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A. Siebert, K. Baillié, M. Béthermin, F. Cantalloube, E. Josselin, N. Lagarde, J. Malzac, J. Richard, L. Selliez, O. Venot (eds)

NEW INSIGHTS ON THE FIRST STARS AND GALAXIES FROM THE JAMES WEBB SPACE TELESCOPE

N. Laporte[1]

Abstract. Since its launch on December 25, 2021, from the Guiana Space Centre, the *James Webb* Space Telescope (JWST) has pushed the frontiers of astronomy, enabling unprecedented discoveries such as the detection of the most distant galaxy ever observed (at redshift $z > 14$), the identification of the most distant AGN, and potential evidence of the first generation of stars. However, these breakthroughs have also raised significant questions. In particular, JWST has revealed a surprisingly large population of massive galaxies at very early cosmic times, less than 300 million years after the Big Bang, a result that challenges predictions of the standard cosmological model. In this contribution, I present recent JWST findings on the physical properties of early galaxies and discuss leading hypotheses proposed to explain this unexpected abundance. These include variations in star formation efficiency, the star formation histories of primordial galaxies, and possible deviations in the initial mass function.

Keywords: Galaxies: high-redshift, Cosmology: early Universe, Galaxies: distances and redshifts

1 Introduction

One of the most exciting challenges in modern extragalactic astronomy is the quest to explore the Cosmic Dawn. This quest began in the 1950s, when the most distant known galaxy was identified at a redshift of $z \sim 0.8$ (Humason et al. 1956). Since then, the development of large ground- and space-based observatories has steadily pushed back the observational frontier, culminating in the achievements of the *Hubble* Space Telescope (HST). With wavelength coverage extending up to 1.6 μm, HST has detected galaxies up to $z \sim 12$. The most distant galaxy identified with Hubble lies at $z \sim 11.9$ (Ellis et al. 2013), confirming both the telescope's ability to reach the edge of its sensitivity and suggesting that the Cosmic Dawn likely occurred at even higher redshifts, beyond $z \sim 12$, within the first 400 million years after the Big Bang (Figure 1). Continuing this search required an instrument capable of probing longer wavelengths than HST. This was one of the primary scientific motivations behind the development of the *James Webb* Space Telescope (JWST).

JWST is a 6.5-meter space telescope located at the second Lagrange point (L2), equipped with four instruments covering the 0.6-28 μm range: the Near Infrared Imager and Slitless Spectrograph (NIRISS) (Doyon et al. 2023), the Near Infrared Spectrograph (NIRSpec, $R \sim 2400$) (Jakobsen et al. 2022), the Near Infrared Camera (NIRCam) (Rieke et al. 2023), and the Mid-Infrared Instrument (MIRI) (Wright et al. 2023). JWST addresses key scientific questions such as the characterization of exoplanet atmospheres (JWST Transiting Exoplanet Community Early Release Science Team et al. 2023), planet formation processes, and the nature of the first stars. The nominal mission duration was five years, but the efficient Ariane 5 launch preserved enough fuel for a possible extension to over a decade.

After more than three years of operation, JWST has already had a large impact on extragalactic astronomy. One measure of this influence is the number of related papers submitted daily to arXiv in the extragalactic category (Figure 2). While the overall submission rate has steadily increased, a clear surge followed the first JWST data release in July 2022. On average, about 10% of daily extragalactic submissions now include JWST data. In this review, I highlight several key results obtained during JWST's first three years, focusing on galaxies within the first billion years of cosmic history.

[1] Aix Marseille Univ, CNRS, CNES, LAM, Marseille, France

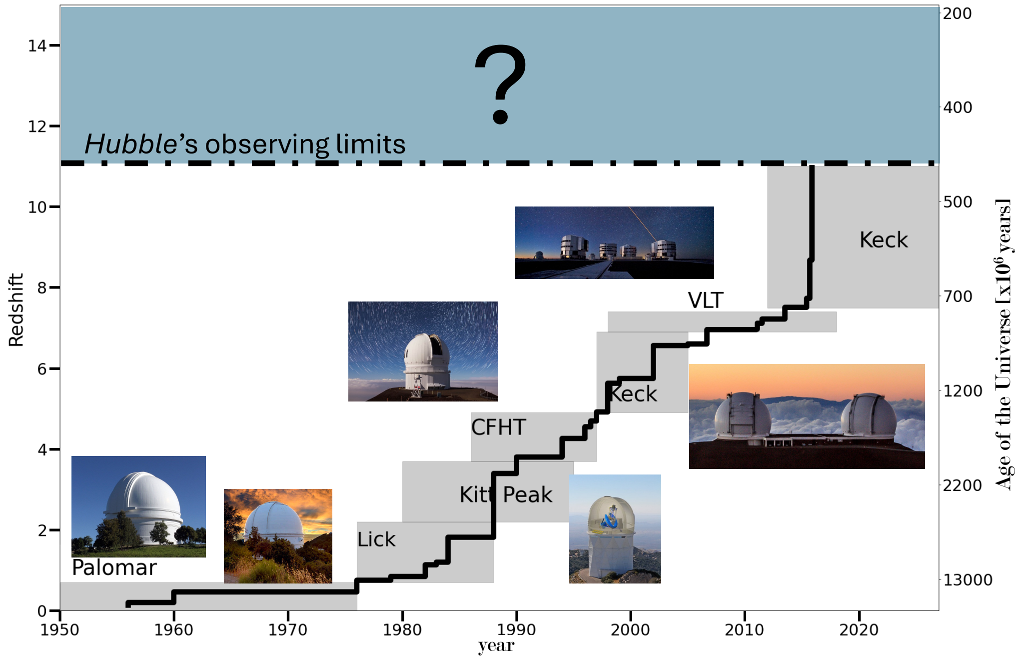

Fig. 1: **The quest for Cosmic Dawn**: The most distant spectroscopically confirmed galaxies over time. Before JWST, the *observational frontier* was set by HST's capabilities at $z \sim 11$. After nearly seven decades of searching, a new instrument capable of observing at longer wavelengths was essential.

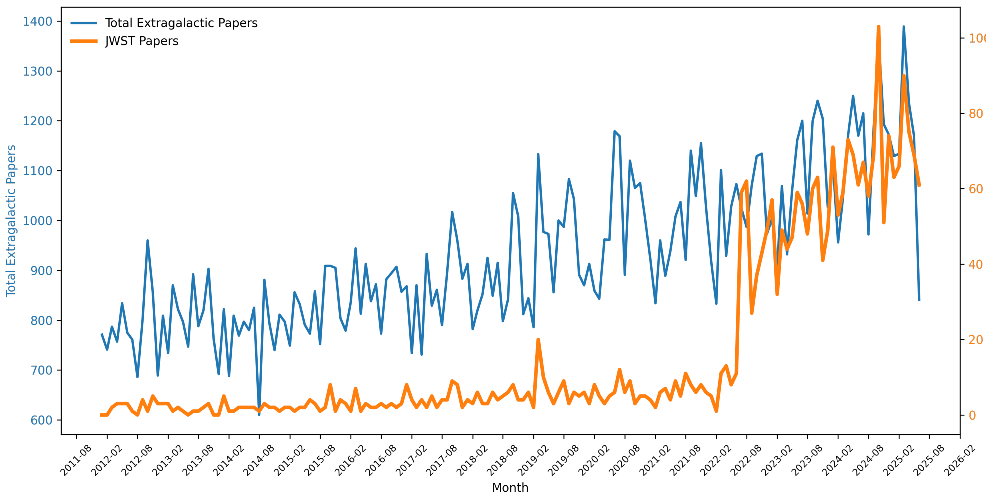

Fig. 2: **Evolution of the number of preprints submitted to arXiv**: Time evolution of extragalactic submissions (blue) compared to those using JWST data (orange), identified by the presence of "JWST" in either the title or abstract. A clear rise is seen following the first public data release in July 2022.

2 Key JWST results on primeval galaxies

In this section, I discuss results in four main areas: the properties of the most distant galaxies, the presence of AGN at very high redshift, the environments of primeval galaxies, and the detection and properties of the first population of stars*.

*Given the number of publications in these areas, this review does not claim to cover them exhaustively.

2.1 *The properties of the first galaxies*

Less than five months after JWST began science operations, the record for the most distant spectroscopically confirmed galaxy was broken with a $z = 13.2 \pm 0.1$ source (Curtis-Lake et al. 2023) from the JADES GTO survey (Eisenstein et al. 2023). As of June 2025, the current record-holder lies at $z = 14.44 \pm 0.02$ (Naidu et al. 2025), with a luminosity two orders of magnitude above $L^{\star}$ at $z \geq 10$ ($M_{UV} = -20.23 \pm 0.06$) and a stellar mass of $\log M_{\star} = 8.1^{+0.3}_{-0.2}$, making it an outlier compared to typical galaxies at such redshifts. While several photometric candidates have been reported at $z \geq 15$ (e.g., Pérez-González et al. 2025, Castellano et al. 2025, Gandolfi et al. 2025), none has yet been spectroscopically confirmed, suggesting we may be approaching JWST's observational limit.

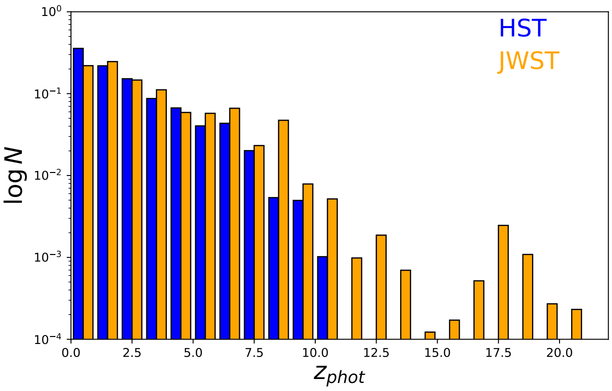

Fig. 3: **Comparison of $z_{\rm phot}$ ranges for HST and JWST**: Normalised photometric redshift distributions from the *Hubble* Frontier Fields survey and the first JWST extragalactic surveys from the *AstroDeep* project (Merlin et al. 2016, 2024).

Beyond the search for the most distant galaxies, JWST has now built a large sample of photometrically selected galaxies beyond *Hubble*'s limits, i.e., $z \geq 12$ (Figure 3). These samples allow, for the first time, constraints on the UV luminosity function less than 500 million years after the Big Bang (Donnan et al. 2024; Finkelstein et al. 2024; Harikane et al. 2025). Preliminary results indicate an overabundance of bright galaxies at very high redshift compared to expectations from the latest *Hubble* results (Figure 4). Several hypotheses are currently discussed to explain this overabundance of $z \geq 10$ galaxies.

Possible explanations include higher star formation efficiencies (SFE) in primeval galaxies, potentially exceeding 50% (Labbé et al. 2023; Xiao et al. 2024). However, models suggest no significant evolution of SFE with dark matter halo mass (Donnan et al. 2025; Shuntov et al. 2025). Another hypothesis is that the star formation histories (SFH) of primeval galaxies may be stochastic, biasing number density estimates (Ciesla et al. 2024), though this effect alone may be insufficient (Carvajal-Bohorquez et al. 2025). Tentative evidence for a top-heavy Initial Mass Function (IMF) has also been seen, but a larger spectroscopic follow-up campaign is needed (Cameron et al. 2024). A small fraction of low-z interlopers has also been considered, but contamination rates appear very low (Hainline et al. 2024).

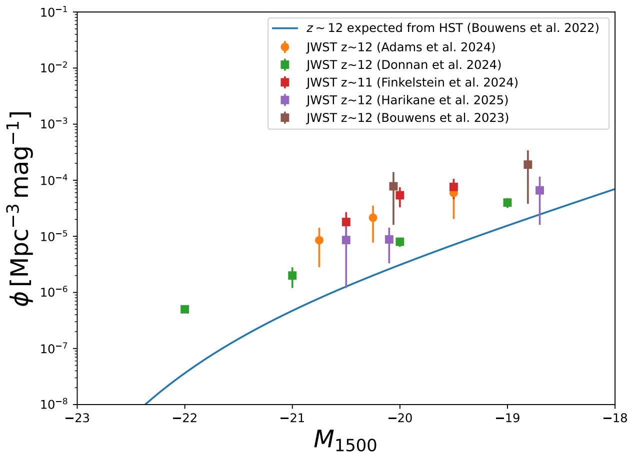

Fig. 4: **Number densities at $z \sim 12$ found by JWST compared with expectations from HST**: The blue curve extrapolates the UV LF evolution from Bouwens et al. (2022) to $z \sim 12$. Coloured points are number densities from Adams et al. (2024); Donnan et al. (2024); Finkelstein et al. (2024); Harikane et al. (2025); Bouwens et al. (2023), showing an overabundance relative to HST expectations.

JWST has also revealed a new class of faint objects undetected by *Hubble*: the Little Red Dots (LRDs - Matthee et al. 2024). These are extremely compact (< 0.2 kpc) and display a "V-shaped" spectral energy distribution, with a very blue UV rest-frame slope and a red optical rest-frame slope (Kokorev et al. 2024). A non-negligible fraction show evidence of AGN activity (Taylor et al. 2025).

2.2 The origin of the first supermassive black holes

One of JWST's most striking early results is the discovery of supermassive black holes less than 500 million years after the Big Bang. The first example was GNz11 (Maiolino et al. 2024a), whose detected emission lines ([NeIV]λ2423 and CII*λ1335) suggest gas densities typical of the broad-line regions of AGN. Since then, dozens of AGN have been identified at $z \geq 5$, with estimated black hole masses ranging from 10^6 to 10^9 $M_\odot$ (Scholtz et al. 2025; Juodžbalis et al. 2025). Their rapid growth challenges standard Eddington-limited accretion models.

Recently, Maiolino et al. (2025) identified an AGN at $z \sim 7.04$ with a metallicity below 0.01 $Z_\odot$. They argue that such low metallicity can only be explained if the black hole is primordial, i.e. formed very shortly after the Big Bang. Other AGN at high redshift show much higher metallicities (Larson et al. 2023), suggesting multiple formation channels (Figure 5). Among all AGN candidates identified by JWST, one lensed source shows a 4.2σ X-ray detection in the *Chandra* 2-7 keV band at $z \sim 10.1$, with a black hole mass of $M_{\rm BH} \sim 10^7$-10^8 $M_\odot$ (Goulding et al. 2023; Bogdán et al. 2024).

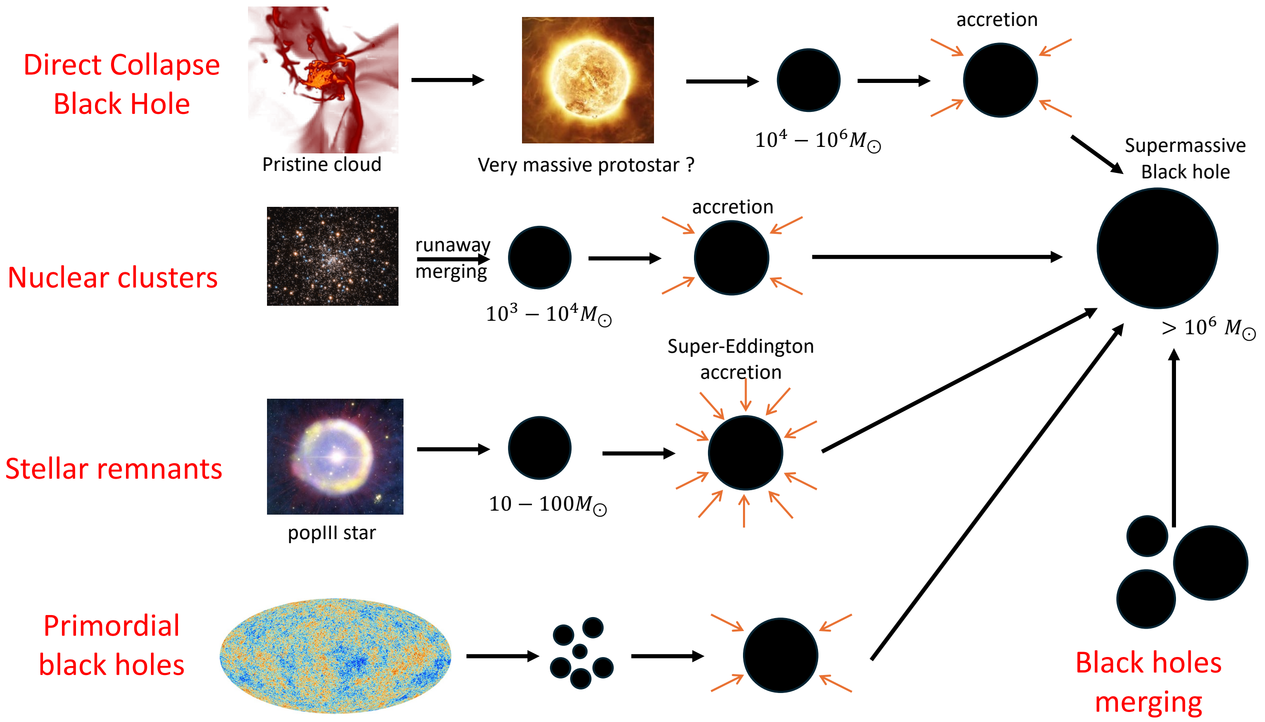

Fig. 5: **Formation mechanisms of supermassive black holes in the early Universe**: All proposed channels lead to $M_{\rm BH} > 10^6 M_\odot$. Adapted from a figure courtesy of Roberto Maiolino.

2.3 The environment of primeval galaxies

Thanks to its larger mirror compared to HST, JWST can detect fainter galaxies at early epochs, enabling studies of the environments of massive systems. This allows testing whether they are isolated or part of protoclusters, and constraining the dark matter halo masses of the first large-scale structures. Simulations predict protoclusters at $z \geq 7$ to span over 10 cMpc ($\sim 4'$), exceeding a single JWST pointing, but their cores are < 1 cMpc ($\sim 25''$), fully accessible to JWST.

Several protocluster candidates have been identified either photometrically (Laporte et al. 2022; Li et al. 2025; Scholtz et al. 2024) or spectroscopically (Morishita et al. 2023; Witten et al. 2025), though all were found serendipitously. A systematic search is needed to assess their abundance and role in reionisation. Tran Van Nhieu et al. (in prep.) use a Voronoi tessellation method to identify protocluster candidates and estimate their dark matter halo masses (Figure 6). The derived masses over cosmic time match predictions for the evolution of a Coma-like cluster.

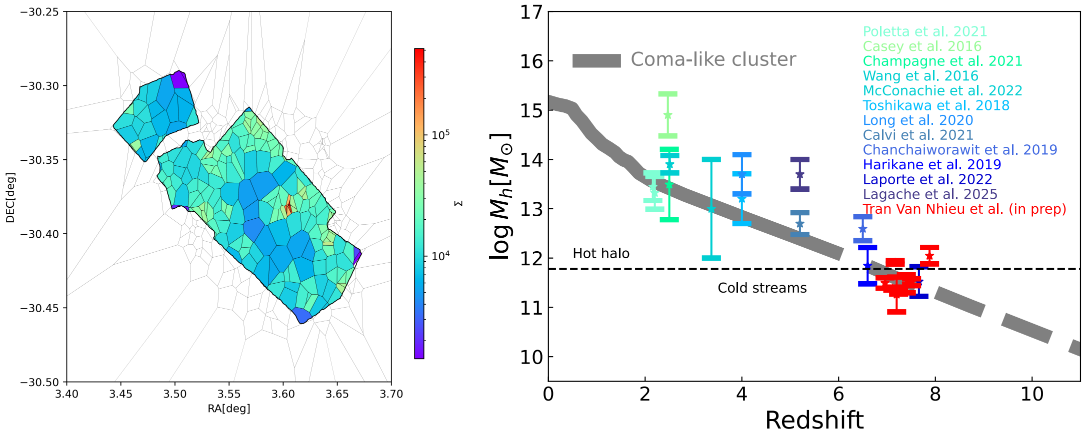

Fig. 6: **Searching for protoclusters in the early Universe**: (*Left*) Example of a Voronoi tessellation map highlighting a protocluster (red). (*Right*) Dark matter halo masses of known protoclusters compared to simulation predictions for a Coma-like cluster.

2.4 The first population of stars

A major goal in modern extragalactic astronomy is the identification of the first, metal-free (Pop III) stars. Formed from pristine gas, these are expected to be very massive ($\geq 1000\,M_\odot$) with short lifetimes of only a few tens of Myr (Klessen & Glover 2023). Their low metallicity ($< 0.01\,Z_\odot$) means they can be selected by spectra showing strong hydrogen (e.g., Lyα, Hα) and helium lines, but no metal lines (Trussler et al. 2023). Several candidates have been reported by JWST (e.g. Vanzella et al. 2023; Maiolino et al. 2024b; Fujimoto et al. 2025), though deeper spectroscopy will be required for confirmation.

3 Conclusions

After more than three years in operation, JWST has already profoundly challenged our understanding of galaxy formation and evolution within the first billion years of cosmic history. The most surprising result is undoubtedly the presence of AGN in the Universe as early as 300 million years after the Big Bang, challenging current models for the formation and growth of the first massive black holes. Our picture of the properties of the first galaxies, shaped by *Hubble* observations, has also been strongly revised in light of the first JWST results: the star formation efficiency of primeval galaxies may be higher than previously thought, and the rate at which the first galaxies form stars may not be continuous but rather bursty. Both factors could help to explain the overabundance of very high-redshift galaxies now observed. However, all these results are still preliminary and will require larger spectroscopic follow-up campaigns. Despite its remarkable capabilities, JWST has limitations. The most critical is its relatively small field of view ($\sim 4'^2$), requiring multiple pointings to build large samples and mitigate cosmic variance. Its spectral resolution ($R \leq 2700$) also limits the detection of faint, narrow emission lines. Both limitations will be addressed by the Extremely Large Telescope (ELT; Gilmozzi & Spyromilio 2007) in the coming decade. ELT's MOSAIC spectrograph will offer a $\sim 50'^2$ field of view (Pelló et al. 2024), while HARMONI (Thatte et al. 2021) and METIS (Brandl et al. 2021) will provide resolutions up to $R \sim 20,000$ and $R \sim 100,000$, respectively. First light is expected around 2028, with scientific operations starting by the end of the decade. In the extragalactic domain, JWST-ELT synergies will be crucial for conducting large spectroscopic follow-up campaigns of JWST-selected targets, enabling the characterisation of early galaxies in terms of metallicity, environment, AGN activity, and the nature of the first stars.

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