# Research Proposal : Intergalactic Medium

The gravitational collapse of the overdense regions in the initial density field leads to the formation of large scale structures in the Universe. A significant fraction of the diffuse gas is in the "Intergalactic Medium" (IGM) that is not associated with collapsed objects (galaxies). The IGM fills most of the volume and exhibits a distinct filamentary structure that has imprints of cosmological initial conditions. Observations indicate that the IGM continuously interacts with galaxies through the exchange of matter and radiation. Pristine intergalactic gas flows into the galaxies, while metal-enriched outflows of gas pollute the IGM. These exchanges play a significant role in shaping the physical, chemical, and dynamical properties of galaxies, as the IGM closely intertwine with these processes. The emission of ionizing radiation from galaxies plays a central role in driving the reionization of hydrogen and helium. The reionization, in turn, alters the thermal and ionization state of the IGM, exerting an influence on subsequent galaxy formation and evolution. Thus, studying the IGM becomes vital from both a cosmological perspective, enabling us to understand large-scale structures ($\sim$ 100 Mpc), and an astrophysical viewpoint, unraveling the intricacies of galaxy formation ($<$ 1 Mpc).

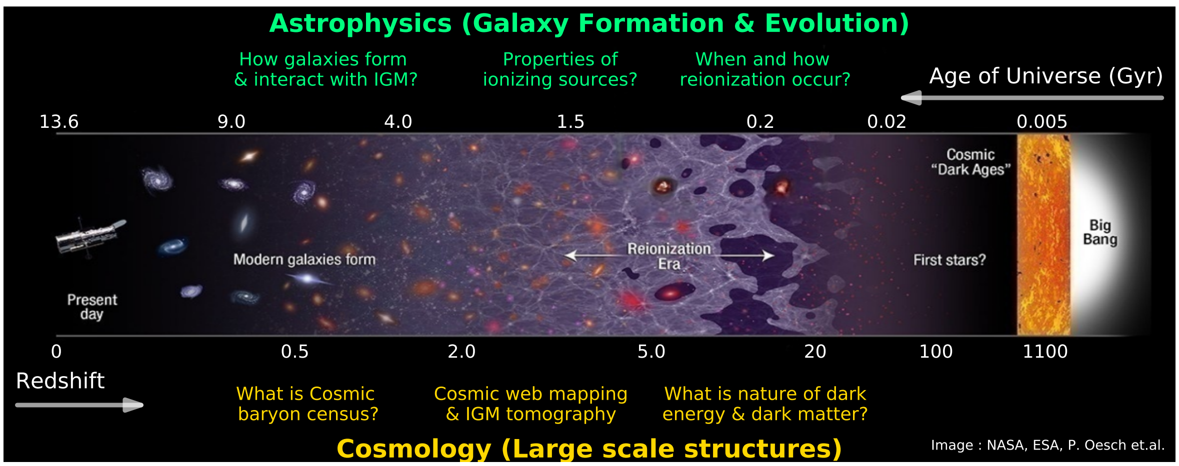


Figure 1: Figure shows a brief timeline of the Universe. The research proposal aims at addressing 5 key questions in modern astrophysics and cosmology using observations of QSO absorption spectra.

The unprecedented quality quasar absorption spectroscopy from ultra-violet to infrared wavelengths obtained using ground and space-based telescopes, has significantly advanced our understanding of the IGM. The observational progress is matched similarly by advancements from cosmological hydro-dynamical simulations, providing valuable insights in to the astrophysical processes that play a crucial role in the IGM. Despite these advances, there are still five important questions that remain to be answered for a deeper understanding of the universe.

1. When exactly and how did reionization occur in the timeline of the universe?
2. What are the underlying characteristics of galaxies and active galactic nuclei (AGN) that play a significant role in driving the processes of reionization?
3. How do galaxies interact with their surrounding environment, and to what extent does this feedback influence large scale structures in the universe?
4. How is matter distributed within the vast filamentary network of the large-scale structure and how does the cosmic web influence the origin and subsequent evolution of galaxies?
5. What are the fundamental properties of dark energy and dark matter that governs the dynamics of the large scale structure in the universe?

The primary objective of my research plan is to address these five core questions. Fig. 1 summarizes my research plan. The abundance of spectroscopic data that we will be acquiring from present and forthcoming observing facilities, coupled with the current progress in cosmological simulations that I have developed in recent years, will provide the necessary tools to contribute significantly in answering these questions.

## Recent developments in the field:

The observations of QSO absorption spectra at various redshifts have greatly improved our understanding of the evolving IGM as shown in Fig. 2. The series of absorption lines blueward of the Ly$\alpha$ emission, known as the Ly$\alpha$ forest, traces the neutral IGM along the sightlines. The distant QSO absorption spectra are composed of three regions: (i) the Ly$\alpha$ forest, (ii) intergalactic metal absorption systems, and (iii) the proximity region close to the QSO.

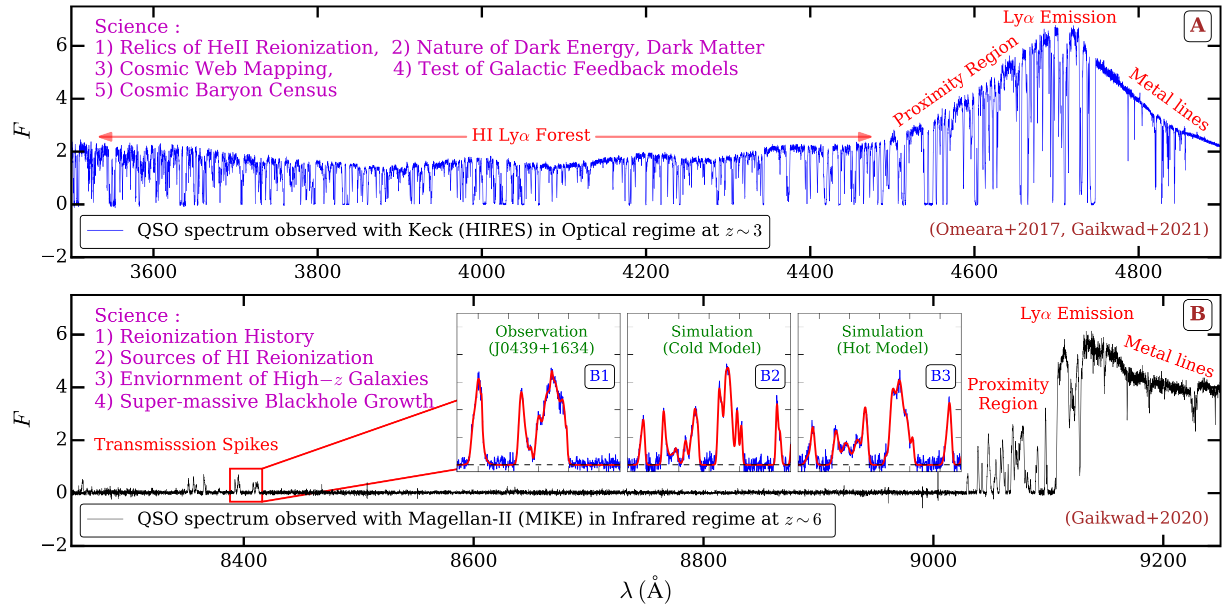


Figure 2: QSO absorption spectra at low ($0 < z < 4$, panel A) and high redshifts ($z > 5$, panel B) exhibit significant evolution in absorption systems, reflecting the changing ionization state of the IGM over cosmic time. The Ly$\alpha$ forest is used to constrain the nature of dark energy, dark matter and the thermal and ionization state of the IGM. The metal absorption systems helps us to understand feedback processes in galaxies, while proximity regions provide insights into AGN properties. Panel B1 to B3 illustrate that the transmission spikes are broader when the IGM is hot and has been used to measure the IGM temperature.

My research has been focused on using Ly$\alpha$ forest to study the H I and He II reionization. Fig. 3 depicts the process of reionization. Reionization is driven by ionizing photons emitted by sources that produce the ionizing radiation field (right slice). This leads to inhomogeneous photo-ionization (bottom slice) and photo-heating of the IGM, increasing its temperature (left slice). The IGM temperature influences the cosmic density field through pressure smoothing, impacting further structure formation (top slice). QSO absorption spectra offer valuable insights into the thermal and ionization state of the IGM. Panel B1 to B3 in Fig. 2 illustrates that the width of the absorption system increases with increasing IGM temperature. By using such broadening effects, we have demonstrated that the IGM is hotter than previously thought, and we have successfully measured the temperature and neutral fraction of the IGM (Gaikwad et al., 2020, 2023). These findings strongly support the late completion of H I reionization at redshift $z \sim 5.2$. Similar study at $2 < z < 4$ reveal a rapid and late He II reionization by QSOs (Gaikwad et al., 2018, 2021). By better measuring the photo-ionization rate from the Ly$\alpha$ forest at $z < 0.5$, we have resolved the photon-underproduction crises in cosmology (Gaikwad et al., 2017a,b). These measurements are widely recognized and contribute to understanding of late-ending reionization scenarios. In this research proposal, I aim to expand my investigation to include the study of metal line systems, proximity regions and galaxy surveys around QSO sightlines.

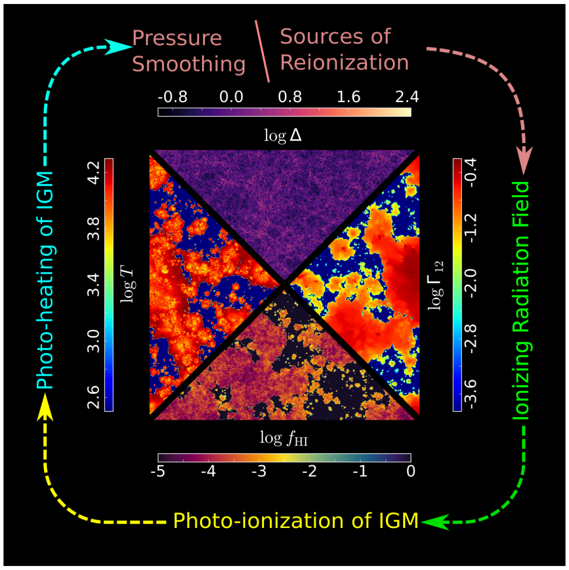


Figure 3: Processes of reionization

# Research Plan

In the upcoming years, my research will center on exploring the connection between the IGM, galaxy formation and large-scale structures. Despite their apparent differences, these different aspects complement each other. By concurrently investigating all these areas, we aim to gain a comprehensive understanding of galaxy formation within the context of cosmology. Below we describe a research plan that involves comparison of observations from various instruments (highlighted in blue) and simulations (highlighted in red) to achieve our diverse science goals.

## I. Astrophysics (Galaxy formation and Evolution)

### 1 When and how did reionization occur in the Universe?

The timing and inhomogeneity of reionization can be characterized by measuring the evolution the neutral fraction, temperature of the IGM and mean free path of ionizing photons. The complexities in modeling the reionization, as shown in Fig. 3, have posed considerable difficulties in measuring these parameters from observations. We have recently advanced our simulations to capture all the necessary physical effects for accurate modeling of reionization, allowing us to measure these parameters from observations with finite uncertainty at $5 < z < 6$ (see Fig. 4, Gaikwad et al., 2023). To rule out various models of reionization requires extending these measurements to higher redshifts. In this research proposal, I plan to measure neutral fraction (at $z > 6$), mean free path ($z > 6$) and temperature fluctuations ($4 < z < 5$) using the observations of Ly$\alpha$ forest and damping wings in high redshift QSO and galaxy absorption spectra. We already have the tools in place for robustly measuring the evolution of these reionization parameters by effectively accounting for various observational systematics and conducting additional observations as demonstrated in Gaikwad et al. (2020, 2023). A significant aspect of my research also involves the development of novel methods of cross-correlating the QSO absorption spectra with 21cm signal from radio telescopes such as uGMRT and SKA. Using such a cross-correlation technique, I aim to mitigate the observational systematics and enhance constraints on reionization history. In addition, I also intend to perform similar analysis of measuring IGM parameters during He II reionization at $2 < z < 4$ where observational constraints are rather limited.

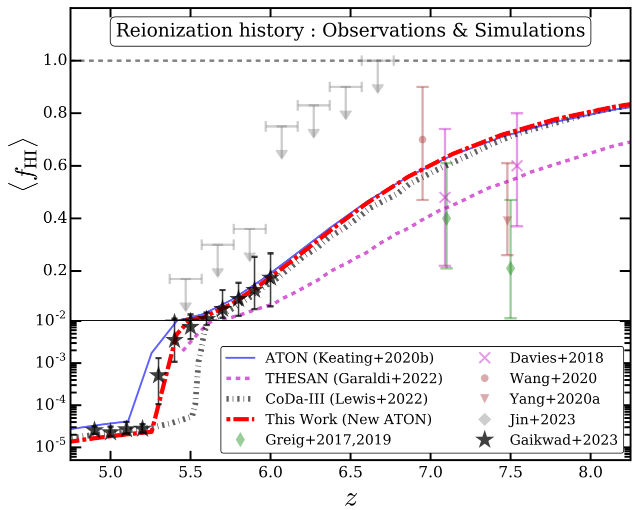

Figure 4: Evolution of average neutral fraction

*Observations (HI Reionization): Keck (ESI), VLT (XShooter), SKA, uGMRT, 21cm Experiments*
*Observations (HeII Reionization): HST-COS, WEAVE survey (Builder Status), Keck (HIRES)*
*Simulations : Sherwood simulation suite and radiative transfer code* EX-CITE, HEART, ATON

### 2 What are the properties of ionizing sources and their distribution in the Universe?

Recent Subaru-HSC and JWST observations with QSOs at the field center have shed light on the galaxy overdensity around these targets. Surprisingly, the most transparent and most opaque QSO sightlines exhibit very similar galaxy overdensities, hinting at little correlation between ionizing sources and reionization topology (see Fig. 5, Christenson et al., 2021). This intriguing finding challenges current models and demands a closer investigation to refine the models of reionization. In current reionization models, the opacity of QSO sightlines is influenced by fluctuations in both the ionizing radiation field and temperature field, but their individual contributions remain somewhat uncertain. To address this, I propose to modify the reion-

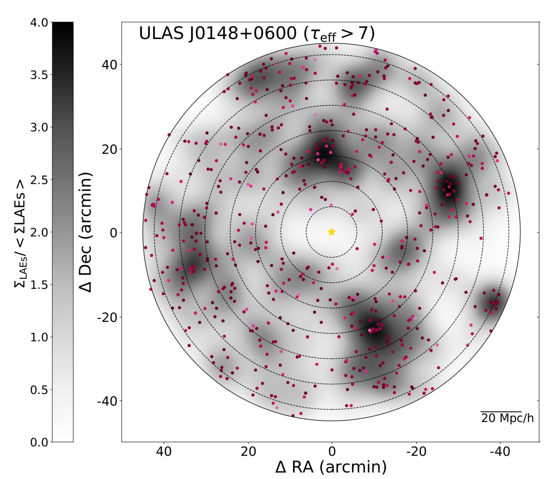

Figure 5: Overdensity around QSO sightline

ization model in our simulations to better understand the impact of these fluctuations on opacity. Utilizing the gap and two-point statistics of transmission spikes in our radiative transfer simulation suite, we aim to quantify correlations between nearby galaxies and transmission spikes in QSO absorption spectra. These statistics will serve two purposes: (i) to compare reionization models with observations from the JWST surveys, and (ii) to forecast the number of QSO absorption spectra and the limiting magnitude of galaxies required to detect such correlation with the upcoming TMT and E-ELT. By doing this, we aim to gain valuable insights into the patchiness of reionization due to distribution of ionizing sources.

*Observations : XQR-30, ASPIRE, EIGERS survey (JWST), Andes (E-ELT), MODHIS (TMT)*
*Simulations : Modification in Ray-Tracing code "HEART" to include realistic source models*

## 3 What are the properties of ionizing sources? (Role of AGN during reionization)

The contribution of AGN to H I reionization has been highly uncertain due to their rapidly declining number density. Recent, JWST observations have revealed a significant number of faint AGNs at higher redshift that were previously undetected (see Fig. 6, Harikane et al., 2023). While their contribution might be subdominant due to escape fraction uncertainties, their presence must be considered when comparing models with observations. These faint AGNs can introduce additional fluctuations in temperature and reionization topology, making the reionization picture more complex. To address this, I plan to model AGNs with varying properties, such as duty cycle, lifetime, and non-isotropic emission, in our ray tracing radiative transfer simulations HEART. The QSO light echos and QSO proximity regions modeled in these simulations will be compared with JWST observations. This study will allow us to study AGN environments of high redshift QSOs, helping to constrain their growth over cosmic time.

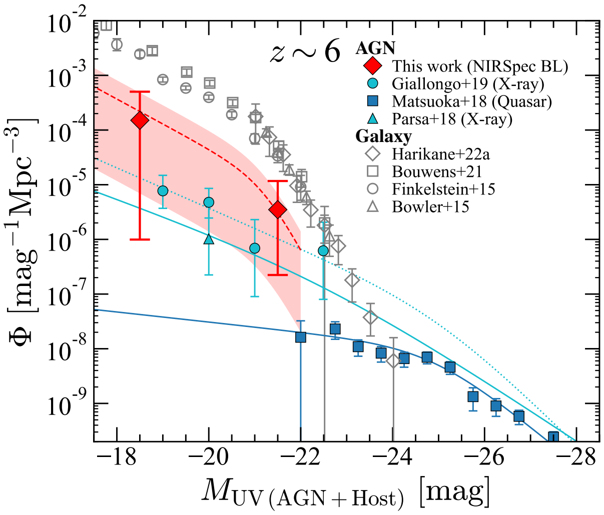


Figure 6: AGN Luminosity function at $z \sim 6$

*Observations : Keck HIRES and VLT UVES, XQR-30, ASPIRE, QSO Light echo program*
*Simulations : Sherwood simulation suite, radiative transfer code HEART with bright sources*

## 4 How galaxies interact with their environment? (Metal enrichment of IGM)

Recent observations have shown substantial metal enrichment of IGM at $5 < z < 6$, highlighting the significance of stellar feedback mechanisms in high-redshift galaxies. Notably, the observed mass content of O I and C IV increases significantly at $z > 5$ which is difficult to reproduce in simulations (see Fig. 7, Davies et al., 2023). There are two main difficulties in understanding metal evolution (i) limited observations of the environment surrounding high-redshift galaxies and (ii) the computationally expensive cosmological simulations to model galactic feedback. To address the first issue, our MUSE large program proposal, focused on studying the environment of high-redshift galaxies, has been accepted. Additionally, we have a valuable metal absorber catalog from XQR-30 to aid in constraining feedback models. To tackle the second challenge, I plan to model metal absorption systems in the IGM using various galaxy feedback models. These simulations will enable to quantify the amount of feedback present in high-redshift galaxies, potentially offering insights into the properties of Pop-III stars, where observational constraints are currently limited.

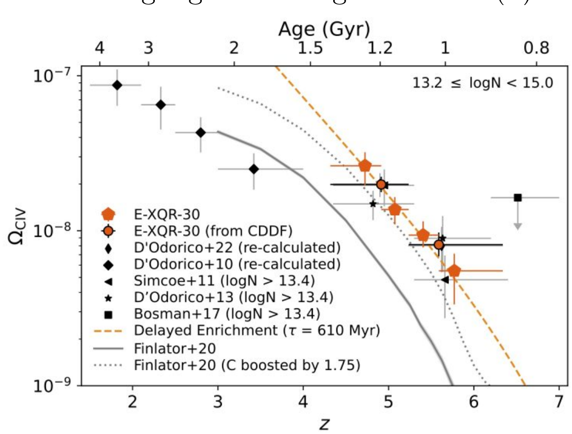


Figure 7: Observed cosmic C IV evolution

*Observations : XQR-30, ASPIRE (JWST), MUSE Large Program approved (CoI)*
*Simulations : CAMELS + Sherwood suite of feedback models, Radiative Transfer code EX-CITE and HEART*

## II. Cosmology (Large Scale Structures)

### 5 Cosmic baryon census and Missing baryon problem (Cosmology with AstroSat)

The observed amount of baryons from various observations doesn't match with that expected from cosmological models, leading to the "missing baryon problem". This discrepancy is prominent at $z < 0.5$, where a significant fraction of baryons exists in the warm hot phase (WHIM) and clusters of galaxies, likely due to shock heating and galactic feedback (see Fig 8, Gaikwad et al., 2017a). Detecting this elusive phase of the IGM has been challenging. I propose two approaches to address this problem: (i) Observing and modeling high ionization metal species, using various galactic feedback models observed in HST-COS spectra, and (ii) Detecting X-ray emissions from the cosmic web. The latter approach involves identifying cosmic web regions using LSST and SDSS surveys and then following up with Astrosat's SXT instrument. The excellent imaging capabilities of SXT instrument in the soft X-ray band with wide field of view offer the potential to observe the X-ray emission from cosmic web.

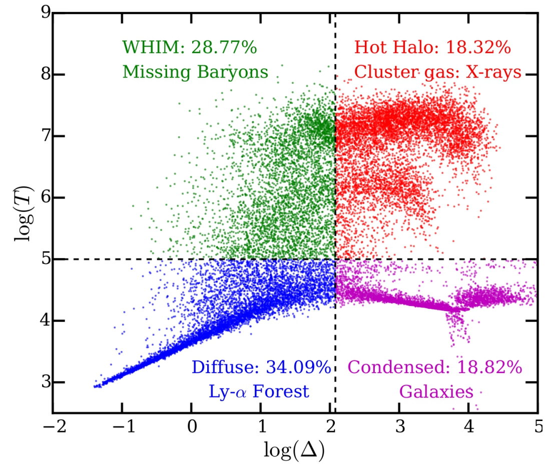


Figure 8: Phase distribution of baryons

*Observations : HST-COS, Astrosat (SXT), LSST, SDSS*

*Simulations : Illustrious, SIMBA and CAMELS suite with various feedback models*

### 6 What is nature of dark matter and dark energy? (Cosmology with IGM tomography)

The Ly$\alpha$ forest, observed along closely spaced background QSOs, allows us to reconstruct the 3D distribution of baryons in the Universe. Such 3D cosmic web mapping carries valuable information about Baryon Acoustic Oscillations (BAO) on large scales, while the small-scale suppression in the density field is sensitive to the free-streaming characteristics of dark matter. The evolution of over-densities and under-densities in the cosmic web eventually lead to the formation of proto-clusters (seeds for galaxy formation) and cosmic voids. An example of correlated structure along a QSO triplet is shown in Fig. 9 (Maitra et al., 2019). My proposed research aims to use the upcoming WEAVE survey's high and low-resolution mode observations to respectively constrain the nature of dark matter and dark energy through the two-point correlation function analysis on different scales. The uncertainties in these measurements stemming from fluctuations in thermal and ionization state of the IGM is crucial, and the projects outlined in §1 of this research proposal directly align with this study. Incorporating data from SKA LOW, which provides HI intensity mapping maps in emission at $z < 5$, I propose to conduct a cross-correlation analysis with the Ly$\alpha$ forest at $2 < z < 4$ in absorption. This complementary approach will enable us to robustly constrain the properties of dark energy and dark matter while effectively mitigating potential observational systematics. The millions of QSO spectra provided by WEAVE will enable us to construct 3D tomographic map of IGM. I plan to study the chemical, dynamical, and physical properties of proto-clusters and cosmic voids in the observed cosmic web. By correlating the statistical properties of proto-clusters and underdense regions at $z > 2$ with corresponding properties of galaxies, cosmic voids and H I intensity maps at later epochs ($z < 1$) from galaxy surveys, we aim to refine our cosmological and galaxy formation models.

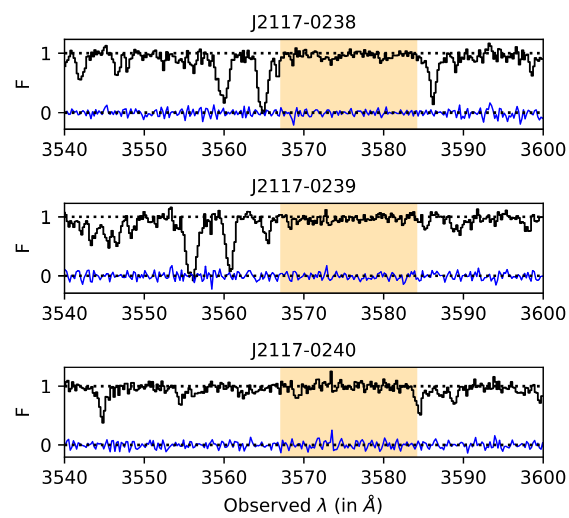


Figure 9: Observed spectra of QSO triplet

*Observations : WEAVE, DESI, VLT (UVES), Keck (HIRES) , SDSS, LSST, E-ELT, TMT, SKA-LOW*

*Simulations : Gadget-4 simulations with varying dark energy and dark matter properties*

## Future Prospects

The 5 key questions presented in this research proposal can be effectively addressed by utilizing data from upcoming observatories. India's substantial involvement in many of these projects, such as uGMRT, SKA, TMT and Astrosat offers a great opportunity to make a significant impact in the global scientific platform. Fig. 10 shows the timeline of major upcoming observatories.

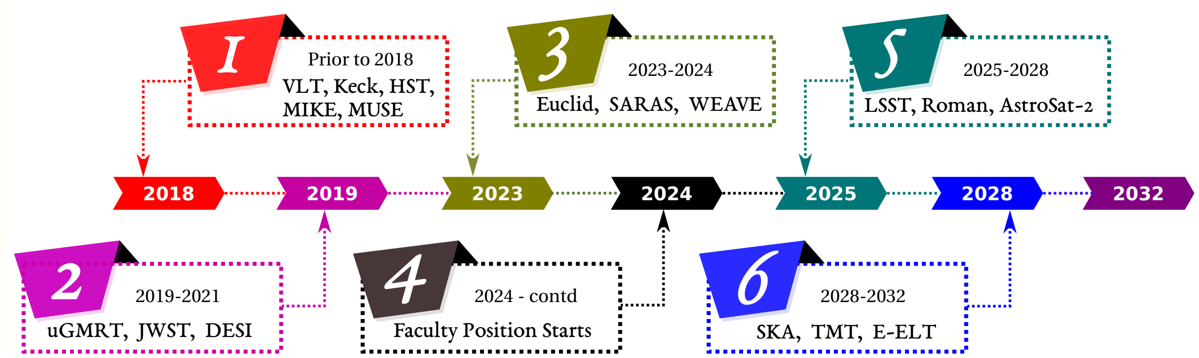


Figure 10: The figure presents an overview of existing and upcoming observatories. The Indian astrophysics community is actively engaged in several of these important projects. My existing collaborations complement India's current involvement in observing facilities.

My research proposal is strategically aligned with the long-term vision of the Indian astrophysics community by synergizing the multi-wavelength data from these observatories.

**Science with TMT :** Using unprecedented high-resolution and long-term stability of MODHIS instrument on TMT, I plan to measure preform various cosmological and astrophysical analyses. This includes studying high-redshift galaxies and the growth of supermassive black holes, as well as constraining the nature of dark matter, neutral fraction, thermal state and pressure smoothing scales of the IGM at early times. While one of the primary objectives of the TMT is to perform the Cosmological Sandage-Loeb test for real-time measurements of the Universe's expansion rate, I also plan to use the same observations to measure the speed of ionization fronts during reionization in real time. This approach aims to maximize the utility of the observational data collected.

**Science with SKA :** India's involvement in the SKA presents a significant opportunity for my research. While the SKA data is expected to be of high quality, it can be affected by foreground contamination and instrumental systematics. To mitigate these challenges, I plan to perform cross-correlation analyses with other observational probes. Specifically, I intend to cross-correlate observed transmission spikes with 21 cm maps to constrain the distribution of ionizing sources in the early universe. I also plan to utilize the SKA instrument to conduct comprehensive measurements of the matter power spectrum using both Ly$\alpha$ forest (small scales) and H I intensity mapping (large scales) observations across various scales at $2 < z < 4$, and to robustly constrain the nature of dark energy and dark matter. My involvement in the WEAVE survey together with India's involvement in SKA will be instrumental in performing these measurements. Additionally, with SKA's enhanced sensitivity, I aim to forecast the observability of 21cm forest with uGMRT, SKA and its application for measuring the cosmological and astrophysical parameters. These complementary approaches hold significant potential for bridging the gap between astrophysics and cosmology.

I am enthusiastic about the opportunity to collaborate with other researchers at the institute and the wider Indian scientific community in tackling the most challenging problems. With a diverse background in analyzing spectroscopic data spanning ultra-violet, optical, and infrared wavelengths, and proficiency in performing state-of-the-art cosmological simulations, I will bring these valuable skills to the Indian scientific community through mentoring, collaborating and organizing workshops, schools. This will help them to effectively utilize upcoming next-generation telescopes and contribute significantly to astronomical research.

## Strategic Goals

**External Funding Strategy:** Securing external funding is of very important to supplement department's funding and expand the reach and impact of my research endeavors. To achieve the scientific goals, I will actively pursue external grants and funding opportunities such as UK Research and Innovation, India-Max Planck partner group (Germany), Indo-French partner group, HECAP (ICTP, Italy) and University of Cambridge (UK). I also plan to apply for various Indian funding agencies such as DST, DAE, and SERB for early researcher career grants.

**Administrative support:** As part of my commitment to scientific community building, I will take the initiative to organize seminars, colloquia, and Astro-ph meetings, fostering collaboration and knowledge exchange within the institute. Drawing upon my previous experience as an organizer, I will actively organize and engage in national and international workshops and conferences, bringing together researchers from diverse backgrounds to facilitate scientific discussions. I am equally committed to teaching and sharing my knowledge with early career researchers to foster their growth and development in the field. Additionally, I will contribute to various essential administrative tasks within the institute, such as library management, computer system administration, conducting graduate school exams, and mentoring early career researchers. By actively engaging in scientific community building and administrative support, I will help to foster a vibrant research environment as well as contribute to the smooth and efficient functioning of the institute's operations.

**Equity and Diversity:** Recognizing India's cultural diversity, I value and respect individuals from various social, economic, linguistic, and religious backgrounds. I am deeply committed to increasing the representation and active participation of underrepresented groups, including women, marginalized communities, and people with disabilities. My experience in outreach and collaborations with students and post-docs from diverse backgrounds have provided me with valuable insights into diverse perspectives and ideas. I will continue to support and mentor early-career researchers from various backgrounds, ensuring that they have equal opportunities to thrive in science.

**Resource Requirements:** To initiate my research at the institute, I primarily require resources for observational data analysis and computer simulations. This includes access to High-Performance Computing (HPC) facilities or cloud computing, with a few million CPU hours per year. For post-processing and code development tasks, I will need (i) a dedicated machine with 256 cores, 1TB RAM, a 128GB NVIDIA GPU card, and 200TB of hard disk storage and (ii) a linux based Lenovo Thinkpad Carbon X1 series laptop. These essential resources will enable me to conduct advanced analyses and simulations necessary for my scientific goals. The projected investment for these machines amounts to approximately 1 Crore INR. Laboratory space is not necessary for my research.

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# Past Research Summary

Prakash Gaikwad

Observations suggest that the IGM has gone through a process of reionization. H I and He I is ionized at $z \sim 6-15$ by early type of stars, galaxies. He II is ionized at $z \sim 3$ by Quasi-Stellar Objects (QSOs). The IGM is imprinted with rich information of cosmological initial conditions and astrophysical processes related to galaxy formation. H I Ly$\alpha$ absorption seen in the background of bright QSO traces the cosmological and physical conditions in the IGM. Recent improvements in observational and numerical techniques have enabled us to perform a detailed comparison between cosmological simulations and observations. However, such a comparison is often limited by observational systematics and computational resources available to perform cosmological simulations. My work has been mainly focused on analyzing observations, extracting the statistical information that can be compared with simulations, developing new techniques to efficiently simulate the IGM, incorporating observational systematics in simulations to generate realistic mocks, measuring the astrophysical parameters from the observations and investigating the implications of measured parameters for IGM physics. In the past few years, my research has focused on measuring the thermal and ionization state of the IGM from observations of the Ly$\alpha$ forest. The ionization state of the IGM is characterized by the evolution of photo-ionization rate ($\Gamma_{\rm HI}$ and $\Gamma_{\rm HeII}$), neutral fraction ($f_{\rm HI}$ and $f_{\rm HeII}$) and mean free path of ionizing photons ($\lambda_{\rm HI}$, $\lambda_{\rm HeII}$). The thermal state of the IGM is thereby characterized by the redshift evolution of normalization ($T_0$) and slope ($\gamma$) of the temperature-density relation ($T = T_0 \Delta^{\gamma-1}$) seen in cosmological simulations. **Fig. 1 summarizes the main results of my current research.**

## (I) Observational Analysis: (Gaikwad et al., 2017a, 2020, 2021, 2023)

I have led the analysis and interpretation of innovative studies of the Ly$\alpha$ forest with the Hubble Space Telescope (COS, $z < 0.5$), the Keck telescope (HIRES, $2 < z < 4$), the European Southern Observatory (VLT, UVES, $2 < z < 4$), Magellan II telescope (MIKE, $5 < z < 6$) and ESO (VLT, XShooter, $5 < z < 6$). The number of spectra, observational systematics and quality of the data obtained from these instruments are quite different (panel A in Fig. 1). *I have developed my own very versatile pipeline to analyze the observations and to compare to mock absorption spectra obtained from numerical simulations.* The pipeline co-adds the spectra, masks the bad pixels, identifies large spectral gaps, automatically removes the possible metal contamination in the Ly$\alpha$ forest, excludes the proximity region around the background QSO and prepares the control sample for measuring astrophysical parameters. The pipeline also automatically fits the observed spectra with multi-component Voigt profiles for detailed analysis.

## (II) Simulation Analysis: (Gaikwad et al., 2017b, 2018, 2019, 2023)

Performing cosmological hydro-dynamical simulations encompassing a wide range of thermal and ionization conditions for the IGM is computationally intensive. Moreover, addressing the complexity of patchy reionization involves solving the computationally demanding radiative transfer equation. To address these challenges, I have developed five essential codes: **EXtended reionization based on Code for Ionization and Temperature Evolution** (EX-CITE), **VoIgt profile Parameter Estimation Routine** (VIPER), **Generating Lyman Alpha forest Spectra in Simulation** (GLASS), **WEAVEification of mock spectra** (WEAVEify), and **Hydrogen Epoch of reionization using a Ray Tracing** (HEART). EX-CITE is a semi-numerical tool for modeling patchy H I and He II reionization. GLASS efficiently generates numerous mock spectra while considering diverse physical effects. WEAVEify extracts properties from observed spectra and incorporates realistic noise, instrumental broadening, and continuum placement in to the mock spectra. VIPER automates the identification of absorption lines and their fitting with multi-component Voigt profiles. HEART, a GPU-based ray-tracing code, models H I and He II reionization self-consistently. These codes facilitate reionization simulations, enabling the computation of summary statistics like flux probability distribution, flux power spectrum, and effective optical depth distribution. By comparing these statistics from simulations with actual observations, we can quantify the evolution of reionization parameters.

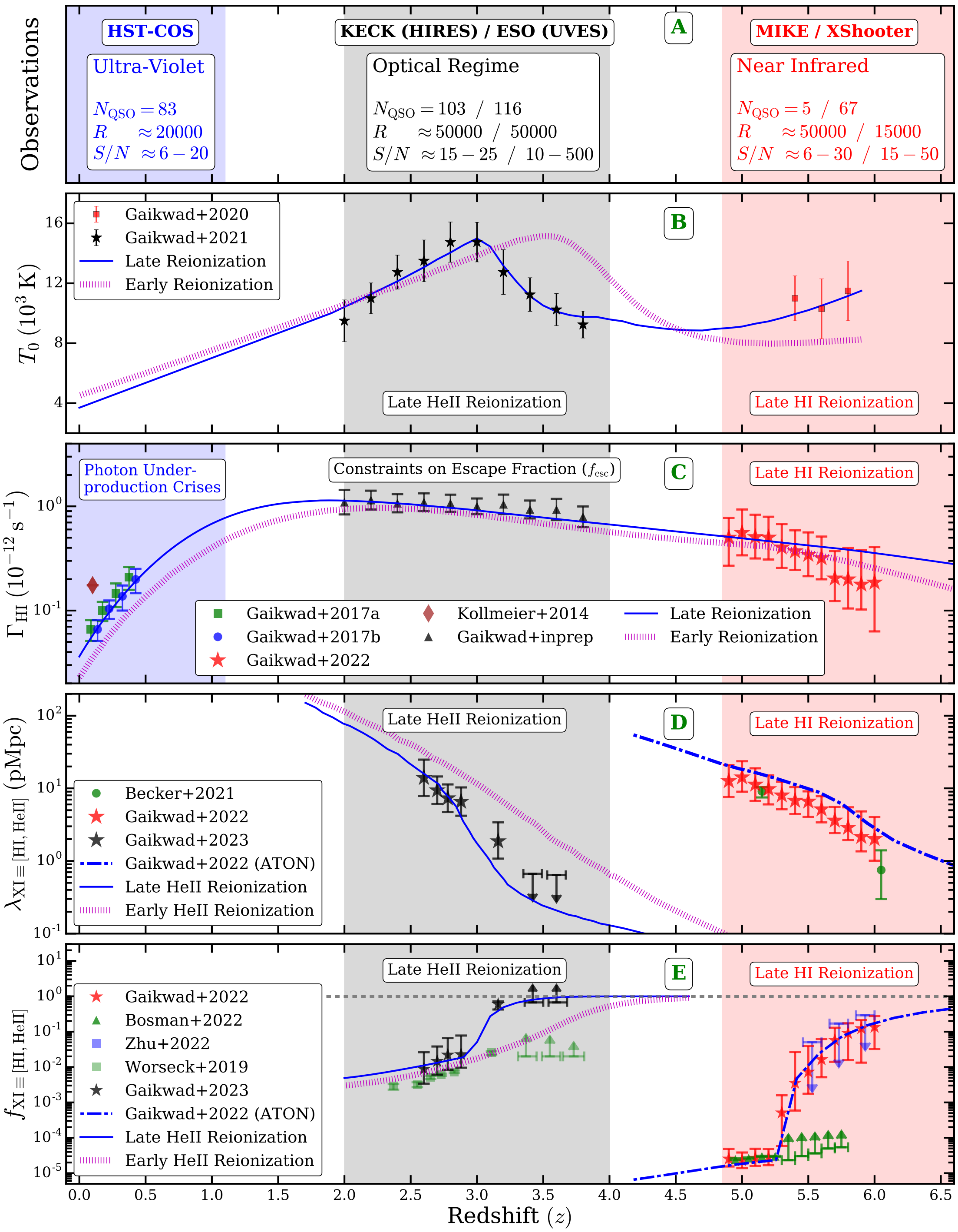


Figure 1: Figure shows summary of our research work (Gaikwad et al., 2017a,b, 2018, 2019, 2020, 2021, 2023). I have developed the codes CITE, GLASS, VIPER, EX-CITE, WEAVEify and HEART to efficiently simulate reionization and analyze the Ly$\alpha$ forest at $z < 6$. This has allowed me (and my collaborators) to accurately measure the parameters characterizing the ionization and thermal state of the IGM from the observations of the Ly$\alpha$ forest with the HST-COS ($z < 0.5$), HIRES / UVES ($2 < z < 4$), MIKE ($5 < z < 6$), XShooter and ESI ($5 < z < 6$) instruments. The data sets from these instruments vary in number, quality and observational systematics of the observed spectra. Panel B, C, D and E show our measured thermal parameter ($T_0$), photo-ionization rate ($\Gamma_{\rm HI}$, $\Gamma_{\rm HeII}$), mean free path ($\lambda_{\rm HI}$, $\lambda_{\rm HeII}$) and neutral fraction ( $f_{\rm HI}$, $f_{\rm HeII}$) evolution accounting for statistical and systematic uncertainties respectively. We also show the evolution of $T_0$, $\gamma$ and $\Gamma_{\rm HI}$ for two reionization histories: (i) early H I and He II reionization (Haardt & Madau, 2012) and (ii) late H I and He II reionization (Faucher-Giguère, 2020). Our main results are: (i) the evolution of these 4 parameters at $z > 5$ is consistent with scenario **in which H I reionization is completed by** $z \sim 5.2$, (ii) our consistent and robust measurement of the the 4 parameters at $2 < z < 4$ is consistent with **late and rapid He II reionization that is completed by** $z \sim 2.88$ and (iii) our $\Gamma_{\rm HI}$ measurements **clearly shows that there is no photon under production crises** at $z < 0.5$ (Kollmeier et al., 2014; Gaikwad et al., 2017a,b). These measurements demonstrates that the observations of QSO absorption spectra put very strong constraints on the thermal and ionization state of the IGM ruling out many models of reionization. We refer the reader to the text below for more details.

## (III) IGM parameters:

Reionization has two profound effects: photo-ionization and photo-heating of the IGM. These effects are characterized by four parameters. The photo-heating is reflected in the evolution of temperature at cosmic mean density, denoted as $T_0$. The photo-ionization involves the evolution of the photo-ionization rate, neutral fraction, and mean free path of ionizing photons. The photo-ionization rate indicates the number of ionizing photons per unit time, while the mean free path reveals the patchiness of IGM during reionization. In our study, we focus on measuring these parameters during the late stages of both H I ($5 < z < 6$) and He II reionization ($2 < z < 4$). We achieve this by comparing simulations with observations of QSO absorption spectra.

## (IV) Implications of measured parameters:

### (i) Evidence for Late H I reionization: (Gaikwad et al., 2020, 2023)

Due to the rapid increase of the Ly$\alpha$ opacity with redshift, the Ly$\alpha$ forest at $z > 5$ show the occurrence of a few transmission spikes and a large scatter in effective optical depth distribution. We have measured the thermal parameter ($T_0$) by comparing the spike width distribution from optically thin and radiative transfer simulations with that from observations (MIKE, instrument, see panel B in Fig. 1). Recently, we measure the photo-ionization rate, mean free path and neutral fraction from a large sample of XShooter spectra by matching the effective optical depth from from our ray tracing code EX-CITE models with observations. Our measurements show that the IGM is significantly hotter than previously assumed and there is significant evolution in mean free path and neutral fraction at $5 < z < 6$. Our measured thermal parameter evolution convincingly establish that HI reionization ends rather late and is only completed by $z \sim 5.2$.

### (ii) Evidence for Late and Rapid He II reionization: (Gaikwad et al., 2018, 2019, 2021)

We have measured the thermal parameter of the IGM in ten redshift bins at $2 < z < 4$ by comparing a sample of 103 Ly$\alpha$ forest spectra observed using HIRES instruments (Keck telescope) with that from our efficient cosmological hydro-dynamical simulations (panel C and D in Fig. 1). We infer thermal parameters using flux power spectrum, line width distribution, wavelet and curvature statistics. The inferred thermal parameters from these statistics agree well within their respective $1\sigma$ errors. We are thus confident, that our thermal parameters measurements are more robust and consistent than previous measurements stretching over 20 years. Using CITE (earlier version of EX-CITE), we also show that the observed thermal parameter can be well reproduced by two existing UVB models, if we assume physically well motivated non-equilibrium evolution with photo-heating rates that are reduced by a moderate factor of $\sim 0.7$. Recently we have analyzed the effective optical depth of He II Ly$\alpha$ forest from HST-COS instrument. By using EX-CITE, we find that the mean free path, neutral fraction and photo-ionization rate of He II is evolving rapidly between $2.88 < z < 3.26$ (Gaikwad+in prep). *These measurements suggests that He II reionization is rapid and also ends later than previously assumed in UVB models.*

### (iii) Resolving Photon-Underproduction crises: (Gaikwad et al., 2017a,b)

The highly ionized state of the IGM at $z < 0.5$ is due to QSOs and galaxies. A recent analysis claimed that the contribution of Galaxies ($f_{\rm esc}$) required to explain the $\Gamma_{\rm HI}$ measurement is significantly larger than claimed observed values (Kollmeier et al., 2014). Thus, a non-standard source of H I ionizing photon would be needed to explain the discrepancy. We have refuted this claim of a "Photon-Underproduction Crisis" by measuring $\Gamma_{\rm HI}$ from a sample of 82 HST-COS spectra (see panel E in Fig. 1). *We find that the measured $\Gamma_{\rm HI}$ evolution is consistent with the scenario where only QSOs contribute to the ionizing background at $z < 0.5$. Our $\Gamma_{\rm HI}$ measurements show that there is no problem in accounting for the observed ionizing photon budget with no ionizing photons escape from galaxies at $z < 0.5$.*

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# Teaching Plan

My teaching philosophy is rooted in the recognition that our rapidly changing world continually presents new challenges. Despite these shifts, the fundamental principles of problem-solving through critical thinking remain same. As an educator, my primary focus is to empower students with the skills to identify problems, think critically, and effectively solve them. I believe in fostering a deep understanding of basic concepts while emphasizing the practical application of learned techniques. Encouraging curiosity among students and nurturing their analytical and critical thinking abilities are central to my teaching approach. By developing problem-solving skills, I aim to equip students with the knowledge and tools to make meaningful contributions to society through a multidisciplinary and innovative mindset. My teaching philosophy harmoniously aligns with the esteemed vision and mission of the IISc. Emphasizing the application of knowledge, promoting curiosity, and encouraging analytical thinking are essential elements of my pedagogical approach, which resonates with the IISc's commitment to academic excellence and societal advancement.

**Teaching methods:** My teaching approach will be a balanced blend of teacher-centered and student-centered methods, tailored to suit different learning contexts and objectives. In the classroom, I'll adopt a teacher-centered approach, providing a structured and organized learning experience to cover fundamental concepts. In labs and tutorials, I'll shift to a student-oriented approach, where students will actively engage in discussions, group projects, problem-solving, and hands-on activities. As a facilitator and mentor, I'll guide and support students, I aim to enhance their curiosity and engagement by nurturing their critical thinking skills to analyze, evaluate, and apply knowledge effectively. The emphasis will be on helping students achieve their learning goals while promoting a practical and application-oriented learning experience. I am open to incorporating technical and innovative methods to make the classroom interactive and dynamic by using keynote presentations, simulations, and short videos to provide real-world experiences and practical insights. These techniques will not only foster a deeper understanding of the subject matter but also encourage active participation and exploration, making the learning process more enjoyable for students.

**Teaching assessment:** In my teaching plan, I will employ both teacher-centered and student-oriented assessment methods to effectively gauge students' understanding and progress. In the classroom setting, traditional examinations will help assess basic concepts, and I will provide feedback to the entire class while identifying critical areas for improvement. Although individual feedback may be challenging in larger classes, I will give special attention to students who need it. In labs and tutorials, students will be evaluated based on their performance in scientific projects, experiments and problem-solving. Scientific experiments and projects will promote real-life collaboration experiences. The examination in labs and tutorials will consist of submitting reports and giving presentations, allowing me to assess their ability to apply knowledge and their oral and written communication skills. Feedback will be provided to the groups of student ensuring their academic growth and success. In designing assessments and projects, I will ensure a balanced level of difficulty that challenges and supports both brilliant students and those with average abilities, fostering an inclusive learning environment that promotes the academic growth of all students.

**Mentoring Students:** As part of my teaching plan, I will actively engage in supervising graduate and under-graduate projects for students at the institute. Drawing from my prior experience in mentoring students through such projects, I will adopt a student-oriented approach, empowering them to develop critical problem-solving skills and gain practical expertise. I will guide and support the students while encouraging them to take ownership of their projects, fostering independent thinking and initiative. This approach will allow students to explore new ideas and techniques to address scientific challenges. By allowing students to take charge of their projects, they will gain a deeper understanding of the subject matter and develop valuable research skills. During project supervision, I will emphasize the significance of scientific methods and ethics through practical, hands-on experiences, offering valuable insights into the research process. I will offer guidance on writing scientific reports and papers, emphasizing the importance of effective communication through presentations and peer interactions. Through this student-centered approach, I aim to create a stimulating learning environment, where students are inspired to explore, innovate, and contribute to the field of astrophysics. My goal is to nurture the next generation of scientists and equip them with the necessary tools to succeed in their academic and professional pursuits.

**Courses :** In line with the physics department's curriculum, I am well-equipped to contribute to a wide array of courses that span both astronomy and general physics.

**JAP COURSES :** With a research background encompassing the analysis of observational data in various spectra, development of radiative transfer codes, utilization of atomic transitions for absorption spectroscopy modeling, expertise in fluid equations through cosmological simulations, and utilization of computational methods such as Octree, I am well-prepared to teach a diverse array of courses. My deep familiarity with radiative processes, fluid dynamics, intergalactic medium dynamics, and cosmological simulations equips me to instruct on 'Radiative Processes in Astrophysics', 'Introduction to Fluid Mechanics and Plasma Physics', 'Galaxies and Interstellar Medium', 'General Relativity & Cosmology', and 'Astronomical Techniques'. My ability to seamlessly bridge the gap between cosmology and galaxy formation adds a unique dimension to these teachings.

In my teaching approach to JAP courses, I am committed to enriching the curriculum by introducing valuable new topics. For instance, in the Radiation Processes course, I plan to incorporate discussions on radiation from molecular lines, including rotational and vibrational transitions (CO and PAHs transitions). Furthermore, in the Galaxies and ISM course, I propose to explore the role of feedback mechanism, Circum-Galactic Medium and dark matter halo in shaping the chemical and dynamical properties of galaxies. The Cosmology and General Relativity course will also encompass statistical descriptions of the universe and concepts like the redshift space distortions and Kaiser effects, while the Astronomical Techniques course will benefit from added introductory talks on Astrostatistics, Big Data mining, and practical projects on Machine Learning.

I envision introducing a compelling new course on Planet and Star Formation, spotlighting the origins of solar system, the intricate atmospheres of exoplanets, and the theoretical framework of planet and star formation sites like proto-planetary and circumstellar disks. Central themes will include habitable zones and advanced observational techniques for detecting exoplanets, aligning with the technological advancements of observatories like JWST, TMT, and E-ELT.

**GENERAL PHYSICS COURSES :** In addition to JAP courses, for more general physics-related courses, my expertise encompasses 'Computational Physics', 'Classical Mechanics','General Physics Laboratory', 'Quantum Mechanics-I','Statistical Mechanics' and 'Mathematical Methods of Physics'. I propose a new course titled 'Advanced Mathematical and Numerical Methods in Physics.' This course explores the essential mathematical and numerical tools pivotal to contemporary research. We will delve into solving first-order ordinary and partial differential equations using the method of characteristics, alongside topics such as Sturm–Liouville theory and the applications of Parabolic, Hyperbolic, and Elliptic PDEs (Heat, Wave, and Laplace's Equation). The course will also emphasize solving PDEs using Green's functions and their practical applications in physics. Additionally, we aim to cover numerical techniques, including FFT, Riemann Solvers, Tree Decomposition, and Fast Multipole Methods. The course structure will comprise 20% assignments, 30% numerical methods projects, and 50% final examination. Through this course, students will gain basic knowledge of mathematical tools and numerical strategies that underpin modern physics research.

**Resources:** In preparing my courses, I am dedicated to aligning them with current academic and industrial requirements. For theoretical courses, I will utilize textbooks and academic journals to provide a strong theoretical foundation for emphasizing diverse perspectives on same topic. To enhance student's comprehension and interest, I will integrate multimedia resources, like educational videos and interactive simulations. Open educational resources will also be leveraged to promote inclusivity and accessibility. In practical courses, students will gain hands-on experience with observational tools and computational software, including access to physics databases and modern research tools. This exposure to authentic research and data analysis will equip students with valuable skills. I am committed to continuous improvement, regularly updating my teaching materials to reflect the latest advancements in physics and meet the evolving needs of students.

**Soft skill courses:** In addition to offering fundamental technical courses in physics, I am keen on organizing courses focused on enhancing student's soft skills. These skills are crucial not only for academic success but also for their professional careers, especially in today's collaborative and team-oriented work environments. The soft skill courses will cover a wide range of topics, including effective communication, report writing, presentation skills, coding practices such as git version control, creative problem-solving approaches, professional and scientific ethics, team collaboration, high-performance computing, and machine learning. These courses can be delivered in various formats, such as workshops, short lecture series, and interactive schools, to provide students with practical and valuable learning experiences.

**Engagement with Industry** A significant part of my teaching plan aim to bridge the gap between fundamental sciences and industry by incorporating relevant skills and knowledge in the course structure. Leveraging my engineering background and connections with industry professionals, I will actively engage with them to understand current standards and requirements. This will enable me to better equip the students with practical and up-to-date training, ensuring they possess sought-after skills and knowledge for their academic and professional success.

**Equity and diversity of students :** Embracing India's diverse community, I will approach students with compassion, acknowledging their varied social, economic, religious, and linguistic backgrounds. I am deeply committed to fostering an inclusive and supportive learning environment that provides equal opportunities for all students, regardless of their background, gender, ethnicity, or ability. I will treat each student with respect and recognizing their unique challenges and needs. I strongly believe in promoting diversity and ensuring that every individual feels valued, respected, and encouraged to excel. It is my priority to create a space where marginalized communities, women, and people with disabilities can thrive and contribute to the learning process. I actively strive to remove barriers to education and embrace diverse perspectives, as I firmly believe that diversity enriches the learning experience.

**Feedback and Continuous improvement :** I believe that continuous improvement is crucial in enhancing the learning experience for students. To achieve this, I am dedicated to seeking feedback from students through various channels. Direct feedback will be collected through Google forms, anonymous department-level surveys, and oral discussions, giving students multiple opportunities to provide their insights. Additionally, interactive engagement during lectures will help gauge their understanding and identify areas for improvement. Flexibility in adapting to the pace and content of the lectures ensures that the course meets students' needs effectively. This feedback-driven approach ensures that the course evolves and continually enhances the learning outcomes for students. Indirect feedback, such as asking questions in class to assess comprehension of past lectures, further contributes to the refinement of my teaching and communication skills.

My multi-disciplinary educational background encompassing various fields in the sciences, along with my significant industry experience, uniquely positions me as a versatile educator capable of delivering a practical and application-oriented approach to teaching. By drawing from my background in diverse scientific disciplines and incorporating industry insights, I can bridge the gap between theoretical concepts and real-world applications. This approach not only enhances students' understanding of scientific principles but also equips them with the skills and knowledge required to thrive in their future careers in science or related industries. Moreover, in my classroom, I will foster an environment where students can explore the connections between academia and real-world practices, empowering them with a holistic education that goes beyond theoretical boundaries.