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Reionization: The Mystery of the Early Universe

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1. INTRODUCTION: THE EPOCH OF REIONIZATION

The nearby universe is defined by non-uniformity. It is filled with colliding galaxies, brilliant supernovae, and objects astronomers are just starting to understand. It is easy to forget that the universe began largely uniform. When the universe cooled enough to emit it's first photons in the form of the Cosmic Microwave Background (CMB), the matter that made up the universe was isotropically smooth to one part per 100,000 Wright (2004). For reference, the surface of a billiard ball is smooth to one part in 300,000 Billiards: The Official Journal of the Billiard Congress of America (2013). To put this in better terms, in this early stage of the universe when the Inter Galactic Medium (IGM) was just beginning to form spatial over-densities which would later become galaxies, it was still three times smoother than a typical billiard ball.

Overtime, the universe transitioned from this uniform state, roughly three fourths hydrogen and one fourth helium Liu & Shaw (2020), to our modern clumpy, chaotic universe. We see through observational evidence that the hydrogen in the early universe was mostly neutral, and the hydrogen in the modern IGM is mostly ionized. This represents a transition we know must have happened. During this transition, the IGM underwent what many cosmologists refer to as a phase transition. We call it a phase transition because it changed the IGM in a fundamental way, just how water is so fundamentally different from ice.

We refer to this phase change as the Epoch of Reionization. During this time period, the smooth IGM collapsed in to objects which began to produce ionizing radiation. This light had enough energy to knock the electrons out of the neutral hydrogen in the IGM, eventually producing enough radiaton to fully ionize it.

This transition happened in bubbles which surrounded the first luminous objects. It began in small localized pockets and gradually spread out until the entire IGM was ionized. It is easier to think about this time period by putting it in to context. Although this paper concentrates on the Epoch of Reionization, we will briefly discuss the other happenings in the universe at this time, and put them in context with our early universe observations.

This work covers a basic view of the Epoch of Reionization. In section two, we contextualize reionization by putting it on a timeline. In section three, we explore the types of sources that drove reionization. In section four, we cover current experimental work to detect the Epoch of Rionization. Finally, in section five, we touch on current theory work on the epoch of reionization.

2. REIONIZATION IN CONTEXT

We start by considering reionization in the context of what else happened around this time period. After the big bang, the universe underwent several complicated chemical reactions and fundamental changes that are beyond the scope of this paper. During this period, the universe began ionized and underwent a period called "recombination" during which these particles came back together to form the neutral hydrogen in the IGM Liu & Shaw (2020). This is only relevant because the time period we discuss here is a re-ionization. The hydrogen has technically already been ionized, it just came back together. Other than this, for the scope of this paper, we will think of everything that happened between the big bang and the post-CMB neutral IGM as something that is certainly very interesting, but not relevant here so we will not discuss it.

As we mentioned in the introduction, the IGM proceeding the CMB emission was relatively calm, diffuse, neutral hydrogen. At this point in the universe, no light is emitted. There is no radiation, and everything is incredibly dark Liu & Shaw (2020). Some cosmologists believe there is light to be detected here, and we discuss this concept further in the Experimental Detections section of this paper. However, we can think of this time as a period of incredible darkness, and we call this the Dark Ages.

Eventually, the regions of diffuse IGM gas that are a bit more dense than neighboring regions collect more and more matter, and collapse to form the first luminous objects in the universe. These luminous objects, whose nature we discuss in the Reionization Drivers section, produce light with sufficient energy to ionize neutral hydrogen in the IGM.

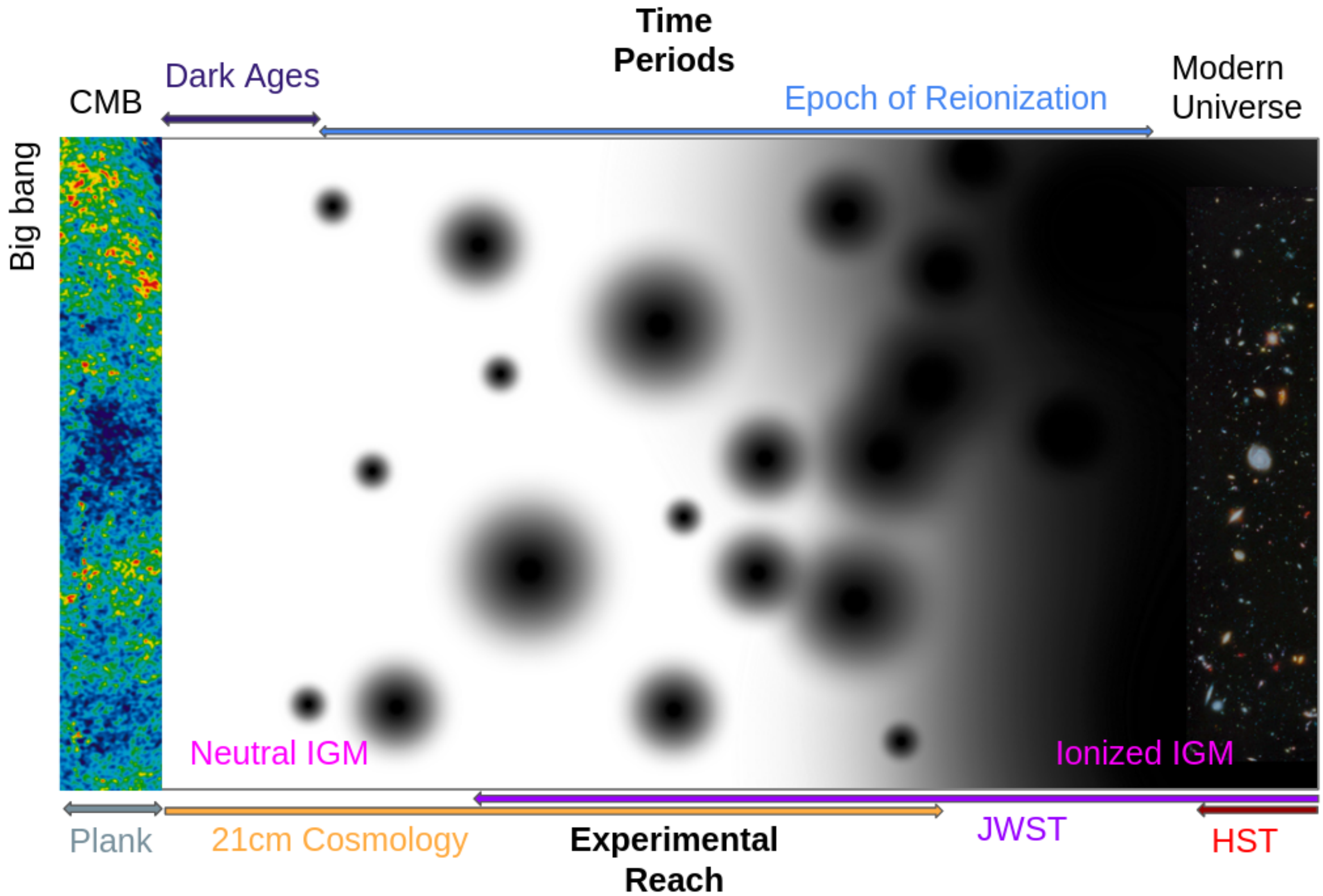

Figure 1. This figure is entirely original work. CMB pattern from NASA.gov plank data, Galaxy image is HST deep field from NASA.gov. Labels on the top of the figure indicate different period in cosmic time while labels below the figure indicate current working experiments and what portions of the universe they might see. We have not seen these axes combined in one figure in any previous work. White background represents a neutral IGM and black represents ionization bubbles, then a fully ionized IGM.

These objects begin to ionize their local IGM, and gradually spreading their ionizing radiation, forming larger and larger bubbles Liu & Shaw (2020). Gradually, these bubbles spread and join. More and more luminous objects form, and as the bubbles overlap they begin to encompass the IGM, forming the modern, largely ionized, IGM that we see today. The transitions between these time periods are illustrated in figure one.

We suspect that this reionization ended somewhere around z $\approx$ 5 Madau & Haardt (2015), but modern experiments hope to constrain this value. In the absence of an all-sky detection of this reionization transition, we can only guess at constraints. This shift happened in a very rough, bumpy manor. Due to this nature, we cannot extrapolate data from individual sources or smaller regions of sky out to an understanding of the entire picture. We need to understand how this transition happened across the whole sky.

3. REIONIZATION DRIVERS

Our view of the Epoch of Reionization comes from narrow views of individual sources. There has never been an all-sky detection of this time period, although this is a booming active area of research.

The first luminous objects that began reionization populated the universe with waves of Ly α photons Liu & Shaw (2020). While these photons can induce spin-flip transitions in neutral hydrogen, they are non-ionizing radiation and they eventually fade in to the Ly α background Liu & Shaw (2020).

As more sources begin to form and this Ly α background is well established, radiation in the IGM becomes dominated by x-ray heating from early luminous objects. This radiation is the first to have sufficient energy to ionize the neutral hydrogen, beginning the Epoch of Reionization Liu & Shaw (2020). While we focus our discussion on ionization of neutral hydrogen, roughly a quarter of the IGM is helium and it also begins to undergo ionization at this point. Now, both the neutral hydrogen and neutral helium undergo photoionization which create free photoelections. This causes a runaway heating, as the photoelectrons collide with more neutral particles and drive ionization Liu & Shaw (2020).

While we understand that this x-ray heating was a major driver, the question of what spit out all these ionizing photons remains a topic of debate. Without direct observations of the ionizing sources, determining what the primary drivers of this state shift were is left largely up to educated guesses. An obvious guess would be that many of the first luminous objects were galaxies. Another smart guess would be active galactic nuclei (AGN). We will learn more about which sources truly drove reionization as current experiments progress and as JWST continues to pick out objects from this time period, but for now this question an area of active research. We will explore two arguments, one that AGN primarily drove reionization, and another that star forming galaxies were to blame.

Star Forming Galaxies as Reionization Drivers

Some of the first strong evidence that star forming galaxies might be the drivers of reionization came with the launch of HST. In a Nature paper, it was reported that star forming galaxies seemed to be prevalent in the early universe Robertson et al. (2010). These early galaxies surely pumped the IGM with large amounts of intense ultraviolet radiation that would have been sufficient to drive reionization.

This study of early galaxies with HST data presents a compelling case that these galaxies may have been the main drivers of reionization. They were detected right around the time period that we expect reionization to have occurred and seem to be capable of producing a sufficient amount of ionizing photons. The study establishes a population of galaxies observed with HST's Wide Field Camera 3 (WFC) and use simulation data to consider the properties of radiation produced by these early galaxies.

Their simulations modeled ionizing photon flux based on a galaxies star formation rate, the ionizing photons produced by a given galaxy, the ionizing photons per unit star formation rate, and then modeled the fraction of these photons that would be capable of escaping the host galaxy Robertson et al. (2010). This gives a picture of the capability of these sources to drive reionization. If most of these galaxies can be assumed to be relatively dust-free, then it can be assumed that most of these ionizing photons will escape the galaxy and participate in reionization. If these assumptions hold, the study concludes that these early star forming galaxies could, and probably did, drive reionization. An example of one of these galaxies is show in figure two.

While this evidence is compelling, it is necessary to mention a key piece of new information. In recent months, spectroscopy from JWST's insturmentation has revealed that many of the star forming galaxies around redshfits where we expect them to interact with reionization are incredibly dusty, much dustier than we expected Donevski et al. (2023).

A key assumption from Robertson et al. (2010) was that these galaxies would have very little dust, and this may turn out to be incorrect, or there may be many more outliers than previously thought. As shown in figure 1, HST has trouble reaching these high-redshift galaxies. Robertson et al. (2010) presents no spectroscopic confirmations because, at the time, we did not have the technology to produce spectra for dim galaxies at these redshifts. JWST can reach back much further in time and is capable of confirming spectroscopicly that these star forming galaxies do, in fact, often have present dust.

AGN and Quasars as Reionization Drivers

Some more recent studies have indicated that Active Galactic Nuclei (AGN) could have been primary drivers for reionization Madau & Haardt (2015). Ionization may have been sustained by background ultraviolet emission from these AGN, which were present during the period of reionization.

The Madau & Haardt (2015) paper follows a very similar methodology to Robertson et al. (2010) but comes to a different conclusion. They note a population of AGNs between a redshift of z=4 and z=6 that could indicate these sources were present and producing sufficient ionizing radiation around the Epoch of Reionization.

The authors also point to CMB measurements from the plank satellite that suggest reionization may have ended by a redshift of $z = 6$. If this is true, they argue that AGN are one of the few objects that could have produced sufficient ionizing radiation to have wrapped up reionization this early in the universe, although they acknowledge that this was likely aided by early star forming galaxies.

However, this paper relies on the assumption that properties of AGN at higher redshift can be extrapolated from the properties of these lower redshift sources. While this may be true, we cannot definitively claim this without observational evidence. Both studies emphasize a need for observational data to come to a conclusion. Robertson

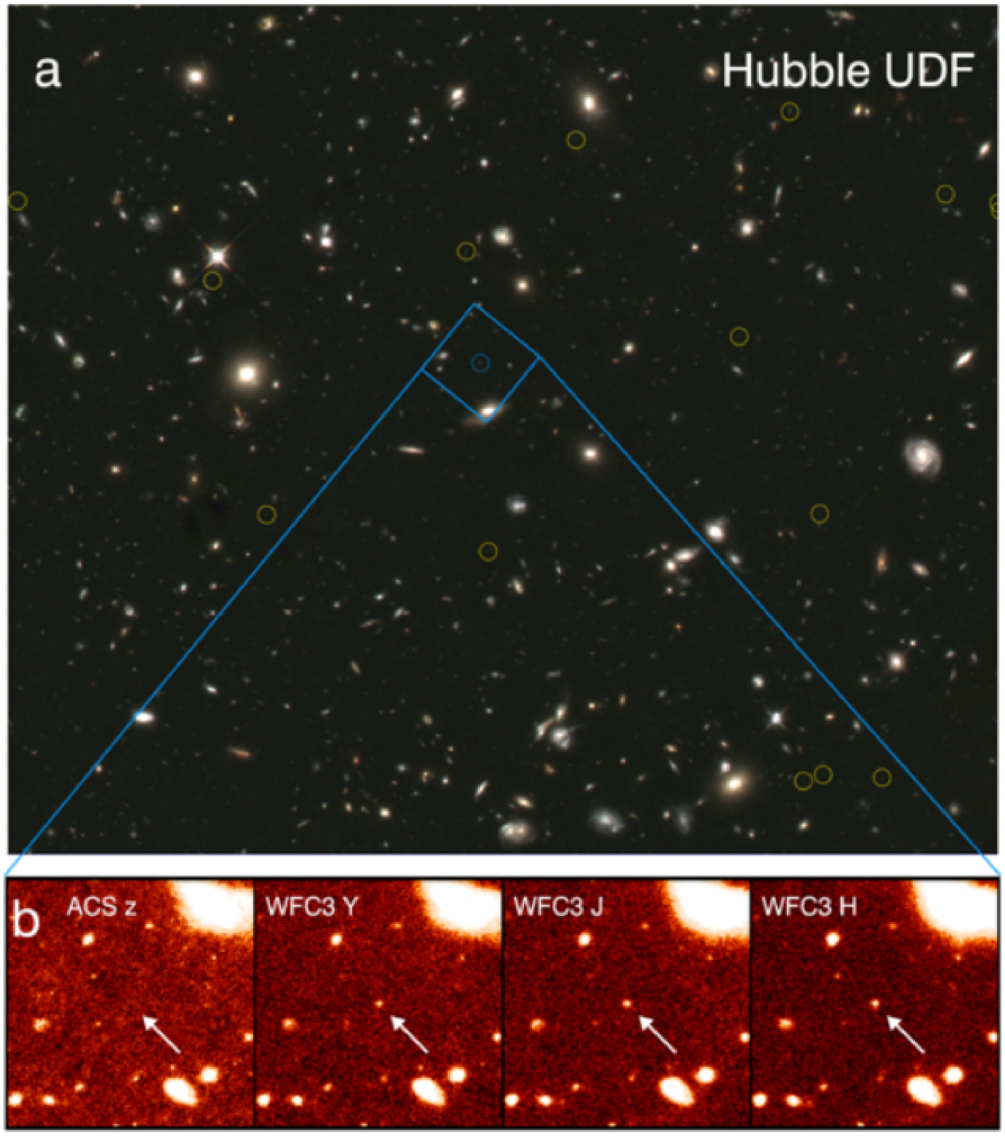

Figure 2. A galaxy from the Robertson et al. (2010) sample. Top panel shows field of view and bottom panel shows the source appearing in redder filters but not bluer filters, indicating a high redshift galaxy.

et al. (2010) even mentions JWST by name as the most likely source of resolution. The question of which sources drove reionization will see its best chance at an answer as more data from JWST develops.

4. EXPERIMENTAL DETECTIONS

To begin to discuss current experimental work on Epoch of Reionization direct detection, we need to return to the idea of what the universe looked like before reionization began. We need to think again about the universe filled almost entirely with neutrally charged hydrogen. These atoms have an extremely small chance of undergoing something called a hyperfine spin-flip transition when they come in close contact. This transition is rare it is considered quantum mechanically forbidden.

Luckily, astrophysicists have a long history of observing quantum mechanically forbidden transitions. When elements gather together in large quantities, these forbidden transitions become expected transitions. This transition in neutral hydrogen is so abundant that we can use it to trace the structure of the milky way and explore planetary nebulae. We know the transition exists, and we can reasonably expect that it occurred in the early universe, especially during the dark ages discussed in figure one.

The 21cm line

We begin with a discussion of the physics of this transition. When we say "neutral hydrogen" we are referring to an electrically neutral atom. It is composed of one proton, one neutron, and an electron. Each of these particles have a few inherent properties, like charge and mass. Another one or these properties is something called "spin" which is a quantity related to a particle's angular momentum. Although it sounds like it might be a measure of the way a particle is moving, it is more a measure of quantum mechanical effects on the particle so it is best to think of this as a property, just like charge or mass Encyclopedia Britanica (2023). This "spin" for an electron can occur in one of two directions. Each direction is associated with a different kind of magnetic field that is generated by the spin of the electron interacting with the proton in the center of the atom. We define this magnetic field as either parallel or anti-parallel Encyclopedia Britanica (2023).

When a neutral hydrogen atom is in isolation, this electron will sit at the lowest energy state that it can. In this state, we call the magnetic field anti-parallel. When this neutral atom collisionaly interacts with neighboring atoms, it gains some energy and the electron moves up to a higher energy state. As the electron moves up to this state, the magnetic field flips to a parallel alignment. We call this process a hyper-fine spin-flip transition Encyclopedia Britanica (2023).

Now that the atom is excited in to the higher energy state, it has some excess energy. The excited hydrogen atom will radiate away it's excess energy in the form of a photon, which has an emission wavelength of 21-cm Encyclopedia Britanica (2023). This is the photon we are so interested in detecting.

Imagine again the universe when it was mostly just neutral hydrogen. We would expect that this background 21-cm radiation covered the sky. It would have been the only light produced in the universe during this time predating stars. As those early bright luminous objects formed, they filled the universe with ionizing radiation and stripped this neutral hydrogen of its electrons. In their absence, the hydrogen is no longer capable to undergoing this spin flip transition. It has nothing to flip! It will never again radiate energy by 21-cm photons.

This is an incredibly important conclusion. It means that there was light emitted in this early universe at a very predictable wavelength and as stars and galaxies formed, they turned off this signal. So if we were to detect this background on the sky of 21-cm photons, we could not only detect matter distributions of the early universe, but map where, how fast, and how densely, the first luminous objects formed. We can take this idea another step further and assume that we could use observational information about this time period to start to uncover how dark matter played a role in early matter distributions Liu & Shaw (2020). In fact, this light is the only way to trace dark matter distributions up until the first bright objects formed, and the signal holds incredible cosmological significance. This background 21-cm radiation is the focus of modern experimental work to detect the Epoch of Reionization.

All Sky Detections

Attempts to detect this 21-cm signal are among some of the most sensitive radio detections being pursued today. This is a field where telescopes are just as much software as hardware and calibration is an art form. It is estimated that the astrophysical foreground, all the radio-bright objects between us and the Epoch of Reionization, are between 4 and 5 orders of magnitude brighter in flux than the signal its self Zuo et al. (2023). This presents an incredible challenge. The light is also highly redshifted, and telescopes operate at extremely low frequency ranges, on the order of 100s of MHz Zuo et al. (2023). This is a frequency range where humans are incredibly noisy in communications, and this needs careful consideration when it comes to calibration and data processing.

The field of 21-cm cosmology has established several conventions for mitigating this interference. Telescopes built for these low-frequency experiments are placed in the most remote areas on the planet, like the deep Australian outback where the Murchison Widefield Array (MWA) is located. Still, incredible consideration needs to be given to human-generated Radio Frequency Interference (RFI). Figure three shows how contaminated a typical observation is from the Murchison Widefield Array. Red streaks indicate contamination. We see uniform streaks in both directions. There are block streaks that are vertical, indicating some kind of RFI that was persistent at a particular time of the day of the observation. We also see horizontal stripes, corresponding to particular frequencies that are very contaminated. Often this corresponds to consistent interference from things like local television channels. Small blobs are less predictable, transient radio sources. All of these require careful mitigation.

The other half of this complicated puzzle lies in foreground mitigation. Because this science is incredibly sensitive and the foregrounds outshine the signal so drastically, this is one of the most important parts of data processing. Shortfalls in this particular part of the data handling pipeline consistently lead to misreporting of redshift limits and false positives. In the worst cases, mishandling of foreground processing can lead to retractions of papers that were

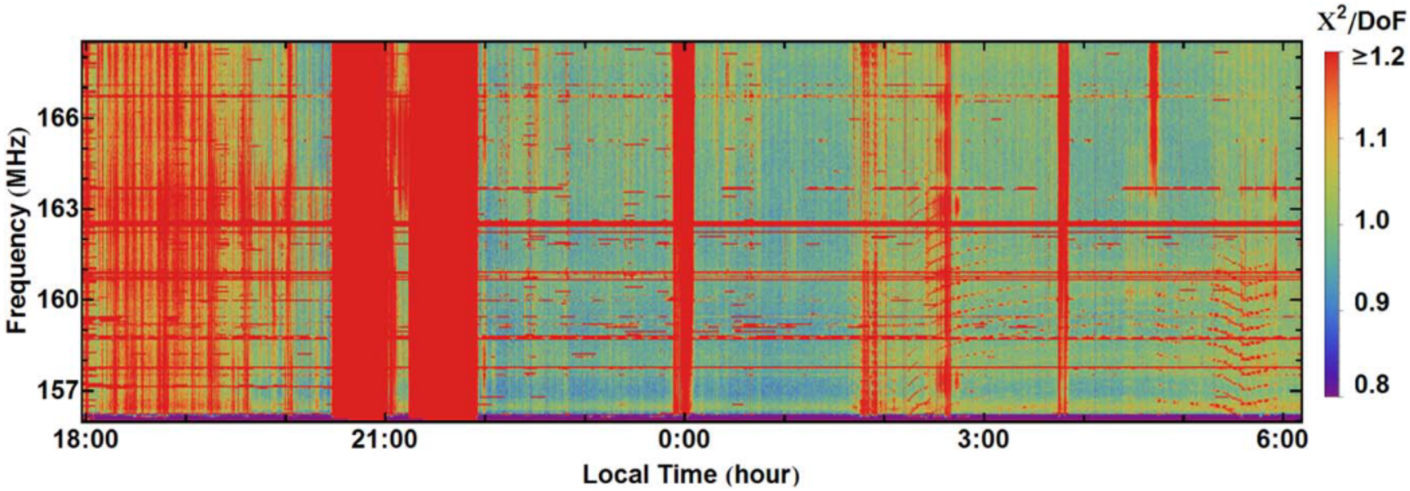

Figure 3. Typical RFI contamination from an observation taken at the Murchison Widefield Array Liu & Shaw (2020).

thought to carry fundamental importance. This happened with the Precision Array to Probe the Epoch of Reionization (PAPER), which had ramifications for not only the papers that came out over years of data that had been incorrectly foreground calibrated, but for a telescope that had been built under the assumption that these redshift limits were correct.

Needless to say, foreground modeling is incredibly important for 21-cm cosmology. There are many flavors of foreground mitigation in this field. One of the most consistently used methods involves something called a foreground wedge.

Radio observations are inherently taken in Fourier space. We know the Epoch of Reionization did not happen uniformly across the whole sky, but in bubbles that gradually joined together. Because of this structure, we expect the signal to be "bumpy" across the sky. This structure to the signal means that it appears in only a specific modes of fourier space Liu & Shaw (2020), and this is a good place to start in removing foregrounds. This technique is often referred to as "foreground avoidance".

We think of this fourier space in terms of "k modes". These are the individual components of the fourier space, just like in a normal fourier transform where k values represent smaller waves that make up the whole function. We express these k modes in a power spectrum in terms of $k_\perp$ and $k_{||}$. These $k_{||}$ modes represent modes parallel to the line of sight of the telescope and the $k_\perp$ modes are perpendicular to the line of sight. The power spectrum is expressed in equation one.

$$P(k_\perp, k_{||}) = \frac{1}{N_{k_\perp, k_{||}} V} \Sigma_{k_\perp} \Sigma_{k_{||}} |T_{obs}(k_\perp, k_{||})|^2 (1)$$

Here, $k_\perp$ and $k_{||}$ are the k modes defining a cylindrical power spectrum P Liu & Shaw (2020). T_{obs} is an integral defined by equation two.

$$T_{obs}(k_\perp, k_{||}) = \int_{-\infty}^{\infty} dr_\perp^2 dr_{||} e^{-i(k_{||} r_{||} + k_\perp r_\perp)} T(r_\perp, r_{||}) (2)$$

T represents a 3-D Fourier transform of the sky, and V a transform along the line of sight Liu & Shaw (2020). Although this math can be a bit much to look at, we can think about what is happening here in simpler terms. This power spectrum is formed by averaging over lots of individual rings. These rings all have a radius of $k_{||}$, which is a bit more apparent if we look at the layout of the infinitesimals in the integral of equation 2. These averaging rings are located at values of $\pm k_{||}$. Each of these rings will contain a number of k modes that we specify in equation one as $N_{k_\perp, k_{||}}$ Liu & Shaw (2020).

Now that we've defined mathematically what we mean when we consider a power spectrum in terms of 21-cm cosmology, we can look a little deeper in to how these affect our ability to mitigate foregrounds. It is best to begin

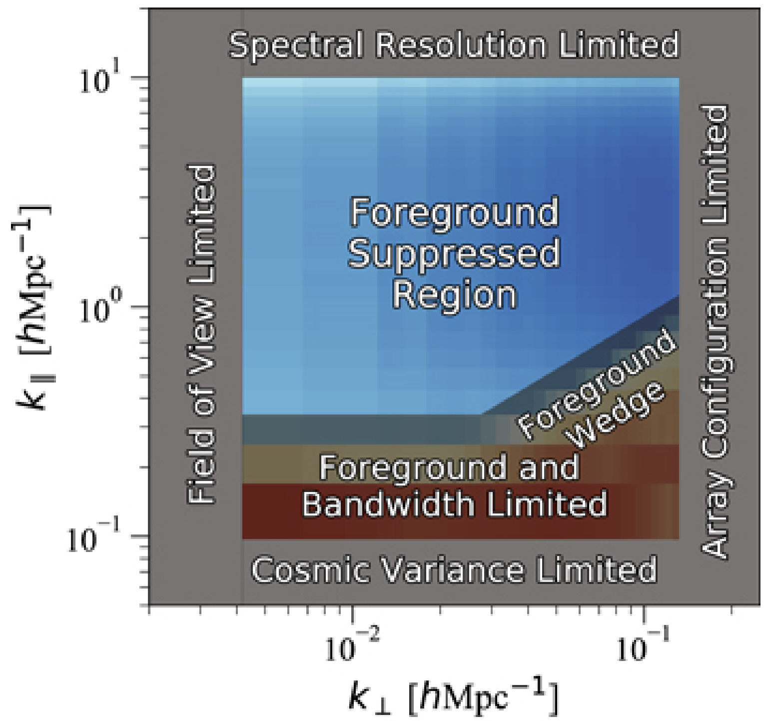

Figure 4. Cartoon of a power spectrum Liu & Shaw (2020).

thinking about the power spectrum by looking at one. Figure 4 represents a cartoon of what a power spectrum looks like.

This diagram is great for thinking about how different k modes affect the observation. First, the $k_{||}$ mode is the mode parallel to a telescope's line of sight. These modes are limited by the field of view and layout of the telescope. The astrophysical foreground occurs in lower $k_{||}$ modes, closer to the telescope. The $k_{\perp}$ modes are sensitive to sky variance. Again, these are modes sensitive to fluctuations perpendicular to the line of sight of the telescope. Something like an astrophysical source would highly vary in this space, so they occur in the lower modes. This leads to a wedge, at the lower right corner of the plot. Because these foregrounds occur in lower modes, mitigation can start with simply avoiding them. Foreground mitigation is a complex science and no easy task, but traditionally it starts here with avoidance of the foreground wedge.

Individual Source Detection

One area that we do have some initial reionization detection in is individual sources. We have already covered a bit of this in our discussion of reionization drivers. We have managed to image and analyze individual sources that probably contributed significantly to reionization. However, this is like studying cosmic history through a straw. We expect reioniztaion to be patchy and occur in bubbles across the sky that gradually join. Individual sources tell us very little about this all-sky transition. An example of one of these sources is shown in figure 5.

As mentioned in the introduction to this paper, we expect that reionization ended around z = 5. At z = 10.6, we can reasonably expect that reionization should still be happening. The universe should be in the process of undergoing its state transition at the point on cosmic time that we observe this galaxy. We can get a very accurate measurement of the redshift from this spectra. The emission lines and Lyman break line up well with a redshift z = 10.6 galaxy, as illustrated in the lower panel of figure 5. However, something strange is going on here. In the top panel, we see are zoomed in on the bluer region of this spectra. This small blip in the spectra has potentially serious implications for cosmology. What we are seeing is Lymanα radiation. This radiation is eaten up by neutral hydrogen and we expect to see no Lymanα photons if this galaxy is in a part of the universe where the IGM is not yet reionized. This could mean that this galaxy, at z = 10.6, exists in a universe where reionization had already occurred.

This has wild implications for cosmology, especially 21-cm experimental cosmology. Within weeks of the publication of this paper, another was published claiming that this detection could be extrapolated to conclude that the universe could not possibly be more than 88 % neutral hydrogen at this point Bunker et al. (2023). This would mean a universe

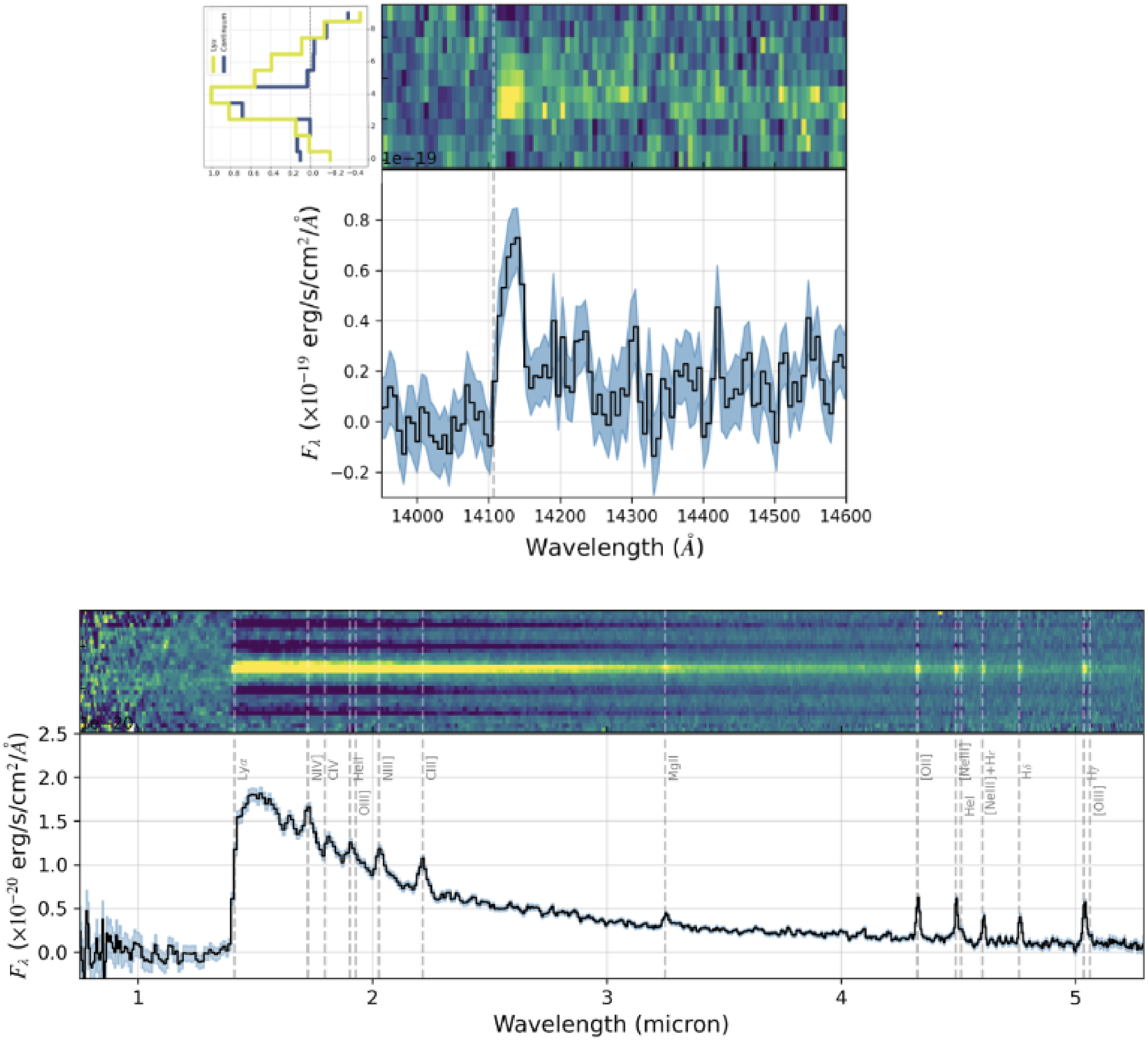

Figure 5. Spectra of a redshift $z \approx 10.6$ galaxy Bunker et al. (2023)

where ionization happened much quicker than we could have imagined, in a way that we have little simulational agreement with and could mean 21-cm cosmology detections are more difficult than previously accounted for, or even not possible at all.

However, this is not quite reason for panic. We have to remember that looking at individual sources is doing cosmology through straws. This does not necessarily break our understanding, and we should not rush to conclusions over a single source. This galaxy is incredibly bright even at such a distance, so it is not shock that it is surrounded by a bubble of ionized IGM. But, we should keep a watchful eye on the sources that will continue to be published as JWST looks out into this reionization period. We may see strong conclusions about this mysterious period in cosmic time over the next few decades as experimental capabilities improve.

5. THEORETICAL WORK

Modern Epoch of Reionization theory work centers for the most part around simulation work. The biggest obstacle to modern theoretical work on the Epoch of Reionization is the lack of observational evidence. Without all-sky data, simulations lack necessary constraints. If the detection work discussed previously is successful, simulations could begin to form extremely accurate, well-defined simulations of this period in the universe which could tell us about matter and dark matter distributions, and how these evolved over cosmic time.

Although there are many teams working with wide varieties of soft ware to simulate this time period, we will concentrate our discussion on one of the most rigorous surveys to date. The Cosmic Dawn III recently released a trillion element simulation in 2023 that combined theoretical and observational data, making it arguably one of the most rigorous surveys Lewis et al. (2022).

The simulation took several approaches that differed from previous simulation work. The simulation grid had a much finer mesh than previously used along with a larger cosmic volume, which allowed for a more fine-tuned picture of the IGM and how it interacted with early luminous sources. This work also gave special attention to feedback from sunpernovae and how this played a role in the reionization transition. The simulation included a wide variety of sources, including both bright quasars and star forming galaxies as we discussed in section three. Putting all these pieces together, this simulation was able to show that the mean free path of ionizing photons around $z = 6$ is relatively short Lewis et al. (2022). This means that ionizing radiation did not have to move far, only a few hundred parsecs, around $z = 6$ before it interacted with particles in the IGM. In other words, the universe was likely just about completely ionized at this point.

This conclusion is a little surprising. The researchers note that additional sources of ionizing radiation are needed to account for reionization finishing so soon Lewis et al. (2022). This is yet another point where we get to mention that observational evidence is of dire importance to understand this time period. With better observations, we can improve our simulations and better understand the early universe.

6. CONCLUSION

The Epoch of Reionization was a fundamentally important period of cosmic time, for which we have little observational data. We know this transition occurred. We have gone through plenty of evidence for it, including both observations and simulations. Yet, we lack a definitive, all-sky look at this period. The coming years and decades will shed a new light on this mysterious chunk of cosmic time. The photons are there. Somewhere hidden behind galaxies and human radio interference, there is an answer to our questions about reionization. We can only hope to one day make the detection that finally fills in this piece in our puzzle of cosmic time.

AI Usage Disclosure: Chat GPT, and AI chat bot, was utilized in the generation of sources for this paper. Sections were described in limited detail and Chat GPT was asked to provide lists of papers that might be relevant to this work. The chat bot had no hand in the generation of any text or figures used in this paper. Chat logs are available if requested.

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