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Divide et Impera: Galaxy Assembly in the Early Universe from NIRSpec/IFU Observations of ALMA/REBELS Galaxies

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Abstract

The discovery in JWST data of numerous bright galaxies at Cosmic Dawn, along with the identification of potentially "Universe-breaking" massive galaxies, is reshaping our understanding of galaxy formation, raising questions about how rapidly galaxies assembled their mass in the early Universe. In parallel with follow-up studies, significant progress can be achieved by characterizing the brightest and most massive galaxies observed when the universe was $\sim 200 - 400$ million years older, likely the most immediate descendants of the tantalizing objects observed at $z > 10$. In this talk, we will present the first results from a NIRSpec IFU R100 program targeting 12 bright, especially high-mass galaxies at approximately 750 Myr of cosmic time ($6.5 < z < 8.5$). Remarkably, this sample also benefits from [CII] and dust continuum estimates from the recent ALMA large program REBELS, making this a unique sample in the panorama of high-redshift studies. Leveraging the JWST's high spatial and spectral resolution across a broad wavelength range, from the rest-frame UV to rest-frame optical, we can reconstruct spatially-resolved maps of their stellar and gas content. These maps enable us to interpret them in terms of in-situ mass assembly, merger-driven star formation, and star-formation history. We will also provide a brief outlook on their formation histories as inferred from gas-phase metallicities. These results will ultimately allow us to assess the star formation efficiency in massive galaxies at early epochs.

In the pre-JWST era, several studies suggested that galaxies assembled their stellar mass at the same rate as their host halos accreted dark matter (e.g., [23, 28]). The groundbreaking resolution and sensitivity of JWST/NIRCam at near-infrared wavelengths have opened a new window onto the early Universe. One of the most surprising findings has been the discovery of numerous luminous galaxy candidates at $z \gtrsim 10$ (e.g., [21, 16, 5, 10, 13, 2, 1, 12, 24, 9]). The improved spatial resolution and sensitivity now allow for more accurate assessments of the stellar populations of these early galaxies through their rest-frame optical emissions.

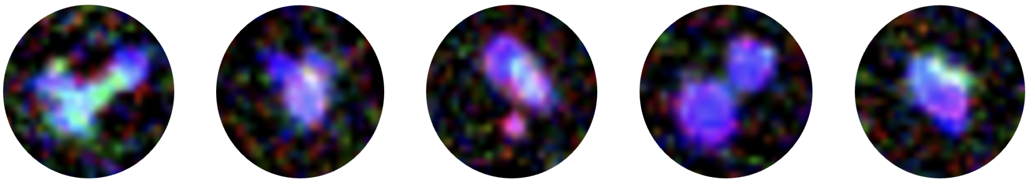

Figure 1: Illustration of the variety of physical processes in massive star-forming galaxies at $z \sim 7$. Represented are false-color stamps of five sources from the REBELS sample with IFU coverage, constructed combining the Hα, rest-frame optical and rest-frame UV light. The diameter of the stamp is about 6 kpc.

Remarkably, the first batch of NIRCam observations already revealed exceptionally massive ($M_\star > 10^{10} M_\odot$) galaxies at $z \gtrsim 8$ (e.g., [18]), indicating a highly dynamic Universe in the initial stages of galaxy formation. While models do predict the existence of such bright galaxies (e.g., [20, 19, 29, 31]), they suggest a much lower frequency than what is observed.

1 A unique sample of exceptionally bright, star-forming galaxies at $z \sim 7$ with ALMA and JWST/IFU observations

Studying sources at slightly later epochs can provide significant progress in understanding early galaxy formation, complementing current probes at the highest redshifts. The brightest and most massive galaxies identified thus far are particularly promising targets. The Re-ionization Era Bright Emission Line Survey (REBELS; [4])—an ALMA Cycle 7 Large program—targets 40 exceptionally bright galaxies ($M_{\mathrm{UV}} \sim -22$ mag) candidates at $6.5 \lesssim z \lesssim 8.5$. These galaxies were selected from 6.5 square degrees of deep optical, NIR, and Spitzer data, primarily in the COSMOS/UltraVISTA and VIDEO/XMM fields. REBELS has confirmed 26 of these galaxies at $6.5 < z < 7.5$ via [CII]$\lambda158\mu$m spectral scans, with dust emission detected in 18. The mass and luminosity of these galaxies align with being descendants of the exceptionally bright galaxies recently found at $z \gtrsim 10$, making them ideal for studying galaxy assembly efficiency in the early Universe. Comparisons of the spatial distribution of [CII], dust continuum, and rest-frame UV light reveal a wide range of physical conditions: massive dusty neighbors hidden from rest-UV detection (e.g., [14]), spatial offsets between dust continuum, [CII], and rest-UV emission, clumpy morphologies, merger events, gradients in dust continuum and [CII] emission, and potential outflows.

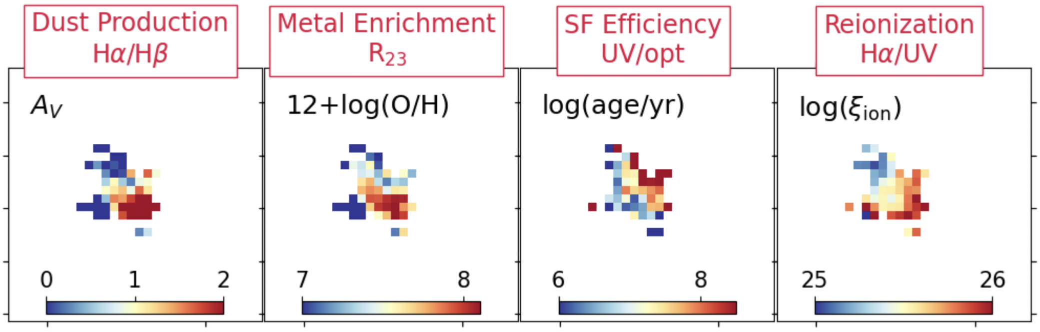

Figure 2: Illustration of the diversity of information provided by the IFU data. Each panel refers to a different physical observable, as labelled at the top. These maps indicate a complex interaction of physical mechanisms that are simultaneously occurring in massive $z \sim 7$ galaxies at the epoch of observation and in their past, without any single process being predominant.

In JWST Cycle 1 GO program 1626 (PI: Stefanon), 12 of these galaxies were observed with 30-minute NIRSpec/IFU Prism integrations, covering the $0.9 - 5.3\mu$m range (rest-frame UV to Hα). Figure 1 shows false-color images of five of these sources, combining Hα, rest-frame optical, and rest-frame UV light. These images reveal diverse morphologies and evolutionary stages within each galaxy's structure.

Figure 2 showcases the depth of information available from the IFU cubes, highlighting several analyses enabled by this dataset. With simultaneous Hα and Hβ coverage, we can create spatially-resolved dust extinction maps via the Balmer decrement. Detection of [OII]λ3727 and the [OIII] doublet at $\lambda \sim 5000$Å allows for gas-phase metallicity measurements. Comparing rest-frame UV emission, tracing recent star formation ($\sim$ 200 Myr; e.g., [17]), with rest-frame optical light from evolved stellar populations (a stellar mass proxy) offers insights into the efficiency of stellar mass assembly. Additionally, comparing Hα emission intensity with rest-frame UV (e.g., [3]) helps probe ionizing field intensity. Remarkably, these maps reveal a complex mix of physical processes active in and shaping these galaxies over time, with no single mechanism dominating.

An illustrative case of JWST-ALMA synergy is seen in one of our sources, where rest-frame UV and dust emissions are spatially distinct, suggesting that roughly 90% of UV light is dust-obscured. Interestingly, the morphology at rest-frame optical wavelengths reveals a substantial ($\sim$50%) stellar population hidden behind dust. This result aligns with recent findings

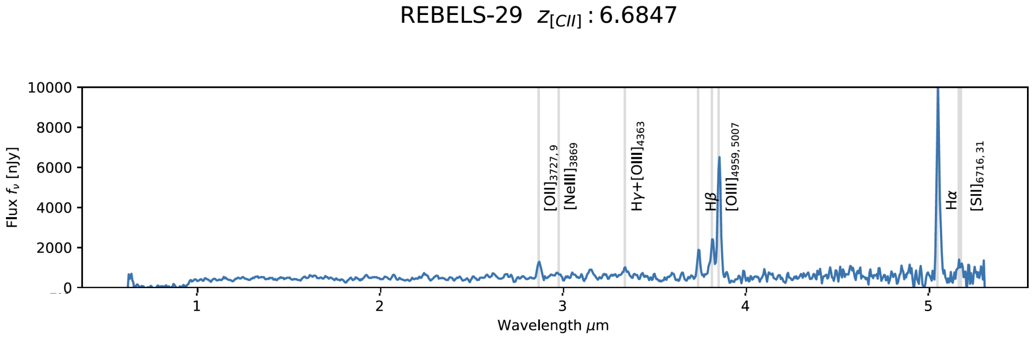

Figure 3: Spectrum, in f_ν units, of the REBELS source with solar metallicity. The main emission lines are indicated and labelled accordingly. Our analysis, based on the resolved stellar population properties, indicates that this galaxy started to form its stars at $z > 9$.

of massive ($M_\star > 10^{11} M_\odot$) dust-obscured galaxies at $z > 4$ (e.g., [32]), indicating that such galaxies are significant contributors to the cosmic stellar mass at these epochs.

2 A massive $Z_\odot$ galaxy in the Epoch of Reionization

Recent studies have revealed massive galaxies with evolved stellar populations up to $z \sim 8$ (e.g., [18, 6, 15, 22, 11, 30]). Additionally, the detection of [OIII]88μm with ALMA ([27, 8]) in GS-z14 – the highest-redshift spectroscopically confirmed galaxy ([7]) – suggests ISM enrichment at early cosmic times. However, metallicity estimates for statistically significant samples of galaxies at $4 \gtrsim z \gtrsim 10$ indicate low values ($\sim 10 - 20\% Z_\odot$), based mainly on faint/low-mass samples, raising questions about ISM enrichment in brighter/more massive galaxies.

Thanks to the IFU observations for the 12 REBELS galaxies, we can now investigate metallicities in more massive galaxies at $z \sim 7$. Our measurements suggest, on average, higher metallicities than those found at similar redshifts, with a substantial dispersion of ~ 1 dex.

Among the REBELS sample, one galaxy displays a metallicity close to $Z_\odot$. Figure 3 shows its spectrum with intense [OIII] and [OII] line emission, and low [SII] and [NeIII] line intensities. Analysis with strong-line diagnostics (R23) and the calibrations of [26] indicate a metallicity of $12 + \log(O/H) = 8.73 \pm 0.15$ [25]. To assess how rapidly this galaxy formed, we used the IFU cube's spatial data to map stellar population age, calculating the Hα to rest-frame optical continuum ratio between 4000 Å and 6500 Å, post emission-line masking. This approximates the specific star-formation rate (sSFR) and inversely relates to age. The resulting map shows a clear gradient, indicating varied stellar mass assembly timescales. SED fitting of spaxels with the lowest sSFR suggests a stellar population age between 200 and 750 Myr, implying that this galaxy began forming stars at $z > 9$.

3 Conclusions

JWST has opened new avenues for exploring even higher redshifts than previously achieved, reaching well into the Cosmic Dawn Era. Most importantly, it facilitates a shift from studying global average population characteristics to physically characterizing individual sources. The synergy between JWST's spatially-resolved optical data and ALMA's dust continuum measurements enable a thorough analysis of a galaxy's assembly history, showcasing the effectiveness of combining these observatories to study high-redshift galaxies. With NIRSpec IFU/Prism observations of 12 bright star-forming galaxies at $z \sim 7$, along with ALMA [CII] and dust continuum measurements from the REBELS program, we have been able to assess their ISM chemical enrichment. Notably, we have identified one galaxy exhibiting solar metallicity. By utilizing the high spatial and spectral resolution afforded by the IFU observations, we estimate that this galaxy began star formation at an epoch corresponding to $z > 9$. This finding aligns with scenarios in which massive galaxies in the early universe undergo intense starburst phases that lead to rapid increases in stellar mass and metallicity.

A forthcoming JWST C3 program (PI: Schouws) aims to acquire NIRCam imaging and WFSS observations of 25 [CII]-luminous, massive star-forming galaxies at $z \sim 7$ (including the 12 galaxies analyzed in this study), which will help characterize their environments, dark matter halos, and identify ionized bubbles.

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