







Back to basics: Little Red Dots as galaxies and dust-obscured AGNs in a synthetic NIRC*am* sky simulated with L-GalaxiesBH

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ABSTRACT

The enigmatic Little Red Dots (LRDs) discovered by the *James Webb Space Telescope* (*JWST*) exhibit properties challenging their interpretation as common galaxies or active galactic nuclei (AGNs). Understanding their nature is key to placing them within our picture of early galaxy and massive black hole (MBH) evolution. To this aim, we build a realistic comparison between LRD observations with photometric properties of galaxies and AGN simulated by the L-GalaxiesBH model in a NIRC*am* mock sky. We model stellar continua and emission lines, the MBH emission from accretion disc, infrared radiation from dusty torus, and lines from narrow and broad-line regions, accounting for dust attenuation and obscuration. Using realistic photometric cuts, we select a population of LRDs including both AGN and galaxies. The LRD fraction peaks at 40 per cent ($\sim 10^{-4} \text{Mpc}^{-3}$) at $z \sim 4$. Our LRDs are central galaxies spanning $M_{\star} = 10^8\text{--}10^{10.5} M_{\odot}$. A population of galaxies with $M_{\star} < 10^9 M_{\odot}$ appear as LRDs due to older stellar populations. At higher masses, LRDs dominate the halo and stellar mass functions ($M_{\text{vir}} > 10^{11.5} M_{\odot}$, $M_{\star} > 10^{9.5} M_{\odot}$), and the interplay between AGN and galaxy emission drives the LRD selection. AGN dominate rest-frame UV-optical emission, while dust obscuration is secondary. LRDs host lighter MBHs ($\sim 10^{6.5} M_{\odot}$) than non-LRDs ($\sim 10^{7.5} M_{\odot}$), with fainter emission unable to balance their hosts Balmer breaks. We find no evidence for dominant heavy-seed origin of MBHs. LRD Galaxies (97 per cent hosting MBHs) and LRD AGNs are dominated, with LRD AGNs showing larger bulges formed mainly via disc instabilities.

Key words: Galaxies: active – Galaxies: high-redshift – Methods: numerical – Quasars: supermassive black holes – Techniques: photometric – Techniques: semi-analytic models.

1 INTRODUCTION

The *James Webb Space Telescope* (*JWST*; M. W. McElwain et al. 2023) has spectacularly transformed our view of the infrared (IR) Universe. This has been possible largely thanks to its Near Infrared Camera and Spectrograph (NIRC*am* and NIRSpec, respectively, P. Jakobsen et al. 2022; M. J. Rieke et al. 2023) and its Mid-Infrared Instrument (MIRI; see G. S. Wright et al. 2023). From detailed studies of local galaxies (e.g. G. Bortolini et al. 2024; H. Haidar et al. 2024; E. Lopez-Rodriguez et al. 2026), to

investigations of active galactic nuclei (AGNs) and galaxies at cosmic noon ($z \sim 2$, R. L. Davies et al. 2024; P. Dokkum et al. 2024; D. J. Setton et al. 2024b; C. Liboni et al. 2026), and extending to the most distant galaxies observed to date (T. Morishita et al. 2024; I. Chemerynska et al. 2026; R. P. Naidu et al. 2025b, see also D. P. Stark et al. 2025 for a recent review), *JWST* is transforming our understanding of galaxy and AGN evolution.

Among its most significant discoveries, *JWST* has unveiled the so-called Little Red Dots (LRDs; J. Matthee et al. 2024), a remarkably common class of high- z sources with point-like apparent morphology and red observed photometric colours (V. Kokorev et al. 2024; J. Matthee et al. 2024; H. B. Akins et al. 2025). Owing to a combination of peculiar spectrophotometric properties, LRDs

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have challenged our understanding of early black hole and galaxy co-evolution since their early discoveries (I. Labbe et al. 2025; J. E. Greene et al. 2024; J. Matthee et al. 2024; H. B. Akins et al. 2025). Generally speaking, LRDs appear as point-like, UV-faint sources ($-14 < M_{UV} < -18$, see I. Labbe et al. 2025) with photometric redshifts spanning $3 < z < 9$ (V. Kokorev et al. 2024; H. B. Akins et al. 2025), and some detections and/or candidates extending to even higher redshifts (T. S. Tanaka et al. 2025; A. J. Taylor et al. 2025). Their most distinctive photometric signature is a ‘V-shaped’ spectral energy distribution (SED), characterized by simultaneously blue rest-frame UV–optical colours ($0.15 - 0.4 \mu\text{m}$) and red rest-frame optical–IR colours ($0.4 - 1 \mu\text{m}$) (see e.g. D. D. Kocevski et al. 2025), a combination that was rarely identified before *JWST*.

SED fitting of LRDs photometric data provides stellar mass estimates of $10^9 \lesssim M_*/M_\odot \lesssim 10^{11}$ (G. C. K. Leung et al. 2025; P. G. Pérez-González et al. 2024a; H. B. Akins et al. 2025; C.-H. Chen et al. 2025a, although these values may be affected by biases in the subtraction of AGN light or stellar age inference, see S. Berger et al. 2025; T. Harvey et al. 2025) and strong Balmer breaks ($\gtrsim 1.5$ dex, J. F. W. Baggen et al. 2024). At the same time, the very compact sizes inferred by their photometric light profiles (~ 10 – 100 pc, see J. F. W. Baggen et al. 2024) imply surprising compactness and densities for galaxies of these masses. As implied by recent works, the combination of such stellar mass estimates and compact sizes would imply a population that is unclear to be stable with such high stellar densities. In detail, C. A. Guia, F. Pacucci & D. D. Kocevski (2024) finds that the stellar density distribution of a sample of 434 LRDs compiled in D. D. Kocevski et al. (2023) and H. B. Akins et al. (2025) peaks at $\sim 10^4 M_\odot \text{pc}^{-3}$, a value 6 orders of magnitudes higher than the derived for the solar neighbourhood, and they report values as high as $10^9 M_\odot \text{pc}^{-3}$. Interestingly, if existed, these stellar systems would rapidly suffer from mass segregation, and would lead to the formation of a very massive star that would leave behind a massive black hole seed of $10^4 M_\odot$ (F. Pacucci, L. Hernquist & M. Fujii (2025); M. C. Vergara et al. (2025), offering a distinct channel for heavy seed formation. In addition, if the photometric ‘V-shape’ is due to stellar continua, then LRDs may harbor evolved (i.e. ‘red’) stellar populations (D. J. Setton et al. 2024a). This appears in contrast with their blue rest-frame UV–optical colours, which suggest young (i.e. ‘blue’) stellar populations. Reconciling these two aspects requires that at least a fraction of the light emitted by young stellar populations is absorbed and reprocessed (into the IR) by dust in the interstellar medium (ISM; see e.g. P. G. Pérez-González et al. 2024b). Nevertheless, the large dust masses needed to support this picture are at stake with the reported lack of FIR detections for LRDs (C. M. Casey et al. 2025; D. J. Setton et al. 2025; M. Xiao et al. 2025).

Interestingly, spectroscopic observations add further complexity to this picture, as a significant fraction of LRDs exhibit broad Balmer $H\alpha$ and $H\beta$ emission lines, with typical full widths at half maximum (FWHM) of $\sim 10^3 \text{ km s}^{-1}$ (e.g. V. Kokorev et al. 2023; R. L. Larson et al. 2023; X. Lin et al. 2024; H. B. Akins et al. 2025). Recent works have tentatively explained these line widths as an effect of galactic dynamics within ultra-compact, star-forming galaxies (J. F. W. Baggen et al. 2024). Alternatively, by interpreting broad lines as indicative of AGN activity, numerous works inferred the mass and luminosity of MBHs responsible for their emission. Currently reported values lie in the $10^7 \lesssim M_{\text{BH}}/M_\odot \lesssim 10^9$ and $10^{44} \lesssim L_{\text{bol}}^{\text{AGN}}/\text{erg/s} \lesssim 10^{46}$ ranges, typical of a mature AGN population (Y. Harikane et al. 2023; V.

Kokorev et al. 2023; J. Matthee et al. 2024; R. Tripodi et al. 2025; J. E. Greene et al. 2026; A. J. Taylor et al. 2025). However, LRDs do not show significant variability in the rest-frame UV–optical, as would be common for typical AGN of similar luminosity and mass. More in detail, the variability time-scales inferred for LRDs appear to be larger than ~ 1 yr (M. Kokubo & Y. Harikane 2025; L. J. Furtak et al. 2025; W. L. Tee et al. 2025). Furthermore, AGN with masses and luminosity comparable to those reported for LRDs would typically appear as X-ray bright sources (D. Weedman et al. 2012; K. K. Gupta et al. 2024; M. Laurenti et al. 2024). Nevertheless, LRDs have so far eluded X-ray detections. This fact, together with their measured low variability, has fuelled speculation that LRDs may be MBHs accreting at super-Eddington rates (F. Pacucci & R. Narayan 2024a; K. Inayoshi, K. Murase & K. Kashiyama 2025; D. Kido et al. 2025; P. Madau 2025). On the other hand, the X-ray weakness may be attributed to significant dust obscuration of the central source, which could also help explain the red optical–IR colours observed in LRDs (K. Inayoshi & K. Ichikawa 2024; M. Yue et al. 2024; F. Pacucci & R. Narayan 2024b). Nevertheless, this picture is again in contrast with the observed blue spectra at UV–optical wavelengths as well as with the lack of strong FIR detections (C. M. Casey et al. 2025; D. J. Setton et al. 2025; M. Xiao et al. 2025). In addition, spectroscopic observations of LRDs showing only narrow lines have also been reported, suggesting that the origin of red photometric colours may be due to the contribution of strong galactic emission lines (see e.g. Z. Zhang et al. 2026).

The difficulty to fit together all these observed features in a single, coherent picture leaves open the possibility that LRDs may represent a complex, multi-face population of objects belonging to a previously unobserved stage of early galaxy formation and galaxy–AGN co-evolution. Therefore, addressing the challenge posed by these objects to current models is an effort which has attracted the keen interest of research communities focusing on galaxy and AGN evolution, both on the observational and theoretical sides. So far, a wide array of possible explanations have been proposed within the rapidly evolving context provided by *JWST* observations. Early works based on NIRCcam and NIRSspec focused on interpreting LRDs properties as produced by either dusty star-forming galaxies (e.g. F. Gentile et al. 2024; M. Xiao et al. 2025), heavily obscured AGN (e.g. C. M. Casey et al. 2024; K. Inayoshi & R. Maiolino 2025) or a combination of both galaxies and AGN (e.g. M. Killi et al. 2024; G. C. K. Leung et al. 2025; J. F. W. Baggen et al. 2024; M. Brooks et al. 2025). In the latter case, the blue colours are typically ascribed to AGN components, either observed directly (thanks to a favourable viewing angle, see e.g. J. E. Greene et al. 2024) or reflected by dense gas surrounding the central engine (whose direct view would be obscured by a dense dusty torus, see J. E. Greene et al. 2024). As discussed above, each of these interpretations has its advantages and shortcomings, with the combined model possibly joining the best of the galaxy-only and AGN-only explanations. Nevertheless, even the combined galaxy–AGN model struggles to account for key observational features, such as the lack of X-ray and FIR detections or the low UV–optical variability. More recently, models which deviate from standard galaxy/AGN-based explanations have been put forward to address the uncommon observed properties of LRDs. These alternatives generally focus on the interaction between a growing MBH and dense gas surrounding it. Within these systems, the emission due to mass accretion onto the MBH would be heavily absorbed by the surrounding gas, naturally producing some of the observed properties typical of LRDs, such as a promi-

nent Balmer break, X-ray weakness and a lack of significant dust emission (see e.g. K. Inayoshi & R. Maiolino 2025; D. Kido et al. 2025; V. Rusakov et al. 2026).

The impressive amount of observational data with such a difficult interpretation has given a strong impulse to the development of numerical simulations and theoretical models aimed at interpreting LRDs. One common approach is to compare the results of current numerical simulations with the overall constraints provided by *JWST* regarding the properties of LRDs, such as their global number densities, typical luminosity as well as BH or galaxy masses (e.g. M. Habouzit et al. 2022; A. Trinca et al. 2024; S. Bonoli et al. 2025; M. Habouzit 2025; K. Inayoshi 2025; P. LaChance et al. 2026). Alternatively, recent works have tackled the direct simulation of LRD photometric properties, offering a more direct comparison with *JWST* observations. M. Volonteri et al. (2025) recently analysed the simulated photometry of AGN and galaxies extracted from the OBELISK simulation. This work showed that attenuated AGN SEDs can explain the ‘V-shaped’ photometric profiles of LRDs, especially in the case of luminous AGN and moderate dust attenuation. This work employs a detailed framework to compute realistic photometric properties of LRDs, based on theoretical models for the emission of AGN and galaxies (see similar results in P. LaChance et al. 2026, by using the ASTRID simulation). On the other hand, recent works have tried to expand these efforts by modelling the photometric counterparts of less standard objects. For instance, E. Cenci & M. Habouzit (2025) followed the first phases of gas infall and star formation within halos that produce massive BH-seeds, showing that this process may go through initial phases characterized by a dense, central gas formation with photometric properties similar to those typical of LRDs. On similar lines, the recent work of K. Inayoshi et al. (2025) explored the possibility that LRDs correspond to the first MBHs forming and accreting within a dense gas obscurer, with the concurring formation of a nuclear stellar cluster, and L. Zwick, C. Tiede & L. Mayer (2025) picture LRDs as supermassive stars surrounded by massive self-gravitating accretion discs.

Overall, the accurate replication of *JWST* observations is made difficult by several factors. On one side, the inherent uncertainty about LRDs nature requires to push current models to the limit in order to mimic their photometry and inferred physical properties. On the other hand, simulating at the same time the wide dynamic ranges and physical processes involved in the evolution of the first astrophysical objects over large cosmological volumes is out of reach for current hydrodynamical simulations. Therefore, the efforts to replicate *JWST* observations over a wide cosmological volume while taking into account the details of BH formation and galaxy evolution models have remained largely unexplored to date.

Our work tries to tackle this aspect by building a detailed simulation of the photometric properties of large LRDs populations at different redshifts. To this aim, we use the *L-Galaxies BH* galaxy-formation model, which was specifically developed to track in detail the formation and evolution of MBHs within a refined galaxy evolution model, applied to *N*-body merger-trees over cosmological volumes (S. Bonoli et al. 2025). Furthermore, *L-Galaxies BH* offers the possibility to build simulated mock-data (i.e. lightcones) of any photometric survey, such as those carried out by the *JWST* (D. Izquierdo-Villalba et al. 2019). In particular, we implement a detailed model to simulate the photometric properties of AGN within the context of *L-Galaxies BH* and build a *JWST*-like lightcone populated

with realistic galaxies and accreting MBHs. With this approach we aim at contextualizing LRDs within state-of-the-art models for the formation and evolution of galaxies and BHs. In particular, under the working hypothesis that LRDs are the observational counterparts of galaxies and AGN, we aim to provide a realistic comparison between *JWST* observations and the result of a state-of-the-art model. The main aim of this comparison is to gain insights about which physical processes drive the emergence of LRDs in the high-*z* universe and what is the context of LRDs within populations of objects not appearing as LRDs at similar redshifts. We underline that this effort is the first step into building a realistic comparison of the properties obtained by current theoretical models and *JWST* observations, over significantly large cosmological volumes. For this reason, we focus on the assumption that the photometry of LRDs (and, in general, high-*z* objects) can be explained by the combination of galaxy and AGN contributions. For simplicity, we refrain to directly explore more complex models which may explain the photometric properties of LRDs (e.g. K. Inayoshi et al. 2025), leaving this task to future works.

This paper is organized as follows: In Section 2, we describe our methods, which include the build-up of *JWST* mock data catalog with the *L-Galaxies BH* model. In Section 3, we describe how we associate a SED to galaxies and active MBHs. In Section 4, we detail the procedure to identify LRDs within our sample of galaxies and AGN. We present our main results in Section 5. Finally, we discuss the shortcomings and caveats of our model in Section 6 and present our conclusions Section 7. Throughout this paper, we use the cosmological parameters determined by the Planck Collaboration et al. (2014a): $\Omega_m = 0.315$, $\Omega_\Lambda = 0.685$, $\Omega_b = 0.045$, $\sigma_8 = 0.9$ and $h = H_0/100 = 67.3/100 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2 THE *L-GalaxiesBH* FORMATION MODEL

We base our analysis on the galaxy and MBH populations generated using the *L-Galaxies BH* semi-analytical model (SAM; recently presented in S. Bonoli et al. 2025). Briefly, the *L-Galaxies BH* framework builds on the version of *L-Galaxies* introduced by B. M. B. Henriques et al. (2015). The latter was specifically designed to self-consistently follow the cosmological assembly of galaxies. It incorporates a wide range of astrophysical processes within dark matter structures defined by merger trees extracted from *N*-body simulations. Crucially for this work, the recent developments presented in D. Izquierdo-Villalba et al. (2020, 2022) and D. Spinoso et al. (2023) enable the detailed modelling of the formation and evolution of both single and binary MBHs within a cosmological context, leading to the *L-Galaxies BH* model.

2.1 The dark matter merger trees

L-Galaxies BH was developed to run on both the Millennium (MS; V. Springel 2005) and Millennium-II (MSII, M. Boylan-Kolchin et al. 2009) merger trees (see S. Bonoli et al. 2025; D. Izquierdo-Villalba et al. 2025). In this work we use the latter, as our primary interest lies in relatively low-mass, high-redshift galaxies. MSII follows the cosmological evolution of 2160^3 DM particles with mass $6.885 \times 10^6 M_\odot h^{-1}$, within a periodic box of $100 \text{ Mpc}/h$ on a side (M. Boylan-Kolchin et al. 2009). The MSII outputs were recorded at 68 discrete *snapshots*, at which DM halos were identified. These structures are defined as gravitationally bound groups of particles with a minimum

mass of $\sim 10^7 M_\odot h^{-1}$ (20 particles). The simulation was originally run under the WMAP1 + 2dFGRS ‘concordance’ Λ CDM cosmology (D. N. Spergel et al. 2003). However, we apply the technique of R. E. Angulo & S. D. M. White (2010) to rescale the results to the cosmological parameters inferred from the Planck first-year data release (Planck Collaboration et al. 2014b), adopted in this work. This allows us to trace the cosmological assembly of galaxies hosted in halos with masses between $\sim 10^8 M_\odot h^{-1}$ and $\sim 10^{14} M_\odot h^{-1}$, within an effective box size of $96 \text{ Mpc } h^{-1}$.

2.2 The baryonic treatment

L-Galaxies BH follows the framework presented in S. D. M. White & C. S. Frenk (1991), assuming that galaxy formation begins at the centers of DM halos. Specifically, once a dark matter halo collapses, a fraction of the surrounding baryonic matter falls into its gravitational potential well. During this infall, the baryons are shock-heated, leading to the formation of a hot gaseous atmosphere. The latter gradually cools down according to a metallicity-dependent cooling function, leading to the formation of a cold gas disc structure. The disc grows in mass until it becomes massive enough to trigger star formation (SF), building up a stellar disc. SF episodes self-regulate the galaxy growth by heating and ejecting cold gas through supernova explosions of massive and short-lived stars. Moreover, the central MBH also contributes to the regulation of galaxy assembly by releasing energy during the quiescent accretion of the galaxy hot gas. In addition to discs, galaxies can develop stellar bulges thanks to either galaxy mergers,¹ or disc instabilities (DIs)² Besides these processes, *L-Galaxies BH* also accounts for environmental effects such as gas stripping and galaxy tidal disruptions.

We stress that the time resolution offered by the MSII snapshots,³ is too coarse to accurately track the baryonic physics involved in galaxy evolution. To overcome this, *L-Galaxies BH* performs an internal time discretization between two consecutive snapshots by defining *substeps* of approximately $\sim 5 - 20 \text{ Myr}$ of time resolution, depending on redshift.

2.3 Massive black holes: formation and growth

L-Galaxies BH includes a detailed description about the genesis (usually referred to as ‘BH-seeding’) and growth of MBHs. Regarding the seeding, *L-Galaxies BH* uses the model presented in D. Spinoso et al. (2023) and Spinoso et al. (in prep), which describes the formation of BH seeds either within the first collapsing halos at $z > 6 - 8$ or within the remnant of major galaxy mergers. The former case encompasses three plausible scenarios for MBH formation, which are highly dependent on the local physical conditions of the intergalactic medium (IGM), traced

¹The SAM uses the baryonic mass ratio of the interacting galaxies to differentiate between major and minor mergers (ratio > 0.2 and < 0.2 , respectively). The former destroy the discs of the two galaxies, leading to a pure spheroidal remnant. In minor mergers, the disc of the larger galaxy survives and its bulge incorporates the entire stellar mass of the less massive galaxy.

²The DI are accounted by the analytic stability criterion of G. Efstathiou, G. Lake & J. Negroponte (1982). If satisfied, the disc stellar mass is transferred to the bulge to restore the disc stability.

³This time resolution corresponds to time intervals of about $\sim 50 - 100 \text{ Myr}$ at $z > 6$ and $\sim 100 - 400 \text{ Myr}$ at $z < 6$.

self-consistently (see D. Spinoso et al. 2023). Seeding scenarios in *L-Galaxies BH* include: (i) Light-seeds, namely black holes formed from the first generation of PopIII stars (see e.g. R. S. Klessen & S. C. O. Glover 2023, for a review), (ii) Intermediate-mass seeds, i.e. MBHs with initial masses of $\sim 10^{3-4} M_\odot$ which are predicted to form within the first, compact, stellar clusters (e.g. Y. Sakurai et al. 2017; B. Reinoso et al. 2018; A. Askar, M. B. Davies & R. P. Church 2021), and finally (iii) Heavy seeds, i.e. compact objects with masses of $\sim 10^{4-5} M_\odot$ which are thought to form via the direct collapse of pristine gas clouds which did not undergo early gas cooling and fragmentation (see e.g. M. A. Latif & A. Ferrara 2016; A. Smith, V. Bromm & A. Loeb 2017; K. Inayoshi, E. Visbal & Z. Haiman 2020, for recent reviews). On the other hand, massive BH seeds of $8 \times 10^4 M_\odot$ forming in the aftermaths of galaxy mergers are modelled as in S. Bonoli, L. Mayer & S. Callegari (2014), although recent works showed that these objects can reach masses of up to $\sim 10^8 M_\odot$ (see e.g. L. Zwick et al. 2023; L. Mayer et al. 2024). These extreme objects may form thanks to the strong, multi-scale inflows produced by gravitational torques during gas-rich mergers (see e.g. P. R. Capelo & M. Dotti 2017; L. Mayer & S. Bonoli 2019).

Once the MBH is seeded in a (proto-)galaxy, the model assigns it a random spin χ . The evolution of the latter is then tracked after MBHs coalescence and gas accretion as in D. Izquierdo-Villalba et al. (2020). Among these two processes, cold gas accretion largely drives the growth of MBHs. This channel is triggered by either galaxy mergers or DIs, each of them driving a specific fraction of the galaxy cold gas towards the galactic center. This enables the formation of a gas reservoir around the MBH (M_{res} , D. Izquierdo-Villalba et al. 2020) which gets progressively consumed in time according to the two-phases model presented in D. Izquierdo-Villalba et al. (2024). In brief, during the first accretion phase, cold gas can be accreted at Eddington-limited rates (A. S. Eddington 1917) or at higher rates (super-Eddington), depending on the environment in which the MBH is embedded. The environmental dependence of gas accretion is evaluated in terms of: i) the ratio between the MBH mass and the amount of gas in the reservoir around it (i.e. $\mathcal{R} = M_{\text{res}}/M_{\text{BH}}$) and ii) the strength of gas inflows induced by galaxy mergers or DIs, namely: $\dot{M}_{\text{inflow}} = \Delta M_{\text{BH}}^{\text{gas}}/t_{\text{dyn}}$, where t_{dyn} is the dynamical time and $\Delta M_{\text{BH}}^{\text{gas}}$ is the fraction of gas added to the MBH gas reservoir. When \mathcal{R} and \dot{M}_{inflow} are larger than 2×10^4 and $10 M_\odot \text{ yr}^{-1}$, respectively a super-Eddington event is triggered. This is characterized by an $f_{\text{Edd}} = L_{\text{bol}}^{\text{AGN}}/L_{\text{Edd}}$:

$$f_{\text{Edd}} = B(\chi) \left[\frac{0.985}{\dot{M}_{\text{Edd}}/\dot{M} + C(\chi)} + \frac{0.015}{\dot{M}_{\text{Edd}}/\dot{M} + D(\chi)} \right], \quad (1)$$

where $L_{\text{bol}}^{\text{AGN}}(L_{\text{Edd}})$ are the MBH bolometric (Eddington) luminosity, \dot{M} (\dot{M}_{Edd}) are the (Eddington) accretion rates and the $B(\chi)$, $C(\chi)$, $D(\chi)$ functions are taken from P. Madau, F. Haardt & M. Dotti (2014). In case the super-Eddington conditions are not fulfilled, an Eddington-limited accretion episode (i.e. $f_{\text{Edd}} = 1$) is triggered instead. The second accretion phase starts when the MBH consumes a fraction, $\mathcal{F} = 0.7$, of the initial M_{res} (i.e. the one determined at the beginning of the first accretion phase). During this stage, the evolution of f_{Edd} is characterized by

$$f_{\text{Edd}} = \left[1 + \left((t - t_0)/t_Q \right)^{1/2} \right]^{-2/B}, \quad (2)$$

where $t_Q = t_d \xi^B / (B \ln 10)$, with $t_d = 1.26 \times 10^8 \text{ yr}$, $B = 0.4$, and $\xi = 0.3$ (see D. Izquierdo-Villalba et al. 2020, for further details about the parameter choice).

2.4 Building the lightcone

In this work, we employ the method described in D. Izquierdo-Villalba et al. (2019) to convert the cosmological comoving box generated by *L-Galaxies BH* into a lightcone, i.e.: a simulated universe in which galaxies are positioned self-consistently in right ascension, declination, and redshift (we refer to D. Izquierdo-Villalba et al. 2019, for details not included in this section).

In short, we generate a lightcone by exploiting the periodic boundary conditions of the MSII. This involves replicating the box simulated by *L-Galaxies BH* at different redshifts in such a way that a custom set of replicas is built. The specific number of replicas required along each Cartesian direction to cover the whole lightcone volume depends on the area, redshift extend and specific orientation of the lightcone viewing angle. The latter is determined in order to minimize the box repetitions within the lightcone volume, following the method of M. G. Kitzbichler & S. D. M. White (2007). By defining the lightcone orientation as $\hat{u} = (n, m, nm)/|(n, m, nm)|$, the two co-prime integers n and m can be chosen to minimize the intersection of the lightcone volume with the box replicas. We fix $n = 5$ and $m = 9$, which provide $(RA, DEC) = (60.95, 77.1)$ deg as the lightcone line of sight. We choose a squared shape for our footprint, with extension $(\delta RA, \delta DEC) = (5, 5)$ deg, corresponding to 5.62 deg^2 (i.e. a factor of ~ 60 larger than what analysed in V. Kokorev et al. 2024). This is a compromise between the simulated sky area and the execution time of *L-Galaxies BH* when producing our lightcone.

Finally, having fixed the lightcone geometry, during the *L-Galaxies BH* execution, galaxies are selected to be part of the mock data catalog by determining the *substep* (see Section 2.2 for the definition of *substep*) at which they cross the observer past lightcone. With this method, we build a mock catalog which includes objects simulated by *L-Galaxies BH* at $z > 4$. In Fig. 1 we showcase the distribution of galaxies within our lightcone.

2.5 The galaxy and MBH populations: model validation

In this section, we validate the populations of galaxies and MBHs which make part of our lightcone. Fig. 2 shows three global statistics computed within two broad redshift bins: $4.5 \leq z < 6.5$ and $6.5 \leq z \leq 8.5$ (left and right column). The top panels display the predicted stellar mass function (SMF), which shows good agreement with observational data. The discrepancies between our predictions and observations at the high-mass end are due to the limited volume of the MSII box, which hinders the sampling of rare, high-density peaks of the DM field where the most massive galaxies are expected to reside.

The middle panels display the AGN bolometric luminosity ($L_{\text{bol}}^{\text{AGN}}$) function (AGN LF). As with the SMF, the model provides a good match to the observed data, in particular to the luminosity function of X. Shen et al. (2020). Recent results from *JWST* observations (including broad-line LRDs) and from deep X-ray data (C. L. Barlow-Hall & J. Aird 2025), point to higher normalization than previously estimated, in particular at very high- z . Indeed, the largest deviations with respect to our models occur at $z > 6.5$, where the model under-predicts the luminosity reported by J. E. Greene et al. (2024) and V. Kokorev et al. (2024). Note that the J. E. Greene et al. (2024) data were reanalysed in J. E. Greene et al. (2026) using a different bolometric correction,

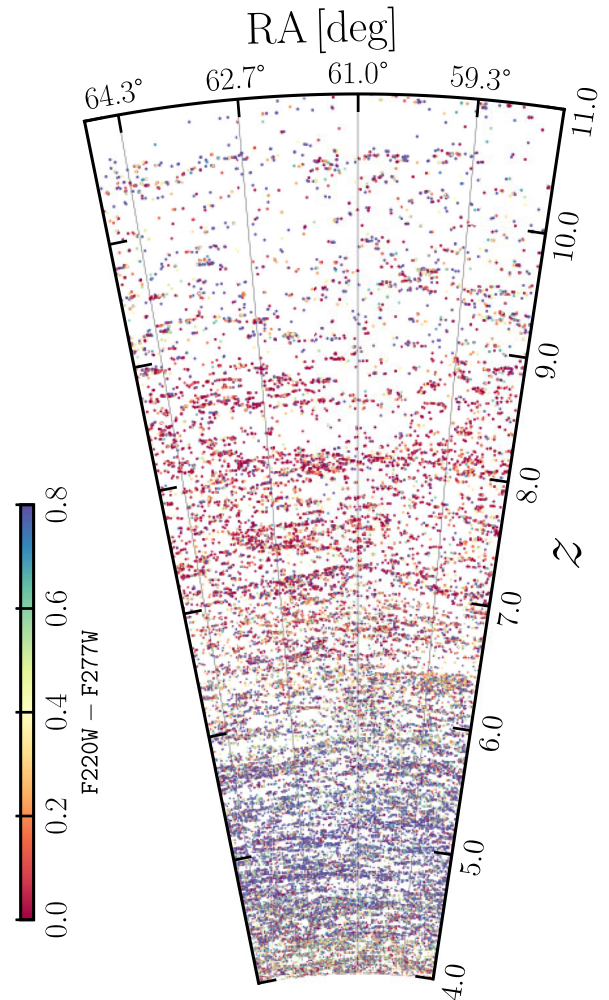


Figure 1. Distribution of galaxies in redshift (z) and right ascension (RA) for a thin slice in declination (DEC) of the *JWST* lightcone used in this work. Each point is colour-coded by its $F220W - F277W$ colour to provide a qualitative idea of the colour shift induced at $z \sim 6$ by different spectral features affecting the $F220W$ and $F277W$ filters.

providing measurements fainter by 1 dex, which are in better agreement with our predictions. Finally, at the highest redshifts and luminosity, we are again limited by the MSII box volume: S. Bonoli et al. (2025) used the combined trees from the MSII and Millennium simulation and obtained a broader dynamical range also in $L_{\text{bol}}^{\text{AGN}}$.

Finally, the bottom panels show the predicted MBH mass function (BHMF), which also shows overall good agreement with respect to the values reported by V. Kokorev et al. (2024) and J. Matthee et al. (2024), derived from virial MBH-mass estimates from LRDs. We observe a slight deviation from these data at $M_{\text{BH}} \sim 10^7 M_{\odot}$, although recent evidence suggests that measured values in the literature may be overestimated (A. Lupi et al. 2024; J. E. Greene et al. 2026; V. Rusakov et al. 2026).

We underline that current constraints regarding the properties of high- z galaxies and AGN are rapidly evolving fields. Therefore, updated observations may provide different constraints, which may eventually require further model calibration. Additionally, advanced techniques in handling DM simulation outputs, like the

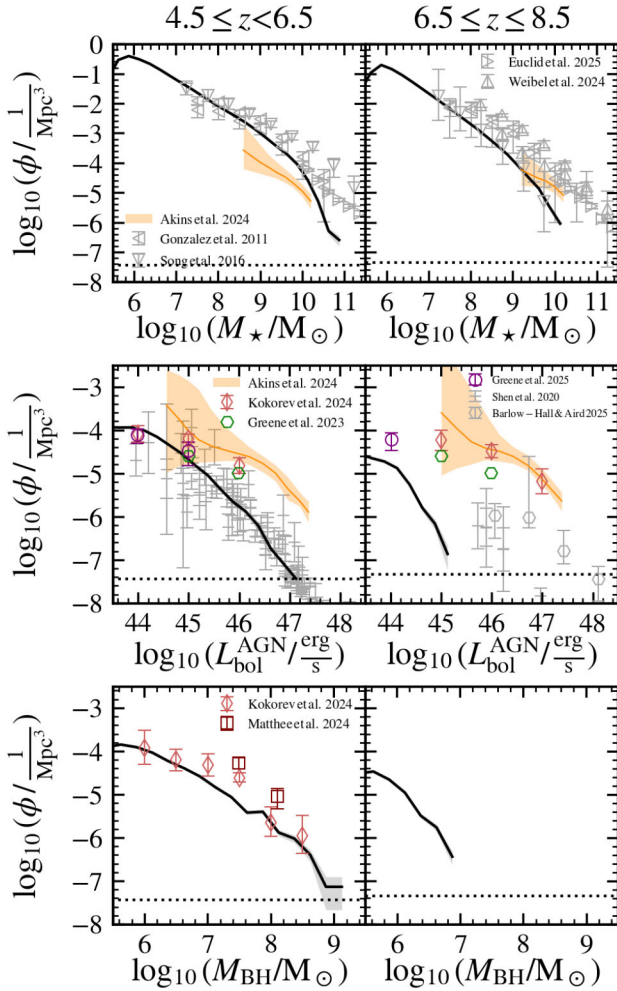


Figure 2. Population of galaxies and MBHs in the simulated lightcone at $4 \leq z < 6.5$ (left column) and $6.5 \leq z < 8.5$ (right column). **Upper row:** Comparison between the predicted stellar mass function (black line) and the observational constraints of V. González et al. (2011); M. Song et al. (2016) and H. B. Akins et al. (2025). **Middle row:** Predicted AGN bolometric luminosity function (black line) and observations from X. Shen et al. (2020); J. E. Greene et al. (2024); V. Kokorev et al. (2024); H. B. Akins et al. (2025); C. L. Barlow-Hall & J. Aird (2025) and J. E. Greene et al. (2026). **Lower row:** Predicted black hole mass function. The results are compared with V. Kokorev et al. (2024); J. Matthee et al. (2024). coloured literature data relate to LRDs.

grafting technique explored in S. Bonoli et al. (2025) can help alleviating the tension found in the highest redshift bins, increasing the number of massive and bright MBHs, as mentioned above. Up to this point, we have compared the outputs of *L-Galaxies BH* to literature data directly, that is: without replicating the exact selection effects under which the latter are obtained. In the following sections, we will detail the MBH SED modelling introduced and photometric selections applied to the *L-Galaxies BH* galaxies and MBHs. This will allow us to perform a realistic comparison with observations as well as to disentangle the contribution of active MBHs within the LRD population.

3 SYNTHETIC SPECTRA AND PHOTOMETRY OF AGN AND GALAXIES

Accurate modelling of the emission from both galaxies and AGN is essential for studying photometrically selected LRDs. In this section, we describe our method to construct the SEDs of galaxies and accreting MBHs within our simulated lightcone. The SED of each object is composed of five main components: galaxy continuum, galaxy emission lines, AGN continuum, AGN torus emission, and AGN emission lines (both broad and narrow). All components include the effects of attenuation due to absorption by dust and atomic gas within the ISM along the line of sight.

3.1 The spectral energy distribution of galaxies

Here we outline the procedure followed to simulate galaxy SEDs. This includes models for (i) the galaxy stellar continuum, (ii) emission lines from star-forming H II regions, and (iii) the effect of dust and gas absorption on both these components. Fig. 3 shows the resulting SEDs (including emission lines) of two $z \sim 6$ galaxies in our lightcone, each with $M_* \sim 10^8 M_\odot$. To illustrate the impact of the ISM, two different lines of sight (LOS) are considered.

3.1.1 The galaxy continuum: emission and attenuation

L-Galaxies BH predicts a wide range of intrinsic properties for each simulated galaxy, such as its stellar mass, SF history, age, and metallicity. To convert these intrinsic quantities into an observed SED, the SAM uses evolutionary population synthesis prescriptions. These are implemented via Simple Stellar Populations (SSPs) models, which predict the time-evolution of the SED emitted by a single star-formation burst of a given mass and metallicity, after assuming an initial mass function (IMF). Consequently, the simulated SEDs of galaxies in a given redshift are obtained by a superposition of SSPs along the galaxy star formation history. Following B. M. B. Henriques et al. (2015), *L-Galaxies BH* uses the C. Maraston (2005) synthesis model with the G. Chabrier (2003) IMF.

Once the galactic continuum emission is computed based on the galaxy evolutionary pathway, the attenuation of this stellar light by dust is accounted following the approach of G. De Lucia & J. Blaizot (2007). As in B. M. B. Henriques et al. (2015), *L-Galaxies BH* assumes that extinction arises from both the diffuse ISM and molecular clouds. The ISM optical depth $\tau_\lambda^{\text{ISM}}$ is computed following the prescription of J. E. G. Devriendt, B. Guiderdoni & R. Sadat (1999), which relates the dust column density to key galaxy properties:

$$\tau_\lambda^{\text{ISM}} = (1+z)^{-1} \left(\frac{A_\lambda}{A_V} \right)_{z_\odot} \left(\frac{Z_{\text{gas}}}{Z_\odot} \right)^s \left(\frac{\langle N_H \rangle}{2.1 \times 10^{21}} \right), \quad (3)$$

where Z_{gas} is the gas metallicity⁴ and $\langle N_H \rangle$ is the mean column density of hydrogen defined as

$$\langle N_H \rangle = \frac{M_{\text{cold}}^{\text{gas}}}{1.4 m_p \pi (aR_{\text{d,gas}})^2}, \quad (4)$$

⁴Note that the metallicity dependence is motivated by B. Guiderdoni & B. Rocca-Volmerange (1987) and sets $s = 1.35$ for $\lambda < 2000 \text{ \AA}$ and $s = 1.6$ for $\lambda > 2000 \text{ \AA}$.

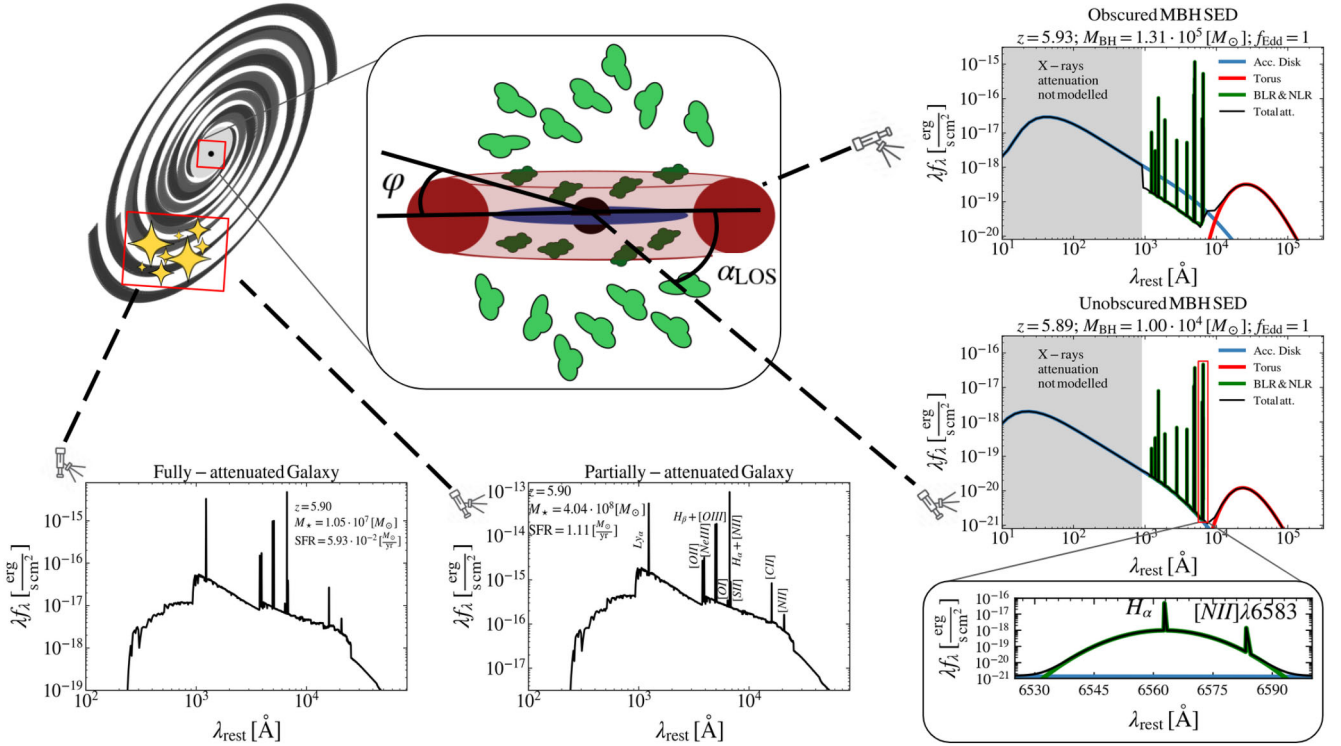


Figure 3. Schematic illustration of the SED components in our galaxy and AGN modelling. On the bottom left we show the SEDs of two galaxies corresponding to different lines of sight (α_{LOS}): one directly towards the ISM and another with a more direct view of the disc plane. On the right, we show a zoom into the nuclear MBH configuration adopted. Different colours in the spectra correspond to different regions of the AGN structure: blue for the accretion disc, red for the torus, and green for the BLR and NLR. In black, we show the total observed SED (i.e. the MBH emission obscured and/or attenuated). Two α_{LOS} are provided, corresponding to the regime of obscuration ($\varphi \leq \alpha_{\text{LOS}}$) and another to non-obscuration ($\varphi > \alpha_{\text{LOS}}$). On the bottom right, we show a zoom-in to the line profiles of $H\alpha$ (6563 Å) and $[\text{N II}]$ (6583 Å) lines.

with $R_{\text{d,gas}}$ being the scale-length of the cold gas disc. The 1.4 factor accounts for the presence of helium, and a is set to 1.68 in order for $\langle N_{\text{H}} \rangle$ to represent the mass-weighted average column density of an exponential disc. We note that the redshift dependence in equation (3) is chosen to reproduce luminosity functions and extinction estimates for Lyman-break galaxies at $z > 5$ (see S. J. Clay et al. 2015; B. M. B. Henriques et al. 2015). Regarding the dust attenuation law, we tested both the one provided by C. M. Gaskell & A. J. Benker (2007) and by K. D. Gordon et al. (2003), with an $R_V = 2.505$ (see similar approach in X. Ji et al. 2025; G. C. Jones et al. 2026). Both of these are common choices in the recent literature focusing on the modelling of high- z galaxies and LRDs. Based on our BHMF, AGN LF, and SMF, we decided to use the one of C. M. Gaskell & A. J. Benker (2007), as it fits better the observational data, although we find very little difference.

Taking into account equations (3) and (4), and assuming a slab geometry for the disc, the mean absorption coefficient can be written as

$$A_{\lambda}^{\text{ISM}} = -2.5 \log_{10} \left(\frac{1 - e^{-\tau_{\lambda}^{\text{ISM}} \csc \alpha_{\text{LOS}}}}{\tau_{\lambda}^{\text{ISM}} \csc \alpha_{\text{LOS}}} \right), \quad (5)$$

where α_{LOS} is the angle between the observer (placed at the corner of the first replica of the MSII box) and the angular momentum vector of the galaxy disc. The variable \csc refers to the co-secant of the α_{LOS} angle. For the molecular cloud component, the model assumes that dust grains embedded within these dense regions

attenuate the light emitted by newly formed stars. To account for this effect, *L-GalaxiesBH* assumes that stars with lifetimes shorter than the typical lifetime of their birth clouds ($\sim 10^7$ yr) are subject to additional attenuation, following the prescription of S. Charlot & S. M. Fall (2000). Specifically, the mean absorption coefficient is given by

$$A_{\lambda}^{\text{BC}} = -2.5 \log_{10} \left(e^{-\tau_{\lambda}^{\text{BC}}} \right). \quad (6)$$

where

$$\tau_{\lambda}^{\text{BC}} = \tau_{\lambda}^{\text{ISM}} \left(\frac{1}{\mu} - 1 \right) \left(\frac{\lambda}{5500 \text{ \AA}} \right)^{-0.7}, \quad (7)$$

and μ is given by a random Gaussian deviate with mean 0.3 and standard deviation 0.2, truncated at 0.1 and 1 (see B. M. B. Henriques et al. 2015, for further details).

We note that *L-GalaxiesBH* separately tracks the stellar emission produced by stars in the galactic bulge and in the disc. As the SAM assumes that only the latter component contains cold gas, we only apply ISM attenuation to the disc stellar emission. In contrast, molecular cloud attenuation affects young stars in both the disc and the bulge.⁵ We note that this distinction in ISM attenuation has a negligible impact on our results, as the majority of high- z galaxies in our sample are either bulgeless or have only a minor bulge component.

⁵Following B. M. B. Henriques et al. (2015), birth cloud attenuation for the stars in the bulge is applied as a fixed value of $A_{\lambda}^{\text{BC}} = -2.5 \log_{10}(0.5)$.

3.1.2 The galaxy emission lines

Following D. Izquierdo-Villalba et al. (2019), we also include the contribution of nine different nebular emission lines in the galaxy SED: Ly α (1216 Å), H β (4861 Å), H α (6563 Å), [O II] (3727Å, 3729Å), [O III] (4959Å, 5007Å), [Ne III] (3870Å), [O I] (6300Å), [N II] (6548 Å, 6583 Å), and [S II] (6717 Å, 6731 Å). To this end, we use the model presented in Á. Orsi et al. (2014) which uses as a foundation the E. M. Levesque, L. J. Kewley & K. L. Larson (2010).⁶ model grid of H II regions. Based on that grid, the luminosity of each emission line is fully characterized by four different parameters: (i) age of the stellar cluster that provides the ionizing radiation (t_*), (ii) density of the ionized gas (n_e), (iii) galaxy gas-phase metallicity (Z_{cold}), and iv) ionization parameter (q). For t_* and n_e we assume constant values ($t_* = 0$ and $n_e = 10 \text{ cm}^{-3}$, see Á. Orsi et al. 2014 for further details). Conversely, the values of q and Z_{cold} are directly set by the cold gas metallicity predicted by `L-GalaxiesBH` adopting:

$$q(Z) = q_0 \left(\frac{Z_{\text{cold}}}{Z_0} \right)^{-\gamma} \quad (\text{cm s}^{-1}), \quad (8)$$

where q_0 , Z_0 , and γ are free parameters set to $2.8 \times 10^7 \text{ cm s}^{-1}$, 0.012 and 1.3, respectively, to match observational measurements of H α , [O II], and [O III] luminosity functions (Á. Orsi et al. 2014; D. Izquierdo-Villalba et al. 2019). Finally, following D. Izquierdo-Villalba et al. (2019), we assume that the profiles of galactic emission lines can be approximated as Dirac delta functions.

As shown by D. Izquierdo-Villalba et al. (2019), it is necessary to consider dust attenuation onto the line-emission luminosity in order to correctly recover the observed line-luminosity functions at $z < 1.5$. This model closely follows equation (5) but with a different assumption for the optical depth, $\tau_\lambda^{\text{line}}$:

$$A_\lambda^{\text{line}} = -2.5 \log_{10} \left(\frac{1 - e^{-\tau_\lambda^{\text{line}} \text{csc} \alpha_{\text{LOS}}}}{\tau_\lambda^{\text{line}} \text{csc} \alpha_{\text{LOS}}} \right), \quad (9)$$

where $\tau_\lambda^{\text{line}}$ depends on the cold gas metallicity as

$$\tau_\lambda^{\text{line}} = C(z) \frac{A_V}{A_B} \frac{A_\lambda}{A_V}, \quad (10)$$

where the values of A_V/A_B and A_λ/A_V are computed based on the same attenuation law chosen for the ISM (see Section 3.1.1). Finally, $C(z)$ is a free parameter set to $C(z) = 161.46 e^{-(0.46 z)}$ calibrated to reproduce the redshift evolution of [O II], [O III], H β , and H α observed luminosity functions (see the appendix of D. Izquierdo-Villalba et al. 2019, for further details).

3.2 The spectral energy distribution of active MBHs

The standard version of `L-Galaxies BH` (S. Bonoli et al. 2025) does not include any SED modelling for the emission of accreting MBHs. In this section, we introduce an AGN emission model to overcome this limitation. Particularly, our AGN SED model includes four main components: (i) the continuum emission from the accretion disc surrounding the accreting MBHs, (ii) the IR emission due to the reprocessing of rest-frame UV-optical light by dust, (iii) emission lines from both narrow and broad line regions

⁶Á. Orsi et al. (2014) obtain theoretical SEDs of H II regions by pairing `Starburst99` (C. Leitherer & T. M. Heckman 1995) together with the `MAPPINGS-III` photoionization code (M. A. Dopita & R. S. Sutherland 1995, 1996; B. A. Groves, M. A. Dopita & R. S. Sutherland 2004).

(NLR and BLR, respectively), and (iv) the effect of dust and gas absorption on all the above components. One key component of the model is the development of a physically informed density profile for the accreted gas, which ultimately determines torus and line emission. To guide the reader, in Fig. 3, we present a schematic overview of the SED assigned to two active MBHs of $10^4 - 10^5 M_\odot$, both accreting at the Eddington limit. These objects are seen from two different viewing angles: one with a direct view of the central engine (unobscured), and the other with the line of sight intersecting the torus (obscured). A zoom-in between $6530 < \lambda < 6600 \text{ Å}$ highlights the resulting line profiles generated by our model (see following sections for details).

3.2.1 AGN continuum

The continuum of an accreting MBH is modelled using the method presented in T. Su et al. (2026)⁷, which computes AGN SEDs as a function of the accretion rate $\dot{m} = \dot{M}/\dot{M}_{\text{Edd}}$. In detail, different emission regimes are modelled depending on how \dot{m} compares to the critical threshold $\log_{10} \dot{m}_{\text{crit}} = -2.9^8$:

(i) At $\dot{m} < \dot{m}_{\text{crit}}$ a disc evaporation model is adopted (F. Meyer & E. Meyer-Hofmeister 1994), where the disc inner region is described by an advection-dominated accretion flow (ADAF), surrounded by an outer thin disc truncated at the radius r_t . The truncation radius is given by (R. E. Taam et al. 2012):

$$r_t = 17.3 \dot{m}^{-0.886} \alpha^{0.07} \beta^{4.61} [R_s], \quad (11)$$

where R_s is the MBH Schwarzschild radius. The accretion disc is optically thin and geometrically thick, and its emission, $L_{\nu, \text{disk}}$, is characterized by multicolour blackbody emission (N. I. Shakura & R. A. Sunyaev 1973):

$$L_{\nu, \text{disk}} = 2\pi h R_s \frac{v^3}{c^2} \int_{r_{\text{in}}}^{r_{\text{out}}} 4\pi r \left[\exp\left(\frac{h\nu}{k_B T(r)}\right) - 1 \right]^{-1} dr, \quad (12)$$

with an effective temperature, $T(r)$:

$$T(r) = \left[\frac{3\dot{M}_{\text{BH}} c^6}{64\pi \sigma_B G^2 M_{\text{BH}}^2} \right]^{1/4} \left[\frac{1}{r} \left(1 - \sqrt{\frac{3}{r}} \right) \right]^{1/4} [\text{K}], \quad (13)$$

where $r = R/R_s$, R is the radial distance to the MBH, k_B is the Boltzmann constant, h is the Planck constant, c is the speed of light, and ν is the rest-frame frequency. Conversely, the ADAF geometry is geometrically thick and optically thin, whose emergent spectra is computed using the self-similar solution of R. Narayan & I. Yi (1994, 1995) with the procedure presented in T. Manmoto, S. Mineshige & M. Kusunose (1997) and E. Qiao & B. F. Liu (2010, 2013).

(ii) At $\dot{m} \geq \dot{m}_{\text{crit}}$, a magnetic-reconnection heated disc-corona model is adopted. In brief, this model assumes that a thin accretion disc extends inward to the innermost stable orbit and is compressed by a planeparallel corona. In the T. Su et al. (2026) model, the energy equilibrium equations are solved for each annulus individually, rather than globally as in the original model (B. F. Liu, S. Mineshige & K. Shibata 2002; B. F. Liu, S. Mineshige & K. Ohsuga 2003). The modified model further considers super-Eddington accretion. As the BH accretion rate increases, an optically thick, radiative pressure-dominated, slim disc-like region

⁷<https://github.com/SuTong1999/agnSED>

⁸This is chosen to ensure continuous radiative efficiency between different accretion regimes, see T. Su et al. (2026) for details

would emerge in the inner part of the disc, replacing the disc-corona configuration, whose effective temperature adopts a modified version of the self-similar solution presented in K.-y. Watarai (2006), namely:

$$T(r) = 4.956 \times 10^7 C^{1/8} f^{1/8} \left(\frac{M_{\text{BH}}}{M_{\odot}} \right)^{-1/4} r^{-1/2} \text{ [K]}, \quad (14)$$

where $f \approx 1$ represents the fraction of the viscously dissipated energy cooled by advection, $C = 1 - \sqrt{3}/r$, M_{BH} the MBH mass, $r = R/R_s$ and R the distance from the central MBH.

3.2.2 The infrared emission: the torus structure

The SED described in the previous sections lacks the torus-like component, i.e. a dusty structure around the MBH, which is thought to be responsible for the IR bump seen in the spectra of an accreting MBH (R. Antonucci 1993; C. M. Urry & P. Padovani 1995). To account for that emission, a hot dusty torus is modelled following R. Barvainis (1987), which describes a smooth structure composed of graphite grains. These have a fixed radius of $a = 0.05 \mu\text{m}$, with a near-IR absorption efficiency curve characterized by $Q_v = q_{\text{IR}} \nu^\gamma$, where $q_{\text{IR}} = 1.4 \times 10^{-24}$ and $\gamma = 1.6$. Each grain emits as a blackbody with an IR luminosity of

$$L_{v,\text{IR}}^{\text{gr}} = 4\pi^2 a^2 Q_v B_v(T_{\text{gr}}) \text{ [erg/(s Hz)]}, \quad (15)$$

where B_v is the standard Planck law for the black-body spectrum. Under the ultraviolet (UV) radiation field generated by the MBH accretion disc, the dust grains reach an equilibrium, and the temperature profile of the overall dust-grain distribution can be described as

$$T_{\text{gr}} = 1587.1 \left(\frac{L_{\text{ion}}}{10^{46} \text{ erg/s}} \right)^{1/5.6} \left(\frac{r}{\text{pc}} \right)^{11.2} e^{-\tau_{\text{torus}}/5.6} \text{ [K]}, \quad (16)$$

where L_{ion} represents the total incident ionizing luminosity, expressed in erg s^{-1} . This radiation corresponds to the portion of the spectrum most effective at heating dust grains which we defined in our model as the integrated luminosity over the wavelength range from 912 \AA to 6564 \AA .⁹ The variable r represents the distance from the central MBH in parsecs, and τ_{torus} is the optical depth of the torus, defined as

$$\tau_{\text{torus}} = \pi a^2 \int_{r_1}^r n_{\text{gr}}(r') dr', \quad (17)$$

The variable n_{gr} corresponds to the radial density profile of the torus smoothly distributed as

$$n_{\text{gr}}(r) = n_{\text{gr},1} \left(\frac{r}{r_1} \right)^{-\beta}, \quad (18)$$

with $n_{\text{gr},1}$ being the grain density at the innermost torus radius r_1 , and β the slope of the distribution. The value of r_1 coincides with the sublimation radius and is defined as:

$$r_1 = r_{\text{subl}} = 1.17 \left(\frac{L_{\text{ion}}}{10^{46} \text{ erg/s}} \right)^{1/2} \left(\frac{T_{\text{subl}}}{1500 \text{ K}} \right)^{-2.8} \text{ [pc]}, \quad (19)$$

⁹At lower wavelengths, photodissociation effects play a role, which is beyond the scope of this work. On the contrary, longer wavelengths are not efficient for dust heating. In fact, one could argue that 6564 \AA is already a conservative value, but we did not find any strong arguments to stop the ionization earlier.

where T_{subl} corresponds to the innermost temperature of the torus fixed at 1500 K (see R. Barvainis 1987, for further details). Note that the factors in equation (16) and equation (19) differ from those of R. Barvainis (1987), as we have recomputed them to account for rounding inconsistencies in the original publication.

Taking into account equations (15), (16), (17) and (18), the total IR emission emitted by the torus can be written as

$$L_{v,\text{IR}} = \Omega \int_{r_1}^{r_2} n_{\text{gr}} L_{v,\text{IR}}^{\text{gr}} r^2 dr \text{ [erg/(s Hz)]}, \quad (20)$$

where r_2 corresponds to the outer extension of the torus and $\Omega = 2\pi [1 - \cos(2\varphi)]$ is the solid angle subtended by the torus as seen from the central source. The value of φ varies between $0 < \varphi < \pi/2$, implying that at $\varphi = 0$ ($\Omega = 0$) there is no torus obscuring the system. In contrast, when $\varphi = \pi/2$ ($\Omega = 4\pi$), the torus has a full coverage of the central MBH.

Consistent with Gravity Collaboration et al. (2024), we assume that the ratio r_2/r_1 is a random variable uniformly distributed between 2 and 20, implying a maximum outer radius of $r_2 = 20 r_{\text{subl}}$. Additionally, Gravity Collaboration et al. (2024) reported that the slope of the torus density profile is typically around 0.5 (see also E. Guise et al. 2022). Motivated by these results, we sample the parameter β from a normal distribution with a mean of 0.5 and a standard deviation of 0.1, restricting values to be strictly positive to avoid nonphysical torus configurations. In the following section, we introduce the model for the gas density profile required to determine the value of $n_{\text{gr},1}$. Given the self-similarity of AGN spectra across redshift, we assume these results to hold also at high- z . In particular, T. W. Jensen et al. (2016); A. Brodzeller et al. (2023) find a tight correlation between SED evolution with z and AGN bolometric luminosity, hinting that the underlying mechanisms that give rise to the different structures behind AGN emission remain similar.

3.2.3 The gas density profile

Motivated by the recent works of C. A. Dong-Páez et al. (2023) and M. Volonteri et al. (2025) we model the gas density profile around the MBH to determine the value of $n_{\text{gr},1}$. To this end, we assume that the gas distribution ρ_{gas} follows the form:

$$\rho_{\text{BH,gas}} = \rho_{0,\text{gas}} \left(\frac{r}{r_{\text{sg}}} \right)^{-\beta_g}, \quad (21)$$

where $\rho_{0,\text{gas}}$ is the central gas density, r_{sg} is the edge of the accretion disc, assumed to correspond with the self-gravity radius (A. Laor & H. Netzer 1989):

$$r_{\text{sg}} = 3586 \alpha^{2/9} \left(\frac{M_{\text{BH}}}{10^8 M_{\odot}} \right)^{-2/9} \left(\frac{R_s}{2} \right) f_{\text{Edd}}^{4/9} \text{ [pc]}, \quad (22)$$

where $\alpha = 0.1$. Finally, we assume that the steepness of the gas distribution is the same as for the torus profile, i.e.: $\beta_g = \beta$. This ensures that the resulting densities are consistent with those expected for the narrow-line region (NLR), and aligns with the interpretation that dust and gas are accreted (or at least influenced) by the gravitational potential of the central source, suggesting a non-nuclear origin for the material funnelled towards the MBH from larger galactic scales. However, we note that if dust were produced in situ by stars evolving within the nuclear region, this assumption would no longer hold. Exploring this scenario lies beyond the scope of this work. To find the value of $\rho_{0,\text{gas}}$, we

consider that

$$\dot{M}_{\text{BH}} \cdot t_{\text{ff}}(r_{\text{Bondi}}) = \int_{r_{\text{sg}}}^{r_{\text{Bondi}}} 4\pi r^2 \rho_{\text{BH,gas}}, \quad (23)$$

where \dot{M}_{BH} is the black hole accretion rate computed by `L-GalaxiesBH`, t_{ff} the free-fall time and r_{Bondi} the Bondi radius, defined as $r_{\text{Bondi}} = 2GM_{\text{BH}}/c_s^2$ where G is the gravity constant and $c_s \propto \sqrt{T_{\text{gas}}}$ is the sound speed. Since `L-GalaxiesBH` does not provide explicit predictions for T_{gas} , we adopt a simplified approach by assuming a fixed temperature of $T_{\text{gas}} = 10^6$ K. This prevents nonphysically large r_{Bondi} relative to the galaxy sizes at $z > 4$, and the resulting gas densities remain consistent with those found in NLRs of AGN (see Section 3.2.4).

After setting all the gas properties around the MBH, we can determine the $n_{\text{gr},1}$ value as

$$n_{\text{gr},1} = \text{DtG} \cdot \frac{\rho_{\text{BH,gas}}(r_1)}{m_{\text{gr}}}, \quad (24)$$

where m_{gr} is the mass of the grain (with a density value of 2.26 g/cm^3) and DtG is the dust-to-gas ratio. Unlike other branches of `L-Galaxies` (see e.g. R. M. Yates, C. Péroux & D. Nelson 2021; M. Parente et al. 2024), the `L-GalaxiesBH` branch does not trace dust. Thus, we determine the DtG randomly between 10^{-2} and 10^{-3} for each object (see M. Volonteri et al. 2025).

3.2.4 The AGN emission lines

Broad and narrow emission lines are commonly observed in the SEDs of accreting MBHs. In this work, we include 11 prominent UV and optical emission lines, namely: $\text{H}\alpha$ (6563 Å), $\text{H}\beta$ (4861 Å), $[\text{He I}]$ (3888 Å), $[\text{Fe II}]$ (1215 Å), $[\text{N II}]$ (6583 Å), $[\text{C III}]$ (1908 Å), $[\text{O III}]$ (4959 Å, 5007 Å), $[\text{Mg II}]$ (2795 Å, 2802 Å), $[\text{C IV}]$ (1548 Å, 1550 Å), $[\text{Si IV}]$ (1393 Å, 1402 Å), and $[\text{N V}]$ (1238 Å, 1242 Å). These lines are modelled leveraging the method developed in Su et al. (in preparation), which we shortly summarize below.

Su et al. (in preparation) employs the AGN continuum model described in Section 3.2.1 as input to the `CLOUDY` photoionization code (G. J. Ferland et al. 2017) to model the emission from the 11 spectral lines listed above. To simulate the narrow-line region (NLR), Su et al. (in preparation) assumes a uniform, constant density throughout the NLR (A. Feltre, S. Charlot & J. Gutkin 2016). The adopted density values in Su et al. (in prep) are computed by finding an empirical relation linking the gas density to M_* and SFR, enabling a physically motivated parameterization of the NLR conditions. The relation is constrained with the MPA-JHU catalog (C. A. Tremonti et al. 2004). However, we highlight that with the gas density profile introduced in Section 3.2.3 we get hydrogen densities in good agreement with those derived from the MPA-JHU relation (of the order of $10^{-1} - 10^5 \text{ 1/cm}^3$). Therefore, those are the ones used to compute our emission for the NLR. Beyond the density, the model requires to define an inner radius of the NLR. The definition adopted is,

$$r_{\text{NLR}} = 100 \sqrt{\frac{L_{\text{bol}}^{\text{AGN}}}{10^{43} \text{ erg s}^{-1}}} [\text{pc}], \quad (25)$$

where $L_{\text{bol}}^{\text{AGN}}$ is the bolometric luminosity of the MBH. To avoid non-physical values at both low and high luminosity, r_{NLR} is restricted to lie within the range 10–400 pc. The outer radius of the NLR is instead defined by `CLOUDY` as the point where the gas kinetic temperature drops below 4000 K. For the broad-line region (BLR), Su et al. (in preparation) assumes the same uniform

gas density structure as for the NLR, but with densities scaled up by a factor of $10^{9.5}$ to reflect the higher typical densities in this internal region. The inner radius of the BLR is set following the empirical relation from S. Panda et al. (2018):

$$r_{\text{BLR}} = 10^{(1.55+0.542 \log L_{5100,44})} [\text{pc}], \quad (26)$$

where $L_{5100,44}$ is the monochromatic luminosity at 5100 Å in units of $10^{44} \text{ erg s}^{-1}$. We note that this definition implies $r_{\text{broad}} < r_{\text{subl}}$, meaning that the BLR lies within the dust sublimation radius.¹⁰ As a result, the lines generated in this region will be subject to attenuation by the torus surrounding the MBH (see the next section for details). The outer radius of the BLR is computed by `CLOUDY` and is defined as the point where the total hydrogen column density reaches 10^{24} cm^{-2} . Finally, the metallicity of the BLR is adjusted to be twice that of the NLR.

Once the key physical parameters are defined, Su et al. (in preparation) runs a suite of `CLOUDY` simulations to predict emission-line luminosity across a broad range of AGN conditions. The resulting outputs are organized into a multidimensional grid that characterizes the emission of the 11 selected lines as a function of four parameters: (i) black hole mass, (ii) accretion rate, (iii) gas metallicity, and (iv) ionization parameter. Thus, for each accreting MBH in our simulated lightcone, the luminosity of the NLR and BLR emission lines is computed by interpolating this grid using the corresponding values of these four parameters. These are all tracked self-consistently by `L-GalaxiesBH` except the ionization parameter, which we compute as

$$U = \frac{Q_s}{4\pi c n_{\text{H}} r_i^2}, \quad (27)$$

where n_{H} is the hydrogen number density, computed as $n_{\text{H,NLR}} = \rho_{\text{BH,gas}}(r_{\text{NLR}})/m_{\text{H}} \text{ 1/cm}^3$ for the NLR (see equation 21), and as $n_{\text{H,BLR}} = n_{\text{H,NLR}} \cdot 10^{9.5} \text{ 1/cm}^3$, following the modelling of Su et al. (in preparation). Finally, Q_s is the ionization photon emission rate derived from the AGN continuum, L_{ν} , as

$$Q_s = \int_{13.6 \text{ eV}}^{0.1 \text{ GeV}} \frac{L_{\nu}}{h\nu} d\nu. \quad (28)$$

Regarding the line profiles, we assume that narrow lines originating in the NLR can be approximated as Dirac delta functions. In contrast, broad lines from the BLR are modelled with Gaussian profiles whose full width at half-maximum (FWHM) is determined by the virial velocity at the BLR radius:

$$\text{FWHM}_i = \left(\frac{\lambda_i}{c}\right) \sqrt{\frac{GM_{\text{BH}}}{r_{\text{BLR}}}} [\text{Å}], \quad (29)$$

where λ_i is the central rest-frame wavelength of the i -th line. We tested our AGN emission-line model by comparing our H_{α} AGN luminosity function with the one measured by recent observational works, finding overall good agreement (see Appendix A).

3.2.5 Attenuation of AGN spectra: Tours and ISM

As we did for galaxies, it is essential to model the obscuration of the SED of accreting MBHs. In particular, the spectrum emitted by the central accreting MBH may pass through the torus before reaching the ISM of the host galaxy. Consequently, the final observed AGN SEDs may be obscured and attenuated by both the

¹⁰We have tested that the values derived for r_{subl} in equation (19) and r_{broad} with equation (26) are consistent with $r_{\text{broad}} < r_{\text{subl}}$.

torus and the ISM. Here we outline the method we use to address both types of dust attenuation.

Torus obscuration: this depends on the opening angle of the torus (φ) and the orientation α_{LOS} of the observer LOS (defined in Section 3.1.1). In particular, if $\alpha_{\text{LOS}} \leq \varphi$, then the intrinsic emission from the accreting MBH is subject to torus obscuration. Thus, the incident radiation is attenuated according to the optical depth at the outer edge of the torus: $\tau_{\text{torus}}(r_2)$. Conversely, if $\alpha_{\text{LOS}} > \varphi$, the incident radiation is not affected by the dusty torus. Consequently, the emerging spectrum f_{λ}^{out} is given by

$$f_{\lambda}^{\text{out}} = \begin{cases} f_{\lambda}^{\text{inc}} & \text{if } \alpha_{\text{LOS}} \geq \varphi, \\ f_{\lambda}^{\text{inc}} e^{-\tau_{\text{torus}}(r_2)} & \text{if } \alpha_{\text{LOS}} < \varphi, \end{cases} \quad (30)$$

where $f_{\lambda}^{\text{inc}} = L_{\lambda}/(4\pi d_L^2)$ is the incident radiation. We assume that the torus attenuation only affects f_{λ}^{inc} at $912 \text{ \AA} < \lambda < 6564 \text{ \AA}$, as these wavelengths have been used to model the torus emission (see equation 16). Shorter wavelengths can photodissociate dust, therefore modelling attenuation at $\lambda < 912 \text{ \AA}$ requires a detailed treatment which lies beyond the scope of this work. Finally, we underline that NLR emission is not subject to torus attenuation as it originates beyond the torus boundaries, in contrast with the BLR light originating within the torus boundaries.

ISM attenuation: Regardless of whether f_{λ}^{out} has been reprocessed by the torus ($\alpha_{\text{LOS}} < \varphi$) or not ($\alpha_{\text{LOS}} \geq \varphi$), it may still undergo additional attenuation as it propagates through the galaxy ISM before reaching the observer. To determine whether ISM attenuation occurs, we define the angular extent of the galaxy disc as

$$\alpha_{\text{crit}} = \arctan\left(\frac{h_d}{R_d}\right), \quad (31)$$

where R_d and h_d represent the radial and vertical scale lengths of the galaxy disc, respectively. While *L-Galaxies*BH self-consistently tracks the evolution of R_d (see Q. Guo et al. 2011), it does not explicitly model h_d . To estimate the vertical scale height, we follow the approach of A. V. Alonso-Tetilla et al. (2024) and assume $h_d = R_d/8$. As in A. V. Alonso-Tetilla et al. (2024), we have also tested alternative disc thickness definitions (namely $h_d = R_d/6$ and $h_d = R_d/15$) and find no significant differences. The final observed AGN spectrum is given by

$$f_{\lambda}^{\text{out, Final}} = \begin{cases} f_{\lambda}^{\text{out}} & \text{if } \alpha_{\text{LOS}} \geq \alpha_{\text{crit}}, \\ f_{\lambda}^{\text{out}} \left(\frac{1 - e^{-\tau_{\lambda}^{\text{ISM}} \csc \alpha_{\text{LOS}}}}{\tau_{\lambda}^{\text{ISM}} \csc \alpha_{\text{LOS}}} \right) & \text{if } \alpha_{\text{LOS}} < \alpha_{\text{crit}}, \end{cases} \quad (32)$$

where the ISM optical depth $\tau_{\lambda}^{\text{ISM}}$ is the same as the one in equation (5).

3.3 Apparent magnitude: The *JWST* filter system

As extensively described in previous sections, the resulting SED for a simulated object is obtained by combining its AGN and stellar SEDs. From these composite SEDs we then obtain our simulated *JWST* photometry. In detail, we apply the standard AB magnitudes definition (see J. B. Oke & J. E. Gunn 1983) to the convolution between the composite SEDs (redshifted according to each source redshift) and the transmission curves of *JWST* filters.

Since this study aims to characterize photometrically selected LRDs while maximizing the comparability with recent observations, we conduct this procedure using the F115W, F150W, F200W, F277W, F356W, and F444W NIRCam filters, which

correspond to those typically used for photometric selections of LRDs (see V. Kokorev et al. 2024; I. Labbe et al. 2024).

3.4 The light profile of galaxies and AGN

Besides photometry, we also construct a toy model to determine the light profile of objects within a given filter j , i.e.: $f_{\lambda, j}(< r)$. To do this, we use a standard Sérsic law (J. L. Sérsic 1963):

$$I(r) = I_e e^{-b_n \left[\left(\frac{r}{r_e} \right)^{1/n} - 1 \right]}, \quad (33)$$

where $b_n = 1.9992n - 0.3271$, while I_e is the intensity at the effective radius r_e and n the Sérsic index. For simplicity, we set $n = 4$ for the galaxy bulge and $n = 1$ for the galaxy disc. Therefore, the total luminosity within a given radius r in a filter j can be determined as

$$\begin{aligned} L_j(< r) &= 2\pi \int_0^r I(r') r' dr' \\ &= 2\pi \int_0^r (I_{\text{disk}}(r') + I_{\text{bulge}}(r')) r' dr' \\ &= 2\pi \int_0^r r' I_e^{\text{disk}} e^{-b_1 \left[\left(\frac{r'}{r_e} \right) - 1 \right]} dr' \\ &\quad + 2\pi \int_0^r r' I_e^{\text{bulge}} e^{-b_4 \left[\left(\frac{r'}{r_e} \right)^{1/4} - 1 \right]} dr' \end{aligned} \quad (34)$$

where I_e is obtained independently for the disc and bulge components. *L-Galaxies*BH determines the luminosity of bulge and disc separately for each given filter j : L_j^{disk} and L_j^{bulge} . Consequently, we can define $I_e^{\text{bulge/disk}} = L_j^{\text{bulge/disk}} / [r_e b_n^{-2/n} \Gamma(2/n)]$, where r_e is the effective disc/bulge length computed by *L-Galaxies*BH. Finally, if a source has an AGN component, we add it to the galactic light profile as a point-like source. The final light profile $f_{\lambda, j}(< r)$ is then:

$$f_{\lambda, j}(< r) = f_{\lambda, j}^{\text{disk}}(< r) + f_{\lambda, j}^{\text{bulge}}(< r) + f_{\lambda, j}^{\text{MBH}} \quad (35)$$

3.5 Classification of galaxies and AGN

One key aspect of our work is the possibility to classify our simulated objects as galaxies or AGN. This is not a trivial choice, as the stellar emission and that of accreting MBHs can concur to produce the final SED of each object. To address this, different methods can be employed, based on photometric considerations. Specifically, an object may be classified as an AGN if the nuclear emission from the accreting MBH dominates the total observed flux over a set of filters. However, given the limited number of filters we use, this method is incomplete and does not account for all information on the final SED. To overcome this limitation, we employ an alternative classification based on the total bolometric luminosity of the MBH (see M. Volonteri et al. 2025, for a similar approach). In detail, we classify an object as AGN when its accreting central MBH has an associated $L_{\text{bol}}^{\text{AGN}} \geq 10^{44} \text{ erg s}^{-1}$. Otherwise, the object is classified as a galaxy.

4 PHOTOMETRIC SELECTION OF SIMULATED LITTLE RED DOTS

Here we present the photometric cuts we use to define our population of LRDs, which are a close replica of those introduced by I. Labbe et al. (2025) and used in V. Kokorev et al. 2024:

$$\text{red1} = \begin{cases} \text{F115W} - \text{F150W} < 0.8 \\ \text{F200W} - \text{F277W} > 0.7, \\ \text{F200W} - \text{F356W} > 1.0 \end{cases}$$

$$\text{red2} = \begin{cases} \text{F150W} - \text{F200W} < 0.8 \\ \text{F277W} - \text{F444W} > 0.7, \\ \text{F277W} - \text{F356W} > 0.6 \end{cases}$$

$$\text{compactness} = \frac{f_{\lambda, \text{F444W}}(< 0.4')}{f_{\lambda, \text{F444W}}(< 0.2')} < 1.7,$$

The `red1` and `red2` cuts are expected to select LRDs at $z < 6$ and $z > 6$ respectively (see V. Kokorev et al. 2024). Interestingly, we find that our simulated colours agree well with these expected redshifts intervals (see Appendix B for the redshift distribution of each colour cut). We underline that, following the results from V. Kokorev et al. (2024), we exclude all objects selected by the above criteria but which show $z < 4$. Moreover, we also exclude objects selected by the `red2` cut with $z < 6$, given their negligible contribution to the overall properties of the `red2`-selected population of objects. On top of the previous cuts, we add the extra cut of:

$$\text{bd_removal} = \text{F115W} - \text{F200W} > -0.5 \quad (36)$$

which is expected to reduce the contamination of brown dwarfs from the selected sample. We underline that, even if we do not model brown dwarfs, we apply this cut to maximize the comparability of our results with recent observational works.

For analogous reasons, we also apply realistic detection limits to all our samples. First of all, we impose a detection cut based on the deepest magnitudes detectable by NIRCcam in the fields typically used for LRDs searches (namely, the GOOD-S field depth values reported in table 1 of V. Kokorev et al. 2024). In detail, we only consider objects that satisfy: $\text{F150W} < 29.6$, $\text{F200W} < 29.5$, $\text{F277W} < 29.8$, $\text{F356W} < 29.6$, $\text{F444W} < 29.3$ mag. Then, we explicitly replicate the approach of V. Kokorev et al. (2024) by only selecting objects with $\text{F444W} < 27.7$ mag.

The colour distributions of our selected samples are presented in Fig. 4. For comparison, we have included a collection of data from V. Kokorev et al. (2024) as red points. Overall, in the `red1` colour space (upper panel), we find 30.05 per cent of our simulated objects within the photometric colours selection, although with a larger spread than observational LRDs. More in detail, we find that 89.71 per cent are compatible with the colours of observed LRDs in V. Kokorev et al. (2024) ($0.7 < \text{F200W} - \text{F277W} < 1.7$ and $1 < \text{F200W} - \text{F356W} < 2.4$). Analogously, for the `red2` cut (middle panel) the 15.93 per cent of our simulated population pass our colour selection, with 67.45 per cent in agreement with the colours observed by V. Kokorev et al. (2024) (we note how the maximum $\text{F277W} - \text{F444W}$ colour we get is 1.66 in comparison to the ~ 2 dex values of V. Kokorev et al. (2024)). Although this being a qualitative assessment, it shows that our model is able to produce reliable simulated colours up to $z > 6$, compatible with those of the observed LRDs presented by V. Kokorev et al. (2024). Overall, these discrepancies are likely due to the different area surveyed by V. Kokorev et al. (2024), smaller by a factor of 0.017 with respect to the large $5 \text{ deg} \times 5 \text{ deg}$ area we model with our lightcone (which translates to 0.094 deg^2 in V. Kokorev et al. (2024) against the 5.62 deg^2 we get). Indeed, this may impact the effective extend of the colour-space region which can be sampled observationally. On the other hand, it is possible that biases in the simulation of our photometric colours, may produce larger variations than those observed in real data. Nevertheless, since the bulk of our simulated objects show colour

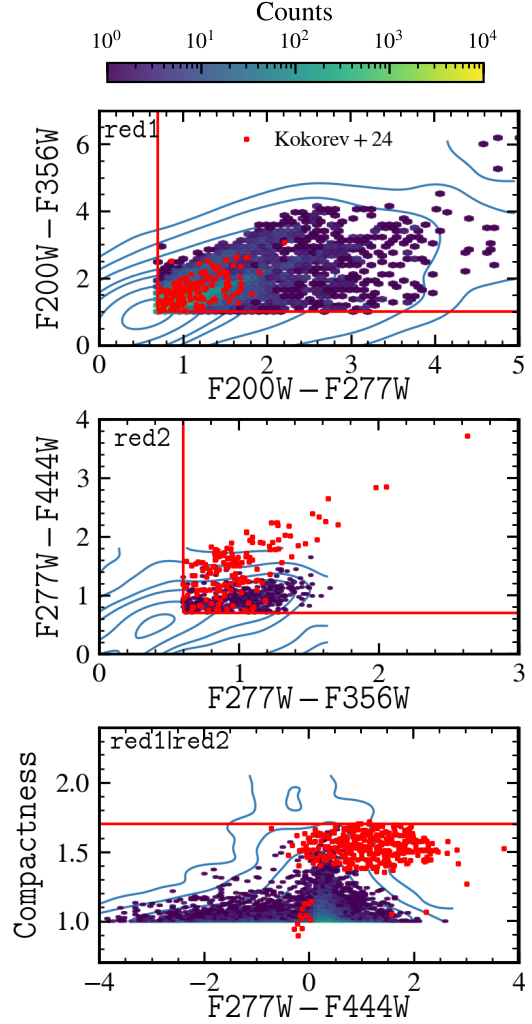


Figure 4. Colour-colour (upper and middle panels) and compactness versus colour (lower panel) diagrams used to define our photometrically selected LRDs. The blue contours correspond to all detected objects. The colour map show the distribution of simulated objects from our lightcone (the colour code represents the number of selected objects in each bin). The red dots represent the sample from (V. Kokorev et al. 2024), with the vertical and horizontal red lines indicating the photometric cuts we apply to replicate their selection.

compatible with the observed ones, we consider these discrepancies as negligible.

Finally, the compactness selection is shown in the bottom panel of Fig. 4. Our selected objects tend to be relatively more compact than those in the V. Kokorev et al. (2024) sample. This is likely due to our simplified light-profile modelling (see Section 3.4). In particular, our normalization of the Sérsic light profile does not account for the variation of its spatial extent across different filters (r_e in equation (33)). The lack of modelling of the *JWST* point spread function (PSF) may also be affecting this result although only to a minor extent, being the F444W filter PSF $\sim 0.14''$. Overall, our compactness cut is the less restrictive among those we impose, including > 99 per cent of objects at $z > 4$ (see Table 1). Consequently, the effect of possible compactness biases on our work are negligible. We also note that V. Kokorev et al. (2024) does not provide a number of objects selected with this cut

Table 1. Number (fractions) of objects selected by the colour and compactness cuts (upper and middle row) as well as by the combination of the two (i.e. our LRDs definition, bottom row). Each column shows a different redshift bin. The numbers and fractions are applied only to the sample of *detected* objects, after removing those identified by the `bd_removal` cut. Red text shows the numbers and fractions for AGN.

Photometric cut		$4 \leq z < 6$	$z \geq 6$
Colour-colour	All	13 859 (30.26 per cent)	621 (15.93 per cent)
	AGN	5816 (75.32 per cent)	151 (82.07 per cent)
Compactness	All	45 744 (99.88 per cent)	3896 (100.00 per cent)
	AGN	7719 (99.97 per cent)	184 (100.00 per cent)
LRDs	All	13 763 (30.05 per cent)	621 (15.93 per cent)
	AGN	5761 (74.61 per cent)	151 (82.07 per cent)

among his detected sample, so assessing the effectiveness of our cut is not as straight forward. Including a more detailed model of the Sérsic profile and *JWST* PSF may improve the agreement between the compactness of our sources and those in V. Kokorev et al. (2024). Nevertheless, addressing this point is beyond the scope of this work.

Hereafter, we define detected objects as those that meet the depth limit described above. Among these, objects that also satisfy the colour and compactness criteria will be referred to as LRDs. Conversely, objects that meet the detection limit but do not fulfill the colour-colour and compactness criteria will be referred to as non-LRD.

5 RESULTS

In this section, we present our simulated LRDs and non-LRDs populations, starting from the analysis of their properties across different redshifts (Section 5.1). In Section 5.2 we analyse how our selection of objects as LRDs, based on realistic photometric cuts (see Section 4), depends on the evolution of their galaxy and MBH properties across redshift. Finally, in Section 5.4, we present a deeper look into the LRDs population, separating them into galaxies or AGN classes (respectively LRD Gal s and LRD AGNs). Our findings will help to contextualize our simulated LRDs within the current paradigm of early galaxy and MBH evolution, providing a tentative interpretation of recent *JWST* observations.

5.1 The properties of photometrically selected LRDs

Here, we analyse the overall properties of our LRD sample, showing their redshift distribution (Section 5.1.1) and comparing their properties against the sample of non-LRDs (Section 5.1.2).

5.1.1 Redshift distribution of LRDs

The redshift distribution of our LRDs is shown in Fig. 5. The photometric selection we apply produces a sample that spans over $4 < z < 10$, with a peak at $z \sim 4$. In the same figure, we also show the evolution of the LRDs number density, which exhibits an increasing trend with redshift. More in detail, at $z \sim 7$ the LRDs number density is $\sim 8 \times 10^{-6} \text{ Mpc}^{-3}$, while at $z \sim 4$ it reaches $\sim 2 \times 10^{-4} \text{ Mpc}^{-3}$ where the number of our LRDs flattens. These values are smaller than the value of $\sim 2 \times 10^{-4} \text{ Mpc}^{-3}$ at $z \sim 7$ reported by P. G. Pérez-González et al. (2024a), which they claim to be constant between $4 < z < 9$. In contrast, we find a ~ 1 dex drop between $z = 5$ and $z = 7$, although then we find that the number

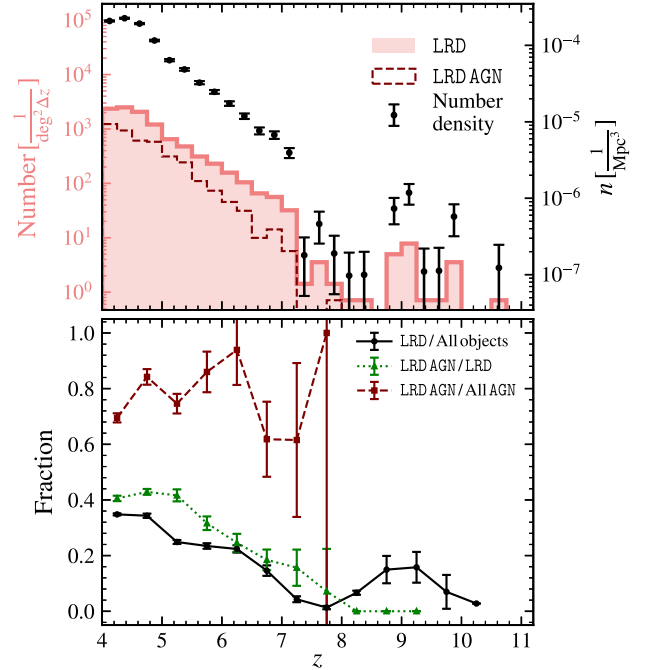


Figure 5. Upper panel: Redshift distribution (red histograms) and number density (black points) of the detected LRDs. Lower panel: Fraction of LRDs over the total number of detected systems (black points), fraction of LRDs classified as AGN over the total number of detected objects classified as AGN (red squares) and fraction of LRDs classified as AGN over the number of LRDs (green triangles). In all the plots, the error bars correspond to the Poisson error.

density sets at a constant value of $\sim 8 \times 10^{-6} \text{ Mpc}^{-3}$ (within error bars). These differences likely arise as a consequence of their different colour selection and survey depth. The incizing trend of LRDs towards low- z can be expected from the combination of completeness effects of flux-limited samples and the fixed mass-resolution of our underlying simulation. Specifically, by applying magnitude cuts (see Section 4), we remove from our samples an increasing number of faint objects at higher redshifts and with the progress of structure growth towards lower redshifts, an increasing number of objects can be resolved and tracked along their redshift evolution within the MSII merger trees.

Although LRDs have a relatively high number density in our samples, they do not represent the full population of detected objects in our lightcone. This is analysed in the lower panel of Fig. 5 where we present the redshift evolution of the fraction of LRDs over the total number of detected objects (black line). We find that at $z > 6$ the population of LRDs only accounts for the 10–20 per cent of the whole detections. This increases at $4 < z < 6$ where LRDs account for 30–40 per cent of objects in our lightcone. Notably, P. G. Pérez-González et al. (2024a) find that at $z \sim 7$, the incidence rate of LRDs in their observed sample is 14 ± 3 per cent, in agreement to what we report.

To further contextualize our LRDs, we also show which fraction of this sample is classified as AGN (AGN: $L_{\text{bol}}^{\text{AGN}} \geq 10^{44} \text{ erg s}^{-1}$, green line). Our results show a clear redshift evolution: less than 20 per cent of LRDs are AGN at $z > 7$, rising up to 30–40 per cent at $z < 7$. Although this indicates that our LRDs are primarily classified as galaxies (hereafter LRD Gal s), those classified as AGN (henceforth LRD AGNs) make up the vast majority of all detected AGN sample in our lightcone. This is also

shown in the lower panel of Fig. 5 where LRD AGNs make up for > 70 per cent of the entire population of detected AGN in our lightcone, independently of redshift.

We stress that estimating these fractions is a key result of our work, which allows us to infer the role played by LRDs within the broader population of high- z objects, as well as their prevalence in photometrically selected (AGN) samples. We also acknowledge that the fractions reported are dependent on the definitions of each sample. Most notably, relaxing the cut on the AGN definition increase the incidence of LRD AGNs in the LRD by 10–30 per cent (see Appendix C). This information is generally challenging to obtain from high- z surveys, due to limitations in either their sampled area, their achieved depth, or their ability to reliably classify high- z sources. In this regard, our study helps fill this observational gap, providing a view of photometrically selected LRDs and LRD AGN within their full cosmological context over a broad redshift interval.

5.1.2 Physical properties of LRDs and non-LRDs samples

Understanding LRDs requires examining their properties and comparing them with those of non-LRDs. In Fig. 6, we show a comprehensive picture of LRDs and non-LRDs¹¹ properties, comparing these two classes of objects in different redshift bins. From top to bottom, each row shows: the SMF, the halo mass function (HMF), the AGN LF and finally the BHMF.

Regarding the SMF, LRDs represent at any redshift the dominant galaxy population at $M_* > 10^{10} M_\odot$, with their distribution exhibiting a prominent peak at $M_* \sim 10^{10} M_\odot$ (see similar results in the simulations of P. LaChance et al. 2026). In contrast, the SMF of non-LRDs peaks at significantly lower masses, around $M_* \sim 10^8 M_\odot$. The SMF comparison also shows that non-LRDs are a factor of ~ 5 less abundant than LRDs in galaxies with $10^9 < M_*/M_\odot < 10^{10}$ and become as abundant as LRDs only for $M_* > 10^{10.5} M_\odot$ at $4 < z < 5$. These trends align with recent observational studies, which suggest that LRDs typically are galaxies with stellar masses of $M_* \sim 10^9\text{--}10^{10} M_\odot$ (see G. C. K. Leung et al. 2025; P. G. Pérez-González et al. 2024a; J. F. W. Baggen et al. 2024; H. B. Akins et al. 2025). Note that the population of LRDs with $M_* < 8 M_\odot$ is minimal, especially at $z > 5$ (indeed it is missing between $6 \leq z < 7$). For the SMF we also provide the SMF derived from *L-Galaxies BH* without applying any cut as in Fig. 2. When comparing the SMF of detected objects with the total SMF, we see that most galaxies above $M_* \sim 10^{10} M_\odot$ are within the detection limit, while the number decreases by 1.5–2.5 dex at lower masses. As for the HMF, LRDs are found within halos spanning a wide mass range of $5 \times 10^{10} < M_{\text{vir}} < 10^{13} M_\odot$, with a characteristic peak at $M_{\text{vir}} \sim 5 \times 10^{11} M_\odot$ (see similar findings in M. Carranza-Escudero et al. 2025; J.-T. Schindler et al. 2025). In contrast, non-LRDs are consistently associated with lower-mass halos, ranging from $10^9 < M_{\text{vir}} < 10^{12} M_\odot$, with a typical halo mass around $M_{\text{vir}} \sim 10^{11} M_\odot$.

Regarding the population of MBHs, it is clearly dominated by LRDs at $z > 6$, as shown by our BHMF. LRDs span a broad mass range, from $10^6 < M_{\text{BH}} < 5 \times 10^8 M_\odot$. However, this trend shifts at $4 < z < 6$, where the number of LRDs with $M_{\text{BH}} > 10^7 M_\odot$

declines sharply. In this higher-mass regime, non-LRDs become more prominent, with their number density increasing by roughly one order of magnitude compared to LRDs. We underline that this shift in BH properties has a significant impact on the photometric selection of our simulated objects as LRDs, as we will analyse below in greater detail (Section 5.2.1 and 5.2.2). Despite this shift, LRDs continue to dominate the mass function at the low-mass end ($M_{\text{BH}} < 10^7 M_\odot$), maintaining their significant presence within the overall MBH population. Interestingly, the trends we observe in the BHMF are reflected in the AGN LFs. At $z > 6$, LRDs dominate the LFs, spanning over two orders of magnitude in luminosity ($10^{44} < L_{\text{bol}}^{\text{AGN}} < 10^{46} \text{ erg s}^{-1}$). However, at lower redshifts, the LRDs population experiences a significant decline in the number of luminous AGN ($L_{\text{bol}}^{\text{AGN}} > 10^{46} \text{ erg/s}$), occupying primarily the intermediate-luminosity range ($10^{44} < L_{\text{bol}}^{\text{AGN}} < 10^{45} \text{ erg/s}$). In contrast, non-LRDs increasingly dominate the LF bright end at $z < 6$, becoming the primary contributors to the high-luminosity AGN population (see Y. Ma et al. 2025 for similar findings).

The results presented in this section reveal two key characteristics of our photometrically selected LRDs. First, they are consistently found at the most massive end of the stellar and halo mass function ($M_* > 10^{9.5} M_\odot$, and $M_{\text{vir}} > 10^{11.5} M_\odot$), regardless of redshift. From the SMF, in addition, we observe the emergence of a low-mass population of LRDs with $M_* \sim 10^{8.5} M_\odot$ at $z < 6$. At the same time, MBHs in the LRD sample tend to be moderately luminous ($L_{\text{bol}}^{\text{AGN}} \sim 10^{45} \text{ erg/s}$) and massive ($M_{\text{BH}} \sim 10^7 M_\odot$). These results highlight a notable distinction in the evolution of simulated LRDs versus non-LRDs in the high stellar mass regime: the former are typically massive galaxies, where stellar growth tends to precede that of their central MBHs. In contrast, at $z < 6$, the MBHs hosted in non-LRDs tend to be more massive than that of LRDs, thereby populating the bright end of the AGN LF. As shown in the next sections, this directly affects the photometry of our simulated objects and their selection as LRD. We stress that our findings do not portray LRDs and non-LRDs as *monolithic* populations, but rather as complex and heterogeneous classes, each comprising a variety of objects.

5.2 The LRD photometry: interplay between galaxy and MBH

To better understand the selection of objects classified as LRDs, in Fig. 7 we present the comparisons between the median photometry of LRD and non-LRD samples. Generally speaking, at $z < 7$ and independently of the host galaxy’s stellar mass, the LRD population exhibits a characteristic ‘V-shaped’ photometric profile. This is visible as a decrease in flux immediately after the Balmer break. The exceptions to this feature are the lowest M_* bin at $6 < z < 7$ and the whole $7 < z < 8$ redshift bin. In the first case, we cannot identify any LRD object in this mass and redshift bin. In the case of $7 < z < 8$, we find an overall very small number of detected objects (see also Figs 5 and 6), hence any features in our median photometry are erased by the low sample statistics. Regarding the non-LRD sample, their median photometry does not display any ‘V-shaped’ feature. Indeed, at any z and M_* , it generally shows a decreasing trend with wavelength, indicative of blue photometric colours for non-LRD.

To investigate the origin of the ‘V-shaped’ feature in LRDs, the small panels of Fig. 7 show the percentage of flux within a given filter that comes from an AGN (accreting MBH). Focusing on the lowest and intermediate stellar mass bins ($10^7 \leq M_* < 10^8 M_\odot$

¹¹As a reminder for the reader, we select LRDs and non-LRDs among our sample of objects that meet the detection limit based on if they meet the photometric and compactness cut (LRDs) or not (non-LRDs)

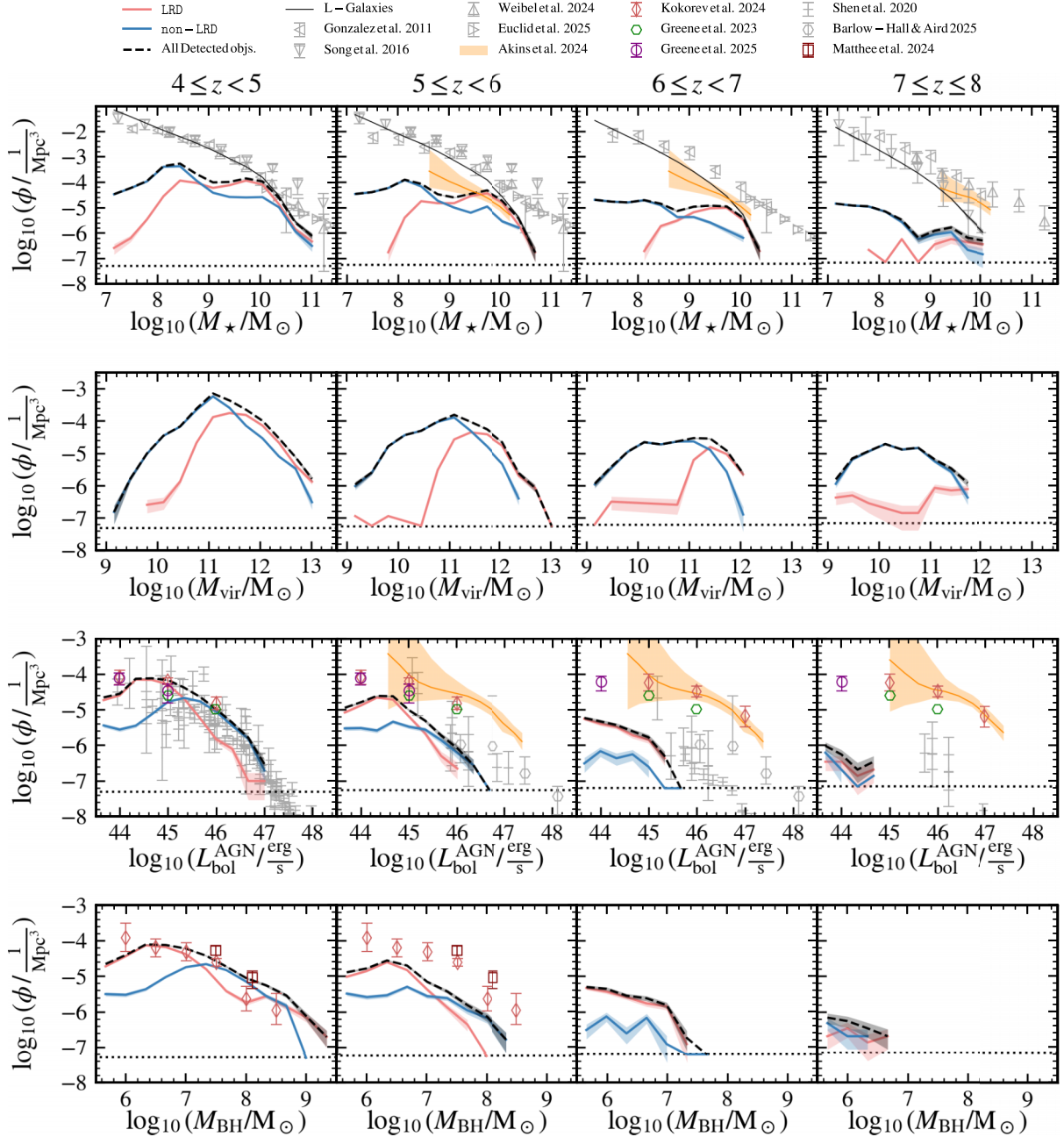


Figure 6. Properties of LRDs and non-LRDs samples (respectively, pink and blue lines) across different redshifts. Different columns correspond to different redshift bins, as shown by the column titles. From top to bottom, on each row we show: the stellar mass function, halo mass function, the AGN bolometric luminosity function and the BH mass function. A collection of recent observational data is shown as points (either grey or coloured) and shaded areas (in orange), as specified by the legend (on top of the figure). Coloured literature points refer to LRD-derived quantities, while the rest correspond to the same as Fig. 2 but with the inclusion of A. Weibel et al. (2024) and Euclid Collaboration (2025) on the stellar mass function. Finally, in each panel the dashed lines show the distributions of all detected objects in our lightcone (i.e. LRDs and non-LRDs together), while the horizontal dotted line shows the number density we would measure if we had only 1 object in the whole lightcone at that redshift. The thin black line in the top row correspond to the *L-GalaxiesBH* line without applying any cuts, as in Fig. 2.

and $10^8 \leq M_* < 10^9 M_\odot$, i.e. top and second rows in Fig. 7), we find that the observed flux is dominated entirely by the stellar component, regardless of redshift. This implies that, for LRDs at this low-mass, the ‘V-shaped’ spectral feature originates solely from the Balmer break ($\gtrsim 3000 - 4000 \text{ \AA}$, rest-frame) produced by the stellar continuum. Notably, this is also valid at all redshifts for

non-LRDs in the lowest mass bin. The strong prevalence of the stellar continuum in the photometry, coupled with the different spectral shapes at fixed stellar mass, suggests that low-mass LRDs and non-LRDs occupy distinct evolutionary stages. As we will show in Section 5.2.1, low- and intermediate-mass LRDs exhibit systematically larger metallicity and generally lower specific star

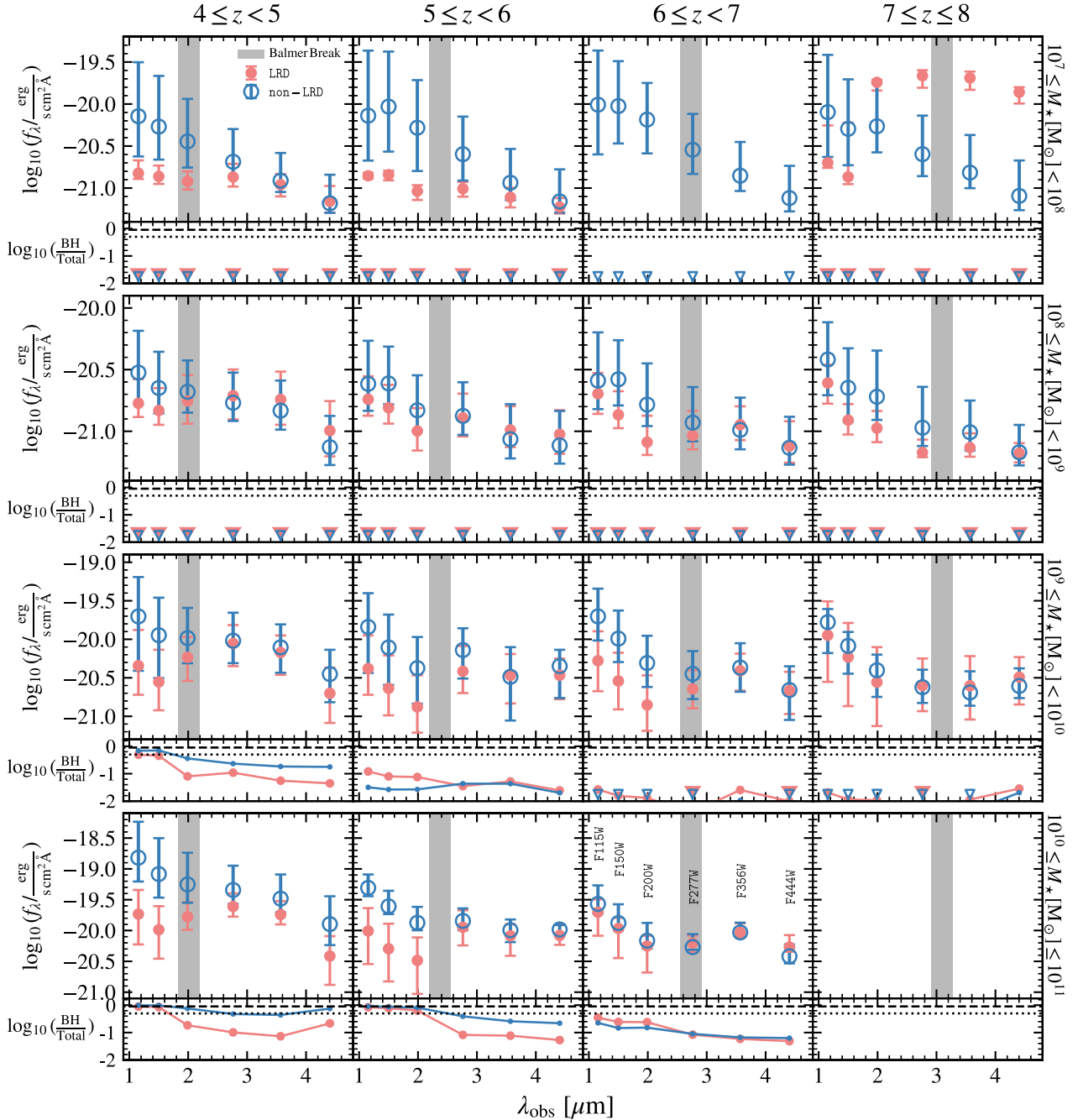


Figure 7. Median photometry of the LRD (filled red circles) and non-LRD (empty blue circles) samples at different redshifts. The error bars correspond to the 16th – 84th percentiles while the vertical grey-shaded areas mark the Balmer break position. The small panels show the fractional contribution of the flux provided by AGN (i.e. accreting MBHs) within each *JWST* filter. The triangles represent the upper limits of this contribution. To guide the reader, the horizontal dashed lines highlight the 90 per cent and 50 per cent value (half of the flux is provided by the AGN). Different panels show different M_* bins, from top to bottom: $10^7 \leq M_* < 10^8 M_\odot$, $10^8 \leq M_* < 10^9 M_\odot$, and $10^9 \leq M_* < 10^{10} M_\odot$.

formation rates (ssFR) when compared to their non-LRD counterparts. These properties are indeed consistent with LRDs showing a stronger Balmer break than non-LRDs.

Moving to the photometry of objects in the most massive galaxies ($10^9 \leq M_* < 10^{10} M_\odot$ and $10^{10} \leq M_* < 10^{11} M_\odot$, third and bottom row in Fig. 7), we also observe different trends depending on redshift and stellar mass, with the AGN contribution to the photometry increasing with lower redshift and higher M_* . At

$6 \leq z < 7$ and $7 \leq z \leq 8$, the behaviour is similar to that of low-mass galaxies, that is: the AGN component rarely exceeds ~ 1 per cent (except for the highest mass bin, where the MBH contribution is almost ~ 50 per cent) while the galaxy component dominates the flux in all filters. However, at $4 \leq z < 5$ and $5 \leq z < 6$, the AGN contribution is appreciable across all filters (even dominating in some cases). At $5 \leq z < 6$, the photometry of LRDs with $10^9 \leq M_* < 10^{10} M_\odot$ shows a ~ 4 – 8 per cent

contribution from AGN in all filters, while this raises to ~ 10 per cent – 15 per cent in F115W, F150W and F200W. In that same z and M_* bin, the MBH in non-LRDs contributes $\lesssim 8$ per cent. In contrast, at $4 \leq z < 5$, 50 per cent of the flux in F115W and F150W is due to the AGN emission for LRDs, while this contribution sits at ~ 10 per cent for F200W, F277W, F356W, and F444W. A similar pattern holds for the non-LRD sample although with an even stronger contribution from AGN. Indeed, this reaches 90 per cent in F115W and F150W at $4 \leq z < 5$ and it accounts for > 40 per cent in F200W, F277W, F356W, and F444W. In the highest mass bin, $10^{10} \leq M_* \leq 10^{11} M_\odot$, these patterns are also seen in a more extreme version. Indeed, both LRDs and non-LRDs are dominated by the MBH emission by $\gtrsim 60 - 90$ per cent in the F115W, F150W (in the $4 \leq z < 5$ and $5 \leq z < 6$ bins) and F200W ($5 \leq z < 6$ bin) filters, while this decreases to ~ 10 per cent for the rest of the filters in LRDs but stays at $\gtrsim 40$ per cent for non-LRDs.

All the results presented above show that the classification of an object as an LRD is closely linked to either the properties of the galaxy stellar population (in low-mass systems) or the interplay between AGN activity and stellar emission (in high-mass systems). In the following sections, we examine these two regimes in detail, investigating both the galaxy and MBH properties that differentiate the LRD and non-LRD samples.

5.2.1 Imprint of galaxy properties on LRDs photometry

As shown in the previous section, the differences between the median photometry of LRDs and non-LRDs are primarily concentrated in the F115W, F150W, and F200W filters at all redshifts (except the highest redshift and lowest M_* bin). Moreover, we showed that the nuclear emission plays a negligible role in the photometry of objects with $M_* < 10^8 M_\odot$. Therefore, the photometric divergences we observe at low M_* should arise exclusively from differences in the underlying stellar populations of our selected objects. To understand the origin of these differences in terms of galaxy physical properties, Figs 8 and 9 compare the specific star formation rate (sSFR) and metallicity of LRDs and non-LRDs as a function of their stellar mass. At $4 \leq z \leq 5$, LRD systems with $10^7 < M_* < 10^8 M_\odot$ exhibit generally lower sSFR ($\lesssim 0.25$ dex) and higher metallicities (~ 0.1 dex) than their non-LRD counterparts. In the higher mass range of $10^8 < M_* < 10^9 M_\odot$, the difference in sSFR is less evident although LRDs still tend to have slightly higher metallicities than non-LRDs. At $5 \leq z \leq 6$, the low-mass LRD population is only present in the $10^8 < M_* < 10^9 M_\odot$ range. As in the previous redshift bin, these LRD galaxies display lower sSFRs ($\lesssim 0.4$ dex) and higher metallicities (~ 0.2 dex). At $6 \leq z \leq 7$, the differences in sSFR between the LRD and non-LRD populations with $10^8 < M_* < 10^9 M_\odot$ largely disappear, leaving only a small metallicity offset (~ 0.1 dex). Finally, at $7 \leq z \leq 8$, this trend is reversed: while LRDs and non-LRDs show comparable metallicities, the former exhibit larger sSFR (~ 0.25 dex) than non-LRD systems.

The observed trends presented above indicate that low-mass LRDs tend to host more evolved stellar populations than their non-LRD counterparts. This naturally results in reduced flux contributions in the bluest *JWST* filters, accounting for the differences observed in Fig. 7. Moreover, even as differences in star formation activity diminish, the persistently higher metallicities of LRDs imply an earlier assembly of their stellar populations, which have experienced more prolonged chemical enrichment

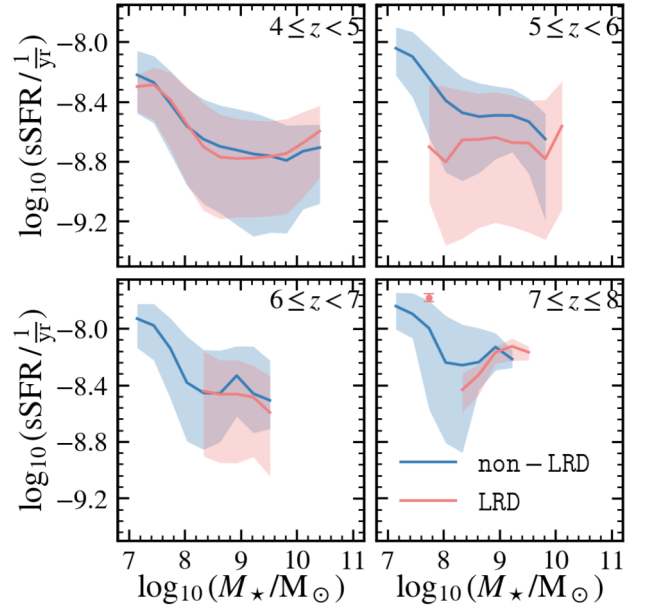


Figure 8. Specific star formation rate (sSFR) and stellar mass plane for the LRD and non-LRD samples (red and blue, respectively). The lines and the shaded areas correspond to the median and 16th – 84th percentiles of the sSFR at a fixed stellar mass. Each panel represents a redshift bin. Dots are shown for cases where only one object is found.

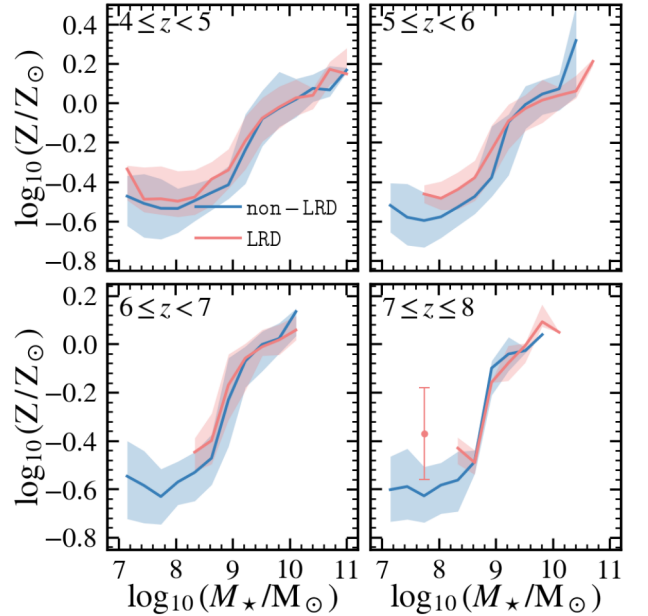


Figure 9. Galaxy metallicity (Z) and stellar mass plane for the LRD and non-LRD samples (red and blue, respectively). The lines and the shaded areas correspond to the median and 16th – 84th percentiles of metallicity at a fixed stellar mass. Each panel represents a given redshift bin. Dots are shown for cases where only one object is found.

compared to the non-LRD sample. Consequently, this extended evolutionary history of LRDs offers a coherent explanation for the photometric and spectral distinctions between the two low-mass populations. In the following section, we explore the differences between the non-LRD and LRD samples at higher stellar masses, with a particular focus on the properties of the MBH population.

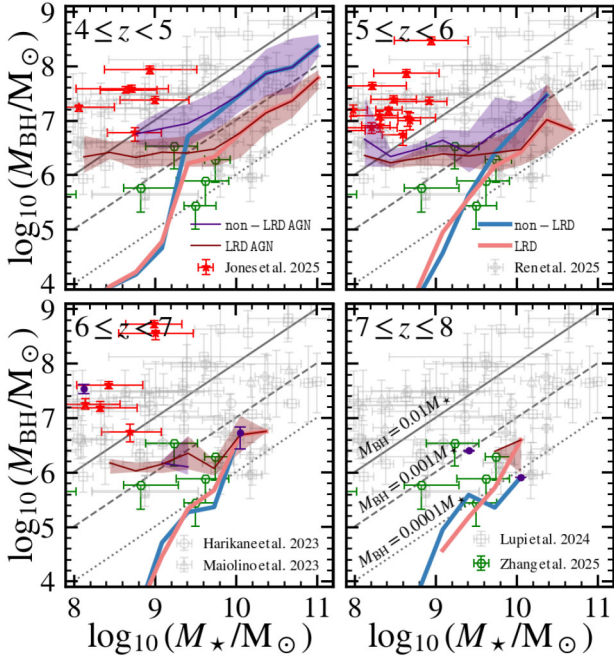


Figure 10. Massive black hole and stellar mass plane for the LRD, non-LRD, LRD AGNs, and non-LRD AGNs samples (tick red, tick blue, brown and purple lines, respectively). The lines and the shaded areas correspond to the median and 16th–84th percentiles of the sSFR at a fixed stellar mass. Each panel represents a redshift bin. Filled dots are shown for cases where only one object is found in the bin. The trends are compared with the observational data of Y. Harikane et al. (2023) (grey circles) and R. Maiolino et al. (2024) (grey triangles), A. Lupi et al. (2024) (grey squares), Z. Zhang et al. (2026) (green circles), W. Ren et al. (2025) (grey stars), G. C. Jones et al. (2026) (red stars). Coloured points refer to literature LRD samples.

5.2.2 Imprint of MBH properties on LRDs photometry

As discussed in previous sections, AGN contributions to the photometry of our detected objects become relevant only at $z < 6$ and $M_* > 10^9 M_\odot$ for both LRDs and non-LRDs (see Fig. 7 and Appendix D for further details). To better understand the interplay between MBHs and their host galaxies, we analyse the role played by accreting MBHs in the $M_{\text{BH}} - M_*$ relation. This will also help to understand the origin of photometric differences between LRDs and non-LRDs seen in Fig. 7. In Fig. 10, we show the median scaling for both LRDs and non-LRDs as well as for the subsamples of these classes defined as AGN¹² (hereafter, LRDAGNs and non-LRDAGNs, red and purple lines). For reference, we show fixed $M_{\text{BH-to-}M_*}$ ratios as diagonal grey lines.

We start discussing Fig. 10 from $4 \leq z < 5$. The results show that for $M_* \gtrsim 10^9 M_\odot$ the median $M_{\text{BH}} - M_*$ relations for non-LRDs and non-LRDAGNs coincide, as do those of LRDs and LRDAGNs. This indicates that AGN accounts for the vast majority of objects at the highest M_{BH} and M_* bins in both LRD and non-LRD samples and explains the strong contribution of AGN in the photometry of these two populations at $M_* \gtrsim 10^9 M_\odot$. Despite these overall similarities, the relations for LRDs and non-LRDs

¹²We stress that our definition of AGN is based on the $L_{\text{bol}}^{\text{AGN}}$ associated to accreting MBHs, a property which is self-consistently tracked by our SAM along MBHs evolution (see D. Izquierdo-Villalba et al. 2020, 2023, 2024; S. Bonoli et al. 2025)

show a remarkable difference. The former is systematically offset by ~ 0.5 dex, with MBHs in non-LRDs being typically more massive than those in LRDs. Thus, combining the significant AGN contribution to the F115W and F150W filters seen in Fig. 7 with the lower black hole masses of LRDs at fixed stellar mass, we conclude that the more pronounced spectral jump observed in $M_* \gtrsim 10^9 M_\odot$ LRDs at $\lambda_{\text{obs}} < 2 \times 10^4 \text{ \AA}$ is driven by a fainter AGN population found in LRDs compared to that in non-LRDs (see further discussion in Section 5.3). As a result, the fainter AGN of LRDs at $M_* \gtrsim 10^9 M_\odot$ cause their UV-to-optical emission not to be bright enough to erase the spectral jump produced by the stellar Balmer break. Conversely, the more massive MBHs powering brighter AGN in non-LRDs produce sufficiently strong UV-to-optical emission to compensate for the stellar Balmer break, effectively diluting the characteristic ‘V-shaped’ feature in the photometric profiles of non-LRDs. These results indicate that, despite LRDAGNs constituting the majority of the AGN population (see bottom panel of Fig. 5), they are typically powered by lower-mass MBHs compared to their non-LRDAGNs counterparts. This is a key result of our work and provides a framework to interpret the abundant population of LRDAGNs recently uncovered by *JWST*. It also implies that LRDs do not represent the entire AGN population at $z > 4$, but are complemented by a less numerous population of ‘ordinary’ bright AGN that lack the distinctive spectral features of LRDs. On the other hand, at $M_* < 10^9 M_\odot$ and $4 \leq z < 5$ we observe a significant drop of the $M_{\text{BH}} - M_*$ relation in both LRD and non-LRD samples, which is not observed for AGN. This is driven by the large number of low-mass MBHs populating this stellar mass range. The discrepancy between AGN-selected samples and the broader LRD and non-LRD populations at $M_* \lesssim 10^{9.5} M_\odot$ points to the existence of a large population of small galaxies hosting low-mass black holes ($M_{\text{BH}} < 10^5 M_\odot$), which may be inactive or shining as very faint AGN (i.e. with $L_{\text{bol}}^{\text{AGN}} < 10^{44} \text{ erg/s}$). This result suggests that the flattening of the $M_{\text{BH}} - M_*$ relations for LRDAGNs and non-LRDAGNs at $M_* < 10^9 M_\odot$ is driven by a small number of active MBHs that are rather overmassive with respect to the bulk of the MBH population and likely undergoing rapid growth. Due to their scarcity, they do not significantly impact the photometric properties of the overall LRDs and non-LRDs populations.

Proceeding towards higher redshifts, at $5 \leq z < 6$ we observe the build-up of the trends observed in the $z < 5$ $M_{\text{BH}} - M_*$ relation. Specifically, MBHs in non-LRDs (either AGN or non-AGN) start to populate the highest bins of $M_{\text{BH}} - M_*$ plane, reaching $M_{\text{BH-to-}M_*}$ ratios of about $\sim 10^{-3}$. LRDs (either AGN or non-AGN) follow a similar trend, but their $M_{\text{BH-to-}M_*}$ ratios only reach $\sim 10^{-3.5}$. Although this offset starts to be visible only at $M_* \gtrsim 10^{10} M_\odot$, it will be fully developed down to $M_* \sim 10^9 M_\odot$ by $z < 5$. As at lower redshifts, the median $M_{\text{BH}} - M_*$ relation for LRDAGNs and non-LRDAGNs with $M_* > 10^{10} M_\odot$ closely tracks that of LRDs and non-LRDs respectively, further supporting the enhanced AGN contribution to LRDs photometry observed at $5 \leq z < 6$ in Fig. 7. These trends break at $z > 6$ as MBHs in both LRDs and non-LRDs exhibit similar $M_{\text{BH}} - M_*$ scaling relations, largely independent of stellar mass. This change of behaviour is most evident at $6 \leq z < 7$, as at $7 \leq z < 8$ the interpretation becomes more uncertain due to the smaller number of systems with $M_{\text{BH}} > 10^5 M_\odot$ (see bottom right panel of Fig. 6). Independently of that, at these high redshifts the ratio between M_{BH} and M_* barely exceeds $\sim 10^{-4}$, confirming that MBHs play a minor role in determining the photometric properties of LRDs and non-LRDs.

In summary, the populations of LRDs and non-LRDs display steep median scaling relations, which hover around typical ratios of $M_{\text{BH}} \sim 10^{-3} M_{\star}$ ($\sim 10^{-4} M_{\star}$) for $M_{\star} > 10^{9.5} M_{\odot}$ ($< 10^9 M_{\odot}$). This is significantly smaller than typical $M_{\text{BH}} - M_{\star}$ values reported by recent observational works, especially for $M_{\star} < 10^9 M_{\odot}$ galaxies where observations point out $M_{\text{BH}} \sim 10^{-1} - 10^{-2} M_{\star}$ (see e.g. Y. Harikane et al. 2023; R. Maiolino et al. 2024). Nevertheless, these discrepancies may be alleviated by considering that the common assumptions underlying observational estimates of MBH masses may induce significant bias. Indeed, as suggested by A. Lupi et al. (2024), uncertainties on the observed values can produce overestimated M_{BH} by up to one order of magnitude, especially in high- z systems which may be growing close to (or slightly above) the Eddington limit (see A. Lupi et al. 2024, also see discussion on selection biases in W. Ren et al. 2025). Also, recent works started posing doubts on the M_{BH} estimates at high- z (V. Rusakov et al. 2026), and recently J. E. Greene et al. (2026) proposed a different bolometric luminosity correction that lowered the L_{bol} estimates by 1 dex, pointing to a lower M_{BH} . On the other hand, a fair comparison between observational data and our results should take into account that the former are likely AGN-dominated samples (e.g. J. E. Greene et al. 2024; R. E. Hviding et al. 2025; K. Ronayne et al. 2025). Overall, our LRDAGNs and non-LRDAGNs populations show much flatter scalings than LRDs and non-LRDs samples at all redshifts for $M_{\star} < 10^{9.5} M_{\odot}$. This is broadly in line with current observations, especially when considering the possible overestimation of BH masses we discussed above (as suggested by A. Lupi et al. 2024). As expected, the most massive bins of LRDAGNs and non-LRDAGNs relations coincide with the relations of the broader LRDs and non-LRDs classes, showing that AGN fractions are close to unity for the most massive LRDs in our samples (as suggested by recent observations, see e.g. R. E. Hviding et al. 2025; K. Ronayne et al. 2025).

5.3 Evolution of the AGN population

As shown in Fig. 10, the first LRDAGNs with $M_{\text{BH}} > 10^6 M_{\odot}$ appear already at $z > 7$. Given the high AGN fractions among LRDs reported in the recent literature (see e.g. M. Carranza-Escudero et al. 2025; E. Durodola, F. Pacucci & R. C. Hickox 2025; D. D. Kocevski et al. 2025), in this section we take a closer look at the redshift evolution of our LRDAGNs and non-LRDAGNs samples¹³ To control for potential differences arising from AGN being hosted in different galaxies, we build a control sample of non-LRDAGNs that replicates the stellar mass distribution of the corresponding LRDAGNs population at each z . The comparison between M_{\star} -matched samples of LRDAGNs and non-LRDAGNs is presented in Fig. 11. On the left panels, from top to bottom, we present the evolution of M_{BH} , $L_{\text{bol}}^{\text{AGN}}$ and of the redshift of the first super-Eddington accretion episode in the MBHs growth history (i.e. $z_{\text{first, Sup. Edd.}}$). On the right panels, from top to bottom, we show the evolution of the total MBHs seed mass, of the fraction of AGN growing in different accretion regimes and of the median redshift of the last super-Eddington accretion episode (i.e. $z_{\text{last, Sup. Edd.}}$). The absence of data at $6 < z < 7$ reflects the lack of non-LRDAGNs objects available to construct a valid M_{\star} -matched control sample.

¹³We acknowledge that the results of this section are highly dependent on the definition of AGN. We explore in Appendix C a more relaxed AGN definition

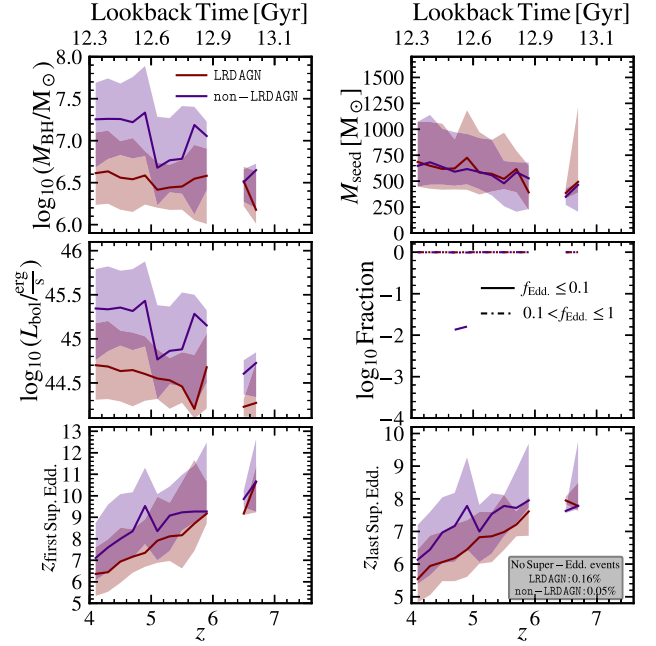


Figure 11. Black hole mass (M_{BH}), initial seed mass (M_{seed}), bolometric luminosity ($L_{\text{bol}}^{\text{AGN}}$), fraction of MBHs accreting a different f_{Edd} , redshift of the last super-Eddington ($z_{\text{last, Sup. Edd.}}$) and redshift of the first super-Eddington ($z_{\text{first, Sup. Edd.}}$) for LRDAGNs and non-LRDAGNs (red and purple, respectively). The lines and the shaded areas correspond to the median and 16th–84th percentiles. The values of f_{Edd} divides between ‘quiescent’ AGN with $f_{\text{Edd}} \leq 0.1$ and Eddington-limited accretion with $f_{\text{Edd}} = 1$.

As anticipated in the previous section, the comparison of black hole masses reveals that at $z < 6$, non-LRDAGNs typically host MBHs more massive by ~ 0.5 dex than LRDAGNs. These larger M_{BH} translate directly into higher bolometric luminosity, as seen in the middle left panel. This correlation arises because the vast majority of the AGN in both samples accrete at or near the Eddington rate ($f_{\text{Edd}} = 1$), as illustrated in the middle right panel. Given these similar accretion rates, the observed differences in M_{BH} must be attributed to a combination of differences in the growth history of MBHs and variations in their initial seed masses. Disentangling this degeneracy is essential to understanding the origin of the mass discrepancy. To investigate this, we compare the redshifts of the first and last super-Eddington accretion episodes between LRDAGNs and non-LRDAGNs. We find that non-LRDAGNs selected at $z < 6$ consistently exhibit higher values of both $z_{\text{first, Sup. Edd.}}$ and $z_{\text{last, Sup. Edd.}}$ compared to LRDAGNs. This indicates that the MBHs powering non-LRDAGNs experienced phases of rapid growth earlier in cosmic time than those hosted by LRDAGNs. As a result, these MBHs had an earlier start in their mass assembly, giving them a significant advantage in reaching higher masses by $z < 6$.

Regarding the seeding, our model indicates that the larger black hole masses of non-LRDAGNs at $z < 6$ cannot be attributed to differences in the initial seed masses. In fact, MBHs powering both non-LRDAGNs and LRDAGNs originate from remarkably similar seeds, with typical total seed masses of $M_{\text{seed}} \sim 500 M_{\odot}$.¹⁴ By directly analysing the formation channels of

¹⁴We emphasize that M_{seed} refers to the total black hole seed mass that contributes to the final M_{BH} at a given redshift. This explains its increas-

BH seeds (not shown here for brevity), we find that 99.5 per cent (98.3 per cent) of MBHs hosted in LRD AGNs (non-LRD AGNs) originally formed as light seeds with masses $\lesssim 100 M_{\odot}$ (i.e. remnants of PopIII stars, see D. Spinoso et al. 2023; S. Bonoli et al. 2025) and never merged with any heavier seed type. This is in contrast with recent studies that suggest a heavy-seed origin for LRDs (e.g. E. Cenci & M. Habouzit 2025; K. Inayoshi & R. Maiolino 2025; J. Jeon et al. 2026). However, the recent work by S. Bonoli et al. (2025), within the framework of the *L-Galaxies BH* model, demonstrates that combining *JWST* observations with pulsar timing array constraints favours a scenario in which MBHs in LRD AGNs arise primarily from light seeds undergoing phases of super-Eddington accretion. Moreover, other studies do not exclude light seeds as plausible progenitors for LRDs, further supporting this interpretation (see e.g. H. Hu et al. 2022; M. T. Scoggins & Z. Haiman 2024). Finally, we note that in our model, heavy seeds tracked by *L-Galaxies BH* never grow efficiently enough to match the black hole masses inferred for LRD AGNs from *JWST* observations, further disavouring their origin as descendants of heavy BH-seeds. We do not explore this point in further detail here, as it will be the focus of a forthcoming study (Spinoso et al. in preparation).

Finally, in Fig. 12 we investigate the obscuration in the LRD AGNs and non-LRD AGNs samples. The upper left panel presents the grain number density in the innermost region of the torus ($n_{gr,1}$), i.e. the area directly illuminated by radiation from the MBH. Although this quantity is challenging to constrain observationally, it offers valuable insight into the degree of AGN obscuration and the reprocessed radiation emitted at IR wavelengths. The results show that LRD AGNs generally exhibit higher dust densities in their nuclear regions. This is not an unexpected result, as in the context of our modelled gas density profiles, higher black hole masses correspond to lower density normalizations. This trend is consistent with the broader picture discussed throughout this section: LRD AGNs are typically in earlier growth phases, retaining larger gas reservoirs that fuel ongoing accretion, while non-LRD AGNs have already consumed much of their available gas during earlier evolutionary stages. The results in $n_{gr,1}$ also contribute to the differences observed in the torus optical depth at the outer radius ($\tau_{torus}(r_2)$) where the LRD AGNs sample exhibits values up to a factor of 1.4 higher than those found in the non-LRD AGNs sample. To further assess the role of the torus in the detection of LRD AGNs, we quantify its contribution using the parameter $f_{coincidence}$, shown in the middle right panel of Fig. 12. This quantity represents the fraction of LRD AGNs that would still be classified as such even if the torus were entirely removed.¹⁵ To guide the reader, a lower $f_{coincidence}$ indicates a stronger dependence on torus-related effects for their selection. As shown, $f_{coincidence}$ decreases slightly with redshift but remains relatively constant, with typical values around $f_{coincidence} \sim 0.9$. This implies that obscuration plays a secondary role and is only relevant for ~ 10 per cent of the LRD AGNs sample, while the majority would still be identified as

ing trend with decreasing redshift, as mergers between MBHs combine the seed mass contributions of each progenitor.

¹⁵Given that the set of NIRCам filters used captures just the rise of the IR emission (the F444W filter peaks at 42500 Å, i.e. 8500 Å at $z=4$, and our torus emission usually peaks at $10^{4-4.5}$ Å, see Fig. 3), the torus effect is mainly present as obscuration of the central source in the rest frame UV-optical.

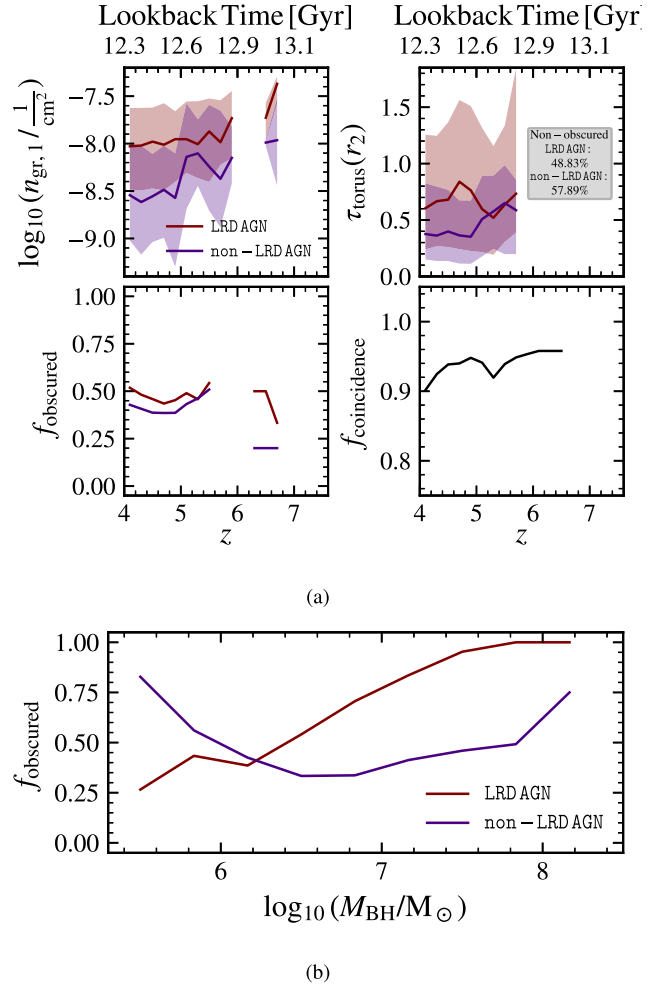


Figure 12. Obscuration properties of the LRD AGNs and non-LRD AGNs samples (red and purple, respectively). The upper panel shows the grain number density at the innermost region of the torus ($n_{gr,1}$), the torus optical depth ($\tau_{torus}(r_2)$), the fraction of obscured objects ($f_{observed}$) and the fraction of AGN that are still selected as LRD AGNs after removing the torus component ($f_{coincidence}$). The lower panel represent the fraction of obscured objects as a function of black hole mass, independently of redshift. In the two upper panels, the solid lines represent the median values of the distributions, while the shaded areas correspond to the 16th – 84th percentiles.

AGN based solely on their host galaxy and MBH accretion properties. Indeed, to assess obscuration, we also examine the quantity $f_{observed}$, which represents the fraction of LRD AGNs and non-LRD AGNs sources that are obscured due to the torus (see Section 3.2.5). This is shown in the lower panels of Fig. 12, where we see how the fraction of obscured objects in both samples is constant regardless of redshift. Specifically, LRD AGNs typically exhibit $f_{observed} \sim 50$ per cent, while non-LRD AGNs sit at slightly lower values of $f_{observed} \sim 40 - 50$ per cent. A more interesting behaviour arises when the mass of the black hole is fixed (Fig. 12b): LRD AGNs consistently show a higher obscured fraction. Interestingly, the LRD AGNs sample displays a clear trend of increasing obscuration fraction with increasing mass, going from 25 per cent to ~ 100 per cent. This behaviour is consistent with the previous finding that the MBHs hosted in LRDs (or LRD AGNs) need to not be bright enough for the v-shape to remain. Therefore,

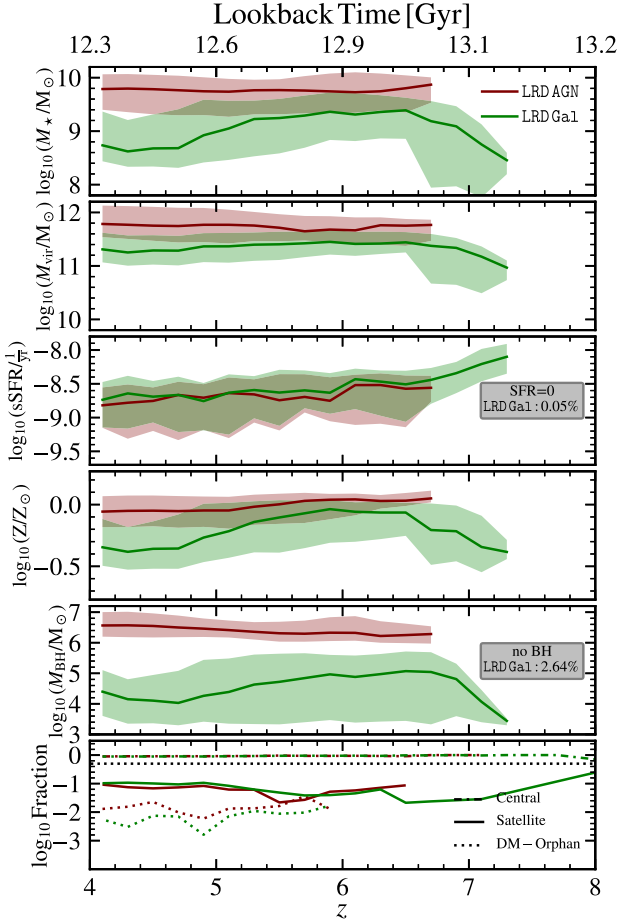


Figure 13. Properties for the LRD AGNs and LRD Gal.s samples (red and green, respectively). From top to bottom: M_* , halo mass, specific star formation rate (sSFR), metallicity (Z), M_{BH} and fraction of galaxies which are centrals or satellites. The solid lines represent the median values of the distributions, while the shaded areas correspond to the 16th–84th percentiles. The text displayed inside grey boxes represents the fraction of galaxies with a null SFR and without a central MBH.

since the LRD selection introduces a bias towards fainter MBHs, and the more massive MBHs are also brighter, it is required for them to be more obscured in order to be selected as LRD (LRD AGNs).

5.4 Galaxies and AGN in the LRD population

As shown in Fig. 5, the photometrically selected LRD population includes both objects classified as galaxies and AGN (LRD AGNs and LRD Gal.s, respectively, see Section 3.5). Our results show that the AGN sample accounts for 40 per cent of the population at $z \sim 4$, decreasing to 10 per cent at $z \sim 7$. In this section, we characterize these two subpopulations and highlight their key differences.

In Fig. 13, we present the evolution in redshift of the median (and 16th–84th percentiles) of the following properties, from top to bottom: stellar mass, halo mass, sSFR, metallicity, black hole mass, and the fraction of systems that are satellites. Regarding stellar mass, the LRD AGNs sample exhibits little to no redshift evolution, maintaining an approximately constant value of $M_* \sim 10^{9.5} M_\odot$. In contrast, the LRD Gal.s sample shows lower stellar masses and a more pronounced redshift evolu-

tion. At $z \sim 9$, LRD Gal.s have $M_* \sim 10^7 M_\odot$, which increases to $M_* \sim 3 \times 10^8 M_\odot$ by $z \sim 4$. These trends are consistent with the results presented in previous sections, where objects with a predominant galaxy (i.e. negligible AGN) contribution in their photometry are typically found in low-mass galaxies. Concerning the halo mass, the trends closely mirror those seen in stellar mass. The LRD AGNs sample exhibits only mild redshift evolution, with $M_{\text{vir}} \sim 5 \times 10^{11} - 10^{12} M_\odot$, whereas the LRD Gal.s sample evolves from $M_{\text{vir}} \sim 10^{10} M_\odot$ at $z \sim 9$ to $M_{\text{vir}} \sim 2 \times 10^{11} M_\odot$ at $z \sim 4$. The differences in both halo and stellar masses result in distinct metallicity profiles between the two populations, with LRD AGNs galaxies being more metal-rich ($Z \sim 1 - 0.7 Z_\odot$) compared to LRD Gal.s galaxies ($Z \sim 0.15 - 0.7 Z_\odot$). Interestingly, both samples show a drop in metallicity around $z \sim 7$, likely due to the infall of pristine gas into the galactic discs. In terms of sSFR, both samples exhibit a decreasing trend, but they remain consistent with star-forming galaxies (sSFR $> 10^{-9} \text{ yr}^{-1}$). Notably, the sSFR values of the LRD Gal.s and LRD AGNs samples are very similar, suggesting that any potential AGN feedback in the LRD AGNs sample is still too weak to quench star formation in their host galaxies. In this respect, the MBHs powering LRD AGNs objects are more massive than those in LRD Gal.s systems. While the former host MBHs with $M_{\text{BH}} \sim 5 \times 10^6 M_\odot$, the latter host systems with MBHs of $M_{\text{BH}} \sim 10^3 - 10^5 M_\odot$. Finally, approximately 90 per cent of the objects in both the LRD Gal.s and LRD AGNs populations are central galaxies, implying that they are the most massive objects in their host dark matter halos, with only about 10 per cent corresponding to satellite galaxies.

Beyond the global properties of galaxies, it is also insightful to examine the morphological characteristics of the two LRD samples. This is shown in Fig. 14 where we show from top to bottom: (mass-weighted) galaxy radius (R_e)¹⁶, disc-to-total ratio (D/T), bulge radius (R_{bulge}), bulge mass assembled via disc instabilities ($M_{\text{DI}}/M_{\text{bulge}}$), the fraction of major and minor mergers undergone by the objects and the median of number of minor mergers. Regarding the galaxy radius, both samples exhibit similar extensions, with a general increase towards lower redshifts. Specifically, at $z \sim 7$, the typical galaxy has a radius of $R_e \sim 500$ pc, while by $z \sim 4$, this value increases to $R_e \sim 800$ pc. These results agree remarkably well with T. Morishita et al. (2024) (also see T. Shibuya et al. 2019; T. B. Miller et al. 2025). This could hint at an extended diffuse emission around LRDs, as recent studies suggest (e.g.: P. Rinaldi et al. 2025; C.-H. Chen et al. 2025b; H. Yanagisawa et al. 2026), which showed that the typical radius of $z > 5$ galaxies ranges between 0.3 kpc and 1 kpc, depending on the *JWST* filter used. Regarding galaxy morphology, both samples are predominantly disc-dominated ($D/T > 0.6$), with the disc component becoming more prominent at lower redshifts. Despite these similarities, the LRD AGNs sample tends to exhibit slightly lower D/T values, indicating a more prominent bulge component. This is further supported by the bulge size, with LRD AGNs galaxies featuring more extended bulges (~ 150 pc) compared to LRD Gal.s galaxies (~ 100 pc). Such a difference is not unexpected, as AGN activity in the *L-Galaxies* BH model is closely linked to the growth of galactic bulges (D. Izquierdo-Villalba et al. 2020). The primary bulge formation scenario, and consequently the main triggering mechanism for MBHs in the LRD AGNs sample,

¹⁶ R_e describes physical radius and is given by $R_e = \frac{M_{\text{disk}} r_{\text{disk}} + M_{\text{bulge}} r_{\text{bulge}}}{M_{\text{disk}} + M_{\text{bulge}}}$.

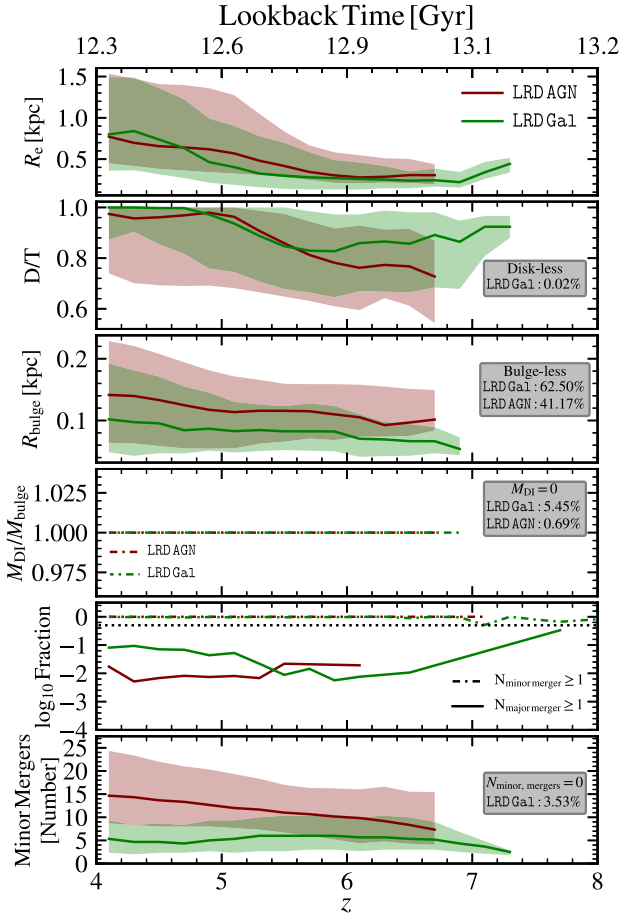


Figure 14. Morphological properties of LRD AGNs and LRD Galaxies (red and green, respectively). From top to bottom: galaxy size, disc-to-Total ratio, bulge size, fraction of bulge mass assembled via disc-instabilities, fraction of objects which underwent major/minor mergers and total number of minor mergers. The lines and shaded areas represent the same as in Fig. 13. The text inside grey boxes shows the fraction of galaxies that lack a disc, lack a bulge, do not have bulge-mass coming from disc-instabilities, and have not undergone any minor mergers.

becomes evident when examining the M_{DI}/M_{bulge} ratio, which quantifies the fraction of the bulge formed via disc instabilities. As shown, 100 per cent of the bulge in both the LRD Galaxies and LRD AGNs samples is assembled this way, likely induced by minor mergers regardless of redshift. Thus, our model indicates that the AGN activity observed at $z > 4$ in LRDs is primarily fuelled by internal processes, rather than by the more violent major merger mechanisms typically associated with AGN triggering at lower redshifts. The bottom panel of Fig. 14 shows that < 10 per cent (< 1 per cent) of the LRD Galaxies (LRD AGNs) sample underwent a major merger, suggesting a relatively quiet merger history of LRD Galaxies and LRD AGNs populations. In terms of minor interactions, all objects in both samples have experienced at least one minor merger. However, LRD AGNs objects have a more active merger history, averaging 10–15 interactions compared to 2–5 for LRD Galaxies objects.

Finally, in Fig. 15, we study the SED attenuation of the LRD AGNs and LRD Galaxies samples by presenting their hydrogen column density (N_H^{ISM}) and dust extinction (A_V^{ISM}) due to the ISM. In terms of A_V^{ISM} , the LRD AGNs sample shows values in the range of $\sim 2-5$, which are systematically higher (by a factor of

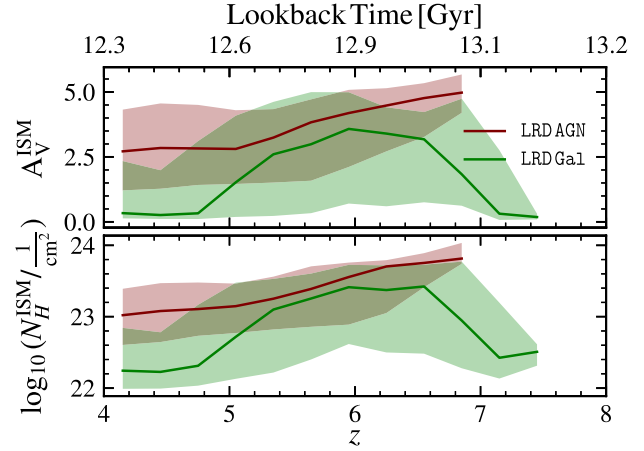


Figure 15. Hydrogen column density (N_H^{ISM}) and dust extinction (A_V^{ISM}) due to the ISM for the LRD AGNs and LRD Galaxies samples (red and green, respectively). The lines and shaded areas represent the same as in Fig. 13.

$\sim 1.3-2$) compared to those of the LRD Galaxies sample. A similar trend is observed for N_H^{ISM} . While LRD Galaxies sources typically exhibit column densities of $N_H^{ISM} \sim 10^{22-23} \text{ cm}^{-2}$, the LRD AGNs sample reaches higher values of $N_H^{ISM} \sim 10^{23-24} \text{ cm}^{-2}$. These differences can be naturally attributed to the already described higher stellar masses of the AGN hosts, which imply larger cold gas and dust reservoirs in their ISM.

6 CAVEATS

Our model relies on several key assumptions, which can affect some of our results and their interpretation. In the following paragraphs, we outline these assumptions, discussing their impact on the work and findings we presented.

(i) The AGN emission framework we developed does not account for the reprocessing of rest-frame X-rays. Therefore, we cannot draw predictions nor gain insights about the X-ray weakness observed in LRDs and high- z AGN (K. Inayoshi & K. Ichikawa 2024; M. Yue et al. 2024; F. Pacucci & R. Narayan 2024b). We stress that the results we presented remain unaffected by this, since the NIRCcam wavelength coverage does not extend into rest-frame X-rays for $z > 4$ sources. We plan to address this point in future works, especially by modelling the spectra emerging from a dense gas obscurer surrounding the central source. Indeed, recent studies suggest that this approach could naturally account for the X-ray weakness observed in high-redshift AGN.

(ii) Our model does not include a treatment of the re-emitted light from the galaxy ISM. However, given that the ISM is expected to have temperatures on the order of a few Kelvin, its peak emission typically occurs at far-IR or submillimetre wavelengths, well beyond the range covered by the NIRCcam filters used in this study. Consequently, our results are not affected by the lack of modelling of the ISM emission.

(iii) Our model for the galaxy compactness is a simplified one based on a single Sérsic profile that may not be capturing the clumpiness or full complexity taking place in high- z galaxies. Furthermore, we do not model the *JWST* PSF nor the wavelength-dependent variations across different filters of the light profile. Since the PSF apertures are typically smaller than the ones considered to compute the compactness, we consider the former effect of secondary order, and the latter the main contributor

to the differences of our simulated objects with observations. These simplifications likely tend to overestimate our sources compactness (as shown in the bottom panel of Fig. 4). As a consequence, we caution the reader to consider our compactness criterion as indicative. Nevertheless, we stress that the vast majority of our simulated sources satisfies the compactness cut we impose (see Table 1), therefore its effect on our LRD samples is negligible.

(iv) In this work, we assume that the radiation reprocessed by dust spans the range $912 \text{ \AA} < \lambda < 6564 \text{ \AA}$. The lower limit of 912 \AA is a reasonable choice, as shorter wavelengths can potentially photodissociate dust. Defining the upper limit is more challenging, so we set it at the rest-frame wavelength of the $H\alpha$ line, since beyond this point, IR emission begins to dominate at the sublimation temperature of 1500 K. While these assumptions are well-grounded, we emphasize that this choice could affect the location of the ‘V-shaped’ feature for some objects.

(v) The gas density profile employed for the narrow-line region (NLR) is consistent with the expected hydrogen number densities. However, applying this same profile to the broad-line region (BLR) leads to unreasonably high ionization parameters. To obtain more physically plausible results, we have opted to scale the hydrogen density of the BLR by a factor of $10^{9.5}$ relative to that of the NLR. Alternative scaling factors could lead to different intensities for the AGN emission lines. However, we have verified that the emission from the BLR does not significantly impact our selection of LRD population.

(vi) Our results indicate that at $z > 7$, the emission from the stellar population dominates the spectral features used to classify objects as LRD. This outcome is partly driven by the fact that, at these redshifts, our model predicts a lower number of massive MBHs compared to recent *JWST* observations. However, the *grafting* technique included in S. Bonoli et al. (2025) allows to sample a broader dynamical range in the BHMF and LF, alleviating the discrepancy at high redshift (although it persists 1–2 dex depending on the growth and seed model, favouring a light seed with Super Eddington growth scenario over one with a more abundant population of heavy BH seeds, see Fig. 8 of S. Bonoli et al. 2025). Therefore the lack of bright and massive MBHs, potentially building up a more numerous AGN population at high redshift is partially a volume issue that arises because of using *Millennium-II* as our background *N*-body simulation. Exploring alternative DM simulations, and extending the analysis with the *grafting* technique would yield a larger population of massive and actively accreting MBHs at $z > 7$, enhancing the contribution of MBH emission in the identification of LRDs. We plan to explore these possibilities in upcoming works.

(vii) Recent models suggest that the ‘V-shaped’ feature could be produced by a dense gaseous envelope around the central source (sometimes referred to as black hole star model, BH \star , see K. Inayoshi & R. Maiolino 2025; X. Ji et al. 2025; R. P. Naidu et al. 2025a). In this scenario, the spectrum at shorter wavelengths of the Balmer break would be associated with an underlying stellar population (such as a nuclear star cluster, see K. Inayoshi et al. 2025), whereas the spectrum at longer wavelengths would correspond to AGN emission reprocessed by a dense, hydrogen-rich environment. This picture is opposite to what we present, unsurprisingly given the fundamental difference between our model and the BH \star one. We acknowledge that modelling a gaseous obscurer would significantly alter the results presented in this

work. Nevertheless, this task should be treated carefully, not only taking into account the details of the BH \star model, but also because of the fact that LRDs represent a complex and diverse class. Under this perspective, both schemes may be playing a role in shaping the observed LRD and (or) AGN populations at $z > 4$. Therefore, while including the BH \star model in our scheme is beyond the scope of this paper, we plan to undertake this task in detail in a future work.

7 CONCLUSIONS

In this work, we explored the properties of $z \geq 4$ LRDs, photometrically selected within their cosmological context in a simulated lightcone. To this end, we used the *L-Galaxies* BH semi-analytic model (S. Bonoli et al. 2025) applied to the merger trees extracted from the high-resolution, *N*-body, cosmological simulation *Millennium-II* (M. Boylan-Kolchin et al. 2009). *L-Galaxies* BH was specifically designed to comprehensively capture several physical processes involved in the formation, growth, and dynamics of MBHs, a key feature which allows us to interpret LRDs populations within the context of current models for the formation and (co-)evolution of MBHs and galaxies.

To accurately model the emission from both galaxies and AGN, we developed a methodology within the *L-Galaxies* BH framework to obtain simulated SEDs. These include five distinct components: galaxy continuum, galaxy emission lines, AGN continuum, AGN torus emission and AGN emission lines (both broad and narrow). Additionally, for all these components, we accounted for attenuation due to absorption by dust and atomic gas along the line of sight.

Our simulated lightcone is designed to mimic *JWST*/NIRCam observations, enabling one of the most direct comparisons to date between simulated and observed LRDs. In an effort to mimic observational selections, we identify the population of LRDs within our lightcone applying the flux limits of the GOODS-S field along with the photometric colour and compactness cuts presented in V. Kokorev et al. (2024). Our main findings are as follows:

(i) The colours of our simulated LRD population show remarkably good agreement with observations. However, our sample tends to be more compact than observed LRDs. We attribute this mainly to the little detail of our light-profile modelling.

(ii) As expected, our simulated LRDs exhibit the characteristic ‘V-shaped’ photometric profile observed with *JWST* NIRCam. In detail, our LRD synthetic photometry shows a ‘dip’ corresponding to filters associated to rest-frame optical-to-NIR wavelengths. For low-mass LRDs ($M_{\star} \sim 10^{7-9} M_{\odot}$), this spectral feature is entirely due to the Balmer break of stellar-continuum origin, with no contribution from AGN emission on average.

(iii) In the high-mass LRDs ($M_{\star} > 10^9 M_{\odot}$), the ‘V-shaped’ photometry arises from the combination of AGN emission (dominating the rest-frame UV-optical) and stellar emission (predominant at longer wavelengths). This preserves the characteristic ‘V-shaped’ profile by combining a ‘blue’ AGN with a ‘red’ galaxy component. Interestingly, we find that this combination arises precisely because of the relatively small BH masses hosted by LRDs. Indeed, these produce low-luminosity AGN which are unable to outshine their galactic hosts at shorter wavelengths than the Balmer break. Brighter AGN (i.e. more massive BHs),

on the other hand, can ‘wash out’ the V-shape produced by the stellar Balmer break and be classified as non-LRDs. We find that the torus obscuration plays a secondary role in the selection, recovering > 90 per cent of the selected LRD AGNs when removing the torus.

(iv) Overall, LRDs represent less than 40 per cent of the total detected sample, with a decreasing trend toward higher redshift. However, when considering only our AGN sample ($L_{\text{bol}}^{\text{AGN}} > 10^{44} \text{ erg s}^{-1}$), LRDs make up 60–80 per cent of the entire population. Despite their relevance within the AGN class, we find that only 40 per cent (10 per cent) of LRDs at $z=4$ ($z=8$) can be classified as AGN, with the rest making up our galaxy population.

(v) LRDs dominate in the high end of the stellar ($M_{\star} \sim 10^{10} M_{\odot}$) and halo ($M_{\text{vir}} \sim 10^{11.5} M_{\odot}$) mass function, independently of redshift. On the other hand, LRDs tend to predominate at low-intermediate bolometric luminosity (i.e. $L_{\text{bol}}^{\text{AGN}} < 10^{45.5} \text{ erg/s}$) and relatively small BH masses ($M_{\text{BH}} \lesssim 10^7 M_{\odot}$). Taking the observed estimates for BH masses at face value, this may hint at the fact that currently discovered overmassive BHs hosted by LRDs may represent a biased sample of a larger and more complex LRDs population. At the same time, BH masses currently inferred from observations may be overestimated, hence alleviating the tension of our results with respect to current constraints..

(vi) When splitting the LRD class in AGN and galaxies, the latter (i.e. LRD Gal)s systematically appear to be less massive systems ($M_{\star} \sim 10^{8-9} M_{\odot}$, $M_{\text{vir}} \sim 10^{11} M_{\odot}$) than LRDs classified as AGN (i.e. LRD AGNs, $M_{\star} \sim 10^{9.8} M_{\odot}$, $M_{\text{vir}} \sim 10^{11.8} M_{\odot}$). In addition, the LRD Gal)s sample tend to be less metal-enriched than LRD AGNs ($Z \sim 0.4 Z_{\odot}$ vs. $Z \sim Z_{\odot}$), and host smaller MBHs ($M_{\text{BH}} \sim 10^5 M_{\odot}$ vs. $M_{\text{BH}} \sim 10^6 M_{\odot}$).

(vii) The LRD Gal)s and LRD AGNs samples are typically disc-dominated galaxies ($D/T > 0.6$) with characteristic sizes of 800 pc. Despite this similarity, the LRD AGNs population tends to host more extended bulges (~ 150 pc vs. ~ 90 pc) which assembled primarily via disc instabilities. We do not find significant differences between the two samples regarding their typical merger history.

(viii) An increasing number of recent works suggested that heavy BH-seeds may be favoured to explain the origin of MBHs hosted in LRDs. Despite including a detailed model for BH-seeding which takes into account at the same time light, intermediate and heavy seeds, we do not find any indication of the prevalence of a heavy-seed origin for LRDs nor for the LRD AGNs classes. With only a few exceptions, nearly all of our simulated LRDs form as light seeds and reach $M_{\text{BH}} > 10^6 M_{\odot}$ by a combination of Eddington-limited and Super-Eddington accretion episodes.

This work represents an important step toward understanding the nature of photometrically selected LRDs, offering theoretical insight into their origin, evolutionary pathways, and physical and photometric properties. Our method allows us to pinpoint the role of accreting MBHs in shaping the photometry of high-redshift objects, building a picture in which LRDs appear as a rich and diverse class of objects. While this study provides foundational groundwork, it should be seen as part of a broader effort to interpret the nature of LRDs. Many open questions remain, particularly regarding the origin of their prominent absorption

features near broad Balmer emission lines, the apparent deficit of hot dust emission and the lack of X-ray detections. These challenges do not appear to have a unique or universal explanation, underscoring the need for further development of theoretical models that jointly address galaxy and AGN emission, as well as the formation and growth of galaxies and MBHs.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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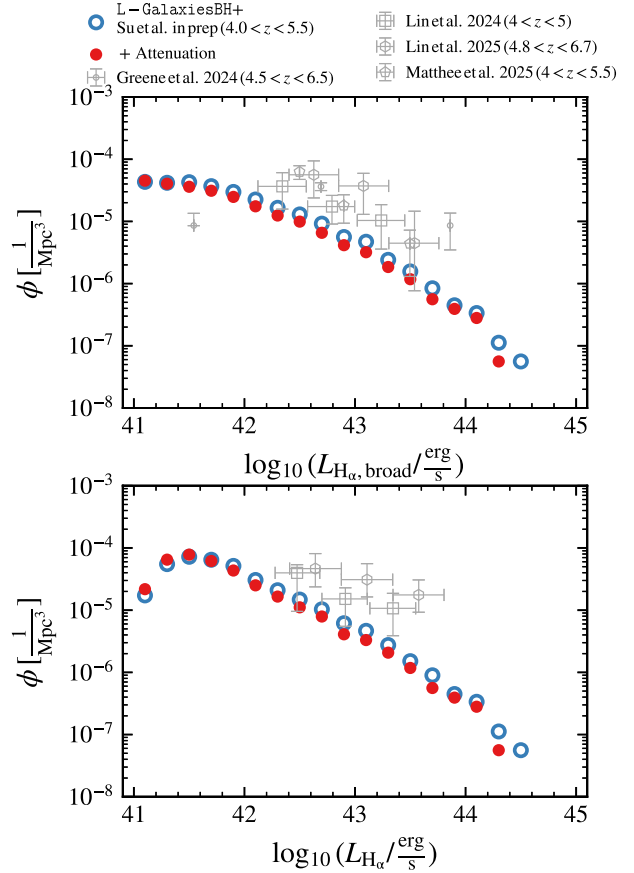


Figure A1. Luminosity functions of our simulated AGN H_α line. Blue empty circles show the luminosity obtained directly from the model of Su et al. (in preparation), while red circles show the dust-corrected values. **Upper panel:** luminosity function for the broad $H_{\alpha, \text{broad}}$ component we model. **Bottom panel:** luminosity function for the broad + narrow H_α components. We compare to data of X. Lin et al. (2024), X. Lin et al. (2026), J. E. Greene et al. (2024), J. E. Greene et al. (2026), J. Matthee et al. (2024), shown as grey symbols.

APPENDIX A: AGN EMISSION-LINES TEST

In this appendix, we examine the luminosity functions of the emission lines considered in this study. Fig. A1 presents the H_α luminosity function associated with MBH emission for both the broad-line region (BLR; top panel) and the total emission (BLR + NLR, bottom panel) at $4 < z < 5.5$. When compared to the observational data, our model underpredicts the number density of emitters by a factor of approximately 2–3. This discrepancy may arise either from an underestimation of the number of emitters or from systematically lower predicted line luminosity (or a combination of both). Such differences likely stem from simplifying assumptions adopted in the MBH line-emission model. A comprehensive analysis of emission-line properties in LRDs and high- z AGN would require a reassessment of these assumptions. However, given the scope of this work and the specific roles of the BLR and NLR in our modelling framework, we leave this for future investigation.

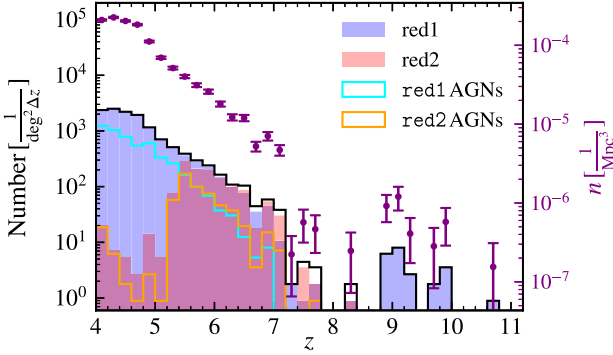


Figure B1. Redshift distribution of *red1* (blue) and *red2* (red). While the left y-axis corresponds to the number of objects per bin of redshift, the right one corresponds to the number density, shown with purple points in the figure. For completeness, we have also added the distribution of AGN selected in each photometric selection.

APPENDIX B: REDSHIFT SELECTION OF RED1 AND RED2

In this appendix, we present the redshift distribution of the *red1* and *red2* photometric selections. As shown in Fig. B1, the *red1* selection primarily identifies galaxies at $z < 6$, although some objects at higher redshifts are also selected. These $z > 6$ *red1* objects make for ~ 8.7 per cent of the total *red1* population, and their number density (per unit area) is typically 1 to 1.5 dex lower than at $z < 6$. In contrast, the *red2* selection predominantly selects objects at $z > 5.5$, with a pronounced peak at $z \sim 5.5$, in nice agreement with the intended behaviour. While some low-redshift interlopers are also present, they correspond to ~ 4.5 per cent of the whole *red2* population and their number density is ~ 2 orders of magnitude lower than that of the high-redshift population.

We stress that, while these redshift distributions are those expected when applying the *red1* and *red2* colour cuts (see V. Kokorev et al. 2024), we did not impose any *a priori* redshift cut on our simulated sources. Therefore, generally recovering these distributions can be seen as an indirect test of our galaxy and AGN SEDs modelling.

APPENDIX C: AGN DEFINITION TEST

Recently, several works focusing on LRDs have reported high fractions of AGN within observationally selected samples (e.g. 71 per cent in D. D. Kocevski et al. 2025). Therefore, it is interesting to understand how the definition of AGN we impose may affect the AGN fractions predicted by our model. As explained in the main body, we define as AGN those objects with $L_{\text{bol}}^{\text{AGN}} \geq 10^{44}$ erg/s to maximize the comparison with recent works, which generally detect AGN emission associated to LRDs above this luminosity (e.g. J. E. Greene et al. 2024; V. Kokorev et al. 2024; J. E. Greene et al. 2026). Nevertheless, it is interesting to explore how our results would change when lowering this threshold. Indeed, this would imply that fainter and lower massive MBHs could be classified as AGN. These objects would show AGN luminosity comparable to that of their host galaxy, effectively hindering the effects of the MBH emission onto the photometric selection.

In Fig. C1 we show the main differences which arise in our results when lowering the threshold to $L_{\text{bol}}^{\text{AGN}} \geq 10^{43}$ erg/s. In particular, we show the black hole mass evolution of LRD AGNs and

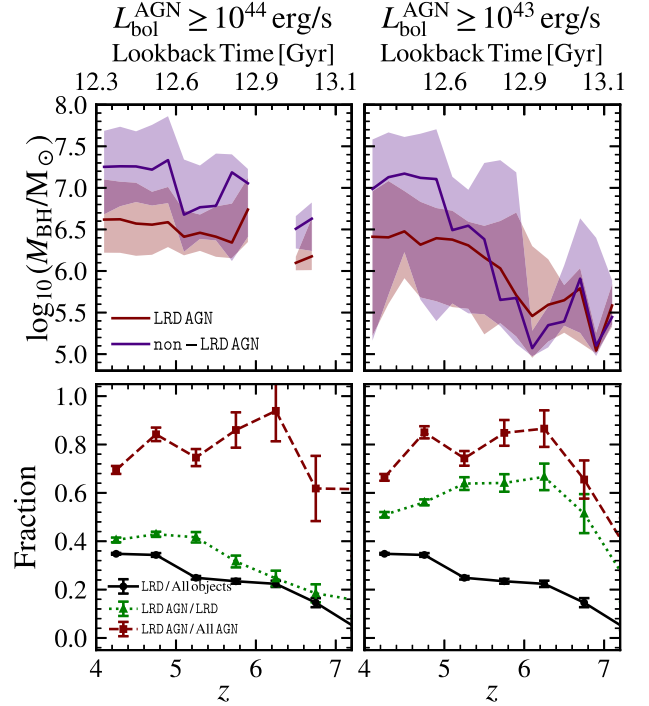


Figure C1. Black hole mass evolution (top panels) of the LRD AGNs and non-LRD AGNs samples for. Bottom panels show the fractions of LRDs over the total number of detected systems (black points), of LRDs classified as AGN over the total number of detected objects classified as AGN (red squares) and of LRDs classified as AGN over the number of LRDs (green triangles). Error bars correspond to the Poisson error. Left column correspond to the same AGN definition used in the main body of the paper (AGN: $L_{\text{bol}}^{\text{AGN}} \geq 10^{43}$ erg s $^{-1}$) and is shown for reference and ease the comparison. Right column correspond to AGN defined as those objects with $L_{\text{bol}}^{\text{AGN}} \geq 10^{43}$ erg s $^{-1}$.

non-LRD AGNs (when the latter are matched in stellar mass to the LRD AGNs, top panels), and the fractions showing the contribution of LRD AGNs to the LRD and AGN populations (bottom panels). These correspond to the top left panel of Fig. 11 and the bottom panel of Fig. 5, respectively. To ease the comparison, we report these two panels in the left column of Fig. C1, while the right column shows the updated results under our new AGN definition.

We note that the black hole mass evolution is now better sampled at all redshifts. In particular, owing to the larger number of sources selected by the lower $L_{\text{bol}}^{\text{AGN}}$ threshold, we observe continuous trends in the evolution of BH mass versus redshift. Regarding LRD AGNs, their typical mass appears to increase from $10^{5.5} M_{\odot}$ to $10^{6.5} M_{\odot}$ going from $z = 7$ down to $z = 4$. On the other hand, the typical mass of non-LRD AGNs shows a more evident evolution, passing from $10^{5.5} M_{\odot}$ at $z = 7$ to $\gtrsim 10^7 M_{\odot}$ at $z = 4$. Interestingly, we observe a clear turning point of the MBH mass of non-LRD AGNs, which increases by 1 order of magnitude between $z = 5$ and $z = 6$. Furthermore, we observe a brief redshift interval where the MBH mass of non-LRD AGNs is on average smaller than that associated to LRD AGNs. This shift at $z \sim 5.5$ is explained as follows: first, we note that at $z > 6$, the contribution of the MBH to the photometry is generally < 50 per cent (see right columns of Fig. D1). Therefore the photometric selection of LRD AGNs and non-LRD AGNs is driven by galaxy properties, hence the fact that MBHs in LRD AGNs appear more massive than

those in non-LRD AGNs can be seen as fortuitous. On the other hand, at $z < 6$, MBHs start to become massive enough (i.e. their associated AGN become bright enough) to significantly affect the photometry. This can be seen by the build-up of the massive-end of our BH mass function (i.e. bottom row in Fig. 6). This implies that MBHs start to play a more prominent role in the classification of an object as LRD or non-LRD. In particular, we observe a clear effect of our colour-based selection: in order to be classified as LRD, an object must show a prominent V-shape. Therefore, as explained in the main body, faint AGN (i.e. less massive BHs) are more likely to be classified as LRDs than bright AGN (i.e. more massive BHs). Consequently, as MBHs evolve in mass, our colour selection tends to classify more massive BHs as non-LRD AGNs, driving the increase of their average BH mass.

As for the fractions, the bottom panels of Fig. C1 show the effect of our new AGN definition on the ratios between the number of objects within different classes. As expected, the overall fraction of LRDs within the sample of detected objects is unaffected (black points and solid lines). This is because the LRDs definition does not depend in any way on our AGN definition.

The most affected fraction is that of LRD AGNs within the LRDs sample (green points and dotted lines). At $z < 5$ this gets boosted by ~ 10 per cent, but at $z \sim 6$ we see a ~ 30 per cent increase. This change is also expected, since a much larger number of LRDs is now classified as AGN under the new AGN definition. Interestingly, we observe a much smaller impact of the new AGN definition on the fraction of LRD AGNs within the entire AGN sample (red points and dashed line). In this case, we still measure fractions of about ~ 60 – 80 per cent at $4 < z < 7$, which is largely comparable to what we found under the more restrictive $L_{\text{bol}}^{\text{AGN}} \geq 10^{44} \text{ erg s}^{-1}$ cut. This shows that, independently of the AGN definitions we tested, the global AGN population in our model is dominated by LRD AGNs. That is: relatively faint AGN, whose emission cannot significantly balance the colour gradient produced by the stellar Balmer-break.

Overall, this analysis suggests that the main results of our work are independent of the specific threshold we impose to define AGN. In particular: we find that LRDs tend to host fainter AGN (i.e. less massive BHs) than non-LRDs also when applying the lower threshold of $L_{\text{bol}}^{\text{AGN}} \geq 10^{43} \text{ erg s}^{-1}$ to define objects as AGN.

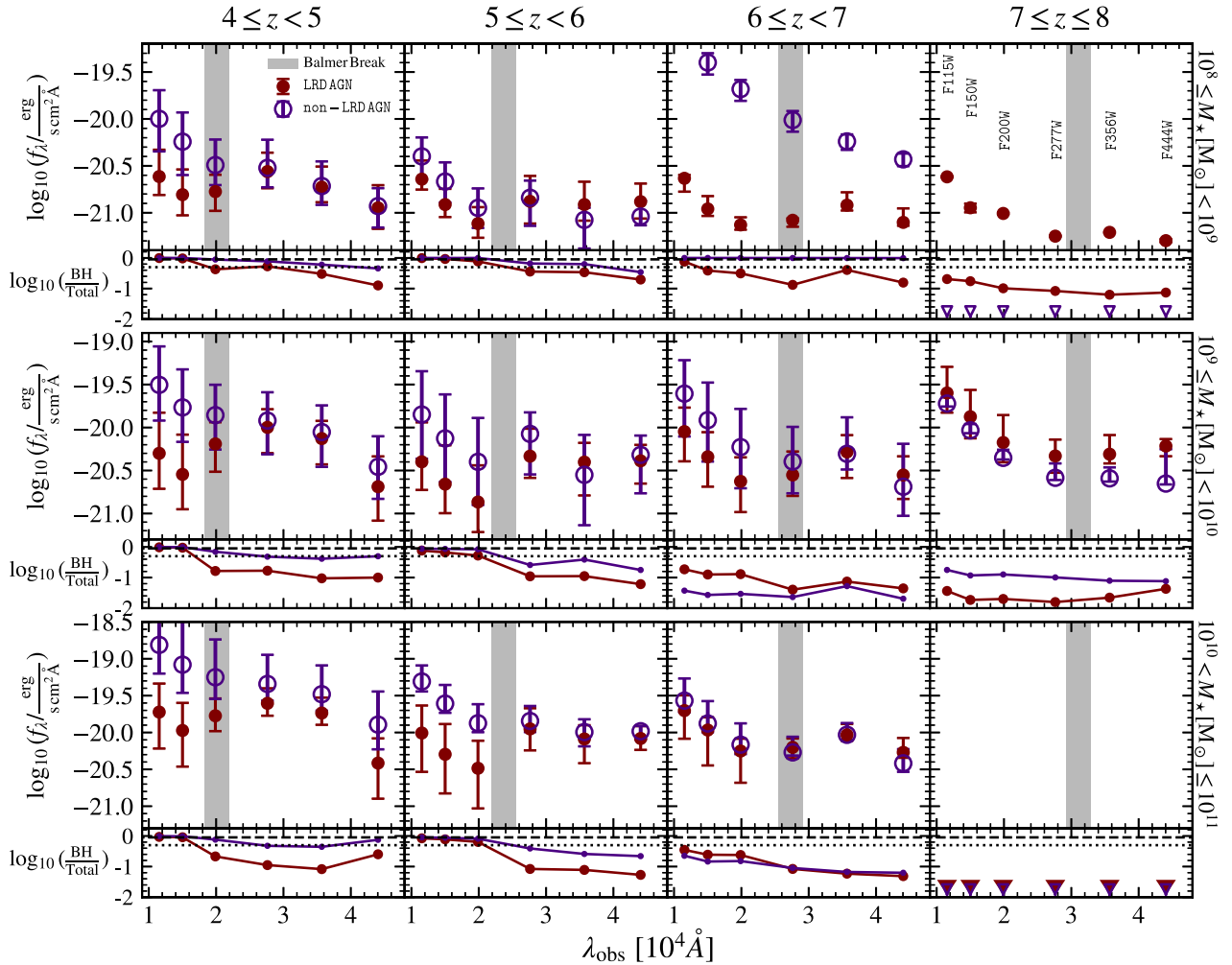


Figure D1. Median photometry of the LRD AGNs (filled dark red circles) and non-LRD AGNs (empty purple circles) samples at different redshifts. The error bars correspond to the 16th – 84th percentiles while the vertical grey shaded areas mark the Balmer break position. The small panels show the fractional contribution of the flux provided by AGN (i.e. accreting MBHs) within each *JWST* filter. The triangles represent the upper limits of this contribution. To guide the reader, the horizontal dashed lines highlight the 90 per cent and 50 per cent value (half of the flux is provided by the AGN). Different panels show different M_* bins, from top to bottom: $10^7 < M_* < 10^8 M_\odot$, $10^8 < M_* < 10^9 M_\odot$, and $10^9 < M_* < 10^{11} M_\odot$.

This is because in our model only the contribution of bright AGN to wavelengths bluer than the stellar Balmer break can erase the V-shape feature targeted by the colour-selection imposed to identify LRDs. Therefore, including fainter MBHs in the AGN class does not affect this result.

APPENDIX D: THE PHOTOMETRY OF LRD AGNs AND non-LRD AGNs SAMPLES

In this appendix, we present the photometry of the LRD AGNs and non-LRD AGNs samples, as shown in Fig. D1. At $z < 6$ the AGN emission dominates the flux in the F115W and F150W filters for all M_* bins, contributing with up to 80–90 per cent of the total flux. In contrast, the AGN contribution in the F227W,

F356W, and F444W filters shows a clear dependence on M_* : at $M_* > 10^9 M_\odot$, AGN emission accounts for only ~ 10 per cent of the detected flux. However, in lower-mass systems, the AGN contribution increases significantly, varying from 30 to 50 per cent. These trends reinforce the findings discussed in Section 5.2.2:

AGN in low-mass galaxies (both LRD AGNs or non-LRD AGNs) tend to be overmassive with respect to the overall $M_{\text{BH}}-M_*$ scaling relations of LRDs or non-LRDs. Finally, at $M_* > 10^9 M_\odot$ we find very similar results as those presented in Fig. 7. This is expected, since the majority of the AGN population lies in this M_* bin.

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