Understanding Giant Bulgeless Discs at Cosmic Morning

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Abstract

Giant bulgeless disc (GBD) galaxies are theoretically expected to be rare in the early Universe, but have been confirmed by JWST imaging to exist well before cosmic noon. Such extreme systems offer valuable opportunities to understand disc formation and galaxy-dark-matter connection. We identified analogues of early giant discs with stellar masses of $\sim 10^{11} M_{\odot}$ and half-light radii up to 6 kiloparsecs in cosmological simulations when the universe was just 2 billion years old, and reveal that they form in young cosmic knots, residing in spherical halos with higher spin and lower central-density than control samples of similar mass. With generally milder merging histories compared to normal disc galaxies, they underwent a early, gas-rich merger that preserved their disc status and deposit gas to a star-forming annulus on the outskirt that drives the optical size large. An embedded, aligned inner disc exists in all the cases: this universal feature is unresolved in JWST mock images and would appear to be a small bulge, but manifested by a Sersic index near unity.

JWST mocks and sample selection

Selection criterion

- Subhalo Type: Centrals
- Mass fraction: $f_{\rm Disc} \geq 0.8$, $f_{\rm ThinDisc} \geq 0.4$, $f_{\rm Bulge} \geq 0.5$
- Stellar Mass: $M_*(r < 5r_{*,1/2}) > 10^{10.5} M_{\odot}$
- Size: $r_{*,1/2}$ greater than the 84th percentile of mass-size relation

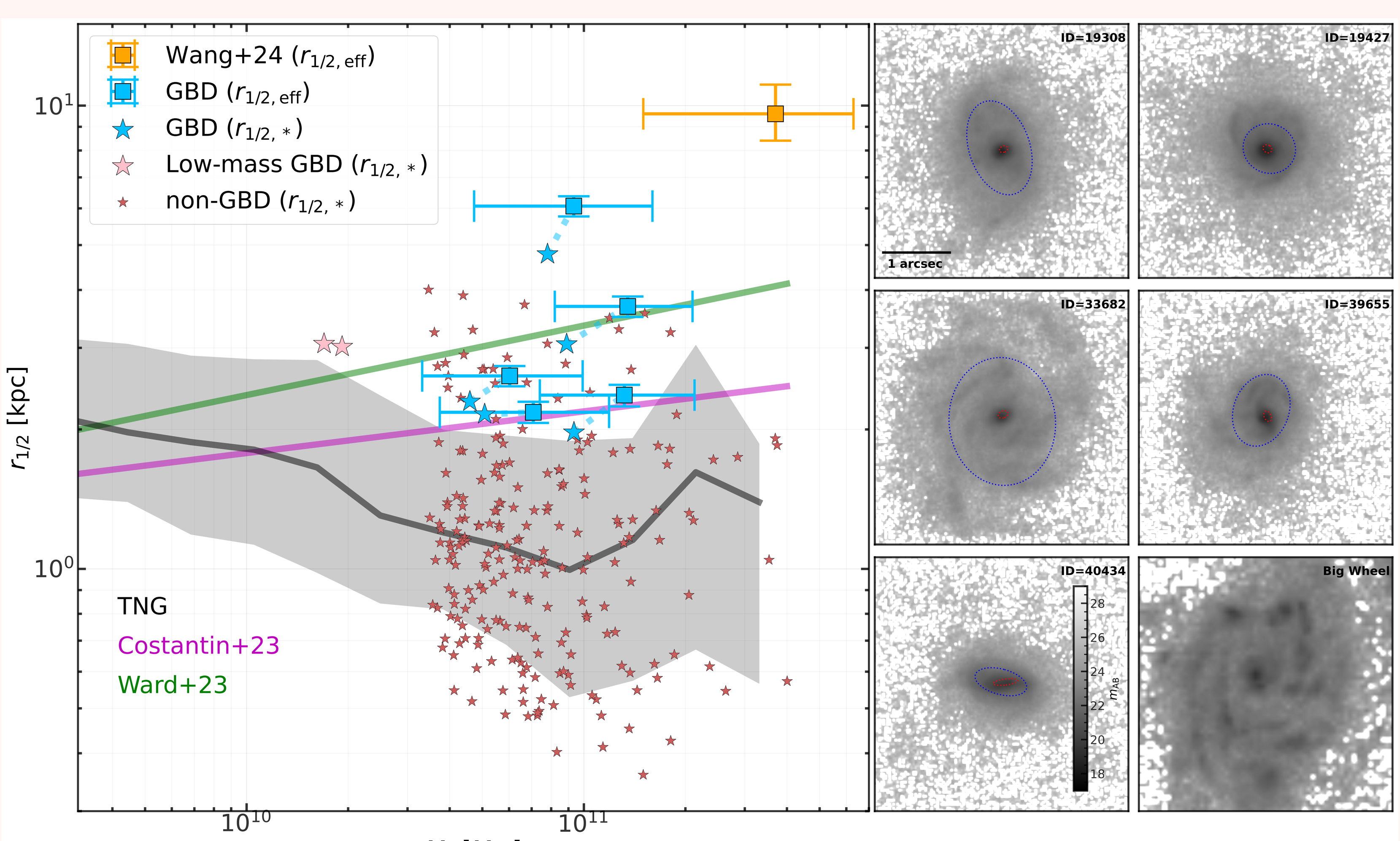

Figure 1. Size-mass relations for both simulated and observed galaxies, along with empirical relations from observations and simulations at $z = 3$

We select GBDs in the TNG100 cosmological simulation at redshift up to 3, based on our developed decomposition method. The simulated GBDs are rare (~2% of galaxies of similar mass) and the occurrence rate decreases towards higher redshifts. 5 analogues identified at $z = 3$, whose sizes and stellar masses are not as extreme but in the same ballpark as the Big Wheel galaxy with half-light radii up to 6 kpc, providing interesting insights.

Their large scale structure as well as edge-on mocks can be further seen in the figure below. They live denser parts of cosmic web (knots and filaments), which allow them to continuously accrete cold gas or experience gas-rich merger and form discs. Edge-on mocks reveal that inner disc might be common at high-z universe.

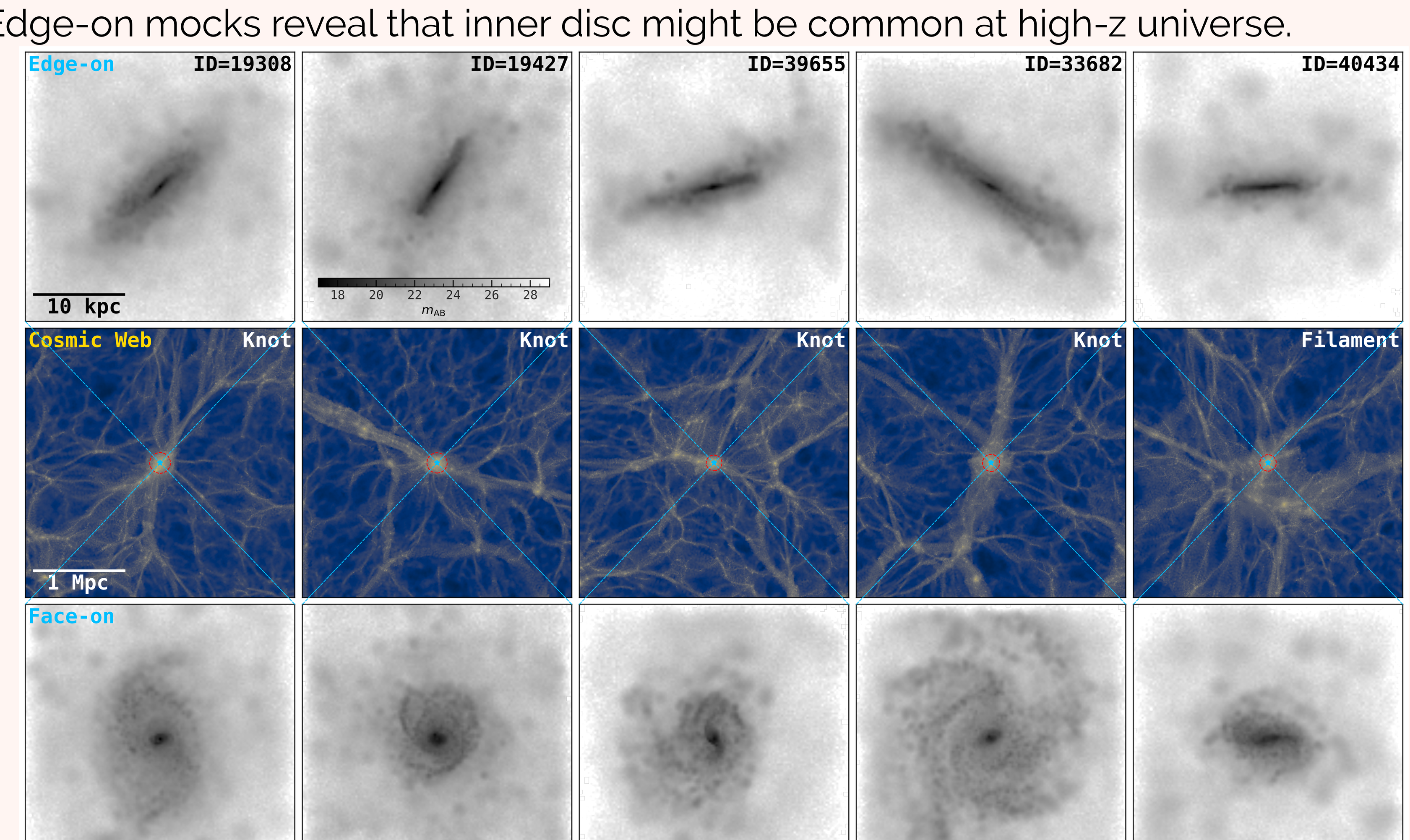

Figure 2. The large-scale environments, along with zoom-in face-on and edge-on mock images for five GBDs at $z = 3$, reveal that GBDs live in dense regions, having extended, thin outer discs while small, compact discs are embedded at their center

The conditions for forming GBDs

Merger and environmental properties

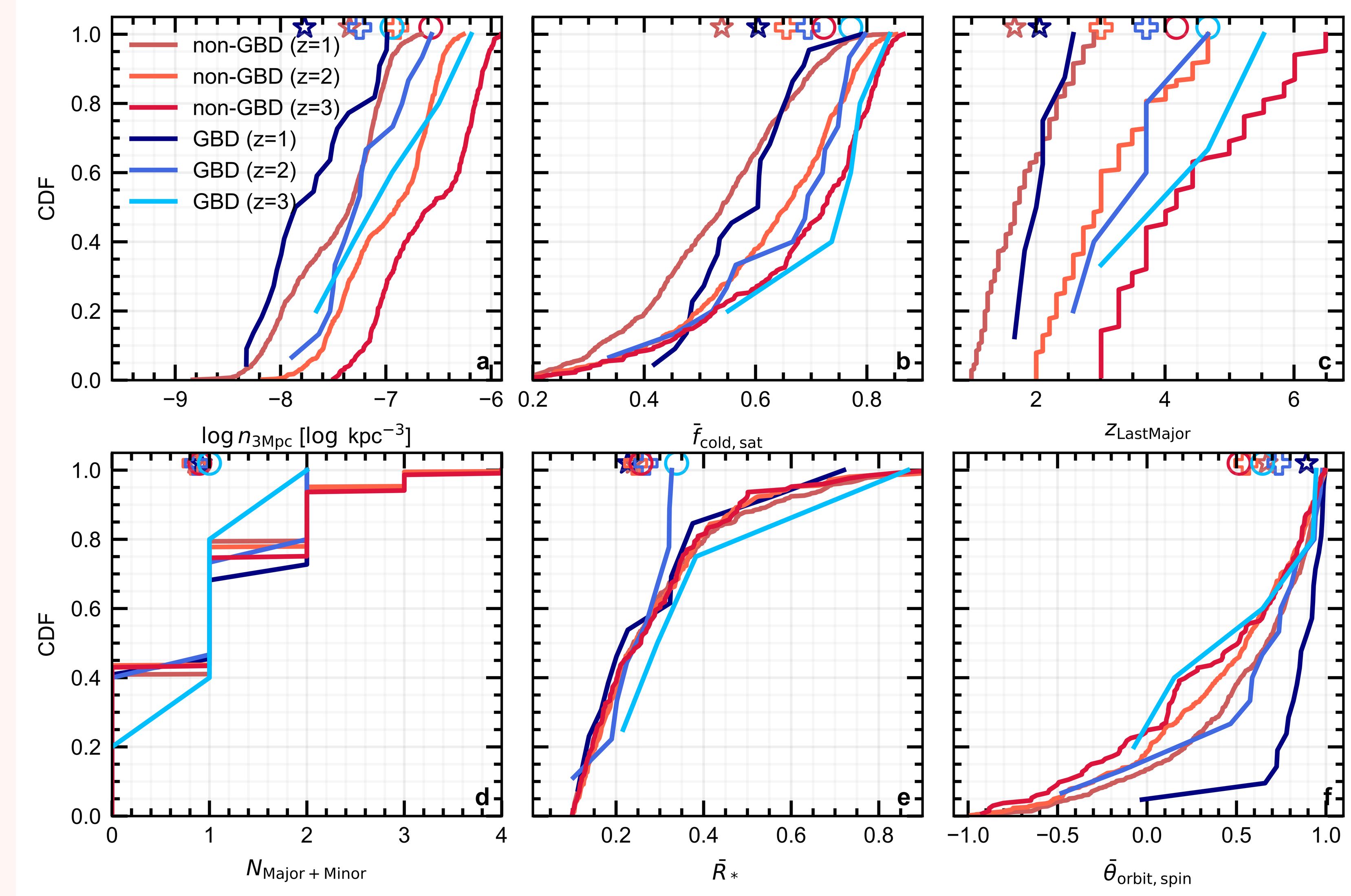

Figure 3. The cumulative distributions of environmental as well as merger conditions for hosting GBDs and non-GBDs at $z = 1, 2, 3$

Slightly lower number density indicate that GBDs are in proto galaxy clusters (**Panel a**). The GBD progenitors tend to accrete satellite galaxies that are more cold-gas rich (**Panel b**), less massive (**Panel e**), and on more coherent orbits (**Panel f**). The last major mergers are happened earlier for them (**Panel c**) while for long term, GBDs experience fewer mergers (**Panel d**).

Halo properties

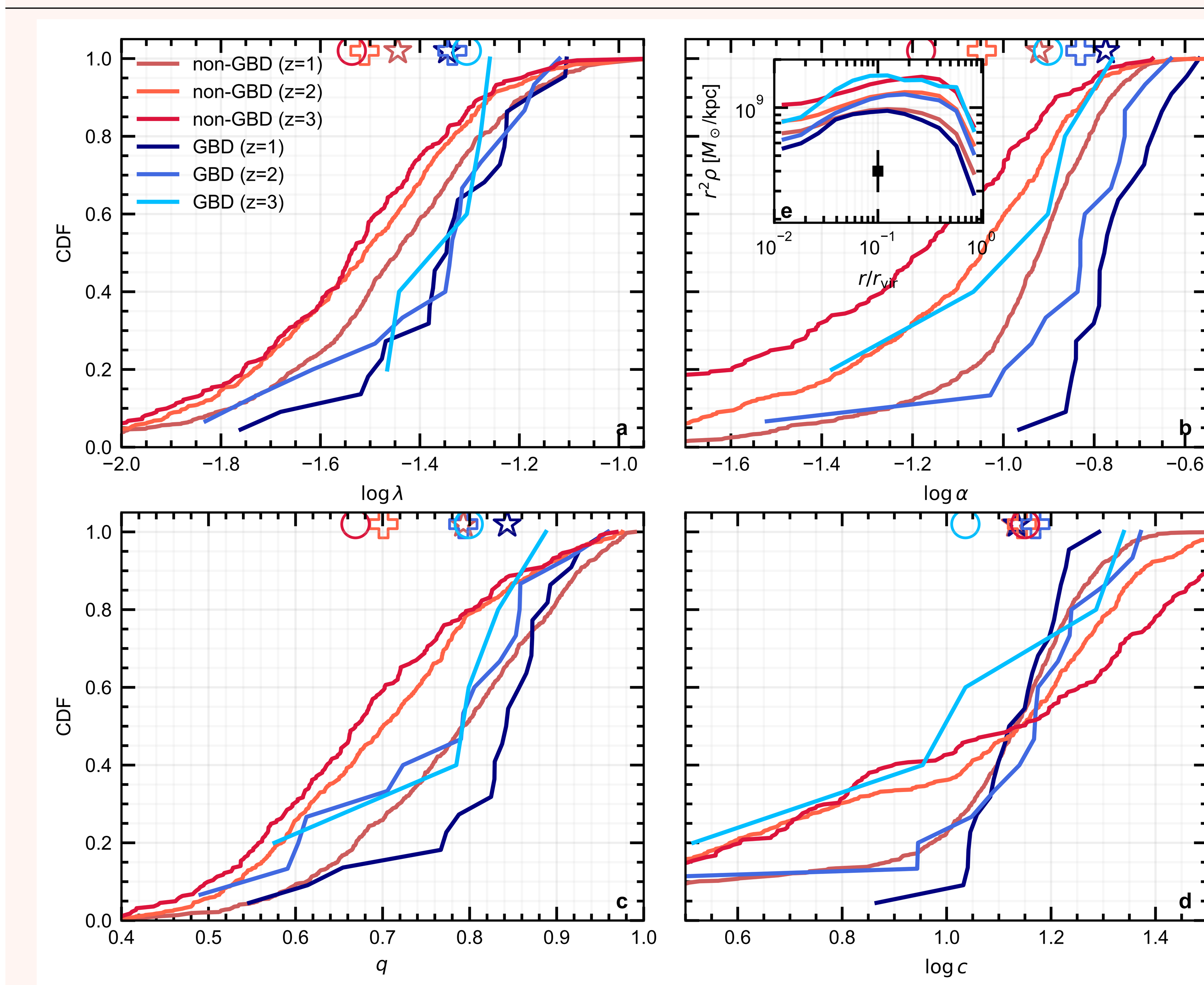

Figure 4. The cumulative distributions of halo conditions for hosting GBDs and non-GBDs at $z = 1, 2, 3$.

GBD host halos have higher specific angular momentum (**Panel a**), in line with the classical view of disc formation. GBD hosts have significantly lower central dark-matter densities (**Panel b**). The dark-matter concentration parameters of GBD halos are slightly lower (**Panel d**). Finally, the GBD halos are also much rounder and thus more relaxed, consistent with their assembly history being more quiescent except for the recent gas-rich merger (**Panel c**).

Conclusions

The formation of giant discs in the high-z universe is closely tied to their environments. Residing in dense regions of the cosmic web ensures a steady cold gas supply. Combined with lower galaxy number densities, this results in milder, earlier mergers that are gas-rich and more coherent. Consequently, their host dark matter halos remain stable. These create the conditions necessary for the emergence of GBDs in the cosmic morning.