup ensures that the assembly histories and internal dynamics of even the smallest mini-halos are statistically and gravitationally resolved.

Given $\Omega_m = 0.266$ and a comoving box size of $L_{box} = 1.0 \text{ Mpc}/h$, where $h \approx 0.71$ is the dimensionless Hubble parameter, the mass resolution is calculated as:

$$m_{dm} = \frac{\Omega_m \rho_{crit} (L_{box}/h)^3}{(N_{root} \cdot 2^{L_{refine}})^3} \quad (1)$$

where $N_{root} = 128$ is the number of grid cells (and dark matter particles) along one side of the root grid, $L_{refine} = 3$ is the particle refinement level applied within the zoom-in region, and ρ_{crit} is the critical density of the Universe, defined as:

$$\rho_{crit} = \frac{3H_0^2}{8\pi G} \approx 1.4 \times 10^{11} M_\odot \text{ Mpc}^{-3} \quad (2)$$

where $H_0 = 71.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (the Hubble constant), and G is the gravitational constant. Note that the factor of $(L_{box}/h)^3$ converts the comoving box length into physical units consistent with ρ_{crit} , which is evaluated using the physical value of H_0 .

Throughout this simulation, a total of 98 snapshots for each run was recorded, providing a movie of how dark matter collapses over time and constructs large-scale structure.

Simulation Post-processing

The post-processing followed an iterative workflow. First, a halo finder was applied to the initial low-resolution runs to identify target systems at $z = 10$. Their coordinates and virial properties were then used as inputs for the MUSIC generator to create refined initial conditions for the zoom-in simulations. Once these high-resolution runs were completed, the halo-finding process was repeated to construct the final merger trees.

Halo Finding

To identify gravitationally bound structures, we utilised the Rockstar halo finder (Behroozi *et al.*, 2013b). This employs a 6D phase-space analysis, which incorporates both particle positions and velocities, facilitating more robust tracking of halos and sub-halos in dense environments compared to traditional Friends-of-Friends methods.

Merger Tree Construction

Following the identification of halos, we constructed the merger trees using the `Consistent-Trees` algorithm (Behroozi *et al.*, 2013a) after achieving the required resolution in the L3 runs. This step ensures physical consistency across snapshots by modelling halo trajectories and identifying cases where halos might be temporarily lost due to deblending or overdensity issues. By simulating the expected orbits of halos, `Consistent-Trees` produced cleaned lineages, which we then analysed using `ytree` (Smith & Lang, 2019) to track the mass assembly history of the most massive halos and their progenitors.

Quantifying Halo Growth through Mergers vs Diffuse Accretion

Using the merger trees constructed from the simulation data, it is possible to identify the progenitor masses for a given descendant halo of mass M_0 at any preceding redshift z . Following the methodology from Fakhouri & Ma (2010), the direct ancestors' halos are ranked by mass such that M_1 denotes the primary progenitor, followed by smaller satellite halos M_i ($i \geq 2$) in descending order with $i = 1, 2, \dots, N_p$. The number of direct ancestors of a halo, N_p , can vary from 1 to high numbers, with 1 corresponding to no merger having happened and 2 being a binary merger. The mass ratio of merging between progenitors is denoted by the variable ξ , defined by $\xi = M_{i>1}/M_1$. This systematic classification enables a clear distinction between halo mergers and smooth accretion.

A common feature in these trees is that the sum of progenitor masses does not exactly match the descendant mass M_0 . This discrepancy leads to the definition of a residual mass term, ΔM :

$$\Delta M = M_0 - \sum_{i=1}^{N_p} M_i \quad (3)$$

While the summation accounts for mass gained through resolved merger events, ΔM captures the mass change occurring outside of these discrete events. Negative values can arise from fly-by events or deblending failures during halo overlap, as well as physical tidal stripping. Conversely, a positive ΔM represents mass gain via the accretion of unresolved progenitors (halos below the particle mass limit) or the smooth accretion of diffuse dark matter from the surrounding environment. In this study, negative values of ΔM are retained in the analysis rather than filtered out. Since the precise origin of each negative event, whether numerical or physical, cannot be unambiguously determined, excluding them would introduce a subjective and potentially systematic bias into the measured accretion rates.

The mass growth of dark matter halos can be further quantified with the mass change rate for each halo with a mass of M_0 at some redshift. Here, Δt denotes the time step between the redshift of M_0 and that of its progenitor, as set by the cadence of stored simulation snapshots:

$$\begin{aligned} \dot{M}_{\text{mer}} &\equiv \frac{\sum_{i \geq 2} M_i}{\Delta t}, & \dot{M}_{\text{acc}} &\equiv \frac{\Delta M}{\Delta t}, \\ \dot{M}_{\text{tot}} &= \dot{M}_{\text{mer}} + \dot{M}_{\text{acc}} = \frac{M_0 - M_1}{\Delta t} \end{aligned} \quad (4)$$

where $\dot{M}_{\text{mer}}$ denotes the mass change rate due to mergers and $\dot{M}_{\text{acc}}$ is mass change rate from accretion or unresolved mergers. The sum of these rates yields the total growth rate, $\dot{M}_{\text{tot}}$, since M_1 is the main (the most massive) progenitor of halo M_0 . Throughout this paper, $\dot{M}$ (without a subscript) refers to $\dot{M}_{\text{tot}}$ unless otherwise stated, and all growth rates are reported in units of $M_\odot \text{ Myr}^{-1}$. Since Δt is set by the fixed snapshot cadence (98 snapshots between $z = 180$ and $z = 10$) rather than by the dynamical state of individual halos, it does not shrink arbitrarily, and so does not introduce spurious divergences in the reported growth rates.

To analyse the complex merger histories, we employed the `ytree` package, a Python-based tool specifically designed for the handling and analysis of merger tree data (Smith & Lang, 2019). This package provides the necessary functionality to perform the calculations described in ‘Quantifying Halo Growth through Mergers vs Diffuse Accretion’. In this study, we utilised `ytree`’s support for parallel computing to efficiently calculate the mass growth rates defined in Equation 4. These calculated rates are saved as custom analysis fields within the tree data, enabling a systematic statistical analysis of the assembly history across the entire halo population.

Criteria for Direct Collapse Black Hole Seeds

With the merger trees and halo growth rates constructed, the final step in the methodology is to define the physical and dynamical criteria used to identify DCBH candidates within the DM-only framework. To identify potential

DCBH host halos, several physical requirements must be satisfied. Ideally, a candidate should possess pristine, metal-free gas, and be exposed to a strong Lyman-Werner (LW) radiation field. However, since this simulation is DM-only, these baryonic conditions are replaced by proxy criteria based on the dynamical properties of the halos. As detailed in ‘[Formation of Direct Collapse Black Holes](#)’, a DCBH typically forms within an atomic cooling halo with $T_{vir} \geq 10^4 K$. Additionally, a rapid mass assembly history, driven by both mergers and accretion, is essential to ensure a sustained collapse. The specific selection criteria used in this work are:

- Virial Temperature: $T_{vir} \geq 10^4 K$, calculated at the simulation redshift.
- LW Radiation Environment: Physical separation to the nearest massive neighbour less than the sum of their virial radii, indicating overlapping potential wells. Nearby massive halos are likely already forming stars and thus emitting LW radiation (see ‘[Formation of Direct Collapse Black Holes](#)’). A target halo residing within the overlapping potential well of such a neighbour is therefore expected to be immersed in a LW radiation field capable of suppressing H_2 cooling, even though this cannot be directly verified in a DM-only simulation.
- Growth Dynamics: At least one major merger ($\xi \geq 0.2$) or a peak accretion rate $\dot{M} \gtrsim 10^6 M_\odot/\text{Myr}$.

Results & Discussion

DCBH Seeds Candidates

As established in ‘[Formation of Direct Collapse Black Holes](#)’, the formation of a DCBH is intrinsically linked to the dynamical assembly history of its host dark matter halo. By applying the selection criteria defined in ‘[Criteria for Direct Collapse Black Hole Seeds](#)’, several potential DCBH seeds within the simulated volume were identified and analysed, focusing on how their specific growth modes support the necessary physical conditions for collapse. The six halos were originally identified as the most massive systems in the lower-resolution base-level simulation. The physical values reported in Table 1 are taken from the corresponding high-resolution L3 zoom-in run for each halo, ranked in descending order by mass.

The virial temperatures (T_{vir}) presented in Table 1 were calculated using the fundamental relation:

$$T_{vir} = \mu m_p G M_{vir} / 3 k_B R_{vir}$$

assuming a neutral primordial gas composition ($\mu \approx 1.22$, appropriate for gas that has not yet been heated by an ionising background). All of the sample halos successfully surpass the $10^4 K$ threshold, confirming their status as atomic cooling halos.

Table 1: Properties of the Most Massive Halos in the Final Run at $z = 10$.

Halo ID	Mass ($M_\odot$)	Virial Radius (kpc)	Virial Temp. (K)
Halo 1	2.79×10^8	1.96	30,281
Halo 2	2.80×10^8	1.97	30,236
Halo 3	1.00×10^8	1.37	15,527
Halo 4	9.33×10^7	1.36	14,594
Halo 5	8.73×10^7	1.33	13,963
Halo 6	6.23×10^7	1.19	11,137

From a DCBH formation perspective, these assembly modes, characterised by both major mergers and episodes of runaway accretion, are critical. While runaway accretion rapidly augments the halo mass toward the atomic cooling threshold, the accompanying major mergers provide the dynamical heating necessary to suppress fragmentation. Such stochastic growth suggests that the instantaneous gas temperature may deviate significantly from the idealised virial values in Table 1, as the rapid mass influx sustains the elevated temperatures set by prior merger-driven heating, further stabilising the gas against fragmentation and temporarily suppressing star formation.

The underlying assembly dynamics of the target halos are more clearly revealed by examining their instantaneous mass growth rates ($\dot{M}$), as depicted in Figure 1. It reveals that four of the sample halos underwent at least one major merger, while Halo 3 and Halo 6 are dominated by episodes of runaway accretion. Halo 2 exhibits a particularly intense surge at $t \approx 400 \text{ Myr}$ and halo 3 at $t \approx 430 \text{ Myr}$, both exceeding $\dot{M} \gtrsim 10^6 M_\odot/\text{Myr}$. This extreme growth rate, which momentarily surpasses those of its more massive counterparts, signifies a runaway growth phase likely triggered by its local environment.

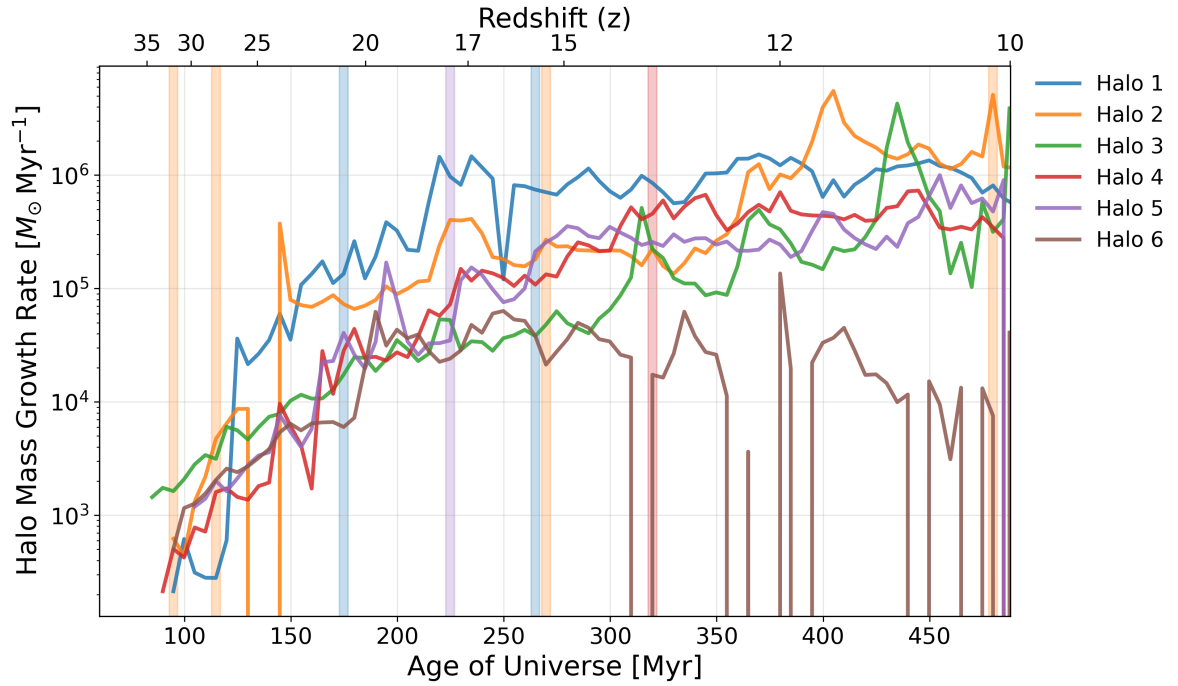


Figure 1: Instantaneous mass growth rate ($\dot{M}$) as a function of cosmic time (bottom axis) and redshift (top axis) for the six most massive halos identified in the simulation volume. The stochastic nature of halo assembly is evident in the frequent high-amplitude spikes, indicating a highly dynamic, non-equilibrium growth phase. Vertical shaded bars, coloured to match each halo's growth curve, mark major merger events ($\xi \geq 0.2$) along its main branch. Halo 3 and Halo 6 exhibit no resolved major merger, and instead grow significantly through smooth accretion. Major mergers do not always coincide with the largest growth spikes, indicating that runaway smooth accretion, rather than merging alone, is often the dominant driver of rapid mass assembly.

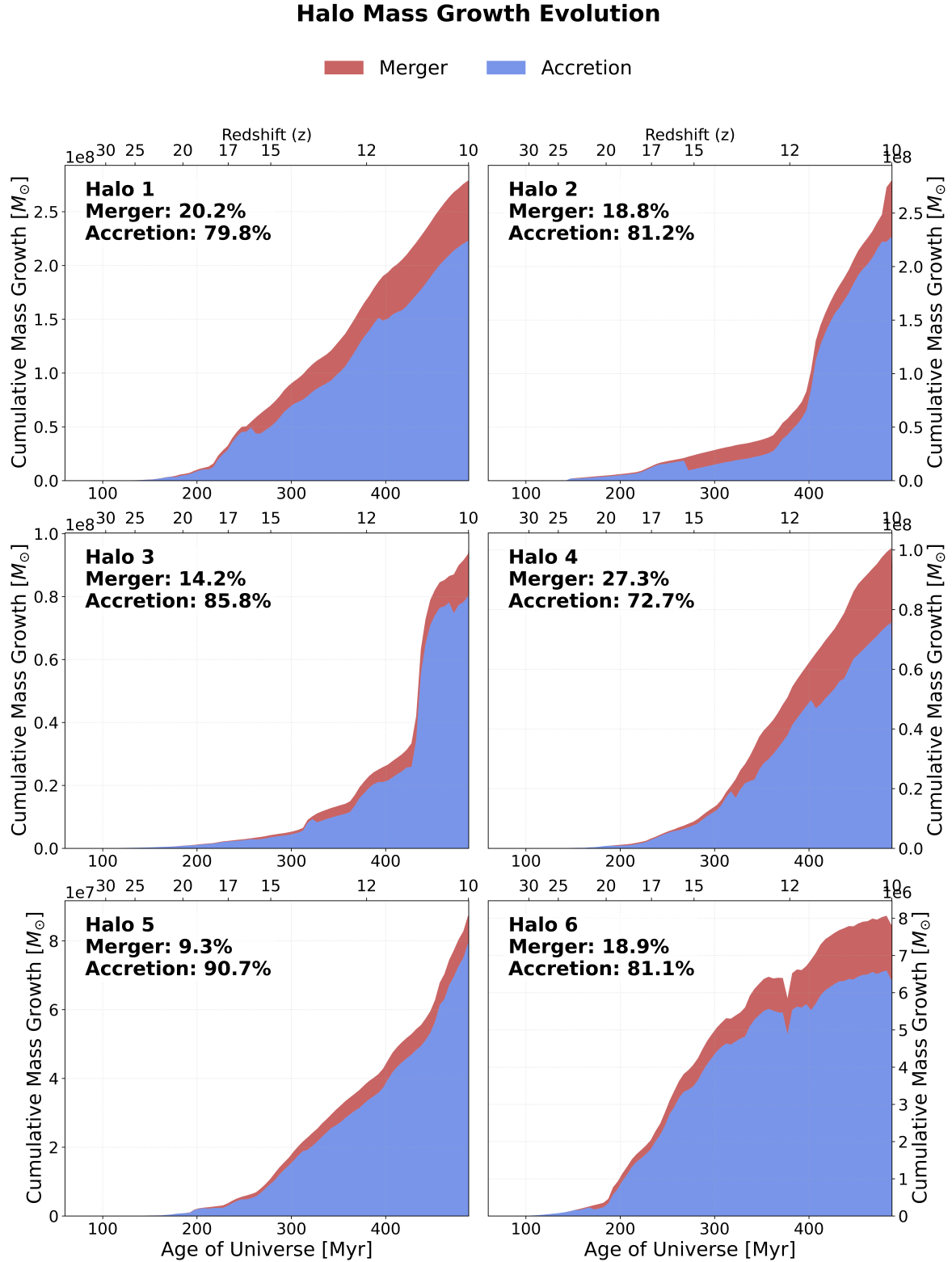


Figure 2: Cumulative mass growth history for the six most massive halos from $z = 35$ to $z = 10$. The total mass is decomposed into contributions from smooth accretion (blue) and stochastic mergers (red). Across all halos, smooth accretion dominates, contributing approximately 80% of the total mass growth on average. In contrast, Halo 5 shows the most quiescent evolutionary path with smooth accretion accounting for 90.7% of its total growth.

As further depicted in Figure 2, the significant mass gains for Halo 2 and Halo 3 (at approximately 400 Myr and 430 Myr, respectively) are primarily driven by rapid runaway accretion, which fosters a favourable environment for DCBH seeds. The results also illustrate that stochastic mergers begin to contribute meaningfully to the cumulative mass growth after 250 Myr, with their relative importance increasing as the halos evolve toward $z = 10$.

While studies such as Fakhouri & Ma (2010) report that mergers can contribute up to 40% of the mass growth in massive halos ($10^{12} M_{\odot}$), our results for the ($> 10^7 M_{\odot}$) regime show a dominant contribution from smooth accretion ($\approx 80\%$). This dominant accretion mode is enhanced by the high background matter density at $z \approx 30 - 10$, nearly 10,000 times greater than today, and is consistent with Genel *et al.* (2010), who found that smooth accretion dominance increases for lower-mass halos, a trend that is redshift-independent, since it stems from their shallower gravitational potentials. This accretion-dominated growth aligns with the theoretical expectation that early halo assembly is driven by rapid, smooth mass transition before entering the merger-rich environment of later epochs. While DCBH formation is often associated with $z > 15$, identifying candidates at $z \approx 10$ remains relevant for explaining the massive quasars observed at $z < 6$, since these halos provide deeper potential wells and richer gas reservoirs than their lower-mass, earlier counterparts.

Beyond rapid mass assembly, the intensified LW background at this later epoch provides a more favourable environment for suppressing H_2 cooling, making $z = 10$ a critical window for the emergence of massive black hole seeds that can rapidly grow into the SMBHs observed in the post-reionisation era. These findings complement recent work by Pries & Wise (2026), who similarly identified rapidly-growing halos in close proximity to a strong Lyman-Werner source as the most conducive environment for DCBH formation, despite operating at different redshifts and volumes.

To visually correlate the growth dynamics with the cosmic web, Figure 3a presents the projected dark matter density of the entire simulated volume. All sample halos are situated at the densest intersections of filaments, providing a consistent supply of mass.

A higher-resolution view of the region containing Halo 3 and Halo 4 (Figure 3b) reveals a highly complex local environment. Unlike the relatively isolated and relaxed morphology of Halo 1, Halo 3 is surrounded by multiple smaller subhalos and is in close proximity to Halo 4. This clustered configuration directly supports the high-amplitude growth spikes observed in Figure 1, confirming that these halos are currently undergoing active assembly phases. Such dynamical proximity is essential for DCBH formation, as it serves as a proxy for both a sustained Lyman-Werner radiation source and the potential for future merger-driven heating, both of which are expected to suppress premature fragmentation.

In addition, the two halos identified in this Figure 3b are separated by only 1.89 kpc at $z = 10$. Relative velocity analysis reveals a negative radial velocity of $v_{rel} \approx -33.5$ km/s, where

$$v_{rel} = \frac{\vec{v} \cdot \vec{r}}{|\vec{r}|} \quad (5)$$

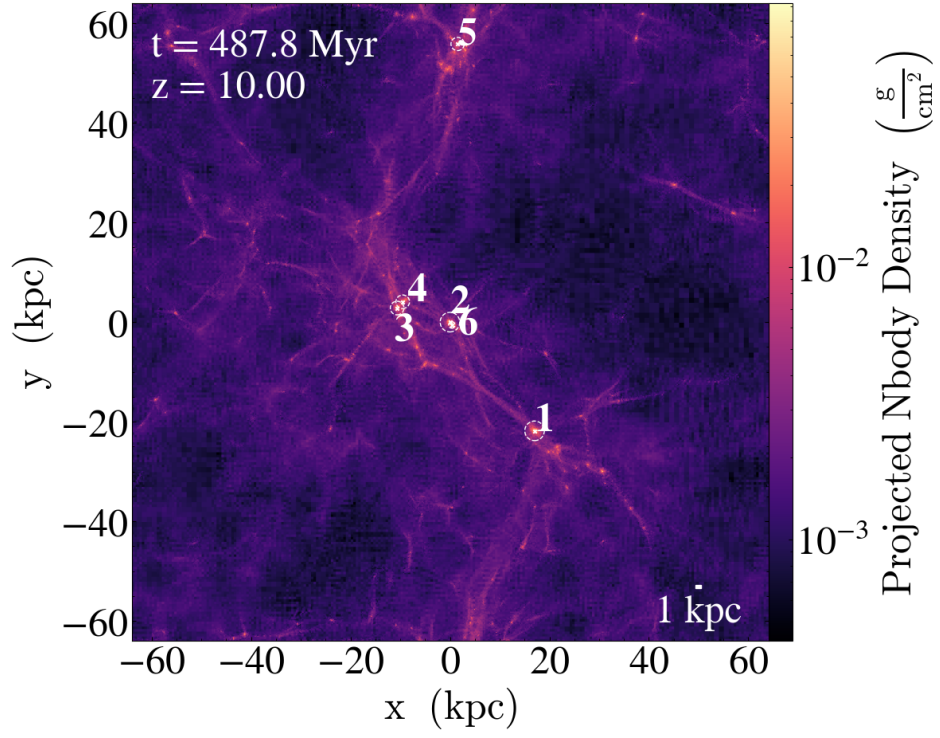
is the component of the relative velocity $\vec{v}$ projected along the relative position vector $\vec{r}$ connecting the two halo centres, indicating that the pair are currently approaching one another. Given their small separation and comparable masses (Table 1), a future merger between Halo 3 and Halo 4 is plausible. This would constitute a major merger event ($\xi \approx 1$) and provide an additional source of dynamical heating, which could further suppress H_2 cooling and sustain the conditions necessary for direct collapse. This suggests that, if the proximity-based proxy reflects the true LW environment, the neighbouring halo may exert a sustained radiative influence on the target halo over an extended period.

A similar argument applies to Halo 2, which experienced a rapid assembly phase in even closer proximity to a neighbouring halo (Halo 6), with a separation of only 1.00 kpc, consistent with our LW proximity criterion.

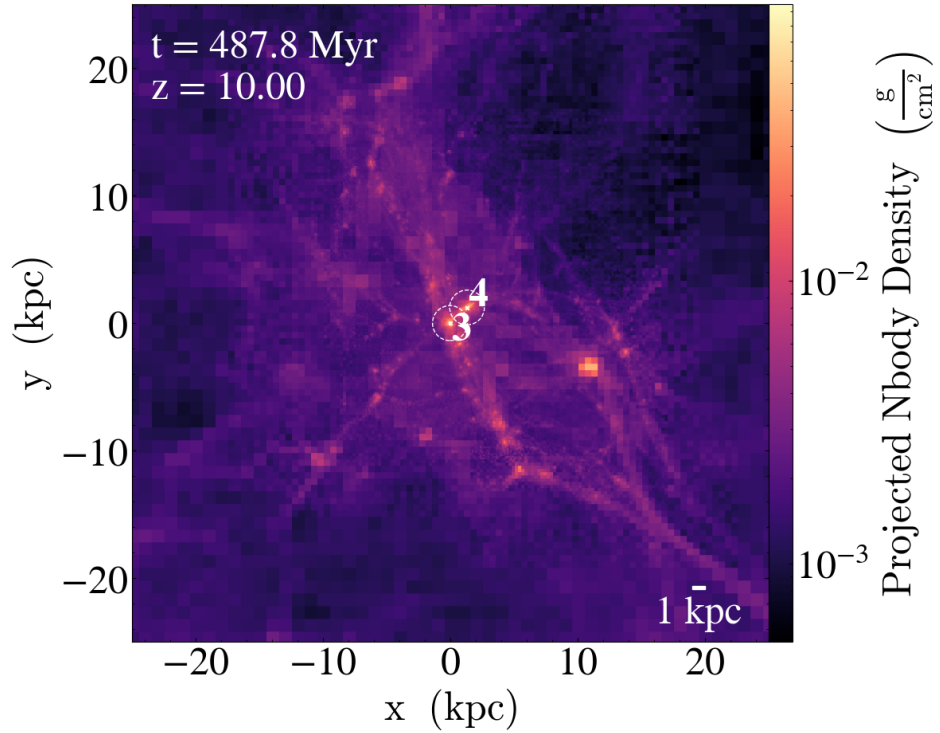
Applying the criteria from ‘Criteria for Direct Collapse Black Hole Seeds’, all six halos satisfy the virial temperature threshold. Of these, Halo 2 and Halo 3 additionally satisfy the LW proximity criterion. Their separations from Halo 6 (1.00 kpc) and Halo 4 (1.89 kpc) fall below the summed virial radii (3.16 kpc and 2.73 kpc, respectively). Both halos also satisfy the growth dynamics criterion, exhibiting peak accretion rates of $\dot{M} \gtrsim 10^6 M_{\odot}/\text{Myr}$. Therefore, Halo 2 and Halo 3 are the only DCBH candidates satisfying all three criteria.

Limitations of the Current DM-only Approach

This DM-only framework neglects several baryonic processes relevant to DCBH formation. Star formation feedback, absent here, could either suppress or trigger further collapse, meaning the reported accretion rates should



(a) Large-scale cosmic web



(b) Zoom-in of Halo 3 and 4

Figure 3: Projected dark matter density snapshots at $z = 10$. **A:** The large-scale structure shows the distribution of halos along filaments. **B:** A detailed view of the Halo 3/4 region, illustrating the high number of nearby companions and tidal features consistent with recent growth activity.

be treated as an upper bound. Similarly, the omission of baryonic pressure support may cause the virial temperatures in Table 1 to underestimate the true value. The framework also cannot track metal enrichment or self-consistent H_2/LW thermodynamics, so the atomic cooling threshold is used only as a dynamical proxy for the true DCBH condition.

Despite these limitations, the identified candidates provide a valuable target list for future hydrodynamic simulations incorporating self-consistent chemistry (e.g., via the `Grackle` chemistry and cooling library) to confirm whether these accretion rates can suppress H_2 cooling.

Conclusion

This study identified two direct-collapse black hole (DCBH) candidates through high-resolution Enzo zoom-in simulations, targeting the six most massive halos in a 1 (Mpc/h)^3 comoving volume by $z = 10$. All six halos exceed the atomic cooling threshold ($T_{\text{vir}} \gtrsim 10^4 \text{ K}$). Of these, Halo 2 and Halo 3 additionally satisfy the Lyman-Werner proximity and growth dynamics criteria, exhibiting runaway accretion rates ($\dot{M} \gtrsim 10^6 M_\odot/\text{Myr}$) and physical separations below the summed virial radii of neighbouring massive halos. Across the six-halo sample, smooth accretion contributed the majority of mass growth ($\approx 80\%$ on average), underscoring the role of sustained accretion, rather than mergers alone, in driving rapid assembly toward the atomic cooling threshold.

More broadly, these results are relevant to early SMBH seed formation scenarios, such as those proposed for JWST observations of ‘Little Red Dots’ at $z > 10$. Accretion rates already exceeding $10^6 M_\odot/\text{Myr}$ in halos crossing the atomic cooling threshold by $z = 10$ suggest that sufficiently massive black hole seeds could form early enough to account for the billion-solar-mass black holes implied by these observations, provided the baryonic conditions for direct collapse are met. As JWST continues to reveal an increasing population of anomalously massive black holes at $z > 10$, identifying the halo environments capable of hosting their formation, as demonstrated in this work, becomes an increasingly pressing step towards resolving the broader SMBH timing problem, and motivates follow-up hydrodynamic simulations that can test whether the baryonic conditions for collapse are indeed realised in these environments. Such simulations could, in turn, generate synthetic observables (e.g. luminosities, colours and spectral signatures) for direct comparison with current and future JWST observations, helping to determine whether observed high-redshift sources such as ‘Little Red Dots’ are consistent with a DCBH origin, and guiding the target selection of the future observational programme aimed at confirming or ruling out this formation channel.

Acknowledgments

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