Highlights of Spanish Astrophysics XII, Proceedings of the XVI Scientific Meeting of the Spanish Astronomical Society held on July 15 - 19, 2024, in Granada, Spain. M. Manteiga, F. González Galindo, A. Labiano Ortega, M. Martínez González, N. Rea, M. Romero Gómez, A. Ulla Miguel, G. Yepes, C. Rodríguez López, A. Gómez García and C. Dafonte (eds.), 2025

The rise of stellar bars: JWST unveils their early formation

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Abstract

Understanding the cosmic evolution of the barred galaxy population is fundamental to quantify their impact on the internal secular evolution of galaxies and dating the formation of the first dynamically cold stellar disks in the Universe. In this context, the new imaging capability provided by JWST is revolutionizing the study of high-redshift disk galaxies, unveiling their complex morphologies for the first time. In this invited contribution, I review the most recent observations of barred galaxies at cosmic noon and beyond. I discuss the first estimate of the barred fraction at $z > 2$ and the observation of stellar bars in the early Universe. Furthermore, I discuss the discovery of ceers-2112, the furthest Milky Way-like barred spiral galaxy observed to date ($z = 3.03$). I put these results in context with the recent view of disk galaxy formation emerging from the first morphological studies of high-redshift galaxies obtained with JWST observations.

1 Morphological diversity in the early Universe

Understanding galaxy morphology and the processes that shape it – such as disk formation, bulge growth, and the relationship between structure and star formation – is critical to explain galaxy formation and evolution. Over the last two decades, our understanding of galaxy structure beyond the local Universe has been deeply driven by observational campaigns using the Hubble Space Telescope (HST; e.g., [1, 2]). Targeting the ultraviolet to optical morphology of galaxies up to redshift $z \sim 2-3$, multiple studies have shown that galaxies at redshifts above $z \sim 1$ tend to appear more irregular in their light distribution than those in the present-day Universe, with peculiar structures being particularly common beyond $z \sim 2.5$

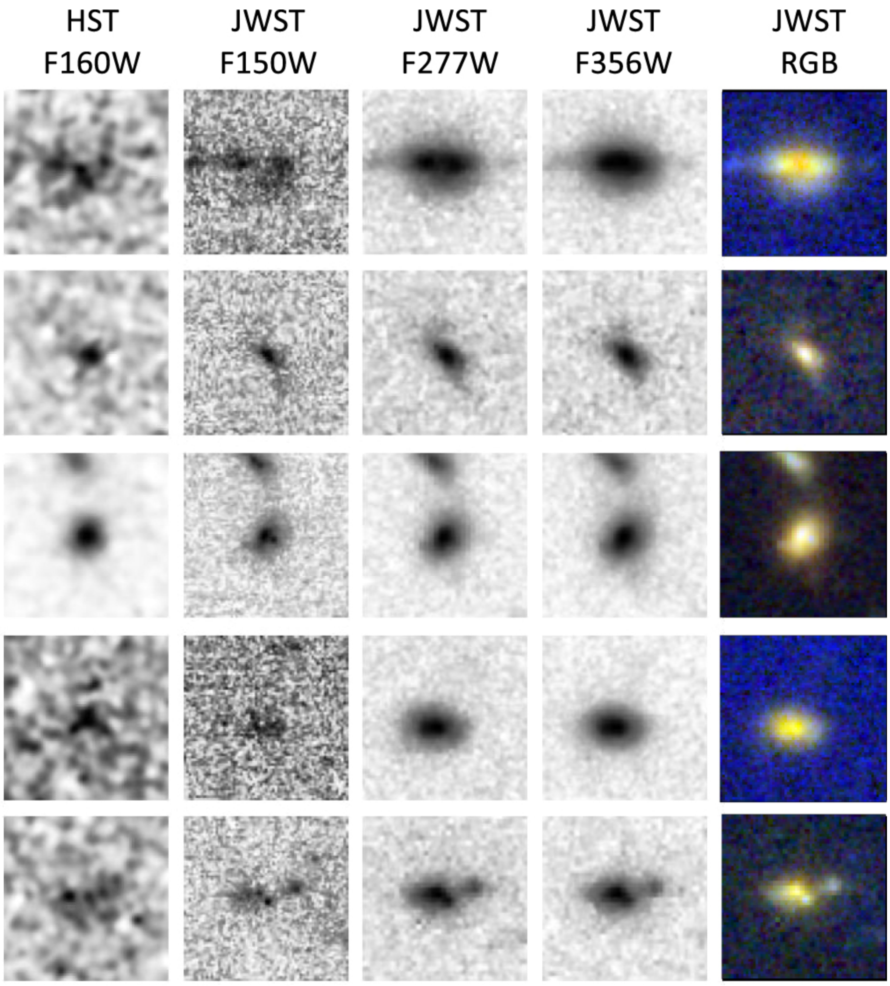

Figure 1: Postage stamps of five galaxies at $z > 3$ with different morphologies in HST WFC3 compared to JWST NIRCam images. Extracted from [11].

[3, 4]. These findings led to the interpretation that early galaxies were more chaotic and lacked the well-defined structures seen in nearby galaxies. However, there are significant limitations to HST's ability to resolve finer details at higher redshifts, primarily due to limited spatial resolution and wavelength coverage, which limit its view into the rest-frame optical light of galaxies back to within just a few billion years after the Big Bang. In this context, different morphological studies already suggested that the first complex structures could start to build up at (and beyond) cosmic noon [5, 6, 7, 8, 9].

The James Webb Space Telescope (JWST) has fundamentally transformed our capability to study the morphology of high-redshift galaxies (see Fig. 1), offering better sensitivity and spatial resolution than HST (and Spitzer). Furthermore, it enables us to target the rest-frame

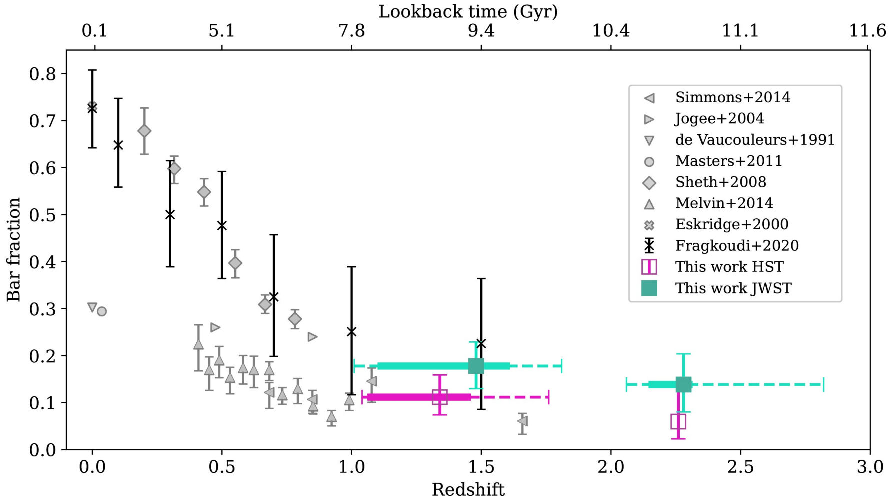

Figure 2: Evolution of the bar fraction presented in [40] (colored squares). Values inferred from JWST NIRCam images at 4.4 μm (green) are compared with those inferred from HST WFC3 images at 1.6 μm (purple). Different gray symbols represent measurements based on previous HST studies.

optical to near-infrared morphology of galaxies up to $z > 6$, unveiling the structure of the bulk of their stellar mass. In this context, recent studies using JWST have revealed that a surprising fraction of galaxies at $z > 3$ show disk-like morphologies, suggesting that galactic disks may have started forming much earlier than previously thought [10, 11, 12]. This revelation has fueled new questions about how and when galaxy diversity began to emerge and about the intrinsic nature of these high-redshift disk galaxies [13, 14, 15]. Importantly, the population of high-redshift disks could host the first complex morphologies commonly seen in the local Universe, including the first stellar bars. The detection of such complex structures at $z > 2$ poses several challenges to our current understanding of structure formation and evolution and on the timescales of such early assembling.

2 The evolution of barred galaxies across cosmic time

To better understand the role of stellar bars in galaxy evolution, we should identify their prevalence in disk galaxies across cosmic times and quantify their formation timescale.

At low redshifts ($z \sim 0$; Fig. 2), near-infrared studies find that around $\sim 70\%$ of massive disk galaxies contain a stellar bar, suggesting that they are very common structures in the local Universe [16, 17, 18]. Stellar bars play a key role in galaxy evolution since they serve as efficient drivers of internal evolution by slowly redistributing angular momentum throughout a galaxy [19, 20]. This redistribution affects baryonic and dark matter [21, 22], promoting gas inflow that can enhance central star formation and create features like bulges and nuclear disks [23, 24, 25, 26, 27]. Furthermore, stellar bars could help in feeding active galactic nuclei (AGN), even if they do not directly fuel them [28].

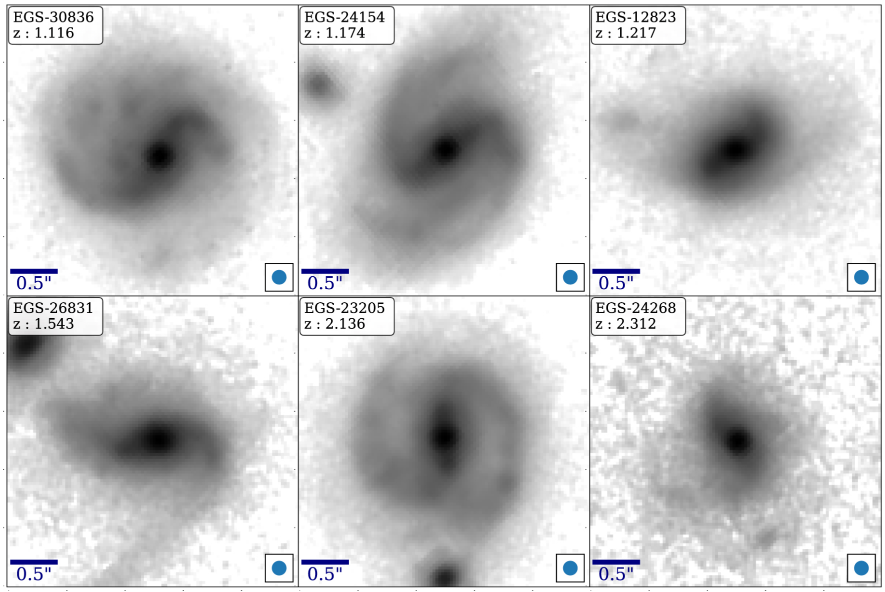

Figure 3: Six barred galaxies at $z > 1$ observed with JWST NIRCam and presented in [38].

At higher redshifts ($z \sim 1$; Fig. 2), HST studies in optical wavelengths yield mixed results on bar prevalence. Some studies report little change in bar frequency [29, 30], while others observe a significant decline [17, 31], suggesting that bar-driven evolution may not begin until about 6 Gyrs after the Big Bang. Attempts to extend bar studies to even higher redshifts ($z \sim 1.5$; Fig. 2) show a marked decrease in bar fraction, down to about $\sim$10% [32]. Some simulations agree with observational results [33, 34], showing that bars are less common in earlier stages of galaxy evolution, especially during merger-driven phases. However, in TNG50 barred galaxies are found even at $z = 6$ [35, 36, 37], but only in the very high-mass regime ($M_\star > 10^{10}\ M_\odot$).

However, identifying bars at the highest redshifts is challenging due to limitations in image depth and resolution. Bars appear smaller at higher redshifts, which may contribute to the observed decline in bar fractions, as smaller bars are harder to detect. Furthermore, the uncertain bar fraction at and beyond $z = 1$ may stem from the specific stellar mass range.

The first stellar bars observed beyond $z = 2$ were reported in [38] and are shown in Fig. 3. Six galaxies with $1.1 < z < 2.3$ were observed with JWST NIRCam in the first epoch of imaging from the CEERS survey [39]. These galaxies are very massive systems ($M_\star \sim 10^{10-11}\ M_\odot$) with quite intense star formation ($\sim 21 - 295\ M_\odot\ \mathrm{yr}^{-1}$).

Leveraging this first study, a systematic search for barred galaxies at $1 < z < 3$ was proposed by [40]. They analyzed $\sim$ 350 disk galaxies in CEERS and PRIMER, finding that the bar fraction decreases from around 18% at $z = 1$ to 13% at $z = 3$ (but see also [41]). Importantly, these values are more than twice the bar fraction observed with bluer HST filters. These results suggest that bar-driven evolution may begin earlier than previously thought, with dynamically stable disks already forming around 11 Gyrs ago.

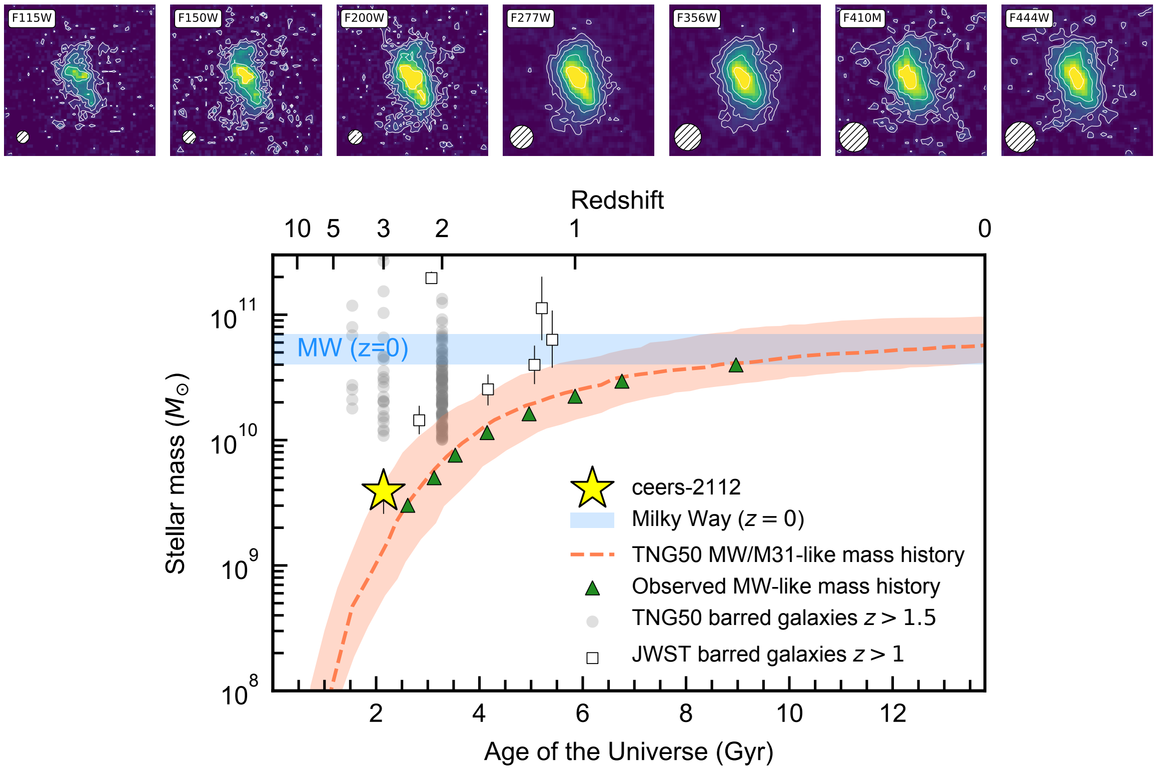

Figure 4: *Top panels:* Postage stamps of ceers-2112 in multiple NIRCam filters. *Bottom panel:* Mass accretion history of ceers-2112 (yellow stars), compared with observed (green triangles) and simulated (red dashed line) Milky Way-like galaxies. Barred galaxies observed in [38] are shown as white squares, while barred galaxies in TNG50 are shown as gray dots [37]. Adapted from [42].

3 ceers-2112: a Milky Way-like barred spiral galaxy at $z \sim 3$

While several galaxies with $M_\star > 10^{10}\ M_\odot$ have been detected using the first JWST datasets, ceers-2112 is the only Milky Way-like barred spiral galaxy observed to date beyond $z = 2$ (see Fig. 4; [42]). The galaxy was observed with JWST NIRCam during the first epoch (21–22 June 2022) of the CEERS campaign [39, 43]. The morphological modeling of the surface brightness reveals the presence of a stellar bar with strength $S_{\rm bar} = 0.23 \pm 0.01$ and length $r_{\rm Ferrers} = 0.42 \pm 0.03$ arcsec (3.3 kpc). The galaxy has a photometric redshift of $z = 3.03^{+0.04}_{-0.05}$, stellar mass of $M_\star = 4 \times 10^9\ M_\odot$, and mass-weighted age of 620^{+150}_{-160} Myr. As shown in Fig. 4, the mass assembly history of ceers-2112 tells us that it can be considered the furthest barred galaxy consistent to be a progenitor of the Milky Way.

This discovery challenges cosmological models predicting that stellar bars are nearly absent in the progenitors of Milky Way-like galaxies at $z > 1.5$ [44, 45]. Given that stellar bars are expected to form over timescales longer than 1 Gyrs [46], ceers-2112 also raises significant questions about current models of bar formation. As discussed in [47], the timescale of bar formation puts strong constraints on the fraction of baryonic over dark matter in the central regions of galaxies as well as the fraction of turbulent gas present at these early times. Thus, galaxies like ceers-2112 could be found only if baryons dominate over dark matter already at $z \sim 3$. Finally, the discovery of ceers-2112 proves that dynamically cold stellar disks could have been in place by redshift $z > 5$, providing a complementary route to confirm previous ALMA results targeting only the gaseous component of high-redshift galaxies and reporting rotationally-supported disks at $z > 4$ and as early as $z \sim 7$ [48, 49].

4 Final remarks and future perspective

The surprising evidence of well-developed stellar and gaseous disks at high redshifts (up to $z \sim 7$), and the observation of stellar bars up to $z > 3$ (even with $M_\star < 10^{10}\ M_\odot$ such as ceers-2112), represents a major challenge in extragalactic astronomy since it was non anticipated in existing theoretical frameworks. From the theoretical side, cosmological simulations have been struggling during the last two decades with an "overcooling problem", where too many baryons are concentrated in the central regions of galaxies. To address this, feedback mechanisms were introduced to redistribute baryons across larger scales. In this context, the discovery of stellar bars in high-redshift disk galaxies suggests the existence of baryon-dominated galaxies as early as $z > 3$, which is difficult to reconcile with current recipes implemented in some of the models. From the observational side, our knowledge of high-redshift disks remains limited. Even in the JWST and ALMA era, barred galaxies at $z > 3$ are at the observational edge of the sensitivity of such observatories. Notably, spectroscopic observations targeting the rest-frame optical and/or near-infrared stellar distribution of high-redshift disks are currently unavailable. This limitation is expected to be addressed in the coming years, with more galaxies observed by JWST. The first IFU dataset targeting two barred galaxies at $z > 1$, namely EGS-24154 and EGS-24154, will soon be available as part of JWST GO3 program 5766 (PI: Cuomo). These observations will put stringent constraints on the evolution of the dynamical status of barred galaxies across cosmic time, limiting the nature (or even existence) of dark matter in galaxies.

Acknowledgments

The project that gave rise to these results received the support of a fellowship from the "la Caixa" Foundation (ID 100010434). The fellowship code is LCF/BQ/PR24/12050015. LC acknowledges support from grants PID2022-139567NB-I00 and PIB2021-127718NB-I00 funded by the Spanish Ministry of Science and Innovation/State Agency of Research MCIN/AEI/10.13039/501100011033 and by "ERDF A way of making Europe".

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