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Black Hole Seeds and Little Red Dots: Connecting Formation and Growth with a JWST Multi-Cycle Treasury Program

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Abstract. JWST has revealed an abundant population of faint active galactic nuclei and a new class of compact, high-redshift sources known as Little Red Dots (LRDs), whose physical nature remains debated, with accreting massive black holes among the leading explanations. The emerging demographics of early black holes, with their high inferred number densities and, in some systems, the apparent excess of black hole mass relative to stellar mass, challenge simple scenarios of black hole seeding and growth. Despite these observational breakthroughs, the origin of early massive black holes remains uncertain, because "black holes have no memory": current samples cannot separate the imprint of seeding from subsequent growth. This white paper identifies the multi-cycle JWST observations needed to revolutionize our understanding of early black hole growth by: (i) distinguishing seeding pathways, (ii) constraining early black hole growth mechanisms, (iii) resolving the physical nature of broad-line emitters and LRDs, and (iv) testing black hole-galaxy co-evolution. These tasks require uniformly selected samples extending to low black hole and host-galaxy masses, allowing self-consistent measurements of black hole mass functions, Eddington-ratio distributions, and host properties. Grating spectroscopy, deep MIRI imaging, and variability analysis through repeated observations of the same fields would provide complementary tests of black hole formation and growth, their connection to host-galaxy evolution, and the nature of newly discovered populations of LRDs. In this white paper, we argue that these joint tests require a coordinated JWST Multi-Cycle Treasury program [1]; such a program could provide the depth, uniformity, and time baseline needed to place substantially stronger, complementary constraints on early black hole formation, growth, and their connection to galaxy evolution.

Scientific Justification

JWST discoveries have challenged our understanding of how the first black holes formed, grew, and began co-evolving with their host galaxies. For example, the detection of broad Balmer lines with full-width at half maximum (FWHM) of $\gtrsim 1000\,\mathrm{km\,s^{-1}}$ revealed accreting black holes of $\lesssim 10^6-10^8\,\mathrm{M}_\odot$ at $z=4-7$, hosted by galaxies with stellar masses of at most $10^8-10^{10}\,\mathrm{M}_\odot$ [2–5]. In

addition, the Little Red Dots (LRDs), compact sources with V-shaped spectral energy distributions and broad lines, outnumber UV-selected quasars of comparable luminosity by $1-2$ orders of magnitude, and they represent $> 1\%$ of all bright sources at high redshift [6–8]. Remarkably, in several of these newly uncovered systems, the black hole mass seems to exceed the local $M_\bullet - M_\star$ relation by factors of $\sim 10-100$ [9–12]. The current black hole frontier sits at $z \approx 10.6$ [4], less than 500 Myr after the Big Bang, where GN-z11 may host a $\sim 10^6 M_\odot$ black hole.

Yet current observations cannot uniquely distinguish between different seeding pathways, accretion mechanisms, and black hole–galaxy evolutionary scenarios, nor can they uniquely identify the nature of the LRDs. In particular, three debates remain wide open. First, black hole mass estimates may be affected by non-virial motions and radiative-transfer effects, including outflows and electron scattering in dense gas, while single-epoch virial estimators are being applied well outside their original calibration range [13–17]. Second, we cannot yet determine whether these systems require massive seeds or can be explained by rapid growth from lighter seeds [18]. Because an overmassive black hole-to-stellar mass ratio can originate both from a heavy seed and a host whose stars formed late, its mere detection does not solve the identification problem. Third, the physical nature of the LRDs is uncertain. While many LRDs display features commonly associated with accreting massive black holes, they are undetected in X-rays and radio, show limited or debated evidence for hot-dust emission, and exhibit weak or undetected variability over the available observational baselines [19–24].

To resolve these questions, future JWST programs should measure, for the same sources: (i) black hole masses, (ii) accretion diagnostics, and (iii) host-galaxy properties. Several elements, including their redshift distribution, abundances, clustering, and host-galaxy environments, all evaluated through a consistent selection function, would constrain seeding, accretion, and stellar assembly, enabling comparisons with theoretical models. These multi-cycle observations would also establish the nature of LRDs: their abundance, measured consistently across redshift ranges, and their variability could trace either existing black holes or an earlier stage of seed formation. We argue that a JWST multi-cycle program should combine deep imaging, spectroscopy, and repeated observations within a common parent population across the first billion years, with well-characterized selection and completeness.

Below we outline four coupled science cases where these constraints will have the greatest impact.

Key Science Cases

The origin of massive black hole seeds

The origin of the first massive black holes (BHs) remains a major open question in early structure formation. Proposed pathways range from light seeds ($\sim 10^2\,M_\odot$), originating from Population III stellar remnants, to intermediate- and heavy-mass seeds ($\sim 10^3$–$10^5\,M_\odot$), produced through stellar dynamical processes, runaway collisions, or the collapse of supermassive stars formed in rapidly accreting gas clouds [25–27]. An additional, intriguing possibility is that the seeds are primordial black holes (PBHs). This option was revived to explain the JWST overmassive population but remains tightly constrained by the cosmic microwave background for masses above $\sim 10^4 M_\odot$ [28–30]. The relative importance of these channels is uncertain and depends on the primordial gas and its thermal, chemical, and dynamical evolution.

Recent simulations have dramatically expanded the range of environments in which we believe that massive seeds may form. Internal radiative feedback can trigger direct collapse in atomic-cooling

haloes [31, 32], while supermassive stars and dense stellar clusters may form even in slightly metal-enriched environments [33, 34]. Additionally, cosmological simulations suggest that rapid galaxy assembly may favor massive seed formation [35].

These pathways lead to different seed properties, especially regarding their initial mass function, occupation fractions, and host-galaxy environments. However, subsequent accretion and mergers can partially erase the initial signatures of the seed population. Semi-analytical models and cosmological simulations, including CAT, DELPHI, BRAHMA, SEEDZ, and AESOPICA, have explored how different seeding prescriptions translate into the evolving BH and host-galaxy properties [36–44].

What could a JWST MCT program do? Distinguishing between seeding scenarios requires going beyond the rare, luminous AGN accessible today, with different observables in two redshift regimes. At $z \approx 5-7$, the imprint of the seed mass function survives below $M_{\rm BH} \sim 10^6 {\rm M}_\odot$, where heavy-seed models predict a deficit of BHs and light-seed models a continuous distribution [37, 40, 42]: the bolometric luminosity function must reach $L_{\rm bol} \approx 3 \times 10^{43}$ erg s^{-1} (a $10^6 {\rm M}_\odot$ black hole at a quarter of the Eddington rate), together with the active fraction in hosts of $M_\star \approx 10^8 {\rm M}_\odot$. At $z \gtrsim 9$ only the bright end is accessible: the number density of 10^6–$10^7 {\rm M}_\odot$ BHs near the Eddington rate ($L_{\rm bol} \gtrsim 10^{44}$ erg s^{-1}) is sufficient to probe the properties of the seeds, because light seeds growing continuously at the Eddington rate cannot have produced them in the time available, although earlier super-Eddington episodes could relax this constraint. Recent JWST observations have begun to uncover such low-mass BHs [45]. Our JWST MCT program could turn these detections into a complete census (first regime) and a volume-limited count (second regime).

Early black hole growth and accretion physics

Constraining the properties of early black hole seeds is, fundamentally, a question of time constraints. A black hole accreting at the Eddington rate (assuming radiative efficiency $\epsilon = 0.1$) e-folds its mass every ~ 50 Myr, so the budget between a seed formed at $z = 25$ [46] and the quasar with a BH mass of $1.6 \times 10^9 \, {\rm M}_\odot$ at $z = 7.64$ [47] is ≈ 11 e-folding times, which is sufficient for a $10^5 \, {\rm M}_\odot$ seed. However, the same (Eddington-limited) growth period is insufficient for a $100 \, {\rm M}_\odot$ seed, which would stop below $10^7 \, {\rm M}_\odot$. GN-z11 poses the same problem at $z = 10.6$, where the budget shrinks to ≈ 6 e-folds: a light seed could not have reached $10^5 \, {\rm M}_\odot$, while the black hole inferred from its spectrum has a mass of $\sim 10^6 \, {\rm M}_\odot$ and is estimated to be accreting at several times the Eddington rate [48].

One possibility to overcome these issues is super-Eddington growth [25, 49, 50]. In slim-disk scenarios, photon trapping efficiently lowers the radiative efficiency, allowing the BH mass to grow faster, so a few episodes at $\lambda_{\rm Edd} \gtrsim 1$ may be enough to close the gap from stellar-mass seeds [51–54]. However, sustaining rapid gas inflow over long timescales is challenging. In fact, feedback starves stellar-mass seeds in low-mass halos [55, 56], and even heavy seeds grow efficiently only within a narrow range of seed and host properties [57].

Cosmological simulations and semi-analytical models show that the efficiency and duty cycles of early BH accretion depend strongly on the interplay between gas supply, stellar and AGN feedback, and their evolving environment [13, 54, 58, 59]. Consequently, the observed abundance of massive BHs at high z cannot be uniquely mapped onto their initial seed masses without properly constraining the accretion histories.

Growth at $\lambda_{\rm Edd} \lesssim 1$ shifts the black hole mass function smoothly in mass with time, whereas episodic super-Eddington growth produces, at any epoch, a majority of dormant BHs and a minority caught in a burst [16, 37, 58–60]. For example, the $4 \times 10^8 \, {\rm M}_\odot$ black hole at $z = 6.68$ accreting at

2% of the Eddington rate [61] is the first clear example of what several studies define as the dormant majority of high-redshift BHs. The Eddington-ratio distribution, and its link to electromagnetic properties, is also an important prediction. Super-Eddington flows are expected to be X-ray weak [21, 62, 63] and, if the inflow is chaotic, to keep the spin low [64], thus lowering ϵ and accelerating growth further. Theoretical models also differ in their predictions for the faint-end AGN luminosity function and on how the active fraction depends on host mass [42, 65].

What could a JWST MCT program do? The distributions of several physical parameters predicted by these theoretical models separate these prescriptions. Of course, distributions require a mass-complete sample rather than a set of candidates, observed at very specific masses. A JWST MCT program would be essential to extend such samples to the lowest masses and luminosities. In this case, the black hole mass function and the Eddington-ratio distribution at $z = 4$–9 would constrain the duty cycle, provided that the program consistently reaches black hole masses of $M_\bullet \sim 10^6\,\mathrm{M}_\odot$. The fraction of X-ray-weak sources, as well as the incidence and kinematics of outflows, would provide complementary tests of super-Eddington accretion and feedback as a function of λ_{Edd}. The same measurements at $z \gtrsim 9$ would provide important timing constraints on seeding scenarios, especially when connected to the Eddington-ratio distribution described above. The detection of massive BHs accreting at low Eddington ratios at very early epochs would place stringent constraints on their previous growth histories [18], but would not by itself establish the need for heavy seeds, since earlier episodes of rapid or super-Eddington accretion may have played a decisive role [16, 51, 54, 59].

The physical nature of Little Red Dots

Broad Balmer lines (FWHM ~ 1000–$4000\,\mathrm{km\,s^{-1}}$) in many spectroscopically confirmed LRDs suggest accreting BHs [6, 66], yet their X-ray weakness and debated hot-dust signatures challenge conventional AGN interpretations [19, 20, 63, 67].

Four main models are debated: (i) accreting BHs, possibly super-Eddington, embedded in gas whose geometry and optical depth shape the observed emission, potentially unifying LRDs and Little Blue Dots [21, 23, 68]; (ii) BHs embedded in dense, reprocessing envelopes, including "black hole stars" and late-stage quasi-stars [69–72]; (iii) very massive or supermassive stars before black hole formation [73, 74]; and (iv) dense stellar clusters in formation [75]. These model categories also differ in the BH phase they describe. Models (i) and (ii) contain BHs already in place that may retain signatures of their seeds, whereas models (iii) and (iv) may probe conditions preceding black hole formation. Simulations predict short LRD-like phases for massive seeds [76], while other models associate LRDs with overmassive BHs embedded in dense gas [77].

Four complementary diagnostics can help distinguish these scenarios. Broad-line profiles probe gas kinematics and radiative-transfer effects (e.g., electron-scattering wings) which complicate virial BH mass estimates [14, 78]. Rest-frame near-infrared emission constrains hot dust, stellar light, and cool photospheres ($T_{\mathrm{eff}} \approx 4000 - 6000$ K), although the latter cannot distinguish an embedded black hole from a supermassive star [24, 71, 73, 79]. Variability probes the size and structure of the emitting region: extended photospheres may suppress rapid fluctuations, whereas stellar clusters can vary through individual massive stars or transients. To conclude, spectropolarimetry provides an additional diagnostic of scattering geometries and obscuration [80].

Remarkably, LRD demographics provide independent constraints. LRDs occur in roughly 1% of galaxies and are most common at $z \approx 4.5 - 8$ [7, 81]. Their abundance is the product of two unknowns: the duration of the LRD phase and the fraction of galaxies that go through it. With

LRDs at $\sim 1\%$ of galaxies over the ~ 700 Myr between $z = 8$ and $z = 4.5$, a supermassive-star phase of ~ 3 Myr [82] would have to recur $\approx 2-3$ times in every galaxy; a ~ 20 Myr quasi-star phase [71] would need one galaxy in three; and ~ 230 Myr of Eddington-limited growth, only a few percent of them. The apparent cutoff of the LRD luminosity function near $L_{\rm bol} \sim 10^{45}$ erg s^{-1} further constrains black hole or envelope masses [83].

What could a JWST MCT program do? Existing tests are limited by small spectroscopic samples, heterogeneous MIRI depths, and short variability baselines [14]. A multi-cycle program, combining deep MIRI imaging with medium-resolution spectroscopy, would uniformly apply these diagnostics. These measurements, coupled with redshift-dependent abundances and completeness, could constrain the relative contributions of different LRD populations and establish whether some trace the formation or early growth of massive BHs.

Black hole–galaxy co-evolution

In the local Universe, BHs weigh $\approx 0.1\%$ of their host's stellar mass [84, 85]. At $z = 4$–7, some JWST-detected broad-line AGN appear to lie 10–100 times above that relation, with offsets exceeding 3σ in some analyses [9]. Remarkably, the offset grows with redshift [12] and, in some sources, the black hole may outweigh the stars [86, 87].

Several issues could compromise these measurements. First, flux-limited samples select BHs on the high side of the intrinsic scatter [88], so the local relation could reproduce an offset of this size if the scatter is larger than expected [42, 89, 90]. The stellar masses of hosts dominated by a point source are highly uncertain, and for most LRDs the host is undetected [91, 92]. In addition, single-epoch virial BH mass estimates carry substantial systematic uncertainties. On the theory side [50], the offset has several possible interpretations: (i) a signature of heavy seeds, which start their life overmassive and lose that memory on a timescale set by the growth of the host [44, 93–98]. In this scenario, the largest offsets occur near the seeding era, at the lowest masses and highest redshifts; (ii) a transient departure from a relation regulated by feedback, to which hosts converge as they grow [99–101]; or (iii) scatter and a selection bias above a relation close to the local one, which is where most large-volume simulations place their BHs at $z \sim 6$ [42, 102, 103].

What could a JWST MCT program do? A JWST MCT program could provide host masses from imaging and continuum spectroscopy that are deep enough for the hosts of LRDs to be directly detected, and dynamical masses from integral-field spectroscopy for a subset of such BHs [4, 104], which provide crucial information regarding the virial calibration and the $M_{\rm BH}$–σ test. The models [e.g. 37, 42, 105] can then be processed through the same selection function and compared with the observations on a like-for-like basis.

Executive summary

The four science cases detailed above converge on one requirement: obtaining black hole masses, accretion diagnostics, and host-galaxy properties for the same sources, drawn from a uniformly selected parent population and revisited across multiple cycles. No combination of independently conceived and executed GO programs can provide these data. With such a uniform sample, the community could make significant advances in understanding the nature of the LRDs, while the Eddington-ratio distribution would show how the first massive BHs grew, and the $M_\bullet$–$M_\star$ relation would rest on a well-characterized population. The high-z community would then have the data to measure black hole growth over the first billion years in a complete, systematic way.

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References

[1] Genesis Community et al. Why a Multi-cycle Treasury Program is essential to maximize JWST's scientific contributions to galaxy formation. *Multi-Cycle Treasury Concept White Paper*, 2026.

[2] Kocevski et al. Hidden Little Monsters: Spectroscopic Identification of Low-mass, Broad-line AGNs at z > 5 with CEERS. *Astrophysical Journal Letters*, 954(1):L4, September 2023. doi: 10.3847/2041-8213/ace5a0.

[3] Harikane et al. A JWST/NIRSpec First Census of Broad-line AGNs at z = 4-7: Detection of 10 Faint AGNs with M $_{BH}$ 10^6-10^8 M $_\odot$ and Their Host Galaxy Properties. *Astrophysical Journal*, 959(1):39, December 2023. doi: 10.3847/1538-4357/ad029e.

[4] Maiolino et al. JADES: The diverse population of infant black holes at $4 < z < 11$: Merging, tiny, poor, but mighty. *Astronomy & Astrophysics*, 691:A145, November 2024. doi: 10.1051/0004-6361/202347640.

[5] Taylor et al. Broad-line AGNs at 3.5 < z < 6: The Black Hole Mass Function and a Connection with Little Red Dots. *Astrophysical Journal*, 986(2):165, June 2025. doi: 10.3847/1538-4357/add15b.

[6] Matthee et al. Little Red Dots: An Abundant Population of Faint Active Galactic Nuclei at z ∼ 5 Revealed by the EIGER and FRESCO JWST Surveys. *Astrophysical Journal*, 963(2):129, March 2024. doi: 10.3847/1538-4357/ad2345.

[7] Kocevski et al. The Rise of Faint, Red Active Galactic Nuclei at $z > 4$: A Sample of Little Red Dots in the JWST Extragalactic Legacy Fields. *Astrophysical Journal*, 986(2):126, June 2025. doi: 10.3847/1538-4357/adbc7d.

[8] Akins et al. COSMOS-Web: The Overabundance and Physical Nature of "Little Red Dots"—Implications for Early Galaxy and SMBH Assembly. *Astrophysical Journal*, 991(1):37, September 2025. doi: 10.3847/1538-4357/ade984.

[9] Pacucci et al. JWST CEERS and JADES Active Galaxies at z = 4-7 Violate the Local $M_\bullet - M_\star$ Relation at $> 3\sigma$: Implications for Low-mass Black Holes and Seeding Models. *Astrophysical Journal Letters*, 957(1):L3, November 2023. doi: 10.3847/2041-8213/ad0158.

[10] Juodžbalis et al. JADES - the Rosetta stone of JWST-discovered AGN: deciphering the intriguing nature of early AGN. *Monthly Notices of the RAS*, 535(1):853–873, November 2024. doi: 10.1093/mnras/stae2367.

[11] Jones et al. The $M_{\rm BH} - M_*$ Relationship at $3 < z < 7$: Big Black Holes in Little Red Dots. *arXiv e-prints*, art. arXiv:2510.07376, October 2025. doi: 10.48550/arXiv.2510.07376.

[12] Gupta et al. A Rapid Evolution in the Observed Mbh/M* Relation at z > 3 Revealed via Spectro-photometric SED-Modeling. *arXiv e-prints*, art. arXiv:2605.30414, May 2026. doi: 10.48550/arXiv.2605.30414.

[13] Lupi et al. Size matters: are we witnessing super-Eddington accretion in high-redshift black holes from JWST? *Astronomy & Astrophysics*, 689:A128, September 2024. doi: 10.1051/0004-6361/202451249.

[14] Rusakov et al. Little red dots as young supermassive black holes in dense ionized cocoons. *Nature*, 649(8097):574–579, January 2026. doi: 10.1038/s41586-025-09900-4.

[15] Pacucci et al. The Little Red Dots Are Direct Collapse Black Holes. *arXiv e-prints*, art. arXiv:2601.14368, January 2026. doi: 10.48550/arXiv.2601.14368.

[16] Trinca et al. Hunting the first cosmic giants: formation and detectability of direct collapse black holes around high-redshift quasars. *Monthly Notices of the RAS*, 551(1):stag1230, September 2026. doi: 10.1093/mnras/stag1230.

[17] Gravity+ Collaboration et al. Spatially resolved broad-line region in a quasar at z = 4: Dynamical black hole mass and prominent outflow. *Astronomy & Astrophysics*, 706:A99, February 2026. doi: 10.1051/0004-6361/202557285.

[18] Fabio Pacucci and Abraham Loeb. The search for the farthest quasar: consequences for black hole growth and seed models. *Monthly Notices of the RAS*, 509(2):1885–1891, January 2022. doi: 10.1093/mnras/stab3071.

[19] Yue et al. Stacking X-Ray Observations of "Little Red Dots": Implications for Their Active Galactic Nucleus Properties. *Astrophysical Journal Letters*, 974(2):L26, October 2024. doi: 10.3847/2041-8213/ad7eba.

[20] Ananna et al. X-Ray View of Little Red Dots: Do They Host Supermassive Black Holes? *Astrophysical Journal Letters*, 969(1):L18, July 2024. doi: 10.3847/2041-8213/ad5669.

[21] Fabio Pacucci and Ramesh Narayan. Mildly Super-Eddington Accretion onto Slowly Spinning Black Holes Explains the X-Ray Weakness of the Little Red Dots. *Astrophysical Journal*, 976 (1):96, November 2024. doi: 10.3847/1538-4357/ad84f7.

[22] Kohei Inayoshi and Roberto Maiolino. Extremely Dense Gas around Little Red Dots and High-redshift Active Galactic Nuclei: A Nonstellar Origin of the Balmer Break and Absorption Features. *Astrophysical Journal Letters*, 980(2):L27, February 2025. doi: 10.3847/2041-8213/adaebd.

[23] Piero Madau and Roberto Maiolino. Little red dots as obscured little blue dots: A super-Eddington unification model. *Astronomy & Astrophysics*, 714:A276, October 2026. doi: 10.1051/0004-6361/202659606.

[24] Pérez-González et al. Little Red Dots: One Photometric Tag Concealing Diverse Spectroscopic Flavors of Massive Star Formation and Black Hole Activity. *arXiv e-prints*, art. arXiv:2602.20247, February 2026. doi: 10.48550/arXiv.2602.20247.

[25] Inayoshi et al. The Assembly of the First Massive Black Holes. *Annual Reviews of Astronomy and Astrophysics*, 58:27–97, August 2020. doi: 10.1146/annurev-astro-120419-014455.

[26] Volonteri et al. The origins of massive black holes. *Nature Reviews Physics*, 3(11):732–743, September 2021. doi: 10.1038/s42254-021-00364-9.

[27] John Regan and Marta Volonteri. Massive Black Hole Seeds. *The Open Journal of Astrophysics*, 7:72, September 2024. doi: 10.33232/001c.123239.

[28] Pratika Dayal. Exploring a primordial solution for early black holes detected with JWST. *Astronomy & Astrophysics*, 690:A182, October 2024. doi: 10.1051/0004-6361/202451481.

[29] Zhang et al. Primordial Black Holes as Seeds for Extremely Overmassive Active Galactic Nuclei Observed by JWST. *Astrophysical Journal Letters*, 1000(1):L19, March 2026. doi: 10.3847/2041-8213/ae4bd0.

[30] Prole et al. Primordial black holes in cosmological simulations: growth prospects for supermassive black holes. *The Open Journal of Astrophysics*, 8:126, August 2025. doi: 10.33232/001c.143643.

[31] Chiaki et al. Direct-collapse black hole formation induced by internal radiation of host haloes. *Monthly Notices of the RAS*, 521(2):2845–2859, May 2023. doi: 10.1093/mnras/stad689.

[32] Kiyuna et al. Internal Radiative Feedback Triggers Global Collapse and Direct-Collapse Black Hole Formation in Metal-free Atomic-Cooling Haloes. *arXiv e-prints*, art. arXiv:2610.03877, October 2026.

[33] Sunmyon Chon and Kazuyuki Omukai. Supermassive star formation via super competitive accretion in slightly metal-enriched clouds. *Monthly Notices of the RAS*, 494(2):2851–2860, May 2020. doi: 10.1093/mnras/staa863.

[34] Sunmyon Chon and Kazuyuki Omukai. Formation of supermassive stars and dense star clusters in metal-poor clouds exposed to strong FUV radiation. *Monthly Notices of the RAS*, 539(3):2561–2582, May 2025. doi: 10.1093/mnras/staf598.

[35] Prole et al. SEEDZ: Rapid Galaxy Assembly as a Pathway to Supermassive Stars, Dense Stellar Environments and Massive Black Hole Seeds. *arXiv e-prints*, art. arXiv:2606.27427, June 2026. doi: 10.48550/arXiv.2606.27427.

[36] Valiante et al. From the first stars to the first black holes. *Monthly Notices of the RAS*, 457 (3):3356–3371, April 2016. doi: 10.1093/mnras/stw225.

[37] Trinca et al. The low-end of the black hole mass function at cosmic dawn. *Monthly Notices of the RAS*, 511(1):616–640, March 2022. doi: 10.1093/mnras/stac062.

[38] Trinca et al. Seeking the growth of the first black hole seeds with JWST. *Monthly Notices of the RAS*, 519(3):4753–4764, March 2023. doi: 10.1093/mnras/stac3768.

[39] Dayal et al. The hierarchical assembly of galaxies and black holes in the first billion years: predictions for the era of gravitational wave astronomy. *Monthly Notices of the RAS*, 486(2): 2336–2350, June 2019. doi: 10.1093/mnras/stz897.

[40] Bhowmick et al. Representing low-mass black hole seeds in cosmological simulations: A new sub-grid stochastic seed model. *Monthly Notices of the RAS*, 529(4):3768–3792, April 2024. doi: 10.1093/mnras/stae780.

[41] Bhowmick et al. Heavy Seeds and the First Black Holes: Insights from the BRAHMA Simulations. *Astrophysical Journal*, 997(2):187, February 2026. doi: 10.3847/1538-4357/ae2607.

[42] Koudmani et al. How to raise a supermassive black hole: interpreting early JWST AGN with the AESOPICA simulations. *arXiv e-prints*, art. arXiv:2607.26177, July 2026. doi: 10.48550/arXiv.2607.26177.

[43] Prole et al. The SEEDZ Simulations: Methodology and First Results on Massive Black Hole Seeding and Early Galaxy Growth. *The Open Journal of Astrophysics*, 9:59236, March 2026. doi: 10.33232/001c.159236.

[44] Mehta et al. The growth of light seed black holes in the early Universe. *Nature Astronomy*, 10:583–592, April 2026. doi: 10.1038/s41550-025-02767-5.

[45] Geris et al. JADES reveals a large population of low-mass black holes at high redshift. *Monthly Notices of the RAS*, 545(1):staf1979, January 2026. doi: 10.1093/mnras/staf1979.

[46] R. Barkana and A. Loeb. In the beginning: the first sources of light and the reionization of the universe. *Physics Reports*, 349:125–238, July 2001. doi: 10.1016/S0370-1573(01)00019-9.

[47] Wang et al. A Luminous Quasar at Redshift 7.642. *Astrophysical Journal Letters*, 907(1):L1, January 2021. doi: 10.3847/2041-8213/abd8c6.

[48] Maiolino et al. A small and vigorous black hole in the early Universe. *Nature*, 627(8002): 59–63, March 2024. doi: 10.1038/s41586-024-07052-5.

[49] Pezzulli et al. Super-Eddington growth of the first black holes. *Monthly Notices of the RAS*, 458(3):3047–3059, May 2016. doi: 10.1093/mnras/stw505.

[50] Marta Volonteri. Theoretical Modelling of Early Massive Black Holes. *arXiv e-prints*, art. arXiv:2510.04599, October 2025. doi: 10.48550/arXiv.2510.04599.

[51] Madau et al. Super-critical Growth of Massive Black Holes from Stellar-mass Seeds. *Astrophysical Journal Letters*, 784(2):L38, April 2014. doi: 10.1088/2041-8205/784/2/L38.

[52] Volonteri et al. The Case for Supercritical Accretion onto Massive Black Holes at High Redshift. *Astrophysical Journal*, 804(2):148, May 2015. doi: 10.1088/0004-637X/804/2/148.

[53] F. Pacucci and A. Ferrara. Simulating the growth of Intermediate Mass Black Holes. *Monthly Notices of the RAS*, 448:104–118, March 2015. doi: 10.1093/mnras/stv018.

[54] Lupi et al. Growing massive black holes through supercritical accretion of stellar-mass seeds. *Monthly Notices of the RAS*, 456(3):2993–3003, March 2016. doi: 10.1093/mnras/stv2877.

[55] Alvarez et al. Accretion onto the First Stellar-Mass Black Holes. *Astrophysical Journal*, 701: L133–L137, August 2009. doi: 10.1088/0004-637X/701/2/L133.

[56] Milosavljević et al. Accretion onto "Seed" Black Holes in the First Galaxies. *Astrophysical Journal*, 698:766–780, June 2009. doi: 10.1088/0004-637X/698/1/766.

[57] Pacucci et al. Conditions for Optimal Growth of Black Hole Seeds. *Astrophysical Journal*, 850, December 2017. doi: 10.3847/2041-8213/aa9aea.

[58] Pezzulli et al. Faint progenitors of luminous z $\sim$ 6 quasars: Why do not we see them? *Monthly Notices of the RAS*, 466(2):2131–2142, April 2017. doi: 10.1093/mnras/stw3243.

[59] Schneider et al. Are we surprised to find SMBHs with JWST at z $\geq$ 9? *Monthly Notices of the RAS*, 526(3):3250–3261, December 2023. doi: 10.1093/mnras/stad2503.

[60] Zana et al. Super-Eddington accretion in protogalactic cores. *Astronomy & Astrophysics*, 708:A7, March 2026. doi: 10.1051/0004-6361/202557006.

[61] Juodžbalis et al. A dormant overmassive black hole in the early Universe. *Nature*, 636(8043): 594–597, December 2024. doi: 10.1038/s41586-024-08210-5.

[62] Lambrides et al. The case for super-Eddington accretion in JWST broad-line active galactic nuclei during the first billion years. *Nature Astronomy*, 10:868–879, June 2026. doi: 10.1038/s41550-026-02813-w.

[63] Maiolino et al. JWST meets Chandra: a large population of Compton thick, feedback-free, and intrinsically X-ray weak AGN, with a sprinkle of SNe. *Monthly Notices of the RAS*, 538 (3):1921–1943, April 2025. doi: 10.1093/mnras/staf359.

[64] A. R. King and J. E. Pringle. Growing supermassive black holes by chaotic accretion. *Monthly Notices of the RAS*, 373(1):L90–L92, Nov 2006. doi: 10.1111/j.1745-3933.2006.00249.x.

[65] Caleno et al. The role of major mergers in triggering super-Eddington accretion. *arXiv e-prints*, art. arXiv:2606.04081, June 2026. doi: 10.48550/arXiv.2606.04081.

[66] Greene et al. UNCOVER Spectroscopy Confirms the Surprising Ubiquity of Active Galactic Nuclei in Red Sources at z $>$ 5. *Astrophysical Journal*, 964(1):39, March 2024. doi: 10.3847/1538-4357/ad1e5f.

[67] Casey et al. Dust in Little Red Dots. *Astrophysical Journal Letters*, 975(1):L4, November 2024. doi: 10.3847/2041-8213/ad7ba7.

[68] Piero Madau and Roberto Maiolino. Little red dots as obscured little blue dots: relative abundances, luminosities, and black-hole masses. *arXiv e-prints*, art. arXiv:2605.05074, May 2026. doi: 10.48550/arXiv.2605.05074.

[69] Naidu et al. A gas-enshrouded and gas-reddened black hole at cosmic dawn. *Nature*, 656 (8127):329–333, August 2026. doi: 10.1038/s41586-026-10846-4.

[70] de Graaff et al. A remarkable ruby: Absorption in dense gas, rather than evolved stars, drives the extreme Balmer break of a little red dot at z = 3.5. *Astronomy & Astrophysics*, 701:A168, September 2025. doi: 10.1051/0004-6361/202554681.

[71] Begelman et al. Quasi-stars: accreting black holes inside massive envelopes. *Monthly Notices of the RAS*, 387:1649–1659, July 2008. doi: 10.1111/j.1365-2966.2008.13344.x.

[72] Mitchell C. Begelman and Jason Dexter. Little Red Dots as Late-stage Quasi-stars. *Astrophysical Journal*, 996(1):48, January 2026. doi: 10.3847/1538-4357/ae274a.

[73] Hosokawa et al. Formation of Primordial Supermassive Stars by Rapid Mass Accretion. *Astrophysical Journal*, 778:178, December 2013. doi: 10.1088/0004-637X/778/2/178.

[74] Devesh Nandal and Abraham Loeb. Supermassive Stars Match the Spectral Signatures of JWST's Little Red Dots. *Astrophysical Journal*, 998(1):124, February 2026. doi: 10.3847/1538-4357/ae32f3.

[75] Chisholm et al. Little Red Dots as Globular Clusters in Formation. *Astrophysical Journal Letters*, 1004(1):L4, June 2026. doi: 10.3847/2041-8213/ae6dae.

[76] Chon et al. Overmassive black holes and little red dots naturally form in simulations. *Nature*, 657(8132):621–625, September 2026. doi: 10.1038/s41586-026-10985-8.

[77] LaChance et al. The Properties of Little Red Dot Galaxies in the ASTRID Simulation. *The Open Journal of Astrophysics*, 9:55493, January 2026. doi: 10.33232/001c.155493.

[78] Madau et al. Wings of little dots: Exponential broad lines from a stratified BLR. *arXiv e-prints*, art. arXiv:2604.04216, April 2026. doi: 10.48550/arXiv.2604.04216.

[79] Chen et al. Spectral Appearance of Self-gravitating Disks Powered by Stellar Objects: Universal Effective Temperature in the Optical Continuum and Application to Little Red Dots. *Astrophysical Journal Letters*, 1003(2):L46, June 2026. doi: 10.3847/2041-8213/ae6b69.

[80] Madau et al. Connecting the little dots in polarized light. *arXiv e-prints*, art. arXiv:2609.06239, September 2026. doi: 10.48550/arXiv.2609.06239.

[81] Fabio Pacucci and Abraham Loeb. Cosmic Outliers: Low-spin Halos Explain the Abundance, Compactness, and Redshift Evolution of the Little Red Dots. *Astrophysical Journal Letters*, 989(2):L19, August 2025. doi: 10.3847/2041-8213/ade871.

[82] Woods et al. Titans of the early Universe: The Prato statement on the origin of the first supermassive black holes. *Publications of the Astronomical Society of Australia*, 36:e027, Jan 2019. doi: 10.1017/pasa.2019.14.

[83] Ma et al. No Luminous Little Red Dots: A Sharp Cutoff in Their Luminosity Function. *Astrophysical Journal Letters*, 1008(2):L64, September 2026. doi: 10.3847/2041-8213/aea071.

[84] John Kormendy and Luis C. Ho. Coevolution (Or Not) of Supermassive Black Holes and Host Galaxies. *Annual Review of Astronomy and Astrophysics*, 51:511–653, August 2013. doi: 10.1146/annurev-astro-082708-101811.

[85] Amy E. Reines and Marta Volonteri. Relations between Central Black Hole Mass and Total Galaxy Stellar Mass in the Local Universe. *Astrophysical Journal*, 813, November 2015. doi: 10.1088/0004-637X/813/2/82.

[86] Furtak et al. A high black-hole-to-host mass ratio in a lensed AGN in the early Universe. *Nature*, 628(8006):57–61, April 2024. doi: 10.1038/s41586-024-07184-8.

[87] Juodžbalis et al. A direct black-hole mass measurement in a little red dot at high redshift. *Nature*, 653(8116):1017–1021, May 2026. doi: 10.1038/s41586-026-10579-4.

[88] Lauer et al. Selection Bias in Observing the Cosmological Evolution of the $M_\bullet - M_\sigma$ and $M_\bullet$-L Relationships. *Astrophysical Journal*, 670(1):249–260, November 2007. doi: 10.1086/522083.

[89] Rachel S. Somerville. Empirical constraints on the evolution of the relationship between black hole and galaxy mass: scatter matters. *Monthly Notices of the RAS*, 399(4):1988–1994, November 2009. doi: 10.1111/j.1365-2966.2009.15325.x.

[90] Li et al. Tip of the Iceberg: Overmassive Black Holes at $4 < z < 7$ Found by JWST Are Not Inconsistent with the Local Relation. *Astrophysical Journal*, 981(1):19, March 2025. doi: 10.3847/1538-4357/ada603.

[91] Chen et al. The Host Galaxy (If Any) of the Little Red Dots. *Astrophysical Journal*, 983(1): 60, April 2025. doi: 10.3847/1538-4357/ada93a.

[92] Durodola et al. Exploring the Active Galactic Nucleus Fraction of a Sample of JWST's Little Red Dots at $4 < z < 8$: Overmassive Black Holes Are Strongly Favored. *Astrophysical Journal*, 985(2):169, June 2025. doi: 10.3847/1538-4357/adced2.

[93] Agarwal et al. Unravelling obese black holes in the first galaxies. *Monthly Notices of the RAS*, 432:3438–3444, July 2013. doi: 10.1093/mnras/stt696.

[94] Natarajan et al. Unveiling the First Black Holes With JWST:Multi-wavelength Spectral Predictions. *Astrophysical Journal*, 838:117, April 2017. doi: 10.3847/1538-4357/aa6330.

[95] Eli Visbal and Zoltán Haiman. Identifying Direct Collapse Black Hole Seeds through Their Small Host Galaxies. *Astrophysical Journal Letters*, 865(1):L9, September 2018. doi: 10.3847/2041-8213/aadf3a.

[96] Fabio Pacucci and Abraham Loeb. The Redshift Evolution of the $M_\bullet - M_\star$ Relation for JWST's Supermassive Black Holes at $z > 4$. *Astrophysical Journal*, 964(2):154, April 2024. doi: 10.3847/1538-4357/ad3044.

[97] Kohei Inayoshi and Kohei Ichikawa. Birth of Rapidly Spinning, Overmassive Black Holes in the Early Universe. *Astrophysical Journal Letters*, 973(2):L49, October 2024. doi: 10.3847/2041-8213/ad74e2.

[98] Scoggins et al. How long do high redshift massive black hole seeds remain outliers in black hole versus host galaxy relations? *Monthly Notices of the RAS*, 519(2):2155–2168, February 2023. doi: 10.1093/mnras/stac3715.

[99] Joseph Silk and Martin J. Rees. Quasars and galaxy formation. *Astronomy & Astrophysics*, 331:L1–L4, March 1998. doi: 10.48550/arXiv.astro-ph/9801013.

[100] A. King. Black Holes, Galaxy Formation, and the M_{BH}-σ Relation. *Astrophysical Journal Letters*, 596:L27–L29, October 2003. doi: 10.1086/379143.

[101] Habouzit et al. Blossoms from black hole seeds: properties and early growth regulated by supernova feedback. *Monthly Notices of the RAS*, 468:3935–3948, July 2017. doi: 10.1093/mnras/stx666.

[102] Weller et al. Overmassive central black holes in the cosmological simulations ASTRID and Illustris TNG50. *Monthly Notices of the RAS*, 522(4):4963–4971, July 2023. doi: 10.1093/mnras/stad1362.

[103] Davari et al. Gravitational Waves from Cosmic Dawn: Tracing Cosmic Black Hole Binaries with ET, LGWA, and LISA. *arXiv e-prints*, art. arXiv:2604.18173, April 2026. doi: 10.48550/arXiv.2604.18173.

[104] Übler et al. GA-NIFS: A massive black hole in a low-metallicity AGN at z $\sim$ 5.55 revealed by JWST/NIRSpec IFS. *Astronomy & Astrophysics*, 677:A145, September 2023. doi: 10.1051/0004-6361/202346137.

[105] Somerville et al. A semi-analytic model for the co-evolution of galaxies, black holes and active galactic nuclei. *Monthly Notices of the RAS*, 391(2):481–506, dec 2008. ISSN 00358711. doi: 10.1111/j.1365-2966.2008.13805.x. URL https://academic.oup.com/mnras/article-lookup/doi/10.1111/j.1365-2966.2008.13805.x.