Investigating black hole-galaxy coevolution with JWST: The highest resolution study of AGN ionization in High-z Radio Galaxies

High-z Radio Galaxies (HzRGs, z=2-4) are among the most massive, luminous, and extreme objects in the universe. These galaxies host powerful relativistic jets driven by the Active Galactic Nuclei (AGN) that influence the large-scale environment of the system through shocking/heating or removing the cold gas needed for star formation. Yet, HzRGs do not appear to be quenching, unlike their low-z counterparts. Instead, HzRGs exhibit intense star formation and evolutionary activity, indicating that our interpretation of "radio-mode" feedback as a quenching mechanism is incomplete. Optical line diagnostics and intensity mapping can disentangle the impact of the AGN/jets from that of starbursts and mergers, enabling us to quantify how jets regulate the environment in HzRGs. However, challenges in resolving rest-frame optical ionization lines at high redshift has inhibited our ability to determine the impact of the jet on its host in HzRGs. For the first time, JWST offers the high resolving power needed to disentangle the extreme environment of HzRGs. We propose to observe key AGN/jet ionization lines ([OIII], [NII], and Hα) in 5 HzRGs using NIRCam narrow and/or medium-band filters. These observations, in conjunction with archival radio observations of the synchrotron-emitting jet, will enable the highest resolution study to date of AGN/jet ionization in HzRGs through spatial and kinematic mapping of the ionized gas emission. This program will reveal how jets regulate the galactic environment during the peak epoch of massive galaxy formation and will have far-reaching implications for the role of radio-mode feedback in driving a galaxy's evolution across cosmic time.

- ## Scientific Justification

HzRGs: Rare Probes of Massive Galaxy Formation and Evolution

High-z Radio Galaxies (HzRGs, z=2-4) are among the most massive, luminous, and extreme objects in the universe. These galaxies exist in a critical era of galaxy growth known as "cosmic noon" and are likely the progenitors of massive, quiescent ellipticals at z=0 (Miley & De Breuk 2008). HzRGs are characterized by their vigorous star formation, large reservoirs of molecular gas, AGN activity, and often, jet-driven outflows (Villar-Martín+1999; Drouart+2016). As such, HzRGs are theorized to be on the brink of self-regulating their growth (Miley & De Breuk 2008). **This critical transitionary state makes HzRGs rare probes of the evolutionary processes that drive a galaxy's transition from a blue, star-forming galaxy to a red, quiescent elliptical.**

Feedback induced by AGN-powered radio jets ("radio mode") can drive galaxy evolution by directly impacting the gaseous environment, resulting in induced or quenched star formation (see Fabian 2012, McNamara & Nelson 2007). In low-z radio galaxies, jets are found to influence their host's gaseous environment through shocking/heating or removing the cold gas needed for star formation. As such, it is hypothesized that quenching by radio jets may drive the transition from a star-forming galaxy to a quiescent elliptical (McNamara & Nelson 2007). To establish the role of radio-mode feedback in the evolution of galaxies, we must understand how jets impact the environment of the most massive, extreme galaxies during the peak of their growth.

Despite much evidence that jets interact strongly with the ISM in HzRGs (McCarthy, Baum & Spinrad 1996; Villar-Martin+ 1997; Emonts+ 2014), the physics of how the jet-ISM interaction impacts star formation in HzRGs remains elusive. Rest-frame optical line diagnostics and intensity mapping can disentangle the impact of the AGN/jets on the ISM from that of concurring evolutionary mechanisms (i.e., starbursts and merging) (Kewley+ 2019; 2013). However, challenges in resolving rest-frame optical lines at high redshift has inhibited our ability to study jet-ISM interactions close to the galaxy's central engine. **For the first time, JWST offers the resolution needed to spatially map the key AGN/shock ionization lines that can probe the local jet-ISM interaction in HzRGs.**

We propose to observe [OIII], [NII], and Hα in 5 HzRGs with NIRCam narrow and medium filters. Rest-frame optical ionized emission can uniquely reveal the impact of jet-ISM interactions by probing the clumpy, warm, ionized ISM close to the central engine of the host galaxy (Durré & Jeremy 2018; Juneau+ 2022). With NIRCam, we will conduct the highest resolution study of the rest-frame optical ionized emission in HzRGs and quantify the relationship between the properties of ionized gas (morphology, kinematics) and jets (structure, orientation, power). **By observing the direct tracers of radio-mode feedback in HzRGs, we also provide a much-needed link between early cosmic noon galaxies and the quiescent radio elliptical galaxies that populate z=0.**

Jet feedback cannot be unveiled without rest-frame optical ionized emission

To date, our ability to probe the morphology and kinematics of AGN and/or shock-ionized gas in HzRGs has been limited by the resolving capabilities of near-infrared telescopes. At low redshift, intensity mapping of rest-frame optical emission provides important morphological and kinematic evidence of AGN feedback. In particular, [OIII] emission is a useful tool for revealing powerful AGN-driven biconical outflows of ionized gas in active galaxies, such as in NGC 7582 (see Figure 1, (Juneau+ 2022)). These winds can affect the environment of the host galaxy by inducing or quenching star formation (Durré & Jeremy 2018). AGN ionization and jet-driven outflows have been well studied at low redshift, but we have lacked the resolution to conduct similar feedback studies in galaxies at the peak of their growth.

Without [OIII] observations in HzRGs, we cannot understand how the jet feeds its host's environment and drives the evolution of these massive galaxies. Recently, cosmological simulations have suggested that jet-powered, high velocity outflows can contribute feedback on sub-kpc scales that effectively quenches star formation, producing a quiescent elliptical (Weinberger+ 2017; Sijacki+ 2007). This is further supported by observations of low-z radio galaxies showing correlations between the jet properties (i.e., inclination and power) with the kinematics and morphology of ionized outflows (Venturi+ 2021). Though there have been only a handful of studies probing [OIII] in HzRGs (e.g., Nesvabda+ 2006; Armus+ 1998), these studies teased the presence of ionized biconical outflows but could not spatially resolve them. By resolving the morphology and kinematics of the ionized gas in HzRGs, NIRCam will unveil the presence of AGN ionized outflows that are uniquely indicative of wide-spread, jet-driven feedback.

The HzRG Sample: Hints of jet-driven outflows of ionized gas

In Table 1, we list our HzRGs sample and outline the parameters of our proposed observations. Our HzRG sample was selected according to the following criteria, in order of priority: 1) Target's redshift enables NIRCam observations of [OIII]; 2) Target's redshift enables NIRCam observations of [NII] + Hα; 3) Target has archival radio observations of the jet and molecular gas; 4) Target shows signs of AGN ionization cones/outflows; 5) Target has additional archival observations, priority given to UV observations of the extended Ly-α halo.

We include in our HzRG sample the Spiderweb Galaxy (MRC 1138-262, z=2.2), one of the most massive early galaxies, consisting of a "web" of tens of protogalaxies (Pentericci+ 2000). Despite exhibiting strong evidence of jet-driven feedback (Nesvadba+ 2006), Seymour+ 2012 derived a high star formation rate of SFR ≈ 1400 $M_{\odot} yr^{-1}$ indicating that the Spiderweb is experiencing a rapidly growing. In one of the few [OIII] studies conducted of an HzRG, Nesvadba+ 2006 resolved three "bubble-like", kinematically distinct zones of [OIII] emission that were reminiscent of projected conical outflows (see Figure 2). The high velocities and FWHMs of these "bubbles" were consistent with jet-driven outflows (Nesvadba+ 2006). If these distinct zones of [OIII] are indeed conical ionized outflows, our proposed NIRCam observations will resolve their morphology and reveal the jet-driven feedback in this massive system.

NIRCam enables highest resolution study of AGN ionization in cosmic noon galaxies

Where other telescopes have failed, NIRCam can definitively reveal the existence of AGN ionization cones in cosmic noon galaxies. Our team constructed a NIRCam AGN Simulation to test if NIRCam could resolve the signatures of AGN feedback in high-z galaxies. The simulation passes real spectral observations of nearby galaxies through a selected NIRCam filter, redshifts the spectral wavelength and flux to a desired redshift and generates a simulated rest-frame optical image of the galaxy at that redshift as "seen" by NIRCam. To show that NIRCam will resolve AGN ionization cones at z=2-4, we passed Multi Unit Spectroscopic Explorer (MUSE) observations of NGC 7582 (z=0) through our simulation, shifting its redshift to z=2.3 to capture [OIII] in NIRCam's 1.64-micron filter. The results of this simulation (see Figure 3), show that NIRCam can indeed "see" ionization cones in cosmic noon galaxies.

By resolving AGN ionization cones and ionized outflows, we can probe the jet's direct impact on its host close to the central engine of the galaxy. In a study of four low-z radio galaxies, Venturi+ 2021 found high-velocity [OIII] outflows directed along the ionization cones that were aligned with the jets in all four targets. The [OIII] emission had line-widths consistent with shock ionization, indicating that the jet is strongly perturbing the gas in the galactic disk (Venturi+ 2021). We will conduct a similar analysis of the local jet-ISM dynamics in HzRGs by combining our proposed observations with archival radio observations of the jet. Regardless of whether ionized outflows are found, the [OIII]/(Hα + [NII]) line ratio will constrain the dominant ionization mechanism in the immediate vicinity of the AGN (Kewley+ 2013). Our observations will enable us to: (1) disentangle AGN/jet ionization from that of starbursts; (2) probe how the jet affects its immediate environment by shocking the gas and/or driving out outflows of ionized gas, thereby reducing the available star-forming material.

<u>HzRGs: A unique window into the larger picture of galaxy evolution</u>

Current galaxy formation models indicate that radio-mode feedback is triggered by the continuous accretion of matter onto the black hole from rapid galaxy growth, suggesting that the radio phase provides a mechanism for galaxies to self-regulate their growth (McNamara+ 2007). As massive galaxies experiencing significant evolutionary activity, HzRGs offer a unique glimpse into the evolutionary role of the radio AGN. For the first time, NIRCam offers the resolving power to disentangle the signatures of radio-mode feedback from that of starbursts and mergers in HzRGs, thus revealing how jets regulate their host's galactic environment during the peak epoch of massive galaxy formation.

AGN feedback has also been implicated in the explanations of numerous galaxy formation and cosmological models, such as the black hole-bulge mass correlation, the observed mismatch in stellar masses at the massive end of the halo mass function, and the color bimodality of galaxies (Hardcastle & Croston 2020). The 2020 Decadal Survey priority area, "Unveiling the Drivers of Galaxy Growth", affirmed that feedback from the central, supermassive black hole is critical to the full picture of galaxy evolution, and requires that we probe the AGN's influence on its host galaxy from the warm, ionized gas at the galactic center to the cold, molecular gas in the outermost regions. Furthermore, by utilizing available archival observations of warm (optical) and cold (radio) gas in low-z radio galaxies, **we will conduct the first multiphasic AND multiscale investigation of radio-mode AGN feedback in galaxies ranging from the peak era of evolutionary activity to the present epoch of quenched systems. <u>The insight provided will be transformative for the field of galaxy evolution and will shed light on JWST's central question: "How did the first galaxies evolve over time?"</u>**

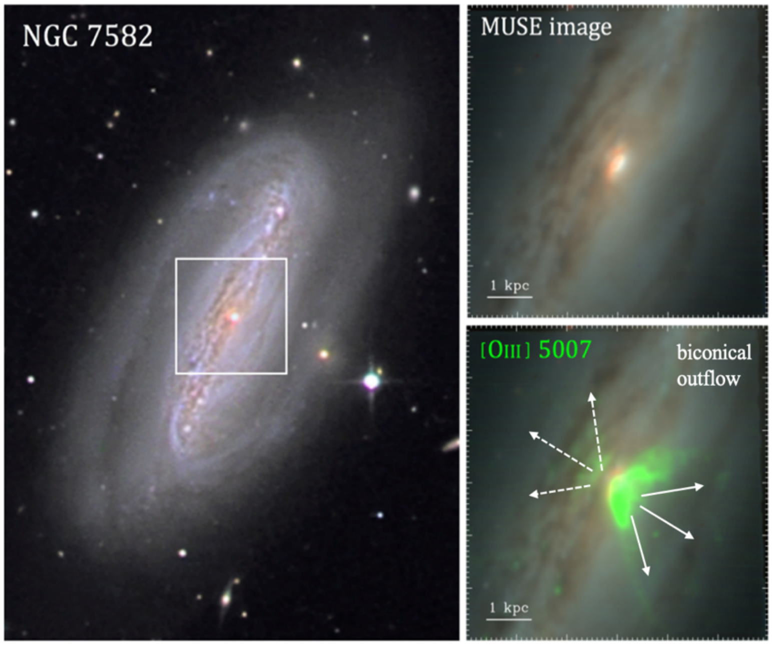

Figure 1. Left: LRGB composite image of NGC 7582 showing galaxy-scale view. White box represents the MUSE field of view. Image credit: S. Binnewies & J. Pöpsel from Capella Observatory. Top right: RGB color image from MUSE spectral cube. Bottom right: RGB image with [OIII] emission (green) showing biconical outflows of ionized gas protruding from the galactic center. Image credit: Juneau+ 2022; Figure 1).

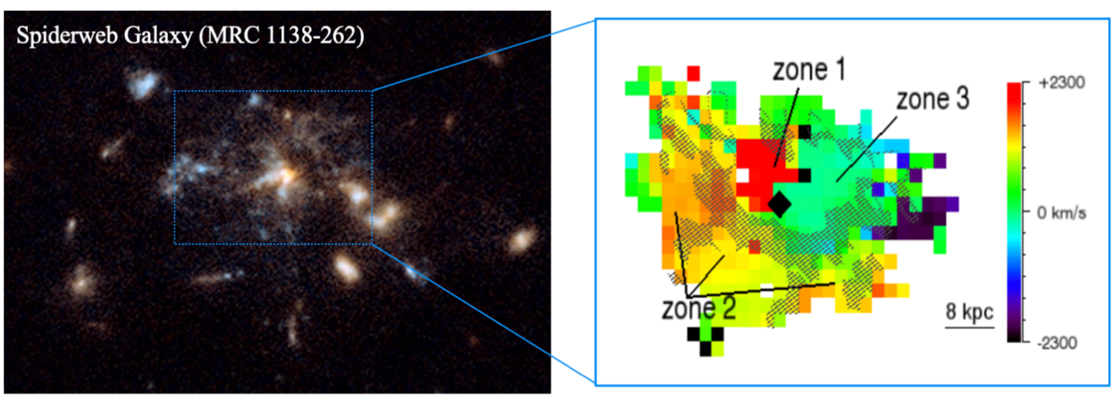

Figure 2. Left is a composite Hubble image of the Spiderweb Galaxy. Image credit: NASA, ESA, G. [OIII] showing three kinematically distinct zones. The zero velocity is defined as the peak surface brightness of the [OIII]λ5007 line. The diamond indicates the position of the radio-loud AGN and the hatched "ring" indicates broad line emission. The bubble-like shapes of the kinematically-distinct [OIII] zones are reminiscent of projected ionization cones, hinting at the presence of ionized outflows in the Spiderweb. Higher resolution [OIII] observations with NIRCam are necessary to resolve the conical morphology of these zones. Image credit: Nesvadba+ 2006, Figure 3.

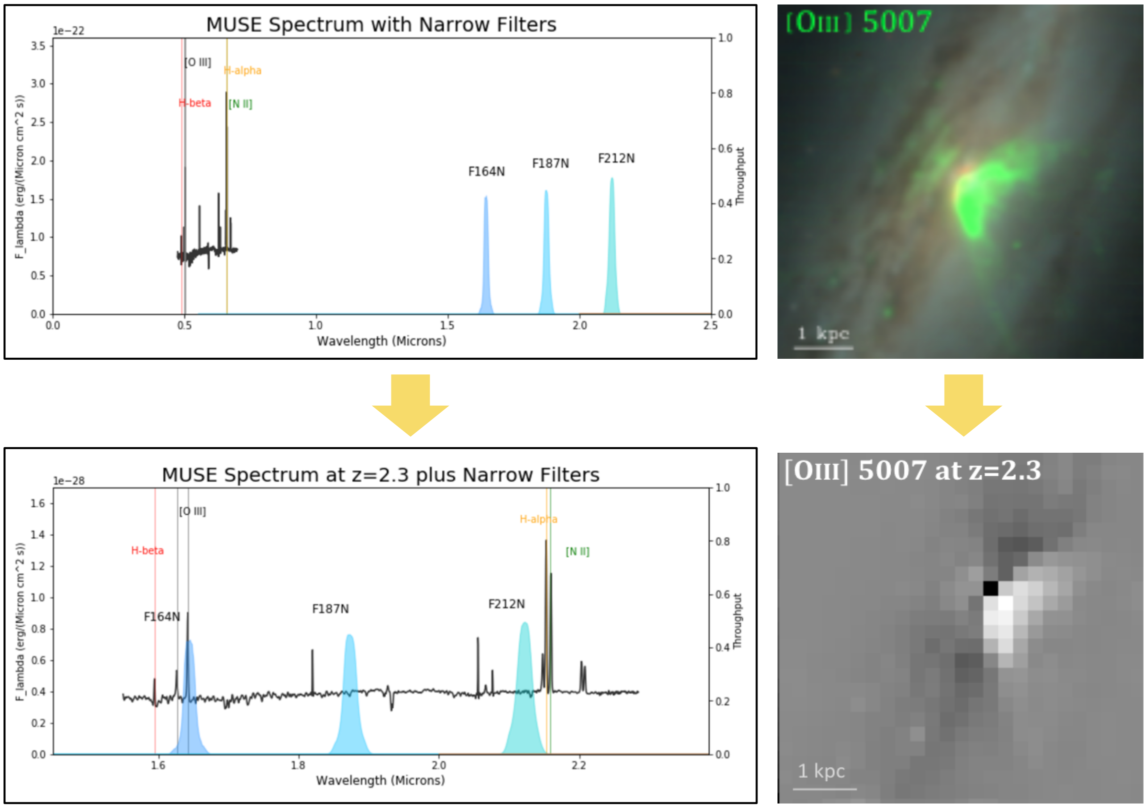

Figure 3: Top left: MUSE spectrum of NGC 7582 with NIRCam narrow-band filters overlaid. Top right: [OIII] ionization cones (green) in NGC 7582 from Juneau+ 2022. Bottom left: Redshifted (z=2.3) MUSE spectrum of NGC 7582 with NIRCam narrow-band filters overlaid. At z=2.3, [OIII] falls into the 1.63 micron narrow-band filter. Bottom right: Simulated NIRCam image of the isolated [OIII] emission (white) in a theoretical, z=2.3 NGC 7582. The simulated image is a conservative rendering of NIRCam's imaging capabilities, with sparse sampling of the pixels in the MUSE image and no dithering applied. **As such, the simulation shows that NIRCam can resolve the morphology and structure of AGN ionization cones in high redshift galaxies!**

ID	z	Lines	Filter
MRC 1138-262 (Spiderweb Galaxy)	2.16	[OIII], [NII]+Hα,	F162N, F210M
4C 41.17	3.38	[OIII], [NII]+Hα	F210N, F300M
Additional (3-4) HzRGs	…	…………………	……………..

Table 1. Proposed observations are outlined by target ID, redshift (z), emission lines, and NIRCam filters.

References

Alatalo+ 2016a, ApJS, 224, 38; Alatalo+ 2016b, ApJ, 827, 106; Armus+ 1998, ApJ, 495, 276; Berton & Järvelä 2021, Univ, 7, 188; Drouart+ 2016, A&A, 593, 109; Durré & Jeremy 2018, ApJ, 867, 149; Emonts+ 2014, MNRAS, 438, 2898; Fabian 2012, ARA&A, 50, 455; Hardcastle & Croston 2020, 88, 101539, NewAR; Hatch+ 2009, MNRAS, 395,114; Juneau+ 2022, ApJ, 925, 203; Kewley+ 2013, ApJ, 774, 10; Kewley+ 2019, ARA&A 57, 511; McCarthy, Baum & Spinrad 1996, ApJS, 106, 281; McNamara & Nelson 2007, ARA&A, 45, 117; Miley & DeBruek 2008, A&ARv, 15, 67; Nesvadba+ 2006, ApJ, 650, 693; Pentericci+ 2000, 361, 25; Seymour+ 2012, ApJ, 755, 146; Sijacki+ 2007, MNRAS, 380, 887; Villar-Martin+ 1997, A&A, 323,21; Villar-Martin+ 1999, MNRAS, 307, 24; Villar-Martin+ 2007, NewAR, 51, 194; Weinberger+ 2017, MNRAS, 465, 3291