Deep NIRCam spectroscopy of an ionized bubble at $z \simeq 6.8$: understanding the galaxy population that drove reionization

Cosmic reionization was driven by the first galaxies in the Universe. These early luminous sources carved out bubbles of ionized gas around them, which grew and overlapped over time until the Universe was completely reionized. To understand the reionization timeline and topology, it is crucial to characterize the entire population of galaxies powering ionized bubbles. However, to date, observations of galaxies in bubbles have been limited to only the most extreme, luminous objects. As such, little is known about the role that the fainter ($L_{UV} < L^*$) galaxy population plays in carving out ionized bubbles, limiting our understanding of the reionization process itself. We propose for deep NIRCam wide field slitless spectroscopy to conduct the first study of the $L_{UV} < L^*$ galaxy population in an ionized bubble identified at $z \simeq 6.8$. We will leverage NIRCam's exceptional sensitivity to obtain deep spectroscopy across the bubble in the F356W filter, targeting the nebular emission lines Hβ and [OIII]λλ4959,5007. We will (1) identify previously unknown, faint galaxies in the bubble, and (2) robustly measure the ionizing photon emissivity of the bubble's galaxy population down to $0.1L^*$. This program will yield the first constraints on which subset of the $L_{UV} < L^*$ galaxy population drove reionization, as well as provide a tantalizing first glimpse into the reionization topology. Ultimately, this program will complement other studies of the galaxy population responsible for driving reionization, such as measurements of the high redshift UV luminosity function, and be a revolutionary step towards fully understanding the evolution of galaxies at early cosmic times.

- ## **Scientific Justification**

$L_{UV} < L^*$ galaxies determine the timeline and topology of reionization

The Epoch of Reionization (EoR) was driven by the first generation of galaxies in the Universe. Theory predicts that these early luminous sources carved out ionized bubbles around them. Over time, individual bubbles grew and overlapped until the entire Universe was eventually reionized at $z \sim 6$ (e.g., Barkana & Loeb 2004, Furlanetto et al. 2004). Thus, $z \gtrsim 6$ galaxies are inextricably linked to reionization, and understanding the ionizing properties of this early galaxy population will provide crucial insights into the reionization process itself.

The galaxy population that dominates the ionizing flux at $z \gtrsim 6$ regulates the reionization timeline and topology. Extremely bright galaxies ($L_{UV} > L^*$, $M_{UV}^* \sim -21$ at $z \sim 7$; Bouwens et al. 2021) produce copious amounts of ionizing photons, but they are rare (e.g., Bowler et al. 2017), and the fraction of their ionizing flux that escapes to ionize the intergalactic medium (IGM) is small (e.g., Steidel et al. 2018). Thus, while the brightest galaxies contribute to reionization, it is clear that fainter ($L_{UV} < L^*$) galaxies are crucial to completely reionize the IGM. However, it is extremely *un*clear exactly which "faint" galaxy population is the most important.

To date, only the most extreme, $L_{UV} > L^*$ galaxies caught in the act of carving out ionized bubbles have been observed, fundamentally limiting our understanding of reionization as a whole. Deep observations of $L_{UV} < L^*$ galaxies during the EoR are critically needed to distinguish the dominant galaxy population responsible for reionization. Such observations are only now possible in the era of the *JWST*. We propose for *JWST*/NIRCam wide field slitless spectroscopy (WFSS) to place the first constraints the ionizing photon emissivity of $L_{UV} < L^*$ galaxies in an ionized bubble identified at $z \simeq 6.8$ (Endsley & Stark 2022). We will observe the rest-frame optical emission from galaxies in the bubble in the F356W grism, targeting the strong rest-optical nebular emission lines Hβ and [OIII]λλ4959,5007, and quantify the ionizing photon production of galaxies in the bubble down to 0.1L*. This program will be the first to directly observe galaxies fainter than L* that are expected to be actively reionizing the Universe, providing the first direct insights into the galaxies that regulate the reionization process and constrain the resulting topology. *JWST* is the only facility with both the sensitivity and wavelength coverage to observe faint $z \sim 7$ galaxies in the rest-frame optical, which is critical to characterize the properties of the sources that drove reionization and answer the questions, "When and how did reionization occur?" and "What sources caused reionization?"

Identifying the galaxy population that drove reionization is critical to constrain the timeline and topology

Models predict that the topology and timeline of reionization depend on the properties of the ionizing sources. Ionizing photon production efficiency is expected to correlate with mass, leading to larger ionized bubbles around more massive galaxies. Meanwhile, the number density of galaxies decreases with mass. Thus, there are fewer, larger bubbles when reionization is dominated by massive, luminous galaxies rather than low-mass, faint systems (Fig. 1; Kulkarni et al. 2016). The dominant population also determines the reionization timeline, as more massive systems take longer to assemble before they can begin producing ionizing photons. Different assumptions for the ionizing sources can lead to a reionization midpoint of either $z \sim 8$ or $z \sim 10$ ($\Delta z \sim 2$!; Robertson et al. 2015, Finkelstein et al. 2019). Constraining the dominant population that drives reionization is thus crucial to distinguish such divergent reionization scenarios.

Direct observations of the brightest ($L_{UV} > L^*$) galaxies suggest that while this population of brightest galaxies contributes ionizing photons to the reionization process, they cannot fully reionize the Universe alone. Recent works argue that the relatively small population of $-21 < M_{UV} < -18$ galaxies can produce enough additional ionizing flux to drive reionization (Naidu et al. 2020). This would suggest a very spatially inhomogeneous, rapid reionization process that starts late (Robertson et al. 2015). However, other authors find that large numbers of $M_{UV} > -15$ galaxies are needed to generate enough ionizing flux. In this case, reionization would have a more homogeneous topology, start earlier, and proceed more slowly (Finkelstein et al. 2019). <u>It is thus critical to directly observe of $L_{UV} < L^*$ galaxies carving out ionized bubbles to identify the sources primarily responsible for driving the reionization process forward.</u>

$L_{UV} < L^*$ galaxies in an ionized bubble at $z \simeq 6.8$ can be identified and characterized

Prior to *JWST*, ground-based near-infrared imaging and spectroscopy has enabled the identification of $L_{UV} > L^*$ galaxies carving out ionized bubbles during reionization. These galaxies can be identified via strong resonant Lyman-alpha (Lyα) emission, sometimes in spatial overdensities (e.g., Matthee et al. 2018, Larson et al. 2022). Notably, since Lyα from galaxies in ionized regions can Doppler shift out of resonance before encountering neutral hydrogen in the IGM, Lyα from galaxies within ionized bubbles is expected to be enhanced relative to that of the general population. Thus, strong Lyα emission is a promising indicator of an ionized bubble.

However, observational limitations of current facilities have prevented the systematic identification and characterization of all but the most luminous, rare galaxies. Here, <u>we propose for *JWST*/NIRCam WFSS to systematically search for $L_{UV} < L^*$ galaxies, and characterize *all* galaxies down to 0.1L* ($M_{UV} \sim -18$), in an ionized bubble at $z \simeq 6.8$</u> (Fig. 2). This bubble was originally identified in the COSMOS field by Endsley & Stark (2022) via a spectroscopic overdensity of $L_{UV} \gtrsim L^*$ Lyα-emitting galaxies. Nine galaxies in an 11×15 arcmin^2 area have been observed to have enhanced Lyα emission, possibly suggesting the presence of a large (radius $\gtrsim$ 3 physical Mpc) ionized region. However, it is unclear if all of the known galaxies belong to the same large bubble, or multiple smaller bubbles. Deep observations of the fainter galaxy population in the bubble will enable robust measurements of the bubble size, and determine if the observed galaxy population can fully ionize the bubble, suggesting that $M_{UV} < -18$ galaxies can power reionization, or if an additional population of galaxies below the detection limit are necessary.

Rest-frame optical spectroscopy is crucial for measuring ionizing properties of galaxies

We will leverage the unprecedented combination of wavelength coverage and sensitivity of *JWST*/NIRCam to observe galaxies down to 0.1L* within the bubble, specifically targeting the rest-frame optical spectrum at $z \simeq 6.8$ using the F356W filter. These observations will encompass the wavelengths of the strong rest-optical nebular emission lines Hβ and [OIII] at $z \simeq 6.8$, and detections of these lines will enable spectroscopic redshift identification and characterization of the ionizing spectrum via photoionization modeling. Additional treasury near-infrared imaging from the *JWST* Cycle 1 GO-1727 program (COSMOS-Webb; PI Kartaltepe, co-PI Casey) over part of the bubble will enable further constraints on the rest-frame UV properties of a subset of the galaxies in the bubble. Altogether, these observations will enable the first constraints on the ionizing properties of $L_{UV} < L^*$ galaxies powering an ionized bubble, crucial to identifying the population responsible for reionizing the Universe.

Our primary objective is to identify and characterize the ionizing properties of all galaxies in the bubble down to a luminosity limit of 0.1L*. We will produce two data products: (1) a spatial map of all galaxies in the bubble down to 0.1L*, and (2) the ionizing photon emissivities of all observed galaxies in the bubble. The well known separation and ratio of the components of the [OIII] doublet will allow us to spectroscopically identify galaxies at $z \simeq 6.8$ and detections of Hβ at the expected location will allow us to further confirm their redshifts. These spectroscopic confirmations will yield the spatial distribution of galaxies and allow us to constrain the size of the bubble. We will further derive the ionizing photon production rates of all observed galaxies within the bubble from the Hβ and [OIII] observations using photoionization models and low-redshift relations. Combined, the spatial map and constraints on ionizing properties of observed $L_{UV} > 0.1L^*$ galaxies within the bubble will allow us to determine whether the observed galaxies produce sufficient ionizing photons to power the observed bubble, or if contributions from galaxies below the detection limit are necessary; see Fig. 3 for a summary of our proposed methods. Ultimately, this will provide the first insights into which subset of the $L_{UV} < L^*$ galaxy population dominated the reionization process.

Our program will enable constraints on the properties of galaxies throughout cosmic time

Through our deep rest-optical spectroscopy, we will obtain the first measurements of the ionizing properties of a population of a galaxy population caught in the act of reionizing the Universe. Combined with our spatial map of the galaxies within the bubble, we will assess which galaxy populations powered the creation of ionized bubbles during the EoR for the first time. Furthermore, as we obtain constraints on the ionizing properties of these galaxies, we will simultaneously constrain their other physical properties, including stellar masses, star formation histories, and ages. These measurements will provide insights into quantities such as the stellar mass function and cosmic star formation rate density, which are crucial to understanding the formation and evolution of high redshift galaxies in general. Additionally, our program will obtain untargeted ~3.6μm spectroscopy over a well-studied field with a significant archive of comprehensive multi-wavelength observations, furthering the legacy value of the COSMOS field. In addition to observing the rest-frame optical at $z \sim 7$, our program will obtain spectra in the rest-frame near-infrared in systems up to $z \sim 3$, and the rest-optical between $z \sim 3$ and $z \sim 7$ (including Hα at $z \sim 4$-5). Ultimately, our program will provide insights into a broad range of key science goals of *JWST*, providing legacy data to enable constraints on the assembly and growth of galaxies across cosmic time, and directly answering the questions "When and how did reionization occur?" and "What sources caused reionization?"

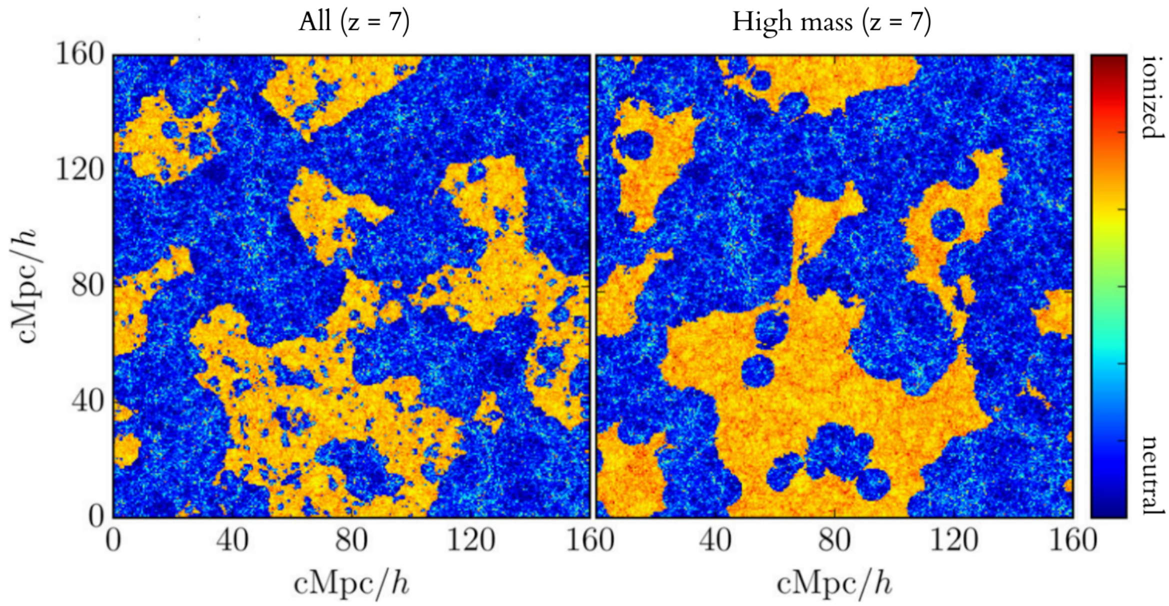

Figure 1. Differences in reionization topology that can result from different assumptions for the mass of sources that contribute ionizing photons. The left panel shows the topology when all galaxies contribute ionizing photons, and the right panel shows the topology resulting when only massive systems contribute. The massive galaxies carve out much larger fully ionized regions by z = 7. *In this proposal, we will observe galaxies down to 0.1L* in an ionized bubble to determine the dominant population that drives reionization and take the first step towards characterizing the reionization topology and timeline.* Adapted from Kulkarni et al. (2016).

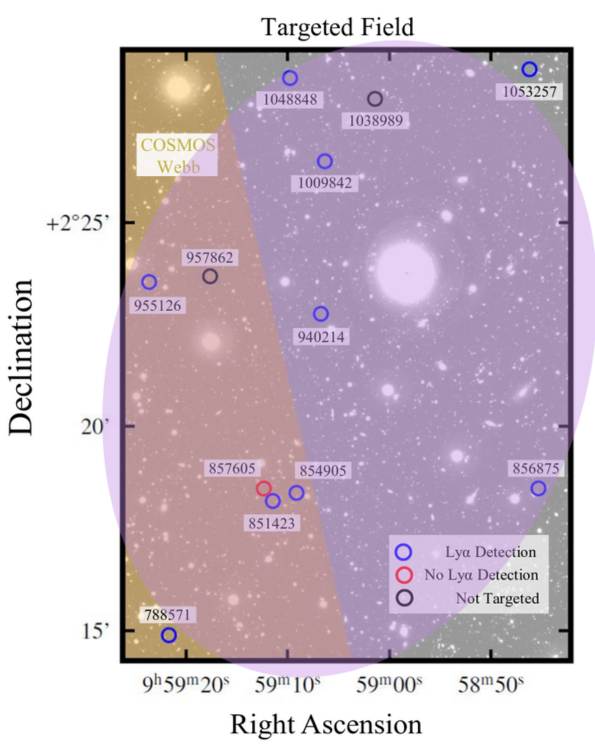

Figure 2. The target field of our program, which contains an overdensity of bright, Lyα-emitting galaxies. Blue circles denote a Lyα detection and red circles indicate a Lyα non-detection. The yellow shaded region denotes the footprint of COSMOS-Webb that overlaps with the field, which will provide rest-UV imaging. *This spectroscopic overdensity of Lyα emitters likely traces an ionized bubble (shown conceptually as the purple oval), and our program will reveal the ionizing properties of galaxies within the bubble that are fainter than current detection limits.*

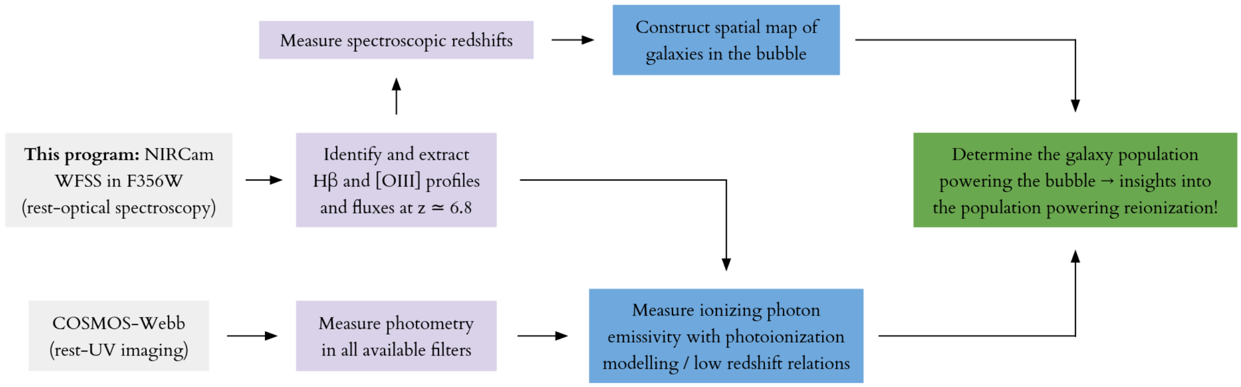

Figure 3. A flow chart summarizing our proposed analysis steps and outcomes. Light grey boxes signify the required data, purple boxes correspond to analysis steps, blue boxes are planned data products, and the final green box is our final goal. We will identify, map, and characterize the galaxies in the ionized bubble identified by Endsley & Stark (2022) down to luminosities of 0.1L*, and ultimately, *combine measurements of the bubble size with the ionizing photon emissivity of the observed galaxy population to determine the galaxy population driving the creation of the bubble.* This will yield our first direct constraints on the galaxies that drove reionization in general.

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