Lyman-α Studies Enabling a Self-Consistent Approach to Reionization

As an astronomer specializing in the epoch of reionization (EoR), my research is dedicated to unraveling the mysteries of the early universe from the perspective of Lyman-α (Lyα) emission. My pioneering work has led to the development of innovative methods to constrain the neutral fraction of the intergalactic medium (IGM), offering new insights into the timeline and processes of reionization. Building on a solid foundation of observational data and theoretical modeling, my current and future projects aim to refine our understanding of the IGM's evolution and the role of the first galaxies in shaping the universe as we know it. At the Astronomy Department in the University of Illinois at Urbana-Champaign (UIUC), I am eager to contribute to and expand upon the institution's distinguished research portfolio, fostering a collaborative environment that bridges the gap between observational astronomy and cosmological theory.

Introduction – Reionization and the Source of Ionizing Radiation

The cosmic tapestry of the early universe, particularly the EoR, presents one of the most compelling puzzles in modern astronomy and observational cosmology. The epoch of reionization (EoR) is a pivotal era in cosmic history, marking the transition from a predominantly neutral intergalactic medium (IGM) to one that is largely ionized. This transition was made by energetic ionizing (or Lyman-continuum; LyC) photons (with $\lambda < 912$Å) emitted by luminous sources in the early Universe. My research endeavors to decode this era by focusing on the Lyα emission as a probe to constrain the neutral fraction of the IGM. This statement outlines my past research, ongoing projects, and future plans in this intriguing domain to answer to key questions: *how and when did reionization occur?* and *what are the primary sources of ionizing photons?*

The conventional thought is that young stars in newly-formed galaxies played a crucial role in emitting ionizing photons although a smaller portion came from accreting black holes (or active galactic nuclei) [19]. In particular, it is crucial to understand the relative contributions of bright vs. faint galaxies to the total ionizing photon budget as their contributions to reionization must be imprinted in the temporal (early vs. late) and spatial evolution (IGM topology) of reionization [4, 15, 20, 24]. If high-luminosity galaxies dominate, reionization will be patchier than if more widely distributed low-luminosity galaxies dominate [21].

Lyα observations have been broadly used to constrain the ionization state of the IGM from its strong suppression by neutral IGM into the EoR [18, 22]. Conversely, ionized bubbles during the EoR can be discernible through Lyα emitters (LAEs), as they provide channels for the escape of Lyα in the mostly neutral IGM [e.g., 1, 2, 6, 13, 23]. Thus, Lyα spectroscopic observations provide one of the most promising and presently accessible means to trace the existence of H I gas in the IGM [5, 9, 14].

Past Research – Reionization Constraints from Lyα Observations

My doctoral thesis at the University of Texas at Austin, entitled "Constraining the End of Reionization with Lyα Spectroscopy," was a pioneering study that utilized Lyα emission to map the ionization state of the IGM during reionization. By analyzing spectroscopic observations of distant galaxies, I performed a statistical analysis on Lyα emission properties of these galaxies. This work led to a series of publications in *the Astrophysical Journal*, developing a method to estimate the neutral hydrogen fraction in the IGM and advancing our understanding of the timeline and topology of reionization [7–9].

In my subsequent postdoctoral research at NASA GSFC, I expanded on these techniques to include the comprehensive datasets of Lyα spectroscopy obtained from the Keck telescopes and the Hubble Space Telescope [10]. This novel approach applied to the most comprehensive spectroscopic data provided a more nuanced understanding of the process of reionization in the IGM and allowed for more precise and direct constraints on the IGM topology during different stages of reionization.

Furthermore, I led two nights of a Keck observing program with the MOSFIRE spectrograph as a PI (obtained through NASA's 2021A Keck allocation). The observations resulted in the new discovery of 10 $z > 7$ Lyα-emitter candidates in the Extended Groth Strip (EGS) field. The newly-discovered Lyα emitters (LAEs) include additional members of the known $z \approx 7.7$, unveiling the largest known ionized structure with a large association of $z \approx 7.7$ LAEs [11].

Moreover, I investigated the Lyα transmission in the IGM during reionization in collaboration with Dr. Hyunbae Park, specialized in theoretical studies on reionization and cosmology [17]. Using Cosmic Dawn II reionization simulation [16], this theoretical study clarifies crucial aspects of the IGM properties (kinetic motions, ionized bubble sizes, and self-shielded systems) that modulate the Lyα transmission. The theoretical predictions made in this study provide a critical ladder from Lyα observations to their constraints on reionization.

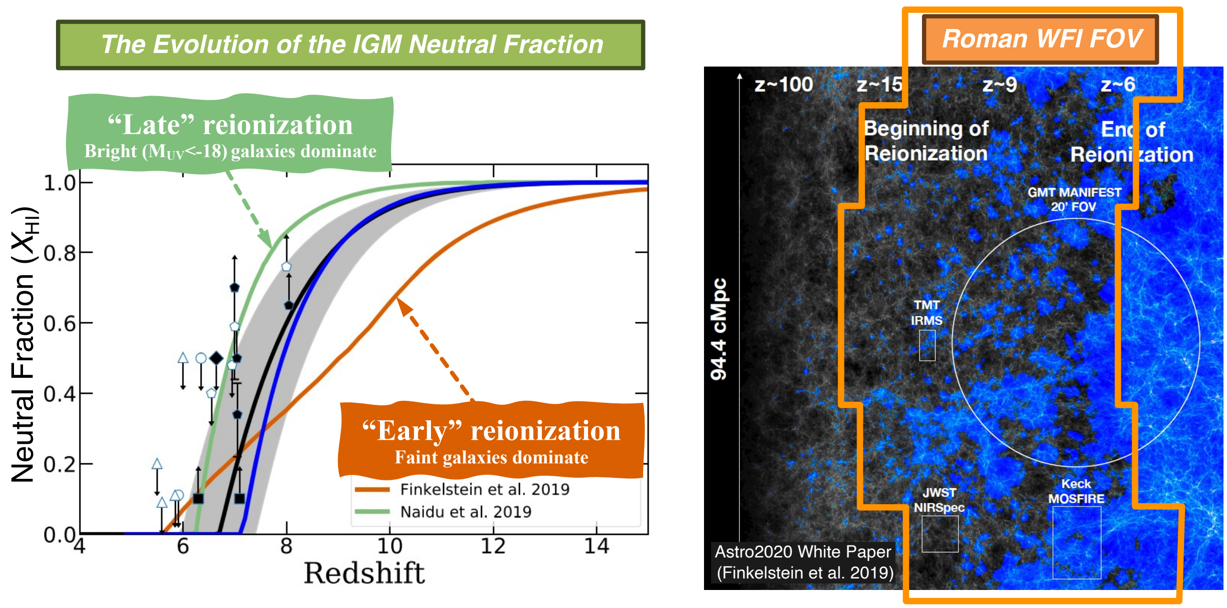
Current Research Focus – Ionizing Photon Escape & Ionized Bubbles

At the Space Telescope Science Institute, I am analyzing the HST photometric observations of LyC photons from highly-magnified, but intrinsically faint galaxies (Jung et al. in prep). The study provides important constraints on escaping LyC fluxes from UV faint-end galaxies (down to $M_{\rm UV} \sim -15$) at $z > 1$ representing a rarely explored domain in previous observations. As these UV faint-end populations pose as potential LyC leakers with their galaxy properties and are considered as pivotal contributors to ionizing photon budget for reionization, it is imperative that we continue further LyC observations in these faint and low-mass galaxies.

Also, in the JWST ERS CEERS collaboration (PI: S. Finkelstein), I am exploiting the capabilities of JWST NIRSpec to conduct rest-optical spectroscopic observations targeting confirmed LAEs at $z > 7$ [12]. In the study, we use two independent constraints of the extent of ionized bubbles, based on the amount of (1) the neutral IGM and (2) the ionizing radiation. We first estimate the Lyα velocity offsets and constrain the required bubble sizes for the escape of Lyα, which basically place lower limits of the ionized bubble sizes. Then, we estimate the total ionizing photon contribution to the surrounding IGM of the LAEs based on rest-optical emission-line measurements and calculate the sizes of the Stromgren spheres, defining upper limits of the extent of ionized bubbles. Obtaining these two independent measurements of the ionized bubbles enables a self-consistent check from one to the other. Our study demonstrates the feasibility of a self-consistent approach to reionization, critical for understanding the role of early galaxies as primary ionizing sources (i.e. varying escape fraction of LyC photons) in the reionization process and for constructing a more detailed reionization timeline and topology with future observations.

Future Research Trajectory – a Self-Consistent Approach to Reionization

With the booming observations of JWST and the advent of next-generation telescopes including Roman Space Telescope, I am preparing to lead a comprehensive survey project to systematically measure Lyα emission across a range of redshifts. The goal is to map the evolution of the IGM's neutral fraction with unprecedented precision. Lyα observations place constraints on the ionization state of the IGM. In the era of JWST, we have an access on a suite of emission lines from rest-UV to optical from reionization-era galaxies, dominant sources of ionizing radiation. This facilitates



(Left) Evolution of the IGM neutral fraction (X_{HI}) as a function of redshift in different reionization scenarios: *early* (red) vs. *late* (green). The figure includes the IGM neutral fraction constraints from analyses of Lyα emission and absorption. **(Right)** Roman WFI field-of-view (orange) overlaid on an illustration of the time history of reionization from the Cosmic Dawn II reionization simulations (Ocvirk et al. 2020). There are large variations in the reported X_{HI} constraints, reflecting the inhomogeneity of reionization. Future Lyα observations of the Roman Space Telescope will synergize with multi-pointing JWST NIRSpec observations of reionization-era galaxies, enabling a comprehensive and self-consistent approach to studying reionization.

a self-consistent approach to reionization, constraining key aspects of reionization such as the extent of ionized bubbles in the IGM (from the analyses of Lyα line properties) and the ionizing photon supplies from the analysis of galaxy internal properties (e.g., escape of LyC photons, stellar populations, ISM properties, and morphologies). With Roman's enormous field-of-view, mapping Lyα will be further expedited. This research will not only refine our reionization models but also inform the design of future cosmological surveys.

At the Department of Astronomy in UIUC, I am enthusiastic about the opportunity to collaborate with other experts, for example, in cosmic microwave background studies (Prof. Joaquin Vieira) and theoretical studies on galaxies in the early universe (Prof. Kirk Barrow). My research aligns with the university's commitment to understanding the early universe and can benefit from synergies in general with the Galaxies and ISM group as well as the Cosmology group. I am also keen to perform my research in conjunction with the Subaru Prime Focus Spectrograph (PFS) data (Prof. Xin Liu) and South Pole Telescope data (Prof. Joaquin Vieira) to enhance the scope and impact of my research.

Conclusion

Through my research on Lyα emissions, I aspire to illuminate the enigmatic epoch of reionization, bringing clarity to the IGM's neutral fraction and its implications for galaxy formation. My proposed research is perfectly aligned with the science interests of the Department of Astronomy, which focuses on observational studies on the extragalactic universe and cosmology. In the long ran, the future radio observations (e.g, Square Kilometer Array) will directly map the distribution of H I during the EoR in the coming years. The research on Lyα emission in this program and these 21cm radio observation studies will complement each other toward understanding the detailed evolution of the IGM and galaxy properties during the EoR. Additionally, Lyα forest studies of quasar observations will reveal residual components of neutral patches around the end of reionization. As a prospective member of the UIUC astronomy faculty, I am dedicated to advancing our cosmic frontier and nurturing the next generation of astronomers to continue this quest, bringing an unprecedented understanding of the reionization history.

References: [1] Castellano et al. 2018, ApJL, 863, L3 [2] Endsley & Stark 2022, MNRAS, 511, 6042 [3] Finkelstein et al. 2019, BAAS, 51, 221 [4] Finkelstein et al. 2019, ApJ, 879, 36 [5] Hoag et al. 2019, ApJ, 878, 12 [6] Hu et al. 2021, Nature Astronomy [7] Jung et al. 2018, ApJ, 864, 103 [8] Jung et al. 2019, ApJ, 877, 146 [9] Jung et al. 2020, ApJ, 904, 144 [10] Jung et al. 2022, ApJ, 933, 87 [11] Jung et al. 2022, arXiv:2212.09850 [12] Jung et al. 2023, arXiv:2304.05385 [13] Larson et al. 2022, ApJ, 930, 104 [14] Mason et al. 2018, ApJ, 856, 2 [15] Naidu et al. 2020, ApJ, 892, 109 [16] Ocvirk et al. 2020, MNRAS, 496, 4087 [17] Park et al. 2021, ApJ, 922, 263 [18] Pentericci et al. 2011, ApJ, 743, 132 [19] Robertson 2022, ARAA, 60, 121 [20] Robertson 2015, ApJL, 802, L19 [21] Smith et al. 2022, MNRAS, 512, 3243 [22] Stark et al. 2011, ApJL, 728, L2 [23] Tilvi et al. 2020, ApJL, 891, L10 [24] Yung et al. 2020, MNRAS,494,1002

Astronomy is an ever-changing discipline with new discoveries. From my learning and research experience, the most crucial thing is to follow up up-to-date knowledge and cast doubts on current consensus. In that sense, my instructors during college led students to spend many hours on doing literature search mainly for the recent papers. One of the primary tasks following the literature search in astronomy classes was finding unsolved problems/possible limitations of the researches in those readings. Moreover, similarly to other natural sciences, students should be equipped with mathematics and fundamental physics subjects. In particular, astronomy does utilize a whole variety of methods/fundamental disciplines (e.g., physics, chemistry, biology, and data science), depending on specific sub-topics. However, it is practically impossible to learn all the subsidiary disciplines before studying astronomy. Therefore, it is very necessary for future astronomers to find their own ways to catch up with the newest research and what knowledge/skills are really needed for the topics. Considering the facts described here, in astronomy classes an instructor should focus on encouraging students to be more proactive and independent in their learning paths.

Teaching and Mentoring Experience

I worked as a teaching assistant for seven astronomy courses during my graduate programs from introductory courses for both non- and astronomy major students to upper-division courses. I also completed a teaching & mentoring training, *Concentration in Teaching and Mentoring* during my PhD years. The program is provided by the College of Natural Sciences at UT Austin, designed to train PhD students or postdoctoral fellows to be well-prepared, engaging, and effective teachers and mentors. Completing the program above, I was able to (1) learn how to build my own courses at different levels (rooted on the evidence-based backward design), (2) provide my own lecture on *the cosmic star formation history in Galaxies and the Universe* in the upper-division class, and (3) develop mentoring strategies on students' research and my own research projects for students.

After PhD, I continued to make every effort on the engagement of teaching and mentoring activities as a postdoctoral fellow. I attended the CRESST II Undergraduate Interaction Day at the NASA Goddard Space Center (GSFC) where I presented my research to the attending undergrad students from local universities. This intended to draw students attention to research conducted in GSFC and share the idea of possible intern projects. I also served as a primary mentor for two summer intern students, being privileged as a postdoctoral fellow previously in NASA GSFC and currently in STScI among renowned institutes.

Teaching Methods and Mentoring Strategies

I subscribe to the philosophy that teaching can be the most beneficial to students when courses are designed following the backward design process, setting the learning objectives and goals first then exploring instructional methods and the appropriate forms of assessment. This needs to be taken differently depending on course levels and class sizes to arrive the desired results.

• **Undergrad Non-Major:** An introductory astronomy course for non-science major students is one of the most popular classes with up to 100 – 200 students. Primary learning objectives include understanding what defines science and acquiring general knowledge of the Universe around us. Teaching introductory astronomy classes often requires an approach similar to public outreach to evoke the interest and the engagement of non-specialist audiences. Thus, lecture materials need to be accessible to a diverse audience, for example, by breaking down scientific jargons and ideas into public language, employing analogies to make scientific concepts relatable and memorable, and utilizing visual aids and interactive learning tools that illustrate scientific ideas. The instructor should encourage students' participation through interactive in-class activities, experiments, and group discussions to have them experience critical thinking and scientific reasoning. In the introductory astronomy classes in which I was a teaching assistant, the instructors used articles from public science journals and online interactive learning materials for interactive in-class activities, and this brought overall high-level engagement and understanding of scientific topics.

• **Undergrad Science/Astronomy Major:** The upper-division undergrad or graduate courses are often provided for small audiences. This allows more direct one-to-one interactions between the instructor and individual students. The audiences are considered as future astronomers who have a significant background in astronomy. Thus the teaching provides in-depth content, involving practical trainings based on critical thinking and problem-solving. Learning objectives should set on specific science topics, making students (1) understand the advanced and current knowledge and major debates in the specific area, (2) integrate and discuss the findings based on scientific critical thinking, and (3) argue their own expectations and interpretation of the topics. As part of a teaching & mentoring training at UT Austin, I had an opportunity to provide my own lecture on *the cosmic star formation history in Galaxies and the Universe* in the upper-division astronomy-major class with the course materials that I have developed. I applied these specific approaches on developing the course materials that consist of lectures, group discussions, and in-class group activities. I learned (and I believe) that it is crucial for students to develop and apply their own ideas through in-class activities as well as to assess them with feedback from peer students in group discussions.

• **Graduate Student Advising:** Student mentoring involves how to define appropriate projects, establish relationships, set expectations, encourage communication, balance guidance and independence, and consider ethical issues and diversity in mentoring. This has to be managed in a tailored way as all individual students find themselves unique in their academic and educational backgrounds. During my postdoc years, I mentored one graduate-level student and one undergrad student. This allowed me to see firsthand how differently students can be benefitted when learning skills and tackling problems in such tailored ways. Specifically, mentoring undergrad student involved more practical trainings on computing skills, basic astronomical tools, and critical reading of astronomy literature while highlighting in-depth discussions on analyzing scientific data, interpreting the results, and drawing conclusions.

Courses I Can Teach and Course Development

My diverse experience in educational training as a teaching assistant, a lecturer, and a mentor qualifies me well to teach a range of courses at both undergraduate and graduate levels. The courses that I can teach at an undergraduate level include for example an introductory astronomy (for both non-science major and astronomy-major students), observational astronomy, galaxies and the Universe, and galaxy evolution. I can teach more specialized and advanced graduate-level courses, including astronomical data analysis, computational astronomy, and galaxies.

I also propose to develop course materials specifically focusing on *the formation and evolution of galaxies in the early universe* as well as on *astrophysical applications of machine learning*, that can be used for teaching undergrad seniors or graduate students.

I was grown up in South Korea. In my childhood, I learned that my home country, South Korea, could be identified as a racially homogeneous nation, and I was in a majority group in every sense during my time in South Korea. Under such circumstances, I was rarely exposed to diversity in race as well as in sexual orientation due to historically conservative culture in Korea. Also, a gender ratio in STEM in South Korea remained severely biased. Being honest, I was not aware of these issues in diversity until I found myself as a minority for the first time as an international during my Summer internship in the University of Oxford in 2011.

In my PhD program in the University of Texas at Austin, there were seven PhD students in my cohort, all male students. I did not recognize the problem at that time. However, the members in the Astronomy Department recognized and admitted the problem on the gender ratio among graduate students and initiated measures to improve the student gender ratio right away in the next admission cycles. Witnessing it was very impressive, which brought my attention to the diverse and inclusive environment.

I joined in regular round-table discussion groups, called "Equity & Inclusion Discussion Group" at UT Austin, promoting self-awareness on diversity, equity and inclusive environment in our professional community and sharing my own experience as an international student in the graduate program. Particularly, I participated in the self-study for the 2017 Department external review self-study as a Graduate student committee, where I identified concerns especially among international students (e.g., enhanced support for dealing with social barriers).

This personal experience, however, was still limited to our professional community. After I moved to NASA's Goddard Space Center as a postdoctoral fellow, I could have numerous opportunities to interact with the public as a scientist in a well-recognized science institute, which allowed me to improve my awareness on the public outreach to promote diversity in STEM area. For example, I participated in NASA's social media Q&A event on May 13-14, 2021 where I provided answers to questions from the public on NASA's James Webb Space Telescope through the NASA's Webb Instagram account, being featured as an Asian American astronomer in honor of Asian American and Pacific Islander Heritage Month.

With my past experience, now I became aware of the values of the activities to advance diversity, inclusion, and equity, and I am fully motivated for seeking further opportunities to learn more from others with diverse perspectives during my fellowship years. First, I believe that outreach activities and scientific communication with the public is critical to connect people to STEM fields. Beyond our professional community, it is well documented that scientist involvement in outreach leads to better outcomes from the public. Meeting a scientist tends to increase interest and learning for the public. Thus, I will reach out local students from diverse backgrounds to inspire an interest in astronomy or other STEM fields through outreach activities. Second, I will continue to stay deeply involved in discussion in the diversity and inclusiveness group in the Astronomy Department to support the diverse and inclusive environment in our professional community. Third, I propose to launch a department-wide mentorship program that is open to all undergraduates, graduates, and postdocs. The program will be designed to foster a career development in astronomy, provide valuable insights, train a mentorship at various levels, and facilitate connections across the department.

List of Past Activities

Graduate student committee for the 2017 Department external review self-study
In preparation of the 2017 Department external review self-study, I served as a graduate student committee member for contributing to writing the 2017 Astronomy Department external review self-study. In the self-study, I contributed on sharing my experience as an international student and discussed where we can improve the graduate program to provide an inclusive environment for international students with diverse backgrounds. This was ultimately for supporting international students' general success in their graduate studies and promote the diversity overall in the Department.

Representative to the Graduate Student Assembly
I was a graduate student representative in the department of Astronomy to the Graduate Student Assembly at UT Austin where I attended regular general assembly meetings for a year where we held a number of forums to develop policies for graduate student interests and goals. The entire activities of the Graduate Student Assembly include but not limited to caring about graduate students welfare, housing, job application, network and research travels, aligned with supporting the diversity and inclusive environment in the Graduate school.

Scientist Featured in a NASA JWST Astronomy Day Q&A in Social Media
I participated in a NASA JWST Astronomy Day Q&A in Social Media from May 13 – 14, 2021. I provided answers in Instagram to the question from the public on JWST as a "featured Asian American astronomer" in honor of Asian American and Pacific Islander Heritage Month, promoting diversity in astronomical communities. This could reveal a general intention of supporting diversity and an inclusive environment in NASA to the public.

Subject Matter Expert for NASA's Webb Space Telescope Community Events
During my time at NASA's Goddard Space Flight Center, I was involved in several public outreach activities to promote the science interest of the public and help people learn the latest updates on NASA's space missions. For instance, I participated in NASA's social media Q&A event on May 13-14, 2021 where I provided answers to questions from the public on NASA's James Webb Space Telescope through the NASA's Webb Instagram account. Also, I am a speaker for JWST pubic talks as part of the Webb Space Telescope Community Events led by the Space Telescope Science Institute, which included giving a public presentation introducing JWST at the Cape Fear Museum of History and Science in Wilmington, North Carolina.