

# Halo-driven Origin and Suppression of Over-massive Black Holes and Little Red Dots

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## ABSTRACT

We present a theoretical model in which the recently detected over-massive black holes (OBHs), and possibly Little Red Dots (LRDs), arise during a halo-driven transient phase preceding the established coevolution of supermassive black holes (SMBHs) and their host galaxies. In this model, halo gravity drives an early phase of rapid black hole growth, leading to systems in high-redshift haloes that lie above the local scaling relations. As the halo evolves, a transition in halo thermodynamics leads to the onset of a hot mode that suppresses accretion, reducing the black hole growth rate and driving the system toward the local black hole mass–stellar mass relation. LRDs may represent an observational manifestation of the rapid, halo-driven growth phase, while OBHs trace its direct mass signature. Our model thus provides a unified framework in which these systems form and evolve toward the regulated coevolution observed in the local Universe.

*Keywords:* Accretion (14) — Hydrodynamics (1963) — Black holes (162) — Dark matter (353) — Early Universe (435) — Supermassive black holes (1663) — Active galactic nuclei (16) — Quasars (1319) — AGN host galaxies (2017) — Galaxy dark matter haloes (1880)

## 1. INTRODUCTION

M. Schmidt (1963) reported a new class of objects showing star-like characteristics but unusually high luminosities. These compact sources were extremely distant and among the most luminous objects in the Universe, and were named ‘quasars’ or Quasi Stellar Objects (QSOs). The properties of QSOs posed a theoretical challenge as no known stellar process could account for such enormous energy output from a compact region. The initial theoretical models suggested that QSOs were supermassive stars (F. Hoyle & W. A. Fowler 1963). However, later these objects were explained by models in which the nuclear part of a galaxy is powered by a compact central engine, now understood to be a supermassive black hole (SMBH) (E. E. Salpeter 1964; Y. B. Zel’dovich 1964; D. Lynden-Bell 1969; C. M. Urry & P. Padovani 1995). The direct detections of supermassive black holes in galactic centres established that nearly all massive galaxies host central SMBHs (J. Kormendy & D. Richstone 1995).

The SMBHs at galaxy centres typically have masses in the range  $10^6 - 10^9 M_{\odot}$  (D. J. Mortlock et al. 2011; E. Bañados et al. 2016; K. Inayoshi et al. 2020), which is extremely high compared to stars and black holes in

binary systems and in fact comparable to the galactic components such as the bulge or disc. J. Magorrian et al. (1998) found a correlation between black hole mass and bulge mass. Later studies revealed an even tighter correlation between the black hole mass and the bulge velocity dispersion, known as the  $M_{\text{bh}}-\sigma$  relation (S. e. a. Tremaine 2002). The galaxy and its components such as the bulge, disc and SMBH, they all form from baryons cooling and sinking in the potential wells of the host dark matter halo. Indeed, L. Ferrarese (2002) reported a correlation between SMBHs and their host haloes.

In the last decade, direct imaging with facilities such as the Hubble Deep Field (HDF) (S. V. W. Beckwith et al. 2006) and the James Webb Space Telescope (JWST) (J. P. Gardner et al. 2006) has found a considerable population of SMBHs at  $z > 6$  (R. Maiolino et al. 2024a,b; K. Inayoshi et al. 2020; M. Yue et al. 2024; R. L. Larson 2023). The existence of SMBHs that early in cosmic history is a theoretical challenge, and the current models rely on super-Eddington accretion (V. Bromm & A. Loeb 2003; J. L. Johnson & V. Bromm 2007; P. Madau et al. 2014) or the direct collapse of gas clouds to create heavy seeds (V. Bromm & A. Loeb 2003; M. C. Begelman et al. 2006; G. Lodato & P. Natarajan 2006). Moreover, the high-redshift black holes seem to be in tension with the local correlations between black holes and their host galaxies (Y. Harikane et al. 2023a;

M. Yue et al. 2024; J. Li et al. 2025; I. Juodžbalis et al. 2026).

Cosmological simulations have explored the coevolution of SMBHs with their host haloes and galaxies (C. M. Booth & J. Schaye 2010; M. Volonteri et al. 2011; Ákos Bogdán & A. D. Goulding 2015). The halo likely plays an important role in growth of its central black hole (M. G. Park 2017; L. Ciotti & S. Pellegrini 2018), and it can drive a rapid growth of the central black hole to SMBH scales, that can explain the recent JWST observations (R. Sharma & M. Sharma 2024). However, once a seed black hole transitions to an SMBH rapidly at high redshift, the growth rate must decrease; otherwise, the SMBH mass would become unrealistic. The decrease in growth rate is also desirable for explaining local coevolutionary relations, as the observed growth in the present-day Universe appears to be self-regulated. Several possible mechanisms have been discussed in the past to cause a decrease in the growth rate, for example, the quenching in growth rate due to radiative feedback from accreting gas (J. Silk & M. J. Rees 1998; A. King 2003) and the onset of star formation and resulting starvation of the central black hole (P. F. Hopkins & E. Quataert 2011; D. Anglés-Alcázar et al. 2017).

The recent discovery of over-massive black holes (OBHs) (Y. Harikane et al. 2023a; M. A. Stone et al. 2024; M. Yue et al. 2024), and Little Red Dots (LRDs) that are likely a manifestation of Active Galactic Nuclei (AGNs) (J. Matthee et al. 2024; I. Labbe et al. 2025; H. B. Akins et al. 2025; C.-H. Chen et al. 2025; V. Rusakov et al. 2026; Y. Pang et al. 2026; R. E. Hviding et al. 2026), have challenged the coevolution paradigm. These high-redshift populations likely benefit from an unrestricted gas supply in dense environments within early halos (F. Pacucci et al. 2025; V. Rusakov et al. 2026; Y. Pang et al. 2026), which aligns with the view that parent halos initially prioritise the growth of the central black hole (R. Sharma & M. Sharma 2024). However, this rapid growth spurt must eventually be curtailed to avoid a catastrophic growth sprint, and to reconcile high-redshift OBHs with the regulated coevolution seen at lower redshifts.

In this Letter, we explore a halo-driven mechanism to explain the early growth of SMBHs. We uncover a halo-driven, macro-scale regulatory mechanism that provides a unified evolutionary picture, beginning with the transition to halo-gravity-driven rapid growth to explain high-redshift SMBHs, followed by halo-thermodynamics-driven regulation as the host halo surpasses a critical mass, resulting in the transition from ‘cold mode’ accretion to a pressure-supported ‘hot mode’ (e.g. A. Dekel & Y. Birnboim 2006) that steers these sys-

tems toward local scaling relations. We specifically test how this ‘spurt-and-quench’ framework accommodates the recent JWST observations of OBHs and LRDs.

In Section 2, we describe the halo-driven transition to rapid black hole growth and compare our results with JWST observations. In Section 3, we introduce the halo-thermodynamics-driven suppression. In Section 4, we analyse the resulting turnover in the  $M_{\text{bh}}-M_{\star}$  and  $M_{\text{bh}}-M_{\text{h}}$  planes. We summarise our findings and discuss the implications for galaxy-SMBH coevolution in Section 5.

## 2. HALO-GRAVITY DRIVEN RAPID GROWTH

We model the early growth of SMBHs using the steady-state hydrodynamic accretion into a combined black hole and halo potential (R. Sharma & M. Sharma 2024). The steady, spherically-symmetric flow is governed by,

$$\frac{d}{dr}(\rho v r^2) = 0 \quad (1)$$

$$v \frac{dv}{dr} = -\frac{1}{\rho} \frac{dp}{dr} - \frac{d\phi}{dr}. \quad (2)$$

Here  $\rho$  is the density,  $v$  the velocity,  $p$  the pressure and  $\phi$  is the combined gravitational potential due to a dark matter halo and a central black hole. For the dark matter, we use a Navarro-Frenk-White (NFW) dark matter profile (J. F. Navarro et al. 1997). By using the Mach number,  $\mathcal{M} = v/c_s$ , and sound speed  $c_s = \sqrt{dp/d\rho}$ , Eq. 2 transforms to,

$$\frac{\mathcal{M}^2 - 1}{2\mathcal{M}^2} \frac{d\mathcal{M}^2}{dr} + \frac{\mathcal{M}^2 - 1}{2c_s^2} \frac{dc_s^2}{dr} = \frac{2}{r} - \frac{1}{c_s^2} \frac{d\phi}{dr}. \quad (3)$$

We consider an isothermal cold flow with temperature  $T = 10^4$  K, and sound speed,  $c_s = [k_{\text{B}}T/(\mu m_{\text{H}})]^{1/2}$ , where  $\mu = 0.6$  is the mean molecular weight,  $m_{\text{H}}$  is the mass of the hydrogen atom. Eq. 3 leads to the following family of solutions,

$$\frac{\mathcal{M}^2}{2} - \ln \mathcal{M} = 2 \ln r - \frac{\phi}{c_s^2} + \text{constant} \quad (4)$$

As shown in R. Sharma & M. Sharma (2024), this system admits three critical points, obtained by setting the right hand side of Eq. 3 to zero. The transonic solution (from Eq. 4) passes through the innermost critical point when the black hole controls the accretion, and through the outermost critical point when the halo governs the accretion. Two crucial parameters determine the relative effects of the black hole and the halo. First parameter is  $\alpha = R_{\text{s}} c_{\text{s}}^2 / (GM_{\text{h}})$ , where  $M_{\text{h}}$  is the halo mass,  $R_{\text{s}} = R_{\text{vir}}/c$  is the NFW scale radius;  $R_{\text{vir}}$  is the halo virial radius and  $c$  is the concentration parameter.

The inverse of  $\alpha$  gauges the strength of the halo gravity. The second crucial parameter is  $\beta = M_{\text{bh}}/M_{\text{h}}$ , which is the ratio of black hole mass to the halo mass. The parameters  $\alpha$  and  $\beta$  dictate through which critical points the solution (Eq. 4) passes, and as a consequence, these two parameters also control the accretion rate, which is,

$$\dot{M}_{\text{bh}} = \frac{4\pi G^2 \rho_{\infty} M_{\text{h}}^2}{c_s^3} \lambda \quad (5)$$

where  $\lambda$  is the dimensionless accretion rate given by,

$$\lambda(\alpha, \beta) \approx \begin{cases} \frac{\beta^2}{4} e^{1/(\alpha\eta)} e^{3/2} \approx 1.12\beta^2 e^{1/(\alpha\eta)} & \alpha > \alpha_{\text{T}} \\ \frac{(1+\beta)^2}{4} e^{3/2} \approx 1.12 & \alpha < \alpha_{\text{T}} \end{cases} \quad (6)$$

The parameter  $\eta = (1 + 1/c) \ln(1 + c) - 1$ , and  $\alpha_{\text{T}}$  is the transition value of  $\alpha$  that separates the two regimes, given by,  $\alpha_{\text{T}} \approx [2\eta \ln(1/\beta)]^{-1}$ . The classic Bondi result  $\lambda = 1.12$  (H. Bondi 1952) is apparent in the two extreme limits. For high  $\alpha \gg \alpha_{\text{T}}$ , the black hole controls the accretion, and for low  $\alpha \ll \alpha_{\text{T}}$ , the halo controls the accretion.

The parameter  $\alpha$  is initially high, and it decreases with redshift as the halo mass increases. Therefore, the accretion rate initially is controlled by the black hole. However, at a specific redshift,  $\alpha$  approaches  $\alpha_{\text{T}}$ , and a transition to a high accretion rate due to the dark matter halo occurs, resulting in a several e-fold increase in the black hole mass over a short span of time (R. Sharma & M. Sharma 2024).

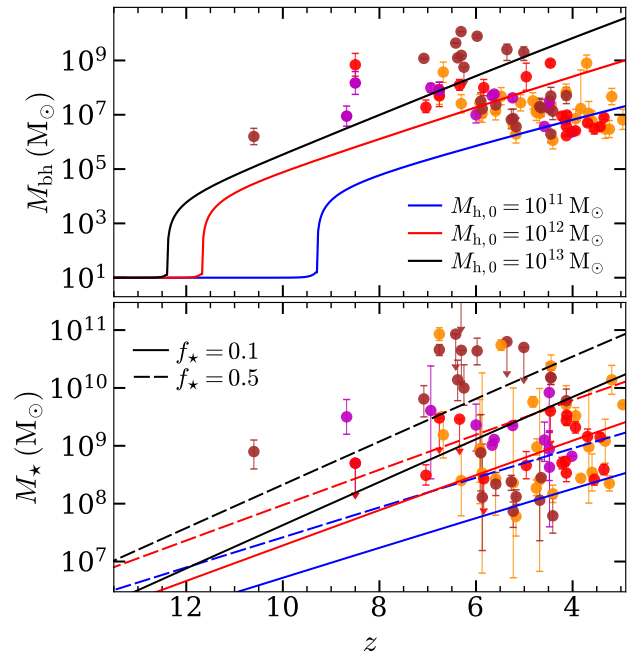
To calculate the evolution of black hole mass, we can integrate the accretion rate in cosmological settings where the dark matter halo mass evolves with redshift (C. A. Correa et al. 2015a). The following integral provides the black hole mass as a function of redshift,

$$M_{\text{bh}}(z) = \int_{z_{\text{h}}}^z \frac{-\dot{M}_{\text{bh}}}{(1+z')H(z')} dz' \quad (7)$$

where  $H(z)$  is the Hubble parameter. We consider a stellar seed of  $10 M_{\odot}$  that begins to grow at an early redshift  $z_{\text{h}} = 25$ . We use the evolution of halo masses with redshift from C. A. Correa et al. (2015a,b), and fiducial value of parameter  $\rho_{\infty} = 10^{-3} \rho_{\text{b}}$ , where  $\rho_{\text{b}}$  is the baryon density in the Universe. We use (Planck Collaboration 2016) cosmological parameters, and a typical value of concentration parameter  $c = 5$  for high redshift haloes (F. Prada et al. 2012; C. A. Correa et al. 2015b).

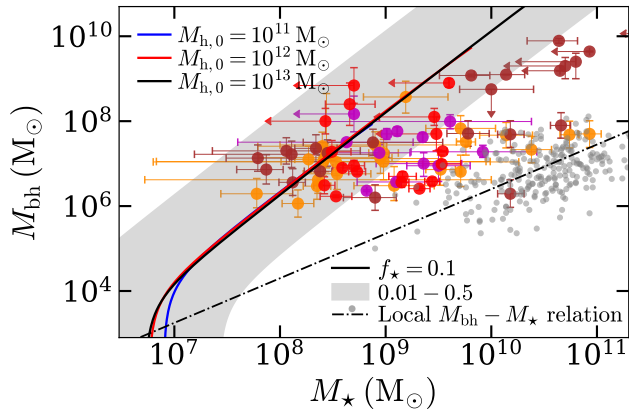
### 2.1. Origin of OBHs and LRDs

In the top panel of Fig. 1, we show the evolution of  $M_{\text{bh}}$  for three different haloes with present day masses  $M_{\text{h},0} = 10^{11}$ ,  $10^{12}$  and  $10^{13} M_{\odot}$  shown as blue, red



**Figure 1.** *Top Panel:* The redshift evolution of the central black hole mass,  $M_{\text{bh}}$ , within dark matter haloes with present day mass  $M_{\text{h},0} = 10^{11}$  (blue curve),  $10^{12}$  (red curve) and  $10^{13} M_{\odot}$  (black curve). The black holes observed by the JWST at  $z \gtrsim 3$  are shown as magenta (Y. Harikane et al. 2023a; V. Kokorev et al. 2023; R. L. Larson 2023), brown (R. Maiolino et al. 2024a,b; M. A. Stone et al. 2024; M. Yue et al. 2024), orange (I. Juodžbalis et al. 2026) filled circles. The LRDs that are increasingly interpreted as AGNs are shown as red circles (H. B. Akins et al. 2025; C.-H. Chen et al. 2025; Y. Pang et al. 2026). *Bottom Panel:* Evolution of the stellar masses corresponding to the black hole masses in the top panel. The stellar masses are obtained by using  $M_{\star} = f_{\star} f_{\text{b}} M_{\text{h}}$  where  $f_{\text{b}}$  is the baryon fraction (Planck Collaboration 2016), and  $f_{\star}$  is the fraction of baryons converted to stars. The solid curves are for  $f_{\star} = 0.1$  and dashed curves for  $f_{\star} = 0.5$ . The JWST observations (filled circles) with stellar masses corresponding to the black hole masses in the top panel are also shown for comparison.

and black curves, respectively. The filled circles represent OBHs (Y. Harikane et al. 2023a; R. Maiolino et al. 2024a,b; M. A. Stone et al. 2024; M. Yue et al. 2024; I. Juodžbalis et al. 2026) and LRDs that are AGN candidates (H. B. Akins et al. 2025; C.-H. Chen et al. 2025; Y. Pang et al. 2026) detected recently by JWST at  $z \sim 3 - 7$ . At a specific redshift which depends on the halo mass, the accretion transitions to the halo-driven rapid phase leading to massive black holes that explains the observations. In high-mass haloes, the transition occurs early, while in low-mass haloes it occurs late. For  $M_{\text{h},0} = 10^{13} M_{\odot}$ , the transition occurs at  $z \approx 12$ , for



**Figure 2.** Evolution of the black hole mass,  $M_{\text{bh}}$ , with the stellar mass,  $M_*$ , in the halo-driven growth model, for haloes with present day masses,  $M_{\text{h},0} = 10^{11}$  (blue curve),  $10^{12}$  (red curve) and  $10^{13} M_{\odot}$  (black curve). The solid lines correspond to  $f_{\star} = 0.1$ , and the shaded region shows the range  $f_{\star} = 0.01-0.5$ . The local  $M_{\text{bh}}-M_{\star}$  relation is shown as grey dots and a black dash-dotted line (A. E. Reines & M. Volonteri 2015). The recent JWST observations are shown as magenta (Y. Harikane et al. 2023a; V. Kokorev et al. 2023; R. L. Larson 2023), brown (R. Maiolino et al. 2024a,b; M. A. Stone et al. 2024; M. Yue et al. 2024) and orange circles (I. Juodžbalis et al. 2026), and the red solid circles represent the Little Red Dots (H. B. Akims et al. 2025; C.-H. Chen et al. 2025; Y. Pang et al. 2026).

$M_{\text{h},0} = 10^{11} M_{\odot}$  at  $z \approx 9$ , while for  $M_{\text{h},0} = 10^{10} M_{\odot}$  it occurs at  $z < 6$ .

The stellar masses corresponding to the JWST black holes shown in Fig. 1, top panel, are also available. To compare, we can calculate the stellar mass theoretically for our model using  $M_{\star} = f_{\star} f_{\text{b}} M_{\text{h}}$ , where  $f_{\text{b}}$  is the baryon fraction in the Universe.  $f_{\star}$  is the cumulative star formation efficiency, which is the fraction of baryons converted to stars. In Fig. 1 bottom panel, we show the calculated evolution of stellar masses in dark matter haloes for  $f_{\star} = 0.1$  (solid lines), its variation for a higher value of  $f_{\star} = 0.5$  (dashed lines), and compare with the JWST observations (colour filled circles). Thus, the halo-driven transition to rapid accretion can explain the recently detected OBHs and SMBHs at high redshift.

The OBHs detected by JWST (R. Maiolino et al. 2024a,b; M. A. Stone et al. 2024; M. Yue et al. 2024) and population of LRD interpreted as AGNs (C.-H. Chen et al. 2025; Y. Pang et al. 2026), typically have masses higher than expected from the local black hole-stellar mass relation (A. E. Reines & M. Volonteri 2015; Y. Harikane et al. 2023a). In Fig. 2, for our theoretical model, we show the  $M_{\text{bh}} - M_{\star}$  relation using solid lines for  $f_{\star} = 0.1$ . We compare our results with the JWST

observations as well as with the local stellar mass-black hole mass correlation. The fraction  $f_{\star}$  is known to depend on the halo mass (P. S. Behroozi et al. 2013; A. Muzzin et al. 2013), and it also likely evolves with redshift (A. Dekel et al. 2023; Y. Harikane et al. 2023b; C. A. Mason et al. 2023; X. Shen et al. 2026). To account for the variation, we show the range of  $f_{\star} = 0.01-0.5$  with the gray shaded region in Fig. 2. Varying  $f_{\star}$  covers the scatter in observational data-points well.

We recover a steeper relation between black hole mass and stellar mass, and our model explains the OBHs at high redshifts. If the black hole growth in our model continues, the masses become unusually high (the black curves in Fig. 1 and 2). However, eventually, the growth of black holes is expected to be regulated as we explore in the next section.

### 3. TRANSITION TO HALO-THERMODYNAMICS DRIVEN SUPPRESSION

The rapid early growth of black holes must eventually be regulated to avoid unlimited mass accumulation leading to unphysical black hole masses. A variety of quenching mechanisms have been proposed, including radiative and mechanical feedback from accreting matter, and merger-driven star formation and associated gas depletion (J. Silk & M. J. Rees 1998; D. Proga et al. 2000; A. King 2003; T. Di Matteo et al. 2005; P. F. Hopkins & E. Quataert 2011; A. C. Fabian 2012).

We consider a fundamental mechanism governed by halo thermodynamics, based on the well-established interplay between cooling and dynamical time-scales that leads to the formation of stable virial shocks in haloes above a critical mass (Y. Birnboim & A. Dekel 2003; A. Dekel & Y. Birnboim 2006; D. Kereš et al. 2005; A. Cattaneo et al. 2006; D. J. Croton et al. 2006; R. G. Bower et al. 2017). In this regime, gas is shock-heated to the virial temperature and the supply of cold, rapidly accreting material to the central regions is significantly reduced, thereby suppressing black hole growth.

One may consider an extension of the halo-gravity driven accretion framework presented in the previous section, by tying the gas sound speed to the evolving halo virial temperature, that would lead to a regulatory behaviour with shallower dependence of black hole mass on halo mass. However, this extension is not self-consistent, because the transonic accretion and expression (Eq. 5) applies only in the cold regime and breaks down if the flow temperature approaches the virial temperature (R. Sharma & M. Sharma 2024). Moreover, the virial temperature does not directly characterise the gas participating in central accretion, which is instead dominated by rapidly cooling material near the atomic

cooling floor,  $T \approx 10^4$  K. We therefore retain a constant sound speed corresponding to  $T = 10^4$  K, appropriate for photoionised cold gas, and incorporate the effect of halo thermodynamics through a suppression factor that reduces the effective gas supply once the halo exceeds a critical mass scale (A. Dekel & Y. Birnboim 2006).

The free-fall time of gas in haloes is typically,  $t_{\text{ff}} \sim (G\rho_{\text{h}})^{-1/2} \sim 0.1$  Gyr, where  $\rho_{\text{h}} \sim 200\rho_{\text{crit}}$  is the characteristic virial density. The cooling time is roughly,  $t_{\text{cool}} \sim k_{\text{B}}T/(n\Lambda(T))$ , where  $\Lambda(T)$  is the equilibrium cooling function, which peaks around  $T \sim 10^{5-5.5}$  K and becomes weakly temperature-dependent at  $T \gtrsim 10^6$  K due to bremsstrahlung cooling (R. S. Sutherland & M. A. Dopita 1993). Further, the post-shock compression timescale,  $t_{\text{sc}}$  (A. Dekel & Y. Birnboim 2006) is of the order of the halo dynamical (free-fall) time,  $t_{\text{sc}} \sim t_{\text{ff}}$ . Considering  $T \sim T_{\text{vir}} \propto M_{\text{h}}^{2/3}$ , for low-mass haloes, the cooling is efficient,  $t_{\text{cool}} \ll t_{\text{ff}}$ , allowing cold, rapidly accreting flows to reach the central regions (S. D. M. White & M. J. Rees 1978; S. D. M. White & C. S. Frenk 1991). However, the cooling time increases with increasing halo mass, and at a critical halo mass,  $M_{\text{h,c}}$ , it becomes comparable to the post-shock compression timescale,  $t_{\text{cool}} \sim t_{\text{sc}}$ , which marks the onset of stable virial shock formation (A. Dekel & Y. Birnboim 2006). In this regime, the halo enters the hot mode thermodynamically, and the accretion of cold gas to central regions is suppressed. In our model, we implement it by multiplying the accretion rate in Eq. 5 and 7 with a sigmoid suppression factor,  $f_{\text{sup}} = (1 + M_{\text{h}}/M_{\text{h,c}})^{-\beta}$ , which has a small effect for  $M_{\text{h}} < M_{\text{h,c}}$  but it effectively suppresses the accretion rate for  $M_{\text{h}} \geq M_{\text{h,c}}$ , mimicking the impact of virial shock heating (Y. Birnboim & A. Dekel 2003; D. Kereš et al. 2005; A. Dekel & Y. Birnboim 2006; A. Cattaneo et al. 2006).

The parameter  $M_{\text{h,c}}$  denotes the critical halo mass above which stable virial shocks develop, marking the transition from cold to hot mode and leading to a reduction in the cold gas supply to the centre (Y. Birnboim & A. Dekel 2003; A. Dekel & Y. Birnboim 2006). In the present-day Universe,  $M_{\text{h,c}} \approx 10^{12} M_{\odot}$ , although theoretical arguments and simulations suggest that  $M_{\text{h,c}}$  decreases with increasing redshift. In low-metallicity gas at high redshift, stable virial shocks may form in haloes with masses as low as  $\sim 10^{11} M_{\odot}$  (A. Dekel & Y. Birnboim 2006), and transition to the hot mode may occur at such low halo masses (D. Kereš et al. 2005). Motivated by these results, we adopt  $M_{\text{h,c}}$  in the range  $10^{11}$ – $10^{12} M_{\odot}$  in our models, noting that at  $z \gtrsim 6$  the lower end of this range is likely more appropriate. We further adopt a fiducial value  $\beta = 2$ , which yields a smooth but effective suppression of the accretion rate; larger values

of  $\beta$  correspond to a more rapid decline in accretion efficiency above  $M_{\text{h,c}}$ .

Star formation is also expected to be impacted by both the early transition to rapid black hole growth and the later transition to suppressed growth. However, the impact of these transitions on black hole and star formation may not be the same. Both the rise and the suppression of black hole growth are expected to occur rapidly, whereas star formation is expected to lag behind (D. M. Alexander & R. C. Hickox 2012). This behaviour reflects the underlying difference in characteristic timescales. While the black hole growth responds on the shorter accretion timescale, the star formation evolves on the longer gas depletion timescale (e.g. L. J. Tacconi et al. 2020). This may naturally lead to a transient phase in which black holes appear over-massive relative to their host galaxies.

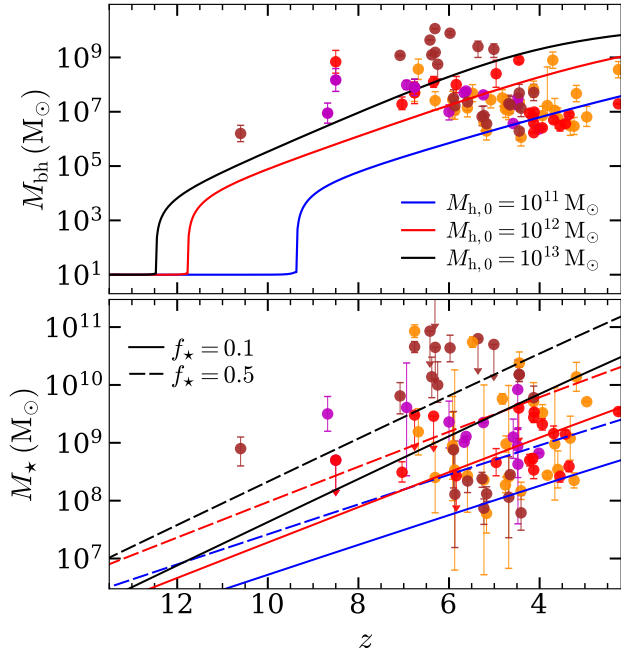
#### 4. RESULTS

We integrate the accretion rate in Eq. 7 for an evolving halo mass, multiplied with an additional factor  $f_{\text{sup}}$  for suppression due to virial shocks. For low halo masses, the cooling is efficient, and the sound speed remains constant corresponding to atomic cooling floor of  $T = 10^4$  K for  $M_{\text{h}} \ll M_{\text{h,c}}$ , to signify a cold mode of accretion and then it is suppressed for  $M_{\text{h}} > M_{\text{h,c}}$  as the rapid accretion is not feasible for hot gas at high virial temperature.

In Fig. 3, we show the calculated evolution of  $M_{\text{bh}}$  (top panel) and  $M_{\star}$  (bottom panel), which compares well with the JWST data. There is a decrease in the black hole mass specifically visible for the massive haloes (black curve) in comparison to Fig. 1, which is due to the suppression in growth as the halo enters hot mode. With JWST, M. A. Stone et al. (2024) and M. Yue et al. (2024) report black holes at redshift  $z \approx 6$  with masses in the range  $10^9$ – $10^{10} M_{\odot}$  (brown circles), which appear to be somewhat above our theoretically calculated black hole mass at that redshift, which is  $\approx 10^9 M_{\odot}$  at  $z \approx 6$ . Though, our theoretical black curve covers the observed range  $10^9$ – $10^{10} M_{\odot}$  in redshift range 6 to 4.

In Fig. 4, we show the black hole to stellar mass relation for our model (solid curves and the shaded region), which explains the unusually high masses of JWST-detected OBHs and LRDs. Further, our model exhibits a suppression causing the black holes growth to settle towards the local coevolutionary trend. The suppression is expectedly mild for  $M_{\text{h,c}} = 10^{12} M_{\odot}$ , and it becomes stronger with increasing  $M_{\text{h,c}}$ .

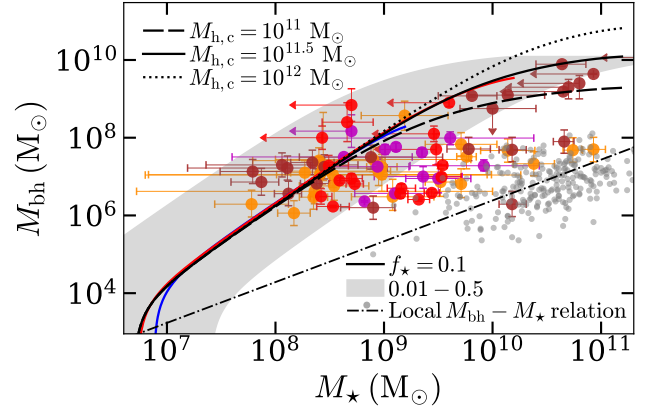
Thus, OBHs and LRDs emerge due to rapid early growth of black holes triggered by host haloes. The rapid phase of growth begins at a redshift that depends on the halo mass. For example, the growth transitions



**Figure 3.** *Top Panel:* Evolution of the central black hole mass  $M_{\text{bh}}$  with redshift,  $z$ , in the halo driven growth model with suppression due to virial shocks for three different dark matter haloes having present day masses  $M_{\text{h},0} = 10^{11}$ ,  $10^{12}$  and  $10^{13} M_{\odot}$  is shown as blue, red and black curves, respectively. The critical halo mass for suppression is  $10^{11.5} M_{\odot}$ . The JWST observations at  $z \gtrsim 3$  are shown as magenta (Y. Harikane et al. 2023a; V. Kokorev et al. 2023; R. L. Larson 2023), brown (R. Maiolino et al. 2024a,b; M. A. Stone et al. 2024; M. Yue et al. 2024), orange filled circles (I. Juodžbalis et al. 2026). The red filled circles represent the Little Red Dots (H. B. Akins et al. 2025; C.-H. Chen et al. 2025; Y. Pang et al. 2026). *Bottom Panel:* Stellar masses corresponding to the haloes in the top panel obtained by using  $M_{\star} = f_{\star} f_{\text{b}} M_{\text{h}}$  where  $f_{\star}$  is the fraction of baryons converted to stars and  $f_{\text{b}}$  is the baryon fraction (Planck Collaboration 2016). The solid curves for  $f_{\star} = 0.1$  and dashed curves for  $f_{\star} = 0.5$ . The JWST observed stellar masses corresponding to the points in the top panel are shown as solid circles.

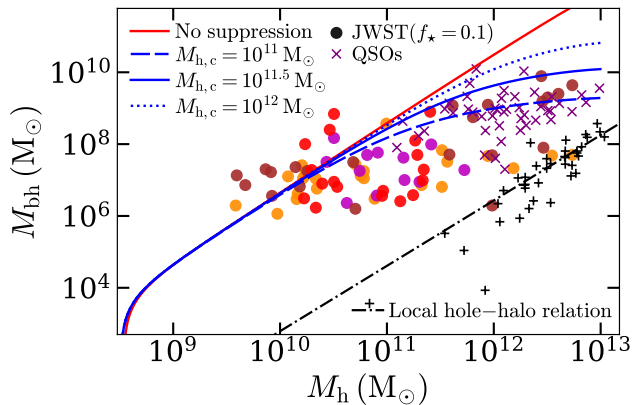
to rapid rates at about  $z \gtrsim 12$  for  $M_{\text{h},0} \geq 10^{12} M_{\odot}$ . Interestingly, the rapid growth begins when the stellar mass is roughly  $10^7 M_{\odot}$  for  $f_{\star} = 0.1$ , irrespective of the halo mass.

After the haloes pass through the transient OBH or LRD phase, the halo-thermodynamics leads them into the ‘hot mode’ dominated by formation of stable virial shocks (A. Dekel & Y. Birnboim 2006), which causes a suppression of the black hole growth. The combination of rapid growth and suppression explains the formation of OBHs and their subsequent evolution to the local  $M_{\text{bh}} - M_{\star}$  relation.



**Figure 4.** Evolution of the black hole mass,  $M_{\text{bh}}$ , with the stellar mass,  $M_{\star}$ , from the halo driven growth model with suppression at a critical value of halo mass,  $M_{\text{h},c} = 10^{11.5} M_{\odot}$ , is shown for three haloes with present day masses,  $M_{\text{h},0} = 10^{11}$  (solid blue curve),  $10^{12}$  (solid red curve) and  $10^{13} M_{\odot}$  (solid black curve). The stellar mass is obtained by using,  $M_{\star} = f_{\star} f_{\text{b}} M_{\text{h}}$ , where  $f_{\star}$  is the fraction of baryons converted to stars and  $f_{\text{b}}$  is the baryon fraction (Planck Collaboration 2016). For  $M_{\text{h},0} = 10^{13} M_{\odot}$ , we have shown the effect of varying  $M_{\text{h},c}$ , from  $10^{11.5} M_{\odot}$  (solid black curve) to  $10^{11}$  (dashed black curve) and  $10^{12} M_{\odot}$  (dotted black curve). Moreover, the solid curves correspond to  $f_{\star} = 0.1$ , and the shaded region shows the range 0.01 – 0.5. The local  $M_{\text{bh}} - M_{\star}$  relation is shown with grey dots and a black dash-dotted line (A. E. Reines & M. Volonteri 2015). The JWST data-points are shown as magenta (Y. Harikane et al. 2023a; V. Kokorev et al. 2023; R. L. Larson 2023), brown (R. Maiolino et al. 2024a,b; M. A. Stone et al. 2024; M. Yue et al. 2024), orange filled circles (I. Juodžbalis et al. 2026), and the Little Red Dots are shown as the red filled circles (H. B. Akins et al. 2025; C.-H. Chen et al. 2025; Y. Pang et al. 2026).

Our theoretical model also explains the coevolution of black hole masses with their host haloes shown as red and blue curves in Fig. 5, compared with the observed high-redshift quasars with known halo masses (K. Shimasaku & T. Izumi 2019) (purple crosses), and also with the latest JWST detected OBHs and LRDs for which we used a fiducial conversion factor  $f_{\star} = 0.1$  to obtain representative halo masses from the measured stellar masses (solid circles). The halo-driven rapid growth models overproduce black hole masses relative to the local hole-halo correlation (L. Ferrarese 2002), shown as a black dash-dotted line in agreement with high-redshift quasars and JWST observations. Interestingly, the rapid growth model without suppression (red curve) has the same slope as the local relation, while the slopes of the models with suppression evolve and decrease as they turn toward the local correlation.



**Figure 5.** Evolution of the black hole mass,  $M_{\text{bh}}$  with halo mass,  $M_{\text{h}}$  in the halo-driven growth model, for a halo with present-day mass  $M_{\text{h},0} = 10^{13} M_{\odot}$ , is shown as a solid red curve. The models with both growth and suppression with  $M_{\text{h},c} = 10^{11}$  (dashed blue curve),  $10^{11.5}$  (solid blue curve) and  $10^{12} M_{\odot}$  (dotted blue curve), where  $M_{\text{h},c}$  is the critical value of halo mass at which the suppression ensues. The correlation observed in the local Universe is shown as a black dash-dotted line and black plus symbols (L. Ferrarese 2002). The quasars from K. Shimasaku & T. Izumi (2019) at  $z \sim 6$  are shown as purple cross symbols. To compare with the recent JWST observations, we infer the halo mass corresponding to the reported stellar mass by using  $M_{\text{h}} = M_{\star}/(f_{\star} f_{\text{b}})$  with  $f_{\star} = 0.1$ . The JWST SMBHs are shown as magenta (Y. Harikane et al. 2023a; V. Kokorev et al. 2023; R. L. Larson 2023), brown (R. Maiolino et al. 2024a,b; M. A. Stone et al. 2024; M. Yue et al. 2024) and orange filled circles (I. Juodžbalis et al. 2026). The LRDs are shown as red filled circles (H. B. Akins et al. 2025; C.-H. Chen et al. 2025; Y. Pang et al. 2026).

## 5. DISCUSSION AND CONCLUSIONS

Recent observations from JWST have revealed a population of high-redshift OBHs (Y. Harikane et al. 2023a; R. Maiolino et al. 2024a,b; M. A. Stone et al. 2024; I. Juodžbalis et al. 2026; M. Yue et al. 2024), and LRDs that are increasingly interpreted as compact, gas-enriched accreting black holes (J. Matthee et al. 2024; C.-H. Chen et al. 2025; Y. Pang et al. 2026; V. Rusakov et al. 2026; R. E. Hviding et al. 2026). While LRDs represent a phenomenologically distinct population, both OBHs and LRDs with known black hole masses lie significantly above the canonical local scaling relations (Y.

Harikane et al. 2023a; F. Pacucci & A. Loeb 2024; J. Li et al. 2025; I. Juodžbalis et al. 2026).

To address the JWST observations, we have investigated hydrodynamic accretion within a combined black hole and NFW halo potential, finding that halo gravity drives an early rapid phase of central black hole growth (Fig. 1, 2, 3, and 4). In this phase, gas at the atomic cooling limit,  $T = 10^4$  K, efficiently reaches the centre, allowing black holes to attain the high masses reported by JWST within the desired cosmological timescales.

Our results further indicate that a transition occurs once the host halo reaches a critical mass scale,  $M_{\text{h},c}$ , beyond which halo thermodynamics limits the gas supply. The onset of stable virial shocks (A. Dekel & Y. Birnboim 2006) suppresses the direct inflow of cold gas and rapidly reduces black hole accretion. In contrast, stellar mass assembly, being spatially extended and able to draw upon existing gas reservoirs, may persist for longer timescales. This reflects an underlying timescale hierarchy, wherein black hole growth responds on the inflow timescale while star formation evolves on the longer gas depletion timescale. Even under the simplifying assumption of a constant star formation efficiency, the rapid phase of accretion followed by a smooth halo-mass-dependent suppression naturally reproduces the observed distribution of high-redshift systems in the  $M_{\text{bh}} - M_{\star}$  plane (Fig. 4).

The evolutionary trajectories predicted by our model pass through the OBH population during the early halo-driven rapid growth phase and subsequently bend toward the scaling relations observed in the local Universe (L. Ferrarese 2002; A. E. Reines & M. Volonteri 2015). In this framework, LRDs may be an observational manifestation of the same rapid growth phase, although the two populations are not necessarily identical.

Overall, our results highlight the central role of dark matter haloes in governing the early growth and subsequent regulation of SMBHs. The initial phase of cold-mode, halo-gravity-driven accretion produces the over-massive black holes observed at high redshift, while the transition to a hot, shock-supported halo leads to a decline in accretion and guides systems toward the coevolutionary relations seen in the local Universe.

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