JWST AND LENSING GALAXY CLUSTERS: REACHING FOR GALAXIES IN THE EARLY UNIVERSE

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How did galaxies form? How have they evolved over cosmic time? These are two central questions that astronomers have investigated now for decades through extragalactic studies. While the existence of galaxies beyond the Milky Way was recognised nearly a century ago, it was not until the 1990s with the launch of the Hubble Space Telescope (HST) that astronomers were able to systematically study distant galaxies and explore their properties and evolutionary histories.

HST revolutionised the field with its remarkable sensitivity and high-resolution imaging and spectroscopic capabilities, allowing astronomers to observe galaxies far beyond the Local Group (the group of galaxies that includes the Milky Way). This enabled astronomers to conduct studies of galaxy formation and evolution via the so-called look-back approach: by observing the light of distant galaxies, astronomers effectively travel back in time, as the light from these galaxies takes billions of years to reach us. This provides a glimpse of how galaxies appeared in the distant past. Hence, by comparing galaxies at various distances, which represent different moments in the universe's timeline, astronomers can map the formation and evolution of galaxies across cosmic history.

HST's Deep Field observations, beginning with the Hubble Deep Field (HDF) in 1995 [1], provided an unprecedented view into the early universe. Among HST's groundbreaking discoveries were EGSY8p7 at redshift $z = 8.7$ [2] and GNz11 at $z = 11$ [3], at the time the two most distant galaxies observed just 600 and 400 million years after the Big Bang, respectively. Despite these remarkable achievements, the depth of HST observations was still limited. HST could only detect a handful of galaxies in the early stages of cosmic evolution, primarily the brightest, most massive, and less dusty sources. This introduced, however, a potential bias in our understanding of the properties of the young universe.

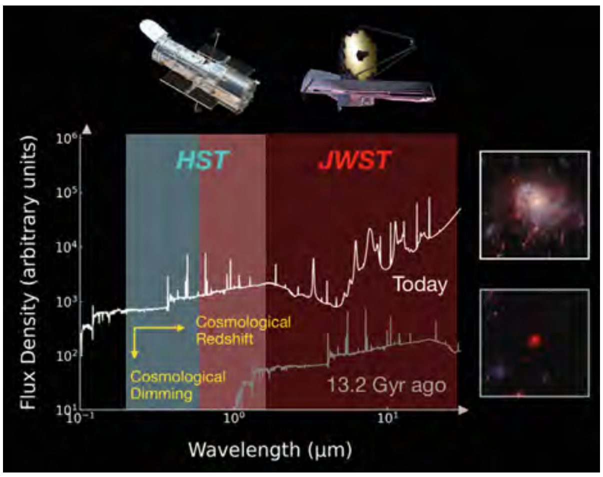
To push the detection limits further, initiatives such as the Hubble Frontier Fields [4] exploited gravitational lensing, an effect predicted by Einstein's General Relativity where light from distant galaxies is magnified by the gravity of intervening galaxy clusters. This technique allowed HST to detect even fainter, more distant galaxies than in traditional blank field surveys (regions devoid of bright foreground objects, thus ideal for deep observations, such as the HDF). These efforts significantly expanded the observed range of galaxies, allowing astronomers to study a wider range of galaxy types, including the lower-mass end of the population (*i.e.* below a billion times the solar mass), thus opening a new window into the early universe and demonstrating the power of galaxy clusters as natural cosmic magnifying lenses (*e.g.* [5][6]).

However, despite its contributions, HST's ability to detect the universe's earliest galaxies was constrained by its wavelength range (0.2–1.6 μm). As the universe expands, light from the most distant galaxies is stretched (redshifted) into longer wavelengths, a phenomenon known as cosmological redshift. Concommitantly, due to the greater distance of these objects, their flux gets dimmer. Due to these reasons much of the light of distant galaxies is moved beyond HST's observational range, leaving the bulk of the earliest galaxy population hidden from view.

Figure 1 illustrates how astronomers observe the light emitted from galaxies at various stages of the history of the universe (today and 13.2 Gyr ago), leveraging the capabilities of both HST and JWST. The graphic demonstrates the effect of cosmological redshift, where light from galaxies is stretched to longer wavelengths as the universe expands, as well as the dimming that makes distant galaxies fainter and harder to detect. The shaded areas correspond to the wavelength ranges covered by these telescopes, illustrating their complementary roles in the study of galaxy evolution. HST, operating primarily in the ultraviolet to near infrared, is limited in its ability to detect galaxies at extreme distances, while JWST, with its extended infrared capabilities, can observe much earlier stages of galaxy formation.

The James Webb Space Telescope (JWST) was designed to do this. Equipped with advanced infrared instruments, such as the Near-Infrared Camera (NIRCam) and the Mid-Infrared Instrument (MIRI), JWST can observe light red-shifted into the infrared (0.7–28 μm), revealing even more distant galaxies than HST. Its extended wavelength range and superior sensitivity and resolution have opened a new era in the study of galaxy formation and evolution, enabling observations of the faintest and farthest objects in the universe. Among the first images released by JWST in July 2022 as part of the Early Release Observations (ERO) program [7], the galaxy cluster SMACS J0723.3–7327 was targeted. These observations led to several groundbreaking discoveries, including the detection of a statistical robust sample of extremely distant galaxies ($z = 9 - 16$), some securely confirmed thanks to spectroscopy while others remains as candidates [8-11]. Detailed analyses of their physical properties, structures, and star formation rates reveal that, while most of these galaxies are characterized by low masses, young stellar populations, and strong bursts of star formation [12], some unexpectedly exhibit higher masses and older stellar populations. This suggests that evolved stellar populations existed even within the first 300 million years after the Big Bang ($z \geq 10$) [11], potentially challenging existing evolution models and sparking significant debate within the astronomical community. In addition, JWST's observations uncovered some of the most distant globular clusters ever observed (*e.g.*, 13]) offering clues to the formation of the still elusive first stars (Population III), the first sources to shine in the universe and that are thought to have constituted the seeds for the formation of the following stellar populations and galaxies.

▾ **FIG. 1:** Image of the HST and artistic rendition of JWST from NASA (see text).



Following the success of the ERO program, JWST has continued targeting several well-known galaxy clusters, including the extensively studied Abell 2744 (Figure 2). In the figure a crowded galaxy field is visible on a black background with one large star dominating the image just right of center. Three areas are concentrated with larger white hazy blobs on the left, lower right, and upper right above the single star. Scattered between these areas are many smaller sources of light; some also have a hazy white glow, while many other are red or orange. These observations, have led to significant findings, not only extending the sample of distant galaxies observed and enlarging the population of faint, low-mass galaxies that were previously inaccessible, but also revealing the presence of a protocluster (z = 7.9)[12]) and numerous galaxy overdensities at different cosmic epochs (z = 2 – 10) that provide crucial insights into the build-up of galaxies and the impact that environment has on shaping galaxy properties (*e.g.* [14]). Moreover, JWST observations in Abell 2744 have unexpectedly revealed a new class of objects, the so-called Little Red Dots (*e.g.* [15]) whose nature is still debated and is currently puzzling astronomers. Through both imaging and spectroscopic surveys, JWST is not only allowing astronomers to map the distribution of distant galaxies but also to study their physical properties in detail and discover new classes of objects. Furthermore, by leveraging gravitational lensing, JWST enables unprecedented insights into the formation and evolution of galaxies in the early universe, particularly those of low- and intermediate-mass galaxies that would otherwise be beyond our current observational reach and is opening doors to the discovery of new, unexpected objects. ■

About the Author

E. Iani is an astrophysicist specialising in Galaxy Formation and Evolution, with a strong focus on the study of lensing galaxy clusters and distant galaxies. He is member of the European Consortium for the JWST/MIRI instrument and principal Investigator of two successful medium size JWST proposals that targeted lensing galaxy clusters. Currently a postdoctoral researcher at the Kapteyn Institute of Groningen.

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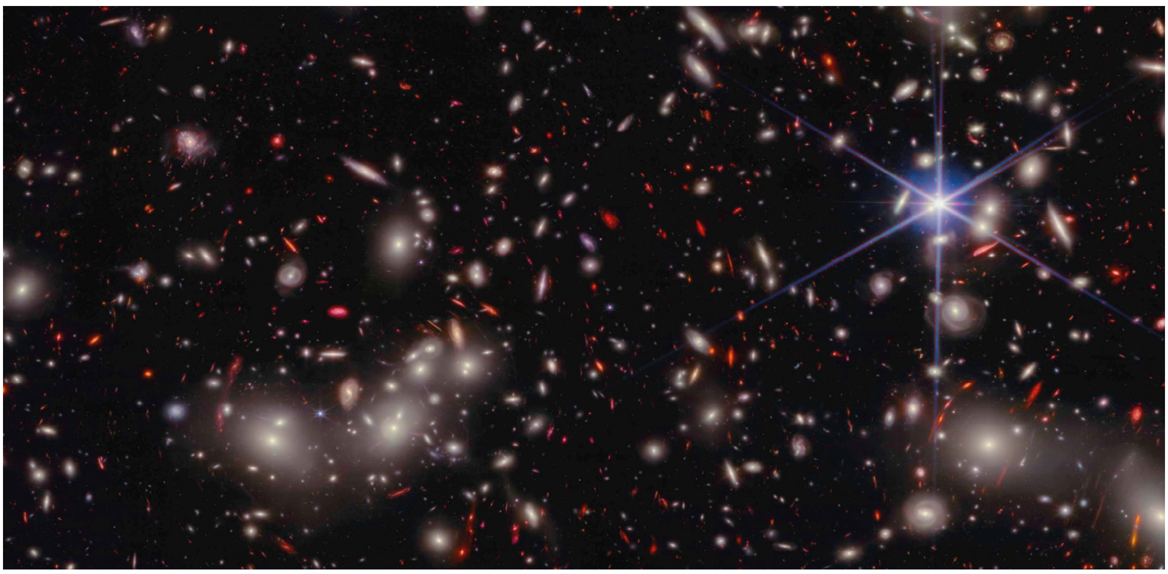

▸ **FIG. 2:** Central region of the Abell 2744 galaxy cluster as observed by the JWST NIRCam instrument (see text). Credits: NASA, ESA, CSA, I. Labbe (Swinburne University of Technology), R. Bezanson (University of Pittsburgh), A. Pagan (STScI).