

# Exploring the Epoch of Reionization: Insights from Next-Generation Telescopes

Shiming Liu \*

Basis International School Guangzhou, Guangzhou, 510000, China

\* Corresponding Author Email: ming.liu17172-bigz@basischina.com

**Abstract.** The Epoch of Reionization (EoR) is a pivot in the history of the universe when filled with neutral hydrogen gas transit to a universe filled with ionized gas due to large-scale ionization processes, and is one of the biggest mysteries in modern cosmology. Nevertheless, scientists remain uncertain on the overall timing of reionization, the primary cause of this energy, and the intricacies of the distribution of ionized bubbles, because there is no direct way to observe such a remote era. This paper review what scientists know about the EoR, present the shortcomings of current facilities, and demonstrate the transformative prospects for spectacular new facilities. This paper address what next-generation instruments such as the James Webb Space Telescope, the Square Kilometer Array, the Nancy Grace Roman Space Telescope, and Extremely Large Telescopes will accomplish in this realm. Such next generation instruments provide new sensitivity, resolution, and sky coverage. Key science goals, the advantage of multi-wavelength observations and some major challenges are also presented in the paper. This paper summarizes how the EoR may ultimately be understood, and stress that it has great potential for refining the state-of-the-art in cosmology as well as in understanding of the galaxy evolution.

**Keywords:** Reionization, cosmic dawn, JWST, SKA, 21 cm cosmology.

## 1. Introduction

One of the most remarkable events in cosmic history was the Epoch of Reionization (EoR)—the transition occurring at the epoch of first stars and galaxies between redshifts  $z \approx 6$  and 15 (approximately 380 million to 1 billion years after the Big Bang), due to radiation from the first stars and galaxies ionized the primordial HI present in the IGM [1]. This transition from cosmic “dark ages” to a transparent cosmos is one of the last great phase transitions in cosmic evolution, and a key frontier of observational cosmology.

Knowledge of the EoR is important for two main reasons. The first of these is that it presents a clear probe into the birth and assembly of the first stars (Population III stars), early galaxies, and possibly the first active galactic nuclei (AGN) fuelled by black holes [2]. Nature of such objects, and their complex mechanisms in altering their vicinity through radiation, explosions, chemical enrichment (feedback processes), and efficiency of producing and ejecting the important ionizing photons (Lyman continuum; LyC) into the IGM, etc., have been the most unresolved questions. Secondly, during the reionization epoch, the IGM temperature and ionization state was drastically changed, which has left persistent effects on the formation of late-time galaxies, as well as observable features in these galaxies [3]. Thirdly, EoR occurs provides useful and powerful tests for both the cosmological model and the theoretical model about the growth of structure in the Universe, other than ways from measuring the cosmic microwave background (CMB) and the baryon acoustic oscillation (BAO) [4]. In addition, The ionization patterns emerging during this epoch additionally preserve valuable insights into primordial density fluctuations from the post-Big Bang era [1].

Although of primary interest, it has turned out to be very difficult to obtain direct observational confirmation about the EoR. Due to the large distances involved the important spectral features are shifted deep into the infrared (IR) part of the spectrum and, at the same time, increasing amounts of HI means the IGM is ever more opaqued to Ly $\alpha$  photons [5]. Despite these indirect clues from observations of high-redshift quasars and galaxies, small samples, possible biases in selection of these objects, and huge challenges in determining whether the photons are actually ionizing photons that

are escaping into the IGM [6]. The 21 cm radio emission from HI is a potentially direct method for probing the neutral IGM. But the challenge here is detecting a faint signal with noiseful contamination from a multitude of other radio sources and instrumental effects, which is not insubstantial for probing neutral IGM [7].

Thus, scientists currently knowledge of the EoR based on CMB polarization observations alone (notably the electron scattering optical depth  $\tau_e$  measured by Planck), inferences by statistical analyses of high redshift galaxies and quasars have to date been incomplete and highly dependent on modeling. Numerous unresolved questions persist, including the temporal evolution of the global neutral hydrogen fraction ( $x_{\text{HI}}$ ), the spatial distribution and morphological characteristics of ionized regions ("reionization bubbles"), the comparative significance of various ionizing sources (low-luminosity galaxies, luminous galaxies, active galactic nuclei), and the impact of diverse feedback mechanisms.

The advent of next generation telescopes will revolutionize this field. These next generation facilities, across different regions of the light spectrum and employing a variety of new techniques provide the sensitivity, sharpness, and capacity to survey large areas required to directly detect the sources that drive reionization and map the evolving ionization state of the IGM. This paper discusses the prospective science on the EoR with these state-of-the-instruments. This paper presents a review of the theoretical picture of the EoR and the observational status; describes the particular reach of future telescopes, such as the James Webb Space Telescope (JWST), Square Kilometer Array (SKA), the Nancy Grace Roman Space Telescope and Extremely Large telescopes (ELTs) and their main scientific objectives and their synergies; describes main challenges; and comments on the future of the subject.

## 2. Theoretical Background

The EoR is defined as the period when the predominantly HI gas filling the space between IGM since recombination ( $z \approx 1100$ ) was reionized. This transition occurred as the first luminous objects began emitting enough high-energy photons (with energy greater than 13.6 eV) capable of stripping electrons from hydrogen atoms. Rather than happening all at once, reionization was a complex, uneven process across space. It was driven by the formation and growth of ionized bubbles around clusters of bright sources; these bubbles eventually overlapped and merged to completely ionize the IGM [1].

Several key phenomena characterize the EoR. The formation of the first stars (Population III), likely massive, metal-free objects born in small clumps of dark matter at  $z > 20$ –30, began producing significant UV light [8]. Feedback from these stars, particularly through radiation evaporating their birth clouds and supernova explosions enriching nearby gas with metals, played a critical role in regulating later star formation and paving the way for the first true galaxies within larger dark matter halos ( $M_{\text{halo}} > 100$  million solar masses). These early galaxies became increasingly important sources of ionizing photons as time went on. Radiation from these galaxies could stifle star formation in smaller nearby halos by heating the IGM and evaporating their gas, while supernova explosions could blast gas out of galaxies with weak gravity, further controlling the growth of ionizing sources [2]. The fraction of ionizing photons, or the escape fraction ( $f_{\text{esc}}$ ), that actually escape from these galaxies into the IGM is a critical, yet poorly understood, factor determining how efficiently reionization proceeded. It is poorly understood because the majority of cosmic simulations are still inserting the escape fraction as a constant value; but in reality, based on observations, the escape fraction does changes within different redshift.

Directly observing these processes faces huge observational obstacles. The main challenge comes from cosmological redshift: light emitted by sources during the EoR ( $z \sim 6$ –15) is stretched by factors of 7 to 16 times its original wavelength. This shifts crucial spectral fingerprints like Ly $\alpha$  (normally at 1216 Å) deep into the near- and mid-infrared (0.85–19.5  $\mu\text{m}$  as we observe it), where observations from the ground are severely hampered by Earth's atmosphere and heat radiation [8]. Furthermore, the rising amount of HI at higher redshifts efficiently absorbs Ly $\alpha$  photons, making the detection of

$\text{Ly}\alpha$  emission from galaxies within or before the peak of reionization very difficult [4]. Cosmic dust, created in the first supernovae and present in early galaxies, adds another layer of difficulty by blocking UV and visible light. Finally, detecting the incredibly faint cosmological signals, especially the global or 3D map (tomographic) of the 21 cm emission from HI, demands extraordinary sensitivity and sophisticated methods to separate the desired signal from much stronger contaminating signals and instrumental noise [9].

### 3. Current Understanding of the EoR

Using current telescopes, some amount of the EoR has been pieced together. High- $z$  quasar spectroscopy via surveys such as the Sloan Digital Sky Survey (SDSS) provided evidence for absorption troughs in high-redshift spectra at  $z > 6$  which demonstrates an exponentially rising neutral fraction of hydrogen at this epoch [10]. More sensitive, though model-dependent, estimates of  $x_{\text{HI}}$  for certain lines of sight have been obtained through observing the  $\text{Ly}\alpha$  damping wing absorption in the spectra of the most far-distant quasars and galaxies [11].

The Hubble Space Telescope (HST), especially through deep imaging projects like the Hubble Ultra Deep Field (HUDF) and Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS), has pushed the discovery of galaxies out to  $z \sim 10$ –11. Studies of how the number of galaxies at different brightness levels evolves (the UV luminosity function, LF) suggest that faint galaxies are numerous enough to potentially drive reionization, if a sufficient fraction of their ionizing photons escape. Measurements of the strength of  $\text{Ly}\alpha$  emission and how common  $\text{Ly}\alpha$ -emitting galaxies are at different redshifts provide indirect clues about the neutral fraction, because HI scatters  $\text{Ly}\alpha$  light. A noticeable drop in the fraction of galaxies showing strong  $\text{Ly}\alpha$  emission at  $z > 6$  supports the idea of an increasingly neutral IGM [12].

The Atacama large millimeter/submillimeter Array (ALMA) has enabled us to constrain the nature of early galaxies by extending the submillimeter infrared light and the far-infrared and other, including ionized carbon fine-structure, lines into the far-infrared ( $158\mu\text{m}$ ) from  $z > 6$ , with occasional glimpses into surprisingly formed systems early on [13].

Cosmological constraints mainly come from the CMB. The Planck satellite's precise measurement of how much CMB light was scattered by free electrons ( $\tau_e \approx 0.054 \pm 0.007$ ) implies that reionization was a relatively drawn-out process, likely starting around  $z \sim 10$  and finishing by  $z \sim 6$  [4], suggesting a midpoint near  $z \sim 7.5$ –8.

Despite these advances, critical gaps in existed knowledge remain. The exact timeline (when it started, peaked, and ended) and how uneven EoR was across space are still poorly known. There is ongoing debate about the main sources of ionizing photons: are they mostly faint galaxies, brighter galaxies, or black hole-powered AGN? Direct detection of escaping ionizing radiation from galaxies at  $z > 6$  is still very rare and hard to confirm [14]. The role of AGN, especially at high redshifts, is highly uncertain. Furthermore, the detailed structure of reionization—the sizes and clustering of the ionized bubbles—remains largely unmapped by observations. Answering these fundamental questions requires telescopes capable of directly probing both the sources and the state of the IGM during the heart of the EoR.

### 4. Next-Generation Telescopes and Their Capabilities

The limitations of old telescopes highlight the urgent need for next-generation facilities specifically designed to tackle the EoR. These instruments offer huge improvements in sensitivity, image sharpness, and ability to survey large areas quickly.

#### 4.1. James Webb Space Telescope (JWST)

Launched in December 2021, JWST is the leading observatory for near- and mid-infrared astronomy. Its large 6.5-meter primary mirror, operation in deep cold, and suite of advanced instruments (NIRCam, NIRSpec, MIRI, NIRISS) provide unmatched sensitivity and sharpness across a broad infrared range [15]. For EoR studies, JWST excels at finding and characterizing galaxies deep into the reionization epoch ( $z > 10$ ) through extremely deep imaging. It can obtain spectroscopic redshifts and measure detailed physical properties (like stellar masses, ages, star formation rates, metal content, dust levels) for high-redshift galaxies using near-IR spectroscopy. This crucially includes detecting Ly $\alpha$  emission and potentially finding signatures of escaping ionizing radiation. JWST also probes the stellar populations within the first galaxies and investigates AGN activity at high redshifts.

#### 4.2. Square Kilometer Array (SKA)

Currently under construction, the SKA will be the world's largest radio telescope, made up of thousands of antennas in South Africa (SKA-Mid) and Australia (SKA-Low). SKA-Low (operating at low radio frequencies, 50–350 MHz) is specifically built to detect the highly redshifted 21 cm signal from HI during the Cosmic Dawn and EoR ( $z \sim 6$ –27) [16]. Its unique power lies in directly mapping the HI by measuring fluctuations in the 21 cm brightness temperature. This enables creating 3D maps (tomography) of the neutral IGM and visualizing the evolving structure of ionized bubbles. SKA-Low might also detect the average (global) 21 cm signal across the sky, offering another way to track the evolution of the neutral fraction. Its incredible sensitivity and speed allow deep, wide-area surveys tracing the hydrogen distribution.

#### 4.3. Nancy Grace Roman Space Telescope

Scheduled for launch in the late 2020s, Roman features a 2.4-meter mirror and a wide-field near-infrared camera with a field of view over 100 times larger than HST's main camera [17]. Roman's main contributions to EoR research will come from its ability to conduct rapid, deep surveys over enormous areas of the sky. This will discover large numbers of rare, bright galaxies at  $z > 6$  and potentially identify large ionized bubbles or structures during reionization. Roman provides the statistical power needed for robust measurements of galaxy numbers at different brightness levels (luminosity function), how galaxies cluster together, and how the prevalence of Ly $\alpha$  emission changes over vast cosmic volumes—essential for understanding the sources and large-scale structure of reionization. Roman also acts as a powerful scout, identifying prime targets for detailed follow-up study with JWST over large regions.

#### 4.4. Extremely Large Telescope (ELTs)

Ground-based telescopes like the European ELT (39m), the Giant Magellan Telescope (GMT, 24.5m), and the Thirty Meter Telescope (TMT, 30m) will achieve incredibly sharp images in the near-IR using advanced systems to correct for atmospheric blurring (adaptive optics) [18]. Their strengths include obtaining extremely detailed spectra (showing motions, variations in metal content, gas flows) for bright galaxies at  $z \sim 6$ –10—something impossible with current ground-based telescopes. In addition, ELTs can study fainter galaxy populations over smaller patches of sky, complementing JWST's wider views. By this way, ELTs are ideal for detailing observations of interesting objects discovered by JWST or Roman.

In total, next-generation telescopes represent a huge step forward: JWST and Roman provide complementary deep and wide views of the galaxy populations driving reionization; SKA provides the ability to directly map the HI gas occupying the early universe; while ELTs add extremely high spatial-resolution to the most luminous objects. In addition, ELTs' integrated sensitivity will yield observations of much fainter objects and structures, and their greatly improved sharpness will permit investigation of galaxy shapes and intrinsic detail at high redshift. Nevertheless, the much larger

mapping rates of Roman and SKA will trace enormous volumes of cosmic history that are pivotal to understanding of the large scale structure and bubble-like morphology of reionization.

## 5. Key Scientific Goals and Strategies

Next-generation telescopes are effective tools to study the key questions related to the EoR, which falls into two connected streams: detection and characterization of the EoR sources, and mapping of the IGM ionization state.

For the detection and characterization of the EoR sources, one of the key will be to probe the first galaxies. JWST is already pioneering this field by finding candidate galaxies out to  $z > 12$  and getting spectra for systems out to  $z \sim 7\text{--}11$ . Deep JWST and Roman Space Telescope surveys will in the future constrain the UV luminosity function deep into the EoR, constraining the abundance and intrinsic brightness of possible ionizing sources. The spectroscopic capabilities of JWST will constrain fundamental parameters—stellar masses, ages, star formation histories, metallicity and the extent of dust absorption—for large samples of galaxies at  $z > 6$  [19]. Understanding whether or not direct observational evidence of Lyman continuum photon escape is an important, yet poorly constrained, parameter. ELTs will have access to high-resolution gas kinematics and chemical inventory in most suitable targets in follow-up campaigns.

Simultaneously, a primary science focus is the direct imaging of the ionization structure of the universe. SKA-Low will enable 21 cm tomography where the fluctuations of the 21 cm signal directly trace the underlying distribution of neutral hydrogen and eventually the evolution of the morphologies of the ionized bubbles. This will directly open up the regimes of characteristic sizes and clustering properties of these bubbles, verifying inhomogeneous reionization models driven by clustered sources. The most powerful tool will be the cross-correlation of SKA's maps of neutral gas with the position of galaxies traced by JWST and Roman surveys, directly associating bright sources with their imprint on the nearby IGM.

Finally, only a multi-wavelength, synergistic approach will ultimately solve the problem of the relative contributions made by faint galaxies, bright galaxies and AGN to the budget of ionizing photons. JWST will survey for AGN, and characterize the ionizing power of galaxies. Roman will sample at large fields the galaxy clustering that sets bubble size. SKA will reveal the topology of the ionization sensitive to clustering and luminosity of the main sources. To break it down, by matching observations of the reionization history—as measured from CMB data, through quasar spectra, from Ly $\alpha$  forest studies, and from the global 21 cm signal—to those predicted from galaxy population models constructed using JWST and Roman data, scientists should be able to extract the dominant actors in the reionization story. The possibility of detecting a large population of AGNs at  $z > 6$  with JWST would certainly require a radical refinement of present models. It is exactly this, multi-dimensional synergy, that is necessary to break the degeneracies from a single-probe observation, and the construction of full and physically-motivated picture of reionization.

## 6. Challenges and Opportunities

Although next-generation telescopes promise unprecedented opportunities for exploration of the EoR, important technical and analysis challenges remain to be met to maximize their potential. One major challenge remains technical and observational in nature. The greatest challenge for the SKA will be separating the extremely low strength cosmological 21 cm signal from the highly contaminating foregrounds from Galactic synchrotron emission and extragalactic radio sources, and from complicated instrumental effects [20]. While advanced foreground removal strategies are actively being developed, this remains the critical field of investigation. Likewise, the precision of the calibration to required accuracy is essential for SKA telescope. For JWST and the Roman Space Telescope, avoiding the impact of cosmic variance in the ultra-deep fields requires observation of

many, widely distributed areas of the sky. And secure spectroscopic confirmations of the faintest galaxies at highest redshifts remain a challenge.

The unprecedented volume and complexity of data generated by next-generation observatories like SKA, JWST, and Roman introduces significant new challenges. SKA alone is projected to generate exabyte-scale datasets, while JWST and Roman will contribute equally massive and intricate data streams. This immense data load demands the creation of entirely new frameworks for storage, management, and processing. Building robust, automated pipelines specifically for SKA's 21 cm cosmology objectives requires vast computational resources and sophisticated algorithms. Similarly, the synergistic analysis of combined multi-wavelength data—incorporating imaging, spectroscopy, and radio interferometry—necessitates innovative statistical methods and highly efficient, interoperable data fusion techniques.

These formidable challenges underscore the critical need for advances in data science and machine learning (ML). In recent years, ML algorithms, particularly neural networks, have emerged as leading solutions for developing effective foreground removal techniques essential for analyzing 21 cm data. Artificial Intelligence (AI) is increasingly indispensable for automating tasks such as source detection and classification in deep imaging surveys, spectroscopic redshift determination, and identifying rare or anomalous objects. Furthermore, sophisticated statistical inference techniques and simulation-based analyses are becoming vital for extracting reliable cosmological parameters from these complex, interconnected datasets.

Ultimately, realizing the full potential of EoR science hinges on an unprecedented level of global collaboration. Multi-messenger astronomy, and big science in general, is inherently an international endeavor. Maximizing the scientific return from flagship projects like SKA, JWST, and the ELTs requires a concerted effort: establishing effective open data sharing policies, standardizing data formats and analysis pipelines, and fostering consortia dedicated to collaborative data analysis. Initiatives such as the International SKA Science Data Challenge and the various JWST/ERS/GO programs are crucial for building the necessary foundational infrastructure and cultivating the global community commitment needed to transform these challenges into breakthrough scientific discoveries.

## 7. Future Outlook

The combined capabilities of next-generation telescopes will usher in a transformative era in our understanding of the EoR, with profound implications across multiple related subfields. Foremost among these advances will be the capability—provided by JWST and the Roman Space Telescope—to image and measure tens of thousands of galaxies at redshifts  $z > 8$ . This will yield robust constraints on their physical properties, the shape of their luminosity functions, and their space densities throughout the reionization era. Spectroscopic confirmation of the  $z > 12$ –15 galaxies will be a routine, which will deliver the first consistent measurements of stellar populations and metal enrichment histories of the time when the universe was the first billion years old.

At the same time, SKA-Low should be in a position to definitely detect the 21 cm power spectrum from EoR itself within few years of science with SKA, eventually mapping this with high fidelity to 3D tomographic mapping of HI. Such measurements will detect the actual shape and clustering of ionized bubbles across the reionization history providing much information on topology of ionization.

Importantly, when scientists combine the multi-wavelength observable, they will achieve a comprehensive and accurate reionization history reconstruction. Scientists can constrain the evolution of the global neutral fraction in synergy with galaxy redshift surveys of JWST and Roman, SKA 21 cm maps, Ly $\alpha$  forests, and CMB constraints, separate faint-galaxy, bright-galaxy and AGN contributions to the budget of ionizing photons. In addition, constraints to the Lyman continuum escape fraction from highredshift galaxies will be more easily achieved.

These discoveries will also have deep impact outside of reionization itself. Accurate measurement of the time and width of the EoR will independently test cosmological models in particular dark matter and small scale structure in the very first moments of the universe. Conversely, an extensive account of the manner in which the reionization proceeded, which aspect has a crucial significance in suppressing the star formation in low mass halos (hence determining both faint ends of the galaxy luminosity function and baryon contents of dwarf galaxies of the late universe).

## 8. Conclusion

The study of EoR represents one of the challenges that cosmology is addressing, providing a window into the period between the CMB-dominated early Universe and the galaxy-dominated Universe that is observable today. Although the contribution of facilities such as HST, ALMA, and Planck have improved the knowledge significantly, important questions still remain on the EoR time scale, nature of the major ionizing sources, and spatial nature of reionization in this transition period due to observational constraints. The next decade of gravitational wave detectors and millimeter wave, far infra-red and x-ray telescopes heralds an exciting era with developments on JWST, SKA, Roman and ELTs. JWST and Roman will characterize the galaxy populations responsible for reionization. SKA will directly map neutral hydrogen to trace the evolution of ionization bubbles, while ELTs will provide high-resolution spectroscopy of prime targets. Collaboration between these facilities is vital: multi-wavelength data will break degeneracies in reionization models and place strong constraints on the escape fraction of ionizing photons. However, 21 cm surveys with SKA face significant computational challenges, primarily due to intense foreground contamination. Overcoming these will require advances in machine learning (ML) and multi-institute cooperation—cooperation that, to be most effective, will likely depend on robust data sharing policies and coordinated observational campaigns. The resulting discoveries will have profound implications extending beyond EoR and cosmology, potentially constraining dark matter models and illuminating processes in the early Universe. Sustained investment in these observatories remains crucial to unraveling the secrets of the cosmic dawn.

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