

INTRODUCTION

Now entertain conjecture of a time, when creeping murmur and the poring dark fills the wide vessel of the universe.

- William Shakespeare

1.1 Cosmic Dawn and the Epoch of Reionization: an overview

According to current understanding, the universe came into existence with a Big Bang approximately 13.7 billion years ago. Universe got cooled as it expanded adiabatically, and over time, different ingredients of our universe such as quarks, protons, neutrons, and then electrons froze out. Finally, about 380,000 years after the Big Bang, neutral hydrogen atoms started to form by recombination of protons with free electrons. With the formation of these first hydrogen atoms, the universe entered a period called the 'Dark Ages' (Miralda-Escudé, 2003; Loeb and Zaldarriaga, 2004). During this time, hydrogen was mostly neutral until the first stars, quasars, and/or the first generation of galaxies appeared. The ignition of the first stars marked the end of the Dark Ages and the beginning of 'Cosmic Dawn' (CD). It happened approximately 100 million years after the Big Bang. When the first stars and galaxies were beginning to form, they emitted the ionizing photons that eventually reionized the neutral hydrogen atoms, and the universe made a transition to the 'Epoch of Reionization' (EoR) (see Barkana and Loeb, 2001; Ciardi and Ferrara, 2005; Loeb, 2006; Haiman, 2016; Liu et al., 2022, for reviews). This period occurred roughly between 100 million and one billion years after the Big Bang and marked a major transition in the evolution of the universe.

Over the past two decades, significant progress has been made in understanding the evolution of universe, from the infancy of the universe to the present day. However, the first billion years of the universe, particularly the period during which the first stars and galaxies were formed, remain largely unobserved. Several probes such as observations of the cosmic microwave background radiation, high redshift quasars, and distant galaxies are being used to unveil the epoch of reionization and cosmic dawn. We give a brief description on the probes of reionization and cosmic dawn.

1.2 Probes of studying the Cosmic Dawn and the Epoch of Reionization

During cosmic dawn, universe was in a very different state than it is today, and so studying this era can provide insights into the origin of structure and formation of the first galaxies. Probes of cosmic dawn include observations of first stars, galaxies, the cosmic microwave background radiation and the intergalactic medium (Loeb, 1998; Dai et al., 2019). The Epoch of Reionization is a critical era in the history of universe. It happened when the neutral hydrogen gas that pervaded the cosmos was reionized by the first stars and galaxies (see Loeb and Barkana, 2001, for review). A variety of probes such as the cosmic microwave background radiation CMBR) (Aghanim et al., 1996; Zaldarriaga et al., 2008), high redshift galaxies including the Lyman-alpha emitters (Dijkstra, Lidz, and Wyithe, 2007; Dijkstra, 2014; Behrens et al., 2019; Witten et al., 2023), high redshift quasars (Mortlock, 2015; Lu et al., 2022) etc are being used to study the epoch of reionization and cosmic dawn.

The Cosmic Microwave Background Radiation (CMBR) is an important probe of the

epoch of reionization (Haiman and Knox, 1999; Zahn et al., 2005; Zahn et al., 2011; Ahn and Shapiro, 2021). During the epoch of reionization, neutral hydrogen gas in the intergalactic medium was ionized by the ultraviolet radiation emitted by the first galaxies. This process imprints signatures on the CMBR radiation that can be detected through observations (Bucher, 2015). Specifically, as the CMBR photons pass through the ionized intergalactic medium they are scattered off by free electrons and become partially polarized. Measurements of the CMBR polarization have been used to probe the timing and during of reionization epoch (Mortonson and Hu, 2008; Sakamoto et al., 2022).

High redshift quasars are also important probes of the cosmic dawn and the epoch of reionization (Madau and Haardt, 2015; Fan, Banados, and Simcoe, 2022; Larson et al., 2023; Arrabal Haro et al., 2023). Quasars are among the brightest and most energetic objects in universe, powered by accretion onto supermassive black holes. Because of their brightness, quasars can be observed out to very high redshifts, corresponding to cosmic epochs as early as the epoch of reionization (Mortlock, 2015). Quasars emit radiation across a broad range of wavelengths. During the final phase of the epoch of reionization, the residual neutral hydrogen in the IGM left a measurable signature on the spectra of high redshift ($\gtrsim 5.5$) quasars, known as the Gunn-Peterson trough (Gunn and Peterson, 1965). The Gunn-Peterson trough is a region in the quasar spectrum where the transmission drops sharply to zero due to the absorption of Ly- α photons by neutral hydrogen atoms. Observations of Gunn-Peterson troughs have been used to provide insights into the final stage of the reionization (Haiman and Loeb, 1999; Becker et al., 2001; Fan et al., 2002).

High-redshift galaxies can also be used to study the reionization. The growing population of high redshift galaxies provides valuable insights into the sources that fueled reionization, as many of these galaxies, especially those at z > 7, were formed during the EoR. These galaxies serve as observational probes for tracking the progress of reionization. In particular, quantities such as the galaxy luminosity functions (Kashikawa et al., 2011), galaxy clustering (McQuinn et al., 2007; Herrero Alonso et al., 2023), and line intensity mapping (Suginohara, Suginohara, and Spergel, 1999; Lidz et al., 2011; Kovetz et al., 2019) can be used to constrain the ionization state, source properties during the reionization.

The discoveries of high-redshift Ly- α emitters (LAEs) have allowed for the study of reionization through their suppression by a neutral intergalactic medium (e.g. Mesinger and Furlanetto 2008, and see Dijkstra 2014 for a review). Constraints on reionization can also be obtained through various methods, including cross-correlating the distribution of LAEs with intergalactic 21-cm emission or adding up the ionized volume surrounding individual LAEs (Dijkstra, Lidz, and Wyithe, 2007). Additionally, Ly- α line emissions are expected to be produced by the first primeval galaxies. The Ly- α photons emitted by a source typically scatter over a characteristic angular radius of about ~ 15" around the source and are broadened and redshifted by about 10³ km/s relative to the source. Detection of the diffuse Ly- α halos around high redshift sources would provide a unique tool for probing the neutral intergalactic medium before the epoch of reionization (Loeb and Rybicki, 1999).

Above probes provide some important information about the sources, ionization state, timing and duration of the epoch of reionization and cosmic dawn. However, in order to get the full picture of the epoch we have to depend on the cosmological 21-cm signal from neutral hydrogen (see Furlanetto, Oh, and Briggs, 2006a; Pritchard and Loeb, 2012; Liu et al., 2022, for reviews). Observations of cosmological HI 21-cm signal will provide 3D picture of our universe over a significant period of cosmic history ranging from the dark ages to the post reionization epoch (Madau, Meiksin, and Rees, 1997a; Ciardi and Madau, 2003; Mellema et al., 2006; Zaroubi, 2013).

However, detection of the cosmological HI 21 cm radiation is challenging because the signal is extremely weak compared to other sources of radio emission in the universe. Additionally, the 21 cm signal is affected by a number of factors, including foreground emission from our own galaxy and other extragalactic sources, instrumental noise, and the complex nature of the astrophysical processes that affect the 21 cm signal (Oh and



Figure 1.1: Figure is adapted from Pritchard and Loeb (2012). The upper panel shows the time evolution of the fluctuations in the 21-cm brightness starting from the Dark Ages i.e. before the formation of first stars to the end of the reionization epoch. The lower panel depicts the expected sky-averaged 21-cm signal and its evolution from Dark Ages to the end of reionization. The solid curve is the 21-cm signal and the dashed line indicates the situation if $T_{21} = 0$.

Mack, 2003; Fan, Carilli, and Keating, 2006). Despite these challenges, the current and upcoming telescopes are trying to bring a new era of studying the high redshift Universe, which will partly bridge the gap between the very high redshift universe probed by the CMB (at $z \sim 1100$) and the low redshift universe (at $z \sim < 6$). By studying the 21 cm signal, we hope to gain insights into the formation of the first stars and galaxies, the evolution of the intergalactic medium, and a complete picture of the epoch of reionization (e.g. Furlanetto, 2016, for a review). The following section presents a brief description of some basics of 21-cm cosmology with a special emphasis on the global 21-cm signal.

1.3 Cosmological HI 21-cm signal

The hyperfine splitting in the ground state of the hydrogen atom allows for a promising observational probe, emitting a photon with a wavelength of $\lambda = 21$ cm (Field, 1958a). Despite the extremely low transition rate, the amount of neutral hydrogen in universe makes it a good probe of the EoR, mapping the distribution of neutral hydrogen across

the sky and probing the 3-dimensional distribution of matter at high redshifts. In Fig. 1.1, the main features of the 21-cm signal are depicted with relevant cosmic time, frequency, and redshift. The signal originates during Dark Ages when the cosmic gas decouples from the CMBR and cools adiabatically with the expansion of universe, before the formation of the first stars. During this period, the 21-cm absorption signal is observed, as shown in the bottom panel of Fig. 1.1, and fluctuations caused by density variations, shown in the top panel of Fig. 1.1. The emergence of the first stars and galaxies changes the properties of the gas, in particular, the scattering of Ly- α photons creates a strong coupling between the excitation of the 21-cm line spin states and the gas temperature, leading to a spatially varying absorption signal. Subsequently, with the emergence of the heating sources, the ambient gas gets heated producing a 21-cm emission signal. Finally, ultraviolet photons ionize the gas, creating dark regions in the 21-cm signal within the ionized bubbles surrounding groups of galaxies. Eventually, all the hydrogen gas except for that in a few dense pockets gets ionized.

The quantity of interest in the context of the cosmological HI 21-cm signal is the differential HI brightness temperature (see, eg. Pritchard and Loeb, 2012; Furlanetto, Oh, and Briggs, 2006b; Bera et al., 2023, for brief reviews on cosmic 21-cm signal). It is defined as the excess brightness temperature relative to a background radio temperature, redshifted to the present observer, and is given by (Bharadwaj and Ali, 2005),

$$T_{21}(\mathbf{n}, z) = T(z) \times \eta_{\mathrm{HI}}(\mathbf{n}, z), \qquad (1.1)$$

where,

$$T(z) = 4.0 \,\mathrm{mK}(1+z)^2 \left(\frac{\Omega_b h^2}{0.02}\right) \left(\frac{0.7}{h}\right) \left(\frac{H_0}{H(z)}\right) \tag{1.2}$$

that depends only on the redshift z, and the cosmological parameters. η_{HI} is the 21-cm radiation efficiency in redshift space and given by,

$$\eta_{\rm HI} = \left(\frac{\rho_{\rm HI}}{\bar{\rho_H}}\right) \left(1 - \frac{T_{\gamma}}{T_s}\right) \times \left[1 - \frac{(1+z)}{H(z)}\frac{\partial v}{\partial r}\right].$$
(1.3)

Here, ρ_{HI} is the density of the neutral hydrogen whereas $\bar{\rho}_{\text{H}}$ is the mean hydrogen density, and **n** is the direction of light propagation. Further, $(\rho_{\text{HI}}/\bar{\rho}_{H})$ arises due to the non-uniform distribution of hydrogen, and the term inside the square brackets arises due to the redshift space distortion in which $\partial v/\partial r$ is the divergence of the peculiar velocity along the line of sight (Bharadwaj and Ali, 2004). Moreover, T_{γ} is the background temperature of radio photons, mostly dominated by cosmic microwave background radiation (CMBR). T_s is the hydrogen spin temperature which is determined by the relative population of the singlet and triplet states of neutral hydrogen atom. It is clear from Eq. 1.1 that 21-cm signal will be in the absorption or emission depending on whether $T_s < T_{\gamma}$ or $T_s > T_{\gamma}$ respectively. The spin temperature (T_s) in Eq. 1.1 is governed by three coupling mechanisms: (i) radiative transition due to the absorption and stimulated emission of CMB photons (couples T_s and CMBR temperature T_{γ} , (ii) spin-flip transition due to atomic collisions (couples T_s and gas kinetic temperature T_g) and (iii) the Wouthuysen-Field effect (Wouthuysen, 1952; Field, 1959) which also couples T_s and T_g . T_s is related to T_g and T_{γ} as (Field 1958b; also see Furlanetto, Oh, and Briggs 2006a for a detailed review),

$$T_s^{-1} = \frac{T_{\gamma}^{-1} + x_{\alpha} T_{\alpha}^{-1} + x_c T_g^{-1}}{1 + x_{\alpha} + x_c},$$
(1.4)

where, T_{α} is the color temperature corresponds to the Lyman- α radiation field. As the Lyman- α photons get absorbed and emitted repeatedly by hydrogen atoms, they are in equilibrium with H-atom, so $T_{\alpha} = T_{\rm g}$ during the cosmic dawn period (Field, 1959; Hirata, 2006). The coupling coefficients, x_c and x_{α} depend on the different processes such as Ly- α coupling (due to Wouthuysen-Field mechanism Wouthuysen, 1952; Field, 1958b), and collisional coupling due to the collisions between two hydrogen atoms, hydrogen atom and an electron or the H-atom and a proton.

The Wouthuysen-Field coupling coefficient is given by (Pritchard and Furlanetto, 2006),

$$x_{\alpha} = \frac{16\pi^2 T_* e^2 f_{\alpha}}{27A_{10}T_{\gamma}m_e c} S_{\alpha} J_{\alpha},$$
(1.5)

where $f_{\alpha} = 0.4162$ is the oscillator strength for the Ly- α transition. Further, J_{α} is the Ly- α photon intensity which will be discussed in Sec. 3.4. Moreover, S_{α} in Eq. 1.5 is a correction factor that takes care of the redistribution of photon energies due to the repeated scattering off the thermal distribution of atoms. It can be expressed as, $S_{\alpha} = \exp(-0.37(1+z)^{1/2}T_g^{-2/3})/(1+4T_g^{-1})$ (Chuzhoy and Shapiro, 2006; Ahn and Shapiro, 2021). As this factor is of the order of unity (Chen and Miralda-Escudé, 2004), we assume it to be $S_{\alpha} = 1$. Also, $T_* = h_p \nu_e / k_B = 0.068$ K is the characteristic temperature for the HI 21-cm transition. The total collisional coupling coefficient can be written as a sum of coupling between H-H, H-p, H- e^- , ($x_c^{\text{HH}}, x_c^{\text{pH}}, x_c^{\text{eH}}$ respectively), and is given by,

$$x_{c} = x_{c}^{\rm HH} + x_{c}^{\rm eH} + x_{c}^{\rm pH}$$

$$= \frac{T_{*}}{A_{10}T_{\gamma}} \kappa_{10}^{\rm HH}(T_{\rm g}) n_{\rm H} + \kappa_{10}^{\rm eH}(T_{\rm g}) n_{\rm e} + \kappa_{10}^{\rm pH}(T_{\rm g}) n_{\rm p}.$$
(1.6)

All the specific rate coefficient values, κ_{10}^{HH} , κ_{10}^{eH} , and κ_{10}^{pH} are given in Pritchard and Loeb (2012). As the universe was mostly filled with hydrogen during cosmic dawn, κ_{10}^{HH} dominate over κ_{10}^{eH} , and κ_{10}^{pH} throughout this period. Although, this collisional coupling is a dominant process during the dark ages, and the coupling between T_s and T_g happens due to the Ly- α coupling during cosmic dawn.

Note that, $\rho_{\rm HI}$ in eq. 1.3, and the number densities of hydrogen $(n_{\rm H})$, electron $(n_{\rm e})$, and proton $(n_{\rm p})$ are determined by the ionization state of the intergalactic medium (IGM). This can be obtained by the evolution in the ionized fraction of hydrogen, x_e (= 1 - $x_{\rm HI}$) which can be written as (Peebles, 1968),

$$\frac{dx_e}{dz} = \left[C_p \left(\beta_e \left(1 - x_e \right) e^{-\frac{h_p \nu_\alpha}{k_B T_g}} - \alpha_e x_e^2 n_{\rm H}(z) \right) + \gamma_e n_{\rm H}(z) (1 - x_e) x_e + c(1 - x_e) I_{\rm CR} + \frac{\dot{N}_{\gamma}}{n_{\rm H}(z)} \right] \frac{dt}{dz}.$$
(1.7)

Here the evolution in ionization fraction is affected due to the photoionization by CMBR photons, recombination, collisional ionization, ionization by cosmic rays, and photoionization by UV photons respectively. The photoionization co-efficient, β_e can be calculated using the relation, $\beta_e(T_\gamma) = \alpha_e(T_\gamma) \left(\frac{2\pi m_e k_B T_\gamma}{h_p^2}\right)^{3/2} e^{-E_{2s}/k_B T_\gamma}$ (Seager, Sasselov, and

Scott, 1999; Seager, Sasselov, and Scott, 2000). The recombination co-efficient, $\alpha_e(T_g) = F \times 10^{-19} (\frac{at^b}{1+ct^d}) \text{ m}^3 \text{s}^{-1}$, where a = 4.309, b = -0.6166, c = 0.6703, d = 0.53, F = 1.14(the fudge factor) and $t = \frac{T_g}{10^4 \text{ K}}$. The Peebles factor is defined by $C_p = \frac{1+K\Lambda(1-x)n_H}{1+K(\Lambda+\beta_e)(1-x)n_H}$, where $\Lambda = 8.3 \text{ s}^{-1}$ is the transition rate from (hydrogen ground state) $2s \to 1s$ state through two photons decay, and $K = \frac{\lambda_a^3}{8\pi H(z)}$. The collisional ionization coefficient, $\gamma_e(T_g) = 0.291 \times 10^{-7} \times U^{0.39} \frac{\exp(-U)}{0.232+U} \text{ cm}^3/\text{s}$ (Minoda et al., 2017) with $h_p \nu_{\alpha} = 10.2 \text{ eV}$ and $U = |E_{1s}/k_B T_g|$. We note that α_e and γ_e depend on the IGM temperature T_g . In contrast, β_e depends on the CMBR temperature (see Chluba et al., 2015, for a detailed discussion). The second last term in eq. 1.7 arises due to ionization by the cosmic rays where c is the speed of light, and I_{CR} is described in section 4.1. Further, \dot{N}_{γ} is the rate of UV photons escaping into the IGM and $n_H(z)$ is the proper number density of the hydrogen atoms (Barkana and Loeb, 2001).

Global signal experiments attempt to detect the sky-averaged T_{21} where the average is taken over all directions of sky at a particular redshift, as shown in the lower panel of Fig. 1.1. Thus the globally averaged differential brightness temperature, $T_{21}(z)$ is given by,

$$T_{21}(z) = 4.0 \,\mathrm{mK}(1+z)^2 \left(\frac{\Omega_{\rm b}h^2}{0.02}\right) \left(\frac{0.7}{h}\right) \left(\frac{H_0}{H(z)}\right) \left(\frac{\rho_{\rm HI}}{\bar{\rho_H}}\right) \left(1 - \frac{T_{\gamma}}{T_s}\right). \tag{1.8}$$

To determine T_{21} , we also need to have the information on the evolution of the gas kinetic temperature, T_g along with the ionization fraction. The evolution of T_g as a function of redshift can be obtained by solving the equation (Kompaneets, 1957; Peebles, 1993; Seager, Sasselov, and Scott, 1999),

$$\frac{dT_g}{dz} = \frac{2T_g}{1+z} - \frac{8\sigma_T a_{\rm SB} T_{\gamma}^4}{3m_e c H(z)(1+z)} \left(T_{\gamma} - T_g\right) \frac{x_e}{1+x_e} - \frac{2}{3k_B} \sum_i Q_i.$$
 (1.9)

The first two terms on the R.H.S. arise due to the adiabatic cooling of baryonic gas due to the expansion of universe and the Compton heating due to the interaction between CMBR and free electrons, respectively. Further, $k_{\rm B}$, $\sigma_{\rm T}$ are the Boltzmann constant, Thomson scattering cross-section respectively and $a_{\rm SB} = 4\sigma_{\rm SB}/c$, where $\sigma_{\rm SB}$ is the Stefan Boltzmann constant. The third term Q_i includes other heating and cooling mechanisms such as heating due to X-rays, cosmic rays, primordial magnetic fields, cooling/heating due to the possible interaction between dark matter and baryons, etc. that impact the evolution in T_q .

As the observations of redshifted 21-cm signal from the neutral hydrogen (HI) is sensitive to the heating and ionization of the IGM, it became one of the most promising tools for studying the cosmic dawn (Furlanetto, Oh, and Briggs, 2006a; Pritchard and Loeb, 2012; Cooray et al., 2019; Padmanabhan, 2021) and the subsequent Epoch of Reionization. There are mainly two separate approaches by which the cosmological HI 21-cm signal from the CD/EoR can be detected, namely, the measurements of (i) global HI 21-cm signal, and, (ii) statistical signal such as power spectrum, Bi-spectrum etc. Several ongoing and upcoming experiments such as the Experiment to Detect the Global reionization Signature (EDGES, Bowman et al., 2018a), Shaped Antenna measurement of the background RAdio Spectrum (SARAS, Singh et al., 2021), Large-Aperture Experiment to Detect the Dark Ages (LEDA, Price et al., 2018), the Radio Experiment for the Analysis of Cosmic Hydrogen (REACH, Lera Acedo, 2019a) etc. are dedicated to detecting the global HI 21-cm signal.

However, the global HI 21-cm signal can not retain information regarding the spatial distribution of HI field and sources, and provide only the global evolution of the HI differential brightness temperature. Radio interferometers, such as the Giant Metrewave Radio Telescope (GMRT, Ali, Bharadwaj, and Chengalur, 2008; Pal et al., 2021), the Murchison Widefield Array (MWA, Beardsley et al., 2016; Patwa, Sethi, and Dwarakanath, 2021), Low Frequency Array (LOFAR, Patil et al., 2017; Mertens et al., 2020), the Hydrogen Epoch of Reionization Array (HERA, DeBoer et al., 2017; Abdurashidova et al., 2022), etc. are trying to detect radio fluctuations in the redshifted 21-cm background arising from variations in the amount of neutral hydrogen. These instruments seek to make detailed maps of ionized regions during reionization and measure properties of hydrogen out to z = 30. Next-generation instruments, such as the Square Kilometre Array (SKA, Mellema et al., 2015), will provide a powerful tool for learning about the first stars and



Figure 1.2: The EDGES observation of global HI 21-cm signal. Each profile denotes the brightness temperature T_{21} for different hardware configurations that were used for the observations denoted as H1, H2,.....P8. The black thick line is the model fit with the highest signal-to-noise ratio. The graph is plotted using the publicly available data at http://loco.lab.asu.edu/edges/edges-data-release/.

galaxies, and they also have the potential to inform us about fundamental physics, such as the density field, neutrino masses, and the initial conditions from the early epoch of cosmic inflation in the form of the power spectrum.

1.4 Observations of global HI 21-cm signal

The observations of global HI 21-cm absorption signal by experiments such as the Experiment to Detect the Epoch of Reionization Signature (EDGES) (Bowman et al., 2018a) have opened up the possibilities to study the evolution of the early stars and galaxies and the thermal state of the intergalactic medium during cosmic dawn. The detected signal shown in fig. 1.2 by black thick line has an absorption depth of $0.5^{+0.5}_{-0.2}$ K centred at fre-

quency 78 ± 1 MHz or redshift $z \sim 17$. The 'U' shaped 21-cm signal caries signatures of early Lyman- α (Ly- α) coupling and heating of the IGM in the redshift range of $\sim 14-22$. However, there seem to be quite controversies exist with the detected EDGES signal. For example, a recent observation by Shaped Antenna measurement of the background RAdio Spectrum (SARAS 3) (Singh et al., 2021) has claimed that the EDGES profile may not be of astrophysical origin. This new measurement rejects the best-fitting profile found by Bowman et al. (2018a) with 95.3% confidence. This observation suggests that Bowman et al. (2018a) observation is not an evidence for new astrophysics or non-standard cosmology. There are also concerns that the unusual EDGES signal may arise due to unaccounted systematics (Hills et al., 2018; Bradley et al., 2019; Singh and Subrahmanyan, 2019; Sims and Pober, 2020). Nonetheless, several explanations have been proposed in order to explain the unusual absorption trough as the absorption depth of the detected signal is almost two times larger than the strongest theoretical prediction. The 21-cm differential brightness temperature depends on the background radio signal, the hydrogen spin temperature and the kinetic temperature of the IGM, explaining the detection of the absorption trough requires additional physics that can lead, for instance, to a high SFR density (Mirocha and Furlanetto, 2019; Mebane, Mirocha, and Furlanetto, 2020; Mittal and Kulkarni, 2022) or high UV luminosity density (Hassan et al., 2023). The depth of the detected signal at $z \sim 17$ could possibly be explained either by a colder IGM achieved via cold dark matter and baryon interaction during cosmic dawn (see e.g., Barkana, 2018; Barkana et al., 2018; Muñoz and Loeb, 2018; Slatyer and Wu, 2018), and the excess radio background over the cosmic microwave background radiation (e.g., Fraser et al., 2018; Pospelov et al., 2018; Feng and Holder, 2018; Ewall-Wice et al., 2018; Fialkov and Barkana, 2019; Ewall-Wice, Chang, and Lazio, 2020).

However, the rise of the absorption signal in the redshift range $z \sim 16 - 14$ requires the IGM temperature to increase very rapidly to match the background radio temperature. The X-ray heating by the first generation of galaxies/black holes is one such possibility that has been widely studied (Pritchard and Furlanetto, 2007; Baek et al., 2009; Mesinger, Ferrara, and Spiegel, 2013; Ghara, Choudhury, and Datta, 2015; Pacucci et al., 2014; Fialkov, Barkana, and Visbal, 2014; Fialkov and Barkana, 2014; Das et al., 2017; Ma et al., 2021). Other possibilities such as heating due to the primordial magnetic field (Sethi and Subramanian, 2005; Bera, Datta, and Samui, 2020), shocks (Xu, Yue, and Chen, 2021), Ly- α photons (Madau, Meiksin, and Rees, 1997b; Chuzhoy and Shapiro, 2006; Ghara and Mellema, 2020; Ciardi, Salvaterra, and Di Matteo, 2010; Reis, Fialkov, and Barkana, 2021; Mittal and Kulkarni, 2021), CMB photons (Venumadhav et al., 2018) have also been explored. However, all these mechanisms have their own parameter spaces that are poorly constrained in the high redshift universe. Thus, how and when did the IGM heating take place during cosmic dawn still remains an unsettled issue.

1.5 Outline of the thesis

Inspired by the upcoming and future observations, we devoted our work to understanding the physical mechanisms that impact the global HI 21-cm signal. Furthermore, we combine constraints derived from the observation of the global 21-cm signal along with the observations from the reionization and post-reionization epoch to shed light on the faint end of the UV luminosity function.

In **chapter 2**, our study on one of the heating sources during the dark ages and cosmic dawn namely, primordial magnetic field (PMF) is described. We investigate the decaying of magnetic fields through ambipolar diffusion (AD) and decaying magneto-hydrodynamic turbulence (DT) processes at different redshifts. We further present the impact of the decaying magnetic field on IGM temperature. Finally, we provide the upper limit on PMFs in the colder IGM background achieved via dark matter-baryon interaction using EDGES constraints on the global 21-cm signal.

We present our semi-analytical models for Population III and Population II star formations in **chapter 3**. Our models include several feedbacks that impact the star formations at high redshifts, in particular, Lyman-Werner, AGN, and Supernovae feedback. We further describe the Ly- α background due to the generation of Ly- α photons from the first stars. In **chapter 4**, we present the detailed mechanisms of the heating processes due to cosmic ray protons and their impact on gas kinetic temperature, T_g , spin temperature, T_s , and the corresponding brightness temperature, T_{21} during cosmic dawn and EoR. We calculate the evolution of CR particles and their energy deposition in IGM during cosmic dawn. We also describe the impact of CR protons in the presence of dark matterbaryon interaction in light of EDGES 21-cm signal detection. Moreover, we present a comparison of heating due to cosmic rays with X-ray heating.

In **chapter 5**, we explore a source model derived from radiative transfer hydrodynamic simulation. We then calibrate our model with recent measurements of global HI 21-cm signal from CD and with several reionization observables to explore the joint parameter space to determine the range of models that naturally reproduce the combined constraints from reionization and cosmic dawn.

In chapter 6, we discuss and summarise our main results obtained. Finally, in chapter 7, we briefly outline the future outlook of this thesis work. Throughout this article we assume a flat, Λ CDM cosmology with the cosmological parameters obtained from recent Planck 2018 (Planck Collaboration et al., 2020a) observation, i.e. $\Omega_{\Lambda} = 0.69$, $\Omega_{\rm m} = 0.31$, $\Omega_{\rm b} = 0.049$, and the Hubble parameter $H_0 = 67.66$ km/s/Mpc, unless otherwise mentioned.