CHAPTER 6

Conclusions & Discussion

We are not at the end but at the beginning of a new physics. But whatever we find, there will always be new horizons continually awaiting us.

– Michio Kaku

This thesis work is dedicated to investigating the impacts of various physical processes on the cosmological HI 21-cm signal, with particular attention to the global HI 21-cm signal. Our study starts with the modeling of the first generation of stars and galaxies and goes on to explore the evolution and energy deposition by magnetic fields and cosmic rays into the intergalactic medium. The research also pays attention to the observational constraints obtained by the EDGES. Moreover, our work also explores the reionization constraints and how they can be combined with the cosmic dawn constraints to highlight the parameter space related to different physical processes that are constrained by different observations together.

In chapter 2, we present the constraints on the primordial magnetic field using the global HI 21-cm absorption signal in the 'colder IGM' background. Constraining the primordial magnetic field is very important as it can shed light on its origin and evolution. We show that the constraints in the colder IGM scenario are different from constraints obtained in the standard scenario. The reason behind it is the colder IGM that enhances

the Hydrogen recombination rate which, in turn, reduces the residual free electron fraction during the dark ages and cosmic dawn. In addition, the coupling between the ionized and neutral component which has a direct impact on the IGM heating also get suppressed in the 'colder IGM' scenario. Moreover, the heating rate due to the Compton process, which depends on the IGM kinetic temperature and the residual free electron fraction, too gets affected when the background IGM temperature is lower. Together all these effects enhance the IGM heating rate due to the primordial magnetic field through ambipolar diffusion and decaying turbulence. Consequently, a small amount of magnetic field would be enough to keep the IGM temperature at a level that can produce global 21 cm signal consistent with the EDGES observation. On the contrary, significantly more magnetic energy would be transferred to the IGM due to the enhanced heating rate which would affect the redshift evolution of the primordial magnetic field itself and the heating at later reshifts. In the light of EDGES data, and considering the DM-baryon interaction we find that the upper bound on the primordial magnetic field can be as high as $\sim 0.4\,\mathrm{nG}$ which is ruled out in the standard model. However, $B_0\gtrsim 1\,\mathrm{nG}$ may not be allowed as this could only be explained with a very highly efficient cooling mechanism that requires dark-matter mass (interaction cross-section) to be quite low (high) than the current predictions. As the 21-cm absorption signal also depends on the mass of the DM particles and the interaction cross-section, we are also able to put limits on the dark matter mass and cross-section using EDGES low band measurements. We see that the allowed region of dark-matter mass decreases while the interaction cross-section increases with the increase in magnetic field. Furthermore, due to the decaying nature of the magnetic field at lower redshifts, we find that the heating due to the primordial magnetic field becomes inefficient in explaining the sharp rise in the 21-cm profile observed by EDGES.

Hence, in chapter 4, we explore another possible mechanism that can heat the IGM substantially. One such candidate is cosmic ray protons that are generated in the termination shocks of supernova explosions. It is well known that the SNe are the main sources of high-energy cosmic rays. Given the expected top-heavy IMF of Pop III stars,

they are all likely to explode as a SNe that can accelerate copious amounts of cosmic rays. Due to the smaller sizes of the host galaxies as well as the higher energetics of the Pop III SNe, the cosmic rays are likely to be generated outside the virial radius of the halo and can escape to the IGM easily. While traversing through the IGM, low energy protons (with energy $\lesssim\,30$ MeV) interact with the neutral hydrogen and free $e^-.$ In case of collisions with free e^- , the entire energy loss by these particles becomes the thermal energy of the IGM, whereas, the interaction between cosmic ray protons and neutral hydrogen results in primary and secondary ionizations, and finally contributes to the heating. We find that cosmic rays resulting from Pop III stars can potentially alter the thermal state of the IGM, and hence the spin temperature, T_s during cosmic dawn. Contrary to Pop III halos, the low energy protons generated from the SNe exploding in massive atomic cooling halos, get confined within the galaxy itself. However, the high-energy protons are likely to escape from Pop II galaxies like our Galaxy and can contribute to the heating. In this case, if a sufficient magnetic field is present in the IGM, these high-energy cosmic ray particles gyrate along the magnetic field lines and excite magnetosonic Alfvèn waves. When these waves get damped, the energy gets transferred to the thermal gas, and can potentially change the temperature of the IGM.

Our model accounts for both metal-free Pop III and metal-enriched Pop II stars, and considers Lyman-Werner feedback on Pop III star formation, and supernova, AGN and radiative feedbacks in Pop II galaxies. The temperature evolution of the intergalactic medium, or in turn, global HI 21-cm signal is calculated self-consistently, taking into account Lyman- α coupling, cosmic ray heating, dark matter-baryon interaction, and adiabatic cooling. We find that cosmic rays are an important source of IGM heating and shape the global 21-cm signal during cosmic dawn. We show that the EDGES signal can be explained by our model, with reasonable efficiency parameters of cosmic ray heating. We also find that even a small fraction of cosmic ray protons is capable of heating the IGM that could wash out the absorption in 21-cm signal. Our results suggest that accurately determined 21-cm signals could be used to probe early cosmic ray heating and constrain the nature of early-generation stars.

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Furthermore, the reionization constraints provide insights into the process by which the first galaxies reionized the universe, while the cosmic dawn constraints provide information on the earliest stages of the universe. By combining these measurements, we identified the parameter space that is constrained by the joint observations in chapter 5, which can be further verified by ongoing and upcoming surveys such as the JWST and the SKA. In particular, we explore the conditions under which the EDGES detection is consistent with other reionization and post-reionization observations, including ionizing emissivity, IGM neutral hydrogen fraction, and Thomson scattering optical depth. The analysis is based on a semi-analytical framework of reionization with a physicallymotivated ionizing source model and an MCMC likelihood sampling to calibrate the source model to different observables. The key findings from this work suggest that lowmass (faint) galaxies play a crucial role in reproducing the inferred UV luminosity density constraint from EDGES, while massive (bright) galaxies dominate the reionization process. This analysis indicates that low-mass galaxies would bridge the gap between cosmic dawn and reionization. This work also shows that low-mass galaxies-dominated models result in a flatter emissivity evolution, resulting in a later onset of reionization, more sudden and shorter reionization duration, and lower optical depth and vice versa. This study acknowledges several limitations, such as the assumption of a linear relationship between $SFR - L_{UV}$ and the fixed values of some model parameters. Nevertheless, the results demonstrate that it is possible to reproduce both cosmic dawn and reionization constraints with faint galaxies-dominated models without requiring new physics or exotic sources. The study sheds light on the roles of faint and bright galaxies during cosmic dawn and reionization and provides avenues for further investigation using upcoming JWST surveys.

In conclusion, this thesis work focuses on investigating the impacts of various physical processes on the cosmological HI 21-cm signal, with particular attention to the global HI 21-cm signal. The study explores the modeling of the first generation of stars and galaxies, the impact of magnetic fields and cosmic rays on the HI 21-cm signal, and the observational constraints obtained by EDGES. The study also combines the reionization constraints with the cosmic dawn constraints to identify the parameter space that is constrained by joint observations. The insights gained from this research can help us to better understand the evolution of the universe and the processes that shaped it. The ongoing and upcoming surveys such as the JWST and the SKA are expected to provide further insights into the early universe and help to refine our understanding of the HI 21-cm signal.