

The evolution of the sizes and angular momentum content of galaxies in the COLIBRE simulations

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ABSTRACT

We analyse the sizes and specific angular momentum content of galaxies in the COLIBRE cosmological hydrodynamical simulations spanning two orders of magnitude in mass resolution. We compare the predicted size–mass and angular momentum–mass relations to a broad range of observational measurements spanning redshifts $z = 0$ to 4. At $z = 0$, COLIBRE reproduces observed size–mass relations over the sampled mass range $10^8 \lesssim M_*/M_\odot \lesssim 10^{11.5}$, and for multiple size definitions, including two- and three-dimensional stellar half-mass radii, half-light radii across several wavelengths, as well as alternative measures such as baryonic half-mass radii and characteristic radii defined by stellar surface density thresholds. The simulations also recover the observed segregation of galaxies in the size–mass plane by morphological type and star formation rate, and reproduce the distinct, approximately parallel sequences followed by star-forming discs and quenched spheroids in the stellar specific angular momentum–mass plane. The angular momentum content of star-forming COLIBRE galaxies matches that of observed systems out to $z \approx 1.5$. At higher redshifts, massive galaxies ($10^{9.5} \lesssim M_*/M_\odot \lesssim 10^{11}$) in the simulations are somewhat smaller than observed, and the separation between star-forming and passive populations in the size–mass plane is reduced relative to observations, while at lower masses the agreement remains good. This apparent discrepancy may reflect the effects of dust attenuation, which is neglected in our analysis and may preferentially obscure the central regions of observed systems. Overall, our findings highlight the close connection between galaxy size, angular momentum, and morphology over cosmic time.

Key words: galaxies: structure – galaxies: kinematics and dynamics – methods: numerical – galaxies: evolution – galaxies: formation.

1 INTRODUCTION

The stellar mass (M_*) and size (R_*) of galaxies are among their most fundamental properties. These quantities are strongly correlated and vary systematically with morphology, star-formation activity, and colour, among other properties (e.g. S. Shen et al. 2003; A. van der Wel et al. 2014; P. G. van Dokkum et al. 2015; R.

Lange et al. 2015; K. E. Whitaker et al. 2017; R. H. W. Cook et al. 2025). As a result, considerable effort has been devoted to characterizing the galaxy size–mass relation (SMR) and its dependence on secondary galaxy parameters in order to constrain models of galaxy formation and evolution.

There is now broad consensus from observational studies on a few key features of the SMR: (1) at fixed mass, late-type discs are typically larger, bluer, and more actively star-forming than early-type spheroids, which are generally smaller, redder, and quenched (e.g. S. Shen et al. 2003; I. Trujillo et al. 2007; K. E.

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Whitaker et al. 2017); (2) at fixed redshift, galaxy size increases on average with stellar mass, while at fixed stellar mass it decreases with redshift (e.g. A. van der Wel et al. 2014; E. Ward et al. 2024); and (3) size evolution is stronger for massive and quenched galaxy populations than for low-mass or star-forming ones, although individual galaxies may transition between these populations (I. Trujillo et al. 2007; A. van der Wel et al. 2014; L. A. Mowla et al. 2019).

The SMR also depends on the underlying distribution of galaxy morphologies. At $z \approx 0$, spheroid-dominated early-type galaxies follow a steep SMR with a logarithmic slope between ≈ 0.4 and 0.6 , while late-type discs exhibit a shallower slope of ≈ 0.3 (S. Shen et al. 2003; R. Lange et al. 2015). Since early-types dominate the population above $M_\star \approx 10^{10.5} M_\odot$ – whereas lower-mass systems comprise a more diverse range of morphologies – the global SMR is observed to steepen above this mass threshold.

Although more difficult to directly observe, the stellar specific angular momentum ($j_\star$) provides a complementary probe of galaxy structure. Early work by S. M. Fall (1983) demonstrated that nearby spiral and elliptical galaxies occupy approximately parallel sequences in the $\log j_\star - \log M_\star$ plane (the angular momentum–mass relation, or AMR for short) with slopes of ≈ 0.7 , but with spheroids offset to lower angular momentum at fixed mass by ≈ 0.7 dex. S. M. Fall & A. J. Romanowsky (2013) confirmed these relations using an updated sample of galaxies that span a broader range of morphological types. They reported similar slopes but larger offsets (≈ 0.9 dex) between pure discs and pure spheroids, and a normalization that depends smoothly on the spheroid-to-total ratio (S/T) between these extremes. K.-H. Huang et al. (2017) confirmed that discs are larger than spheroids of the same stellar mass, in a manner that is consistent with the morphology-dependent normalization of the $j_\star - M_\star$ relation inferred by these earlier studies.

In the standard picture of disc formation, dark matter haloes acquire angular momentum through tidal torques from surrounding large-scale structure (F. Hoyle 1951; P. J. E. Peebles 1969; S. D. M. White 1984). Because baryons and dark matter are initially well mixed, they are expected to gain similar specific angular momenta at early times. However, simulations indicate that present-day galaxies retain only a fraction of their initial angular momentum (C. S. Frenk et al. 1985), which correlates with the fraction of halo mass retained by galaxies (e.g. L. V. Sales et al. 2009, 2010). In hydrodynamical simulations such as TNG100, late-type galaxies retain ~ 50 – 60 per cent of their halo’s specific angular momentum, while early types retain only ~ 10 – 20 per cent (S. Genel et al. 2015; V. Rodriguez-Gomez et al. 2022), broadly consistent with observational estimates of angular momentum retention fractions (S. M. Fall & A. J. Romanowsky 2013, 2018; L. Posti et al. 2018; E. M. Di Teodoro et al. 2021). Reproducing both the magnitude of angular momentum retention and its dependence on morphology is therefore essential for matching observed galaxy sizes.

Early hydrodynamical simulations of galaxy formation suffered catastrophic angular momentum losses and produced galaxies that were too small and had too little angular momentum when compared to observed systems (e.g. J. F. Navarro, C. S. Frenk & S. D. M. White 1995; J. F. Navarro & M. Steinmetz 1997). This shortcoming was later attributed to limited resolution and ineffective or absent stellar feedback (e.g. R.

J. Thacker & H. M. P. Couchman 2001; A. H. Maller & A. Dekel 2002), which allowed excessive radiative cooling and efficient star formation in galaxy progenitors. Mergers between these dense stellar clumps transferred orbital angular momentum to the halo, reducing $j_\star$ and leading to overly compact galaxies.

The problem was alleviated in subsequent higher-resolution simulations that incorporated efficient stellar and active galactic nucleus (AGN) feedback (e.g. F. Governato et al. 2004, 2007; T. Okamoto et al. 2005; C. Scannapieco et al. 2008). By reheating or expelling gas, such feedback delays star formation and suppresses early angular momentum loss. All modern simulations now include these processes, and some – though not all – successfully reproduce the observed sizes and angular momentum distributions of galaxies, as well as their dependence on morphology, colour, and star formation rate (e.g. J. Schaye et al. 2015; G. F. Snyder et al. 2015; A. F. Teklu et al. 2015; M. Furlong et al. 2017; V. Rodriguez-Gomez et al. 2022).

In the GIMIC simulations (R. A. Crain et al. 2009), galaxies with $10^9 \lesssim M_\star/M_\odot \lesssim 10^{10.5}$ have realistic sizes and rotation velocities (I. G. McCarthy et al. 2012), whereas more massive systems are overly compact and excessively star forming, likely due to the absence of feedback from supermassive black holes, which is known to affect the properties of massive systems. Galaxies in the original Illustris simulation (M. Vogelsberger et al. 2014) also display an SMR that is systematic offset from the observed relation, with galaxies of $M_\star \lesssim 10^{11} M_\odot$ being larger than observed by roughly a factor of 2 (G. F. Snyder et al. 2015). Y. Dubois et al. (2016) showed that the sizes of star-forming galaxies in the Horizon-AGN simulation (Y. Dubois et al. 2014) are broadly consistent with observations, but quiescent systems below $M_\star \approx 10^{11.3} M_\odot$ are larger than star-forming ones, inconsistent with what is observed. A similar trend in the size of star-forming and passive galaxies has been reported for SIMBA (R. Davé et al. 2019).

Yet a number of simulations show good agreement with observations. The EAGLE simulation (M. Furlong et al. 2017), in particular, reproduces the $z = 0$ SMR of A. van der Wel et al. (2014) to within ≈ 0.1 dex for both star-forming and passive galaxies, and matches the evolution of galaxy sizes from $z \approx 2$ to $z \approx 0$ to within ≈ 0.2 dex. Similarly, the Magneticum-Pathfinder simulations produce a galaxy population with size distributions consistent with observations, particularly for early-type galaxies (F. Schulze et al. 2018; K. Dolag et al. 2025).

Simulations that broadly match the SMR and its dependence on galaxy type also tend to reproduce the observed AMR. This has been demonstrated for EAGLE (C. d. P. Lagos et al. 2017) and Magneticum-Pathfinder (A. F. Teklu et al. 2015), where discs and spheroids occupy distinct but approximately parallel sequences in the $\log j_\star - \log M_\star$ plane, as observed, with similar behaviour also found in the Illustris simulation (S. Genel et al. 2015).

Despite this progress, quantitative comparisons between simulations and observations remain sensitive to measurement methodology. In simulations, galaxy sizes are typically measured directly from particle data within fixed three-dimensional apertures that also define the stellar mass, so the inferred masses and half-mass radii depend on the adopted aperture, at least for massive systems (e.g. M. Furlong et al. 2017). In contrast, observational sizes are often light-weighted and therefore wavelength dependent, reflecting dust attenuation and spatial variations in

the stellar mass-to-light ratio. Galaxies generally appear larger at shorter wavelengths (e.g. B. Vulcani et al. 2014; K. A. Suess et al. 2019), because young stars preferentially reside at large radii and centrally concentrated dust attenuates blue light. To reduce biases when comparing simulations with observations, it is increasingly common to construct mock images of simulated galaxies by modelling the spectral energy distributions of stellar particles, sometimes including additional effects such as dust attenuation, background emission, and instrumental noise. Sizes measured from such light-weighted images are systematically larger than their mass-weighted counterparts (e.g. J. van de Sande et al. 2019; A. de Graaff et al. 2022).

While sizes are traditionally measured using half-light or half-mass radii, alternative definitions have been proposed that aim to better capture the physical extent of galaxies. For example, I. Trujillo, N. Chamba & J. H. Knapen (2020) introduced the radius R_1 , defined by a stellar surface density threshold of $1 \text{ M}_\odot \text{ pc}^{-2}$. This roughly matches the typical gas density threshold for star formation (e.g. J. Schaye 2004; S. H. A. Rajohnson et al. 2022) and serves as a useful proxy for the ‘edge’ of the *in situ* stellar component (e.g. N. Chamba, I. Trujillo & J. H. Knapen 2022). Meanwhile, Z. Hua et al. (2025) used the complete census of galactic baryons to measure the ‘baryonic size–mass relation’ of galaxies in the Spitzer Photometry and Accurate Rotation Curves sample (SPARC; F. Lelli, S. S. McGaugh & J. M. Schombert 2016).

In this paper, we study the sizes and angular momentum content of galaxies in the COLIBRE¹ cosmological hydrodynamical simulations (J. Schaye et al. 2026; E. Chaikin et al. 2026a), which reproduce a broad range of observed galaxy properties across cosmic time. These include the stellar mass function, star-formation rates, passive fractions, and the masses of atomic and molecular gas and dust (J. Schaye et al. 2026; E. Chaikin et al. 2026b), as well as the resolved Kennicutt–Schmidt relation (C. d. P. Lagos et al. 2026). Focusing on galaxies at $z \lesssim 4$, we compare the simulated size–mass and j_* – M_* relations to observational measurements, and examine their dependence on morphology, star-formation activity, and size definition. Our primary goal is to assess how well COLIBRE reproduces these observed relations across galaxy populations, redshifts, and size definitions. In this respect, the paper is intentionally more descriptive than theoretical, with a focus on identifying where the model succeeds or fails to reproduce observations, thereby helping to clarify the physical regimes and galaxy populations for which the simulation provides a robust description. We consider both standard measures (half-mass and half-light radii) and alternative metrics such as R_1 and the half-baryonic mass radius, $R_{\text{bar},50}$. Results at $z > 4$, and those based on mock observational imaging, including dust, will be presented elsewhere.

This paper is organized as follows. Section 2.1 describes the COLIBRE simulations, while Section 2.2 outlines our halo and galaxy identification methods. Our analysis techniques are presented in Section 2.3. Section 3 presents our main results, including (1) the SMR at $z = 0$ (Section 3.1) and its evolution with redshift (Section 3.2); and (2) the AMR relation at $z = 0$ (Section 3.3) and its evolution with redshift (Section 3.4). We summarize our findings in Section 4. We validate some of our choices and assumptions in the appendices, including tests of the minimum

stellar particle number (Appendix A), differences between central and satellite galaxies (Appendix B), and the dependence on aperture choice (Appendix C) and observational scatter in stellar masses (Appendix D). In Appendix E, we compare the Sérsic indices measured for simulated and observed galaxies.

2 SIMULATIONS AND ANALYSIS

2.1 The COLIBRE simulations

2.1.1 Cosmology and initial conditions

Our analysis is based on COLIBRE, a new suite of cosmological hydrodynamical simulations of galaxy formation (J. Schaye et al. 2026). All simulations were run with the SWIFT code (M. Schaller et al. 2024), using the SPHENIX smoothed particle hydrodynamics (SPH) scheme to model hydrodynamic interactions between gas elements (J. Borrow et al. 2022).

Initial conditions (ICs) were created at $z = 63$ using MONOFONIC (O. Hahn, C. Rampf & C. Uhlemann 2021; M. Michaux et al. 2021) employing second order Lagrangian perturbation theory. Cosmological parameters are from the Dark Energy Survey Year 3 (DES Y3; T. M. C. Abbott et al. 2022) ‘ $3 \times 2\text{pt} + \text{All Ext.}^\dagger$ ’ Lambda cold dark matter (ΛCDM) model.

All of our initial conditions contain four times as many dark matter particles as baryonic ones, whereas nearly all previous cosmological simulations adopted equal numbers for both species (see M. Tremmel et al. 2017; A. D. Ludlow et al. 2023, for exceptions). This choice ensures that all particle species have comparable masses, including stellar particles, which inherit the masses of their gaseous progenitors. As a result, the effective resolution of stellar structures is increased by suppressing spurious, irreversible energy transfer from dark matter to stellar particles, which can artificially heat galaxies, inflate their sizes, and disrupt ordered motions² (e.g. A. D. Ludlow et al. 2019, 2021, 2023; M. J. Wilkinson et al. 2023).

COLIBRE features three resolution levels, with particle masses of $\sim 10^5$, 10^6 , and $10^7 \text{ M}_\odot$, and five box sizes ranging from 25 to 400 comoving Mpc (cMpc) in factors of 2. We will distinguish runs using an identifier that encodes the box size (L) and approximate base-10 logarithm of the particle mass (m); for example, L200m6 refers to the $(200 \text{ cMpc})^3$ volume simulated with baryonic and dark matter particles of mass $m \sim 10^6 \text{ M}_\odot$. Gravitational forces between particles of all types are softened using a H. Wendland (1995) C2 kernel below a time- and resolution-dependent spatial scale of $3 \times \epsilon$, where ϵ is the ‘Plummer-equivalent’ softening length. At $z = 0$, these are $\epsilon_{\text{prop}} = 0.35, 0.7$, and 1.4 kpc for the m5, m6, and m7 resolutions, respectively.

In this paper, we mainly present results from the highest resolution runs available for each volume (L025m5 or L050m5, L200m6, and L400m7), and reserve runs of lower resolution or smaller volumes to assess convergence (see Appendix A). Table 1 provides details of the runs, including the box size, the numbers

²As discussed by A. D. Ludlow et al. (2021), the primary benefit of this approach is not that dark matter and stellar particles have similar masses, but that it increases the number of dark matter particles in haloes where galaxies form. This, in turn, prolongs the local relaxation time and reduces numerical heating driven by two-body interactions. Disparate particle masses leads to a secondary effect, commonly referred to as mass segregation.

¹<https://colibre.strw.leidenuniv.nl/>

Table 1. Relevant numerical parameters of the COLIBRE simulations. Columns provide a simulation label, the model for active galactic nucleus feedback, the comoving box side-length (L), the total number of dark matter and baryonic particles (N_{DM} and N_{bar} , respectively), the initial dark matter and baryonic particle masses (m_{DM} and m_{bar} , respectively), and the maximum comoving (ϵ_{com}) and physical (ϵ_{prop}) softening lengths.

Label	Model	L (cMpc)	N_{DM}	N_{bar}	m_{DM} ($M_{\odot}$)	m_{bar} ($M_{\odot}$)	ϵ_{com} (kpc)	ϵ_{prop} (kpc)
L400m7	thermal-AGN	400	4×3008^3	3008^3	1.94×10^7	1.47×10^7	3.6	1.4
L200m7	thermal-AGN	200	4×1504^3	1504^3	1.94×10^7	1.47×10^7	3.6	1.4
L200m6	thermal-AGN	200	4×3008^3	3008^3	2.42×10^6	1.84×10^6	1.8	0.7
L100m6	thermal-AGN	100	4×1504^3	1504^3	2.42×10^6	1.84×10^6	1.8	0.7
L050m5	thermal-AGN	50	4×1504^3	1504^3	3.03×10^5	2.30×10^5	0.9	0.35
L025m7	thermal-AGN	25	4×188^3	188^3	1.94×10^7	1.47×10^7	3.6	1.4
L025m6	thermal-AGN	25	4×376^3	376^3	2.42×10^6	1.84×10^6	1.8	0.7
L025m5	thermal-AGN	25	4×752^3	752^3	3.03×10^5	2.30×10^5	0.9	0.35
L200m7h	hybrid-AGN	200	4×1504^3	1504^3	1.94×10^7	1.47×10^7	3.6	1.4
L100m6h	hybrid-AGN	100	4×1504^3	1504^3	2.42×10^6	1.84×10^6	1.8	0.7

and initial masses of dark matter and baryonic particles, as well as the maximum co-moving and proper gravitational softening lengths.

2.1.2 Sub-resolution models and calibration

COLIBRE includes sub-resolution models for radiative cooling and heating (S. Ploekinger et al. 2025), star formation (F. S. J. Nobels et al. 2024), black hole growth (Y. M. Bahé et al. 2022; F. S. J. Nobels et al. 2022), dust formation and its role in the regulation of molecular gas (J. W. Trayford et al. 2026), chemical enrichment, and turbulent mixing (C. A. Correa et al. 2026). Stellar feedback is implemented through stellar winds, radiation pressure, H II region heating (A. Benítez-Llambay et al. 2026), and supernovae (including a stochastic thermal component as well as a kinetic component to drive turbulence; C. Dalla Vecchia & J. Schaye 2012; E. Chaikin et al. 2023). COLIBRE includes two models for black hole feedback: a purely thermal AGN mode (C. M. Booth & J. Schaye 2009, thermal-AGN hereafter) and a hybrid thermal/kinetic jet model (hybrid-AGN) that explicitly tracks the spin of the central supermassive black hole (F. Huško et al. 2026; runs that adopt this feedback scheme will be labelled with an ‘h’ suffix; e.g. L200m6h). The results presented in Sections 3.1 to 3.4 were obtained from the thermal-AGN model; we compare them to results from the hybrid-AGN scheme in Section 3.5.

Complementing these feedback and enrichment processes, COLIBRE’s treatment of the interstellar medium avoids imposing an effective equation of state, enabling gas to cool radiatively to temperatures ≈ 10 K. Gas particles are eligible to form stars when they satisfy a local gravitational instability criterion that depends on gas density, particle mass, and the local thermal and turbulent velocity dispersions, rather than being explicitly linked to gas temperature. Consequently, star formation occurs predominantly – but not exclusively – in cold ($T \lesssim 10^4$ K), dense gas with low velocity dispersion, conditions that are important for accurately modelling galaxy sizes and the vertical structure of galactic discs. Because the instability criterion is evaluated at the resolution limit of the simulation, the typical densities of star-forming gas particles increase with increasing resolution, while their temperatures and turbulent velocities decrease. To achieve this, COLIBRE employs the chemistry solver CHIMES (A. J. Richings, J. Schaye & B. D. Oppenheimer 2014a, b) to track the non-equilibrium abundances of primordial elements, atomic and molecular hydrogen, helium (in all neutral and ionized phases),

and dust within each fluid element, along with their associated heating and cooling rates. Element-by-element metal-line cooling rates are computed using HYBRID-CHIMES (S. Ploekinger et al. 2025) for nine elements – C, N, O, Ne, Mg, Si, S, Ca, and Fe – assuming chemical equilibrium, but are corrected to account for the non-equilibrium free electron densities from the hydrogen and helium reaction network.

Sub-grid models for stellar and AGN feedback were calibrated at m7 resolution using Gaussian process emulators that were trained on ~ 200 simulations of the same $(50 \text{ cMpc})^3$ volume (see E. Chaikin et al. 2026a, for details). Parameters for m7 runs were obtained by fitting the emulator to the Galaxy and Mass Assembly (GAMA) Survey DR4 $z = 0$ galaxy stellar mass function from S. P. Driver et al. (2022, GSMF) and to the (projected) SMR of J. A. Hardwick et al. (2022). The fit was performed over the galaxy stellar mass range $10^9 < M_*/M_{\odot} < 10^{11.3}$, applying equal weights to both data sets. At the m5 and m6 resolutions, sub-grid parameters were adjusted manually to achieve convergence. The coupling efficiency of AGN feedback was independently calibrated so that the black hole mass–stellar mass relation agreed with the observed relation for massive galaxies for which robust black hole mass estimates are available. This calibration strategy yields excellent weak convergence³ in key galaxy properties across all resolution levels.

More details about the calibration and convergence between runs of different resolution can be found in J. Schaye et al. (2026), E. Chaikin et al. (2026a), and in Appendix A.

2.2 Halo and galaxy identification

Dark matter particles are assigned to top-level haloes using a Friends-of-Friends (FoF) algorithm (we employ a linking length equal to 0.2 times the mean dark matter inter-particle separation; M. Davis et al. 1985); gas, stellar, and black hole particles are

³As discussed in J. Schaye et al. (2015), ‘weak convergence’ refers to agreement across resolution levels when sub-grid models are recalibrated independently at each resolution. In this approach, sub-grid parameters are allowed to compensate for changes in galaxy properties arising from different numerical parameters, such as mass and force resolution. Throughout this paper, remarks about ‘good convergence’ across resolution levels explicitly refer to weak convergence rather than implying insensitivity to unresolved physics.

assigned to the same FoF halo as the nearest dark matter particle within the linking length, provided it belongs to one.

Galaxies and their dark matter haloes were identified using HBT-HERONS (V. J. Forouhar Moreno et al. 2025), an updated version of HBT+ (J. Han et al. 2018) suitable for hydrodynamical simulations. An iterative unbinding procedure that accounts for the binding energies of all particle species was used to decompose FoF haloes into self-bound sub-structures. This process leverages the hierarchical formation of structure in Λ CDM and assumes each sub-halo originated as the central sub-halo of an earlier FoF group. Snapshots were thus processed sequentially from early to late times, using each sub-halo's particles to identify its descendant in subsequent snapshots. This particle-tracking approach improves sub-halo identification, especially for deeply nested satellites and those embedded in dense regions of their hosts (Á. Chandro-Gómez et al. 2025; V. J. Forouhar Moreno et al. 2025).

When multiple central sub-haloes merge on to a single descendant FoF group between two adjacent snapshots, the central is assigned to the most massive progenitor, provided no others are within 20 per cent of its mass. Otherwise, the sub-halo with the lowest orbital kinetic energy in the rest frame of the host FoF halo is selected.

We associate central galaxies with central sub-haloes and satellite galaxies with satellite sub-haloes, and exclude the latter from our analysis unless stated otherwise (see Appendix B for an assessment of how this choice affects the SMR and AMR).

2.3 Measurements of galaxy properties

The halo and galaxy catalogues were post-processed with the Spherical Overdensity Aperture Processor (SOAP; R. McGibbon et al. 2025), which calculates a wide range of sub-halo and galaxy properties. We obtain the stellar mass of each galaxy, M_* , by summing the individual masses of bound stellar particles that lie within 50 kpc of its centre. Stellar masses defined this way reproduce those inferred from mock observations of EAGLE galaxies (A. de Graaff et al. 2022), and unless otherwise stated, this definition is adopted in all figures that follow.

To obtain specific star formation rates (sSFRs) we sum the instantaneous SFRs of bound gas particles within a 50 kpc aperture and divide by M_* . Galaxy morphologies are quantified using the kinematic disc-to-total mass fraction, D/T . To estimate D/T , we double the mass of bound stellar particles within 50 kpc that counter-rotate with respect to their net rotation to approximate the bulge component, subtract this mass from the total stellar mass to obtain the disc mass, and divide it by M_* . The resulting D/T values correlate strongly with other kinematic morphology indicators, such as the co-rotating stellar mass fraction, κ_{co} (e.g. L. V. Sales et al. 2010; C. A. Correa et al. 2017), and the ratio of azimuthal velocity to velocity dispersion (V. J. Forouhar Moreno et al. 2026).

The 50 kpc apertures⁴ used to calculate M_* , sSFR, and D/T are centred on the most-bound particle (of any type). All galaxy properties presented hereafter are defined in a proper coordinate system.

⁴See Appendix C for a comparison of the SMRs and AMRs obtained for different choices of the spherical aperture.

2.3.1 Galaxy sizes

In Sections 3.1 and 3.2, we compare the sizes of COLIBRE galaxies with several observational data sets. Our approach mimics standard observational analysis methods, although we defer full forward-modelling of the simulated galaxies to future work. Unless stated otherwise, we include only stellar particles bound to each galaxy when estimating its size, and we have verified that our results are not strongly affected by this choice.

In what follows, we consider several measures of galaxy size motivated by these observational data sets. One is the three-dimensional stellar half-mass radius, $r_{*,50}$, defined as the radius of a sphere centred on the galaxy that encloses half of M_* . This simple measure provides a clear indication of a galaxy's physical extent and how it evolves over cosmic time.

We also compute several two-dimensional size measures directly from the particle data: the stellar half-mass radius, $R_{*,50}$, and the u -, r -, and z -band⁵ half-light radii, denoted $R_{u,50}$, $R_{r,50}$, and $R_{z,50}$, respectively. For the u and z bands, we also compute the radii enclosing 90 per cent of the light, $R_{u,90}$ and $R_{z,90}$, respectively.

We also estimate $R_{*,50}^{\text{Ser}}$ and $R_{r,50}^{\text{Ser}}$ by fitting single-component J. L. Sérsic (1963) profiles to the stellar-mass and r -band surface-density profiles [$\Sigma_*(R)$ and $\Sigma_r(R)$, respectively]. Both $\Sigma_*(R)$ and $\Sigma_r(R)$ are initially computed over the radial range $-2 \leq \log(R/\text{kpc}) \leq 3$ in logarithmic radial bins of width $\Delta \log R = 0.1$. We then fit the profiles over a restricted range $r_{\min} \leq r \leq r_{\max}$, where $r_{\min}$ is the innermost bin that encloses 10 stellar particles. The outermost bin, $r_{\max}$, is the smaller of either 50 kpc, or the farthest bin that contains at least 10 stellar particles.⁶ These measurements use three orthogonal projections of each galaxy (along the simulation's native x -, y -, and z -axes); the two-dimensional sizes presented below are averages over these orientations.

Fig. 1 shows median $\Sigma_*(R)$ profiles for galaxies within ± 0.15 dex of $M_* = 10^9 M_\odot$ and $10^{11} M_\odot$. Coloured lines denote different simulations; error bars indicate the 16th to 84th percentile scatter among individual galaxies in each mass bin, and are shown only for the L200m6 run for clarity. Grey lines show the mean best-fitting Sérsic profiles in each mass bin, obtained by averaging fits to the median profiles at fixed mass; grey shading indicates the range of the individual fits. Thick line segments mark the radial range used for fitting. Note that the two-dimensional half-mass radii inferred from the Sérsic fits (upward arrows) agree well with those measured directly from the particle data (coloured circles). Note too that the profiles obtained for the different resolution runs are in good agreement down to radii that are much smaller than the gravitational softening lengths (ϵ_{prop} ; marked by downward pointing arrows), suggesting that softening is not necessarily a limiting factor in resolving galaxy sizes (see also A. D. Ludlow et al. 2020; A. D. Ludlow et al. 2023). This justifies the choice of $r_{\min}$ used for profile fitting, which is typically smaller than the softening length.

⁵COLIBRE stores the rest-frame, dust-free AB magnitudes of star particles in the GAMA bands, computed following J. W. Trayford et al. (2015). These were calculated from G. Bruzual & S. Charlot (2003) (GALAXEV) stellar population synthesis models convolved with the relevant filter transmission curves, and depend on each particle's age and metallicity.

⁶We have verified that the values of $R_{*,50}^{\text{Ser}}$ and $R_{r,50}^{\text{Ser}}$ obtained this way are in good agreement with those obtained directly from the particle data. Note that we use the superscript 'Ser' to denote half-mass sizes estimated from Sérsic fits.

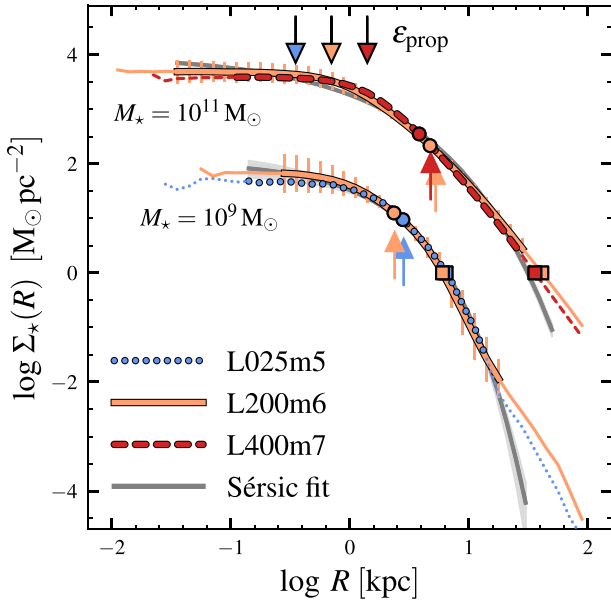


Figure 1. Median stellar surface density profiles, $\Sigma_*(R)$, for $z = 0$ central galaxies of mass $M_* = 10^9 M_\odot$ and $10^{11} M_\odot$. Different line styles correspond to different simulations. Thick segments mark the radial range used for profile fitting and error bars indicate the 16th to 84th percentile scatter in $\Sigma_*(R)$ for individual galaxies in L200m6. Grey lines show the mean of the best-fitting Sérsic profiles obtained separately for each simulation and mass bin; shaded grey regions span the range corresponding to individual fits to each of the median $\Sigma_*(R)$ profiles. Coloured circles show median $R_{*,50}$ values measured directly from the particle data, and upward arrows indicate the values inferred from the best-fitting Sérsic profiles. Squares correspond to the radius R_1 at which $\Sigma_* = 1 M_\odot \text{pc}^{-2}$. Downward arrows mark the $z = 0$ gravitational softening lengths, ϵ_{prop} , for each simulation, which exceed the minimum radii where profiles from runs with different resolutions converge.

Following I. Trujillo et al. (2020), we also consider another size measure, the radius R_1 where the stellar surface density profile drops below $\Sigma_1 \equiv 1 M_\odot \text{pc}^{-2}$ (coloured squares in Fig. 1). We calculate R_1 from the face-on projection of the stellar surface mass density profiles – defined in the plane perpendicular to the net angular momentum vector of the bound stellar particles – by linearly interpolating between the radial bins that bracket Σ_1 . The $\Sigma_*(R)$ profiles are constructed in the manner described above. This mimics the observational analysis of I. Trujillo et al. (2020). All bound stellar particles are used to calculate R_1 , regardless of their distance from the galaxy centre.⁷ For the lowest mass galaxies, R_1 typically exceeds $R_{*,50}$ by factors of a few, increasing to ≈ 10 for the most massive galaxies in our sample.

Finally, we examine the baryonic size–mass relation, which accounts for both stellar and gaseous components. It is defined by the half-baryonic-mass radius, $R_{\text{bar},50}$, and the total baryonic mass, M_{bar} . Baryonic half-mass radii are derived from cumulative mass profiles (i.e. curves of growth, CoGs) constructed by integrating the face-on stellar and gas surface-density profiles. For most galaxies, the gaseous component extends far into the halo and has no obvious ‘edge’; the total baryonic masses and the

corresponding half-mass radii are thus poorly defined. To address this, we follow the procedure that Z. Hua et al. (2025) applied to SPARC galaxies and impose an outer boundary at the radius R_{HI} where the H I column density first falls below 10^{20}cm^{-2} (which is of order $1 M_\odot \text{pc}^{-2}$). Gas surface-density profiles are computed out to this limiting radius using the H I masses of gas particles, multiplied by a factor of 1.33 to account for helium and heavier elements.⁸ Separate CoGs are constructed for the stellar and H I components and then combined to obtain $R_{\text{bar},50}$. The total baryonic mass is the sum of the stellar mass, M_* , and the H I mass (scaled by 1.33) enclosed within R_{HI} .

To illustrate these size definitions, Fig. 2 shows two example galaxies from L025m5 as virtual *Hubble Space Telescope* (HST) observations. The left panel shows a star-forming disc galaxy ($M_* = 8.8 \times 10^{10} M_\odot$, $\text{SFR} = 2.5 M_\odot \text{yr}^{-1}$), while the right panel shows a passive spheroid ($M_* = 1.5 \times 10^{11} M_\odot$, $\text{SFR} = 0.2 M_\odot \text{yr}^{-1}$). In each panel, the circles indicate the projected stellar half-mass radius, $R_{*,50}$, the baryonic half-mass radius, $R_{\text{bar},50}$, and the surface-density radius R_1 , defined by $\Sigma_*(R_1) = 1 M_\odot \text{pc}^{-2}$.

Both images were created using the algorithm described in Huško et al. (in preparation), which uses SPH interpolation to assign dust masses and stellar luminosities to cells of a Cartesian grid centred on each galaxy. Stellar light is attenuated by dust, accounting for both chemical composition and grain size using a one-dimensional radiative transfer model (light scattered along the line of sight – a minor contribution to the total flux – is neglected). The final images combine HST ACS/WFC⁹ F475W (blue), F625W (green), and F775W (red) filters.

To ensure that these size measurements are robust to numerical resolution, we restrict our analysis to central galaxies with stellar masses $M_* \geq 100 \times m_{\text{bar}}$ (see Appendix A for a justification of this choice). For $R_{*,50}^{\text{Ser}}$ and $R_{\text{bar},50}^{\text{Ser}}$, which are obtained from profile fitting and are therefore more sensitive to particle noise, we impose a more conservative requirement of $M_* \geq 500 \times m_{\text{bar}}$.

2.3.2 Galaxy angular momentum

The angular momentum of each galaxy is computed with respect to its most bound particle and centre-of-mass velocity of the relevant component. Unlike our estimates of stellar mass and SFR, the stellar particles used here are not restricted to any aperture; instead, we include all particles that are gravitationally bound to the central galaxy.¹⁰ We define the stellar specific angular mo-

⁸This approach mimics the observational analysis of SPARC galaxies by Z. Hua et al. (2025), but neglects the contribution of H_2 and ionized hydrogen in the galaxy outskirts. However, the resulting baryonic mass–size relations obtained as described above are consistent with those obtained when including both ionized and molecular gas.

⁹Hubble Space Telescope Advanced Camera for Surveys Wide Field Channel.

¹⁰Unlike our measurements of stellar mass and size, both of which are restricted to a 50 kpc aperture, we do not impose an aperture when calculating j_* , but instead use all bound stellar particles. This better reflects observational attempts to estimate j_* , which typically derive cumulative $j_*(< R)$ profiles out to large radii (often ≈ 5 – 10 disc scale lengths) and often require convergence at large R . When kinematic data or surface brightness profiles are limited to smaller radii, they are commonly extrapolated to estimate the total angular momentum assuming a flat rotation curve. For late-type galaxies, the resulting j_* values are generally close to total specific angular momentum of an exponential disc with scale length R_d and flat rotation velocity V_{flat} , for which $j_* = 2 R_d V_{\text{flat}}$.

In simulations and observations, j_* is sensitive to aperture choice because stars at large radii contribute little to the total mass but can carry

⁷For the vast majority of galaxies, similar values of R_1 are obtained when all stellar particles are used to construct their surface mass density profiles, regardless of whether or not those particles are gravitationally bound to a galaxy.

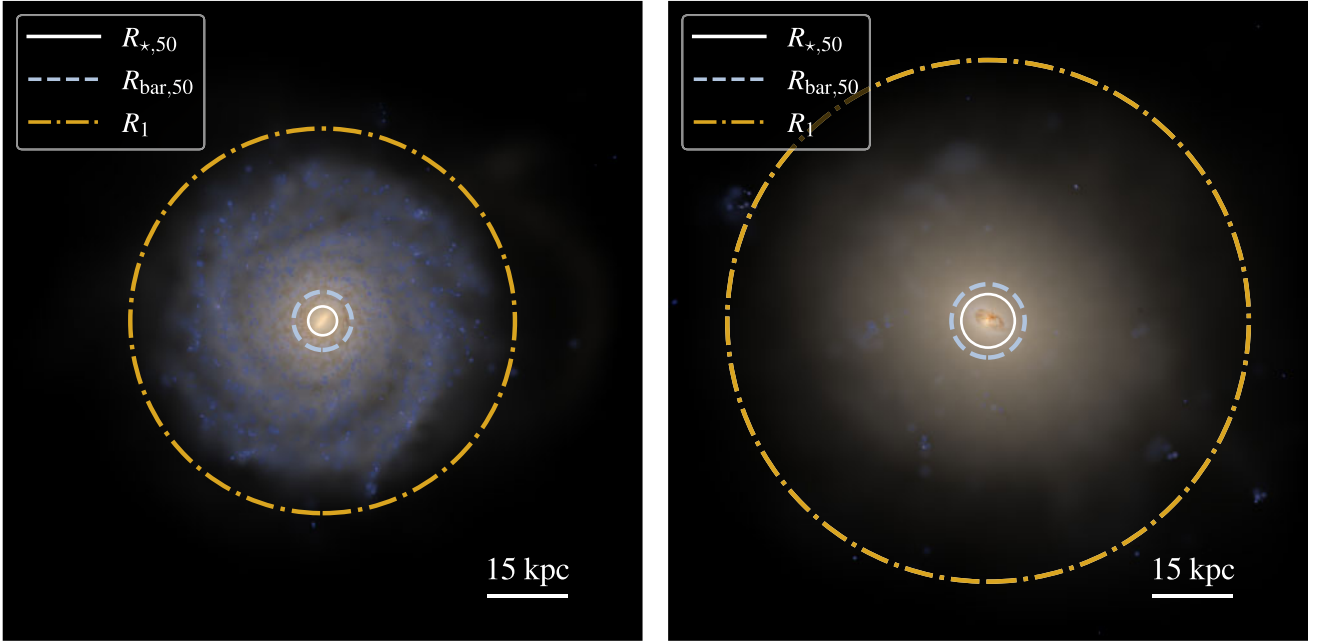


Figure 2. Virtual *Hubble Space Telescope* observations of a $z = 0$ star-forming disc galaxy (left panel; $M_\star = 8.8 \times 10^{10} M_\odot$, $\text{SFR} = 2.5 M_\odot \text{yr}^{-1}$) and a passive elliptical galaxy (right panel; $M_\star = 1.5 \times 10^{11} M_\odot$, $\text{SFR} = 0.2 M_\odot \text{yr}^{-1}$). Both galaxies are viewed along a line of sight parallel to the total stellar angular momentum vector. The circles in each panel highlight three measures of galaxy size used in this paper (see Section 2.3.1 for details). From smallest to largest: (1) the two-dimensional half-stellar-mass radius, $R_{\star,50}$ (solid white circle); (2) the two-dimensional half-baryonic-mass radius, $R_{\text{bar},50}$ (dashed light blue circle); and (3) the radius R_l at which the stellar surface density profile first drops below $\Sigma_\star = 1 M_\odot \text{pc}^{-2}$ (dot-dashed yellow circle). The image scale is indicated by the horizontal line in the lower-right corner, which spans 15 kpc.

mentum as $j_\star = J_\star / M_{\star,\text{bound}}$, where $J_\star$ is the magnitude of the angular momentum of bound stellar particles and $M_{\star,\text{bound}}$ is their total mass.

We also compute the baryonic angular momentum, $J_{\text{bar}} = J_\star + J_{\text{gas}}$, where J_{gas} is obtained from gas particles within R_{HI} , weighted by their H I fractions and multiplied by 1.33 to approximately account for heavier elements (primarily helium). This follows the procedure used for SPARC galaxies by Z. Hua et al. (2025); we compare our results to theirs in Section 3.3.2. The specific baryonic angular momentum is then $j_{\text{bar}} = J_{\text{bar}} / M_{\text{bar}}$, with $M_{\text{bar}} = M_{\star,\text{bound}} + 1.33 M_{\text{HI}}$. Gas fractions are defined as $f_{\text{gas}} = 1.33 \times M_{\text{HI}} / M_{\text{bar}}$.

As with the baryonic half-mass radius, J_{bar} does not capture the full angular momentum of all baryonic material: it excludes contributions from ionized and molecular gas, and treats heavy elements only approximately. We adopt this simplified definition to enable a fair comparison with observational measurements of baryonic angular momentum by Z. Hua et al. (2025). A follow-up paper will present a more comprehensive analysis of the evolution of the total galactic baryonic angular momentum content of COLIBRE galaxies.

2.4 Calibration versus prediction in simulation-observation comparisons

COLIBRE sub-grid models for supernova and AGN feedback were calibrated to reproduce the median $z = 0$ galaxy size-mass rela-

tion of J. A. Hardwick et al. (2022) over the stellar mass range $10^9 < M_\star / M_\odot < 10^{11.3}$. Their galaxy sample is drawn from the xGASS survey (The extended GALEX Arecibo SDSS Survey; B. Catinella et al. 2010, 2018) and spans redshifts $0.01 < z < 0.05$. Sizes were inferred from projected stellar mass surface density profiles. These were constructed from double- and single-J. L. Sérsic (1963) profile fits to g -, r -, and i -band images by R. H. W. Cook et al. (2019), which were used to independently model the disc and (if present) bulge components. The fitted profiles, obtained using ProFit (A. S. G. Robotham et al. 2017), were combined and converted to stellar mass surface density profiles using the stellar mass-to-light conversion of S. Zibetti, S. Charlot & H.-W. Rix (2009). The surface mass density profiles were then integrated to $10 \times R_{50,r}$ (where $R_{50,r}$ is the r -band half-light radius from R. H. W. Cook et al. 2019) to obtain the cumulative stellar mass; the total stellar mass corresponds to the mass enclosed within $10 \times R_{50,r}$, which is used to define the half-mass radius.

COLIBRE's calibration used two-dimensional stellar half-mass radii measured directly from the particle data for galaxies of mixed morphology. Stellar masses and sizes were measured at $z = 0$ within 50 kpc apertures and therefore do not exactly match the observational techniques used to infer the galaxy sizes to which the sub-grid models were calibrated. Although obtaining a good match to these observations, as COLIBRE does, is by no means trivial, comparisons of simulated and observed size-mass relations based on similar size definitions are not fully independent tests of the model, and some level of agreement is expected by construction if the calibration was successful.

To provide a more independent test, the comparisons presented below employ data sets and measurement techniques that differ from the size estimates used for calibration. These include

substantial angular momentum. We quantify the impact of imposing a finite aperture in Appendix C.

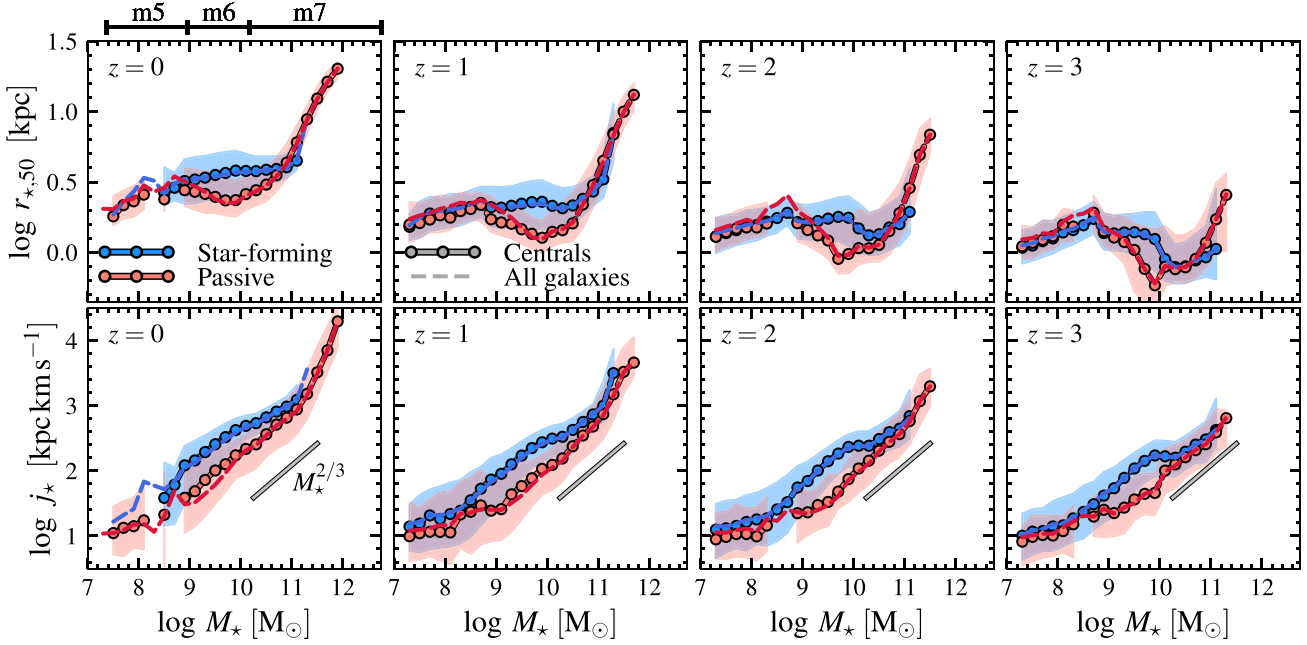


Figure 3. Three-dimensional stellar half-mass radius ($r_{*,50}$; upper panels) and stellar specific angular momentum (j_* ; lower panels) as a function of stellar mass at $z = 0, 1, 2$ and 3 (left to right). Median relations are constructed by combining galaxies from different runs above a resolution-dependent mass limit. For m5 resolution (L025m5 at $z = 0$, and L050m5 at $z > 0$) we include all galaxies with $M_* \geq 100 m_{\text{bar}}$; for L200m6 and L400m7, we include galaxies with $M_* \geq 500 m_{\text{bar}}$ and $\geq 1000 m_{\text{bar}}$, respectively. The line segments above the upper-left panel indicate the stellar-mass range where each simulation contributes the highest number of galaxies. Connected circles show relations for central galaxies, while dashed lines show the entire galaxy population (centrals plus satellites). Shaded regions denote the 16th–84th percentile scatter for the full distribution of centrals. Blue lines show the median relations for galaxies within 0.5 dex of the redshift-dependent star-formation main sequence defined by equation (1) (star-forming systems), while red lines show the medians for galaxies at least 0.5 dex below the main sequence (passive systems). Only bins that contain at least 25 galaxies are plotted. The grey line segment in the lower panels shows the $j_* \propto M_*^{2/3}$ scaling predicted by the virial theorem. For $z \lesssim 2$ and $10^9 \lesssim M_*/M_\odot \lesssim 10^{11}$, star-forming central galaxies are larger (by ≈ 0.1 – 0.3 dex) and have higher j_* (by ≈ 0.2 – 0.5 dex) than passive galaxies. Conversely, massive ($M_* \gtrsim 10^{11} M_\odot$) and low-mass ($M_* \lesssim 10^9 M_\odot$) star-forming and passive have similar sizes and angular momenta at all redshifts. Including satellite galaxies does not affect the trends, which can be seen by comparing the dashed lines to the connected circles.

$z = 0$ size–mass relations based on alternative size definitions (e.g. light-weighted sizes in multiple bands in Section 3.1.1, sizes inferred from surface density thresholds in Section 3.1.2, or size estimates obtained from the entire baryonic content of galaxies in Section 3.1.3), different measurement procedures (particle-based versus profile fitting; Section 3.1.1), or sub-samples defined by morphology, star-formation activity, or gas fraction. These choices can introduce systematic differences in the inferred galaxy sizes, so the level of agreement with observations depends on how robustly COLIBRE reproduces the internal structure of galaxies in the local Universe.

Truly predictive tests arise from observables that were not part of the calibration. These include the redshift evolution of the size–mass relation (Section 3.2), relations obtained for independent samples of different galaxy types, and all relations involving baryonic or stellar specific angular momentum (Section 3.3). In particular, the $z > 0$ size–mass relations and all j_* – M_* relations, as well as their dependence on galaxy type, constitute genuine predictions of the model. The level of agreement with observations therefore provides a non-trivial validation (or refutation) of the underlying physical models implemented in COLIBRE.

2.5 An initial view of the $r_{*,50} - M_*$ and $j_* - M_*$ relations

Fig. 3 shows the median $r_{*,50} - M_*$ (upper panels) and $j_* - M_*$ relations (lower panels) for central galaxies in L025m5 (or L050m5

for available redshifts), L200m6, and L400m7 using connected circles. Dashed lines show relations for the full galaxy population, including satellites. For clarity, galaxies from all simulations have been combined to construct a single median relation. To balance the requirements of high resolution and good statistics, we adopt a resolution-dependent lower mass limit corresponding to $100 m_{\text{bar}}$, $500 m_{\text{bar}}$, and $1000 m_{\text{bar}}$ for the m5, m6, and m7 resolutions, respectively. The line segments above the upper-left panel indicate the range of stellar mass over which each resolution level contributes the largest number of galaxies. Convergence with resolution is demonstrated explicitly in later figures.

Different columns correspond to results at $z = 0, 1, 2$, and 3 . Blue curves show the median relations for star-forming galaxies, i.e. those lying within 0.5 dex of the redshift-dependent star-formation main sequence,¹¹ approximated as

$$\log [\text{sSFR}(z)/\text{Gyr}^{-1}] = 0.40z - 0.04z^2 - 0.73 \quad (1)$$

Red curves show medians for passive galaxies, i.e. those that lie at least 0.5 dex below this sequence. We choose these thresholds

¹¹Equation (1) provides a useful proxy for the star-forming main sequence. It was obtained by fitting a second-order polynomial to the combined median $\text{sSFR}-M_*$ relations calculated independently for L025m5 (for $z \leq 0.5$), L050m5 (for $z \geq 1$), L200m6, and L400m7, at redshifts $z = 0, 0.5, 1, 2, 3$, and 4 , and over the stellar-mass range $7.5 \leq \log(M_*/M_\odot) \leq 10$ in bins of width $\Delta \log M_* = 0.2$.

in order to sample the full population of galaxies at all redshifts. In subsequent figures, we adopt definitions of star-forming and passive galaxies that are tailored to the observational data sets against which COLIBRE is compared.

Key features of the size–mass relations in Fig. 3 are as follows. (i) The median $r_{*,50} - M_*$ relations for both galaxy types are approximately flat below a characteristic mass of $M_* \approx 10^{10.5} M_\odot$, although star-forming galaxies at $z \leq 1$ exhibit a slight increase in size with stellar mass. (ii) At all masses, galaxy sizes increase towards lower redshift, irrespective of galaxy type. (iii) At intermediate masses ($10^9 \lesssim M_*/M_\odot \lesssim 10^{11}$ at $z \leq 2$ and $10^9 \lesssim M_*/M_\odot \lesssim 10^{10}$ at $z \geq 2$), star-forming galaxies are, on average, larger than passive systems by ≈ 0.2 – 0.3 dex, regardless of whether satellite galaxies are included. (iv) Among the most massive systems, sizes increase sharply with mass at low redshift, but by $z = 3$ the relation develops a pronounced ‘U’-shape, with sizes decreasing to a minimum near $M_* \approx 10^{10.5} M_\odot$ before rising rapidly at higher masses. (v) At $z = 3$, this ‘compaction’ mass scale roughly separates galaxies with the highest sSFRs ($\log[\text{sSFR}/\text{Gyr}^{-1}] \gtrsim 0.5$; typically less massive) from quenched systems ($\log[\text{sSFR}/\text{Gyr}^{-1}] \lesssim -2$; typically more massive), although this is not shown explicitly in Fig. 3.

Key features of the $j_* - M_*$ relations are as follows. (i) At intermediate mass and for all redshifts, star-forming galaxies have higher median j_* than passive ones by ≈ 0.2 to 0.5 dex, depending on mass. (ii) The $j_* - M_*$ relations of both star-forming and passive galaxies follow approximate power laws with slopes ≈ 0.7 (cf. the solid grey line). (iii) At the highest masses and for $z \leq 1$, there is evidence for an upturn in j_* for passive galaxies, though this trend is sensitive to the aperture used to measure j_* (see Appendix C). (iv) At all redshifts, active and passive galaxies with $M_* \approx 10^{11} M_\odot$ have similar j_* values regardless of their sSFR. These results are unaffected by the exclusion of satellite galaxies.

3 RESULTS

3.1 Size–mass relations at $z = 0$

In this section, we compare the size–mass relations of COLIBRE galaxies with observational data sets that were not used to calibrate the sub-grid models. Although each survey employs its own methodology to estimate stellar masses and sizes, several common elements can be summarized here.

Stellar masses are typically derived from multiband optical imaging combined with stellar population synthesis modelling, with corrections for dust and AGN and an assumed initial mass function. For a fixed initial mass function, this results in random uncertainties of ≈ 0.1 – 0.3 dex in M_* , depending on redshift and data quality in addition to unknown systematic uncertainties (e.g. C. Conroy, J. E. Gunn & M. White 2009; A. Gallazzi & E. F. Bell 2009; A. S. G. Robotham et al. 2020; C. Pacifci et al. 2023). When comparing to observational results, we therefore apply a redshift-dependent lognormal scatter to the simulated stellar masses to mimic these uncertainties.¹²

¹²Following E. Chaikin et al. (2026b), we add a lognormal scatter to M_* with mean zero and standard deviation $\sigma_{\text{random}}(z) = \min(0.1 + 0.1z, 0.3)$ dex, consistent with the functional form advocated by P. S. Behroozi, C. Conroy & R. H. Wechsler (2010), although with slightly different parameters. Specific star formation rates and specific angular momenta are calculated using the measured (i.e. unscattered) values of

The data sets considered below span a range of depths and modelling approaches. The $z = 0$ SMR of J. A. Hardwick et al. (2022) is based on xGASS galaxies whose structural parameters were derived using PROFIT (A. S. G. Robotham et al. 2017). For GAMA galaxies, stellar masses, surface-density (and surface-brightness) profiles, and sizes were obtained from updated multiband photometry using the PROFUSE pipeline (A. S. G. Robotham, S. Bellstedt & S. P. Driver 2022), adopting the stellar population synthesis models of G. Bruzual & S. Charlot (2003), a G. Chabrier (2003) initial mass function, and a D. Calzetti et al. (2000) dust law. The IAC Stripe82 Legacy Project (J. Fliri & I. Trujillo 2016; J. Román & I. Trujillo 2018a), analysed by I. Trujillo et al. (2020), provides deep multiband imaging corrected for inclination and dust attenuation; stellar masses are derived by integrating the surface mass-density profiles to an isophotal limit of $g = 29$ mag arcsec^{−2}. The SPARC survey comprises 175 nearby late-type galaxies whose stellar mass distributions are inferred from 3.6 μm surface photometry obtained with the *Spitzer Space Telescope*.

We compare these data sets in Fig. 4, which summarizes the range of observationally inferred $z = 0$ size–mass relations considered in this work. The upper panel shows mass-weighted size estimates, including the two-dimensional half-mass radii $R_{*,50}$ of GAMA galaxies from S. Bellstedt et al. (2024), the surface-density threshold radius R_1 of I. Trujillo et al. (2020), and the baryonic half-mass radii $R_{\text{bar},50}$ of Z. Hua et al. (2025). Also shown is the $R_{*,50} - M_*$ relation of J. A. Hardwick et al. (2022), which was used to calibrate COLIBRE’s sub-grid physics models. For reference, we include the corresponding $z = 0$ $R_{*,50} - M_*$ relations for all galaxies in the L025m5, L200m6, and L400m7 simulations, where $R_{*,50}$ is measured directly from random projections of the stellar particle distributions. These simulated relations show good convergence and are in excellent agreement with the SMR of Hardwick et al. The simulated $R_{*,50}$ values were used to calibrate COLIBRE’s sub-grid physics models and should be compared only to this data set; they are shown for completeness but are not analysed further, as they have been presented previously by J. Schaye et al. (2026) and E. Chaikin et al. (2026a). The different size definitions exhibit substantial systematic differences, and we therefore defer detailed comparisons with the corresponding observational data sets to subsequent sections.

The lower panel shows light-weighted size estimates from GAMA Data Release 4,¹³ including the half-light radii in the r –, z –, and u –bands, and the radii $R_{u,90}$ and $R_{z,90}$ enclosing 90 per cent of the u – and z –band light, respectively.

In the following sections, we compare these observational relations to COLIBRE’s simulated galaxy population. For more rigorous tests of COLIBRE’s predictions, we will sometimes present results separately for disc and spheroid sub-samples, or for star-forming and passive systems, using similar selection criteria for the simulated and observed galaxies. Hereafter, we restrict our analysis to central galaxies in the thermal-AGN model. For the observational data sets we do not distinguish between central and satellite galaxies; however, we demonstrate in Appendix B that our $z = 0$ results are insensitive to the removal of satellites from the simulated sample.

M_* . We examine the impact of redshift-dependent scatter in M_* on the SMR and AMR in Appendix D.

¹³<https://www.gama-survey.org/dr4/>.

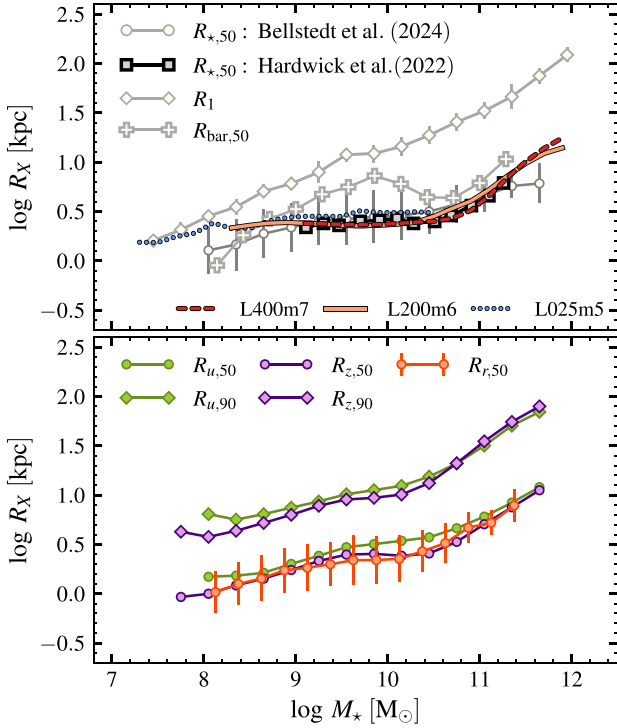


Figure 4. The upper panel shows mass-weighted size estimates: the two-dimensional half-mass radii $R_{*,50}$ from xGASS (J. A. Hardwick et al. 2022) and GAMA (S. Bellstedt et al. 2024), the radius R_1 at which the stellar surface density equals $\Sigma_* = 1 \text{ M}_\odot \text{ pc}^{-2}$ (I. Trujillo et al. 2020), and the baryonic half-mass radii of SPARC galaxies (Z. Hua et al. 2025). Also shown are the median $z = 0$ two-dimensional half-mass radii of COLIBRE galaxies in L025m5, L200m6, and L400m7 (coloured lines). The latter, shown for all galaxies (centrals plus satellites), were computed directly from the stellar particle data and were used to calibrate COLIBRE’s sub-resolution physics models; these relations should only be compared with the observed $R_{*,50} - M_*$ relations. The lower panel shows light-weighted sizes from the GAMA Survey, including the r -band two-dimensional half-light radii $R_{r,50}$ (S. Casura et al. 2022), and the radii enclosing 50 and 90 per cent of the u - and z -band light. Error bars, where present, correspond to the 16th to 84th percentile scatter.

In all subsequent figures, simulated and observed size–mass and angular momentum–mass relations are constructed using bins of fixed logarithmic width, $\Delta \log M_* = 0.2$. The plots follow a common visual scheme: connected symbols with error bars denote observed median relations and their 16th to 84th percentile scatter, while lines and shaded regions show the corresponding medians and scatter from the simulations. When galaxies are separated by morphological type, late-types are shown in blue and early-types in red; different resolution levels are distinguished by line style. When all galaxies are shown irrespective of type, simulations are distinguished by line style and colour. Across all figures, a given resolution level is represented by a consistent line style.

3.1.1 Stellar size–mass relations

The upper panels of Fig. 5 show the median $R_{*,50}^{\text{Ser}} - M_*$ relations obtained from single-component Sérsic fits to the stellar surface-density profiles, $\Sigma_*(r)$, of $z = 0$ central galaxies containing at

least 500 stellar particles. The left panel shows results for the full sample, regardless of morphology. The middle and right panels separate galaxies by best-fitting Sérsic index, with $n_s \leq 1.5$ for late-types (middle) and $n_s \geq 2.5$ for early-types (right). Different resolution runs are plotted individually and demonstrate good convergence. Thick lines denote mass bins containing more than 10 galaxies, while thin lines indicate bins with fewer; shaded regions indicate the scatter in the L200m6 run. In COLIBRE, the median $R_{*,50}^{\text{Ser}}$ is relatively flat below $M_* \approx 10^{10.5} \text{ M}_\odot$, but increases by roughly 1 dex over the subsequent ≈ 1.5 dex increase in stellar mass.

Circles with error bars show the observational relations for GAMA galaxies from S. Bellstedt et al. (2024), who used updated multiband photometry and the PROFUSE (A. S. G. Robotham et al. 2022) pipeline to construct stellar mass maps that were used to infer the surface mass density profiles. As for the simulations, structural parameters for the observed sample are obtained from single-component Sérsic fits, with galaxies classified as pure discs ($n_s \leq 1.5$; middle panel) or pure spheroids ($n_s \geq 2.5$; right-hand panels). Error bars indicate the 16th to 84th scatter.

The lower panels show the r -band SMRs, compared to the measurements of S. Casura et al. (2022), derived from KiDS (Kilo-Degree Survey) r -band imaging of the GAMA-II equatorial region (S. P. Driver et al. 2011; J. T. A. de Jong et al. 2013). Sizes were obtained from single-component Sérsic fits using PROFIT (A. S. G. Robotham et al. 2017). The left panel shows the full population, while the middle and right panels present the late- and early-type sub-samples, adopting the same n_s thresholds for the simulations and observations. For comparison, these panels also include the SDSS r -band power-law size–mass relations of S. Shen et al. (2003) as dot-dashed lines.

Overall, we find excellent agreement between the simulated and observed measurements of $R_{*,50}^{\text{Ser}}$ and $R_{r,50}^{\text{Ser}}$ across the entire resolved stellar mass range. We have also compared size estimates in other optical bands, again obtaining good consistency. Fig. 6 illustrates this using the $R_{u,50} - M_*$ (upper left) and $R_{z,50} - M_*$ (upper right) relations, where sizes were measured directly from the particle data rather than from Sérsic fits. Grey points show the corresponding GAMA measurements derived in the same manner as $R_{r,50}$ from S. Casura et al. (2022). Although our measurements do not account for dust attenuation, we nevertheless find good agreement in both optical bands (which are separated by roughly 250–300 nm) in both the normalization of the relations and their intrinsic scatter.

The lower panels of Fig. 6 show that this agreement extends to $R_{u,90}$ and $R_{z,90}$, which probe larger radii that were not considered during calibration of COLIBRE’s sub-grid physics models. The agreement is particularly good in the z -band. However, for simulated galaxies with $M_* \lesssim 10^{10.5} \text{ M}_\odot$, the $R_{u,90}$ values are on average slightly smaller than observed (but still within the scatter), possibly reflecting the stronger sensitivity of shorter-wavelength light to dust, the effects of which are not included in our analysis of simulated galaxy sizes.

3.1.2 The $R_1 - M_*$ relation

Fig. 7 compares the $R_1 - M_*$ relation for $z = 0$ central galaxies in COLIBRE with observations from I. Trujillo et al. (2020). The top panel shows the full sample of observed and simulated galaxies. The bottom panel splits the observed galaxies into discs and

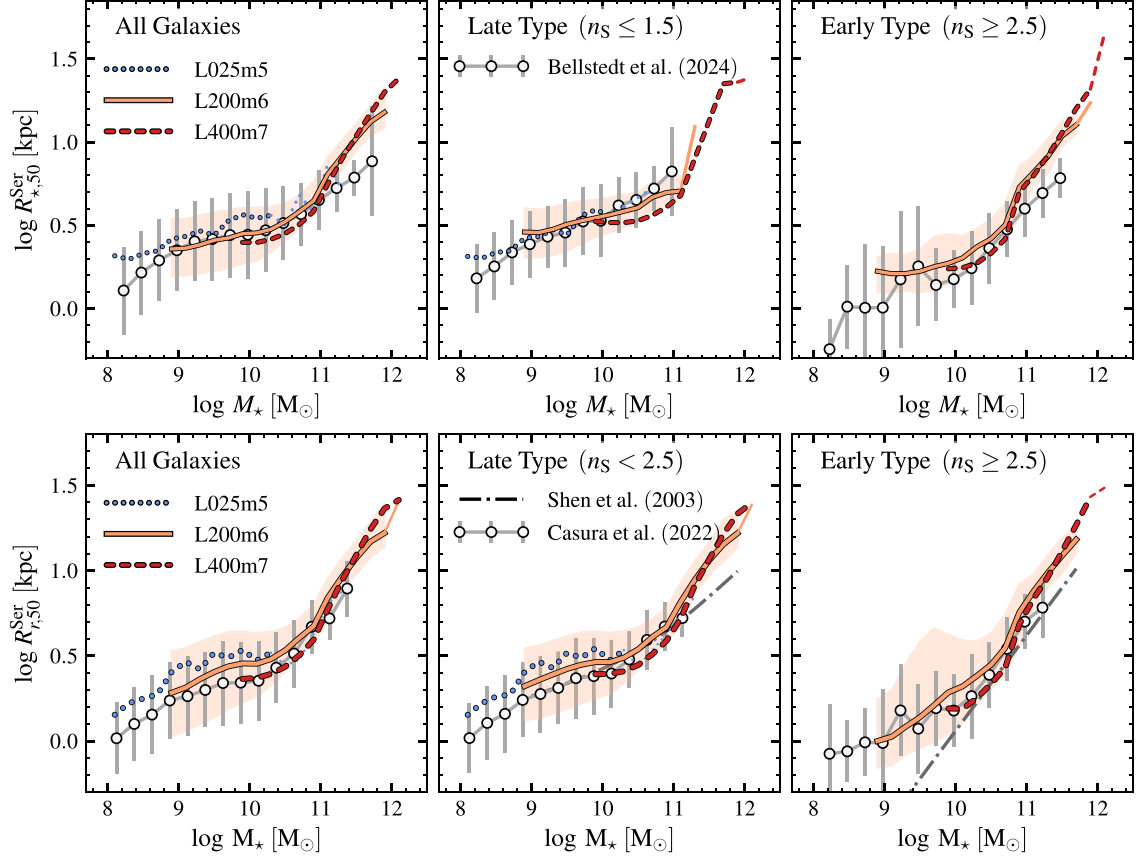


Figure 5. Size–mass relations for $z = 0$ central galaxies in the COLIBRE simulations compared with recent observations. The top panels show median two-dimensional stellar half-mass radii, $R_{*,50}^{\text{Ser}}$, compared with observational measurements from S. Bellstedt et al. (2024). The bottom panels show the median two-dimensional r -band half-light radii, $R_{r,50}^{\text{Ser}}$, and are compared with the measurements of S. Casura et al. (2022) (connected circles) and S. Shen et al. (2003) (dot–dashed lines). In both cases, galaxy sizes were measured from single-component Sérsic fits to the stellar mass surface density or r -band surface brightness profiles, as described in Section 2.3. Results from L025m5, L200m6, and L400m7 are shown using dot–dashed, solid, and dashed lines, respectively, with thin line segments indicating mass bins that contain fewer than 10 galaxies. The shaded regions highlight the 16th to 84th percentile scatter for L200m6. Observed data are plotted as connected symbols, with error bars indicating the 16th–84th percentile range. The left column shows results for all central galaxies, regardless of morphological type. The middle and right columns show late- and early-type central galaxies, respectively, for which morphological classification is based on Sérsic index, n_s : in the top (bottom) panels, galaxies with $n_s \leq 1.5$ ($n_s \geq 2.5$) are classified as late-type, and those with $n_s \geq 2.5$ as early-type. Overall, COLIBRE reproduces the size–mass relations for both early- and late-type galaxies, and achieves good convergence across resolution levels.

spheroids based on visual classifications.¹⁴ COLIBRE galaxies lack visual classification and are divided by the kinematic D/T ratio: $D/T \geq 0.6$ for late-types and $D/T \leq 0.3$ for early-types. The values of R_1 obtained for our simulated galaxies are converged and agree well with the observational results over ≈ 5 dex in stellar mass (see also E. Arjona-Gálvez et al. 2025; C. Dalla Vecchia & I. Trujillo 2025, for similar results from other cosmological simulations). Low-mass galaxies ($M_* \lesssim 10^{8.5} M_\odot$) exhibit a roughly constant stellar surface density of $\Sigma_* \approx 10 M_\odot \text{pc}^{-2}$, which increases to $\Sigma_* \approx 100 M_\odot \text{pc}^{-2}$ for more massive systems ($M_* \gtrsim 10^{10.5} M_\odot$).

¹⁴I. Trujillo et al. (2020) use deep imaging data from the IAC Stripe82 Legacy Project (J. Fliri & I. Trujillo 2016; J. Román & I. Trujillo 2018b), and target galaxies have redshifts $z < 0.09$ and span the mass range $10^7 M_\odot < M_* < 10^{12} M_\odot$. Galaxies with $M_* > 10^9 M_\odot$ were taken from the catalogue of P. B. Nair & R. G. Abraham (2010), which includes visually classified morphologies. These data were supplemented with lower mass galaxies ($10^7 M_\odot < M_* < 3 \times 10^9 M_\odot$) from the catalogue of C. Maraston et al. (2013), which lacks morphological information.

COLIBRE also approximately reproduces the morphology dependence of the $R_1 - M_*$ relation seen in the lower panel, which is weak for both the simulations and observations.

3.1.3 The baryonic size–mass relation

Finally, Fig. 8 compares the $z = 0$ baryonic SMR of late-type central COLIBRE galaxies (defined as kinematic $D/T \geq 0.6$) with observations of late-type galaxies from the SPARC survey (Z. Hua et al. 2025). Dotted, solid, and dashed curves show the median relations for L025m5, L200m6, and L400m7, respectively. Each sample is split into gas-rich ($f_{\text{gas}} \geq 0.6$; blue) and gas-poor ($f_{\text{gas}} \leq 0.3$; red) sub-samples, where $f_{\text{gas}} = 1.33 M_{\text{HI}}/M_{\text{bar}}$. Connected squares indicate the corresponding relations for SPARC galaxies, selected using the same gas-fraction thresholds and plotted with the same colour scheme. Both the simulated and observed relations show strong segregation by gas fraction.

There is good agreement between the median relations from L025m5 and L200m6 for the gas-rich samples, and between all

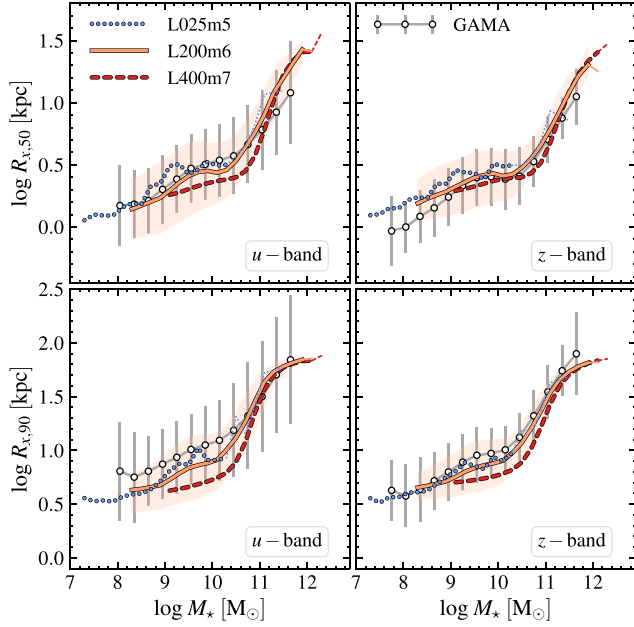


Figure 6. Characteristic radii $R_{x,50}$ (upper panels) and $R_{x,90}$ (lower panels) where ‘x’ represents the u -band (left column) and z -band (right column) as a function of stellar mass. Coloured lines show the median relations for simulated central galaxies at $z = 0$ and do not include the effects of dust attenuation; thick and thin lines correspond to bins that contain ≥ 10 and < 10 galaxies, respectively. Shaded regions denote the 16th to 84th percentile scatter for L200m6. Connected circles show the median observational relations from the GAMA survey, with error bars indicating the 16th–84th percentile range.

simulations for the gas-poor samples, with all matching the observational relations within the observed scatter. This agreement is noteworthy given the heterogeneous selection function of the SPARC sample. The median relation from L400m7 for the gas-rich sub-sample, however, is offset to smaller $R_{\text{bar},50}$ at fixed baryonic mass, suggesting the presence of a population of compact gas-rich galaxies in this low-resolution run.

Overall, these results demonstrate that COLIBRE accurately reproduces the characteristic galaxy sizes at $z = 0$ inferred from optical surface-brightness profiles, stellar surface-density profiles, and the low-density outskirts of galaxies quantified by the radius R_1 . This consistency across multiple, physically distinct size definitions provides confidence that at $z = 0$ the spatial distribution of both stars and baryons in COLIBRE galaxies is realistic.

3.2 Redshift evolution of the stellar size–mass relation

For higher-redshifts, we compare COLIBRE with the recent measurements of A. van der Wel et al. (2024), based on multiband *HST* imaging. Stellar masses and star-formation rates are from the J. Leja et al. (2020) catalogue, which used the Prospector- α model (J. Leja et al. 2017; B. D. Johnson et al. 2021) to perform non-parametric modelling that accounts for dust attenuation and obscured AGN. We also compare our simulated galaxies to recent observational results of J. Song et al. (2026), based on *HST* + *JWST* multiband imaging. Stellar masses for this data set were obtained from dust-corrected multiband images using CIGALE (M. Boquien et al. 2019).

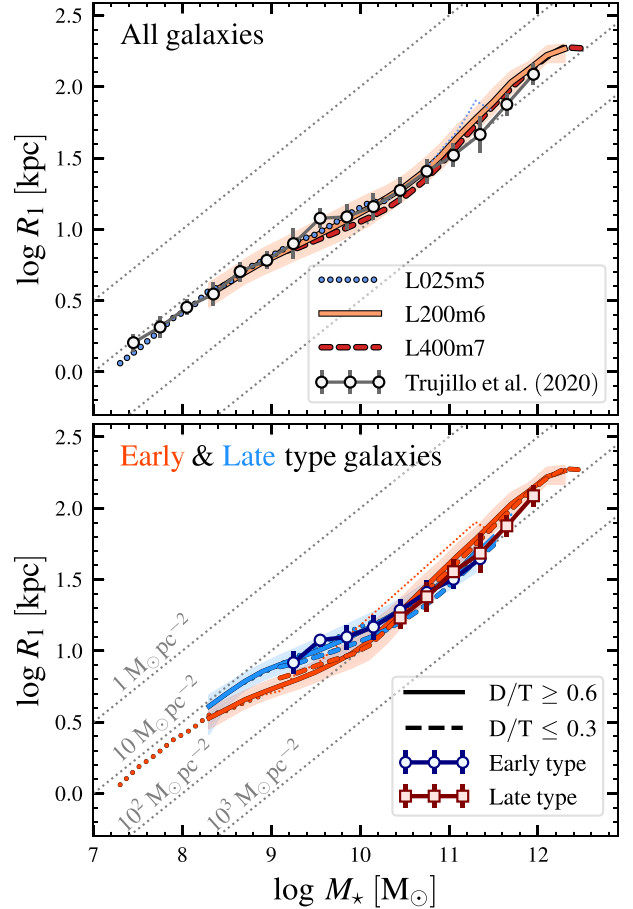


Figure 7. Size–mass relations for $z = 0$ central galaxies compared with the observational results of I. Trujillo et al. (2020). Sizes are defined by the radius R_1 where the (face-on) stellar surface mass density drops below $\Sigma_1 = 1 \text{ M}_\odot \text{ pc}^{-2}$. Different line styles correspond to median relations for different resolution levels. Shaded regions and error bars show the 16th to 84th percentile range for the (L200m6) simulations and observations, respectively. The upper panel shows the full samples of observed and simulated galaxies; the lower panel separates galaxies by morphological type. Observed morphologies (available for galaxies with $M_* \gtrsim 10^9 \text{ M}_\odot$) are based on visual classifications: ellipticals (E0–S0+) are shown in red, spirals (S0/a–Im) in blue. For COLIBRE, we use the kinematic disc-to-total ratio, D/T , as a proxy for morphology, as indicated in the legend. The grey dotted lines correspond to tracks of constant stellar surface density. COLIBRE demonstrates excellent convergence across resolution levels and aligns closely with the observed data.

Fig. 9 shows the (three-dimensional) stellar half-mass radius, $r_{*,50}$, as a function of stellar mass for central COLIBRE galaxies across several redshift intervals. The upper panels present results for central galaxies in the m5 resolution runs (combining L025m5 and L050m5; dotted lines), L200m6 (solid lines), and L400m7 (dashed lines). We include measurements from all available snapshots that span each of the redshift intervals. Connected grey circles represent observed galaxies from A. van der Wel et al. (2024). Their three-dimensional half-mass radii were derived by de-projecting two-dimensional half-mass radii, $R_{*,50}$, measured from stellar mass maps derived from multiband CANDELS *HST* imaging.

The lower panels of Fig. 9 separate galaxies into star forming and passive sub-samples based on their star formation rates,

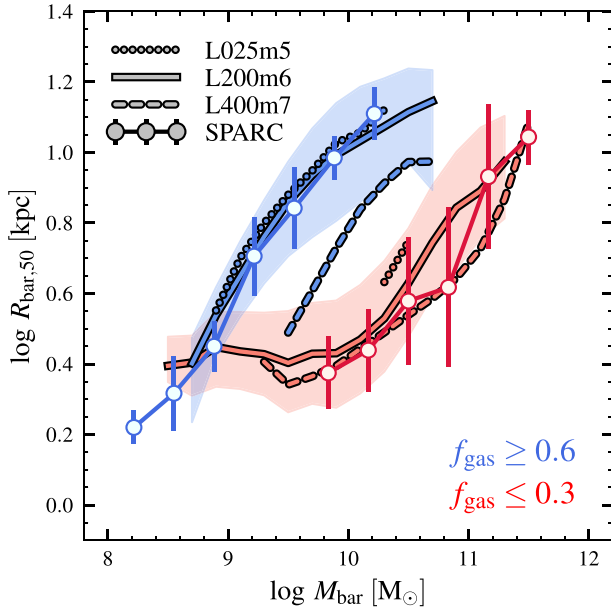


Figure 8. The $z = 0$ baryonic SMR for late-type (i.e. kinematic $D/T \geq 0.6$) central COLIBRE galaxies, compared with disc galaxies from the SPARC survey (Z. Hua et al. 2025). Dotted, solid, and dashed curves show the median relations for L025m5, L200m6, and L400m7, respectively. Each simulation sample is divided into gas-rich ($f_{\text{gas}} \geq 0.6$; blue) and gas-poor ($f_{\text{gas}} \leq 0.3$; red) sub-samples, where $f_{\text{gas}} = 1.33 M_{\text{HI}}/M_{\text{bar}}$. Connected circles denote the corresponding SPARC relations, selected with the same gas-fraction thresholds and plotted using the same colour scheme. Both simulated and observed relations show strong segregation by gas fraction. Overall, COLIBRE reproduces the SPARC relations but the lower-resolution run (L400m7) contains an excess of overly compact gas-rich systems.

using the same classification criteria for the simulated and observed galaxies. Galaxies are classified as passive if their star formation rates place them at least 0.8 dex below the star-forming main sequence at their respective redshifts; otherwise, they are classified as star forming. This scheme is the same as that adopted by A. van der Wel et al. (2024), who define the main sequence using the parametrization of J. Leja et al. (2022). For COLIBRE galaxies, we approximate the redshift-dependent star-forming main sequence using equation (1).

Overall, COLIBRE accurately reproduces the redshift evolution of the observed stellar mass-size relation at $z \lesssim 1.5$, including the qualitative differences between star-forming and passive populations. The agreement is particularly good at $z \lesssim 0.75$, and remains so at higher redshifts for galaxies with $M_{\star} \lesssim 10^{10} M_{\odot}$. For higher stellar masses, systematic offsets are apparent at $z \gtrsim 0.75$: passive galaxies in COLIBRE tend to be larger than observed by ≈ 0.1 dex, while star-forming galaxies are smaller by ≈ 0.2 dex. As a result, the separation of the SMRs for star-forming and passive galaxies in COLIBRE is smaller than observed. These differences – particularly for star-forming galaxies – may be reduced once the effects of dust attenuation on inferred galaxy sizes are explicitly modelled, as dust can preferentially obscure the central regions of galaxies and increase measured sizes. Note, however, that star-forming galaxies in the m5 runs approximately reproduce the observed relations at all redshifts.

Fig. 10 extends the comparison up to $z = 4$. Observational measurements are taken from J. Song et al. (2026), who

combined multiband photometry to derive galaxy sizes corresponding to rest-frame $1 \mu\text{m}$ imaging. These wavelengths are expected to be less sensitive to stellar population gradients, metallicity variations, and dust attenuation than rest-frame optical measurements. Sizes correspond to circularized half-light radii, $R_{1\mu\text{m},50}$, and were obtained using GALFIT (C. Y. Peng et al. 2002) after combining archival *HST* data with new *James Webb Space Telescope* (*JWST*) observations of the CANDELS fields (N. A. Grogin et al. 2011; A. M. Koekemoer et al. 2011). Only galaxies with reliable GALFIT measurements and sizes exceeding the effective pixel scale are included.

The median relations and 16th to 84th percentile scatter are indicated by connected circles and error bars, respectively. For COLIBRE, median relations are shown using different line styles, as in previous figures, with shaded regions indicating the 16th–84th percentile scatter for L200m6. To facilitate a consistent comparison, simulated galaxy sizes correspond to rest-frame $1 \mu\text{m}$ half-light radii, which we approximate using the two-dimensional half-light radii measured in the GAMA Y -band ($1.02 \mu\text{m}$). These sizes were estimated from the corresponding surface brightness profiles, calculated within 50 kpc apertures and for random orientations. Galaxies whose sizes fall below the observational resolution limit of the J. Song et al. (2026) sample are excluded.

As in Fig. 9, we find good agreement between the simulated and observed size-mass relations at low and intermediate redshifts, i.e. $z \lesssim 2$. At higher redshifts, systematic differences emerge. In particular, for $10^{9.5} \lesssim M_{\star}/M_{\odot} \lesssim 10^{11}$, simulated galaxies are smaller than observed systems by ≈ 0.1 – 0.5 dex depending on their mass, while the size-mass relations at lower masses and for the highest-mass galaxies remain in good agreement. While we leave a comparison to virtual observations to future work, preliminary tests indicate that accounting for dust attenuation increases the apparent sizes of intermediate-mass COLIBRE galaxies. At $z = 3$, for example, the sizes of galaxies with $M_{\star} \gtrsim 10^9 M_{\odot}$ increase by between ≈ 0.1 and 0.4 dex, with the largest increase occurring at $M_{\star} \approx \text{a few} \times 10^{10} M_{\odot}$, which is comparable to the mass scale where we find the largest size differences between observed and simulated galaxies at this redshift (see the lower panel, second from the right).

We have also compared the SMRs of star-forming and passive COLIBRE galaxies to those of J. Song et al. (2026), although we do not show these results explicitly. Consistent with the trends seen in Fig. 9, we find that at redshifts $z \gtrsim 1$ the separation between the SMRs of star-forming and passive galaxies is less pronounced in COLIBRE than in the observations. In this regime, star-forming simulated galaxies are typically smaller than their observed counterparts, while passive simulated galaxies are typically larger. This suggests that differences in the structure of star-forming and quiescent systems at early times are somewhat muted in the simulations, or that the effects of dust should not be ignored when modelling the dependence of the simulated SMR on star formation activity.¹⁵

3.3 The specific angular momentum–mass relation at $z = 0$

The results above show that COLIBRE’s simulated galaxy population reproduces the observed stellar SMR, including its systematic

¹⁵This result does not depend on whether or not observational errors are added to the stellar masses.

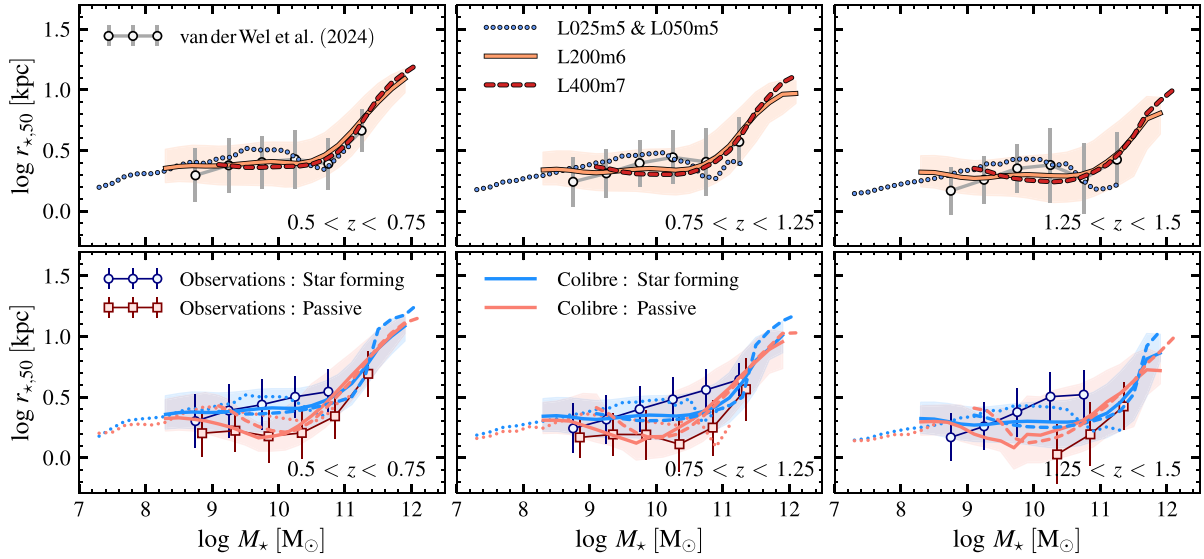


Figure 9. Median $r_{*,50}$ – M_* relations at redshifts $0.5 < z < 1.5$. The upper panels show all observed galaxies and simulated central galaxies; the lower panels show median trends for sub-sets of star-forming (blue) and passive (red) galaxies separately. These classifications are based on each galaxy’s distance from the z -dependent star formation main sequence (see the text for details). Median relations for m5 (which combine L025m5 and L050m5), L200m6, and L400m7 are shown as dotted, solid, and dashed lines, respectively, to illustrate numerical convergence. In all panels, shaded regions indicate the 16th to 84th percentile scatter for L200m6. Simulated data include all available outputs within the redshift intervals listed in each panel. Observational results from A. van der Wel et al. (2024) are shown for comparison. Their medians are shown with connected circles for the full sample in the upper panels and for the star-forming sample in the lower panels; connected squares in the lower panels show medians for the passive sample. Observational error bars denote the 16th–84th percentile range. The simulations reproduce the observed redshift-dependence of the size–mass relation, as well as its dependence on star formation activity for $z \lesssim 0.75$. However, for galaxies with $M_* \gtrsim 10^{10} M_\odot$ at $z \gtrsim 0.75$, the separation between the active and passive relations is smaller than observed.

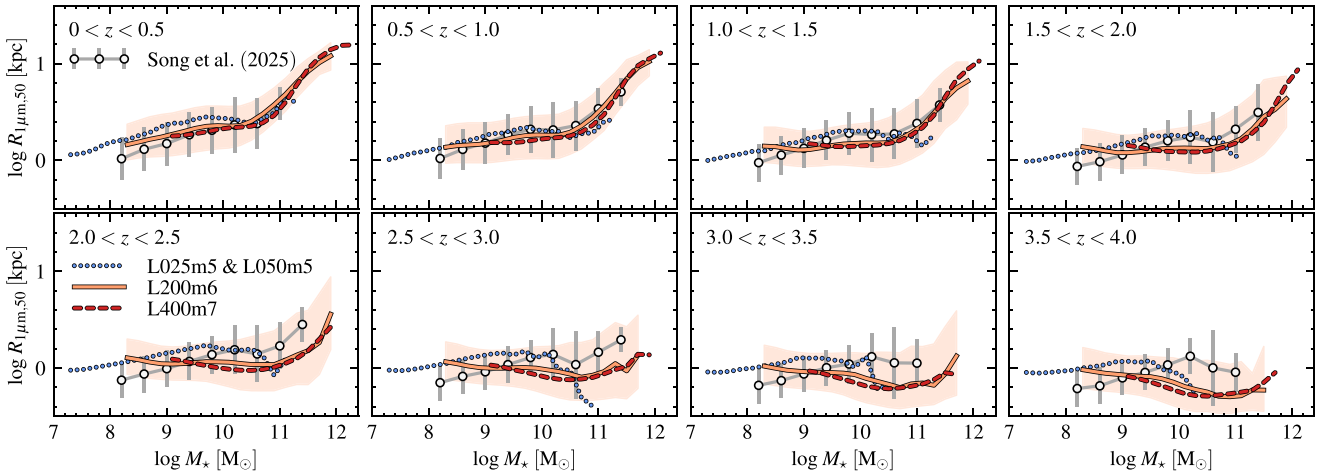


Figure 10. Two-dimensional half-light radii, $R_{1\mu m,50}$, as a function of stellar mass, M_* , for all observed and simulated central galaxies over the redshift range $0 \leq z \leq 4$. Sizes are estimated from $1\mu m$ surface brightness profiles measured within 50 kpc apertures and for random orientations. Different panels correspond to redshift bins of width $\Delta z = 0.5$. Dotted, solid, and dashed coloured lines show the median relations for m5 (combining all available outputs from L025m5 and L050m5), L200m6, and L400m7, respectively; the orange shaded region shows the 16th to 84th percentile scatter for L200m6. Median relations for observed galaxies from J. Song et al. (2026) are shown using connected circles; error bars indicate the 16th–84th percentile range. Observed sizes correspond to half-light radii measured from rest-frame $1\mu m$ images. We approximate these measurements in COLIBRE using half-light radii derived for the GAMA Y –band ($1.02\mu m$).

dependence on galaxy type, particularly for $z \lesssim 1$. Observational studies similarly reveal a strong morphological segregation in the stellar specific angular momentum–mass plane, with star-forming discs and passive spheroids occupying distinct, roughly

parallel sequences (e.g. S. M. Fall & A. J. Romanowsky 2018). Motivated by this, we now extend our analysis to the stellar specific angular momentum–mass relation, adopting the same morphological classifications that were used for galaxy sizes.

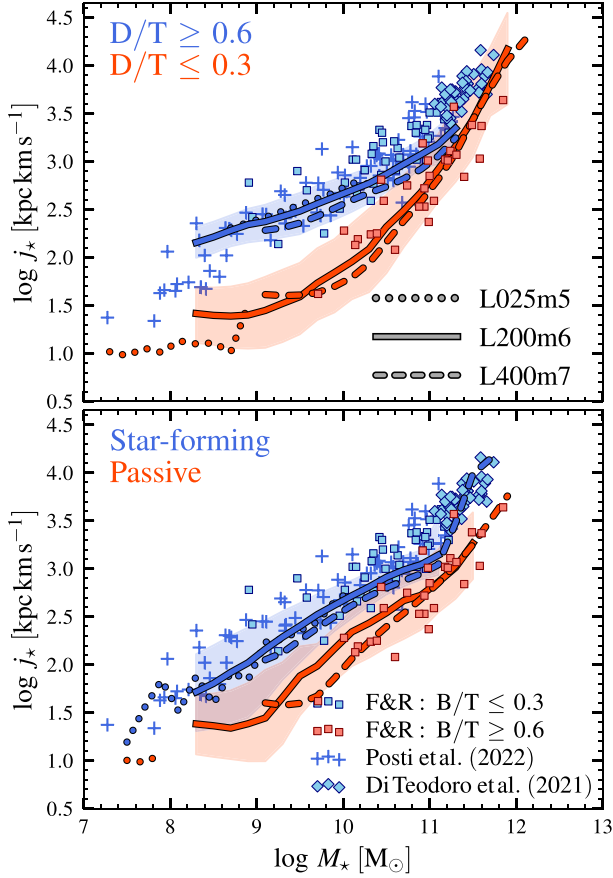


Figure 11. Median stellar specific angular momentum (j_*) as a function of stellar mass (M_*) for simulated central galaxies at $z=0$. Early- and late-type systems are shown in blue and red, respectively. Dotted lines indicate L025m5, solid lines L200m6, and dashed lines L400m7. In the top panel, galaxies are classified by their kinematic disc-to-total ratio, D/T ; in the bottom panel by star-formation activity (see the text for selections). Observational measurements for disc galaxies are shown from L. Posti et al. (2018, plus signs) and E. M. Di Teodoro et al. (2021, diamonds). Results from S. M. Fall & A. J. Romanowsky (2018) are included for systems with $D/T \geq 0.6$ (blue squares) and $D/T \leq 0.3$ (red squares). For both classification schemes, COLIBRE reproduces both the slope and normalization of the observed $j_* - M_*$ relations.

3.3.1 The stellar angular momentum–mass relation

In Fig. 11, we plot the median $z=0$ $j_* - M_*$ relations, using different line styles for the different resolution levels. Galaxies are classified either by their kinematic disc-to-total ratio (D/T , top panel) or by sSFR (bottom panel). In the latter case, star-forming galaxies lie within 1 dex of the main sequence (i.e. equation 1), while passive systems are at least 2 dex below it. In both cases, the simulated population separates cleanly into two sequences that persist over the full mass range and exhibit good convergence between resolutions. Late-type or actively star-forming systems define a higher-normalization relation, while early-type or passive galaxies populate a lower- j_* sequence.

We compare these results to observational measurements from L. Posti et al. (2018, blue plus signs), S. M. Fall & A. J. Romanowsky (2018, blue and red squares), and E. M. Di Teodoro et al. (2021, blue diamonds). The SPARC-based measurements of L. Posti et al. (2018) and the massive spiral galaxies studied by E.

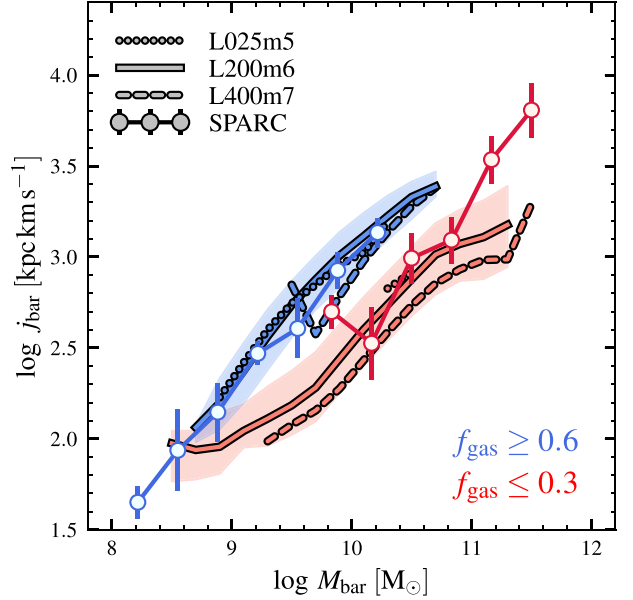


Figure 12. The specific baryonic angular momentum–mass relation for $z=0$ late-type central galaxies (kinematic $D/T \geq 0.6$) in COLIBRE, compared to SPARC galaxies from Z. Hua et al. (2025). Dotted, solid, and dashed lines show the median relations for L025m5, L200m6, and L400m7, respectively, computed separately for systems with gas fractions $f_{\text{gas}} \geq 0.6$ (blue) and $f_{\text{gas}} \leq 0.3$ (red). Connected circles of matching colour show the corresponding median relations for SPARC galaxies selected using the same gas-fraction thresholds. The simulated relations are well converged and closely reproduce the observed trends, including their dependence on gas fraction.

M. Di Teodoro et al. (2021) trace the locus of late-type systems in COLIBRE, while the morphologically diverse sample of S. M. Fall & A. J. Romanowsky (2018) brackets the early- and late-type sequences.

Overall, COLIBRE reproduces both the slopes and relative normalizations of the observed $z=0$ $j_* - M_*$ relations. The offset between late- and early-type systems, as well as the degree of intrinsic scatter – both of which depend on stellar mass and sample selection – are consistent with observational constraints, indicating that the simulated galaxies capture the strong morphology dependence of stellar angular momentum seen in the local Universe. This mirrors the good agreement with the observed morphology-dependence of the SMRs shown in Section 3.1.

3.3.2 The baryonic angular momentum–mass relation

Fig. 12 presents the baryonic angular momentum–mass relation for $z=0$ late-type (kinematic $D/T \geq 0.6$) central galaxies in COLIBRE. Median relations are computed separately for gas-rich ($f_{\text{gas}} \geq 0.6$) and gas-poor ($f_{\text{gas}} \leq 0.3$) systems, where $f_{\text{gas}} = 1.33 M_{\text{HI}}/M_{\text{bar}}$. The different COLIBRE volumes are indicated using the same line styles as in Fig. 11.

For comparison, we also show median relations for SPARC galaxies (Z. Hua et al. 2025), selected using the same gas-fraction thresholds and plotted as connected circles with the same colour scheme as the simulations. At fixed gas fraction, galaxies follow approximately parallel relations in the $\log j_{\text{bar}} - \log M_{\text{bar}}$ plane, with good convergence between the L025m5, L200m6, and L400m7 runs. All simulated measurements remain broadly

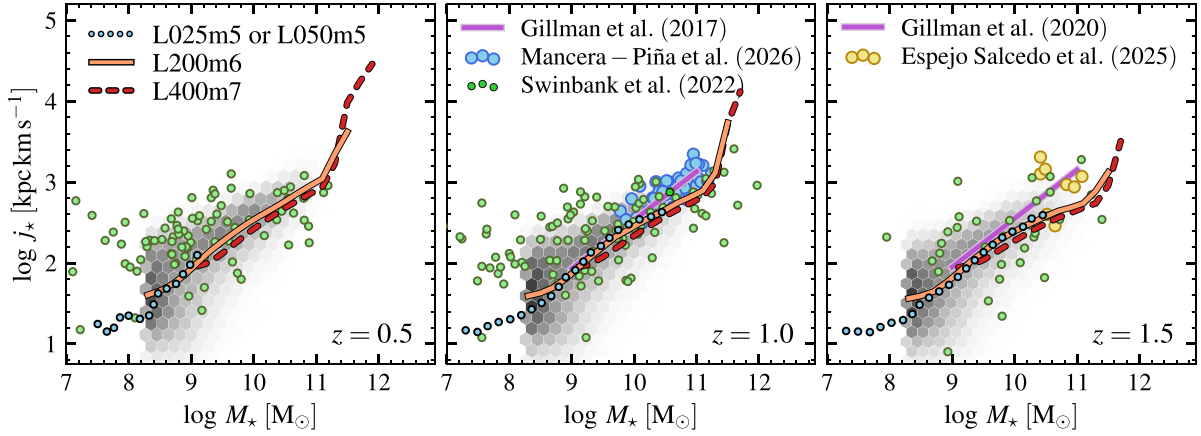


Figure 13. The j_* – M_* relations for central simulated galaxies at $z = 0.5, 1.0$, and 1.5 (left to right, respectively) that lie within 1 dex of the redshift-dependent star-formation main sequence. The distributions of galaxies in L200m6 are shown as a two-dimensional histogram; dotted, solid, and dashed lines indicate the median relations from L025m5 or L050m5, L200m6 and L400m7, respectively. In all panels, observational measurements from A. M. Swinbank et al. (2017) are shown as green points. In the middle panel, observations from C. M. Harrison et al. (2017) are shown as a purple line, and individual galaxies from P. E. Mancera Piña et al. (2026) as blue circles. The right-hand panel shows the observed relation from S. Gillman et al. (2020, purple line) and individual galaxies from J. M. Espejo Salcedo et al. (2025, yellow circles) that cover the redshift range $1.4 \leq z \leq 1.6$. The simulations demonstrate excellent convergence across resolution levels and align closely with observed relations.

consistent with the normalization and scatter of the corresponding observational relations.

Overall, the angular-momentum content of $z \approx 0$ central galaxies in COLIBRE is in good agreement with observational constraints, including its dependence on galaxy type, and independent of whether galaxies are classified by morphology or star-formation activity, or whether angular momentum is defined for the stellar or total baryonic component. This mirrors the level of agreement found for the various size–mass relations discussed in Sections 3.1 and 3.2.

3.4 Redshift evolution of the stellar specific angular momentum–mass relation

Fig. 13 extends the comparison between simulated and observed $j_* - M_*$ relations to redshifts $z \approx 0.5, 1.0$, and 1.5 . Grey hexagons show two-dimensional histograms of the $\log j_* - \log M_*$ distribution for central star-forming galaxies (i.e. within 1 dex of the redshift-dependent star formation main sequence) in L200m6, while solid orange lines indicate the median relation. Dotted blue and dashed red lines show the corresponding medians for L050m5 and L400m7, respectively. At all redshifts, the relation exhibits an upturn at $M_* \gtrsim 10^{11} M_\odot$, above which j_* rises more steeply with mass – though measurements in this regime are particularly sensitive to aperture effects (see Appendix C).

Green points show observational measurements from A. M. Swinbank et al. (2017), which are based on the K-band Multi-Object Spectrograph (KMOS) Survey and MUSE (Multi-Unit Spectroscopic Explorer) observations of star-forming main-sequence galaxies spanning $0.28 \leq z \leq 1.65$. Galaxies with $0.28 \leq z \leq 0.75$ appear in the left, those with $0.75 < z \leq 1.25$ in the middle, and those with $z > 1.25$ in the right panel. At all redshifts, the simulated galaxies reproduce both the normalization and scatter of these observations.

The middle and right panels also include observational fits from C. M. Harrison et al. (2017) and S. Gillman et al. (2020), derived from the KMOS Redshift One Spectroscopic Survey

(KROSS) at $z \simeq 0.9$ and the KMOS Galaxy Evolution Survey (KGES) at $z \simeq 1.5$, respectively. In the middle panel, we additionally show individual $z \simeq 0.9$ galaxies from P. E. Mancera Piña et al. (2026) as blue circles, and in the right panel we show measurements for star-forming galaxies at $1.4 \leq z \leq 1.6$ from J. M. Espejo Salcedo et al. (2025).

Overall, we find good agreement between simulated and observed $j_* - M_*$ relations across the full redshift range considered, with most observational measurements lying within the intrinsic scatter of the simulated galaxy population. There is a hint that massive simulated galaxies ($M_* \gtrsim 10^{11} M_\odot$) at $z = 1.5$ have somewhat less angular momentum than observed systems, but the shape of the relation in this regime is sensitive to scatter in M_* , which tends to artificially flatten the relation (see Appendix D).

3.5 Comparison of the thermal-AGN and hybrid-AGN feedback models

All results presented in the preceding sections were obtained from runs that adopted the thermal-AGN feedback model. Here, we compare those predictions with an alternative hybrid scheme, in which thermal feedback is supplemented by kinetic jet-driven outflows. Both models were calibrated at m7 resolution to reproduce the $z \approx 0$ galaxy stellar mass function of S. P. Driver et al. (2022) and the size–mass relation of J. A. Hardwick et al. (2022) over the stellar mass range $10^9 < M_*/M_\odot < 10^{11.3}$. Other galaxy properties, including angular momentum, were not part of the calibration, nor was either model tuned to match $z > 0$ observations. Differences between the two schemes therefore provide insight into the sensitivity of galaxy structure to the details of AGN feedback.

In addition to their treatment of AGN feedback, the models differ slightly in their implementation of supernova feedback: the normalization of the gas-density-dependent heating temperature, $\Delta T_{\text{SN}}(\rho_{\text{gas}}) \propto \rho_{\text{gas}}^{2/3}$, is reduced in the hybrid-AGN model, resulting in lower heating temperatures at fixed ρ_{gas} . This adjust-

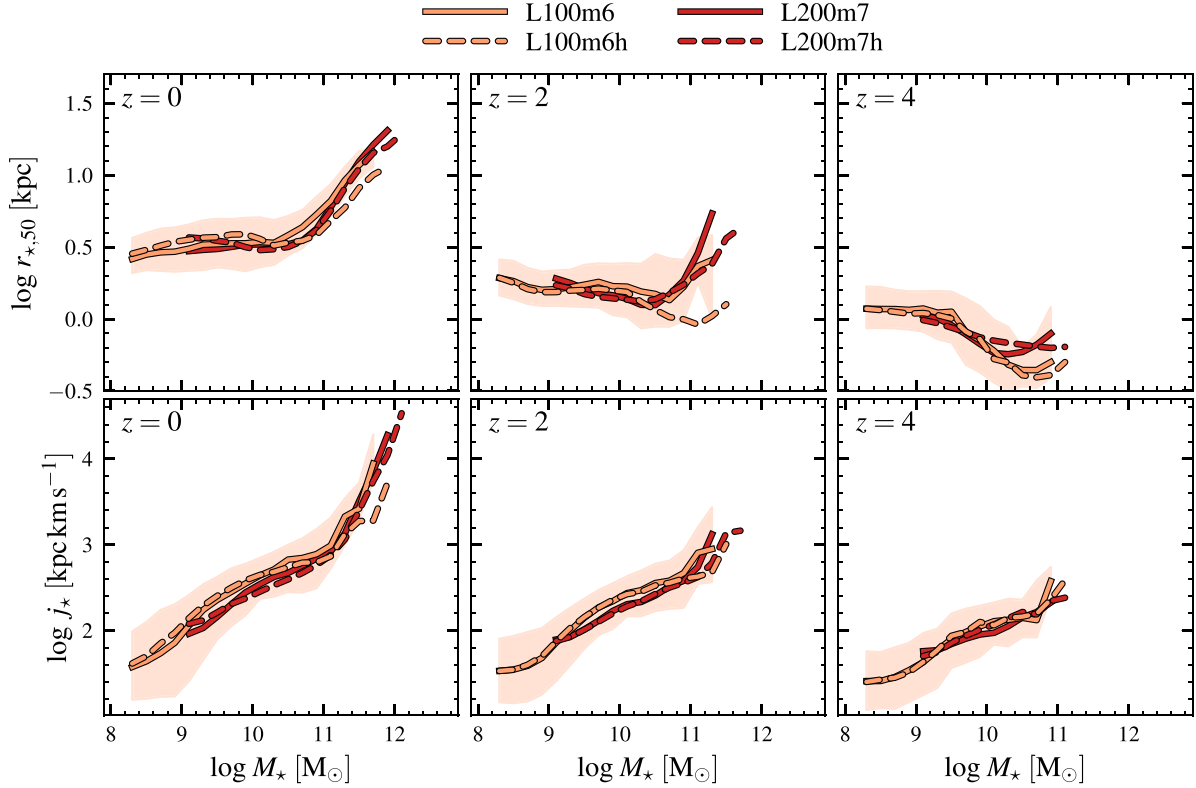


Figure 14. Comparison of the $(100 \text{ cMpc})^3$ m6 (orange) and $(200 \text{ cMpc})^3$ m7 (red) COLIBRE volumes adopting the thermal- (solid lines) and hybrid-AGN (dashed lines) feedback schemes. Shaded regions show the 16th to 84th percentile scatter for galaxies in L100m6. Other runs exhibit comparable scatter, and are not shown for clarity. Columns correspond to $z = 0, 2$, and 4 . The top row shows the 3D size-mass relation for central galaxies with $M_* \geq 100 \times m_{\text{bar}}$. Stellar masses and sizes are measured from bound stellar particles within 50 kpc of the galaxy centre. The bottom row shows the stellar specific angular momentum-mass relation for $M_* \geq 100 \times m_{\text{bar}}$, where j_* is computed from all bound stellar material. The thermal- and hybrid-AGN schemes produce similar galaxy properties at both resolutions.

ment is intended to partially offset the stronger AGN feedback in the hybrid scheme (see F. Huško et al. 2026, for details).

We present this comparison at two resolution levels: L100m6 and L100m6h, and L200m7 and L200m7h, the latter being the largest simulation volume available for the hybrid-AGN scheme. This choice maximizes the number of massive galaxies while ensuring comparable statistics between the two volumes. Fig. 14 summarizes the comparison between the size-mass relations (upper panels) and the specific angular momentum-mass relations (middle panels) at redshifts $z = 0, 2$, and 4 (left to right).

At $z = 0$, the feedback schemes produce closely matching $r_{*,50}$ - M_* and j_* - M_* relations, as expected given the calibration. Small differences between the median relations of L200m7 and L200m7h lie well within the 16th–84th percentile scatter at all masses. The same is true for L100m6 and L100m6h, although there is some indication that the most massive galaxies at this resolution, $M_* \gtrsim 10^{11.5} M_\odot$, are ≈ 0.1 – 0.2 dex smaller and have correspondingly lower j_* in the hybrid-AGN model.

At $z = 2$, the size-mass and angular momentum-mass relations remain very similar at low masses. In the m6 runs, however, galaxies with $M_* \gtrsim 10^{10.5} M_\odot$ are systematically larger in the thermal-AGN model (by ≈ 0.3 dex), whereas in the m7 runs differences appear only at $M_* \gtrsim 10^{11} M_\odot$ (and typically remain within ≈ 0.2 dex). Above $M_* \approx 10^{11} M_\odot$, galaxies in the thermal-AGN model also exhibit slightly higher specific angular momentum (by ≈ 0.2 dex), although these offsets are confined to the

most massive systems and are subject to small-number statistics. These trends are consistent with more efficient removal of low-angular-momentum gas in the thermal-AGN model at these redshifts.

At $z = 4$, the median size-mass and angular momentum-mass relations are again very similar between the two schemes, with each lying within the scatter of the other. Differences between the models are therefore small across the full redshift range considered here.

Overall, the two feedback schemes produce very similar size-mass and angular momentum-mass relations, with only modest differences emerging for the most massive galaxies at intermediate redshift. Taken together, these results indicate that the structural properties of galaxies in COLIBRE are reproduced consistently across resolution levels and AGN feedback implementations.

4 SUMMARY

We have presented the stellar size-mass and specific angular momentum-mass relations for central galaxies in the COLIBRE simulations (J. Schaye et al. 2026; E. Chaikin et al. 2026a), and compared them to a wide range of observational data sets. COLIBRE improves upon previous cosmological simulations by offering: (i) a suite of volumes and resolutions that surpass previous simulation programs; (ii) a supersampled dark matter density

field (four dark matter particles per baryonic particle), which reduces spurious energy transfer and improves the effective resolution of baryonic structures; (iii) gas cooling below 10^4 K, enabling star formation in dense and cold gas; and (iv) improved sub-grid models and a calibration strategy anchored to observed $z \approx 0$ galaxy sizes, the stellar mass function, and black hole masses, yielding improved convergence across resolutions.

The main results of our work are as follows:

(i) The stellar size–mass relation exhibits a shallow slope below a characteristic mass $M_\star \approx 10^{10.5} M_\odot$. Above this mass, galaxy sizes increase strongly with stellar mass at $z \lesssim 2$, while at $z \approx 3$ they exhibit a ‘U-shaped’ trend, initially decreasing before increasing again at the highest masses. Below the characteristic mass, late-type galaxies are consistently larger (by ≈ 0.2 – 0.3 dex) and have higher specific angular momentum than early types at fixed mass and redshift. Both populations follow approximately parallel $j_\star$ – $M_\star$ relations, with offsets comparable to those observed between spiral and elliptical galaxies in the local Universe (Fig. 3).

(ii) Galaxy sizes in COLIBRE are in excellent agreement with observations across a range of size definitions and samples. We find good agreement between two-dimensional half-light radii derived from single-component Sérsic fits to r -band surface brightness profiles and measurements from S. Casura et al. (2022), as well as between two-dimensional half-mass radii and the mass–size relations of S. Bellstedt et al. (2024, Fig. 5). This agreement extends to the u – and z –band, and to the radii $R_{u,90}$ and $R_{z,90}$ enclosing 90 per cent of the galaxy light in these bands (Fig. 6).

(iii) We also find very good agreement between the simulated R_1 – $M_\star$ relations and the measurements of I. Trujillo et al. (2020) over 5 orders of magnitude in stellar mass, including when the relations are split by galaxy morphology (Fig. 7). R_1 is the radius at which the stellar surface density falls below $\Sigma_1 = 1 M_\odot \text{pc}^{-2}$, and is typically larger than the projected half-mass radii used to calibrate COLIBRE’s sub-grid models by ≈ 0.2 – 1.0 dex, depending on stellar mass.

(iv) Similarly, the $z = 0$ ‘baryonic’ size–mass relations of late-type galaxies in COLIBRE, in which both stellar and gaseous components are included, agree very well with results from the SPARC survey (Z. Hua et al. 2025, Fig. 8).

(v) At intermediate redshifts ($0.5 \lesssim z \lesssim 1.5$), the simulated three-dimensional half-mass radii $r_{\star,50}$ are in good agreement with deprojected CANDELS size measurements from A. van der Wel et al. (2024, Fig. 9). Comparisons of $1 \mu\text{m}$ half-light radii over the range $0 \leq z \leq 4$ to the observations of J. Song et al. (2026) also show good agreement at $z \lesssim 1.5$. At higher redshifts ($z \gtrsim 2$), galaxies with $M_\star \gtrsim 10^{9.5} M_\odot$ are typically smaller than observed by ≈ 0.1 – 0.3 dex, depending on mass (Fig. 10). While the size–mass relations of both star-forming and quenched galaxies agree well with observations at $z \lesssim 1$, the separation between these populations becomes less pronounced than observed at higher redshift. Differences in the simulated and observed size–mass relations at high redshift are possibly due to the effects of dust attenuation, and will be addressed in future work.

(vi) At $z = 0$, late-type, star-forming discs have higher stellar specific angular momentum than quenched ellipticals, typically by ≈ 0.5 – 0.7 dex depending on mass. Early- and late-type galaxies, classified using either their kinematic disc-to-total ratio or their offset from the star-forming main sequence, follow dis-

tinct $j_\star$ – $M_\star$ relations with comparable scatter, in good agreement with observations of spirals and spheroids in the local Universe (Fig. 11). The baryonic angular momentum–mass relation – defined using all baryons associated with a galaxy – also agrees well with observations of late-type galaxies, including its dependence on gas fraction (Fig. 12).

(vii) The good agreement between the simulated and observed angular momentum–mass relations at $z = 0$ extends at least to redshifts $z \approx 1.5$, with most available observational measurements lying within the intrinsic scatter of the simulated galaxy population (Fig. 13). This mirrors the similarly strong agreement found for the size–mass relations over the same redshift range.

(viii) Our conclusions are robust to the adopted model for AGN feedback (Fig. 14) and to the exclusion of satellite galaxies from the analysis (Fig. B1). However, the inferred sizes, stellar masses, and angular momenta (but not the kinematic morphology) do depend on the choice of spherical aperture within which these quantities are measured (Figs C1 and C2).

In summary, the COLIBRE simulations provide a self-consistent and observationally successful framework for studying the evolution of galaxy sizes, angular momentum, and morphology across cosmic time. The close correspondence between simulated and observed scaling relations – across multiple size definitions, redshifts, galaxy populations, and resolution levels – implies that COLIBRE is capturing the main physical processes that establish these relations; namely, feedback from stars and black holes. In addition, COLIBRE produces size–mass and angular-momentum–mass relations that converge well across ~ 2 orders of magnitude in stellar mass, including for both early- and late-type populations. This makes COLIBRE a powerful tool for future studies aimed at disentangling the roles of angular momentum acquisition and retention, feedback, mergers, and environment in shaping the galaxy population. We plan to address these issues in a follow-up paper.

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DATA AVAILABILITY

The COLIBRE data underlying the figures and results presented in this paper are available from the corresponding author upon reasonable request. A public version of the SWIFT simulation code (M. Schaller et al. 2024) is available at <http://www.swiftsim.com>. The COLIBRE-specific modules implemented within SWIFT will be released at a later stage alongside the public simulation data.

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APPENDIX A: CONVERGENCE TESTS FOR GALAXY SIZES AND ANGULAR MOMENTUM

Fig. A1 compares the $r_{*,50}-M_*$ (upper panels) and j_*-M_* (lower panels) relations for thermal-AGN models run with different numerical resolutions. Stellar half-mass radii, $r_{*,50}$, are measured directly from the particle data. To avoid mixing resolution effects with differences arising from simulation volume, we compare runs of varying resolution at fixed box size. Results for the available $(25 \text{ cMpc})^3$ volumes are shown in the left-hand panels, while those for the $(200 \text{ cMpc})^3$ volumes are shown in the right-hand panels.

For each set of curves, thick lines indicate stellar mass bins that both exceed $M_* = 100 \times m_{\text{bar}}$ (the nominal resolution limit adopted throughout this paper for quantities measured directly from particle data) and contain ≥ 10 galaxies. At lower masses, the relations are shown with thin lines. We find that the sizes and angular momentum content of galaxies resolved with ≥ 100 stellar particles converge well between simulations of different resolution. This resolution threshold was therefore adopted in the preceding analysis. At lower masses, the curves deviate, with

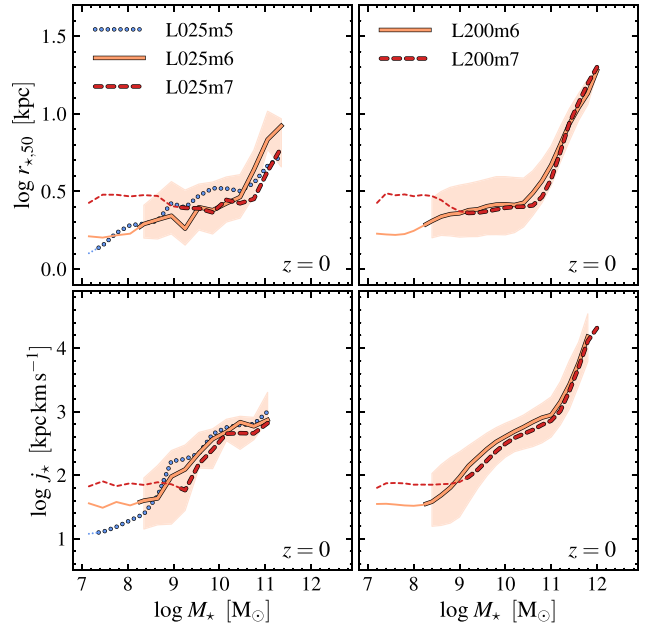


Figure A1. Convergence of the three-dimensional stellar half-mass radii ($r_{*,50}$; upper panels) and total stellar specific angular momentum (j_* ; lower panels) of central galaxies at $z = 0$ in the thermal-AGN COLIBRE simulations. Simulations of different numerical resolution are compared at fixed box size: $(25 \text{ cMpc})^3$ volumes are shown in the left-hand panels, while $(200 \text{ cMpc})^3$ volumes at the available resolutions are shown in the right-hand panels. The colour scheme and line styles follow those adopted throughout the paper. Thick lines span stellar mass bins from the nominal resolution limit, $M_* = 100 \times m_{\text{bar}}$ (where m_{bar} is the initial baryonic particle mass), up to the highest mass bin containing ≥ 10 galaxies. Thin lines extend to lower stellar masses. Runs of different resolution exhibit good convergence for masses $M_* \gtrsim 100 \times m_{\text{bar}}$.

poorer resolution corresponding to larger galaxy sizes and higher amounts of angular momentum.

APPENDIX B: CENTRALS VERSUS SATELLITES

The results presented in Section 3 focus exclusively on central galaxies in COLIBRE. This raises the possibility that the inferred relations between galaxy size, stellar angular momentum, and stellar mass may be biased if satellite galaxies exhibit systematically different structural or kinematic properties due to, for example, differences in their environmental evolution.

Fig. B1 compares the median $r_{*,50}-M_*$ (top panels) and j_*-M_* (bottom panels) relations for central galaxies at $z = 0$ with those measured for the full galaxy population (left-hand panels) and for satellites alone (right-hand panels) in L200m6. We find that the relations derived for centrals alone are in close agreement with those obtained for the full population, indicating that restricting our analysis to centrals does not significantly bias our results.

When centrals and satellites are considered separately, the correspondence remains good, although modest differences are apparent. At $10^9 \lesssim M_*/M_\odot \lesssim 10^{10.5}$, satellite galaxies are, on average, slightly more compact than centrals whereas lower-mass satellites are larger. For all $M_* \lesssim 10^{11} M_\odot$, satellites have lower stellar specific angular momentum than centrals of the same mass. These offsets are small, however, and do not qualitatively affect the trends discussed throughout this work.

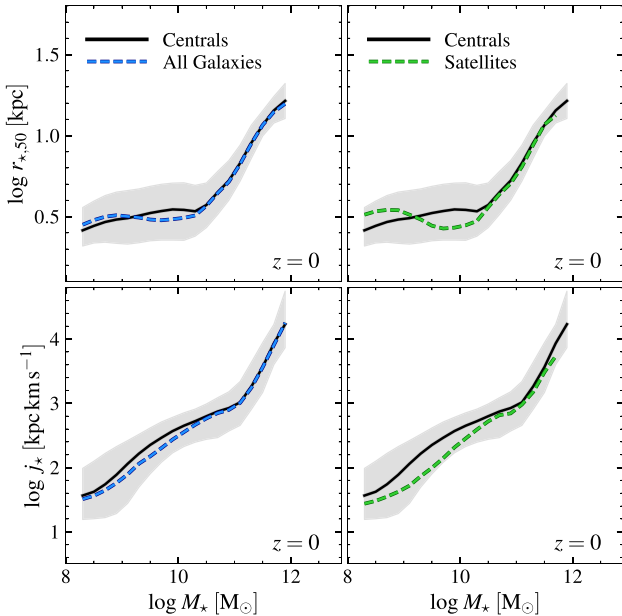


Figure B1. The median $z = 0$ $r_{*,50}-M_*$ (top panels) and j_*-M_* relations (bottom panels) for different galaxy samples in the L200m6 (thermal-AGN) simulation. The left-hand panels compare central galaxies (solid black lines) with the full population of central and satellite galaxies (dashed blue lines). The right-hand panels compare central galaxies with satellites only (dashed green lines). Grey shaded regions indicate the 16th to 84th percentile scatter for central galaxies. Note that the SMR and AMR for the full galaxy sample (centrals plus satellites) is very similar to the relations obtained for centrals alone.

The results plotted in Fig. B1 are limited to $z = 0$, but we find similar, often better agreement between the corresponding relations for centrals and satellites at higher redshifts.

APPENDIX C: THE EFFECT OF APERTURE RADIUS ON GALAXY SIZE AND ANGULAR MOMENTUM

The stellar masses, sizes, and D/T ratios used in this paper were calculated using bound stellar or gas particles within 50 kpc of the galaxy centre; stellar specific angular momentum was calculated using all bound stellar material. Here, we examine how these quantities depend on the choice of the three-dimensional spherical aperture within which they are measured. Specifically, we compare the fraction of bound stellar mass enclosed within apertures of radius $r_{\text{ap}} = 10, 30, 50$, and 100 kpc to the total bound stellar mass, and assess the corresponding impact on galaxy size, angular momentum, and morphology. We focus on central galaxies in the $(400 \text{ cMpc})^3$ volume run with the thermal-AGN feedback model, which maximizes the number of massive galaxies for which aperture effects are expected to be most important.

Fig. C1 shows the fraction of bound stellar mass enclosed within each aperture as a function of total bound stellar mass, $M_{*,\text{bound}}$. Below $M_{*,\text{bound}} \approx 10^{10.5} M_\odot$, all curves overlap, even for the smallest aperture considered ($r_{\text{ap}} = 10$ kpc), indicating that essentially all bound stellar material in galaxies below this mass lies within 10 kpc of the galaxy centre. At higher masses the curves diverge, with smaller apertures enclosing a progressively

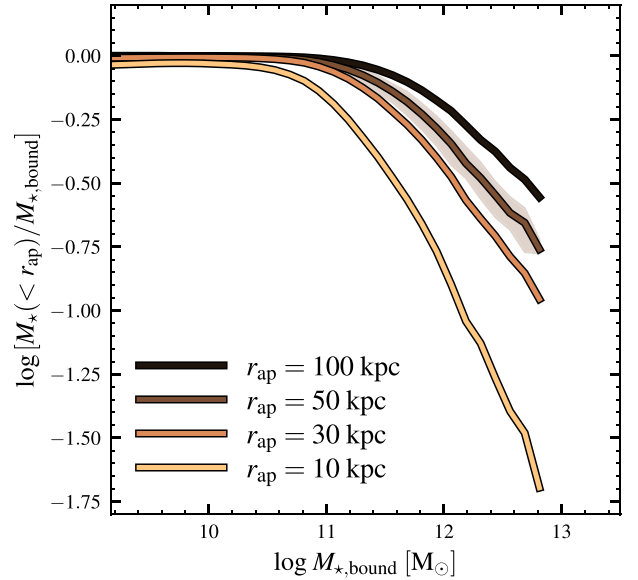


Figure C1. Median fraction of bound stellar mass enclosed within different three-dimensional spherical apertures as a function of total bound stellar mass, $M_{*,\text{bound}}$. Results are shown for $z = 0$ central galaxies in L400m7 (thermal-AGN), which has the largest volume and therefore contains the highest number of massive galaxies for which aperture effects are most significant. For our fiducial choice, $r_{\text{ap}} = 50$ kpc, we highlight the 16th to 84th percentile scatter with a shaded region. While this fiducial measure captures nearly all bound stellar material for systems below $M_{*,\text{bound}} \lesssim 10^{11.5} M_\odot$, an increasing fraction of bound mass resides beyond 50 kpc in more massive systems.

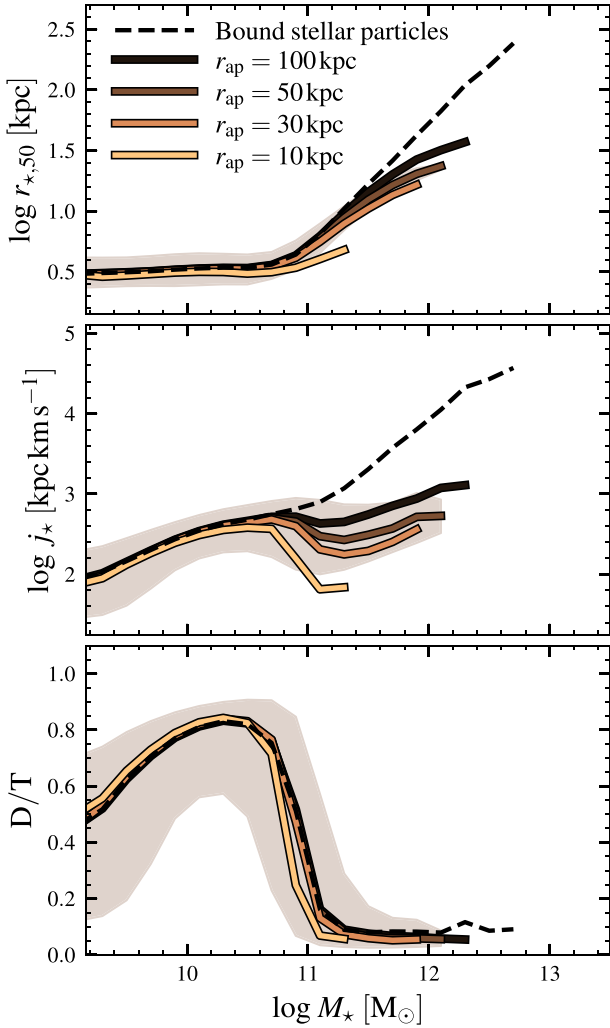


Figure C2. The median $z = 0$ $r_{*,50}$ – M_* (top), j_* – M_* (middle), and D/T – M_* (bottom) relations for central galaxies computed using bound stellar particles within different three-dimensional apertures (coloured curves). Dashed black curves show the relations obtained using all bound stellar particles. Results are shown for L400m7 (thermal-AGN), which maximizes the number of massive galaxies for which aperture effects are most pronounced. In all cases, quantities plotted on the vertical and horizontal axes were computed using the same aperture. For our fiducial choice ($r_{\text{ap}} = 50$ kpc), galaxy sizes for $M_* \lesssim 10^{11.5} M_\odot$ are consistent with results obtained using all bound stellar particles. Conversely, the specific angular momentum of all bound stellar particles exceeds that measured within any finite aperture considered for $M_* \gtrsim 10^{11} M_\odot$. The kinematic disc-to-total ratio remains largely insensitive to the choice of aperture across the entire mass range.

smaller fraction of the total bound stellar mass. For example, at $M_{*,\text{bound}} = 10^{12} M_\odot$ only ≈ 15 per cent of the bound stellar mass is contained within $r_{\text{ap}} = 10$ kpc; this increases to ≈ 37 , 48, and 64 per cent for $r_{\text{ap}} = 30$, 50, and 100 kpc, respectively. Since galaxy sizes decrease with increasing redshift, the fraction of bound stellar mass enclosed within fixed physical apertures is found to increase at earlier times (not shown explicitly here).

Fig. C2 illustrates the impact of aperture choice on the $r_{*,50}$ – M_* (top), j_* – M_* (middle), and D/T – M_* (bottom) relations for central galaxies. In all cases, quantities plotted on the vertical and hori-

zontal axes were computed using the same aperture. For comparison, relations obtained using all bound stellar particles are shown as dashed black curves. Consistent with Fig. C1, galaxy properties at $M_* \lesssim 10^{10.5} M_\odot$ are insensitive to the choice of aperture. At higher masses, larger apertures yield systematically larger galaxy sizes and higher specific angular momenta.

When all bound stellar particles are included, the size–mass relation is well described by a broken power law, with a transition at $M_* \approx 10^{10.7} M_\odot$. Below this mass, median sizes are approximately constant at ≈ 3 kpc, while above it sizes increase steeply with stellar mass. The angular momentum–mass relation obtained using all bound stellar material follows an approximate power law for $M_* \lesssim 10^{10} M_\odot$, steepens for $M_* \gtrsim 10^{11} M_\odot$, and exhibits a shallower slope at intermediate masses. This curvature reflects the combined influence of the mass–morphology relation, the shape of the stellar-to-halo mass relation, and the morphology-dependent normalisation of the j_* – M_* relation.

Throughout this paper, galaxy sizes and stellar masses are measured within a three-dimensional 50 kpc aperture. For this choice, median sizes closely track those obtained using all bound stellar particles for $M_* \lesssim 10^{11} M_\odot$. At higher masses, sizes measured within 50 kpc are systematically smaller due to the exclusion of loosely bound stellar material associated with extended stellar haloes. For the most massive galaxies, sizes based on a 50 kpc aperture can differ from those measured using all bound stellar mass by up to ≈ 0.3 dex. This agrees with the results of M. Furlong et al. (2017) based on the EAGLE simulation.

Specific angular momentum is considerably more sensitive to aperture choice than galaxy size, but again only at high stellar masses ($M_* \gtrsim 10^{10.7} M_\odot$). This is because stellar particles at large radii contribute disproportionately to the total angular momentum budget. Had the nominal 50 kpc aperture been applied to the calculation of j_* , the median specific angular momentum would differ substantially from that obtained using all bound stellar material: by approximately 0.5 dex at $M_* \approx 10^{11.2} M_\odot$, increasing to ≈ 1.2 dex at $M_* \approx 10^{12} M_\odot$. Aperture definitions should therefore be treated with care when comparing the angular momentum content of simulated galaxies to that inferred from observations.

Finally, the kinematic D/T ratios shown in the bottom panel of Fig. C1 are largely insensitive to the choice of aperture. This implies that our selection of early- and late-type galaxies based on D/T is robust to aperture effects.

APPENDIX D: THE EFFECT OF REDSHIFT-DEPENDENT SCATTER IN STELLAR MASSES

Fig. D1 shows the $r_{*,50}$ – M_* (top) and j_* – M_* (bottom) relations at $z = 0, 1, 2$, and 4 (left to right, respectively). Thick dashed lines represent the intrinsic relations measured directly from the simulated particle data. Thin lines show these relations after accounting for observational errors by adding a redshift-dependent lognormal scatter, $\sigma_{\log M_*}$ (see footnote 12). 10 realizations of the scatter are shown in each case. For clarity, we only plot L200m6 (orange) and L400m7 (red); L025m5 and L050m5 yield consistent results.

The impact of scatter in M_* depends on both mass and redshift. Where the intrinsic relations are relatively flat (e.g. $r_{*,50}$ – M_* at $M_* \lesssim 10^{10.5} M_\odot$ for $z \leq 2$, or $M_* \lesssim 10^{9.5} M_\odot$ at $z = 4$), adding scatter has little effect. In this regime, horizontal shifts in M_* do not significantly change the corresponding ordinate values, and the medians remain stable.

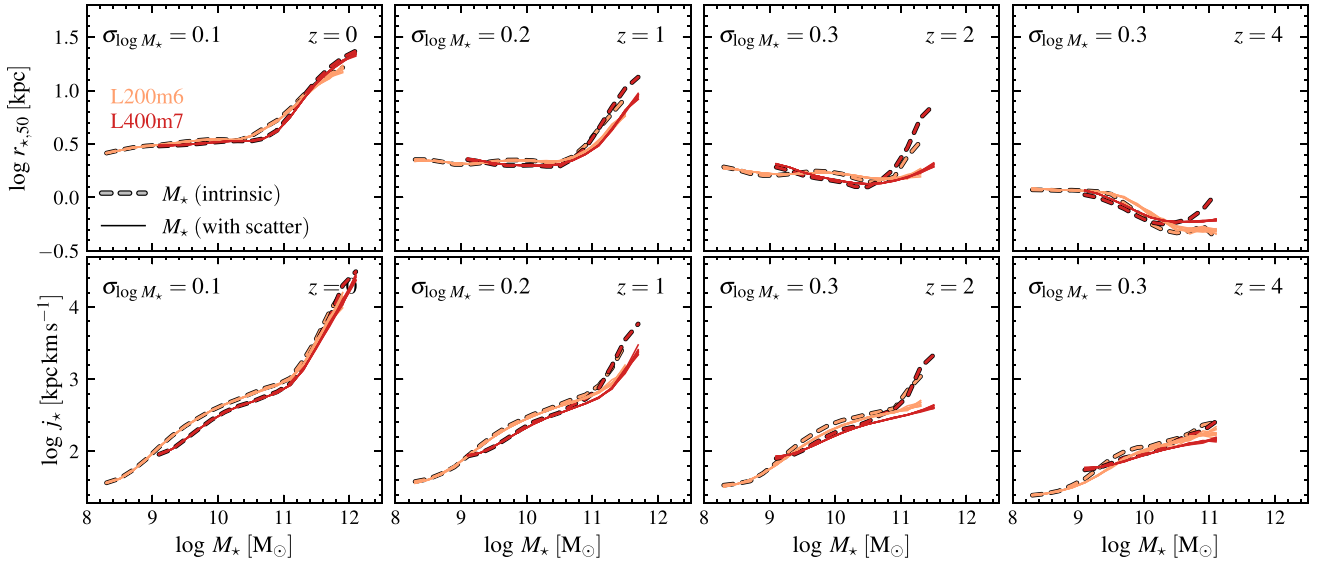


Figure D1. The median $r_{*,50}$ – M_* (top) and j_* – M_* (bottom) relations at $z = 0, 1, 2$, and 4 (left to right, respectively). Thick dashed lines show the intrinsic relations, where all quantities are measured directly from the simulated particle data. Thin solid lines show the corresponding relations after adding a random lognormal scatter to the stellar masses and repeating this procedure 10 times. The standard deviation of $\log M_*$ ($\sigma_{\log M_*}$) is indicated in each panel. Orange and red lines show results for L200m6 and L400m7, respectively. When $\sigma_{\log M_*}$ is small (leftmost panels), or when the relations are relatively flat, adding scatter to M_* has little effect. For steeper relations and larger $\sigma_{\log M_*}$, the impact on the median relations can be significant (up to ~ 0.5 dex at some masses and redshifts).

By contrast, when the intrinsic relations are steep and the scatter is large (e.g. both relations for $M_* \gtrsim 10^{11} M_\odot$ at $z \geq 1$), the median relations becomes systematically shallower. This is due to the shape of the galaxy stellar mass function, which decreases towards higher masses. At fixed M_* , more galaxies scatter upward from lower masses – where sizes and angular momenta are typically smaller – than scatter downward from higher masses. This Eddington bias leads to shallower $r_{*,50}$ – M_* and j_* – M_* relations. For intrinsically declining relations, the effect is reversed, and the slopes become steeper.

APPENDIX E: SÉRSIC INDICES FROM FITS TO STELLAR SURFACE MASS DENSITY PROFILES

The Sérsic index characterizes the shape of surface brightness and stellar mass density profiles: late-type galaxies typically exhibit exponential profiles with $n_s \approx 1$, whereas early-type systems are better described by G. de Vaucouleurs (1948) profiles with $n_s \approx 4$. Fig. E1 shows distributions of Sérsic indices obtained from fits to stellar mass surface density profiles (Σ_* ; top panels) and unattenuated r -band surface brightness profiles (Σ_r ; bottom panels) for GAMA galaxies and for $z = 0$ central galaxies in L200m6 and L400m7.

The COLIBRE galaxies exhibit a relatively narrow range of Sérsic indices, with a weak stellar mass dependence. Median values increase from $n_s \approx 1.7$ (1.8) in the lowest stellar mass bin to $n_s \approx 2.2$ (2.2) in the highest mass bin for the Σ_* (Σ_r) profiles, indicating that inferred Sérsic indices are largely independent of whether they are measured from stellar mass or r -band light profiles.

In contrast, GAMA galaxies exhibit both a broader distribution of Sérsic indices and a stronger stellar mass dependence, with median values increasing from $n_s \approx 1.4$ (1.2) to $n_s \approx 3.8$ (3.4) across the same stellar mass range for the Σ_* (Σ_r) profiles. Ob-

servationally inferred values also depend on the imaging tracer, consistent with L. S. Kelvin et al. (2012), who reported systematic differences between n_s values inferred from optical and near-infrared imaging.

Similar discrepancies between simulated and observed Sérsic index distributions were reported for mock stellar mass and r -band imaging of EAGLE galaxies by A. de Graaff et al. (2022), who likewise found narrower distributions and a weaker stellar mass dependence than observed, but a stronger dependence on imaging technique than found here for COLIBRE.

However, several methodological differences should be noted when comparing our results to observational measurements. Our Σ_* and Σ_r profiles are spherically averaged and do not include dust attenuation, instrumental effects, background noise, or point-spread-function convolution. In addition, we perform one-dimensional fits to radial profiles, whereas observational studies typically fit two-dimensional Sérsic models, often allowing for radius-dependent ellipticity. Sérsic indices can also be sensitive to the adopted fitting range. In our analysis, the inner fitting radius corresponds to the innermost bin enclosing at least 10 stellar particles, while the outer fitting radius corresponds to the outermost bin containing at least 10 stellar particles, or 50 kpc if larger. If the inner regions are affected by numerical resolution – although Fig. 1 suggests this is not the case – or if the surface brightness at large radii falls below the observational background level, then our fitting procedure may yield systematically different Sérsic indices from those inferred observationally. Nevertheless, the similarity between our results and those of A. de Graaff et al. (2022) suggests that simulated galaxies may exhibit systematically different radial distributions of stellar mass and light from those observed in real galaxies.

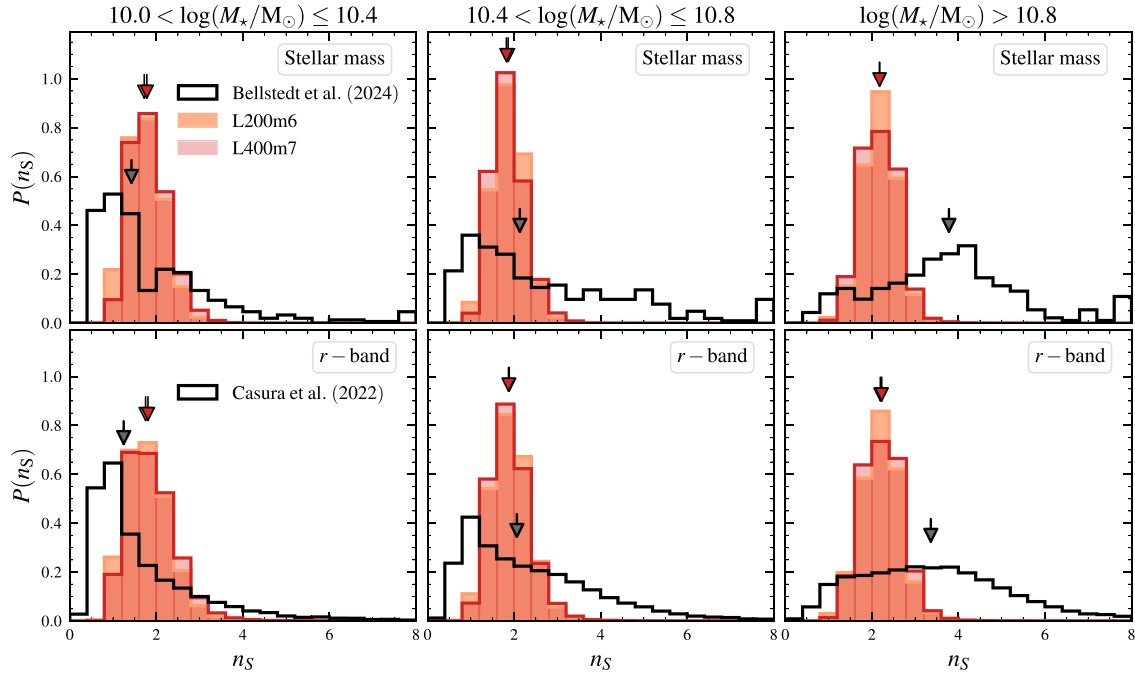


Figure E1. Distributions of Sérsic indices for $z = 0$ galaxies in bins of stellar mass. Top panels show results from fits to stellar mass surface density profiles, Σ_* , while bottom panels show fits to r -band surface brightness profiles, Σ_r . Black histograms show all GAMA galaxies from S. Bellstedt et al. (2024) (top) and S. Casura et al. (2022) (bottom); orange and red histograms show central COLIBRE galaxies from L200m6 and L400m7, respectively. The Σ_* and Σ_r profiles of COLIBRE galaxies exhibit relatively low Sérsic indices, with median values $n_S \approx 2$ and weak stellar mass dependence. In contrast, GAMA galaxies span a broader range of n_S and exhibit a stronger dependence on stellar mass. Morphologies inferred from Sérsic fits therefore suggest that COLIBRE contains a lower fraction of bulge-dominated galaxies ($n_S \approx 4$) than GAMA.

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