

Little Red Dots are Direct-Collapse Black Hole-Forming Galaxies

DANIEL J. WHALEN,¹ MUHAMMAD A. LATIF,² KONSTANTINOS TOPALAKIS,³ FERGUS CULLEN,⁴ DEVESH NANDAL,⁵ AND SADEGH KHOCHFAR⁴

¹*Institute of Cosmology and Gravitation, Portsmouth University, Dennis Sciama Building, Portsmouth PO1 3FX*

²*Physics Department, College of Science, United Arab Emirates University, PO Box 15551, Al-Ain, UAE*

³*Department of Physics, Aristotle University of Thessaloniki, Thessaloniki 54124, Greece*

⁴*Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK*

⁵*Center for Astrophysics, Harvard and Smithsonian, 60 Garden St, Cambridge, MA 02138, USA*

Submitted to AAS journals

ABSTRACT

“Little Red Dots” (LRDs) at $4 < z < 8$ are one of the most challenging discoveries by *JWST* to date because their distinctive V-shaped spectra and compact morphologies (100 - 200 pc) defy conventional astrophysical interpretation. Previous attempts to explain LRDs as compact stellar systems, heavily-cocooned black holes with differential flows, supermassive stars, or more exotic objects like ‘black-hole stars’ either cannot show how they formed, explain the origin of the dense shells needed for the absorption features in their spectra, or account for their observed abundances or inferred lifetimes. Here we show that LRDs are simply **direct-collapse black hole galaxies** in which the **BH is still shrouded by the massive disk** that created it. Our cosmological simulations yield spectra that are good matches to those of LRDs because high densities at the center of the disk **trap X-rays from the BH** and produce the **observed Balmer absorption features** while allowing UV, optical and reprocessed IR flux to partly escape. The host galaxy forms a dense $10^8 M_\odot$ cluster of stars with a radius of 150 pc next to the BH, consistent with observations of LRDs. Our models reproduce a wide variety of LRD spectra from typical objects like RUBIES-EGS-42046 at $z = 5.28$ to those with the strongest Balmer breaks such as MoM-BH*-1 at $z = 7.76$ and those at the highest redshifts like CAPERS-LRD-z9 at $z = 9.29$.

Keywords: active galactic nuclei – supermassive black holes — early universe — dark ages, first stars — galaxies: formation — galaxies: high-redshift

1. INTRODUCTION

Over 300 “Little Red Dots” (LRDs) have now been discovered at redshifts $z \sim 4 - 8$ (Matthee et al. 2024; Greene et al. 2024; Kocevski et al. 2025; Greene et al. 2026). Their distinctive V-shaped spectra, compact morphologies ($\sim 100 - 200$ pc), and high luminosities with little or no X-ray emission challenge conventional astrophysical explanations. A growing body of work now

suggests that the red continua of LRDs are not simply due to dust-reddened starlight. Their spectra often turn over near the Balmer limit, producing the characteristic V-shaped spectral energy distribution (SED) in which the rest-UV remains relatively blue while the rest-optical continuum is very red (Setton et al. 2024). These features can arise if the central source is hidden inside an optically thick, dust-poor reprocessing layer whose emergent photosphere is cool, with $T_{\text{eff}} \sim 4000\text{--}6000$ K (Liu et al. 2025). In this picture, the observed color is set by the opacity structure of dense hydrogen-rich gas rather than by an old stellar population. Such a photosphere could naturally mask a much hotter ionizing source and convert its radiation into the red optical continuum seen by the *James Webb Space Telescope* (*JWST*).

Corresponding author: Daniel J. Whalen
dwhalen1999@gmail.com

Corresponding author: Muhammad A. Latif
latifne@gmail.com

Line spectra provide independent evidence for dense gas very close to the power source. Several LRDs show broad Balmer emission, extreme Balmer decrements, Balmer absorption, and in some cases P-Cygni-like structure or blueshifted absorption components (Inayoshi & Maiolino 2025; Torralba et al. 2026; Matthee et al. 2026). These features are difficult to produce in low-density nebulae because the $n = 2$ level of hydrogen must be collisionally populated for strong Balmer absorption to appear. The inferred densities are therefore very high, typically $n \gtrsim 10^9\text{--}10^{11} \text{ cm}^{-3}$, and the required columns are often near or above the Compton-thick regime. The blueshifted absorption components are especially important because, in the usual P-Cygni interpretation, absorption blueward of the systemic Balmer or helium line traces dense gas with an outward line of sight velocity component.

This has led to a physical picture in which many LRDs are compact engines embedded in dense cocoons or shells of gas. In the highest-quality spectra, the broad Balmer and helium wings may be shaped by electron scattering rather than by purely virial motions in a classical broad-line region (Rusakov et al. 2026a). The same cocoon can also explain why LRDs are luminous in the rest-frame optical but weak in X-rays, radio emission, and hot dust emission compared with ordinary unobscured AGN (Maiolino et al. 2025; Setton et al. 2025; Rusakov et al. 2026a). The observational constraints therefore point to a compact source surrounded by a high covering-factor reprocessing medium, with a cool photosphere outside and a dense ionized or partially ionized layer inside.

Supermassive primordial stars (SMSs) with prior mass ejections that build up dense shells can recreate many of the spectral features of LRDs (Nandal & Loeb 2026) but their short lifetimes (1 - 2 Myr) cannot account for the numbers of LRDs observed to date. Hypothetical ‘black-hole stars’ invoked to account for more extreme examples of LRDs (Naidu et al. 2026) require the existence of quasi-stars (e.g., Begelman et al. 2008) that have never been found to form in any numerical simulation of supermassive stellar evolution to date (Hosokawa et al. 2013; Woods et al. 2017; Haemmerlé et al. 2018; Herrington et al. 2023; Nandal et al. 2025) because the onset of triple- α and CNO burning in the contracting protostar prevents the early collapse of the core into a BH. Massive, compact stellar clusters (Baggen et al. 2024) cannot easily account for the extremely high gas densities needed for the Balmer self-absorption features in LRD spectra or how the clusters themselves formed.

Direct-collapse black holes (DCBHs) due to the collapse of SMSs are a more promising route to the rise

of LRDs because they are persistent sources that last for tens of Myr and are more likely to appear in relatively narrow *JWST* fields of view (e.g., Jeon et al. 2026). Their observed numbers to date are also on par with the number density of DCBHs found in cosmological simulations at similar eras (Habouzit et al. 2016). But their successes so far in reproducing the V-shaped spectrum of LRDs either do not account for the compact stellar clusters inferred from their SEDs or depend on simplified 1D geometries that cannot rule out the possibility of X-ray breakout at early times, which would seriously limit the number of LRDs observed today (Rusakov et al. 2026b; Sneppen et al. 2026; Pacucci et al. 2026). Nevertheless, DCBHs can solve many problems associated with LRDs because they form in extremely high densities at the center of the massive accretion disk that created the SMS, which have been previously shown to prevent X-ray breakout in cosmological simulations (see Figure 1 of Whalen et al. 2020) and their host halos exhibit centrally-peaked density profiles that are conducive to the formation of compact clusters of stars at later times. Recent cosmological simulations also show that DCBH host galaxies exhibit the high BH / stellar masses observed in LRDs (Latif et al. 2026).

We present cosmological simulations with radiation hydrodynamics that show that DCBH formation in primordial halos can produce LRD spectra and their compact stellar populations. In Section 2 we describe our numerical simulations of DCBH birth and rise of compact stellar populations in the host galaxy at later times. We describe our spectrum calculations and compare our SEDs to those of several LRDs in Section 3 and conclude in Section 4.

2. NUMERICAL METHODS

No single simulation can resolve X-rays from a DCBH deep in its accretion disk while evolving its host galaxy over the times required to follow the rise of stellar populations, so we compute LRD spectra in two stages. First, we initialize and evolve a $10^5 M_\odot$ DCBH at the center of an atomically-cooled accretion disk like those in which SMSs form but with a luminosity of $\sim 10^{45} \text{ erg s}^{-1}$, corresponding to a $10^7 M_\odot$ BH accreting at the Eddington limit, to determine if the disk can trap X-rays at the BH masses inferred for LRDs. This procedure yields the lower limit for X-ray breakout because the disk and host halo in reality will have grown to higher masses by the time the BH reaches LRD masses (see, e.g., Patrick et al. 2023). We then use the densities, temperatures and electron mass fractions of the ultracompact H II regions deep in the disk to compute DCBH spectra with Cloudy.

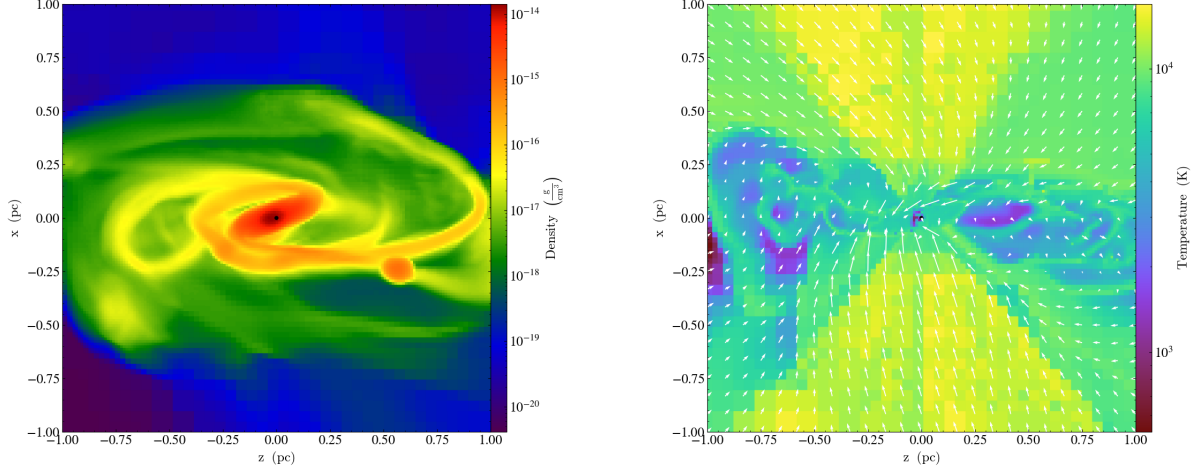


Figure 1. The DCBH and its accretion disk. Left: densities, which reach 10^{10} cm^{-3} in the vicinity of the BH shown as the black dot. Right: temperatures and velocity vectors in the disk, in which the H II region is trapped at the center on scales below those of the image.

Next, we extract the ages, masses and metallicities of the stars in the DCBH host galaxy simulated by [Latif et al. \(2026\)](#) when the BH has reached $\sim 10^7 M_\odot$ to compute the stellar component of the LRD spectrum with the Binary Population and Stellar Synthesis (BPASS) code. This latter simulation was the first to evolve a DCBH for several hundred Myr while fully resolving Pop II and III star formation in the host galaxy with X-rays from the BH and ionizing UV, winds and SNe due to the stars but not the accretion disk itself. The DCBH and stellar spectra from our fiducial host galaxy are then merged to produce LRD SEDs. This approach enables us to self-consistently model both components of LRD spectra without being held to the shortest timescales dictated by processes deep in the accretion disk.

2.1. DCBH / Disk Simulation

We evolve the DCBH in its accretion disk with Enzo, an adaptive mesh refinement (AMR) cosmology code with gas and dark matter dynamics, ionizing photon transport, and nonequilibrium primordial gas chemistry and cooling ([Bryan et al. 2014](#)). Enzo has a third-order piecewise-parabolic method for hydrodynamics ([Bryan et al. 1995](#)) with an HLLC Riemann solver for better stability with strong shocks and rarefaction waves ([Toro et al. 1994](#)). Dark matter is evolved with an N -body particle-mesh method ([Efsthathiou et al. 1985](#); [Couchman 1991](#)) and self-gravity is calculated with a multigrid Poisson solver. We use six-species nonequilibrium primordial gas chemistry (H, He, e^- , H^+ , He^+ , He^{2+}) with cooling due to collisional excitations and ionizations of H and He, recombinations of H and He, bremsstrahlung

emission, and inverse Compton cooling by the cosmic microwave background (CMB).

We propagate X-rays through the simulation volume with the MORAY raytracing radiation transport code ([Wise & Abel 2011](#)). Energy from electrons due to X-ray photoionizations is partitioned between thermalization in the gas and secondary ionizations ([Shull & van Steenberg 1985](#); [Kim et al. 2011](#)) and radiation pressure due to photoionizations is included in updates to the momentum equations. We assume monoenergetic 2 keV BH photons, consistent with the average quasar spectral energy distribution ([Sazonov et al. 2004](#)) and observations that show 90% of the X-ray flux from BHs at $z > 6$ to be at 0.5 - 2 keV ([Nanni et al. 2017](#); [Smidt et al. 2018](#)). This choice produces the lowest mass at which X-rays from the DCBH can break out of the disk and terminate the LRD spectrum because 2 keV photons have the longest mean free path through the gas over this range in energy.

The BH is treated as a sink particle and point source of X-ray photons, and we assume Eddington-limited Bondi-Hoyle accretion ([Latif & Khochfar 2020](#)):

$$\dot{M}_{\text{BH}} = \min \left(\frac{4\pi G^2 M_{\text{BH}}^2 \rho_{\text{B}}}{(c_s + v_{\text{rel}})^3}, \frac{4\pi G M_{\text{BH}} m_{\text{p}}}{\epsilon_{\text{r}} \sigma_{\text{T}} c} \right) \quad (1)$$

where $\dot{M}_{\text{BH}}$ is the accretion rate, $\epsilon_{\text{r}} = 0.1$ is the radiative efficiency, G is the gravitational constant, M_{BH} the black hole mass, ρ_{B} is the density at the Bondi radius, c_s is the sound speed, v_{rel} is the gas velocity relative to the BH, m_{p} is the proton mass and σ_{T} is the Thomson scattering cross-section. The Bondi accretion radius is

$$R_{\text{B}} = \frac{2GM_{\text{BH}}}{c_s^2}, \quad (2)$$

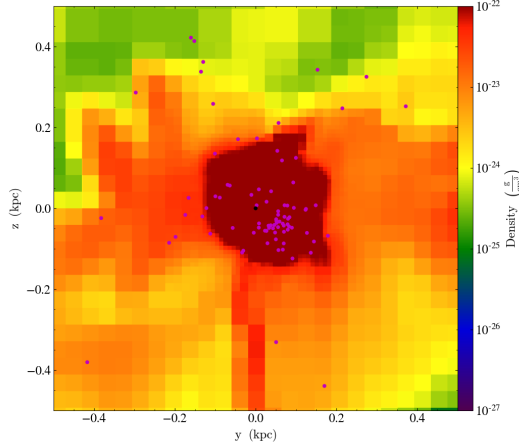


Figure 2. The compact massive stellar cluster enclosing a DCBH in its host halo at $z = 12.7$ from the Enzo simulation in [Latif et al. \(2026\)](#). The stellar mass is $1.2 \times 10^8 M_\odot$, the great majority of which is due to chemically-enriched Pop II stars. Purple dots mark the positions of small Pop II star particles, which are mostly clustered within a 150 pc radius, and the black spot shows the position of the DCBH, and the few white spots are Pop III stars.

which is 20 - 30 pc for the DCBH and is well resolved by our minimum cell size of 0.009 pc. The BH luminosity is

$$L_{\text{bol}} = \epsilon \dot{M}_{\text{BH}} c^2, \quad (3)$$

where the radiative efficiency, $\epsilon = 0.1$. We scale this luminosity up by a factor of 40 to fluxes of $\sim 10^{45} \text{ erg s}^{-1}$, those of a $10^7 M_\odot$ BH radiating at about the Eddington limit, to determine if the disk still traps X-rays from it after it has grown to this mass.

The SMS that created the DCBH considered here did not alter flows in its vicinity prior to collapse. To reach $10^5 M_\odot$, an SMS must accrete at average rates $\gtrsim 0.03 M_\odot \text{ yr}^{-1}$ (Figure 4 of [Woods et al. 2017](#)) and stellar evolution calculations show that such stars are cool ($\sim 5500 \text{ K}$) and red over their short lifetimes, producing little ionizing UV radiation that can drive outflows that could reduce or halt accretion onto them ([Haemmerlé et al. 2018](#); [Herrington et al. 2023](#); [Nandal et al. 2024](#)). Our simulations thus capture the true state of flows onto the DCBH at birth.

Our simulation box is $1 h^{-1} \text{ Mpc}$ with a 256^3 root grid and three nested grids that span 20% of the top grid and are centered on the halo for an maximum initial resolution of 1024^3 . We initialize the run at $z = 150$ with Gaussian random perturbations from MUSIC ([Hahn & Abel 2011](#)) with *Planck* second-year cosmological parameters: $\Omega_M = 0.308$, $\Omega_\Lambda = 0.691$, $\Omega_b h^2 = 0.0223$, $\sigma_8 = 0.816$, $h = 0.677$ and $n = 0.968$ ([Planck Collaboration et al. 2016](#)). We allow up to 15 levels of refinement

Table 1. SED Fit Parameters

LRD)	$\log L_{\text{bol}}$	A_v (BH)	A_v (stars)
RUBIES-EGS-42046	45.15	0.4	0.05
RUBIES-UDS-154183	45.25	0.5	0.5
MoM-BH*-1	45.35	0.9	0.4
RUBIES-EGS-14295	45.5	1.6	0.1
CAPERS-LRD-z9	45.25	1.05	0.2

after the onset of collapse for a maximum spatial resolution of 0.009 pc. Our refinement criteria are: (1) a baryonic overdensity threshold of 4; (2) a dark matter mass refinement condition of $0.0625 \rho_{\text{DM}} r^{\ell\alpha}$, where ρ_{DM} is the dark matter density, $r = 2$ is the refinement factor, ℓ is the refinement level, and $\alpha = -0.3$ ensures super-Lagrangian refinement; and (3) enforcing a minimum of 32 cells per Jeans length ([Latif & Khochfar 2020](#); [Latif et al. 2022](#)). The BH is evolved for 0.3 Myr after initialization in the disk, not enough time for new Pop III stars to form in the disk or halo.

2.2. Stellar Population

We show the stellar population of the DCBH host galaxy at $z = 12.7$ in Figure 2, when the BH has reached $\sim 10^7 M_\odot$ in the [Latif et al. \(2026\)](#) Enzo simulation. The stars have a total mass of $1.2 \times 10^8 M_\odot$, $2000 M_\odot$ of which are Pop III stars, and at this point the halo has a metallicity of $0.02 Z_\odot$. They are confined to a radius of $\sim 150 \text{ pc}$ at the center of the halo, where gas densities are highest ($\sim 10^4 \text{ cm}^{-3}$), demonstrating that DCBH host galaxies can exhibit the compact morphologies of LRDs. We extract the masses, ages and metallicities of the stars at this redshift for our BPASS spectra. The dense stellar cluster is a simple result of the $\sim r^{-2.2}$ dark matter / gas density profile of the halo, which concentrates fuel for star formation at its center as shown in Figure 2. Consistent with recent observations of lensed LRDs in which the blue stellar component is separated from the red AGN component by 50 - 100 pc (e.g., [Baggen et al. 2026](#); [Golubchik et al. 2026](#)), the DCBH is offset by the center of the cluster by about 75 pc.

3. DCBH DISK SPECTRA

The halo begins to atomically cool when it reaches a mass of $1.44 \times 10^7 M_\odot$ at $z = 17$. It forms a massive disk at its center, at which time we turn on X-rays from the DCBH at the center of the disk. We show an overhead view of the disk in the left panel of Figure 1 at 100 kyr, when it is approximately 1 pc in diameter. As we show in the right panel of Figure 1, X-rays from the DCBH

are confined to the center of the disk. Although temperatures in the ultracompact (UC) H II region reach $\sim 10^7$ K because of X-ray heating, it remains trapped deep in the halo throughout the run because of gas densities that exceed 10^{10} cm^{-3} and large ram pressures due to heavy infall that can reach $1 M_\odot \text{ yr}^{-1}$, as shown by the velocity vectors. There are fluctuations due to turbulent flows in the disk but bolometric luminosities average $\sim 0.85 L_{\text{Edd}}$.

We calculate spectra with Cloudy v23.01 (Gunasekera et al. 2023) from the properties of the environment of the DCBH in our Enzo model and the ionizing DCBH spectrum from Latif & Whalen (2025) normalized to specific bolometric luminosities. We computed a grid of models over bolometric luminosities $\log L_{\text{bol,BH}} = 44.5 - 46.0$, inner cloud radii $\log R = 16.8 - 18.5 \text{ cm}$, hydrogen number densities $\log n_{\text{H}} = 10 - 11.5 \text{ cm}^{-3}$, turbulent velocities $\log v_{\text{turb}} = 1.5 - 3.5 \text{ km s}^{-1}$, and column densities $\log N_{\text{H}} = 23.5 - 26.0$. Spherical geometry is assumed with a fixed gas metallicity $\log Z/Z_\odot = -2.0$. While our Enzo simulations show that free electron mass fractions due to the UC H II region of the DCBH exist in its vicinity, Cloudy does not perform line broadening due to scattering by free electrons. We therefore convolve our DCBH spectra with a Gaussian kernel to account for broad-line emission, followed by convolution with the wavelength-dependent observed line-spread function and resampling onto the instrumental wavelength grid. Other physical processes like turbulent gas velocities can produce similar broadening. We calculated SEDs for the stellar population with BPASS v.2.3 (Eldridge et al. 2017; Byrne et al. 2022) from the masses, ages and metallicities of the individual star particles in the DCBH host halo in Latif et al. (2026) at $z = 12.7$, again assuming a spherical geometry but with a fixed gas density of $n_{\text{H}} = 10^3 \text{ cm}^{-3}$ and a metallicity $\log Z/Z_\odot = -2.0$. The stellar and DCBH spectra were summed to produce the final output spectrum. The DCBH and stellar dust extinction coefficients and L_{bol} used in the fits are shown in Table 1.

We show fits of our spectra to five fiducial LRD SEDs in Figures 3 and 4: RUBIES-EGS-42046, a fairly typical LRD at $z = 5.28$ (Hviding et al. 2025; Pacucci et al. 2026), RUBIES-UDS-154183, an LRD with an exceptional, cliff-like jump at $z = 3.55$ (de Graaff et al. 2025; Sneppen et al. 2026), MoM-BH*-1, an outlier with the strongest observed Balmer break at $z = 7.76$ (Naidu et al. 2026), RUBIES-EGS-14295, an extended source with a v-shaped spectrum at $z = 4.89$ (Hviding et al. 2025), and CAPERS-LRD-z9, the highest redshift LRD found to date at $z = 9.29$ in which the BH / stellar mass ratio may be as high as 0.3 (Taylor et al. 2025).

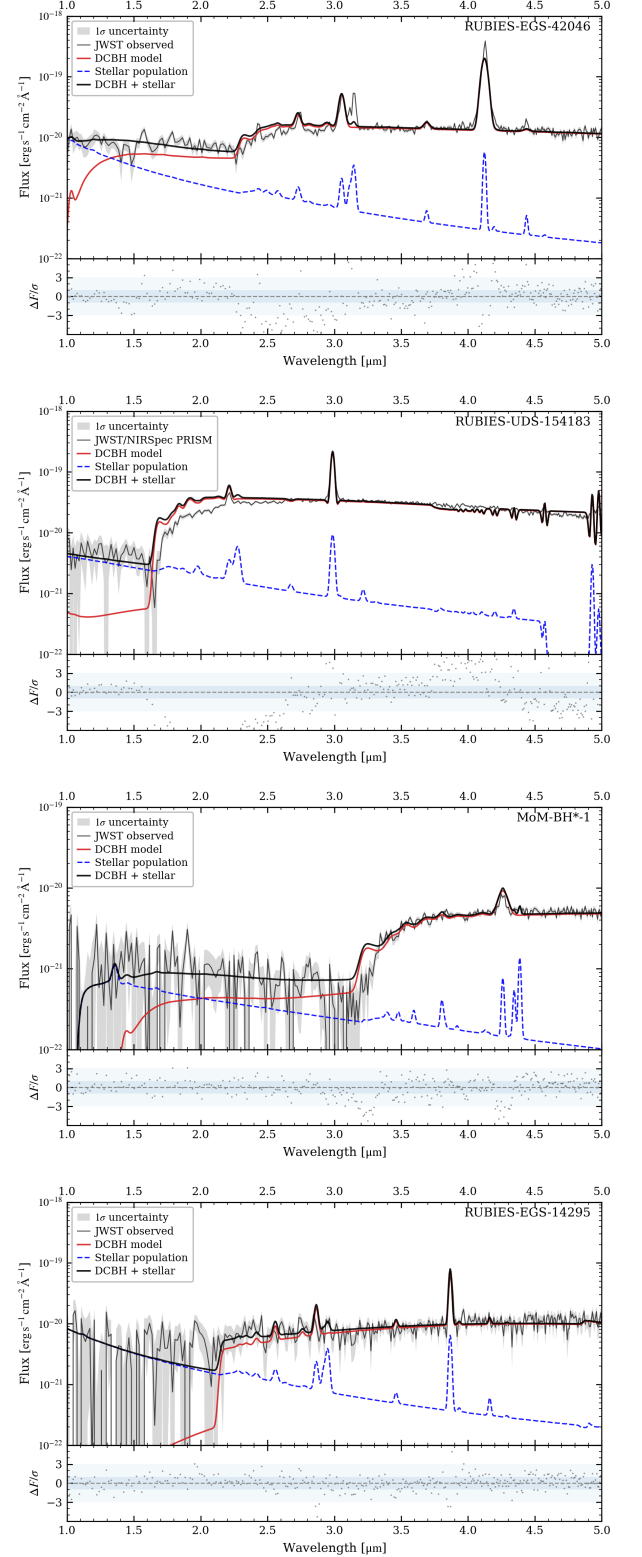


Figure 3. Our spectral fits to a variety of LRD SEDs. From top to bottom: RUBIES-EGS-42046 at $z = 5.28$, RUBIES-UDS-154183 at $z = 3.55$, MoM-BH*-1 at $z = 7.76$, RUBIES-EGS-14295 at $z = 4.89$.

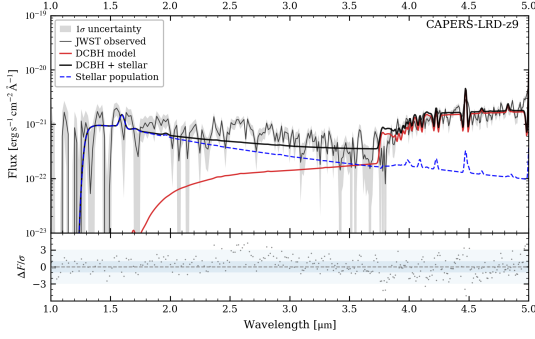


Figure 4. Our spectral fit to CAPERS-LRD-z9 at $z = 9.29$.

The DCBH can account for nearly all the RUBIES-EGS-42046 spectrum down to $\sim 1.5 \mu\text{m}$ because stars only contribute a few percent of the flux above this wavelength but they are necessary below $1.5 \mu\text{m}$ because the DCBH spectrum falls off so sharply there. Pacucci et al. (2026) are able to fit this spectrum with just a DCBH and some dust extinction due to a small ($\sim 6000 M_\odot$) population of stars but preprocess their AGN spectra prior to use in Cloudy so it differs from ours in spite of their common origin (Yue et al. 2013).

The other four LRDs all require a stellar component to match the blue components of their SEDs below $1.5 - 3.5 \mu\text{m}$. In particular, we find that the bolometric flux of a $10^7 M_\odot$ BH radiating at the Eddington limit and a stellar mass of $1.2 \times 10^8 M_\odot$ yield a good fit to the CAPERS-LRD-z9 spectrum, whose corresponding masses had previously been inferred to be $\sim 3 \times 10^8 M_\odot$ and $10^9 M_\odot$, respectively (Taylor et al. 2025). Such masses would be difficult to explain from cosmological structure formation because SF would somehow have to have been suppressed as the BH rose to large masses. Our M_{BH}/M_* ratio is much more in line with those inferred for other LRDs and overmassive BH galaxies such as UHZ1 (Castellano et al. 2023a; Bogdán et al. 2023; Goulding et al. 2023) and GHZ9 (Atek et al. 2023; Castellano et al. 2023b; Kovács et al. 2024).

4. CONCLUSION

We find that DCBH host galaxies can account for a wide range of LRD spectra, from typical ones like RUBIES-EGS-42046 at $z = 5.28$ to outliers with strong Balmer breaks such as MoM-BH*-1 at $z = 7.76$ and even those with extreme BH / stellar mass ratios such as CAPERS-LRD-z9 at $z = 9.29$, without resorting to exotic or hypothetical objects such as quasi-stars or black-hole stars. They can also create the massive, compact stellar populations required for LRD morphologies and that are thought to contribute the bluer component of most LRD spectra. The clusters are a natural result of

star formation in $r^{-2.2}$ dark matter density profiles in which fuel for star formation is concentrated at the center of the halo. The recent discovery that the red and blue components in gravitationally-lensed LRDs are separated by 50 - 100 pc (e.g., Baggen et al. 2026; Golubchik et al. 2026) reinforces the notion that they are DCBH galaxies, as the BH and stellar cluster in our simulation exhibit similar offsets (see, e.g., Regan et al. 2017).

Although the DCBH and stars in our models formed at $z \sim 17$ and 13, too early to be any of the LRDs found so far, cosmological simulations indicate that DCBH formation may have peaked at lower redshifts, $z \sim 8 - 10$ (Habouzit et al. 2016), from which they then could have evolved into LRDs by $4 < z < 8$. DCBH disk and host galaxy morphologies (and thus spectra) at these lower redshifts would have been similar to those at the higher redshifts in our models and could explain the observational characteristics of LRDs found to date, especially given that their luminosity functions are consistent with the number densities of DCBHs at $z \sim 8 - 10$. In Habouzit et al. (2016), DCBH production peaks over this redshift range and then falls off as the cosmos becomes enriched by metals. This may explain why the number of LRDs sharply drops below $z \sim 4$ because as the DCBHs born at $z \sim 8 - 10$ grow in mass over time, their X-rays finally break out of their natal disks and the LRD spectra disappear, without new DCBHs to replace them. Furthermore, the failure of X-rays to break out of the disk even at effective BH masses of $\sim 10^7 M_\odot$ suggests that LRDs are objects that can persist for tens of Myr, their inferred lifetimes from observations (e.g., Sun et al. 2026), given Salpeter times for BHs growing at the Eddington limit.

Given the numbers of LRDs found to date, it is clear that *JWST* could find them at much earlier stages because can detect $10^5 M_\odot$ DCBHs at up to $z \sim 20$ (Barrow et al. 2018; Whalen et al. 2020), whose X-rays would certainly be trapped by the accretion disk. Although dimmer, they would retain the Balmer breaks and absorption features of LRDs but have less prominent blue components because of lower total stellar masses in the host galaxy. Although the radio fluxes predicted for LRDs are generally too low for detection by current telescopes (consistent with current observations that LRDs are radio quiet; Whalen et al. 2021; Latif et al. 2025) they could be found by the Square Kilometer Array (SKA) and Next Generation Very Large Array (ngVLA). Radio observations may therefore also probe the formation pathways of LRDs in the coming decade.

1 MAL thanks the UAEU for funding via UPAR grant
 2 No. G00005454. SK acknowledges funding via STFC
 3 Small Grant ST/Y001133/1. FC acknowledges sup-
 4 port from a UKRI Frontier Research Guarantee Grant
 5 (PI Cullen; grant reference EP/X021025/1). DN
 6 was supported by the Swiss National Science Fund
 7 (SNSF) Postdoctoral Fellowship, grant number: P500-
 8 2235464. SK acknowledges funding via STFC Small
 9 Grant ST/Y001133/1.

REFERENCES

- Atek, H., Chemerynska, I., Wang, B., et al. 2023, *MNRAS*, 524, 5486, doi: [10.1093/mnras/stad1998](https://doi.org/10.1093/mnras/stad1998)
- Baggen, J. F. W., van Dokkum, P., Labbé, I., & Brammer, G. 2026, *ApJL*, 1006, L14, doi: [10.3847/2041-8213/ae82fe](https://doi.org/10.3847/2041-8213/ae82fe)
- Baggen, J. F. W., van Dokkum, P., Brammer, G., et al. 2024, *ApJL*, 977, L13, doi: [10.3847/2041-8213/ad90b8](https://doi.org/10.3847/2041-8213/ad90b8)
- Barrow, K. S. S., Aykutalp, A., & Wise, J. H. 2018, *Nature Astronomy*, 2, 987, doi: [10.1038/s41550-018-0569-y](https://doi.org/10.1038/s41550-018-0569-y)
- Begelman, M. C., Rossi, E. M., & Armitage, P. J. 2008, *MNRAS*, 387, 1649, doi: [10.1111/j.1365-2966.2008.13344.x](https://doi.org/10.1111/j.1365-2966.2008.13344.x)
- Bogdán, Á., Goulding, A. D., Natarajan, P., et al. 2023, *Nature Astronomy*, doi: [10.1038/s41550-023-02111-9](https://doi.org/10.1038/s41550-023-02111-9)
- Bryan, G. L., Norman, M. L., Stone, J. M., Cen, R., & Ostriker, J. P. 1995, *Computer Physics Communications*, 89, 149, doi: [10.1016/0010-4655\(94\)00191-4](https://doi.org/10.1016/0010-4655(94)00191-4)
- Bryan, G. L., Norman, M. L., O’Shea, B. W., et al. 2014, *ApJS*, 211, 19, doi: [10.1088/0067-0049/211/2/19](https://doi.org/10.1088/0067-0049/211/2/19)
- Byrne, C. M., Stanway, E. R., Eldridge, J. J., McSwiney, L., & Townsend, O. T. 2022, *MNRAS*, 512, 5329, doi: [10.1093/mnras/stac807](https://doi.org/10.1093/mnras/stac807)
- Castellano, M., Fontana, A., Treu, T., et al. 2023a, *ApJL*, 948, L14, doi: [10.3847/2041-8213/accea5](https://doi.org/10.3847/2041-8213/accea5)
- . 2023b, *ApJL*, 948, L14, doi: [10.3847/2041-8213/accea5](https://doi.org/10.3847/2041-8213/accea5)
- Couchman, H. M. P. 1991, *ApJL*, 368, L23, doi: [10.1086/185939](https://doi.org/10.1086/185939)
- de Graaff, A., Rix, H.-W., Naidu, R. P., et al. 2025, *A&A*, 701, A168, doi: [10.1051/0004-6361/202554681](https://doi.org/10.1051/0004-6361/202554681)
- Efstathiou, G., Davis, M., White, S. D. M., & Frenk, C. S. 1985, *ApJS*, 57, 241, doi: [10.1086/191003](https://doi.org/10.1086/191003)
- Eldridge, J. J., Stanway, E. R., Xiao, L., et al. 2017, *PASA*, 34, e058, doi: [10.1017/pasa.2017.51](https://doi.org/10.1017/pasa.2017.51)
- Golubchik, M., Furtak, L. J., Allingham, J. F. V., et al. 2026, *A&A*, 710, A226, doi: [10.1051/0004-6361/202558407](https://doi.org/10.1051/0004-6361/202558407)
- Goulding, A. D., Greene, J. E., Setton, D. J., et al. 2023, *ApJL*, 955, L24, doi: [10.3847/2041-8213/acf7c5](https://doi.org/10.3847/2041-8213/acf7c5)
- Greene, J. E., Labbe, I., Goulding, A. D., et al. 2024, *ApJ*, 964, 39, doi: [10.3847/1538-4357/ad1e5f](https://doi.org/10.3847/1538-4357/ad1e5f)
- Greene, J. E., Setton, D. J., Furtak, L. J., et al. 2026, *ApJ*, 996, 129, doi: [10.3847/1538-4357/ae1836](https://doi.org/10.3847/1538-4357/ae1836)
- Gunasekera, C. M., van Hoof, P. A. M., Chatzikos, M., & Ferland, G. J. 2023, *Research Notes of the American Astronomical Society*, 7, 246, doi: [10.3847/2515-5172/ad0e75](https://doi.org/10.3847/2515-5172/ad0e75)
- Habouzit, M., Volonteri, M., Latif, M., Dubois, Y., & Peirani, S. 2016, *MNRAS*, 463, 529, doi: [10.1093/mnras/stw1924](https://doi.org/10.1093/mnras/stw1924)
- Haemmerlé, L., Woods, T. E., Klessen, R. S., Heger, A., & Whalen, D. J. 2018, *MNRAS*, 474, 2757, doi: [10.1093/mnras/stx2919](https://doi.org/10.1093/mnras/stx2919)
- Hahn, O., & Abel, T. 2011, *MNRAS*, 415, 2101, doi: [10.1111/j.1365-2966.2011.18820.x](https://doi.org/10.1111/j.1365-2966.2011.18820.x)
- Herrington, N. P., Whalen, D. J., & Woods, T. E. 2023, *MNRAS*, 521, 463, doi: [10.1093/mnras/stad572](https://doi.org/10.1093/mnras/stad572)
- Hosokawa, T., Yorke, H. W., Inayoshi, K., Omukai, K., & Yoshida, N. 2013, *ApJ*, 778, 178, doi: [10.1088/0004-637X/778/2/178](https://doi.org/10.1088/0004-637X/778/2/178)
- Hviding, R. E., de Graaff, A., Miller, T. B., et al. 2025, *A&A*, 702, A57, doi: [10.1051/0004-6361/202555816](https://doi.org/10.1051/0004-6361/202555816)
- Inayoshi, K., & Maiolino, R. 2025, *ApJL*, 980, L27, doi: [10.3847/2041-8213/adaebd](https://doi.org/10.3847/2041-8213/adaebd)
- Jeon, J., Liu, B., Bromm, V., et al. 2026, *ApJ*, 998, 148, doi: [10.3847/1538-4357/ae3725](https://doi.org/10.3847/1538-4357/ae3725)
- Kim, J.-h., Wise, J. H., Alvarez, M. A., & Abel, T. 2011, *ApJ*, 738, 54, doi: [10.1088/0004-637X/738/1/54](https://doi.org/10.1088/0004-637X/738/1/54)
- Kocevski, D. D., Finkelstein, S. L., Barro, G., et al. 2025, *ApJ*, 986, 126, doi: [10.3847/1538-4357/adbc7d](https://doi.org/10.3847/1538-4357/adbc7d)
- Kovács, O. E., Bogdán, Á., Natarajan, P., et al. 2024, *ApJL*, 965, L21, doi: [10.3847/2041-8213/ad391f](https://doi.org/10.3847/2041-8213/ad391f)
- Latif, M. A., Aftab, A., Whalen, D. J., & Mezcuca, M. 2025, *A&A*, 694, L14, doi: [10.1051/0004-6361/202453194](https://doi.org/10.1051/0004-6361/202453194)
- Latif, M. A., & Khochfar, S. 2020, *MNRAS*, 497, 3761, doi: [10.1093/mnras/staa2218](https://doi.org/10.1093/mnras/staa2218)

- Latif, M. A., & Whalen, D. J. 2025, *ApJL*, 990, L58, doi: [10.3847/2041-8213/adfec6](https://doi.org/10.3847/2041-8213/adfec6)
- Latif, M. A., Whalen, D. J., Khochfar, S., & Cullen, F. 2026, *ApJL*, 1003, L40, doi: [10.3847/2041-8213/ae67f0](https://doi.org/10.3847/2041-8213/ae67f0)
- Latif, M. A., Whalen, D. J., Khochfar, S., Herrington, N. P., & Woods, T. E. 2022, *Nature*, 607, 48, doi: [10.1038/s41586-022-04813-y](https://doi.org/10.1038/s41586-022-04813-y)
- Liu, H., Jiang, Y.-F., Quataert, E., Greene, J. E., & Ma, Y. 2025, *ApJ*, 994, 113, doi: [10.3847/1538-4357/ae0c19](https://doi.org/10.3847/1538-4357/ae0c19)
- Maiolino, R., Risaliti, G., Signorini, M., et al. 2025, *MNRAS*, 538, 1921, doi: [10.1093/mnras/staf359](https://doi.org/10.1093/mnras/staf359)
- Matthee, J., Naidu, R. P., Brammer, G., et al. 2024, *ApJ*, 963, 129, doi: [10.3847/1538-4357/ad2345](https://doi.org/10.3847/1538-4357/ad2345)
- Matthee, J., Torralba, A., Pezzulli, G., et al. 2026, *arXiv e-prints*, arXiv:2603.17667, doi: [10.48550/arXiv.2603.17667](https://doi.org/10.48550/arXiv.2603.17667)
- Naidu, R. P., Matthee, J., Katz, H., et al. 2026, *Nature*, 656, 329, doi: [10.1038/s41586-026-10846-4](https://doi.org/10.1038/s41586-026-10846-4)
- Nandal, D., & Loeb, A. 2026, *ApJ*, 998, 124, doi: [10.3847/1538-4357/ae32f3](https://doi.org/10.3847/1538-4357/ae32f3)
- Nandal, D., Whalen, D. J., Latif, M. A., & Heger, A. 2025, *ApJL*, 994, L11, doi: [10.3847/2041-8213/ae1a63](https://doi.org/10.3847/2041-8213/ae1a63)
- Nandal, D., Zwick, L., Whalen, D. J., et al. 2024, *A&A*, 689, A351, doi: [10.1051/0004-6361/202449562](https://doi.org/10.1051/0004-6361/202449562)
- Nanni, R., Vignali, C., Gilli, R., Moretti, A., & Brandt, W. N. 2017, *A&A*, 603, A128, doi: [10.1051/0004-6361/201730484](https://doi.org/10.1051/0004-6361/201730484)
- Pacucci, F., Ferrara, A., & Kocevski, D. D. 2026, *arXiv e-prints*, arXiv:2601.14368, doi: [10.48550/arXiv.2601.14368](https://doi.org/10.48550/arXiv.2601.14368)
- Patrick, S. J., Whalen, D. J., Latif, M. A., & Elford, J. S. 2023, *MNRAS*, 522, 3795, doi: [10.1093/mnras/stad1179](https://doi.org/10.1093/mnras/stad1179)
- Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2016, *A&A*, 594, A13, doi: [10.1051/0004-6361/201525830](https://doi.org/10.1051/0004-6361/201525830)
- Regan, J. A., Visbal, E., Wise, J. H., et al. 2017, *Nature Astronomy*, 1, 0075, doi: [10.1038/s41550-017-0075](https://doi.org/10.1038/s41550-017-0075)
- Rusakov, V., Watson, D., Nikopoulos, G. P., et al. 2026a, *Nature*, 649, 574, doi: [10.1038/s41586-025-09900-4](https://doi.org/10.1038/s41586-025-09900-4)
- . 2026b, *Nature*, 649, 574, doi: [10.1038/s41586-025-09900-4](https://doi.org/10.1038/s41586-025-09900-4)
- Sazonov, S. Y., Ostriker, J. P., & Sunyaev, R. A. 2004, *MNRAS*, 347, 144, doi: [10.1111/j.1365-2966.2004.07184.x](https://doi.org/10.1111/j.1365-2966.2004.07184.x)
- Setton, D. J., Khullar, G., Miller, T. B., et al. 2024, *ApJ*, 974, 145, doi: [10.3847/1538-4357/ad6a18](https://doi.org/10.3847/1538-4357/ad6a18)
- Setton, D. J., Greene, J. E., de Graaff, A., et al. 2025, *ApJ*, 995, 118, doi: [10.3847/1538-4357/ae1500](https://doi.org/10.3847/1538-4357/ae1500)
- Shull, J. M., & van Steenberg, M. E. 1985, *ApJ*, 298, 268, doi: [10.1086/163605](https://doi.org/10.1086/163605)
- Smidt, J., Whalen, D. J., Johnson, J. L., Surace, M., & Li, H. 2018, *ApJ*, 865, 126, doi: [10.3847/1538-4357/aad7b8](https://doi.org/10.3847/1538-4357/aad7b8)
- Sneppen, A., Watson, D., Matthews, J. H., et al. 2026, *arXiv e-prints*, arXiv:2601.18864, doi: [10.48550/arXiv.2601.18864](https://doi.org/10.48550/arXiv.2601.18864)
- Sun, W. Q., Naidu, R. P., Matthee, J., et al. 2026, *The Open Journal of Astrophysics*, 9, 62505, doi: [10.33232/001c.162505](https://doi.org/10.33232/001c.162505)
- Taylor, A. J., Kokorev, V., Kocevski, D. D., et al. 2025, *ApJL*, 989, L7, doi: [10.3847/2041-8213/ade789](https://doi.org/10.3847/2041-8213/ade789)
- Toro, E. F., Spruce, M., & Speares, W. 1994, *Shock Waves*, 4, 25, doi: [10.1007/BF01414629](https://doi.org/10.1007/BF01414629)
- Torralba, A., Matthee, J., Pezzulli, G., et al. 2026, *A&A*, 707, A75, doi: [10.1051/0004-6361/202557537](https://doi.org/10.1051/0004-6361/202557537)
- Whalen, D. J., Mezcuca, M., Patrick, S. J., Meiksin, A., & Latif, M. A. 2021, *ApJL*, 922, L39, doi: [10.3847/2041-8213/ac35e6](https://doi.org/10.3847/2041-8213/ac35e6)
- Whalen, D. J., Surace, M., Bernhardt, C., et al. 2020, *ApJL*, 897, L16, doi: [10.3847/2041-8213/ab9d29](https://doi.org/10.3847/2041-8213/ab9d29)
- Wise, J. H., & Abel, T. 2011, *MNRAS*, 414, 3458, doi: [10.1111/j.1365-2966.2011.18646.x](https://doi.org/10.1111/j.1365-2966.2011.18646.x)
- Woods, T. E., Heger, A., Whalen, D. J., Haemmerlé, L., & Klessen, R. S. 2017, *ApJL*, 842, L6, doi: [10.3847/2041-8213/aa7412](https://doi.org/10.3847/2041-8213/aa7412)
- Yue, B., Ferrara, A., Salvaterra, R., Xu, Y., & Chen, X. 2013, *MNRAS*, 433, 1556, doi: [10.1093/mnras/stt826](https://doi.org/10.1093/mnras/stt826)